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PhD IN SOIL DEFENSE AND CONSERVATION, ENVIRONMENTAL VULNERABILITY AND HYDROGEOLOGICAL PROTECTION

Cycle XXVI

ENGINEERING GEOLOGICAL CHARACTERIZATION OF VOLCANIC ROCKS OF ETHIOPIAN AND SARDINIAN HIGHLANDS TO BE USED AS CONSTRUCTION MATERIALS

Sector of Scientific Disciplines: *Applied Geology [GEO/05]*

Presented by: *Tesfaye Asresahagne Engidasew*

Doctoral Program Coordinator: *Prof. Felice Di Gregorio*

Tutor: *Prof. Giulio Barbieri*

Academic Year 2012/2013

I certify that although I may have conferred with others in preparing this thesis, and drawn upon a range of sources cited in this work, the content of this PhD dissertation is my original work.

Engidasew Tesfaye Asresahagne

Disclaimer

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Tesfaye Asresahagne Engidasew
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Abstract

This thesis presents the results of the study conducted on the "Geoengineering characterization of volcanic rocks from Ethiopian and Sardinian highlands to be used as construction materials". Though, the two project areas are geographically far apart, both are partly covered with volcanic rocks mainly consisting of basic and subordinate felsic rocks.

The research was conducted in two countries; part I, the Ethiopian Project area located on the northwestern central Highlands of the Amhara regional state. It is characterized by rugged topography being situated on the western margin of the Main Ethiopian Rift, while, Part II, the Sardinian Project area, is located in the northwestern central part of the Island stretched from Abbasanta-Borore on the Altopiano di Abbasanta.

The major objectives of the study in both project areas include; a) engineering geological characterization of the volcanic rocks of Sardinian (Abbasanta-Borore area) and Ethiopian highland (Tarmaber formation) to be used as construction materials b)assessing the volcanic rocks for their suitability to be used as building stone and coarse aggregates/construction materials with regard to the various time honoured standards and specifications like American Society for Testing and Materials(ASTM), British Standards(BS), American Association of State Highway and Transportation Officials (AASHTO), Ente Nazionale Italiano di Unificazione (UNIEN) c) presenting a conceptual framework which puts forward a vision for future crushed aggregate characterization of the Tarmaber formation, d)evaluation and comparison of the physical and mechanical properties of the Sardinian highland Plio-Quaternary basalt with that of Ethiopian Tarmaber formation(basalt).

The field work in the Ethiopian study area was accomplished in two phases, the first field work was conducted during the months of February and July, 2011 and the second was in February and September, 2012, while the Sardinian project field work was carried out during May and June, 2012. In all these field work periods geological traverses, field documentations and adequate samples were collected for the various laboratory tests in both project areas. Laboratory testing of chemical, physical and mechanical properties were carried out to characterize the volcanic rocks from both study areas to ascertain the suitability of the rocks as construction materials.

Geologically, the Ethiopian study area is part of the Miocene Shield volcanic terrain that covered the western and north western central plateaux of Ethiopia forming a conspicuous land feature in East Africa. The studied area is specifically covered with the Tarmaber formation (Megezez subdivision) consisting of aphyric basalt, phyric basalt, trachybasalt, ignimbrite/rhyolite, tuff and minor trachyte.

Thorough literature review has been conducted on volcanic rocks as construction materials and from the compiled information a laboratory testing program was envisaged and conducted on the samples collected from the studied areas. Selection of the tests was based upon the tests' precision, efficiency, and predictive capabilities and relevancy for the specific geographic location and geologic formation. In the laboratory testing phase of this project, the proposed tests were used to evaluate the full range of the project area crushed aggregate resources. Moreover, a conceptual laboratory test flow diagram is developed for future aggregate characterization of the Ethiopian project area. Furthermore, a geological map is prepared outlining the various lithotypes which could help to predict the geo-engineering properties of the rocks by identifying the rock types.

The Ethiopian project area is the major source and future potential of crushed coarse aggregates by both private and public sectors. This study has identified recent advances in the understanding and testing of crushed aggregates to be produced from the Tarmaber formation (Megezez subdivision).

The geo-engineering properties depend on the mineral composition, texture and overall fabrics of the rock. Each of the rock type crushed aggregate demonstrates rather well defined ranges of geo-engineering properties and mineralogical characteristics. The laboratory work included Uniaxial Compressive Strength, Abrasion resistance, Ultrasonic pulse velocity, Bulk density, Water absorption, Specific gravity, Porosity, Petrographic examination, Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), Los Angeles Abrasion Value (LAAV), Sodium Sulphate Soundness Value (SSSV), X-ray Diffraction(XRD) and Alkali-Silica Reactivity(ASR), Water soluble Sulphate and Chloride tests.

The physical and mechanical properties like Water absorption, Flakiness and Elongation indices, and Specific gravity, strength and durability parameters have been determined and examined critically with reference to suitability and stability, taking into consideration the various specifications and time honoured standards. Hence, based on the geo-engineering and *petrographic properties, optimal end uses of the different rock types have also been discussed even though the current study is mainly geared towards crushed aggregate sources for cement and asphalt concrete mix.*

The field and laboratory works were compiled and compared together to reveal the engineering performance of the basaltic rocks in terms of crushed coarse aggregates suitability. The basaltic rocks show a variety of textural and mineralogical characteristics, which may affect their physical and mechanical properties as well as their use as construction materials. The Uniaxial compressive strength of the basaltic rock ranges from 130MPa to 350MPa, Ultrasonic pulse velocity from 4000m/s to7000m/s, Open porosity from 0.95% to 3.08%, Bulk density from 2.8g/cm^3 *to 3.03g/cm*^{3}*, Point load index from 4.83 to15.29MPa, Water absorption from 0.33% to 1.08%, Dynamic Elastic Modulus from 64GPa to 120GPa, Abrasion Resistance(Capon wheel) from 15.5mm to 25.2mm, Specific gravity from 2.51 to 3.00, SSSV from 1% to 10%, ACV from 15% to 30%, AIV from 20% to 36%, TPFV from 110kN to 200kN, Los Angeles Abrasion Value from 12% to 30%, Flakiness index from 15% to 37%, and Elongation index from 15% to 38%. The Alkali-Silica Reactivity test was carried out using 'Mielenz quick chemical' test (ASTM C289) and few basaltic flow layers were found to be potentially Alkali-Silica Reactive. The petrographic examination and XRD analysis also confirmed the presence of reactive quartz and harmful zeolite group minerals.*

In this study, the different rock types has been investigated as sources of individual rock type crushed aggregate for specific end use rather than aggregates comprised of various rock types. In this respect, the aphyric basalts are found to be the most suitable crushed aggregate source for ordinary Portland cement and asphalt concrete, sub base and base course. The porphyritic basalt and glassy rhyolite should be used in unbound pavements only. The minor amounts of zeolite bearing uppermost layer of phyric columnar basalt also should be avoided from concrete making for safe stability of structures due to risk of potential Alkali silica reactivity.

Geochemically the Tarmaber formation represents alkaline-subalkaline bimodal mafic-felsic volcanic series. The mafic volcanic suite is more abundant and characterized by alkaline basalts and minor silica undersaturated rocks (basanites) and the felsic suite is relatively less abundant and represented by strongly welded ignimbrite/rhyolite, tuff and minor lava flows of trachyte. Furthermore, the mafic suite is characterized by sodic affinity on conventional K_2O *versus* Na_2O *diagram. The* Fe_2O_3 *content is high for all the samples (11.53-15.79%) and high* $Na_2O + K_2O$ *content (~4.04-6.2%) is typical of alkaline basalts of Tarmaber formation. The*

MgO is low (3.45-7%), while 0.3-1.3%P_2O_5 and 2.8-4.5%TiO_2 are relatively high. Loss On Ignition (LOI) varies between 0.5% and 1.5% indicating the unaltered nature of the sampled rocks.

The geo-engineering properties of the Tarmaber formation (the basalts and pyroclastics/ignimbrite) indicated that the pyroclastics (ignimbrite) are found to be good building materials with regard to their high uniaxial compressive strength, abrasion resistance and weathering index. However, their relatively higher water absorption and porosity limit them not to be used in public walkways, horizontal pavements, public car parks and flooring in supermarkets in an open environment as intensive use while some flow layers of the basalts are mainly suitable for production of coarse aggregates for cement concrete mix.

The Sardinian project area is part of the Plio-Quaternary volcanic rocks that covered the north western central plateaux of the island forming flat topped land feature. The studied area is specifically covered with the 'Basalti di Plateau'' consisting of porphyritic basalt, vesicular basalt, andesitic basalt and trachybasalt. The physical and mechanical tests conducted on these rocks proved the high potential of the studied rocks to be used in the construction industry. The Uniaxial compressive strength ranges from 35 to 177MPa, Ultrasonic P-wave velocity from 4143m/s to 6066m/s, Water absorption from 1.51 to 3.11%, Porosity from 0.64 to 10.33%, Specific gravity from 2.26 to 2.71, Bulk density from 2.2 to 2.69g/cm^3, Abrasion Resistance(Capon wheel) from 19.4 to 23.6mm, Point Load index from 1.98 to 7.05MPa, ACV from 19 to 46%, LAAV from 17 to 33%, Dynamic Young's Modulus from 33GPa to 92GPa to mention a few test results. Furthermore, Alkali Silica Reactivity test, X-ray diffraction analysis and detail petrographic studies were conducted on the collected Sardinian samples. According to the Alkali Silica Reactivity test, a sample is found to be deleterious (highly reactive) and later XRD analysis and petrographic study also confirmed the Alkali Silica Reactivity test result.

The Sardinian samples have shown acceptable abrasion resistance values and uniform physical and mechanical properties which guarantee to be used as dimension stone/cut stone. The Abbasanta-Borore Plio-Quaternary basalt resource is huge; however, some clays in some samples were indicated by the XRD analysis and these clays might have deleterious effect when using these basalts as aggregate; therefore, the clay fraction should be determined with quantitative XRD analysis for curiosity, otherwise, almost all the conducted aggregate tests indicated relatively good quality aggregate resource except the vesicular basalt. The vesicular *basalt showed poor aggregate test values, like LAAV and Water absorption, ACV and Uncompacted bulk density. However, for its aesthetic value, the vesicular basalt could be used for indoor and sheltered cladding purposes as the case may be.*

One of the purposes of this research was to compare some of the engineering properties of basaltic rocks to determine whether there are similarities and differences between each of the different source countries, Ethiopia and Sardinia. This is particularly interesting given the distance between the two countries and the different processes that have occurred since the formation of these basaltic rocks. The Ethiopian volcanic successions lack rocks of intermediate composition (bulk rock chemistry: SiO_2, 52-63%), defining strong silica gap as observed in other volcanic areas, suggesting the bimodal volcanism nature of the Ethiopian volcanic suite in non subduction tectonic setting and implying anorogenic magmatism probably connected to plume/hot spot source.

Geochemically, the Sardinian Plio-Quaternary volcanic rocks lack significant ultrabasic compositions (i.e., bulk rock silica SiO_2 composition <45% are rare, Lustrino et al., 2007) while the Ethiopian Tarmaber formation bulk rock silica composition reaches as low as 42% and not greater than 51% while the Sardinian rocks reaches as high as 63% (andesitic). Intermediate rocks are totally absent in the Ethiopian Tarmaber formation. The physical and mechanical properties of the Tarmaber basalt are found to be higher than the Sardinian Plio-Quaternary basalts. Although grouped under the engineering term "basaltic", there are distinct differences within the specific types present in each of the countries considered in this study, i.e. mainly basaltic andesite in Sardinia and basalt in Ethiopia.

Evaluation of the physical and mechanical data indicates that the Ethiopian basalts are typically of higher density and resistance to static crushing than the Sardinian Plio-Quaternary basalt. The difference in engineering properties of aggregates from Sardinia on one hand and Ethiopia on the other hand is explained partly by the chemical composition of the material, but also by geological age, geological history and climate.

In both countries the geological history of the basalts might have influenced the aggregate properties. Furthermore and more importantly, regional conditions (such as hydrothermal activity) might have influenced the rock properties and alteration products. The physical and mechanical properties of the Ethiopian basalts have shown better compliance with the various specifications than the Sardinian basaltic samples especially the aggregate test results.

Comparison of the results is revealing that different physical and mechanical trends are observed from rocks that are similar in basic mineralogical composition. This suggests that the relationships between physical and mechanical properties are often specific to rock type and occurrence.

Aggregate quarrying provides necessary raw materials for infrastructure and civil development; however, mining and/or quarrying operations have a non-zero environmental impact. By the very nature of the requirements for the final products, dimension stone and aggregate quarrying is a clean industry from a polluting point of view. Natural aggregates and dimension stone are used in its natural state, and do not require concentration and extraction from an ore; it is these latter two processes that result in significant environmental impacts. However, the visual impacts are often significant, given that many deposits are situated in topographically high areas. The environmental impacts of dimension stone and aggregate quarrying are mainly of temporary duration, and can be effectively managed via revegetation, landscaping, rock shading, if appropriate planning and consideration is followed from the exploration stage through to quarry closure. Hence, quarrying and post-quarrying activities should always target the mitigation of potential environmental and/or social impacts.

Key words: ***Dimension stone, crushed aggregate, physical properties, mechanical properties, chemical properties, mineralogical composition, Debrebirhan (Ethiopia), Abbasanta-Borore (Sardinia)***

"Like stones rolling down hills, fair ideas reach their objectives despite all obstacles and barriers. It may be possible to speed-up or hinder them, but impossible to stop them" (José Marti, 1957)

"Whatever the project a person has to execute, the* LION *teaches us to begin it with full thrust of your power and not to relax till the task is completed"(Chanakya Neeti, 1942)

"Everything has been thought of before, but the problem is to think of again" (Johann Wolfgang VonGoethe, 1937)

"I am thankful to all those who said* NO *to me it's because of them I did it myself" (Albert Einstein)

DEDICATION

This thesis is dedicated to 'in loving memory of my late grandmother, Kelkayelesh Desalegn (1915-1996)'

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List of acronyms

AAR	Alkali Aggregate Reaction
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACR	Alkali Carbonate Reaction
ASR	Alkali Silica Reaction
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
ASTM	American Society for Testing and Materials
APAT	Agenzia per la Protezione dell'Ambiente e per i servizi Tecnici
BRE	Building Research Enterprise
BS	British Standards
CIPW	Cross, Iddings, Pirsson and Washington
CAS	Central Statistics Authority
CFB	Continental Flood Basalt
DEM	Digital Elevation Model
DIGITA	Dipartimento di Geoingegneria e Tecnologie Ambientali
EN	European Standards
FIEC	European Construction Industry Federation
GSE	Geological Survey of Ethiopia
HT	High Titanium
ICAR	International Centre for Aggregate Research
ICOLD	International Commission of Large Dams
ISTAT	Istituto Nazionale di Statistica Ufficio Regionale per La Sardegna
ISRM	International Society for Rock Mechanics
LIP	Large Igneous Province
LAAV	Los Angeles Abrasion Value
LOI	Loss On Ignition
LT	Low Titanium
MER	Main Ethiopian Rift
NMA	National Meteorology Authority
PUNDIT	Portable Ultrasonic Non-Destructive Digital Indicating Tester
REE	Rare Earth Elements
RILEM	Reunion International des Laboratories et Experts des Materiaux (French)
RMR	Rock Mass Rating
SSSV	Sodium Sulphate Soundness Value
TAS	Total Alkali Silica
TPFV	Ten Percent Finesse Value
TCDSCo	Transport Construction Design Share Company
UCS	Uniaxial Compressive Strength
UNI	Ente Nationale Italiano di Unificazione(Italian)
USA	United States of America
USGS	United States Geological Survey
UEPG	European Aggregates Association
VP	Ultrasonic P-wave Velocity
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

CHAPTER ONE

1. Generalities

This is a study for award of a PhD research conducted on the physical and mechanical characterization of volcanic rocks from Sardinia and Ethiopia for construction materials. Rocks and cement have been used for construction since ancient times, although the relative importance of these resources has changed with time. Many ancient civilisations developed the use of natural stone to a fine art, and dimension stones still occupy an important place in architecture, particularly in the construction of prestigious buildings in the developed world.

Rocks to be used as construction materials in this thesis refers to dimension stone and crushed aggregates that have been produced from natural rocks using hand tools and motorized machines. In construction, stone refers to a rock that has been quarried or mined and worked for use in constructing the building fabric (Shadmon, 1989; Dimes, 1999).

The human race has relied on natural rocks for the construction of buildings since the ancient times. Historical evidence on the use of stone in buildings is found in many ancient structures including caves hewn in stone. Shadmon (1996) has described that only one (the Hanging Gardens of Babylon) of the Seven Wonders of the World is not wholly made of stone. Despite being associated with such archaic technological exploits, stone still remains a significant material for the construction of buildings. Nowadays, stone can be used in the construction of the built environment in several ways as described by Hornbostel (1991).

Stones can be used as construction materials. The types and uses include: rough stone, rubble stone, dimension stone, monumental stone, stone tiles, flagstone, crushed and broken stone and stone dust or powder as shown in Figure 1-1.

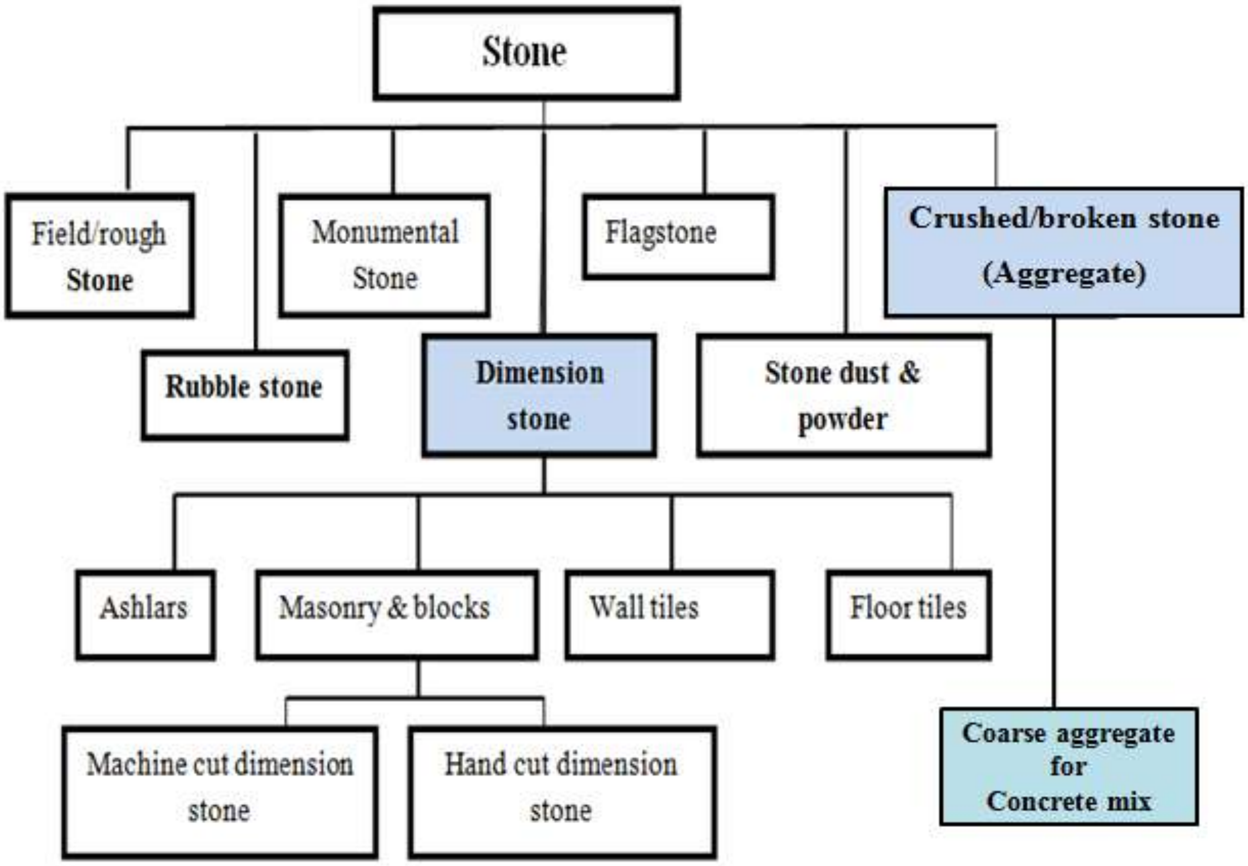

Figure 1-1 Common types of construction stone use

Hornbostel (1991) gives detailed descriptions of the various types of stone used in building construction as summarized below

Stone Type/Use	Description
Field/rough stone	Also known as rough building stone. Consists of rock faced masses of various sizes and shapes
Rubble stone	This refers to irregular stone fragments having at least one good face that are obtained from quarries. It can be cut and made into blocks and pieces for building walls, veneers, copings, sills etc
Dimension stone	Also referred to as cut stone or ashlar. It may be obtained as finished products from stone mills done to a specific size, squared to dimensions each way and to specific thickness. There are two types of finishes; the surface is rough or the natural split of the stone and the surface is smooth, slightly textured or polished. It can be used for exterior or interior surface veneers of buildings, prefabricated panels, preassembled systems, toilet partitions, flooring, stair treads, copings, sills, bearing walls etc

	Ashlar is now included under dimension stone; it refers to smaller, rectangular stone with a flat-faced surface, generally square or rectangular, having sawed or dressed beds and joints
Monumental stone Flagstone	Refers to flat slabs of thin stone generally from 1 to 2 in. (25.4 to 50.8 mm) thick, either irregular or squared, with the surfaces smooth, slightly rough, or polished Flagstone is used in the exterior for paths, walks, and terraces and on the interior as stair treads, flooring, blackboards, copings, sills, countertops, etc
Crushed stone	Crushed or broken stone consist of chips, granules, or irregular shapes that have been graded and sized for construction work. Crushed stone usually begins at ¼ in. (6.35 mm) and runs by various stages to 2½ in. (63.5 mm) size. It differs from large-size gravel in being usually composed of only one kind of rock. It is used as aggregate in concrete work and asphalt walks, roads, driveway paths, and other travelled areas, as surfacing material for asphalt shingles, siding, and built-up roofing; and in terrazzo and artificial stonework
Stone dust	Stone dust or powder is used for surfacing asphalt paving, as fill in paints, for resilient flooring etc

The common ways in which stone can be used in wall construction (stone masonry) are shown in figure 1-1 (Hornbostel 1991)

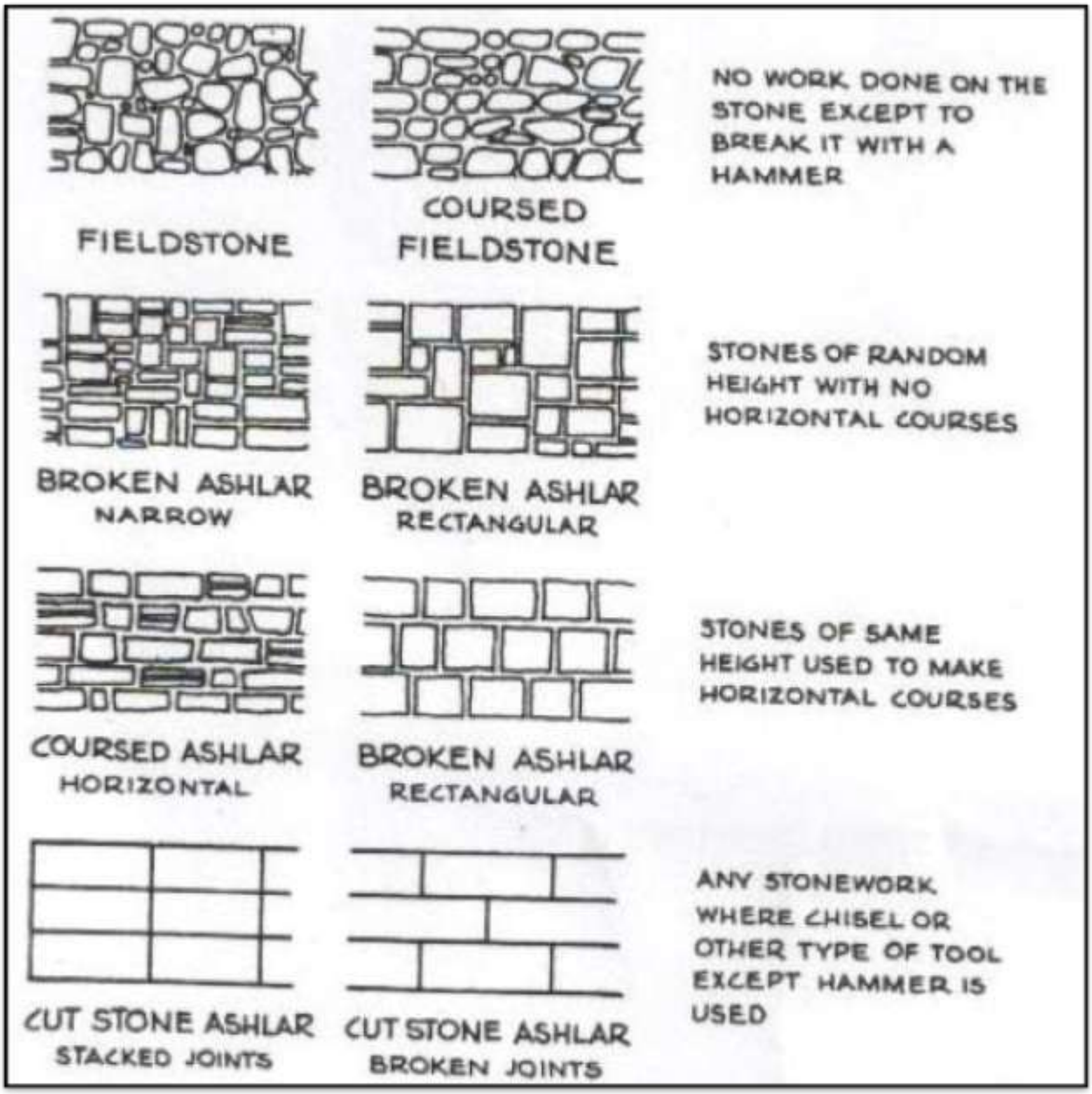

Figure 1-2 Common types of masonry works

Dimension stone refers to rock that has been cut and worked to a specific size or shape for use in building (Ashurst and Dimes 1977). There are different types of dimension stones that may be used in the building envelope including tiles for roofing, tiles or slab stone for floor finish, tiles for wall finish and blocks for stone masonry. The focus of this study is partly on stone masonry also known as ‘cut stone’ or ‘ashlar’ (Hornsbostel 1991) and crushed stone aggregates for Portland cement concrete mix. In this context, dimension stone takes the meaning attributed to it by Prentice (1990) as pieces of stone that have been cut into regular (three) dimensions and used for wall construction.

However, for any industrial scaled operation on building stone, it is of vital importance that the deposit can give commercial-sized blocks (minimum 220 x 120 x 100 cm) and/or slabs of uniform quality, with production costs matching the market price (Shadmon, 1996).

According to Shadmon (1989) there are two categories of tools used in extracting and working (manufacturing) dimension stone, i.e. hand tools or machine tools. Hand tools, in this case, include: levers, jacks, picks, hammers and chisels for extraction; chisels (including pneumatic), drills, saws, grinding stones and polishing powder for stone-working (Shadmon 1989). On the other hand, machine tools include: jack-saws, saws, wire-saws, chain-saws, mechanical chisels for extraction; saws, planers or, grinders and polishers for manufacturing (Shadmon 1989).

Every stone material used in such projects originates from quarries and undergoes a long “story” before it can become a finished product: research, study, quarry work, technical tests and, lastly, processing and finishing to meet in full the technical and aesthetic requirements of each kind of application (Primavori 1999).

Structures which are covered with natural stone have more economic and longer service period. Moreover, they give more aesthetic and prestigious appearance, compared to alternative materials. Day by day, joint application of natural stones in harmony with other construction materials, have increased. The properties of natural stones as appearance, colours, physical and mechanical properties, must be defined correctly to identify their end use. The correct choice of natural stone can be achieved by using suitable material in correct places and in correct manner, according to existing related norms and standards.

Ethiopia has one of the oldest and most complex geology of any country on earth, with fine examples of classical geological features, many unique minerals (REE) and, of course, significant riches in the form of exploitable industrial and precious minerals. Up to now, the geology and related mineral and mining industry contributed no significant role in the economic development of the country, which is still at its early stage.

During the last decades and especially during the 1990’s, systematic prospecting for building stone in Ethiopia has been carried out by both the Geological Survey of Ethiopia (GSE) and private companies, and a number of building stone deposits throughout the country have been put into small scale production. This is reflected by the extensive use of Ethiopian stone in new buildings in the capital and other major cities of the country (Walle et al. 2000).

In the fiscal year 2008-09 (the latest year for which data were available), the mining and quarrying sector accounted for only, 0.4% of the gross domestic product. The value of output in the mining sector increased by 6% in the fiscal year 2008-09 and was expected to rise in the coming years. An estimated 300,000 to 500,000 Ethiopians were employed in artisanal mining activities (D'Souza, 2009). Little of Ethiopia's expected mineral potential has been exploited, although foreign investment was increasing. Also mined in limited quantities were brick clay, kaolin, common clays, columbium (Niobium), diatomite, feldspar, semiprecious gemstones (fire opal, amethyst, peridot, rose quartz), rock salt, scoria, natural soda ash, sand and gravel (crushed construction stone), dimension stone, granite, limestone, gypsum and anhydrite, lignite, lime and pumice.

To date, the demand for geological construction materials is escalating from time to time due to the construction boom which is evidenced by unparallel expansion and upgrading of infrastructures such as highways, airports, dams, schools, hospitals, public and private buildings in major cities and particularly in Addis Ababa (Figure 1-3, USGS, 2010). According to these data, the production of volcanic rocks construction materials (basalt, ignimbrite and rhyolite) is surprisingly increasing while granite, marble and limestone production on the other hand is getting declining in Ethiopia. This implies that there are high demands of volcanic rocks in the form of crushed aggregates, selected aggregates, cobble stone and flagstone, masonry and even as dimension stone. On the other hand, there is no proper characterization of these rocks towards its physical and mechanical properties for which purpose they are best suitable and preferable. So, it is utmost important to characterize these rocks towards its suitability as construction materials considering the various physical and mechanical properties and standard/specifications and hence to identify their suitable end use.

Among the construction activities undertaking in Ethiopia, road construction by federal and regional governments, government sponsored housing projects (especially condominiums), and real estate projects are remarkable, and especially the later is contributing its part to solve critical housing problems in the capital and major cities.

Currently, Ethiopia is striving to continue its economic development by expanding its infrastructural network and constructing economic and social service giving buildings, high standard highways, hydro-power and irrigation dams and other schemes. Such construction boom needs also high standard and project specific engineering geological understanding of construction materials for safe and durable civil structures. It is anticipated that the current fast development in developing countries in urbanization undoubtedly requires more housing and infrastructure which in turn demand high tonnage and quality geomaterials as an input.

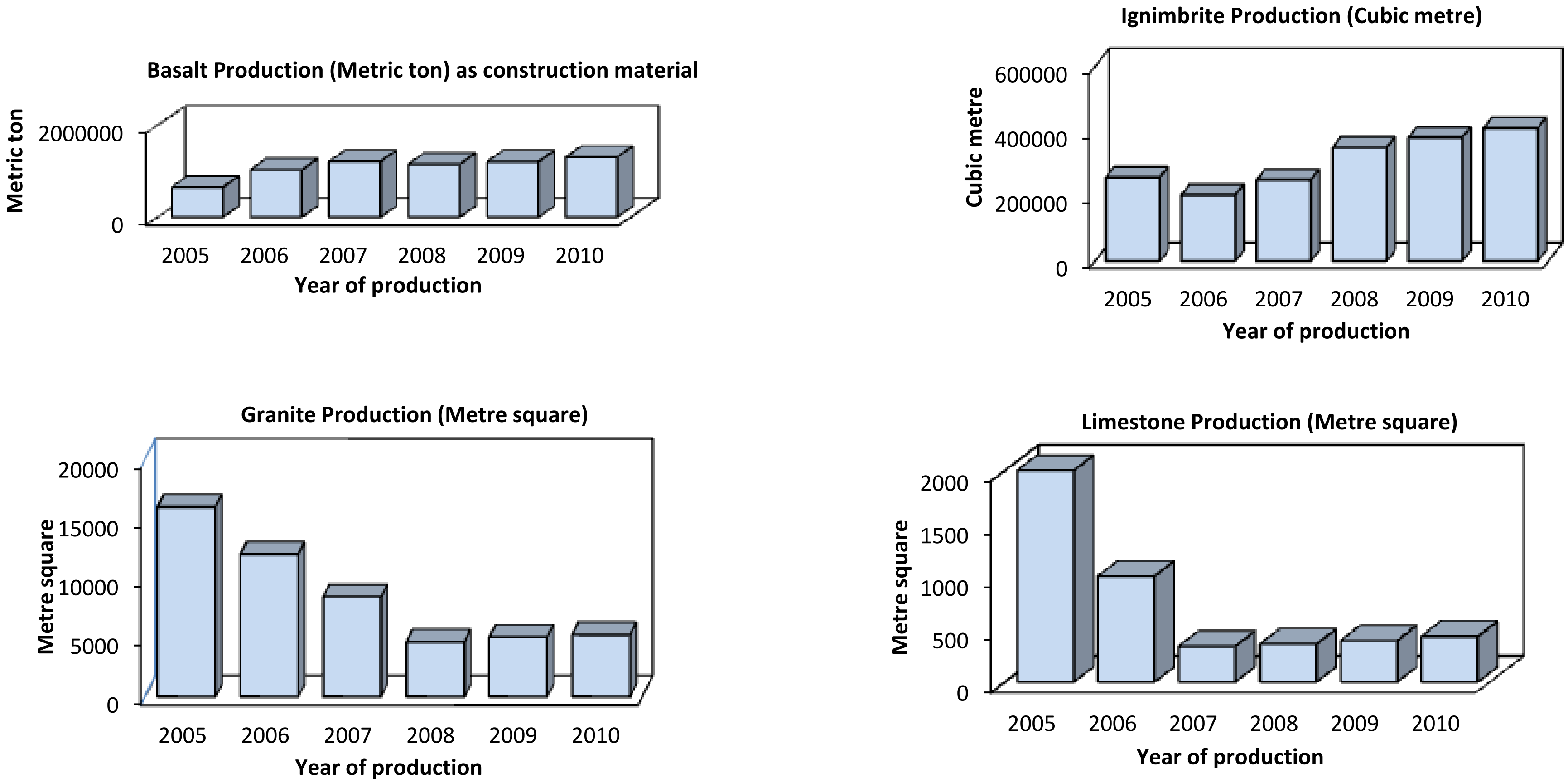

Figure 1-3 Construction mineral production of Ethiopia (2005-2010)

There has been a recent increasing demand for the identification of quality aggregate sources in Ethiopia for the construction of roads, airport runways and multi-story buildings, etc. In addition, the government has encouraged micro-business entrepreneur of aggregate producers in the country aiming to ensure continuous supply and creating job opportunity.

Due to the current rapid infrastructure development in Ethiopia, it is found timely to characterize and identify in-situ hard-rock aggregate sources that could potentially be developed into quarries in the recent future and equally it is found important to assess the existing small scale quarries currently used as aggregate source with regard to suitability in view of the current tight standards and specifications.

With the recent increasing demand for high quality volcanic rock-derived aggregates, the focus has been shifted to developing new sources in the peripheries of the major cities in Ethiopia. The crushed rock coarse aggregates derived from volcanic rocks in these areas are almost currently dominating the market for both asphalt and cement concrete mix but are not adequately available and fully characterized to produce standard cement concrete. This has prompted the government to seek and identify still new potential volcanic rock aggregate sources in the country (Table 1-1 and Figure 1-4).

Year of Production	**Production (m^3)**
2004	443,798
2005	169,958
2006	384,568
2007	281,385
2008	179,119
2009	398,789
2010	456,987

Table 1-1 Production of coarse aggregate in Addis Ababa and surroundings (after Denamo, 2012)

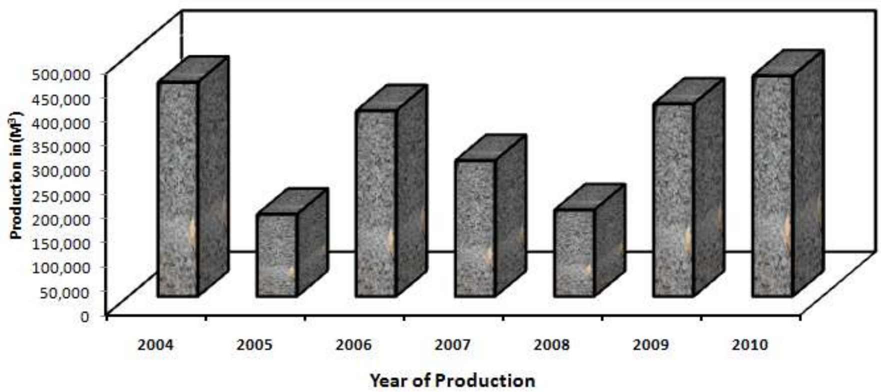

Figure 1-4 Coarse aggregate production in Addis Ababa and surroundings

The construction industry is demanding by 50% supply of coarse aggregate every year (Table 1-2 and Figure 1-5) in Addis Ababa and its surroundings alone. Detail studies carried out so far have shown that the ever increasing demand for quarry output, the continuous increase in the budget allocated to the construction sector and the new economic policy etc. are providing more favourable condition especially for the quarry operation sector (KASMA Engineering PLC, 2004: as cited in Denamo, 2012).

Year of production	Demand(m^3)	Supply(m^3)	Excess demand(m^3)	Percentage gap
2003	829,583	399,840	429,743	51.8
2004	871,062	415,834	455,228	52.26
2005	914,615	432,467	482,148	52.72
2006	960,346	449,766	510,580	53.17
2007	1,008,363	467,757	540,606	53.61
2008	1,245,763	564,345	681,578	54.71
2009	1,462,923	645,760	817,163	55.87
2010	1,600,542	765,457	835,085	52.17

Table 1-2 Supply and demand of coarse aggregate in Addis Ababa

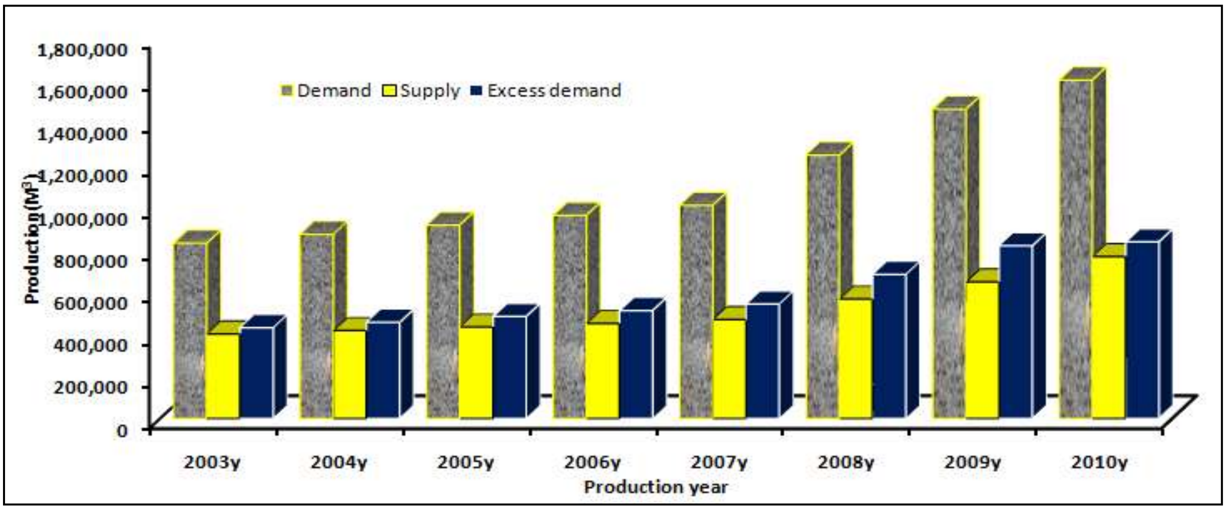

Figure 1-5 The supply and excess demand of coarse aggregate in Addis Ababa and surroundings

1.1 Location

The presently studied area is located in north central Ethiopia, some 120kms north east of the city of Addis Ababa. It is bounded in the east with the Main Ethiopian Rift. It is situated on the south eastern part of the north western highland plateau of Ethiopia (Figure 1-6). The north western highland plateau of Ethiopia is one of the four spectacular physiographic features comprising of a number of raised volcanic peaks in the region.

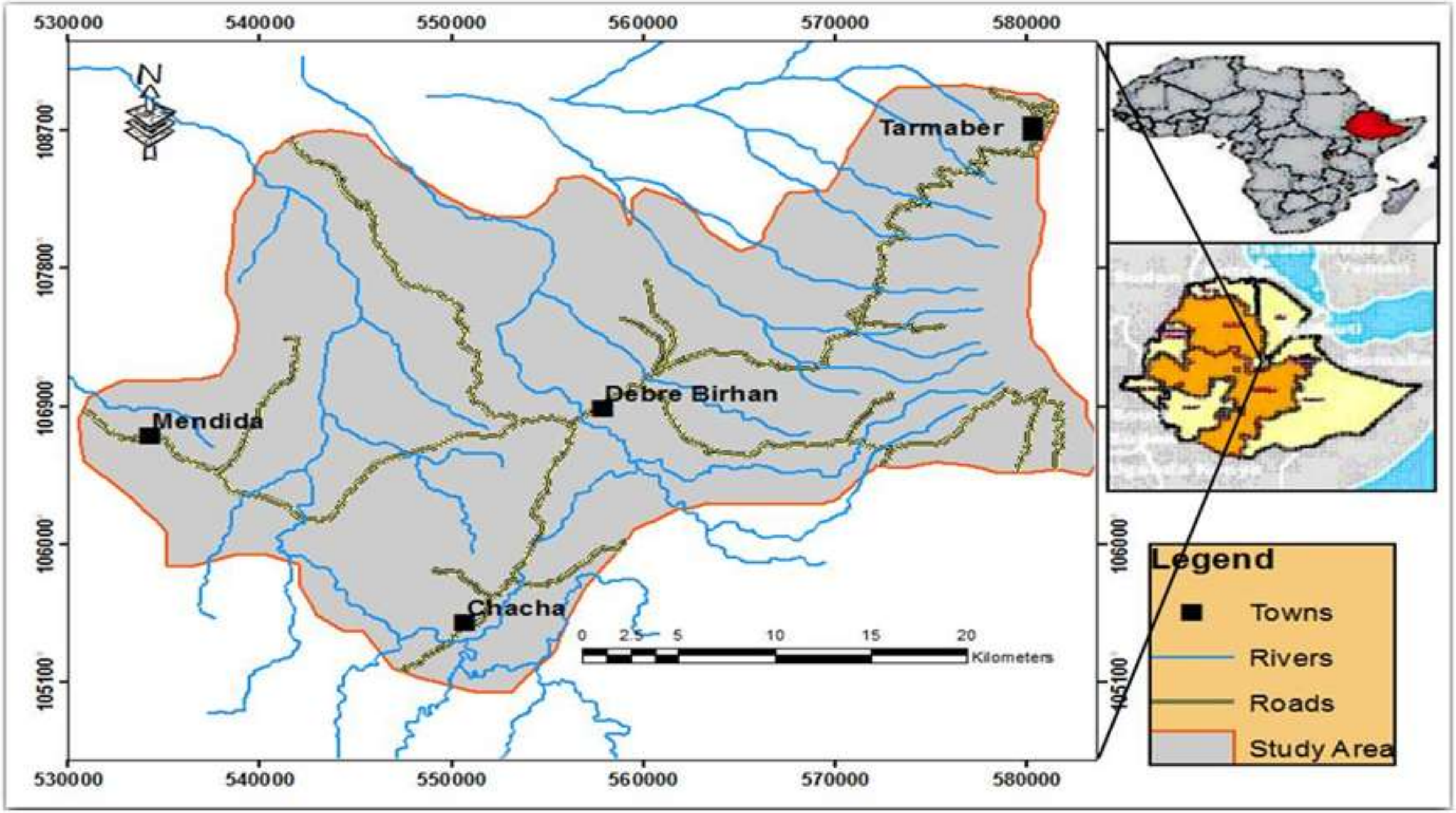

Figure 1-6 Location map of the studied area

1.2 Problem statement

The exploration, production and utilisation of raw materials for construction play a key role in the development of all countries. Geologists, construction engineers and regional planners are frequently confronted with the question of evaluating the usability and quality of occurrences and deposits of construction raw materials (Lorenz and Gwosdz, 2006).

Basaltic rocks are used extensively as engineering materials including aggregates for Portland cement concrete mix and asphaltic concrete, rock fill for dams and breakwaters, material for railroad ballast and highway base courses and cut stones (Goodman, 1993). The quality of the produced aggregates mainly depends on the properties of parent rocks. Hartley (1974); Ramsay et al. (1974); Lees and Kennedy (1975); Kazi and Al-Mansour (1980) and Smith and Collis (2001) have discussed in detail the many geological factors among which petrographical composition, texture, particle shape, pores, etc that affect the mechanical degradation of aggregates.

However, texture of a rock is an additional and complex factor affecting its physical and mechanical properties. Changes in mineralogical composition and texture of basalts affect physical and mechanical properties and, therefore, their quality as aggregate and other types of uses. On the other hand, basaltic rocks generally have higher unit weight than other rocks and, therefore, basalt aggregate has high relative density.

Bell (1998) indicated that rocks like basalts tend to produce angular fragments when crushed and angular fragments may reduce the workability of the mix. That is, it cannot be placed easily and offers less resistance to segregation. Nevertheless, angular particles are said to produce a denser concrete on the other hand. In general, strong and hard or brittle rocks produce a higher proportion of flakes than weak rocks, although the latter generate more fines in crushing (Smith and Collis, 2001). In concrete, surface roughness is required for a satisfactory bond between aggregate and cement or asphalt; except that carbonate rock particles bond well with cement paste even when smooth (Franklin and Dusseault, 1991).

Basalts are also having some potential risk from the point of Alkali Silica Reaction in some cases. Fookes (1980) gave examples of aggregate materials that cause Alkali Silica Reaction from basaltic crushed aggregates. In addition, according to Wakizaka (2000), volcanic glass and some other constituents existing in some volcanic rocks can cause Alkali Silica Reaction.

Basaltic rocks are the most widespread and voluminous rock in the north western central highlands of Ethiopia and they are used for various construction purposes and likely to continue to be the main source of construction materials in the future mostly as ashlars and crushed aggregates. In general, the use of basaltic rocks as aggregate material and building stone in Ethiopia is very intensive regardless of the quality consideration in which roads and buildings deteriorate and incur additional cost for re-enforcement before the designed engineering life. This is due mostly to the use of poor quality aggregate both susceptible to Alkali Silica Reactivity (ASR) and with marginal physical and mechanical properties. **Normal weight aggregates** are necessarily produced from basalts in Ethiopia while masonry stone like ashlars, cobble stone and others are produced from ignimbrites and related acidic rocks.

It is well known that the Uniaxial Compressive Strength of concrete is influenced by, among other parameters, the quality and proportion of fine and coarse aggregate, the cement paste and the paste-aggregate bond property. These, in turn, depend on the macro and microscopic structural features of source rocks including total porosity, pore size and shape, pore size distribution and the bond between individual solid components. Other qualities of concrete such as durability and abrasion resistance are also highly influenced by the aggregate, which also depends on strength of parent rock, soundness, surface texture, gradation and so on.

N**ormal weight aggregate,** i.e. Bulk density (1200-1600kg/m^3) and Specific gravity (2.4-2.9) is mostly produced in Ethiopia by crushing parent rocks using mechanical crushers or traditional methods. As stated above, basaltic rock is one of the most used source rock in this regard, which is used mainly for coarse aggregate production in and around the project area.

The physical properties like Specific gravity, Porosity, Thermal behaviour, and the chemical properties of an aggregate are also attributed to the parent materials. The size, surface texture and shape which are essential for concrete workability and bond characteristics between the cement pastes and aggregate are, however, attributes of the production mode in some way. It is, therefore, essential to understand the mechanical, physical and chemical properties of aggregate and its modes of production in an effort to produce the required quality of concrete. Abebe et al (2002) examined the mechanisms of Alkali Silica Reactions and explained the potential of such reactions in Ethiopia by studying: i) the mineralogical and chemical composition of limited and selected basaltic rocks, ii) the oxide concentration of silica sand obtained from different localities, iii) the alkali content of cements produced in Ethiopia and

iv) the temperature and relative humidity of Ethiopian conditions. The study stressed the necessity for laboratory analysis of aggregate samples with a specific attention to those aggregates which are more likely susceptible to Alkali Silica Reactions according to the source rocks from which they are produced.

In addition, researches carried out by Addis Ababa University, Technology Faculty (Tigist, 2003; Tigist, et al., 2002; Girma, 1983 and others) have shown the possibility of producing high strength concrete from Ethiopian highland basaltic rocks aggregate provided that proper physical and mechanical and geological investigation are carried out. As a result they emphasized the need of proper physical and mechanical characterization of the basaltic source rocks to produce standardized concrete. So far in Ethiopia, unfortunately, during aggregate testing for concrete production, no attention is given to test deleterious materials (ASR and ACR minerals, swelling minerals, chlorides, sulphates, iron mineral and metallic oxides, organic matter and micas) which are rather very critical in selecting an aggregate for the production of Portland cement concrete or asphalt concrete.

Therefore, it has been confirmed that detail investigation of aggregate properties is highly important to assure quality against strength and deleterious materials of aggregates produced from volcanic source rocks in Ethiopia. This strongly demands a detail engineering geological characterization of the selected volcanic parent/source rocks towards the production of dimension stone and aggregates since volcanic source rocks as construction materials are compositionally quite non-uniform and spatially varied. On the other hand, dimension stone requires strength (usually excessive), hardness and workability, colour and fabric, porosity, resistance against fluctuating physical, chemical and biological conditions. Surprisingly, a small amount of basalt is now having other applications such as fibrous insulators, cultivation substrate replacing soil in greenhouses, abrasion resistant lining of pipelines, fertilizer, filter, rebar, packing goods, fire resistant tools production and so many others, however, these basaltic uses are not so far practiced in Ethiopia.

The mineralogical composition of basalts exhibit different chemical and mechanical properties. Their physical and chemical stability differ greatly from flow to flow. The constituents have also different textural and structural features and they are variously interlocked. Therefore, the decision on suitability of basalts for any utilization needs both comprehensive physical and mechanical characterisation and detailed petrological study. Besides, the physical and mechanical tests should be performed in accordance with the respective accepted standards. Even though, the selection of rocks for construction purposes is predetermined by workability and local availability, it is highly influenced by the preferences of contractors. Missing a comprehensive characterization, erroneous rock selection could result in shortening of the designed engineering life of civil structures. An empirical approach is not sufficient today and the selection of rocks is based on a multidisciplinary examination. The right and strict procedures for testing of any rock construction materials are formulated and available in any country, although there are some variations from country to country. These procedures consist of sampling, sample preparation, and treatment and evaluation. The approved rock testing systems are even aged and static; they characterise only status quo at the time of testing (Kuhnel, 2003). More dynamic, innovative techniques express changes of properties in time and help to better predict rock deterioration. However, a generally accepted world unified system of material testing seems far reaching and seems a dream at present.

Therefore, with the current increasing demand of rocks as construction materials, it is critically important to characterize new and existing quarries towards their suitability for the production of quality construction materials as coarse aggregate and cut stones. This is the timely need of the Ethiopian construction industry.

1.3 Research Objective

This research is the first effort to study the physical and mechanical properties in order to classify the Tarmaber basaltic rocks in central Ethiopian highland as construction materials; and secondly this work will go through examining the suitability of these basalts for various civil structure construction applications by evaluating the physical and mechanical properties of both the Ethiopian and Sardinian basalts. The in-service performance of civil structures depends on the engineering properties of aggregates being used. Prior to the present research, no systematic studies were carried out to evaluate the engineering characteristics of Tarmaber basalts that could serve as database for the current and future use. This study presents relevant physical and mechanical parameters for specifications and classifies the aggregates for various end uses especially for Portland cement concrete mix.

The main objectives of this research are:-

- Engineering geological characterization of the volcanic rocks of Sardinian (Abbasanta-Borore area) and Ethiopian highland (Tarmaber formation) to be used as construction material (as building stone and coarse aggregate)

- Assessing the volcanic rocks for suitability towards using as building stone and coarse aggregates/construction materials with regard to the various specifiations
- Presenting a conceptual framework which puts forward a vision for crushed aggregate characterization of the Tarmaber formation
- Evaluation and comparison of the physical and mechanical properties of the rock materials of the Sardinian highland Plio-Quaternary basalt with that of Ethiopian Tarmaber formation

1.3.1 Specific objectives

- Establish the physical and mechanical properties of the volcanic rocks (Uniaxial Compressive Strength, ultrasonic P-wave Velocity, water absorption, porosity, apparent density etc of both sites
- Carry out all relevant crushed coarse aggregate tests (ACV, LAAV, AIV, ASR, TPF, SSSV, ASR, etc)

1.4 Methodology

This research work includes desk work, field investigation, laboratory test, data processing, interpretation and report writing. Five stages are followed to carry out the research work and are described below. The research methodology and principles are described in chapter four in more detail.

Data acquisition

The desk study shall concentrate on a review of archive data from topographic maps, thematic maps and existing reports, while the field work stage involves the primary geological, engineering geological and geomorphologic information acquiring.

The study consists of five main stages.

Stage 1: ***THE INITIAL STAGE-*** involves literature survey and site reconnaissance. The literature survey includes collection of 1:50,000-100,000 scale topographic and geological maps of the study area and its vicinity, and gathered both published and unpublished reports, papers and supplementary documents, if any while the site reconnaissance survey is devoted to visiting of the research area and collection of limited number of samples as an appraisal for further planning.

Stage 2: THE SECOND STAGE-geological field studies are executed in order to observe variations and uniformity and characteristics of the Tarmaber formation and Abbasanta-

Borore basalts in the study area. Lithological contacts of units of the sequence are mapped to understand the various flow layer spatial configurations.

Stage 3: THE THIRD STAGE-involves mapping of the study area by conducting geological traverses aiming at delineating the volcanic sequences and geological documentations and selecting of sampling sites, at this stage it is decided where to take samples.

Stage 4:THE FOURTH STAGE-comprises collection and preparation of samples for laboratory tests. Rock blocks taken from the field are prepared for the various tests. In spite of the difficulties to get representative specimens with current simple hand tools and techniques, preparation of the specimens for testing is carried out in the laboratory by manual and mechanical system in a very sensitive manner to get representative samples. Upon completion of this stage, a set of physical and mechanical tests are performed on the samples (Figure 1-7). The physical and mechanical properties to be determined comprised of but not limited to; Porosity, Bulk density, Real density, Water absorption, Schmidt hammer rebound test, Uniaxial compressive strength, Point Load strength index, Abrasion test, Ultrasonic P-wave Velocity, Durability index and some other relevant aggregate tests (Aggregate Crushing Value, Aggregate Impact Value, Los Angeles Abrasion Value, Ten Percent Fines Value, Sodium Sulphate Soundness Value, Weathering index, etc). Mineralogical (X-Ray Diffraction), chemical (X-Ray Fluorescence Spectroscopy) and petrographical studies have been also carried out. Thin-sections were prepared and studied with optical microscopy for this specific purpose.

POST FIELD AND LABORATORY WORK:

Stage 5: THE FIFTH STAGE-covers the final evaluation of the overall field and laboratory data and the assessment of the suitability of the two country basalts towards using as construction materials both in local and industrial scale level as dimension stone and concrete aggregate production.

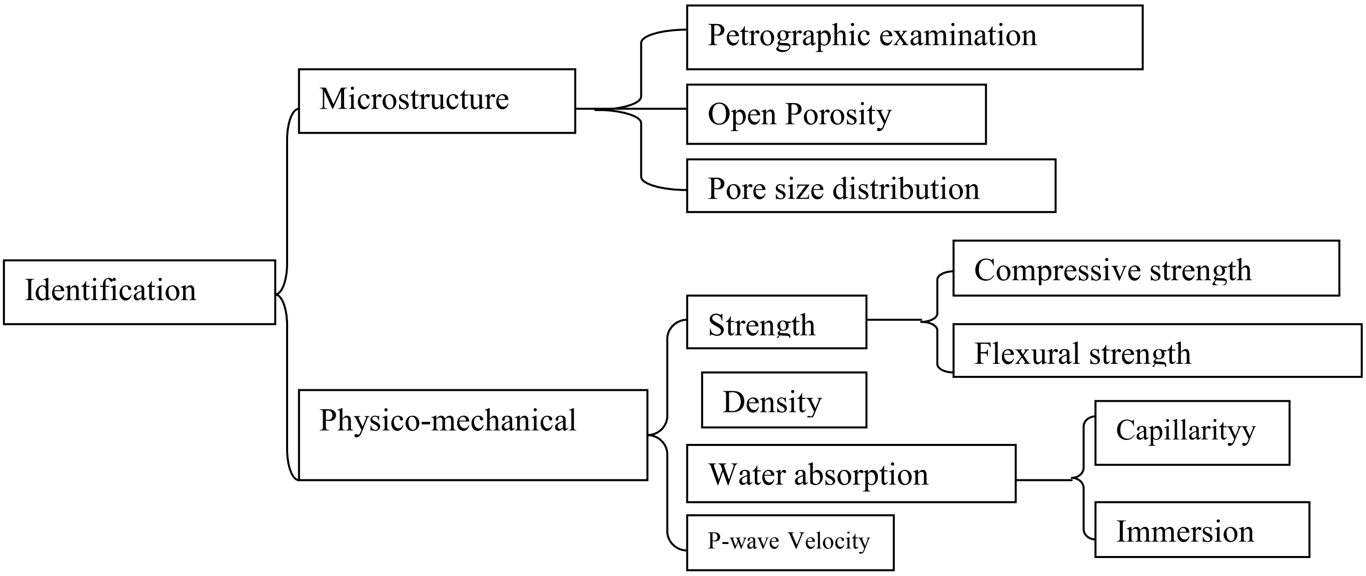

Figure 1-7 Flow charts for laboratory test work

1.5 Thesis outline

This research work is carried out into two geographically apart countries (Ethiopia and Italy) but has long historical attachments and today both countries are enjoying high level social, political and economical relations. This thesis is organized into two parts and sixteen chapters. Furthermore, one more chapter is devoted to comparison of the physical and mechanical properties of the two study areas (Ethiopia and Sardinia); as well similarities and differences are described under this chapter.

Part I: Ethiopian Project area

Part I consists of 9 chapters (1-9); Chapters one and two describe, generalities, objectives, literature review, methodology and principles to be followed for laboratory testing for both project areas, while chapter three, four, five, six, seven, eight and nine deal with only the regional and local geology, laboratory results, discussion, conclusion and quarrying environmental impacts of the Ethiopian project area.

Chapter one gives a general introduction to rocks as construction material, introducing the research problem statements, the research objectives and its significance and contribution of knowledge to the society at large.

Chapter two reviews wide and detail literatures in regard to volcanic rocks as construction material uses, specifically basalts and pyroclastic/ignimbrite in the various parts of the world starting from the ancient times to the present. However, this chapter mainly concentrates on literatures describing the use of volcanic rocks in the two countries (Ethiopia and Italy) in most cases. The chapter reviewed documents into two divisions as dimension stone and coarse crushed aggregates.

Chapter three provides an overview of the regional geologic, tectonic and stratigraphic setting of the volcanic cover of the north central highland of Ethiopia and addresses in detail also the study area's local geology and tectonics. It discusses the detail geological features with regard to spatial distribution of the major geologic units, particularly the Tarmaber formations (Megezez subdivision) that are potential sources of construction stone deposits. Besides, this chapter describes the general landscape and climatic situations of the region in detail.

Chapter four addresses the major laboratory methods and principles of investigation used in this research for characterization of the Tarmaber formations(Ethiopia) and Abbasanta-Borore basalts (Italy) to be used as dimension stone/cut stone. It mainly discusses the principles and procedures, standards and the necessity of the physical and mechanical tests to be conducted.

Chapter five discusses the results of the in situ and laboratory tests. Furthermore, the data are interpreted with regard to the various standards (UNIEN, ASTM, AASHTO and BS) and to the classification of the materials according to the laboratory results.

Chapter six focuses on characterization of coarse crushed aggregates produced from Tarmaber basalts. The physical and mechanical properties of the coarse aggregates are tested in the engineering laboratory of the Ethiopian Transport Construction and Design Laboratory, Geological Survey of Ethiopia Central Laboratory and Cagliari University. The results of the various physical and mechanical properties were compared and evaluated with known standards including UNIEN, AASHTO, ASTM and BS.

Chapter seven focuses on the environmental impacts of construction stone quarries in creating land use conflicts and displacing people. It also indicates the possible mitigation methods to be employed after a quarry is abandoned.

Chapter eight is devoted to discussion of results of the laboratory and field observations with regard to dimension stone and coarse crushed aggregates suitability for Portland cement concrete mix and other end uses.

Chapter nine is spared for conclusion of this research effort on the Ethiopian project area.

Part II: Sardinian Project area

Part II consists of six chapters (10-16) and is totally devoted to the Sardinian study area and lastly one more common chapter entitled 'Comparison of the two project areas on the similarities and differences of the chemical, physical and mechanical properties' is discussed considering the geographical locations.

The following is a brief outline of the chapters of the thesis that have come forth at the end of the schedule of this research activity of the Sardinian Project area.

Chapter ten deals with specific geological background information on the Plio-Quaternary basalts of Sardinian Project area, while **Chapter eleven** focuses on the general geology and local geological settings. **Chapter twelve** presents the results of the various physical and mechanical properties of the Abbasanta-Borore basalts towards its suitability as dimension stone/cut stone, while **Chapter thirteen** characterizes the physical and mechanical properties laboratory test results of the Abbasanta-Borore basalts for using as crushed aggregate for concrete mix.

Chapter fourteen raises issues associated with environmental impacts of quarrying activity and possible mitigation methods. **Chapter fifteen** discusses the overall laboratory test and field investigation results of the Sardinian study area and **Chapter sixteen** draws conclusions on the Sardinian study area results. **Finally**, **Chapter seventeen** presents comparison of results of the Ethiopian Project area and Sardinian are presented; similarities and differences of the physical and mechanical properties are discussed in detail with respect to their geographical location and geological setting.

CHAPTER TWO

2. Literature review

The literature review normally provides a context for the present research. It covers two topics, related but not overlapping, those of dimension/building stone and coarse crushed aggregate of volcanic rocks. This chapter serves the purpose of helping the researcher to understand the state of knowledge (Denscombe, 1998) to bring together different points of views, and to identify common features and criteria in a coherent flow to evaluate the physical and mechanical properties of the volcanic rocks towards suitability for the intended end uses.

Geologic materials have been first utilized by humans as tools for hunting, such as axes, arrow heads, scrapers made from hard rocks and minerals such as chert, flint, obsidian, and quartzite. When the humans formed first organized groups and settlements, permanent shelters became a necessity. The first structures were simple mud huts, but quickly progressed to more elaborate buildings as hierarchic structure and religion developed. The use of stone in the form of field stone and later dimension stone culminated in such elaborate structures as the pyramids of Egypt and other similar structures. To bind the solid rock pieces in building construction, clay was initially used as a cementaceous material, followed by burnt lime mixed with sand to form lime mortar, and ultimately, cement was perfected by the Romans, using limestone and volcanic ash as raw materials to produce a strong and durable binder. The combination of cut stone and binding materials were used to construct large structures such as castles for defence, permanent bridges over rivers, and viaducts for water supply.

As needs for transport routes evolved, the building of roads utilized stone of all varieties as the top surface layer on which wheeled conveyances of various types could travel with ease. The use of stone, sand and gravel for road construction remains the chief use of these geologic materials till the present time.

Geologic materials can roughly be classified into consolidated, cemented deposits (rocks), and unconsolidated, mostly surface deposits (soils, as used in engineering sense). There are, of course, instances where a poorly consolidated or cemented deposit would fall between these two broad categories. Rocks, in turn, are classified by their origin: igneous, or those formed from a molten lava or magma; sedimentary and metamorphic. All rock types have an utilization potential, but are not suitable for given use. Igneous and metamorphic rocks tend to be harder, stronger, and more brittle, more resistant to abrasion, whereas sedimentary rocks are often softer, more porous, and sometime less durable (Hudec, 1999).

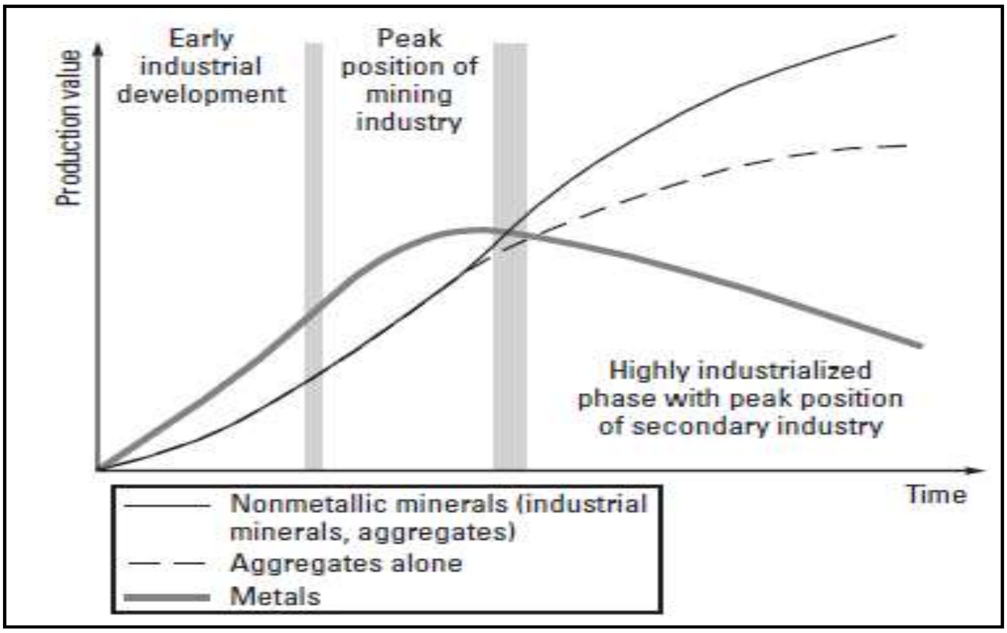

Figure 2-1 Comparison of the production trends of metallic ores, industrial minerals, and aggregates in industrialized world (Wellmer and Lorenz, 1999; modified from Bristow, 1987)

During the last 20 years, the production and use of building stone and aggregates have generally steadily increased worldwide, and today rocks as construction material has reached a position as one of the world's most important mineral resources (Figure 2-1). For several countries, export of stone has become a significant economic activity. For some others, the recognition of local sources of building stone and aggregate have proved a steady supply of low cost and durable construction materials for local purposes.

Likewise, during the last decades, and especially during the 1990's, systematic prospecting for building stone in Ethiopia has been carried out by both the Geological Survey of Ethiopia (GSE) and private companies, and a number of building stone deposits throughout the country have been put into production. This is supported by the extensive use of Ethiopian stone in modern constructions in major and smaller cities.

For local housing and construction, easy workable rocks are required in preference to rocks with attractive aesthetic qualities. The stone is shaped and worked to finished products (hewn slabs and building blocks) in the quarry and/or at the construction site. It is primary importance that the rocks need to be worked with simple technology to a minimum cost. In Ethiopia, there are long traditions in using the Tertiary volcanic rocks for such purposes.

2.1 Vocanic rocks as construction materials

Man has always used natural rocks and stones for his own purposes-indeed, it was his ability to do so which distinguished early man from his distant ancestor. At first, stone was only used for weapons and tools; but early in his history man began to use rock for buildings; at first to improve his cave or shelter; but later to construct his dwellings. Still, in the knowledge age to date, rocks are used to build prestigious buildings from selective certain varieties of rocks.

Volcanic rocks are usually fine-grained or aphanitic to glassy in texture. They often contain clasts of other rocks and phenocrysts. Volcanic rocks are named according to both their chemical composition and texture. Volcanic rocks are composed of minute, strong, tough mineral crystals, generally arranged in an extremely dense, interlocking manner. This structure results in negligible porosity, great strength and durability within the service life of the engineering structures. One of the common volcanic rocks is basalt which has diverse engineering and industrial applications.

The term '**BASALT**' was used in the 1st Century by Caius Plinius (Natural History, AD 77), of Ethiopian origin meaning "black" **(*http://www.newworldencyclopedia.org/entry/Basalt*)** and introduced in geology by **Georgius Agricola** in about the middle of 1500's(Louise Van Rooy, 2000). There are various studies about basalt reported in the literature. As a result of such studies dealing with basalt, it has been concluded that basaltic aggregates increase the quality of concrete when used with Portland cement (Goodman, et al., 1993; Tasong, 1998).

Basalt has long been a material in the fortifying of concrete and the construction of tiles, slabs and other architectural components. Basalt is naturally fire resistant and is essential in the production of basalt fibers for insulation. Studies have suggested that basalt fibers may be a viable replacement for harmful asbestos fibers. Basalt is also one candidate in the future for CO_2 underground storage for environmentally friendly chemical reactions (Kumar, et al., 2005).

According to literatures, in 1923 basalt rocks began to be studied for its applications in the fiber industry. In the 1960s it began to be extensively tested for U.S. and Soviet military fiber applications as an alternative to asbestos. Nations that were once part of the Soviet Union are the centre of modern basalt fibre research. Later on, China is now the leading country in basalt fiber technology and basalt rebar production and use in the construction industry. Basalt rebar is becoming popular also in other parts of the world because it's chemical corrosion resistant and higher tensile strength than steel rebar.

Basalt is a very common volcanic rock with relatively low silica content. The strange of basalt (lava stone) is its vesicular and natural feature, seeing from its cutting surface; the holes are much bigger in the upper and smaller downwards and more highly concentrated. This kind of stone material has the special features which other stone material doesn't have for its individual holes, such as sound absorption and insulation, heat insulation and reserve, frozen proof etc. It has good sightseeing for the continuous big and small holes, with primitive simplicity and elegant style. Every environmental test of the basaltic stone is all fine under very strict inspections; it is green environmental building material. It also has features of sour and alkali proof so that it can be used in many areas (Shadmon, 1989).

Basaltic rocks are the most abundant ones on earth. Similarly, the central part of Ethiopian highland is covered with huge basaltic flow which is poorly studied, so far there is no available physical and mechanical and geotechnical data about these rocks in the present study area. But as it has been said above basaltic rocks have many interesting physical and mechanical properties to be considered for many technical purposes. The currently studied basalts cover large area and are close to settlements and infrastructures so that they could easily be used in the construction industry with reasonable transport cost. Traditionally, rocks as construction materials in the Ethiopian plateau are an important material since the beginning of human settlement in the area. The rural villages are totally built of basalt and ignimbrite rough and rubble stones in a crude way.

2.1.1 Building/dimension stone

The Egyptian pyramids were built from quarried stone in about 2800 B.C., and the Babylonians used cut stone in 600 B.C. to build the renowned Hanging Gardens, one of the Seven Wonders of the World. The Greeks and Romans also used cut and finished stone widely as construction, decorative, and statuary materials. The Greeks quarried marble as early as 447 B.C. Throughout history; the geologic availability of geomaterials has been a principal factor affecting techniques of construction, structures and stability, decorative detail and overall aesthetic aspects of buildings and monuments. Greece and Rome, for instance, had abundant locally available stone, all of which were used in the construction of the principal monuments of classical time. About 314 B.C, Theophrastus listed characteristics that made building stone valuable: a) found in large areas and made up of whole layers, b) can be extracted in whole blocks, c) possesses pleasing and other aesthetic features, such as smoothness and are relatively hard. In the 2300 years since these observations, all we have added are the ability to resist the accelerated weathering common in today's urban or acid rain environment (Dolley, 2004). The term 'building stone' includes any type of rock, shaped and dressed to blocks or slabs, used for construction. Building stone is a more general term than the term 'dimension stone', which is restricted to cut-to-size slabs and blocks.

Dimension stone can be defined further as natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size (width, length, and thickness) and shape (Currier, 1960). Specific colour, grain texture and pattern, and surface finish of the stone are normal requirements. Durability (essentially based on mineral composition, hardness and past performance), strength, and the ability for the stone to take a polish are other important selection criteria. Barton, 1968 and Dolley, 2004 also defined dimension stone as natural rock quarried for the purpose of cutting and (or) shaping to a specific size.

Scientific and commercial descriptions of the different dimension stone types overlap. The scientific description generally focuses on the mineral composition and its geographic locality; the commercial description focuses primarily on the colour and locality of origin. In some parts of the world, basaltic and ignimbritic rocks are mined as dimension stone which commercially are named as 'black granite.' For example, some African countries are known internationally for black granite production to mean dolerite, basalts and gabbros. The petrological term black granite is also a commercial term referring to a mafic family of rocks whose mineralogy and texture ranges from the coarse grained gabbros to the fine-grained dolerites (Antonides and Virta, 1998).

Volcanic lava and pyroclastic rocks are mostly used close to their natural resources to minimize transport cost. Their degree of fracturing is often characterized by the presence of different generations of discontinuities that enhance workability, but prevent the production of blocks for the stone industry. They exhibit various colours and sometimes very appreciated like "Sparta Green" andesite (Greece) or the porphyritic rhyolite known as "Imperial Egyptian porphyry" (Fiora and Alciati, 2006b). The other important historic uses of volcanic rocks includes the production of grinding wheels, which were also transported over a considerable distances from their original place.

Volcanic rocks (lava) and pyroclastics proved to be excellent building materials since ancient times. In Latium (Italy), the Etruscans and later the Romans made extensive use of the

"Peperino Albano Tuff" ("Lapis Albanus"). The most famous Italian volcanic rock is the porphyry from Atesina porphyry plate form, providing an excellent paving material (Fiora, 2006a).

Most volcanic rocks involved in constructions and for pavements are obtained by natural splitting. This technique is still widely applied to produce many finished porphyry items for example in Italy, for the "Trentino Porphyry" and the "Euganean Trachyte", quarried since Roman times and for the "Lava Stone" basalt from Mt. Etna. The splitting is facilitated by the cooling fissures, e.g. the columnar basalts provide traffic bollards once appropriately cut to size.

In Sardinia, in fact stone is the most used natural material in masonry and, from a building point of view; it is the major element that characterizes Sardinian rural building, because of the countless varieties which could be found in the Island (Carlo, 2003). A large number of the Nuraghi are built of large irregular blocks of basaltic rocks. The Nuraghi are a very well-known Sardinian symbol. It is actually its most representative monument, which recalls its millenary history. Its construction is quite impressive. It can reach 20m, of height. The most important Nuraghes can even count 15 interconnected towers. These constructions were built by the dry-stone technique ("pietra a secco"), without any cohesive material. So, it seems unbelievable that they have survived completely up to our times. They represent a real prehistoric architectural jewel and document the high developmental level reached by the bronze civilization and are mostly made from basaltic rock slip.

Tuffs and ignimbrites are also widely used currently in buildings all over the world. These new varieties display unusual colours, such as green, yellow, orange and red-violent. Thus their decorative applications are significantly enlarged throughout the world. Among nations, new producers of pyroclastic stone are Armenia and Turkey (Fiora, 2007). Basalts with columnar fissuring are supplied by Vietnam and China; the typical "columns" are cut and polished to be used as indoors furnishing or as small cubes. The local market in many other countries uses also volcanic rocks. Examples include basalts in **Jordan** and **Syria**, nowadays mainly used as paving/flooring and furnishing, they were once an important building and ornamental material (Fiora, 2008).

In Spain, for example, in the Tenerife Island the "Molinera Basalt", in Fuerteventura the "Tindaya Stone" and in La Gomera the "Red Stone" are quarried. These stones are the building materials of recent prestigious development, for example, for the Government Palace in Santa Cruz of Tenerife (Fiora, 2006). In the Cape Verde Islands, as well as in the Azores islands, basalts and pyroclastics are frequently used as a masonry material and ornamental architectural elements. They are also taken as paving cubes in old and new roads (Fiora, 2007).

Similarly, basalt is widely used for local construction, both as building stone and aggregate, in those parts of Ethiopia where such rocks are available in large area coverage and with good quality. A large number of small basalt quarries are found throughout the Central Highlands, and crudely shaped pieces are worked with simple tools and manpower. In general, so far, the basalt deposits are not considered to be of specific interest for more industrial-scaled building stone exploitation in Ethiopia.

However, basalts of columnar and vesicular types are used intensively in rural parts of the central highland of Ethiopia. The former could, with simple technology, represent a potential for the production of split paving stone, while the latter, due to its excellent workability, could be used for ashlars and facades. On the other hand, there are sizeable deposits of tuffs, rhyolite and ignimbrites. These rocks are generally porous, soft to carve and easy to split, and for a long time, ignimbrite and tuff have represented the most important building stones of Addis Ababa (Karstaedt and Wondafrash 1986). Due to the high porosity, these rocks have excellent insulating properties for indoor use. A number of small quarries are worked in the vicinity of the currently studied area, mainly by hand, using simple tools. The ignimbrites are somewhat harder to work than the tuffs, and therefore more commonly used for rubble than ashlars. Due to their softness, such rocks are, however, not very suitable for use as paving stone and stairs. Tuffs and ignimbrite deposits are also exploited at several other places in the country for various purposes. For instance, the famous, rock-hewn churches of Lalibela are carved in soft tuffs, and these rocks have also been employed more recently for local construction in several parts of Ethiopia.

2.1.2 Crushed rocks/aggregates

The term aggregate has its origins in the 15th century from the Middle English *aggregat,* derived from Latin *aggregatus,* past participle stem of *aggregare* “to add to,” literally “to bring into the flock,” ultimately from the stem *greg*-“flock”. As the name indicates, aggregates are rock fragments that are together in a mass. Crushed stone aggregate is therefore, “the product of resulting from the artificial crushing of rocks, boulders or large cobble stones", substantially all faces of which have resulted from the crushing operation (Langer, 1988).

Aggregate is the most fundamental component of construction. It is used as an unbound material in base courses and as a bound material in bituminous and Portland cement concretes. Aggregate constitutes about 90% of the volume of base courses and bituminous concrete and 65 to 75% of the volume of Portland cement concrete. Aggregate is exposed to a number of physical and chemically degrading forces during processing, transporting, and construction. As the main load carrying component of unbound and bituminous and Portland cement concretes, if the aggregate fails, the facility fails to perform its design intent.

Two primary sources of aggregate are bedrock and deposits of sand and gravel. In areas where these traditional sources of aggregate are scarce, other less common sources are considered, such as volcanic cinders and shell. Blast furnace slags, mine tailings and other waste products are locally used as aggregates. There is also a growing trend of recycling existing concrete and asphalt as aggregate (Langer and Granzman, 1993). However, the current study is dealt with only bedrock /crushed rock aggregates and the others will no more dealt with hereafter.

The main characteristics that make material useful as mineral aggregates are bulk density, durability and compressive strength, inert chemistry or lack of reactivity, and uniformity of composition. Aggregate materials must be stable against breakdown in use and in stockpiles; free from joint flaws and micro-cracking; strong enough to withstand loading applied in use (both tensile and compressive); of low porosity and permeability in individual particles and chips; non-plastic; chemically inert in use, not coated with any substance nor polished to a degree where adhesion of bitumen or cement is adversely affected; and not deeply weathered (Grant-Taylor and Watters, 1976; Dolar-Mantuani, 1983). A large variety of rock types are suitable for aggregate, however some uses may require specific properties that meet rigorous standards.

Hard, chemically stable rocks are required for concrete aggregate, earth dam construction and sealing chips. Sealing chips for roads need to be resistant to abrasion and chemical attack, rough surfaced to prevent skidding on wet or oily surfaces, and able to bind with bitumen.
European standards (UNIEN12620:2002) defines aggregates as granular material used in construction, while the American Society for Testing of Materials(ASTM), 1994 defines crushed stone aggregate as" the product resulting from the artificial crushing of rocks,

boulders, or large cobble stones, substantially all faces of which have resulted from the crushing operation.” The physical and chemical properties of aggregates result from the geologic origin and mineralogy of the potential source and its subsequent weathering or alteration. The largest significance of natural aggregates is in construction, and much of that aggregate is used in Portland cement concrete or bituminous mixes. Aggregate used in roads, buildings and concrete production are subjected to much detail specification, and these specifications and others could vary from area to area (Mielenz, 1994).

The specification for natural aggregate in Portland cement concrete or bituminous mixes is generally more rigorous and specific than for other construction related uses. If aggregate can meet the specification for these uses, it will satisfy almost any other use (Langer and Knepper, 1995). Aggregate characteristics can be divided into three groups (1) physical and mechanical properties (2) chemical properties, and (3) contaminants.

Concrete is a versatile and most popular construction material in the world. It is produced by mixing fine and coarse aggregates, cement, water and additives in a certain prescribed proportion. Aggregates are known to be particles of rock or equivalent which, when brought together in a bound or unbound condition, form part or whole of an engineering or building structure. Aggregates, both fine and coarse, take about 65-75% by volume of concrete and are important ingredients in concrete production.

It is well-known fact that the compressive strength of concrete is influenced by, among other things, by the quality and proportion of fine and coarse aggregate, the cement paste and the paste-aggregate bond characteristics. These, in turn, depend on the macro and microscopic structural features including total porosity, pore size and shape, pore size distribution and morphology of the hydration products, and the bond between individual solid components. Other qualities of concrete such as durability and abrasion resistance are also highly dependent on the aggregate, which in turn depends on strength of parent rock, purity, surface texture, gradation and so on.

Basically three classes of aggregates are identified depending on their weight: light weight, normal weight and heavy weight. **Normal weight aggregate** is generally produced in Ethiopia by crushing parent rocks using mechanical crushers or traditional methods and it is the focus of this study. Basaltic rock is a good example of parent rock in this regard, which is used mainly for coarse aggregate production in and around the currently studied area, Ethiopia. Basaltic bedrocks are crushed both mechanically and manually in some cases to produce coarse aggregates, however, bed rocks like rhyolite and trachyte, limestone and some others are used for production of aggregates in different parts of the country in limited amount, KASMA Engineering PLC, 2004 (Figure 2-2).

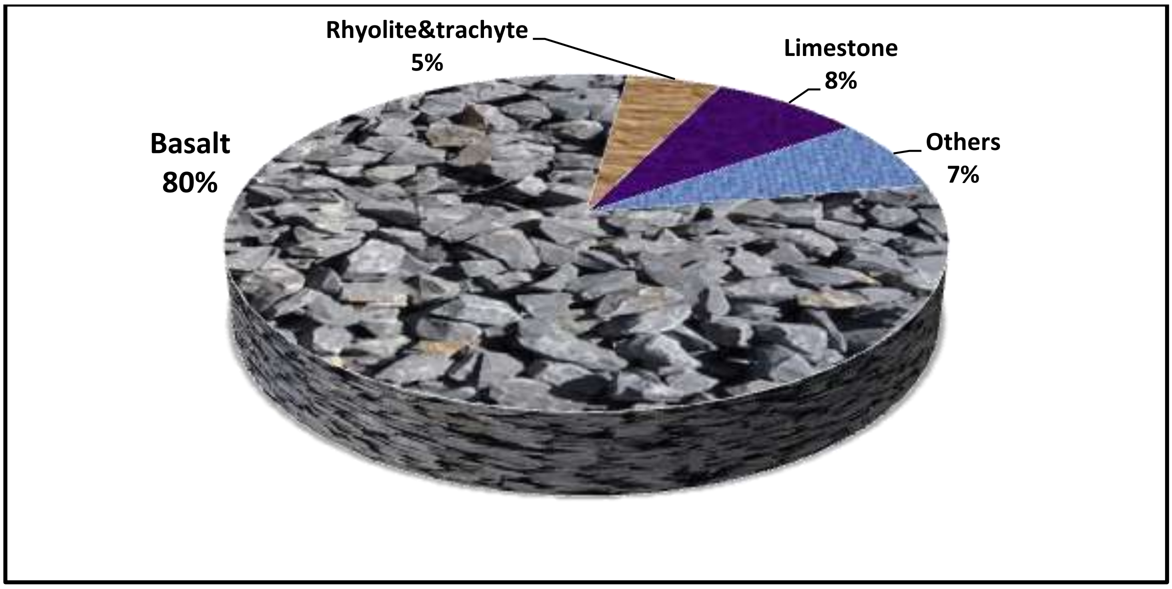

Figure 2-2 Chart showing aggregate production source rocks in Ethiopia

Aggregates can be classified further as natural or artificial depending on their sources of production. Natural aggregates are obtained from quarries by processing crushed rocks or from riverbeds while artificial aggregates are obtained from industrial plants by products such as blast furnace slag and others. Natural aggregates are most commonly produced and are relevant for Ethiopian construction sector since artificial aggregates are hardly produced in the country (Figure 2-2).

The physical and mechanical properties of aggregates are inherited from parent materials, while the properties of the parent material in turn depend on its geological formation. As mentioned earlier, the most commonly used and available crushed aggregate source rock in Ethiopia is basalt. Generally, basalt is a fine-grained extrusive rock, of which the glass content is relatively low, however, more detail mineralogical, physical and mechanical properties of the basaltic rock of the studied area is given, in the next chapters herein after.

Coarse aggregate for concrete shall consist of natural gravel, crushed gravel, or crushed stone, free from coating of clay or other deleterious substances. It shall not contain harmful materials such as salts, iron pyrites, coal, mica, laminated materials, tree roots, shale, or any materials which may attack the reinforcement, in such a form or in sufficient quantity to affect adversely the strength and durability of the concrete. If necessary, coarse aggregate shall be washed to remove deleterious substances. The coarse aggregate shall comply in all respect with the requirements of UNIEN, ASTM or BS 882. Characterization of the physical and mechanical properties of construction materials in concrete and asphalt application has always been a challenge to the construction sector. However, it is the primary task of the industry to assess and evaluate the properties at material level as far as the engineering structure service life is concerned.

Therefore, aggregate characterization is the paramount importance to promote the construction industry for better quality and performance in cement concrete, asphalt and other construction types. Aggregate characterization is the process of classification of aggregate resources on the basis of physical and mechanical properties for various construction applications, so that it can be used according to its suitability. The general approach of aggregate characterization proposed by Fookes, 1998 is shown in Figure 2-3.

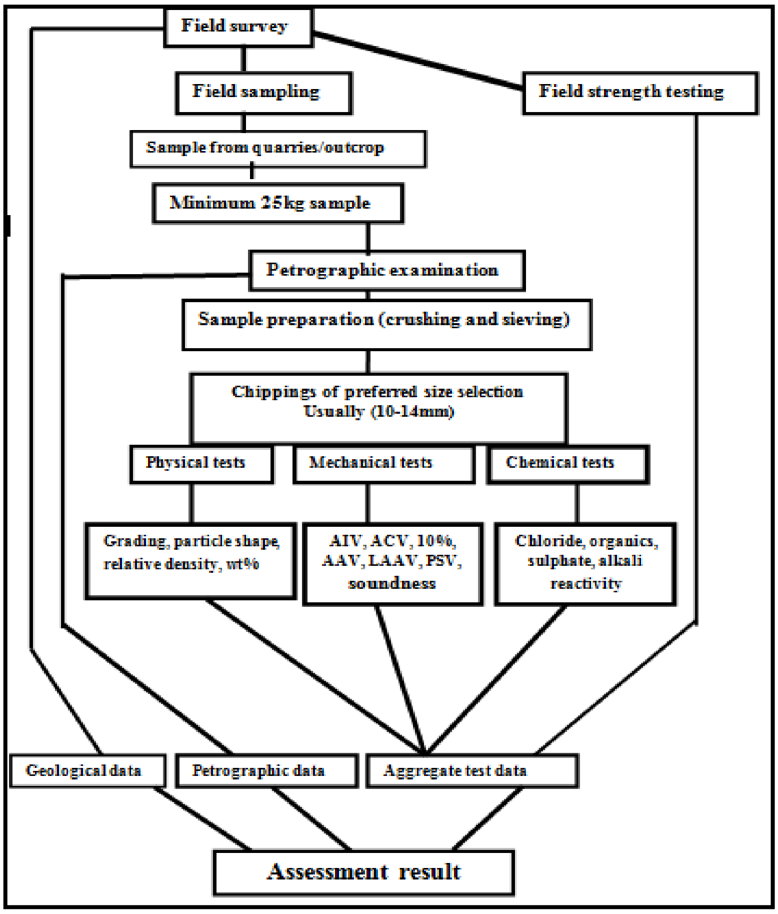

Figure 2-3 Flow charts for aggregate characterization (Fookes, 1998)

CHAPTER THREE

3. General geology and landscape

3.1 Landscape

3.1.1 Physiography of the study area

Ethiopia can be divided into four major physiographic regions; the north western plateau, the south eastern plateau, the Main Ethiopian Rift and the Afar depression. The lowest elevation in Africa is located in the Afar depression, Dallol (-126m below sea level), while the highest elevation is, Ras Dashen (4620m above sea level). The study area is found in the north western central eastern part of Ethiopian highland which is bounded on the east by an active rift margin (Figure 3-1).

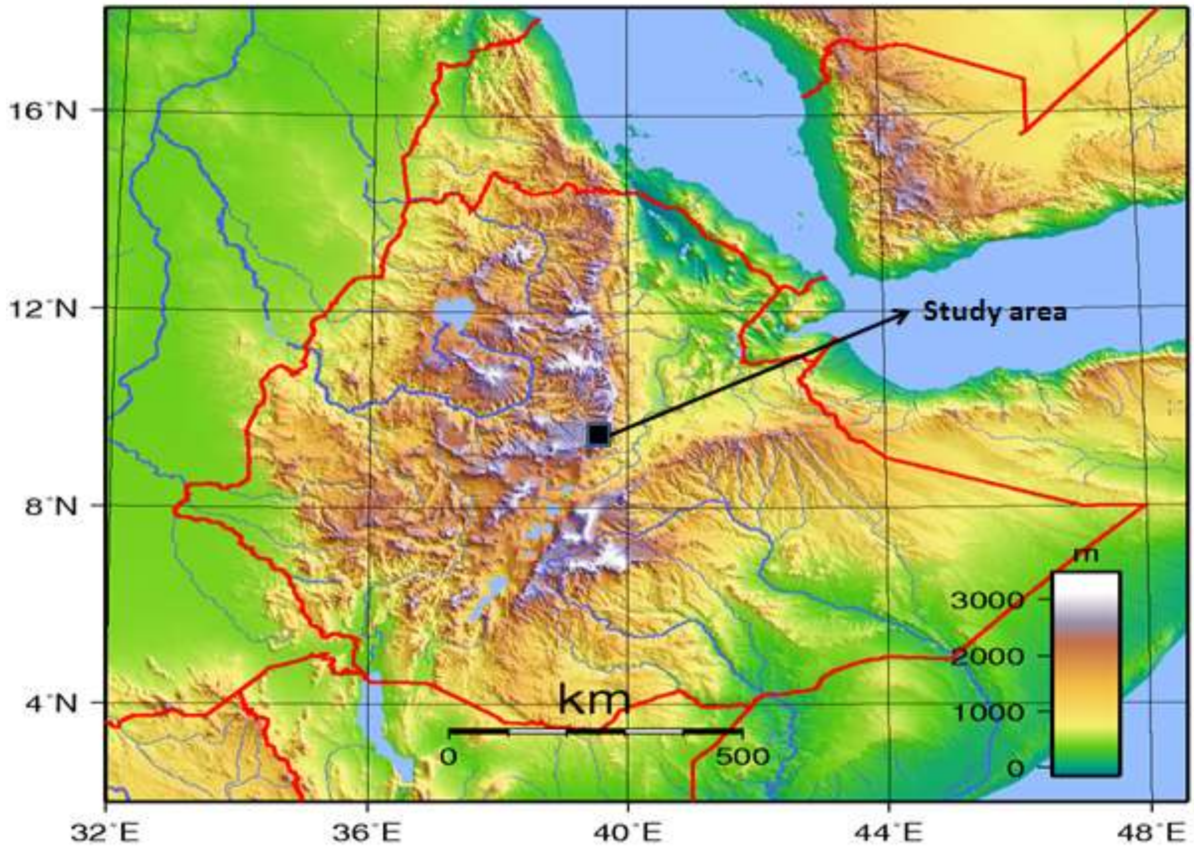

Figure 3-1 Topographic map of Ethiopia with major rivers and lakes

The north western plateau is bounded by the Ethiopian rift on the eastern and south eastern sides while Abay/Blue Nile gorge and Tekeze gorge border it on the north western and south western sides. One major drainage basin is located in the studied area: the Jemma river basin that is confluent with Abay (Blue Nile) river along with a number of its tributaries: Gado, Ayseram, Mofer wuha, Lege yida, Dalecha and Beresa. A large portion of the hills is sparsely vegetated except for some patches on the eastern and northern sides where subsistence farm lands are located. Big trees in these areas were obviously cleared for farming purposes.

Generally, the studied area could be regarded as rugged and hilly. The area is gently slanting to the west at 5-10 degrees, with generally shallow dipping slopes on the northern and flat laying on the southern side. The western part is very steep while the eastern and the north eastern parts are relatively dominated with flat topography. The south central and south eastern parts are also flat. The central part is characterized by low laying valley floor in which the elevation reaches as low as 1960m a.s.l, while the highest peak in the study area reaches 3700m a.s.l. Steep slopes are very common on the western and eastern part which reaches up to 40-45 degrees on maximum (Figure 3-2 and Figure 3-3).

Figure 3-2 The north western rugged part of the study area as seen from east to west

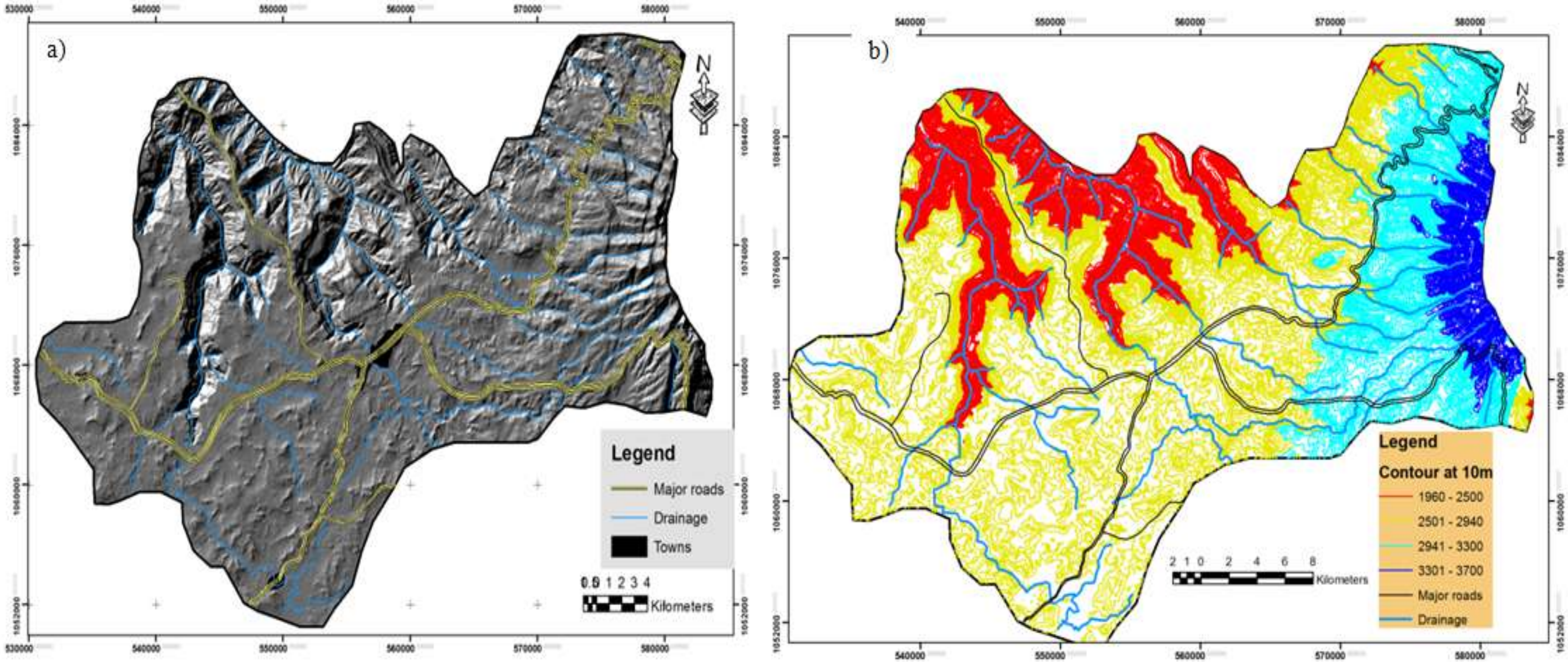

Figure 3-3 Maps showing, a) Hill shade view of the project area showing the relatively rugged topography, b) Contour map of the study area

3.1.2 Climate, vegetation and land use

The climate of Ethiopia varies from equatorial desert to hot and cool steppe, and from tropical savannah and rain forest to warm temperate, from hot lowland to cool highlands. The altitude varies from around 120m below sea level in the Afar region (Dallol depression) up to 4620m a.s.l on the Ras Dashen Mountain ranges. The Main Ethiopian Rift valley and the Afar regions are semi-arid to hyper-arid.

Both in space and time, in Ethiopia, rainfall shows an uneven distribution. This is partly due to the presence of one major and one small rainy season, in most part of the country. A secondary consequence is that a large amount of rainfall on the highlands is concentrated as run-off in river valleys, which drain into the low-lying areas where annual rainfall is low. Accordingly, based on altitude, the climate can be categorized into five groups (Table 3-1).

Altitude(m) (a.s.l)	**Mean annual temperature (^{0}C)**	**Description**	**Local name**
3,300 and above	10 or less	Cool	*Kur*
2,300 - 3,300	10 – 15	Cool temperate	*Dega*
1,500 - 2,300	15 – 20	Temperate	*Woina Dega*
500 - 1,500	20 – 25	Warm temperate	*Kola*
below 500	25 and above	Hot	*Bereha*

Table 3-1 Climatic category of Ethiopian local system

The prevailing climatic condition of the studied area is "Dega-Woina Dega"(Temperate) with mean annual rainfall of 800-1000 mm/yr and temperature of 10-15°C (NMA-National Meteorology Agency of Ethiopia). Scarce vegetation coverage of Eucalyptus tree in the highlands and scrub in the low lying areas are dominant other than the extensively cultivated landmass in the plain areas with the exception of a protected forest in the northern part of the study area, called “Wof Washa” where the only tunnel way in Ethiopia is found constructed during the Italian presence in the country.

The region is characterized by Semi-bimodal rainfall pattern, i.e. a dry season from October to January, separating the long and short rainy seasons of June to September and February to May respectively.

Relative humidity

The relative humidity of the area is an important factor in both dimension stone deterioration/durability and Alkali Aggregate Reaction in concrete mix. The mean relative humidity of the area recorded at the Debrebirhan station over a period of 23 years from 1983 to 2005 is 69.5 % and reaches its peak in the rainy season from July to September, while the minimum relative humidity is registered in May and June (Figure 3-4). The annual range of relative humidity is about 20 % (Ethiopian Meteorology Agency as cited in Abay Master Plan study).

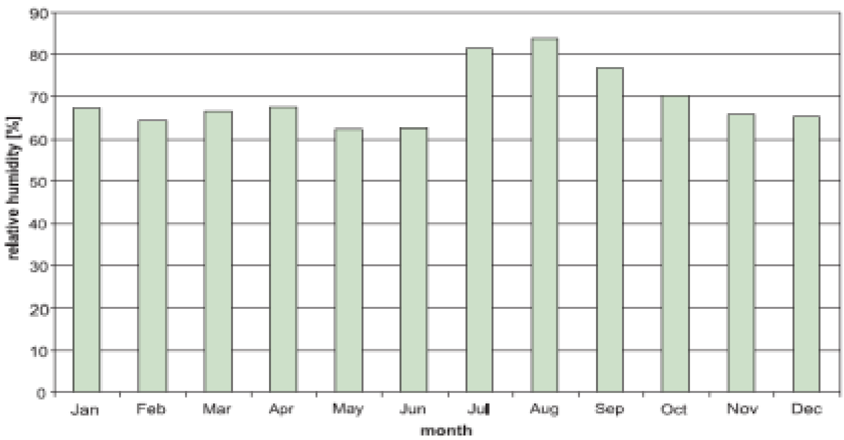

Figure 3-4 Mean monthly relative humidity of Debrebirhan station

Debrebirhan town is located at the centre of the studied area and higher consumer of in-situ rocks crushed aggregate production and dimension stone. The in-situ rock sources for aggregate production and dimension stone are basalt and ignimbrite, respectively. The main highway from Addis Ababa to Dessie also passes through Debrebirhan town and recently this highway was built in a new design and used aggregates and other construction materials from the currently studied area rock formations. Furthermore, the aggregates produced from the surrounding of Debrebirhan area are transported as far as Mehalmeda (100km, north), Dessie (200km, north) and Addis Ababa (100km, south) which have almost similar climatic condition as of Debrebirhan area. The Debrebirhan climatic station has a continuous observation from 1983 to date, so the period 1983 to 1992 is selected to show the relative humidity, temperature and precipitation. The precipitation shows bimodal distribution with maximal values in summer months (June–October) and negligible values during winter months (Figure 3-5). The average monthly temperatures are also periodic with differences of about 4°C between winter and summer months (Figure 3-6).

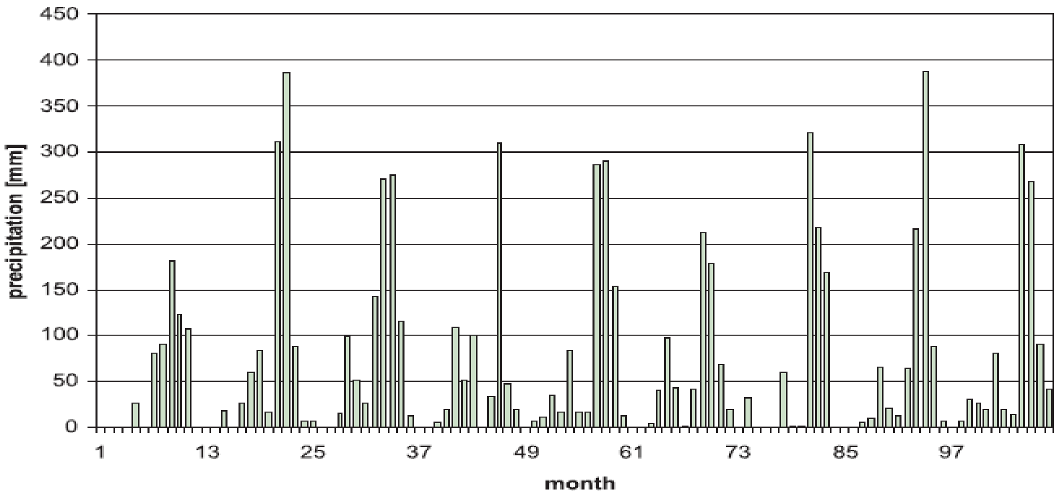

Figure 3-5 Monthly values of precipitation observed at Debrebirhan climatic station

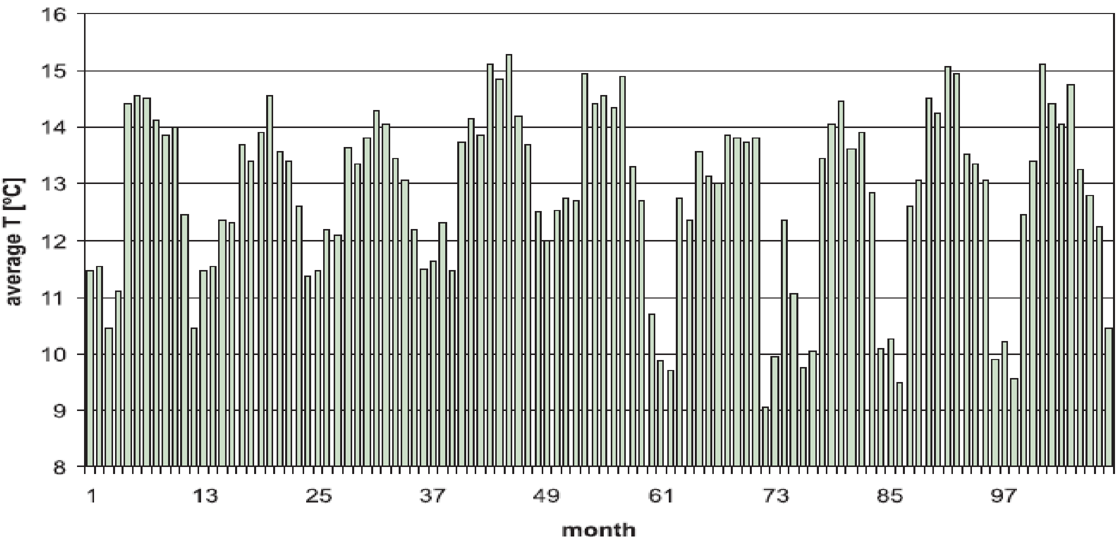

Figure 3-6 Monthly values of average temperature observed at Debrebirhan climatic station

3.1.3 Socio-economy of the project area

The studied area is located in the north central part of the country characterized by high population growth rate (CSA, 2010). This has led to a very tense economic activity through farming transforming the natural environment into a seriously stressed condition. This in turn has led to accelerated land degradation by erosion, various mass wasting processes and reduction in productivity of soil. These conditions aggravated landslide occurrence which is the main problem in the area devastating farm and grazing lands. Nevertheless the rate of change of land degradation which can be caused by the land use and land cover change may or may not match to the recurrence interval of landslides in the area.

Subsistence of the local community depends on rain fed agriculture and some limited irrigation schemes. Major crops produced are Barely, Wheat, Sorghum, Teff, Pea and Lentil.

Also fire wood and forest products are marketed extensively contributing to the destabilization of the already critically standing steep slope of soil developments and weathered and jointed bed rocks. There are few privately owned artisanal building stone quarries which created very limited job opportunity in the currently studied area. The quarry operation is carried out mainly by hand tools and paid on piece rate system. The rocks produced in this way are marketed for local construction as ashlars, rubbles and rough stone and cobblestone etc. Specifically, the cobble stone production in the project area is increasing dramatically since 2010 by organized youngsters supported by government funding, however, this intensive cobblestone production is done without any geo-engineering (physical and mechanical) study of the source rocks which might result in shortened service life time and other quality problems which has started to be seen even in a short time by now (2-3 years).

3.2 Regional geological setting

The basement upon which all younger lithologic formations were deposited consists of the oldest rocks in the country. It is exposed in areas where all the younger cover rocks were removed by erosion (Figure 3-7). Numerous studies exist on the geochemical and petrological aspects of the basement rocks of Ethiopia (Teklewold, et al. 1990; Mulugeta and Barker, 1997; Worku and Schandelmeir 1996; Tadesse et al. 1999, 2000; Asfawossen and Barbey, 2003; Mulugeta, et al 2006, etc.). The Precambrian basement rocks are exposed in all climatic regions of the country along with intrusive bodies. These rocks consist of granites, granodiorites, gabbro, gneiss, migmatites, granulites, amphibolites, schists, phyllites, etc. The Neoprotrozoic sequence lies at a critical geotectonic boundary between the Arabian-Nubian Shield (mostly Juvenile crust) to the north and Mozambique belt (mostly reworked older crust) to the southern part of Ethiopia.

In Ethiopia, the Palaeozoic and Mesozoic rocks are made up of sedimentary formations. This formation is described in detail by Mohr, 1971; Merla et al 1973; Bosellini et al 1997, 2001, etc. The Palaeozoic formations are localized in the Ogaden and Tigray regions covering only limited areal extent. In the eastern part of the country, Palaeozoic deposits occur in Chercher named as Waju sandstone, which is friable sandstone with frequent shale intercalation as trough filling on the basement rocks.

In the northern part of Ethiopia, they are essentially constituted of Edagarbi glacial deposits and Enticho sandstones (Beyth 1972). The glacial rocks have measured thickness of 150-180m, where considerable thickness encompasses dark gray tillite at the base, massive siltstone and shale overlain by red and green shale. The Enticho sandstone is made of white, calcareous, coarse-grained sandstone containing lenses of silt and conglomerates. The Mesozoic sediments of Ethiopia occur mainly in three areas: the Ogaden basin, Tigray region and Nile/Abay basin. These include sandstone, limestone, shale and gypsum. However, the thickest Mesozoic sequence occurs in the Ogaden basin which reaches up to several thousands of metres.

The earliest and most extensive groups of volcanic rocks are the Trap Series, erupted from fissures during the early and middle Tertiary. The Plio-Quaternary volcanics are largely restricted in the Rift valley. Substantial shield volcanoes consisting mainly of basalt lava were developed on the Ethiopian plateau during the Miocene and Pliocene (Kazmin, 1975). The Ethiopian volcanic rocks were divided into two main Series: Trap Series (or Plateau Series) and Rift volcanic (Mohr, 1971; Zanettin and Justin-Visentin, 1974; Zanettin, 1993).

In early Cenozoic extrusion of flood lavas occurred from fissures and centres and covered the great part of the Mesozoic sedimentary rocks and some deeply weathered basements. The total area covered by flood basalts in Ethiopia has been estimated to be 600,000 km^2 (Mohr and Zanettin, 1988). These flood lavas have been divided into two groups: Ashange group consists predominantly of thick basalt lava flows, trachytes and rhyolites with interbedded pyroclastics erupted from fissures. The post Ashange cycle is a plateau sequence which contain Aiba and Alaji fissural volcanism (32-25Ma). The Aiba basalts (32-25Ma) are typical of transitional basalts with homogeneous composition. They are followed by Alaji volcanic, containing interlayer silicic rocks (peralkaline rhyolite) and transitional basalts. Their emission is controlled by tectonics (Zanettin, 1993). The fissural Alaji volcanism is followed by central type volcanism, which built up large shield volcanoes called Tarmaber central volcanics (Mohr, 1971b). The maximum thickness of Trap Series on the Ethiopian plateau is 3500m and is represented by Simien Mountain while in the southern plateau the maximum thickness is 2500 m a.s.l on Arsi highland (zanettin, 1993 and Kazmin, 1976). However, recent classification approach by various authors, based on TiO_2 contents of the Ethiopian continental flood basalt grouped into three magma types: two high-Ti groups (HT1 and HT2) and one low Ti group (LT). The transitional to tholeiitic LT suite exhibits low TiO_2 and high SiO_2. In contrast, the HT2 suite exhibits high TiO_2, low SiO_2 content.

The HT1 series is intermediate between the LT and HT2 groups. These three groups of lavas originated from different parental magmas. They display distinct differentiation trends, either controlled by the removal of a shallow level gabbroic (Plg+Ol+Cpx) assemblage (LT and HT1 suites) or by deeper Ol+Cpx fractionation (HT2 suite). Most of this thick continental flood lava pile was emplaced over a short time interval (about 1-2 Ma, Pik, et al, 1998). The three contrasted magma types do not reflect a temporal evolution of their sources but rather a strong spatial control. Indeed, the north western Plateau may be subdivided into two different sub provinces as all the low-Ti basalts are located in the northern part of the plateau, and the high-Ti basalts are exposed in the eastern and southern parts. The LT and HT1 basalts display compositional ranges similar to those of the low and high-Ti groups from other main Continental Flood Basalt provinces e.g. Parana (South America), Deccan (India), Karoo (South Africa), Siberia (Soviet Union), Columbia River flood basalts (North America) and some others. However, the HT2 group exhibits extreme Oceanic Island Basalt (OIB) like compositions. This unusual geochemical signature suggests the involvement of deep mantle in the genesis of the HT2 magmas. The LT compositions rather reflect the participation of the continental lithosphere, through mantle derived melts and/or crustal contamination (Pik, et al, 1998).

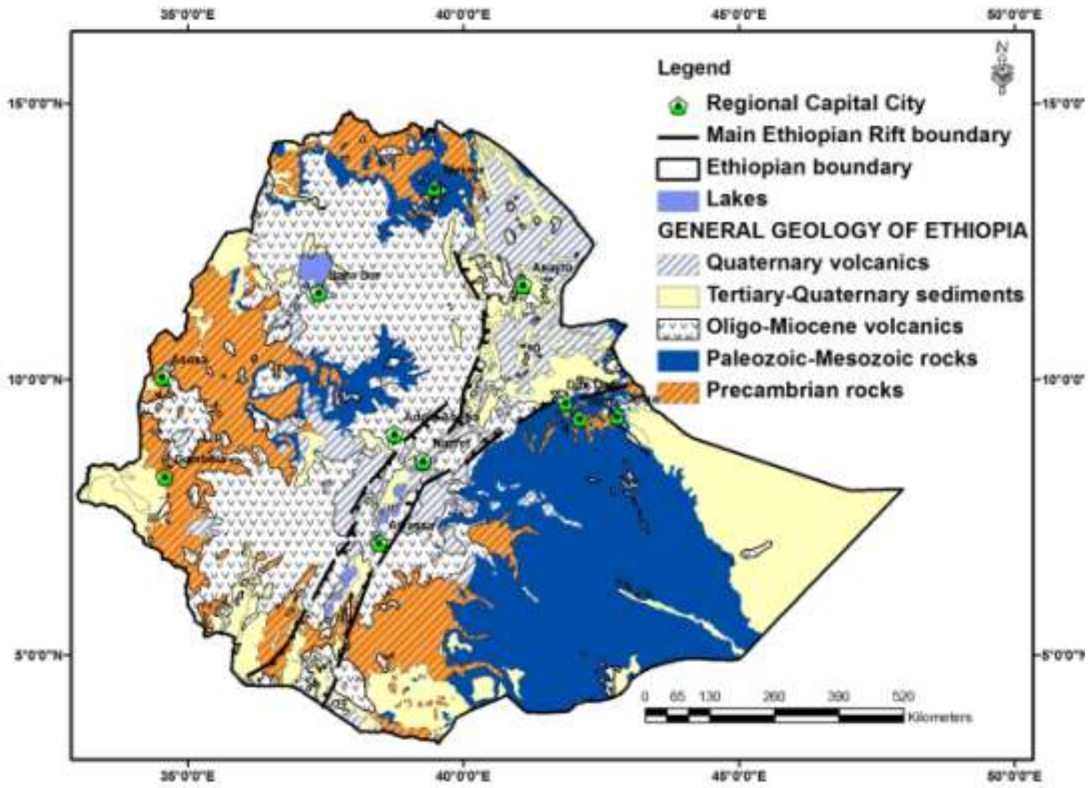

Figure 3-7 Generalized geological map of Ethiopia (modified from GSE, 2000)

3.2.1 Regional Stratigraphy

Rift volcanic postdate the formation of the Rift System in Ethiopia, i.e. post Miocene or Plio-Quaternary. Most of the rocks are confined to the Rift System and unique outcrop on the NW plateau is found south of Lake Tana. There are two fold divisions of the lavas of the Rift volcanic Series, an earlier alkaline-silicics series followed by scoraceous flood basalts. Considering that, the last phase of the Trap series was one of extrusion of alkaline-silicic lavas of Wachacha, Yerer, Chilalo etc, which may even postdate the major rifting and faulting movements. The major basalt types are olivine bearing porphyritic basalts. The basalts of Rift volcanic series are more scoraceous than the plateau basalt and are made of labradorite and bytownite augite, olivine and abundant iron oxide. The texture is commonly holocrystalline.

Generally, the Ethiopian Cenozoic volcanics are volumetrically predominated by basalts. Alkaline and tholeiitic basalts are equally abundant. The plateaus of Ethiopia have been host to tholeiitic and alkaline basalts. The detailed study of local stratigraphy and radiometric age determination (Mohr, 1962; Zanettin, et al 1974; Barberi, et al 1975) has shown that the volcanic rocks have been emplaced during two phases of volcanic activity.

The first phase is known by extensive fissural basaltic eruptions built up thick piles of plateau lavas; Ashange, Alaji and Aiba basalt, 30-20Ma with the maximum frequency being 30Ma. These are overlain by locally interfingered with rhyolitic and trachytic ignimbrites and by shield like volcanoes of Tarmaber formation (alkaline character).

The second phase (15Ma-recent) is related with the Main Ethiopian Rift (MER) opening and extrusion of silicic volcanic and subordinate basalt flows. In the central part, the main volcanic units are: Anchar and Arba Guracha silicics, 14-10Ma, outcropped along the margin of the rift and range in composition from transitional basalt with affinity to alkaline and rare comenditic and pyroclastics of pantellerite.

3.2.2 Regional tectonics

The East African Rift system is one of the largest structural features of the Earth's crust and runs about 6000km from Syria (north) to Mozambique (south). The Ethiopian Rift valley is NE-SW aligned graben, which runs for about 1000 kms from Afar to the Ethio-Kenya border and has in average 70 km width (Mohr, 1971).

The upper part of the Main Ethiopian Rift (MER) is characterized by NE to NNE aligned structures while the southern sector is characterized by N-S structures. The rift system is formed by a complex pattern of narrow belts of parallel faulting, sunken strips of land between two faults giving the characteristic rift valleys or grabens and horst structures. It shows a complex fault system, characterized by the interplay of a N30ºE-N40ºE trending border fault system with the Quaternary Wonji Fault Belt (WFB), which is constituted by right stepping en-echelon N-S to N20ºE trending faults.

The intersection of these fracture systems has given rise to the large sunken triangular region known as Afar. The Afar depression is a roughly 800 km sided triangular region bounded to the west by the great scarp of the NW Ethiopian plateau which is the focus of this study (part of it at least), to the south by the scarp of SE plateau and to the NE by the horst of Danakil Alps. The Rift spreading rate in the northern part of the MER is 0.5 cm/year and 2cm/year in the Red Sea, and intermediate rate, 1cm/year for Afar (Zanettin, 1993).

The Afar depression is considered as an example of triple rift junction since it lies at the intersection of the Gulf of Aden Rift and Red sea oceanic ridges with east African continental rift. Its north eastern edge is bounded by the Danakil microplate, while its western and southern borders follow the escarpments of the Ethiopian and Somalian plateau (Figure 3-8).

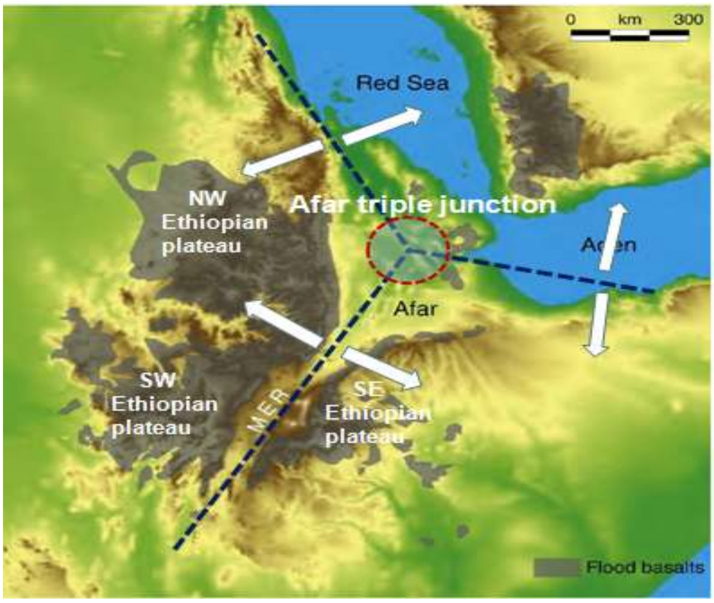

Figure 3-8 Tectonic setting of Ethiopia (Afar triple junction)

3.2.3 Geological setting of the north central Ethiopian highland

The Ethiopian volcanic rocks cover nearly one third of the surface area of the country (Figure 3-9). This Cenozoic Ethiopian continental flood basalt province is located at the junction of three rifts: two oceanic rifts, Red Sea and Gulf of Aden, and the East African continental rift (Hoffman et al, 1998). The extensive, complex, Continental Flood Basalt (CFB) province which occurs in Ethiopia and Yemen consists of Oligocene pre-rift volcanism related to the Africa–Arabia continental break-up. The basalts of the north western Ethiopian Plateau show exceptionally diverse ranges of compositions. The tectonic and volcanic activities that occurred in the Cenozoic era have a prominent influence in the building up of the existing landmass of Ethiopia and the surrounding area and therefore an immense uplifting of the area (Arabo-Ethiopian landmass) that occurred at the beginning of Cenozoic era, resulted in the fracturing and outpouring of huge quantity of lava that form flood basalts in Ethiopia (Doilicho, et al., 1991). The volcanic flows of these huge quantity forms Large Igneous Province (LIP) in east Africa and are mainly tholeiitic with some alkaline and transitional alkaline members with ages ranging from 30 to 15Ma (Hoffman, et al., 1997). As it could be understood, from the works of several scholars and researchers, the Ethiopian Continental Flood Basalt (CFB) province (~30Ma, 3×10^5 km^3 by volume), with in which the current study area is situated, was formed as a result of impingement of the Afar mantle plume beneath the Ethiopian lithosphere (Hoffman, et al., 1997). This province includes major sequences of rhyolitic ignimbrites generally found on top of the flood basalt sequences. Their volume is estimated to be at least $60,000km^3$, which represents 20% of that of the trap basalts/flood basalts. The Ethiopian plateau bordering the rift and which includes the study region consists of a thick succession of flood basalts and lesser amounts of rhyolites overlain by a huge amount of ignimbrites. According to Hoffman et al (1997), immediately following the flooding of the vast volcanic plateau basalt, a number of large shield developed on the surface of the volcanic plateau, after which subsequent volcanism was largely confined to regions of rifting (Keiffer et al, 2004).

On the north western Ethiopian Plateau, these Oligocene flood basalts are overlain by less voluminous Miocene lavas, erupted from large central vent volcanoes (Shield volcano) which is the focus of this study. Ethiopia has a unique geological setting to study the process of volcanism during continental rifting, both from pre-rift continental flood basalts up to sea-floor spreading basalts. However, the focus of this study is on the Miocene central type volcanism (Shield volcano) from the north central Ethiopian Plateau, represented by Tarmaber formation. The Miocene Tarmaber formation, represents basaltic shield volcanics on the north western and south eastern plateaus covering an area of about $47,000km^2$(8%) of the total flood basalt aerial coverage in the country. Two subdivisions made the Tarmaber formations, these are the Tarmaber Megezez subdivision with an absolute age of 16-13Ma (Kazmin, 1979) which is transitional to alkali basalt and outcrops mainly in the central Highland plateau and rift escarpments while the Tarmaber Guessa subdivision with an absolute age of 26–16Ma (Kazmin, 1979) which is alkaline to transitional basalt, often ridge and cliff forming shield volcanoes with minor trachytic, ignimbrite and phonolite flows. This formation dominantly outcrops in the north western highland plateau part of the country. The Tarmaber shield volcanoes become progressively younger to the south eastern and south western part of the north western Ethiopian plateaus. These post trap volcanism signatures, i.e. the shield volcanoes, are conspicuous features of the Ethiopian plateaus. The shields are formed predominantly of volcanic rocks as mentioned above with mainly alkaline compositions. The basal diameters of the shields range from 50 to 100 km and Ras Dashen (4620m a.s.l) is the present summit of the eroded Simien shield volcano. This shield rises almost 2000m above the top of the flood basalts. There are other smaller shields (in both diameter and height above the flood basalt plateau) with their respective ages. The lava flows of the shield volcanoes are thinner and less continuous than the underlying flood basalts. Besides, they are more porphyritic, containing abundant and often large phenocrysts of plagioclase and olivine. Like the flood volcanic, the shield volcanoes are bimodal and contain sequence of alternating basalts, rhyolitic and trachytic lava flows, tuffs and ignimbrites, especially near their summits. The composition of the lavas in some of the younger volcanoes is more variable and includes nephelinite and phonolites (Zanettin, 1993) in addition to alkali basalts.

The magmatic characters of both the flood basalt and the shields vary from north to south and within each region, the character of the shield volcanoes match that of the underlying flood basalts. The shield volcanoes are magmatically similar to the underlying flood basalts. The tholeiitic Simien shield overlies tholeiitic flood basalts, and the alkaline Choke and Guguftu shields overlie alkaline flood basalts (Figure 3-9). As it has been indicated by Zanettin (1974) a large ignimbritic cover outcrops in the central eastern portion of the Ethiopian plateau between Amba Alaji and Debrebirhan (part of the current study area) along the Afar margin. The Alaji volcanic overlays the extensive flood basalt and underlays continuously the shield volcanic (Tarmaber formation) which is mainly represented by huge masses of ignimbrite and minor trachytes (Figure 3-10). The general stratigraphy of the Cenozoic and the Tarmaber formation is depicted on Figure 3-11.

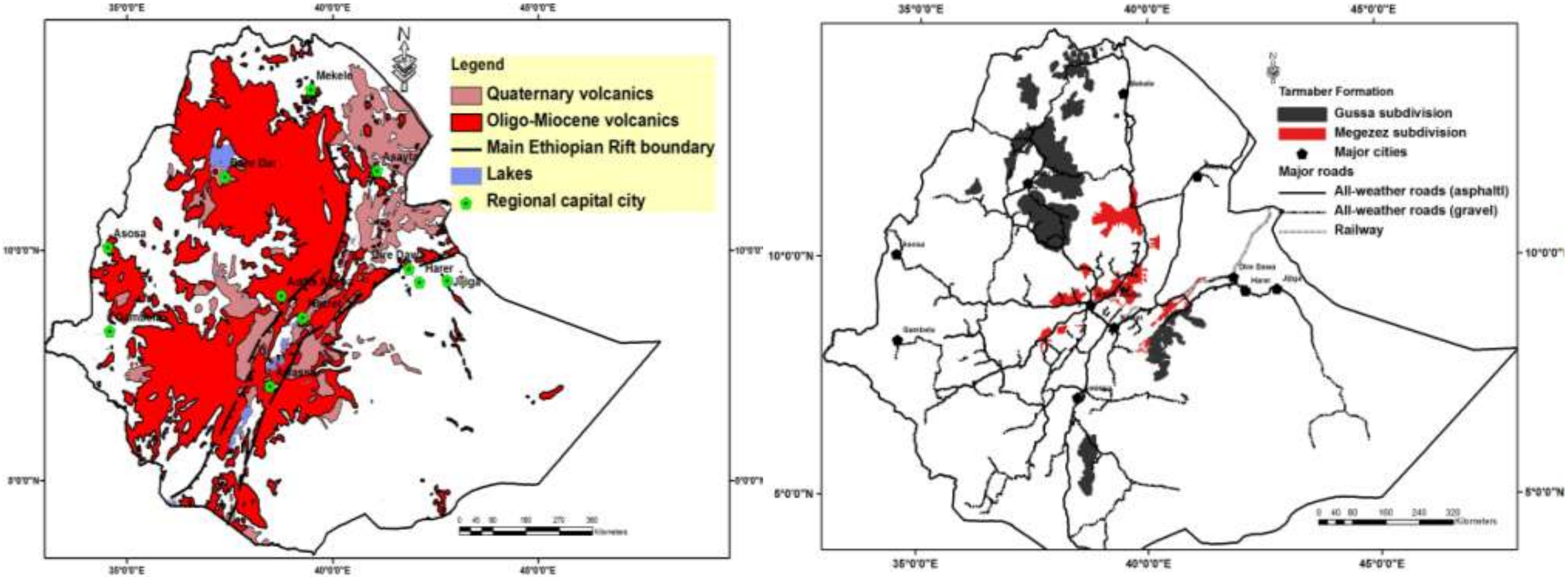

Figure 3-9 The Oligo-Miocene and Quaternary volcanic rocks of Ethiopia (left) and Miocene Tarmaber formation (right)

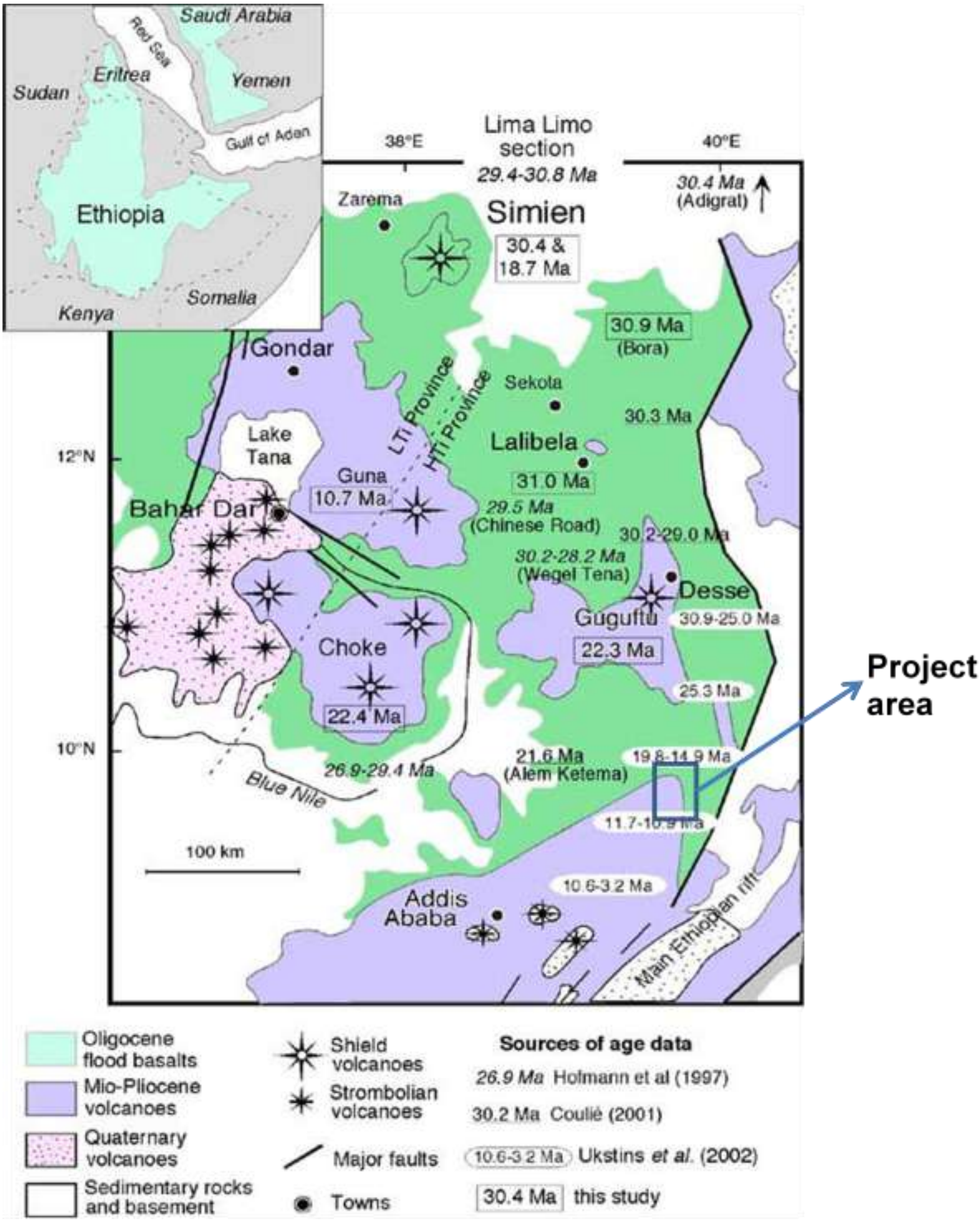

Figure 3-10 Geological map of the north central part of the Ethiopian plateau showing the extent of the flood volcanism and the location and ages of the major shield volcanoes. The dashed line indicates the boundary between the LT and HT provinces. The inset shows the location of the Ethiopian volcanic plateau (gray) in horn of Africa (adopted from Kieffer et al., 2004).

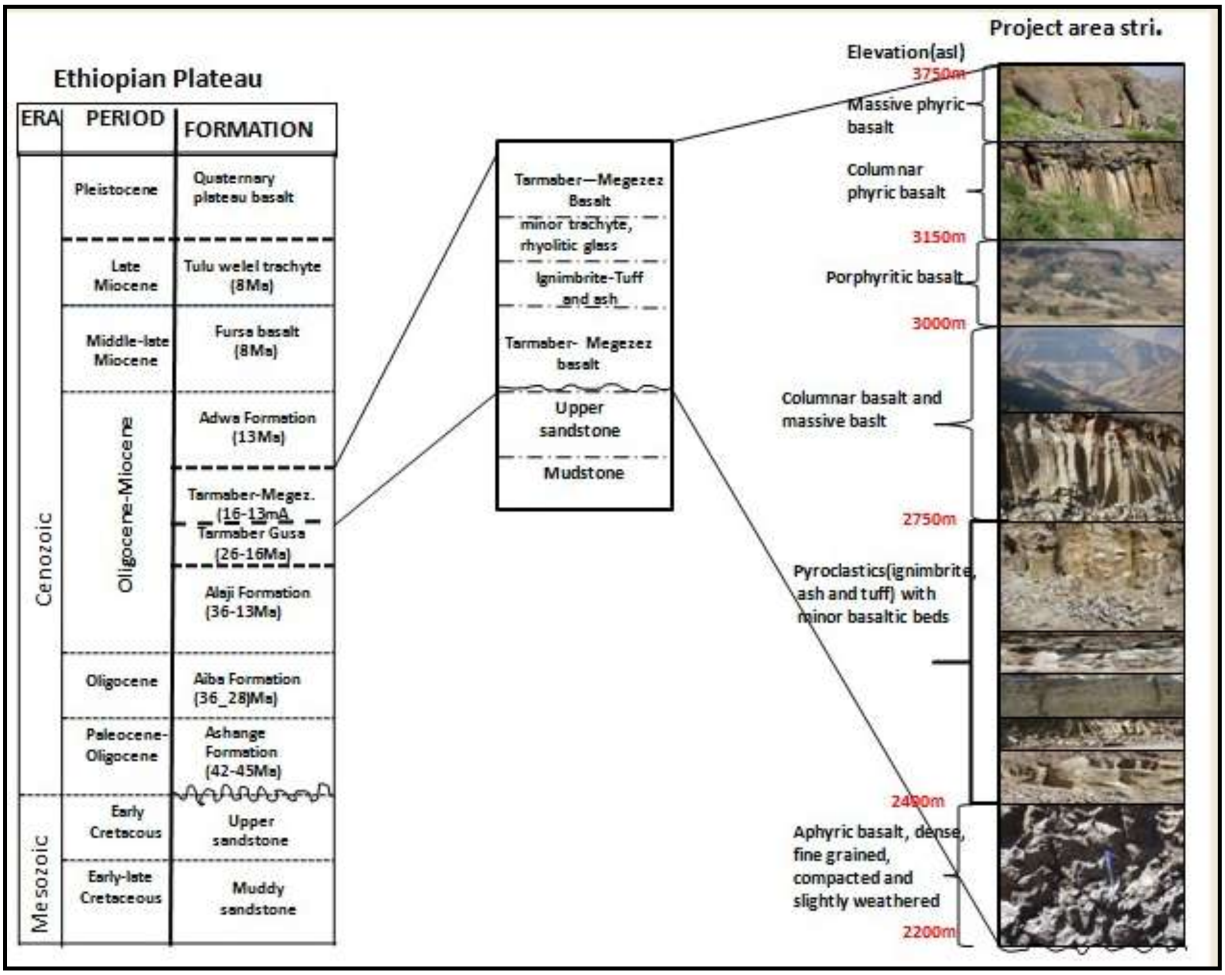

Figure 3-11 Regional stratigraphy of the Cenozoic volcanic rocks and local stratigraphy of the project area (right)

3.3 Local geological setting of the study area

The key to identifying a potential source of construction materials is an understanding of the geology of the region, focusing on a general study of stratigraphy, origin, and structural set up of the area in question for exploitation of crushed stone/aggregate and dimension stone/cut stone. The distribution of geologic units potentially suitable for crushed stone and dimension stone in the currently studied area are shown on the geologic map including sections and images (Figure 3-12 and 3-13).

The geology of the studied area, as described by previous workers comprises one major formation that essentially makes up the region, i.e., Tarmaber formation (Megezez subdivision). The current detailed study described the rock types, stratigraphy and geological structures of the studied area as follows.

As it has been stated in the previous sections, the currently studied area is situated in the central eastern part of the north central highland flood basalt and shield volcanic plateaus of

Ethiopia. The voluminous outpouring of lava on the central part of Ethiopia built imposing stacks of superimposed basalt flows, as much as some hundreds of metres thick, probably reaching the maximum in the currently studied area. Such piles were believed to be fed from fracturing and fissuring linear zones in the continental crust through which basaltic magma emerge in successive pulses, flooding out over the surrounding vast region. The low viscosity of these volcanic basalt lavas resulted in the formation of subdued or planar land features in the study area. The formation is dissected by deep valleys draining to the west. The lower part of the studied area is covered with minor ignimbrite and rhyolitic tuff with considerable basaltic flow layers while the upper part (eastern portion) is covered with typical shield like volcanic rocks (basalt) rising as high as 3700m a.s.l. The shield volcanoes are mainly alkaline-transitional except for a thin veneer of alkali basalt on the top. Outcrops of the shield basalts on hand specimens can be described as fresh to moderately weathered, vesicular, columnar and porphyritic in places with, plagioclase and olivine phenocryst as the dominant mafic mineral and augite as a minor constituent.

Based on the stratigraphic relationships, among the various units, taking existing relatively thin ignimbritic and rhyolitic ignimbrite of a basal unit of the overlaying basalt lava flows and physical individuality of the local lithological units, terms like upper most basalt, lower most basalt, middle basalt are used in the proceeding sections of this thesis.

As it has been said earlier, the major part of the study area is covered with Tarmaber formation, specifically by the Tarmaber-Megezez subdivision, basaltic rock units. The Tarmaber-Megezez subdivision attains an approximate thickness of more than 300 metres in the study area with occasional units of strongly welded tuff, loose tuff, and ignimbrite/rhyolitic glass. This formation basically comprises of basaltic units with texturally and mineralogicaly varied flow layers. The lower base of the formation is marked by fine grained, hard and compact columnar basalt. Detail petrographic analysis revealed a range of textures and phenocryst abundances. Most samples are porphyritic with phenocrysts up to 5.5mm in size. The studied thin section samples are hypocrystalline to holocrystalline, with glass restricted to the groundmass in most cases. The columnar basalt consists of phenocrysts of rare plagioclase and pyroxene (TB-TS-15 and 16) with trace amounts of zeolite (~3%) and groundmass of laths of plagioclase and glass. All of the basaltic rock samples that were studied petrographically contain olivine phenocrysts, and also many thin section samples contain pyroxene and plagioclase phenocrysts. Crystal development of phenocrysts ranges from anhedral to euhedral. Iddingsite alteration is common, though generally comprising less than 5-10% of the volume of observed olivine phenocrysts. Opaque inclusions, probably chromian spinel, are common in olivine phenocrysts. The XRD and XRF analysis of this unit reveals low silica (42-44%wt) and high total alkalis. According to Total Alkali Silica (TAS) classification (Le Bas, 1986), it is basaltic-basanite. The columnar basalt gives way to the massive/tabular basalt which forms relatively gentle slopes. It is fractured and slightly weathered on the surface. On top of the massive basalt, a thin layer of vesicular basalt forms almost flat topography and it is fine grained with rare amygdales of calcite/zeolite. The vesicles range from few mms to 5mm in diameter. Next to it, are the loosely welded tuffs/ash which are light yellow in colour, comprises of fragments of basalt, pumice as observed megascopically. Just on top of the tuff, again the massive basalt follows and above it again columnar basalt comes. Lastly, rhyolitic tuff, ignimbrite and spatter cone hills of basalts cover the top part of the study area. The rhyolitic tuff, mostly grading to rhyolitic glass covers the town Debrebirhan, especially western part of the town. The rhyolitic glass is dark with phenocrysts of sanidine and quartz (TB-TS-00) showing faint columnar jointing which at a glance looks basalt and even wrongly has been used as aggregate quarry for concrete and asphalt mix. The rhyolitic glass comprises Alkali Silica Reactive constituent like opaline silica and chert.

The outcrops of the Tarmaber basalt lava, as correctly described earlier, occur as a continuous sub-horizontal band alternating with subordinate ignimbrite/pyroclastic deposits. These fresh basalt units occur in a layered fashion in most places where outcrops are normally associated with a highly weathered volcanic tuff and ignimbrite. The ignimbrite unit comprises of relatively fresh various rock fragments including basalt and pumice clasts in a weak, ashy glassy matrix. This band of volcanic rock exposure is continuous, can be as high as several tens of metres and wraps around hills for about several kilometres in most places. The basalt lava is generally variously grained and it has variable degree of fracturing and slight weathering pattern. The uppermost basalt is highly phyric/porphyritic with phenocrysts of plagioclase up to 5-6 cm in size.

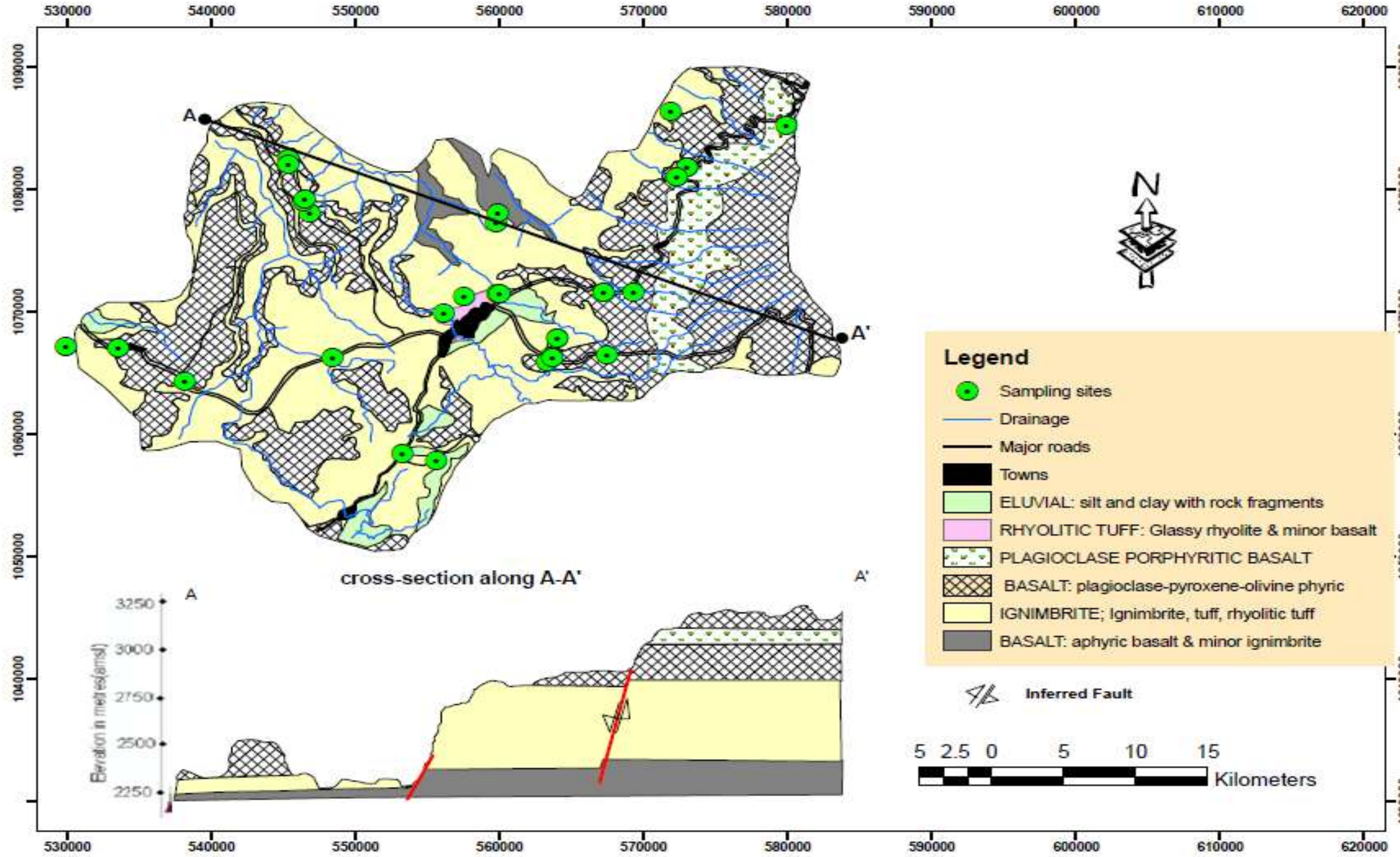

Figure 3-12 Schematic geological map of the studied area

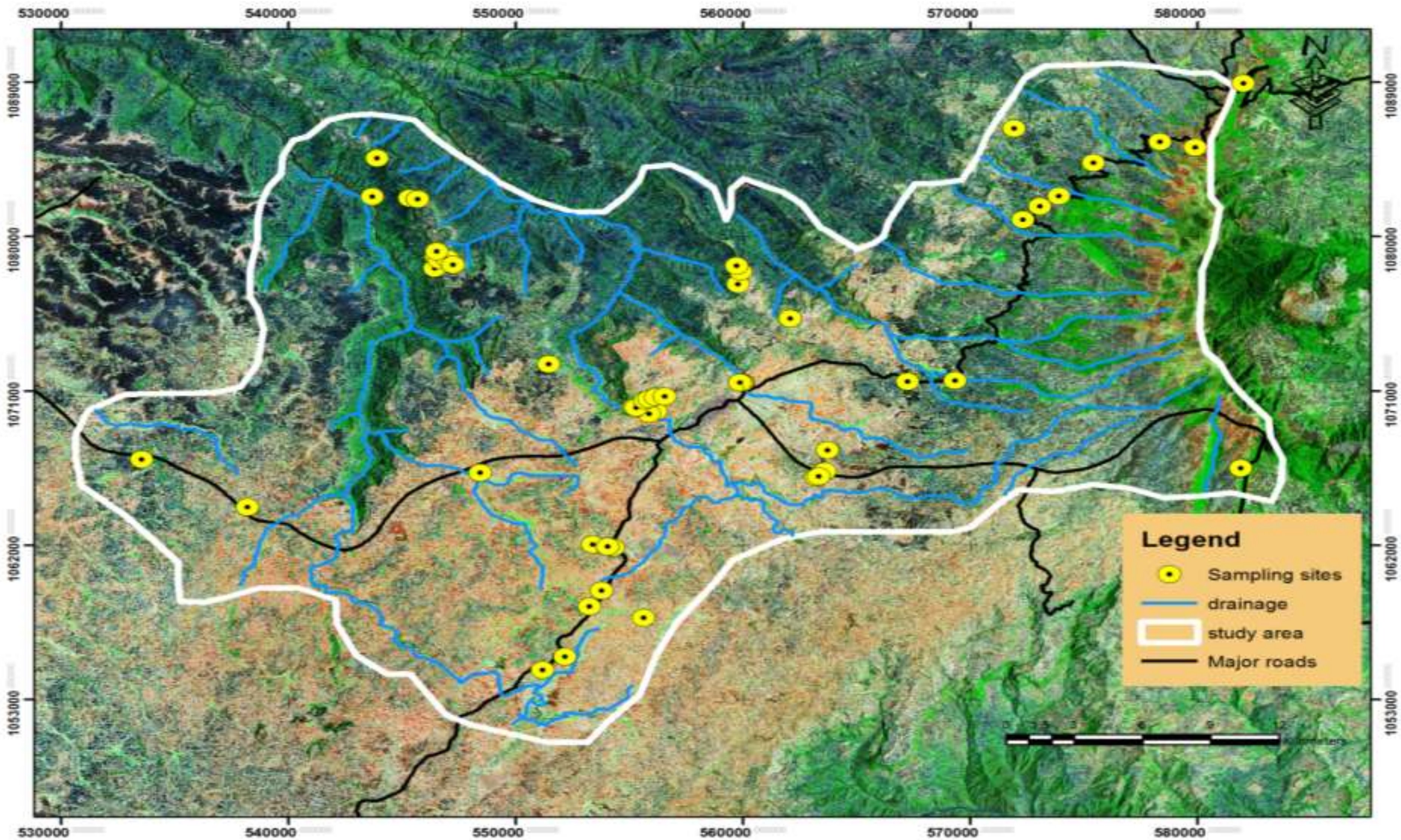

Figure 3-13 Enhanced Thematic Map (ETM) of the study area (band 7, 5 and 3)

Generally, the studied area is covered with basaltic rocks, ignimbrite, rhyolitic glass and occasional loosely welded tuff. The detail description of the rock units with respect to the macroscopic and microscopic examination are given below.

3.3.1 Rhyolitic tuff/rhyolitic glass

The rhyolitic glass is dark coloured, grading to rhyolitic-ignimbrite, pitchy luster rhyolitic glass and dark-gray aphanitic basalt looking at a glance. This lithostratigraphic unit is dense, fine grained typically porphyritic and commonly exhibiting flow texture with phenocrysts of quartz and alkali feldspar (sanidine) in a glassy and cryptocrystalline groundmass. It is largely composed of volcanic glass. The upper part of this rhyolitic glass show faint columnar jointing which is easy for manual quarrying as observed in the field where active small quarries are abundantly found across this unit (Figure 3-14A, C, and D).

The rhyolitic glass unit, as observed from top to bottom is only slightly weathered on hand specimen and thin section study. The thin section study revealed that the rhyolitic glass is affected by microfractures and in some cases these microfractures are filled with secondary minerals of opaline silica and iron hydroxides (Figure 3-14B).

Figure 3-14 Plates showing, A) Faintly columnar jointed rhyolitic glass, B) Thin section microscopic view under crossed nicol of the rhyolitic glass, C) Less jointed variety of the rhyolitic glass, D) Highly brecciated and fractured variety of the rhyolitic glass

3.3.2 Basalt (plagioclase-pyroxene-olivine phyric)

This basaltic unit is with phenocrysts of plagioclase, pyroxene and rare olivine with minor constituents of Fe-oxide/opaque and glass. The groundmass is composed of laths of plagioclase and pyroxene, in rare cases, with trace amounts of biotite (Figure 3-16). Some thin sections show ophitic and subophitc texture which could be resulted from the cooling history of the rock. And in rare cases, poikiolitic textures are also observed. This basaltic unit mainly occupy relatively higher elevation and is affected by slight weathering pattern. Fresh outcrop is only possible to get along the newly built road cut which runs from Debrebirhan to Addis Ababa and along cliff sides (Figure 3-15).

Figure 3-15 Plate showing the general outcrop nature of the plagioclase-olivine-pyroxene phyric basalt

Figure 3-16 Plate showing, A) Outcrop of the plagioclase pyroxene olivine basalt, B) Microscopic photo under plane polarized light showing plagioclase and olivine, opaque in laths of plagioclase and glassy groundmass, x10

3.3.3 Plagioclase porphyritic basalt

The plagioclase porphyritic basalt is found sandwiched between the plagioclase-pyroxene-olivine phyric basalt. It is only slightly weathered and forms gentle slopes. It is also found as big detached blocks ranging in size from 2 to 3 metres in diameter. As it has been said earlier this unit is dominated with phenocrysts of plagioclase and some olivine phenocrysts which are deutrically altered to iddingsite (Figure 3-17).

The plagioclase phyric basalt is the most abundant rock type and mostly occupies the higher grounds of northern part of the studied area; Tarmaber village and adjacent high peaks, where it attains its maximum thickness. It is medium to coarse grained and dark gray, comprising of plagioclase phenocyrsts as big as 5-6cm in length. The plagioclase phyric basalt shows random faint columnar jointing (at north of Debrebirhan city). Furthermore, this unit exhibits variation in phenocryst both in size and concentration from bottom to top. The lower part of the unit is characterized by relatively big and concentrated plagioclase phenocrysts while the upper portion is marked by relatively small and less abundant plagioclase phenocrysts with vesicular nature at the topmost part. The only tunnel route in the country is built in this unit before 70 years ago by the Italians during their presence in the country. The tunnel route is 1km long serving for traffic highway which connects the capital city (Addis Ababa) with the northern part of the country and still it is intact and serving with little maintenance work recently (Figure 3-18).

Petrographic studies of the plagioclase phyric basalt show an average composition of groundmass 15%, plagioclase 43%, pyroxene (augite), 35%, olivine, 5% and opaque minerals 2%. The plagioclase and olivine grains are altered to trace sericite and iddingsite respectively. The groundmass is dominated with plagioclase and pyroxene micro-laths. The rock exhibits porphyritic and ophitic to seriated textures.

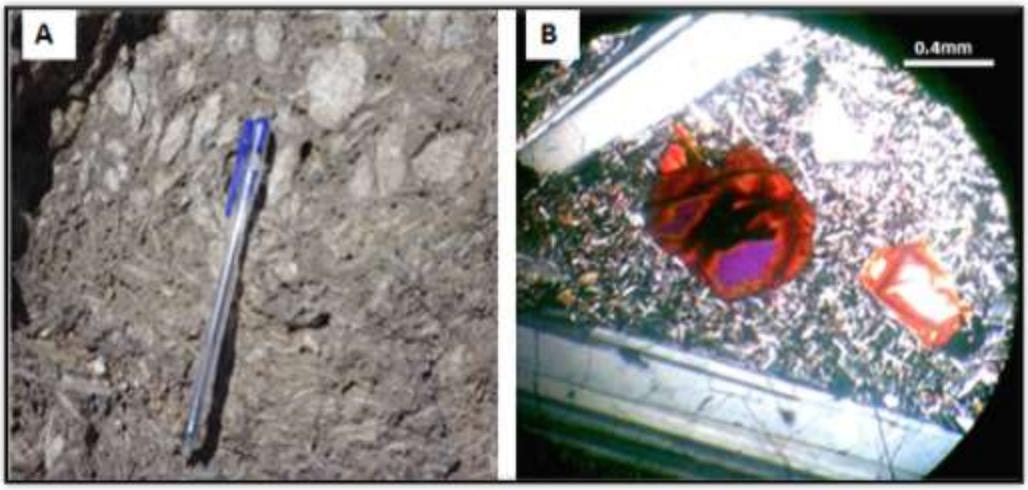

Figure 3-17 A) Plate showing phenocrysts of plagioclase in hand specimen, B) Microscopic photo under plane polarized light showing phenocrysts of plagioclase and olivine in groundmass of laths of plagioclase

Figure 3-18 Tunnel route (1km long) constructed in the plagioclase porphyritic basalt, the only tunnel way in the country

3.3.4 Ignimbrite (welded tuff)

The ignimbrite/welded tuff unit is exposed mainly at the surrounding of Debrebirhan city, along the Ankober-Aliyu Amba road on the eastern part of the studied area. It has sharp contacts with the overlying and underlying basalts. It comprises occasional layers of loosely compacted tuff and rhyolitic tuff. The ignimbirites are coarse grained with various lithics of rocks and minerals including basalt, pumice; however, the dominant rock lithics are basalt, pumice and rhyolites.

The ignimbrite forms gentle to steep cliffs, elongated ridges and sporadically distributed isolated hills. It is medium to coarse grained, light/bluish/brownish gray to gray (fresh colour) to dull/dark gray (weathering colour), highly consolidated to welded tuff and intercalated with columnar joint, vertical joints, and fractured varieties. It occurs on top of the aphyric basalt (Figure 3-19 and 3-20).

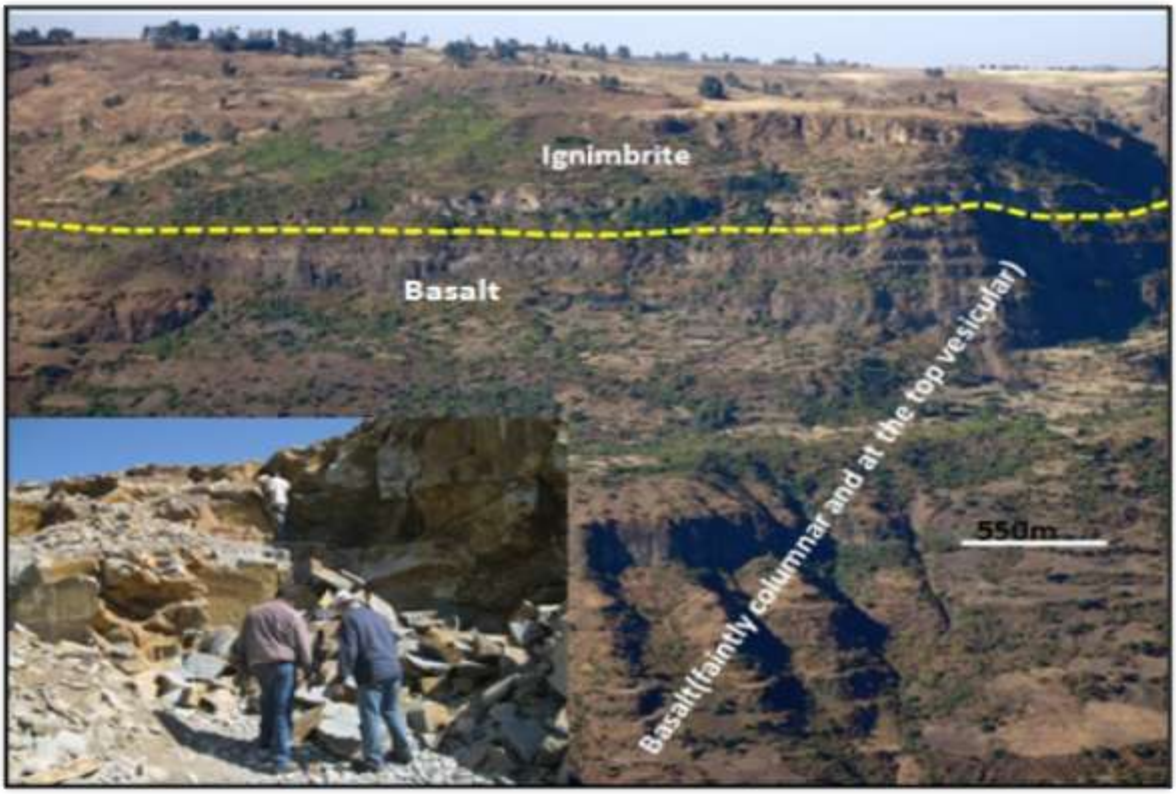

Figure 3-19 The ignimbrite on top of the aphyric basalt with sharp contact, the left corner inlet map is small ignimbrite quarry used for local masonry stone

The ignimbrite contains rock fragments of rhyolite and basalt ranging up to 2cm in diameter and elongated fibrous glass shards (fiamme), whereas the amount of rock fragments significantly varies from place to place. There are two distinct layers of ignimbrite. The upper layer is white to light yellow while the lower one is dark and contain basaltic rock fragments in most cases. The thin section studies have shown the ignimbrite has an average composition of glass 40%, sanidine 20%, rock fragments 20%, quartz 10%, sphene 2% and iron oxide/opaque 3%.

Figure 3-20 Small quarry faces on ignimbritic rocks around Debrebirhan city

Just alternating with the ignimbrites, loosely welded tuff/ash is occasionally observed in the whole section of the ignimbritic unit. The ash is forming mostly gentle slope and flat topography. It is white, light yellow, pink and light brown (fresh colour) to red, yellowish gray and black (weathering colour). It contains small fragments of basalts and pumice even visible on hand specimen (Figure 3-21a and b).

Figure 3-21 Plate showing loosely welded tuff/ash in between the ignimbrites, A) Gentle topography and friable nature of the tuff, B) Rock fragments on a close up view of the loosely welded tuff/ash

3.3.5 Basalt (aphyric)

The aphyric basalt is fine-grained, dark coloured, representing mostly the columnar basalt with side dimensions of 20-30 cm. There is very little sign of weathering, generally less than 2%. However, some exposures show concentric ferrous oxide films, sometimes up to 0.5 mm deep. Crushed samples are very angular, with sharp edges, due to the largely fine texture. No discontinuities are visible in hand specimen or large blocks of the columnar basalt except the columnar joints. However, the massive/tabular varieties are strongly fractured with 2 prominent discontinuity sets on megascopic scale; moreover it is also more affected by weathering than the columnar type basalt. This unit contains also vesicles and occasionally these vesicles are found filled with zeolite/calcite.

The massive type of this unit is the most abundant, fine grained, dark gray to black (fresh colour) to bluish gray (weathering colour), while the columnar jointed unit is relatively rare and with shallow thickness as compared to the massive one (Figure 3-22 and 3-23).

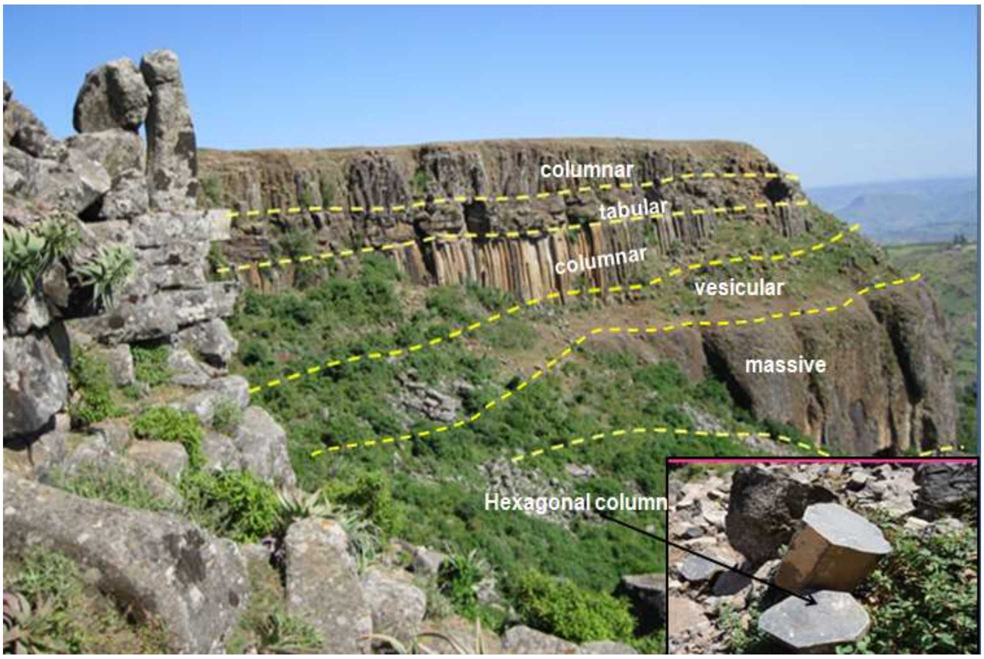

Figure 3-22 Plate showing the massive, vesicular, and columnar basalt flow layers

Figure 3-23 The various outcrop of the phyric basalt occupying the lower part of the studied area

3.4 Geochemistry

The main mineral constituents of basaltic rocks include both calcic and sodic plagioclase, pyroxene and some other minor constituents in general, with different accessory minerals determining their exact petrological name. In engineering terms, these mineralogical differences are not usually so important except in the way they influence alteration. For example, olivine is a high temperature mineral and is more susceptible to alteration than augite. Thus olivine basalt is likely to be more altered than olivine free basalt. Other factors of significance to the engineer are the variations in the physical properties of the rock, in particular grain size, texture, porosity, discontinuities and other variation in quality.

Although grouped under the engineering term “basaltic”, there are distinct differences within the specific types when considering the chemical composition of basalts of different areas. In both countries the geological history of the basalts has influenced the aggregate properties. Furthermore and more importantly, regional conditions (such as hydrothermal activity) have influenced the rock properties and alteration products.

It is evident that individual sources of aggregate within rock type groupings do not perform in similar ways. A simple classification must therefore recognise that differences occur at a local level. It is also doubtful whether it is appropriate to include different rock types when correlations are made between different test methods. Rather than use the collective terms such as basalt a much better level of immediate understanding would be achieved if knowledge of local problems and performance capability were available.

So, geochemists have determined the geologic, magmatic and/or tectonic affinities of igneous rocks for decades (e.g. Pearce and Cann, 1973; Winchester and Floyd, 1977). To do this, representative major element data of samples from the Tarmaber basalts and rhyolite/ignimbrite rocks are presented in Table 3-2. Therefore, 15 whole rock samples were pulverized with agate mill to the required size fraction and analyzed at the ALS laboratory group (in Spain) using X-Ray Fluorescence Spectrometry (XRFS) with high accuracy, and accordingly data were compiled and analyzed using Microsoft Excel, and Petrograph software (Petrelli et al., 2005) to classify the rocks of the study area.

Major and minor elements are the main chemical constituents of magmas. Their concentrations, expressed as wt% of element oxides (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5), are variable and range from a fraction of percent to some tens of percents. Most of the samples show very low Loss On Ignition (LOI) indicating the low alteration effects except two samples which are collected from glassy rhyolite/tuff; the rest indicated low H_2O and CO_2. So, there is no need to recalculate the major element oxides composition to normalize (100%) on hydrous free basis.

Several workers have proposed chemical classifications for assigning the nomenclature of volcanic rocks.

- Total Alkalis Silica (TAS) classification (Figure 3-24) after Le Bas et al (1986)
- K_2O versus SiO_2 classification (Figure 3-25) after Peccerillo and Taylor, 1976
- Calculated normative mineralogy (CIPW) Table 3-2

The chemical results revealed that rocks which were considered basalts in the previous studies and used for aggregates are now found to be basanites, rhyolitic glass, and trachybasalt. The rocks were classified on Total Alkali Silica (TAS), using Le Bas et al (1986) including the CIPW norms. Of course, there are also samples which fall in the basalt field of TAS classification.

Oxide	**Major element (wt %)**														
	TB-TS-1	**TB-TS-2**	**TB-TS-5**	**TB-TS-7**	**TB-TS-10**	**TB-TS-11**	**TB-TS-12**	**TB-TS-14**	**TB-TS-16**	**TB-TS-18**	**TB-TS-21**	**TB-TS-22**	**TB-TS-23**	**TB-TS-24**	**TB-TS-25**
SiO2	46.97	73.16	45.36	65.36	42.2	51.4	50.07	67.79	42.35	66.47	48.64	73.68	44.35	73.07	47.87
TiO2	3.03	0.34	3.05	0.55	3.56	2.86	2.85	0.56	4.09	0.5	3.49	0.31	0.31	0.29	3.19
Al2O3	16.33	10.4	14.72	12.63	12.63	14.05	13.43	12.52	14.34	12.61	16.19	10.95	14.48	10.32	18.04
Fe2O3	13.4	5.14	13.09	5.73	15.71	11.61	13.63	4.04	15.61	5.42	12.24	4.29	15.79	5.06	11.53
MnO	0.22	0.17	0.28	0.29	0.3	0.16	0.19	0.2	0.25	0.24	0.18	0.11	0.22	0.18	0.17
MgO	4.49	0.13	4.51	0.47	6.12	5.09	5.37	0.32	5.5	0.42	3.45	0.12	7.06	0.11	3.6
CaO	7.88	0.22	9.22	0.86	10.18	9.6	10.08	0.29	9.24	0.84	7.9	0.2	10.16	0.19	8.74
Na2O	4.41	4.57	4.03	4.8	4.1817	2.48	2.54	3.84	3.92	5.59	3.97	4.35	2.91	4.42	3.74
K2O	1.8	4.63	2.19	4.39	1.985	1.2	0.59	5.11	1.82	4.27	1.57	4.68	1.13	4.63	1.51
P2O5	0.743	0.035	1.356	0.069	1.299	0.294	0.291	0.04	1.049	0.056	0.662	0.039	0.495	0.041	0.58
LOI	0.54	0.86	1.86	3.72	1.43	1	0.95	4.85	1.52	2.61	1.36	1.03	1.12	1.07	0.72
Total	**100**	**99.65**	**100**	**98.92**	**99.72**	**100**	**100**	**99.58**	**100**	**99.07**	**100**	**99.74**	**98.165**	**99.36**	**100**
	Norm(CIPW)														
Q	0	30.99	0	19.4	0	9.81	9.51	24.91	0	17.59	2.18	31.63	0	31.65	0.38
Or	10.4	27.36	12.94	25.94	11.73	7.09	3.49	30.2	10.76	25.23	9.28	27.66	6.68	27.36	8.92
Ab	37.32	27.22	33.29	40.52	23.78	20.98	21.49	32.49	29.69	41.09	33.59	30.27	24.62	27.31	31.65
An	19.45	0	15.61	0	9.83	23.66	23.5	1.18	16.16	0	21.72	0	20.38	0	27.98
Ne	0	0	0.44	0	6.29	0	0	0	1.88	0	0	0	0	0	0
Di	3.97	0.27	9.15	2.36	16.32	9.89	12.01	0	7.45	2.26	1.32	0.07	9.27	0.29	0.9
Hy	0	0.2	0	0.07	0	8.09	7.81	0.8	0	0	7.98	0.27	6.56	0.14	8.55
Ol	6.55	0	4.9	0	5.38	0	0	0	7.18	0	0	0	4.27	0	0
Ht	0	1.81	13.09	5.7	15.71	11.61	13.63	4.04	15.61	3.53	12.24	2.3	15.79	1.99	11.53
Il	0.47	0.36	0.6	0.62	0.64	0.34	0.41	0.43	0.53	0.51	0.39	0.24	0.47	0.39	0.36
Ap	1.76	0.08	3.21	0.16	3.08	0.7	0.69	0.09	2.48	0.13	1.57	0.09	1.17	0.1	1.37

Table 3-2 Analytical data for major element (in Wt %) and calculated CIPW norms

3.4.1 Geochemistry of the Tarmaber basalt

The basalts of the Tarmaber formation represent broadly ultrabasic to basic rock suits in the compositional range (42.2-51.4%SiO_2, 3.45-7.06%MgO, 2.85-4.5%TiO_2, 11.53-15.79%Fe_2O_3, 12.63-18.04%Al_2O_3). The data of all the basaltic samples plotted on the TAS diagram (Figure 3-24) plot within basanite, basalt and trachybasalt fields. The samples plot mainly within the alkaline and few in sub alkaline fields based on recommended dividing line of Miyashiro (1978) which delimits alkaline series (inlet on right top corner of Figure 3-24). As seen in the Table 3-3 (CIPW and major element concentration), the total Fe_2O_3 content is high for all the samples (11.53-15.79%), high Na_2O +K_2O content (~4.04-6.2%) is typical of alkaline basalts of Tarmaber Formation. The MgO is low (3.45-7%), while 0.3-1.3% P_2O_5 and 2.8-4.5%TiO_2 are high, probably suggesting highly evolved magma source. Loss On ignition varies between 0.5% and 1.5% which is very low; meaning that most of the samples are unaltered. So, according to TAS classification, the Tarmaber formation comprises of basalts, basanites, trachybasalts and ignimbrite/rhyolites. Stratigraphically, the basalts occupy the lower portion of the formation while the basanites are found at the middle part and the uppermost part is basalt-trachybasalt (transitional) with interfingering of rhyolite/ignimbrites in the studied area.

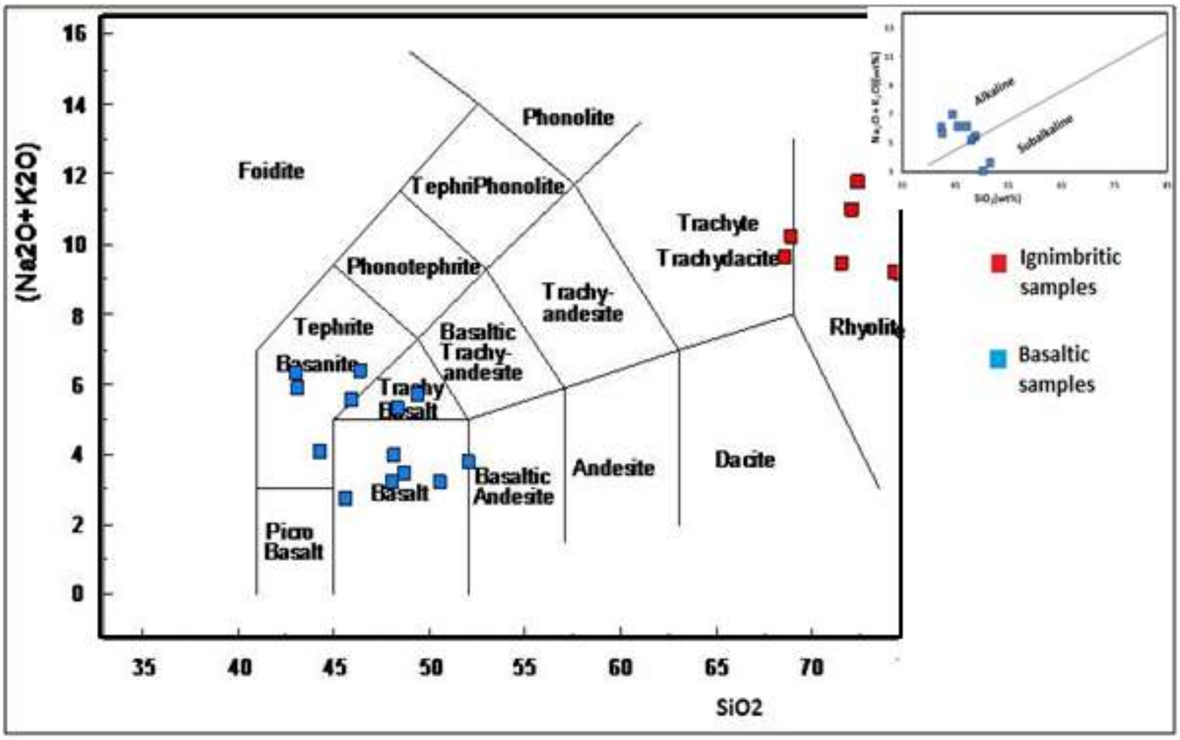

Figure 3-24 Analysed samples plotted on TAS diagram according to Le Bas et al., 1986

Figure 3-25 shows the composition of samples of the study area in terms of SiO_2 versus K_2O diagram (after Peccerillo and Taylor, 1976). Data of the samples are displayed in a SiO_2 vs. K_2O plot suggesting high-K-calc-alkaline affinities typical of an anorogenic plate boundary setting for the studied area.

The widespread occurrence of basalt and ignimbrite/rhyolite without significant andesite (intermediate rocks) indicates the bimodal volcanism nature of the studied area. Bimodal volcanism occurs at continental rifts and hotspots underlying continental lithosphere. Partial melting of the mantle generates basaltic magma. The rising basaltic magma partially melts continental crust, resulting in the dual occurrence of basalt and rhyolite (Peccerillo, 2005).

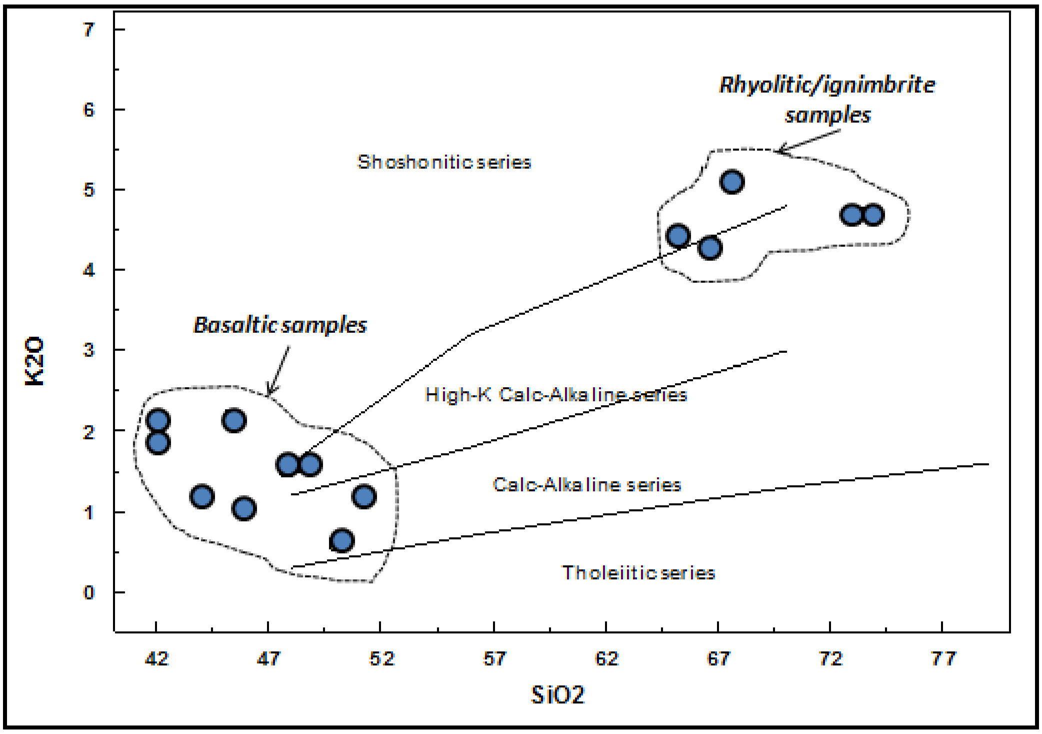

Figure 3-25 Classification diagram for Tarmaber basalts in terms of SiO_2 versus K_2O (Wt %)

The significant geochemical characteristics of the Tarmaber basalts are summarized below.

- The basaltic samples broadly define a negative trend of TiO_2, P_2O_5, Fe_2O_3, CaO, Al_2O_3, Na_2O, MgO, and K_2O with increasing SiO_2; however the patterns for individual oxides vary slightly. The very low MgO (3.45-7%) and low Mg#(<60) could suggest highly evolved magma by some sort of fractionation, further trace element analysis is required to fully understand the petrological genesis of the basaltic rocks
- The samples show generally very low MgO contents (mostly <7%) and low Mg#(<60)
- On the Na_2O versus K_2O diagram, the samples show sodic affinity (Figure 3-26)

As it is commonly accepted, alkaline magmatic rocks have solidified from magmas derived from upper mantle with different type and degree of partial melting (Wilson, 1989). Alkaline rocks contain excess Na and K than required for the formation of feldspars (Wilson, 1989). The excess of alkalies were used for the formation of feldspathoids, alkali amphiboles, alkali pyroxenes (aegirine, aegirine-augite), and the other alkali-rich minerals. Silica undersaturated alkaline rocks contain silica-depleted minerals as feldspathoid and sodalite in normative and modal mineralogical composition and do not contain any free quartz (Table 3-3). Generally, in the most restricted sense, alkaline rocks are deficient in SiO_2 with respect to Na_2O, K_2O, and CaO to the extent that they become "critically undersaturated" in SiO_2, and *nepheline* or *leucite* appears in the norm and modal analysis (Wilson,1989).

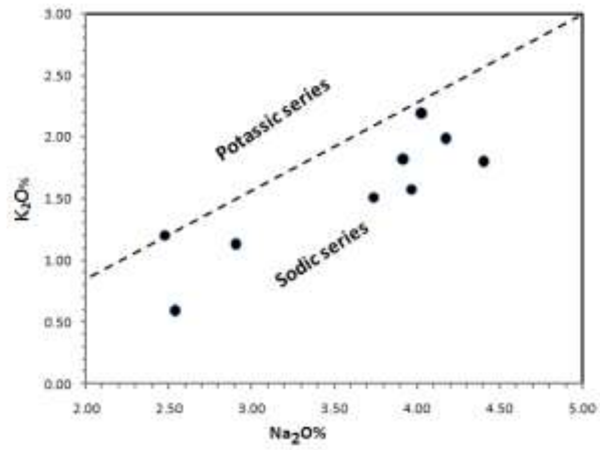

Figure 3-26 Na_2O versus K_2O diagram showing the Sodic affinity of the basaltic samples

Both mineralogically (Modal) and geochemically(Norm) well defined silica undersaturated alkaline rocks are observed on outcrop scale forming columnar joints at least for a minimum thickness of 25-40m and unlimited strike length. The basanites from this area, which have been widely used as aggregate for concrete, are not free from expansive constituents and also could release alkalis and thereby produce very alkaline pore solutions in concretes.

Alkaline rocks are essentially ultrabasic to intermediate in terms of SiO_2 content, and range from transitional (olivine and hypersthene-normative) to mildly (relatively low normative nepheline contents) and strongly alkaline (high normative nepheline and, in some cases, also normative leucite) types (alkali basalts, basanites, tephrites, hawaiites, mugearites, benmoreites).

Oxides	Major element (wt %)								
	Sample number								
	TB-TS-1	**TB-TS-5**	**TB-TS-10**	**TB-TS-11**	**TB-TS-12**	**TB-TS-16**	**TB-TS-21**	**TB-TS-23**	**TB-TS-25**
SiO_2	46.97	45.36	42.2	51.4	50.07	42.35	48.64	44.35	47.87
TiO_2	3.03	3.05	3.56	2.86	2.85	4.09	3.49	0.31	3.19
Al_2O_3	16.33	14.72	12.63	14.05	13.43	14.34	16.19	14.48	18.04
Fe_3O_2	13.4	13.09	15.71	11.61	13.63	15.61	12.24	15.79	11.53
MnO	0.22	0.28	0.3	0.16	0.19	0.25	0.18	0.22	0.17
MgO	4.49	4.51	6.12	5.09	5.37	5.5	3.45	7.06	3.6
CaO	7.88	9.22	10.18	9.6	10.08	9.24	7.9	10.16	8.74
Na_2O	4.41	4.03	4.1817	2.48	2.54	3.92	3.97	2.91	3.74
K_2O	1.8	2.19	1.985	1.2	0.59	1.82	1.57	1.13	1.51
P_2O_5	0.743	1.356	1.299	0.294	0.291	1.049	0.662	0.495	0.58
LOI	0.54	1.86	1.43	1	0.95	1.52	1.36	1.12	0.72
Total	100	100	99.72	100	100	100	100	98.165	100
Mg#	37	38	40	45	41	39	35	45	36
k_2O/Na_2O	0.41	0.54	0.47	0.48	0.23	0.46	0.39	0.38	0.4
CaO/Al_2O_3	0.48	0.63	0.81	0.68	0.75	0.64	0.49	0.7	0.76
K_2O/TiO_2	0.6	0.72	0.04	0.42	0.21	0.44	0.44	3.64	0.47
K_2O/Al_2O_3	0.11	0.15	0.16	0.09	0.04	0.13	0.1	0.08	0.08
S.I	18.63	18.93	21.86	24.98	24.27	20.48	16.25	26.26	17.66
D.I	47	46	41.8	37.88	34.55	42.33	45.05	31.3	40.95
	Norm (CIPW)								
Q	0	0	0	9.81	9.51	0	2.18	0	0.38
Or	10.4	12.94	11.73	7.09	3.49	10.76	9.28	6.68	8.92
Ab	37.32	33.29	23.78	20.98	21.49	29.69	33.59	24.62	31.65
An	19.45	15.61	9.83	23.66	23.5	16.16	21.72	20.38	27.98
Ne	0	0.44	6.29	0	0	1.88	0	0	0
Di	3.97	9.15	16.32	9.89	12.01	7.45	1.32	9.27	0.9
Hy	0	0	0	8.09	7.81	0	7.98	6.56	8.55
Ol	6.55	4.9	5.38	0	0	7.18	0	4.27	0
Ht	0	13.09	15.71	11.61	13.63	15.61	12.24	15.79	11.53
Il	0.47	0.6	0.64	0.34	0.41	0.53	0.39	0.47	0.36
Ap	1.76	3.21	3.08	0.7	0.69	2.48	1.57	1.17	1.37

Table 3-3 Analytical data for major element (*in Wt %)* calculated CIPW norms of the basaltic samples

3.5 Local geological structures

As being located on the western extreme margin of the Main Ethiopian Rift (MER), the studied area is slightly affected by brittle structures which show similar trend with the MER. The major geologic structures in the studied area are mostly localized in the eastern boundary having a series of NE-SW normal faults with variable strike length (few meters up to kilometres). These structural elements within the study area are identified by the combination of results from aerial photo interpretations, Landsat imagery and Digital Elevation Model (DEM) analysis, and field observations. The tectonic structures are associated with the extensional tectonics. They include faults, photo lineaments, local shear zones, fractures and joints, having variable magnitude and orientations.

In the north eastern part of the area, distinct normal faults are observed. These normal faults are NE-SW (mainly rift oriented) and NW-SE trending transcurrent faults. The NE-SW trending normal faults are characterized by a series of parallel step faults having different magnitudes. The step faults at the eastern boundary of the study area are dipping towards east (rift centre). Minor faults on outcrop scale are clearly observed in some units of the study area (Figure 3-27)

Figure 3-27 Plate showing normal faults, A) Faults on the rhyolitic glass, B) Faults on the aphyric basalt

Differently oriented lineaments with variable strike length are recognized in the study area (Figure 3-28). The most abundant and prominent lineament trends are NW-SE, E-W and NE-SW directions. It is noted that the NW-SE and E-W trending lineaments are cross cutting the NE -SW trending one. Some of these lineaments could be concealed faults and most of the stream/river valleys are also controlled by these lineaments.

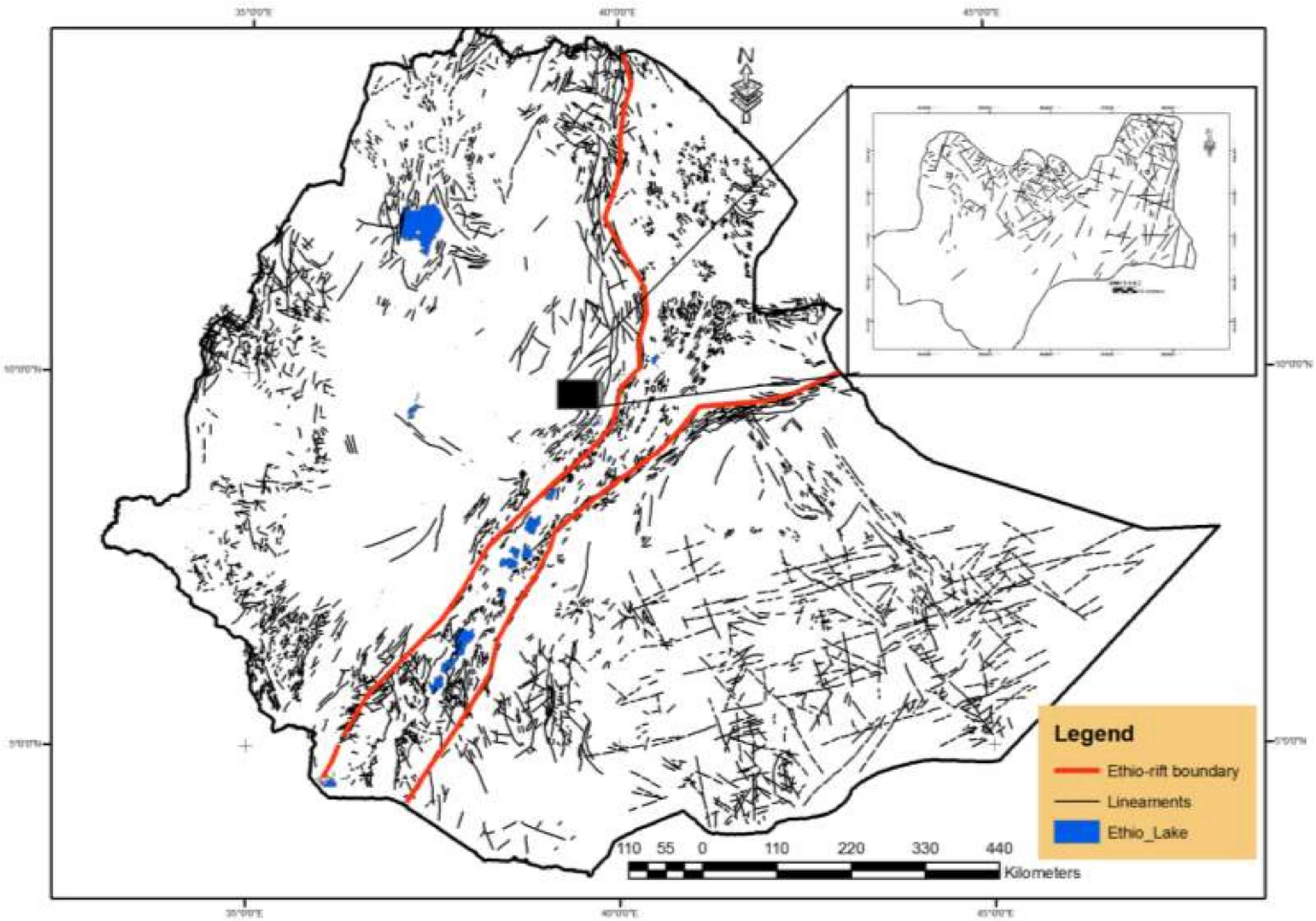

Figure 3-28 Lineament map of Ethiopia and project area (top right corner inlet)

Differently oriented joint sets and irregular fractures (few mm to cm in width) are observed in the study area. They are penetrative to non-penetrative joints, having significantly variable strike length. The first set is striking 005-065^0, the second striking 095-120^0 and the third set striking 135-175^0. Mostly in the ignimbrite rocks, two sets of joints are observed; these are horizontal (dipping 30^0 towards SE) and vertical (trending 170^0 and N10^{0}E) set of joints. In addition, irregularly oriented columnar joint sets (mostly hexagonal faces) are also observed in the ignimbrites and basalts.

Most of the joints are unfilled and closed, however, in some cases open joints with Fe-oxide staining are observed. The joints are planar, curved, mostly non persistent and closely spaced and closed.

CHAPTER FOUR

4. Geoengineering characterization methods of building/dimension stone

This chapter deals with the methodologies and principles adopted for physical and mechanical tests and procedures used to describe or evaluate the physical, mechanical, chemical and petrographic characteristics of building/dimension stone and aggregates. A number of time honoured tests are available in the published literatures and standards such as American Society for Testing and Materials (ASTM), American Association of State Highways and Transportation Officials (AASHTO), British Standards (BS) and European Standards (UNIEN) can be adopted to characterize rocks as construction materials. Therefore, a brief introduction and scope of these tests/methodologies are presented in this chapter while the results and calculations/specifications are presented in the next chapters (chapter 5 and 6).

A number of in-situ hard-rock samples were collected from active quarries and outcrops considered to be potential future quarry sites during this field investigation. The present study area is mostly dominated by gorges and dissected by westward streams and rivers of the 1st and 2nd order tributaries of the Blue Nile basin, so that access to the outcrops was a problem in transporting the sample blocks; however, big blocks of the samples have been carried on the back, managing to climb the hills and cross the rivers for a long distance to reach to the site where the car was parked. The samples were collected in such away to represent the various flow layers both vertically and laterally as far as access to the specific site allows. Prior to sampling, a sampling plan was prepared and sampling corridors were outlined according to the field observation to minimize errors in the sample evaluation. These samples were used to measure and study density, water absorption, specific gravity, porosity, petrographic examinations, mechanical properties and a number of relevant aggregate engineering tests. For the aggregate tests, the samples were prepared in such a way that blocks of rocks were collected directly from the individual rock types and reduced manually into smaller pieces and then crushed to the required size with mini laboratory jaw crusher to get the necessary size grading for the various tests (The volume of samples is indicated in Table 4-1, chapter 4 and sampling location, Chapter 5, Figure 5-27).

4.1 In situ investigation methods

4.1.1 Schmidt hammer (ISRM, 1978a & ASTM: 2001)

The Schmidt hammer, as an index tool for non-destructive testing of concrete in situ, has been used also in rock mechanics practice, mainly for estimating the Uniaxial Compressive Strength (UCS) and Young's Modulus(Ed) of rock materials (ISRM, 1978a).

The harder the surface, the shorter the penetration time (i.e. smaller impulse) or depth (i.e. lesser work or energy loss) and hence the greater the rebound i.e. smaller momentum change. The distance traveled by the piston after rebound (expressed as a percentage of the initial extension of the key-spring) is called the rebound value (H_R), which is considered to be an index of surface hardness.

There are different types of Schmidt hammers with their main difference found in the way to display the acquired results: with sliding pointers (N-34, L-9) or digitally (Digi-2). For the current research, the test was conducted with Schmidt hammer N-34(Figure 4-1) and it was carried out on in-situ outcrops at 10 points with a minimum separation of 50 cm. During the test, a spring-loaded mass impacts the material and the rebound value is read from the sliding mark. Ten values are acquired for each test and the extreme and mean values, in addition with the standard deviation are recorded.

The Schmidt hammer was primarily used for measuring the strength of hardened concrete (Schmidt 1951). Nevertheless, several studies have correlated its results for a prediction of several stone properties (Török 2008). It is well established by many researchers that the Schmidt hammer rebound value correlated with compressive strength are most commonly studied aspect of rock mechanics (Miller 1965; Barton and Choubey 1977; Sachpazis 1990 and Kahraman 2001). The use of the rebound values in the calculation of other mechanical properties has been also studied (Katz et al. 2000). Moreover, rocks state of weathering has been also estimated by evaluating the hammer values (Török 2003; Christaras 1996; Török et al. 2004; and Bell 1993). The N hammer, producing a lesser scatter in the data, proved to be more efficient than the L hammer in predicting Uniaxial Compressive Strength and Young's Modulus (Aydin, 2005). ASTM (2001) suggested taking at least 10 single impact readings, discarding those differing from the average by more than 7 units, and averaging those left.

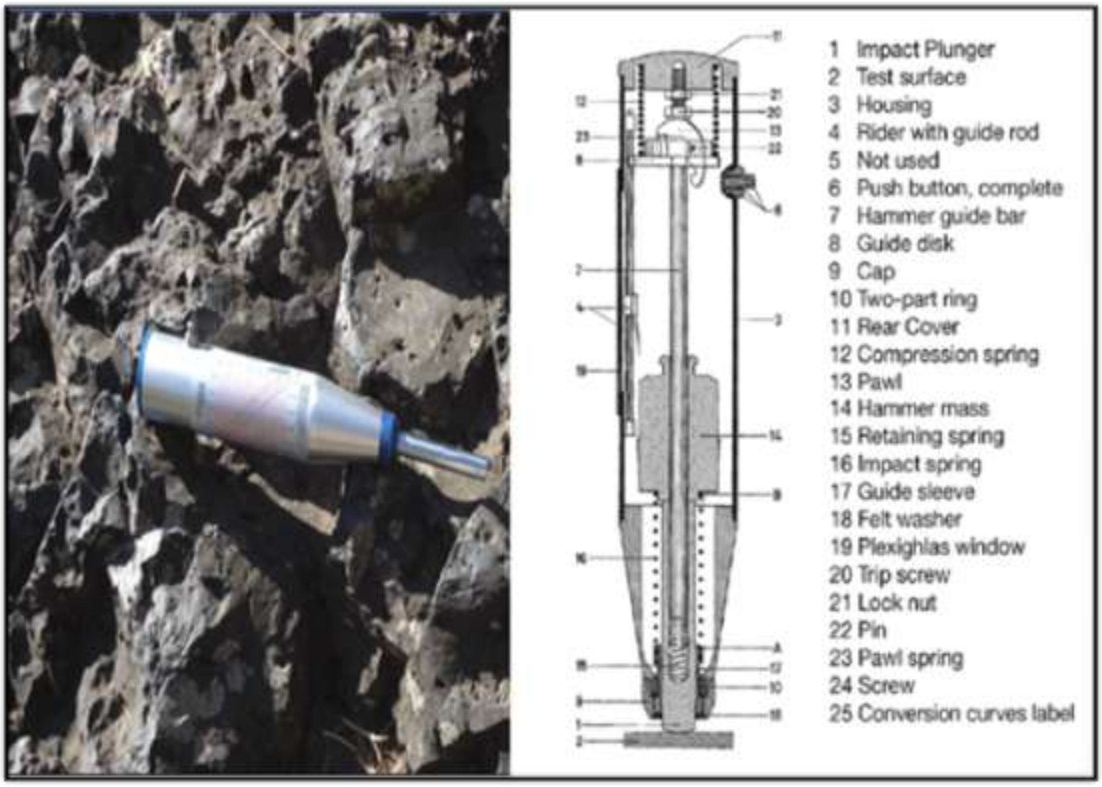

Figure 4-1 The Schmidt hammer and its longitudinal section used in this study

As a result of industry wide acceptance of rock testing to determine the mechanical properties for geological design and construction projects, the use of expensive laboratory testing and equipment are required for engineering projects. The Schmidt hammer rebound number (H_R) has been used by prior researchers to measure the engineering properties of different types of rocks and it is decided to use it in the current study area as in-situ test.

4.1.2 Rock Quality Designation (RQD)

The Rock Quality Designation index (*RQD*) was developed by Deere et al., 1967 to provide a quantitative estimate of rock mass quality from drill core logs. RQD is defined as the percentage of intact core pieces longer than 100 mm (4 inches) in the total length of core. However, Palmström (1982) suggested that, when no core is available but discontinuity traces are visible in surface exposures or exploration adits, the *RQD* may be estimated from the number of discontinuities per unit volume. The suggested relationship for clay-free rock masses is:

$$RQD = 115 - 3.3JV \qquad \text{(equ.4-1)}$$

In another attempt, recently, Palmströn (2005) suggested a new relationship between RQD and JV,

$$RQD = 110 - 2.5\text{JV} \qquad \text{(equ.4-2)}$$

Where *Jv* is the sum of the number of joints per unit length for all joint (discontinuity) sets known as the volumetric joint count and defines as the number of joints intersecting a volume of one m^3, where the jointing occurs mainly as joint sets the following equation can be used:

$$JV = \frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} \dots \dots \dots \dots \dots . \frac{1}{Sn} \dots \dots \dots \text{.......................} \quad (equ.4\text{-}3)$$

where S1, S2 and S3 are the average spacing in meters for the joint sets

Consequently, Hudson and Priest (1979) suggested the following formula to calculate RQD in the absence of drilled core:

$$RQD = 100e^{-0.1\lambda}\,(0.1\lambda+1) \dots\dots\dots\dots\dots\dots\dots\dots \text{..............} \quad (equ.4\text{-}4)$$

Where λ is the average discontinuity frequency per metre,

RQD is a directionally dependent parameter and its value may change significantly, depending upon the borehole orientation. The use of the volumetric joint count can be quite useful in reducing this directional dependence. In the context of this discussion, the most important use of *RQD* is to calculate the block size. Due to the significant of the joint number (Jn) in rock masses, for each rock type, it is calculated and presented as ratio RQD/Jn. The block size is an extremely important parameter in rock mass behaviour (Barton, 1990, ISRM, 1978).

The quotient **(RQD/Jn)**, representing the structure of the rock mass, is a crude measure of the block or particle size, with the two extreme values (100/0.5 and 10/20) differing by a factor of 400. If the quotient is interpreted in units of centimetres, the extreme 'particle sizes' of 200 to 0.5cm are seen to be crude but fairly realistic approximations (taking nominal value of RQD=10 and the maximum value RQD=100). Probably, the largest blocks should be several times this size and the smallest fragments less than half the size. Block size in this work is used as a common expression for the degree of jointing, density of joints, block volume, and joint spacing only.

4.2 Analysis under laboratory conditions

To determine the physical and mechanical properties of the various rocks found in the project area, rock block samples were collected directly from the site for the laboratory tests. Cube samples were prepared from these blocks according to AASHTO, UNIEN, BS and ASTM standards for Bulk density, Real density, Porosity, Uniaxial compressive strength, Point Load and *P*-wave velocity, etc and measurements were carried out according to the standard methods as described in the proceeding sections.

The physical properties that have been measured include Density, Specific gravity, Water absorption, Porosity, Real density, Degree of saturation, Petrographic examinations and the mechanical properties are Schmidt hummer rebound hardness test, Point load strength index, Ultrasonic P-wave velocity, Uniaxial Compressive Strength and etc. These laboratory measured values enable to classify the studied Tarmaber formation into various rock strength classes and end uses.

4.2.1 Physical and mechanical tests

4.2.1.1 Petrographic Examination-Polarising microscope (UNIEN 12407:2000)

In assessing of a rock for use as a dimension stone, the first requirement is petrographic study to identify its mineralogy, grain size, textures, fabrics and weathering states. All these processes are in turn determined by the geological processes which formed the rock. A good understanding of these processes and effects will enable to determine a rock's suitability as construction materials. For precise description of the rocks, thin sections of the various rocks of Tarmaber Formation were prepared and studied under polarizing microscope.

The petrographic description of 25 samples from outcrops and quarries were done based on the UNIEN 12407:2000. Even though, the aim of this examination is the classification of the natural stone, also observation of features that influence its chemical, physical and mechanical behaviour are carried out. Generally, the petrographic examination of rocks used for dimension stone and aggregate are crudely categorized into three steps, a) classification, b) an aid in the assessment of aggregate performance, c) detection of potentially deleterious constituents. The thin sections were prepared at the Geological Survey of Ethiopia (GSE) central laboratory and at Cagliari University, Department of Chemical and Geological Sciences. A portion of each material was mounted on a slide and mechanically reduced to a thin sheet of about (0.030 ± 0.005) mm thickness. The thin sections examinations were done in Dipartimento Di Geoingegneria e Tecnologie Ambientali (DIGITA) of Cagliari University. When necessary, microscopic photographic aspects of the thin sections were taken with a tele-camera fitted on the polarising microscope.

4.2.1.2 Uniaxial Compressive Strength (UCS) (UNIEN 1926:1999)

Uniaxial Compressive Strength (UCS) is one of the most important input parameters used in rock engineering (Sonmez et al., 2006), and therefore it is crucial to understand rock nature and rock behaviour.The Uniaxial Compressive Strength (UCS) is probably the most useful rock index properties for the characterization of rocks in the engineering context. So all the standards have detailed regulations on this test and many authors have addressed on the effect of the sample size effect on the results of the test. The standards described briefly also the form and dimensions of the sample, the conditions of parallelism of the faces, even the rate of load application during the test.

The Uniaxial Compressive Strength test has been performed according to the standard UNIEN 1926:1999. The specimens have been dried at constant mass using a ventilated oven at 70^0c for 24 hours. Before performing the test, the dimensions of the specimens have been measured. The height of the specimen was considered as H, whereas, L1 and L2 were the cross sectional dimensions: L1 was obtained by averaging 2 measures taken on the upper and lower face of the cube in one direction and was calculated to the nearest 0.1 mm. Also L2 was obtained by averaging 2 measures taken on the upper and lower face of the cube in the direction perpendicular to L1 and was calculated to the nearest 0.1 mm. Further, Lt was obtained by averaging L1 and L2 (Figure 4-2). Later, the load has been applied continuously at a constant stress rate until the sample failed. The maximum load has been recorded (F) and was approximated to the nearest 1kN. Further, the Uniaxial Compressive Strength (R) of the specimen was represented by the ratio: F/ (Lt * Lt). A computerized machine with a maximum capacity of 400MPa was used for this test. For each sample 3 cubes were prepared and measured, and the average was taken.

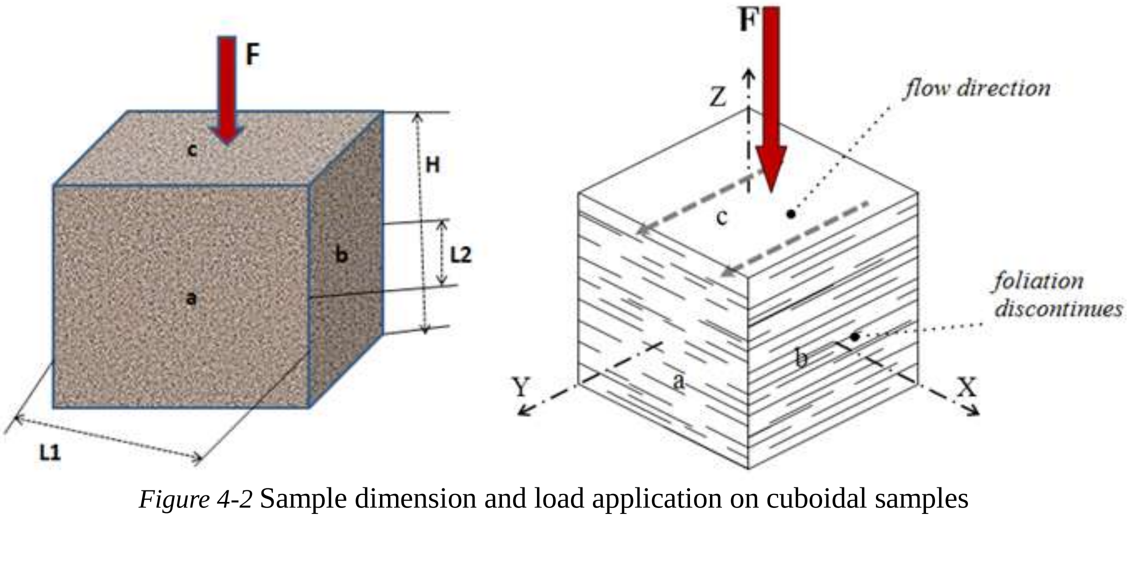

Figure 4-2 Sample dimension and load application on cuboidal samples

4.2.1.3 Determination of abrasion resistance (UNIEN 14157)

The abrasion resistance is governed by UNIEN and it is very important test for materials used for especially as slabs, corridors, even roads for vehicles. Abrasion can be defined as the wear caused by fine solid particles. It is certainly the most important form of stress on natural stone slabs, as far as flooring and paving are concerned.

A floor, badly designed in function of abrasion resistance, will rapidly wear and its surface finish will change (loss of brilliance, modification of the colour, etc…) in the most walked areas. Sometimes, the abrasion effect will provoke the formation of a "patina" on stones composed of essentially one mineral.

The specimen is painted and is placed on the holding part, the dispenser is open and the abrasive starts to fall down (corundum), the wheel starts to turn. After 75 rotations it stops and the specimen is taken out. The print (groove) given by the wheel is measured. The groove has a rectangle shape and the width is measured in the middle section after having drawn the two longitudinal lines (Figure 4-3).

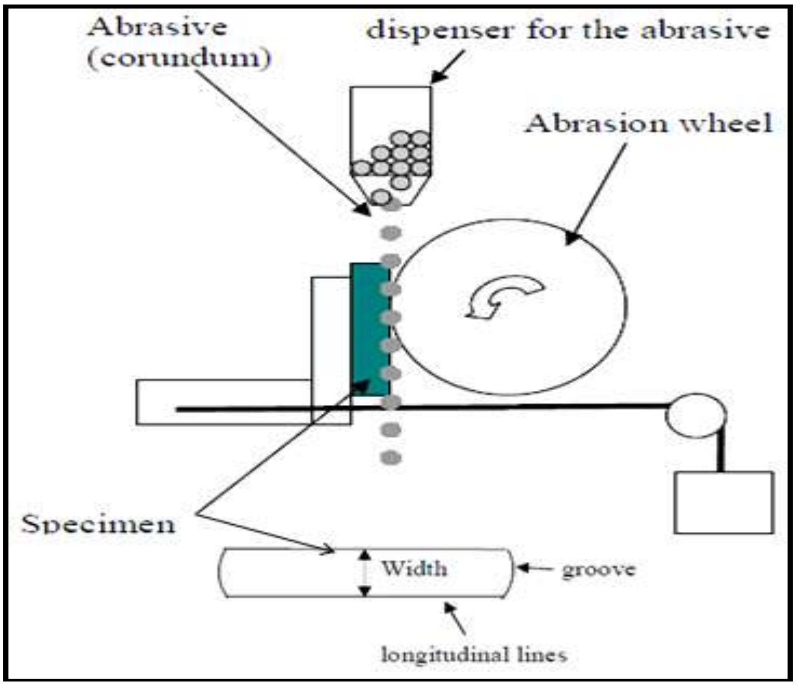

Figure 4-3 Scheme of the abrasion machine and the specimen during the test and after the test

4.2.1.4 Determination of Point Load Strength (ISRM 1985)

The Point Load Test (PLT) is an accepted rock mechanics testing procedure used for the calculation of a rock strength index. This index value can be used to estimate other rock strength parameters.

The PLT is an attractive alternative to the UCS because it can provide nearly similar data at a lower cost. The PLT has been used in geotechnical analysis for over thirty years (ISRM, 1985). The PLT involves the compressing of a rock sample between conical steel platens until failure occurs. The apparatus for this test consists of a rigid frame, two point load platens, a hydraulically activated ram with pressure gauge and a device for measuring the distance between the loading points.

The International Society of Rock Mechanics (ISRM, 1985) has established the basic procedures for testing and calculation of the Point Load Strength index. There are three basic types of point load tests: axial, diametral, and block or lump. The axial and diametral tests are conducted on rock core samples. In the axial test, the core is loaded parallel to the longitudinal axis of the core, and this test is most comparable to a UCS test.

The point load test allows the determination of the uncorrected Point Load Strength index (Is). It must be corrected to the standard equivalent diameter (De) of 50 mm. If the core being tested is "near" 50 mm in diameter (like NX core), the correction is not necessary. The procedure for size correction can be obtained graphically or mathematically as outlined by the ISRM procedures. The value for the Is_{50} is determined by the following equation.

$Is_{50} = F/De^2$…………………………………………………………………………… *(equ.4-5)*

where, F = Failure Load, De= Equivalent core diameter

The above equation can be written also as below

$Is=4.F/\pi.D^2$ for cores,

$Is=F/W.D$ for blocks and irregular lumps, $W.D=A= (\pi/4)*De^2$, $De^2=D^2$ for diametral test, but $De^2=4A/\pi$ for axial, block and lump tests, D=thickness of specimen, W-width of the sample, A-minimum cross-sectional area of a plane through the platen contact point (Figure 4-4). The Is_{50} should be corrected for size effects, with the following formula, Brook (1985) and the ISRM (1985), $Is_{50}=f\ (4.F/\pi.D^{2)}$, and $f=\sqrt{De}/50$, where f is size correction factor.

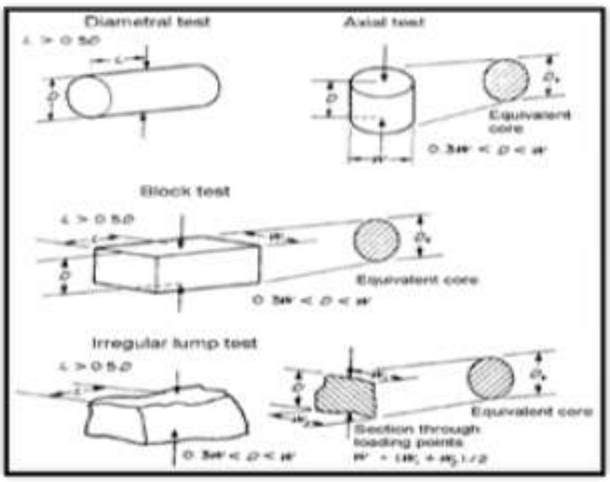

Figure 4-4 Specimen shape requirements for different test types after Brook (1985) and ISRM (1985)

4.2.1.5 Determination of Ultrasound P-Wave Velocity (ASTM 597and UNIEN 12504-4)

The first report of the measurement of the velocity of mechanically generated pulses through concrete appeared in the USA in the mid 1940s. It was found that the velocity depends primarily upon the elastic properties of the material and was almost independent of geometry. The potential value of this approach was apparent, but measurement problems were considerable, and led to the development in France, a few years later, of repetitive mechanical pulse equipment (Bungey et al. 1996).

At about the same time work was undertaken in Canada and the United Kingdom using electro-acoustic transducers, which were found to offer greater control on the type and frequency of generated pulses. This form of testing has been developed into the modern ultrasonic method, employing pulses in the frequency range of 20–150 kHz, generated and recorded by electronic circuits (Millard et al., 1996).

Since 1972, ultrasonic P-wave Velocity measurements are applied to determine the quality of stones, especially limestone, in order to demonstrate its homogeneity or its degree of alteration (Mamillan, 1972). Mamillan (1975) applied ultrasonic P-wave Velocity measurements to stone conservation and diagnostic state of alteration on marble sculptures introducing a new nondestructive methodology to stone conservation. Bouineau (1978) proved the relation between ultrasonic velocity, Uniaxial Compressive Strength, Modulus of Elasticity and apparent density of the rock materials. In 1989, Guerrero underlined the use of the ultrasonic technique to estimate physical and mechanical properties without the need to measure them.

The ultrasonic or ultrasound terminology is used for the high-frequency sound waves which mean higher frequency than the range of human hearing (Meola, et al. 2005 and Carlomagno, 2005; Bray, et al., 1992: as cited in Akevren, 2010). The ultrasonic testing is a useful technique especially for the examination of stones in terms of their elasticity, anisotropy, mechanical strength and state of deterioration (Christaras, 1999). Ultrasonic pulse velocity measurement can be performed in three different ways, which are direct, semi-direct and indirect methods (Kahraman, *et al*., 2008; Meola, *et al*., 2005). In this study, the direct method of measuring the ultrasonic velocity is applied (Figure 4-5). The important influential factors are rock type, mineralogical composition, rock texture and structure, grain size and shape, density, porosity, anisotropy, pore water, confining pressure, temperature, weathering and alteration zones, bedding planes, and joint properties (Yasar and Erdogan, 2004: as cited in Moradian, 2009).

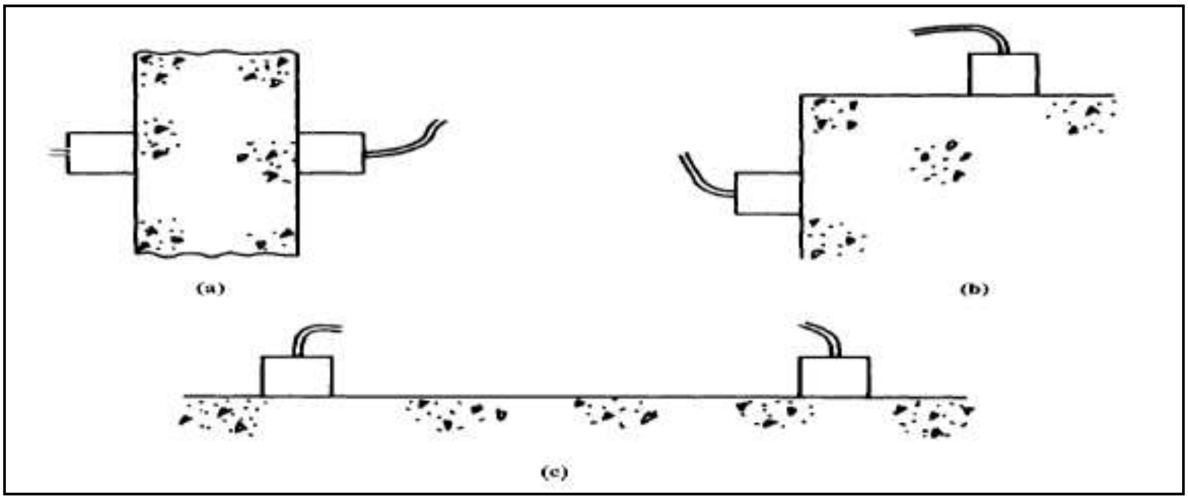

Figure 4-5 Types of ultrasonic reading, a) Direct, b) Semi direct, c) Indirect

Ultrasonic Pulse Velocity (Vp) measurements of compression waves have been carried out using a high-energy pulser receiver on the driving side and a 2-channel digital storage oscilloscope on the receiving side for the recording travelled time. The P-wave Velocity (Vp) is determined using the time-of-flight measurement technique at 82 kHz frequency as the sample size allows good contact with this transducer. This test is conducted for the following reasons:-

- evaluating the uniformity of rocks within a similar member
- locating internal voids and cracks
- estimating severity of deterioration
- estimating compressive strength (with correlation of Uniaxial Strength tests)

The *P*-wave Velocity of intact rock for this study was measured on cubic samples using the PUNDIT Mk V instrument designed with a high order of accuracy and stability. Three cube samples which have equal sides of 50mm*50mm*50mm were prepared for one test, so 9 measurements were made for a single test and the mean is taken as representative value (Figure 4-6). The test is governed by ASTM 597, BS1881:203 and UNIEN 12504-4 test methods. The test method is totally non-destructive and it is possible to repeat the test at the same point at different times to determine changes of Vp with time. End surfaces of the samples were polished to a sufficiently smooth plane to provide good coupling. A good acoustic coupling between the transducer face and the rock surface is necessary for the accuracy of transit time measurement. Stiffer grease was used as a coupling agent in this study. Transducers were pressed to either end of the sample and the pulse transit time was recorded. Each parallel side of the cubes were systematically marked with paint, as shown in Figure 4-6.

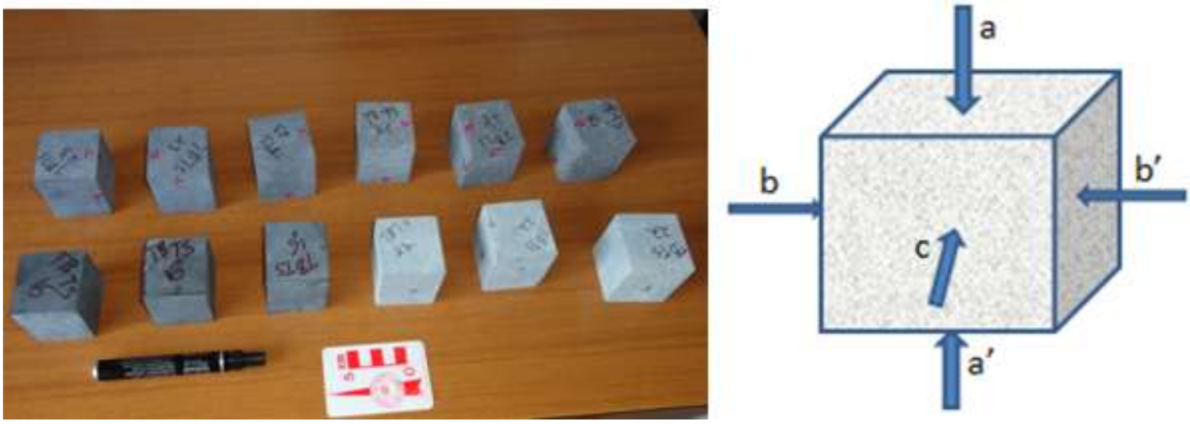

Figure 4-6 Samples marked and ready for measurement

P-wave Velocity values were calculated using the following formula:

$$Vp\ (m/sec) = \frac{\text{length of the sample } (d)}{\text{Travel time } (tp)} \quad \ldots\ldots \quad (equ.4\text{-}6)$$

where Vp is the P-wave Velocity (m/s), *d* is the distance between transmitter and receiver, and *tp* is the time that the P-wave takes to travel the distance *d.*

4.2.1.6 Water absorption (UNIEN1925:1999 and UNIEN 13755:2001)

Water absorption by capillarity (UNIEN1925:1999)

The capillary suction was measured based on the UNIEN 1925: 1999. Dry samples were submerged in (3 ± 1) mm of water and the capillary-rise absorption was measured in function of the time. Cubes were cut with dimensions of 50mm*50mm*50mm. They were dried to constant mass at the temperature of (105 ± 5) ºC. The samples were placed in a tank on a net support and they were submerged in water until the depth of (3 ± 1) mm. The level of the water was maintained at that level during the measurement, adding water when it was necessary and closing the tank to avoid evaporation in case of slow capillary absorption. The capillary-rise absorption was marked in each certain interval of time which was initially very short and later longer.

Water absorption at atmospheric pressure (EN 13755: 2001)

The scope of this method is to determine the water absorption of the natural stone samples by immersion in water at atmospheric pressure. The procedure of the measurement is based on the EN 13755: 2001.

The specimens were cubes of about 50 mm *50mm*50mm. They were dried to constant mass at the temperature of (70 ± 5) ºC. Their dry mass *md* was measured. The samples were placed in a tank on special supports and then tap water was added until the specimens were completely immersed to a depth of (25 ± 5) mm of water. In each certain interval of time which was initially very short and later longer, the specimens were taken out of the water, quickly wiped with a damp cloth and then weighted within 1 min to an accuracy of 0.01 g (*mi*). After the measurement, the specimens are immediately immersed again in water to continue the test up to constant mass of specimens. The result of water absorption at each interval was expressed as a percentage to the nearest 0.1 % by the following equation:

$$\mathbf{Ai} = \frac{mi - md}{md} * \mathbf{100} \quad \text{(equ.4-7)}$$

The mass of the last weighing is the saturated one *ms* and based on this, the total water absorption at atmospheric pressure *wtabs%* after immersion was calculated by the aforementioned equation replacing *Ai* with *wtabs* and *mi* with *ms*.

4.2.1.7 Porosimetry (UNIEN 1935:2006 and UNIEN 1926:2006)

Open porosity (UNIEN 1936: 2006)

The goal of this measurement is to characterize the open porosity of the stone samples, determined by vacuum assisted water absorption. The method that was followed and that is described below is based on the UNIEN 1936: 2006 for natural stone. Under vacuum water can penetrate into pores with diameter larger than 100nm (Meyer et al. 1994: as cited in Theodoridou, 2009). The open porosity by vacuum assisted water immersion is defined by the difference between the mass of the given specimen of stone immersed in water under vacuum and the mass of the same specimen when dried, expressed in terms of the volume of the dry specimen.

The specimen was dried in a ventilated oven at (70 ± 5) ºC for 24 hours. The mass *md* of the dried specimen was measured. Right after the determination of the *md*, the specimen was immediately placed in a vacuum tank in which the air pressure was then lowered up to (2.0 ±0.7) kPa in order to eliminate the air contained in the open pores of the specimen. After a period of at least 2 hours, demineralised water was transferred from its initial tank into the tank in which the specimen was placed and the amount of water was sufficient to submerge the specimen, completely covering it with at least 20mm water. The same pressure was maintained during the introduction of water. As soon as the specimen was fully submerged, the vacuum was maintained for at least 2 hours before the pressure was raised to the atmospheric value. The measurement of the wet mass *ms* took place 24 hours after the vacuum was abolished. Before each weighing, the surface of the specimen was dried with a damp tissue so as to have water saturated surfaces. At that time, the specimen was also weighed while it was submerged in water, with a precision of at least 0.1% and this value is called *mh*.

The absorption of water by immersion under vacuum is obtained from the expression:

$$\boldsymbol{Open\ porosity} = \frac{ms-md}{ms-mh} * \mathbf{100} \quad \text{(equ.4-8)}$$

in which: *md* is the dry mass expressed in grams; *ms* is the mass of the specimen saturated with water and *mh* is the apparent mass of specimen submerged in water, after water absorption in vacuum, expressed in grams.

Total open porosity (UNIEN 1926:2006)

The total open porosity was determined at the Chemical and Geological Sciences Department of Cagliari University according to the method described in UNIEN 1926:2006. Three specimens of about 2x2x2cm dimensions were prepared for each samples brought from the field. After the preparation, the specimens were dried at 60 ºC and the dry weight *md* was determined. Using the Helium ultrapycnometer, the real density of the specimen $\boldsymbol{\rho r}$ was measured and their bulk density $\boldsymbol{\rho b}$ was determined by a pycnometer. The total open porosity **Nt** is given by the following equation as a percentage:

$$\boldsymbol{Total\ porosity(Nt)} = \mathbf{1} - \frac{\rho b}{\rho r} * \mathbf{100} \quad \text{(equ.4-9)}$$

Furthermore, on the basis of the results from the Helium ultrapycnometer and the pycnometer, the real density ρr and the bulk density ρb of the specimens were calculated dividing the dry weight with the real volume *(Vr)* and the bulk volume (*Vb*) correspondingly:

$$\rho \boldsymbol{r} = \frac{md}{Vr} \quad \text{and} \quad \rho \boldsymbol{b} = \frac{md}{Vb} \quad \text{(equ.4-10)}$$

or alternatively,

$$\rho \boldsymbol{r} = \frac{md}{md-msus} \quad \text{and} \quad \rho b = \frac{md}{msat-msus} \quad \text{(equ.4-11)}$$

where, md is dry mass, msus is suspended mass in water, and msat is water saturated mass in air

4.2.2 Chemical tests

4.2.2.1 X-Ray Diffraction (XRD)

The mineralogical composition of the two types of fresh samples (basalt and ignimbrite) was further investigated by using the X-Ray Diffraction method on the crystal atoms of the minerals of each sample. During the X-Ray Diffraction, an incident beam strikes the crystal atoms and therefore it scatters resulting in changes in radiation intensity. The diffraction pattern that is produced is used for identifying the atomic structure of the crystals. The type of the observed diffraction patterns is confirmed by the exact matching of the intensities of its peaks with those that belong to reference materials. A small amount of the material to be tested was grounded in a porcelain mortar until it had powder consistency. The powder was considered to be fine enough passing through the 0.063mm sieve. The powder diffraction method is obviously used the atomic arrangement in a material to exhibit:

- Each substance in a mixture produces its own characteristic diffraction pattern independently of the others
- The X-Ray Diffraction pattern discloses the presence of a substance as that substance actually exists in the specimen
- Only a small amount of the material is required for the analyses
- The test is non-destructive on the prepared specimen

Test method	*Relevant standard used*	*Total number of analysed samples*	*Location of analysis*
Petrographic examination	UNIEN 124070:2000	25	Cagliari University
Uniaxial Compressive Strength	UNIEN 1926:1999	57	Cagliari university
Point Load Index(Ip_{50})	ISRM, 2001	22	Cagliari university
Ultrasonic Velocity	BS1881:203 and UNIEN 12504-4	66	Cagliari University
Water absorption (at atmospheric pressure and capillarity)	UNIEN 1925: 1999 and EN 13755: 2001	29	Cagliari University
Open Porosity	UNIEN 1936: 2006	29	Cagliari University
Total open porosity	UNIEN 1926:2006	29	Cagliari university
Apparent density	UNIEN 1926:2006	29	Cagliari university
Real density	UNIEN 1926:2006	29	Cagliari university
X-Ray Diffraction	-	5	Cagliari university
Chemical tests(XRF)	-	15	Spain
Flakiness Index and Elongat.	BS 812: Part 105-1-2	20	TCDSCO, Ethiopia
Specific gravity	AASHTO T-85	11	TCDSCO. Ethiopia

Water absorption(for aggregates)		11	TCDSCO, Ethiopia
Uncompacted bulk density	AASHTO T-19	10	TCDSCO, Ethiopia
Aggregate Impact Value	BS 812: Part 112	11	TCDSCO, Ethiopia
Ten Percent Fine Value	BS 812; part 111	11	TCDSCO, Ethiopia
Aggregate Crushing Value	BS 812: Part 110	11	TCDSCO, Ethiopia
Los Angeles Abrasion Value	AASHTO T-96	11	TCDSCO, Ethiopia and Sardinia region geotechnical Lab.
Sodium Sulphate Soundness Value	AASHTO T-104	11	TCDSCO, Ethiopia
Secondary mineral rating	-	10	Cagliari
Weathering index	-	10	Cagliari
Alkali Silica Reactivity	ASTM C 289	10	TCDSCO, Ethiopia
Water soluble chloride	BS 1377	4	TCDSCO, Ethiopia
Water soluble sulphate	BS 1377	4	TCDSCO, Ethiopia

Table 4-1 Methods of analysis and tests, relevant standards, total number of analysed samples and location of the analysis, where TCDSCO-Transport Construction Design Share Company

CHAPTER FIVE

5. Results of the investigation

5.1 Insitu investigations

5.1.1 Schmidt hammer

The Schmidt hammer values on the blocks of the selected rocks are presented in Table 5-1 and Figure 5-1. The Schmidt hammer values are higher for the more compact stones such as the aphyric basalt and columnar basalt (TB-Cs-1, TB-Cs-6, TB-Ts-10, and TB-Ts-12). The ignimbrites which are strongly welded (TB-Ts-3 and TB-Ts-8) also exhibit relatively higher rebound values. Most of the less compacted ignimbrites/tuff (TB-Ts-13, TB-Ts-14, and TB-Ts-26) gave relatively lower values than the strongly welded tuff (ignimbrite). Generally, the basalts exhibit superior rebound number than the ignimbrite and tuffs (Figure 5-1). The Schmidt hammers rebound number for the basaltic units vary from 40-54 while the pyroclastics unit Schmidt hammer rebound number ranges from 21-44. Generally, the Tarmaber basalts exhibit relatively less scattered Schmidt hammer rebound than the pyroclastic rocks. The lower Schmidt hammer rebound number is recorded from sample TB-Ts-13, which is poorly welded tuff. Since the Schmidt hammer rebound number is influenced by the hardness of the constituent minerals of a rock, it does not consider empty cavities.

Basaltic rock samples		**Pyroclastics rock samples**	
Sample N.	Schmidt hammer rebound value (H_R)	Sample N.	Schmidt hammer rebound value (H_R)
TB-Cs-1	53	TB-Cs-2	36
TB-Cs-5	49	TB-Cs-3	40
TB-Cs-6	52	TB-Cs-4	31
TB-Ts-10	54	TB-Cs-8	38
TB-Ts-11	43	TB-Cs-9	29
TB-Ts-12	53	TB-Ts-13	21
TB-Ts-16	50	TB-Ts-14	35
TB-Ts-18	42	TB-Ts-22	35
TB-Ts-21	40	TB-Ts-24	44
TB-Ts-23	49	TB-Ts-26	28
TB-Ts-25	47		

Table 5-1 Schmidt hammer rebound values of the basaltic rock samples and Pyroclastics (ignimbrite and tuff) samples

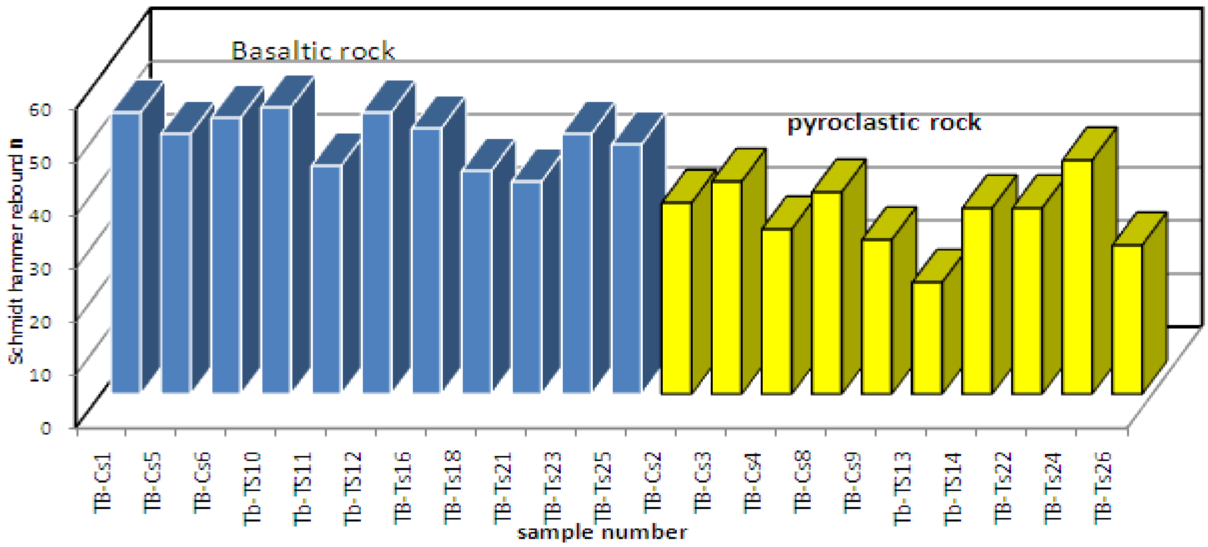

Figure 5-1 Bar graph showing the values of the Schmidt hammers for basaltic and ignimbritic samples

5.1.2 Rock Quality Designation (RQD)

The ratio of **RQD/Jn** directly reflects the smallest block size exhibited by aphyric basalt and the largest size shown by porphyritic olivine basalt (Figure 5-2). The RQD/Jn parameter was utilized to give an abstraction about the crude block sizes of the examined rock mass. The higher RQD/Jn values, the more massive rock and it can be used as slabs; hence RQD/Jn can be taken as a primary criterion for the quarrying method. In other words, the small RQD/Jn is preferred for crushed stone (Table 5-2 and Figure 5-2).

Rock type	Texture	RQD	Joint sets	Jn	RQD/Jn
Porphyritic-olivine basalt	Dark to dark bluish coloured, fine to medium grained, slightly weathered and less jointed	95	3	9	10.6
Aphyric basalt	Dark coloured, fine grained, densely jointed, moderately weathered on the surface	76	3	9	8.4
Glassy rhyolite	Light gray to dark coloured, unweathered and less jointed	91	3	9	10.1
Ignimbrite	Light yellow, gray coloured, less jointed and slightly weathered	86	3	9	9.6

Table 5-2 Results of field descriptions and measurements of RQD/Jn in the study area

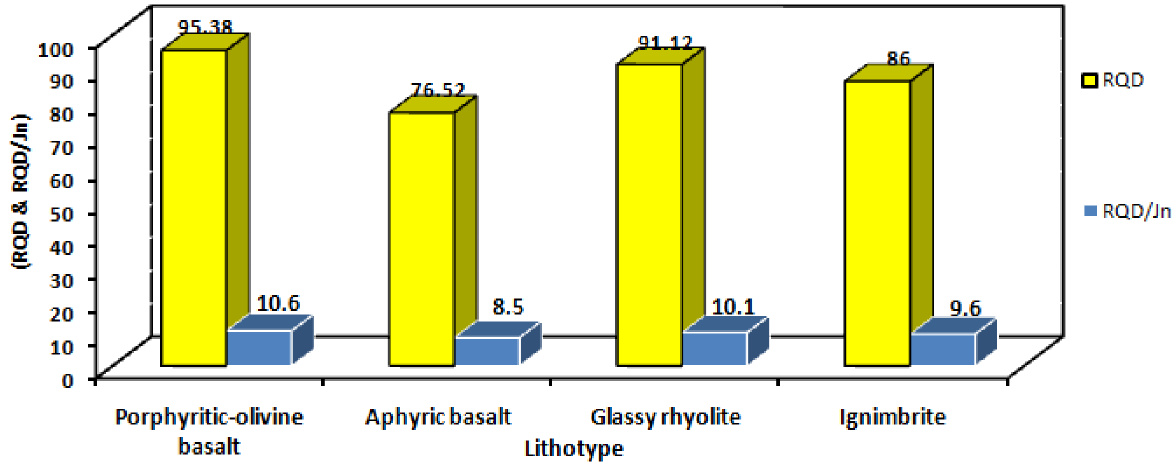

Figure 5-2 Bar graph showing the RQD and block size (RQD/Jn)

5.2 Laboratory test results

5.2.1 Physical and mechanical tests

5.2.1.1 Petrographic examinations

Petrographic examinations were conducted on about 25 thin sections prepared from the various lithological units outcropped in the studied area and active quarries aiming to detect deleterious constituents and microfractures. The petrographic examinations of the thin sections were done in the laboratory of DIGITA (Dipartimento Di Geoingegneria e Tecnologie Ambientali) at the University of Cagliari with a petrographic microscope fitted with tele-camera connected to a PC. The thin section slides were prepared in the Geological Survey of Ethiopia (GSE) which has a good reputation in rock laboratory and in the Cagliari University, Department of Chemical and Geological Sciences. Each thin section is described in detail (Table 5-3 and Figure 5-3, 5-4, 5-5 and 5-6). However, the volcanic rocks classified with modal value (microscopic) as basalts can have substantial variations in chemical compositions. Therefore, chemical analysis is absolutely necessary to distinguish, for example, between trachybasalt and basanite. Both of these chemical sub-types of basalt comprise of plagioclase, augite, and olivine and Fe-Ti oxide.

Generally, about 11 representative thin sections from Tarmaber basalt rocks and 14 from pyroclastics (ignimbrite, tuff and rhyolitic glass) were prepared and examined under a polarizing microscope. The detail descriptions of each thin section are available in Appendix1; however, the summarized descriptions are given in Table 5-3.

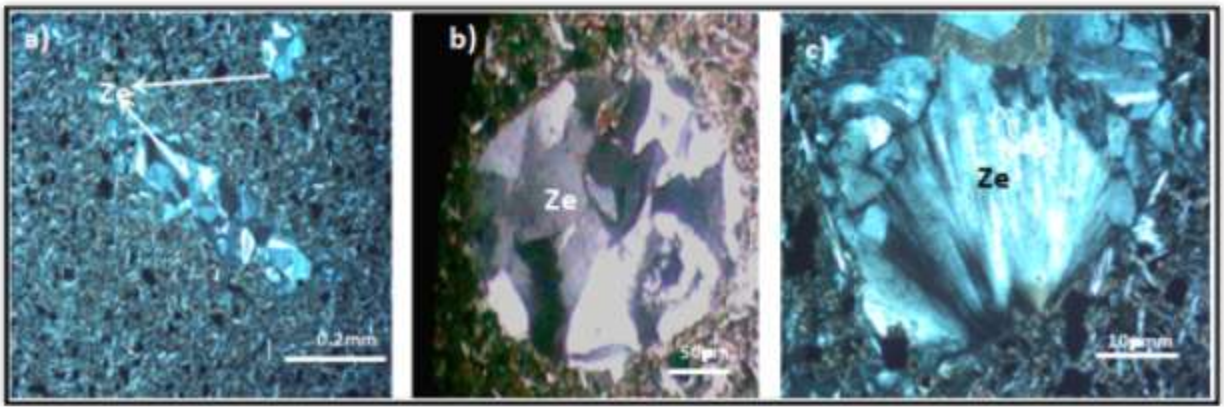

Figure 5-3 Microscope photo under polarizing light showing zeolite mineral from sample number TB-TS-15(a, b) and c) TB-TS-16, Ze-zeolite in plagioclase lath and iron oxide and glassy groundmass

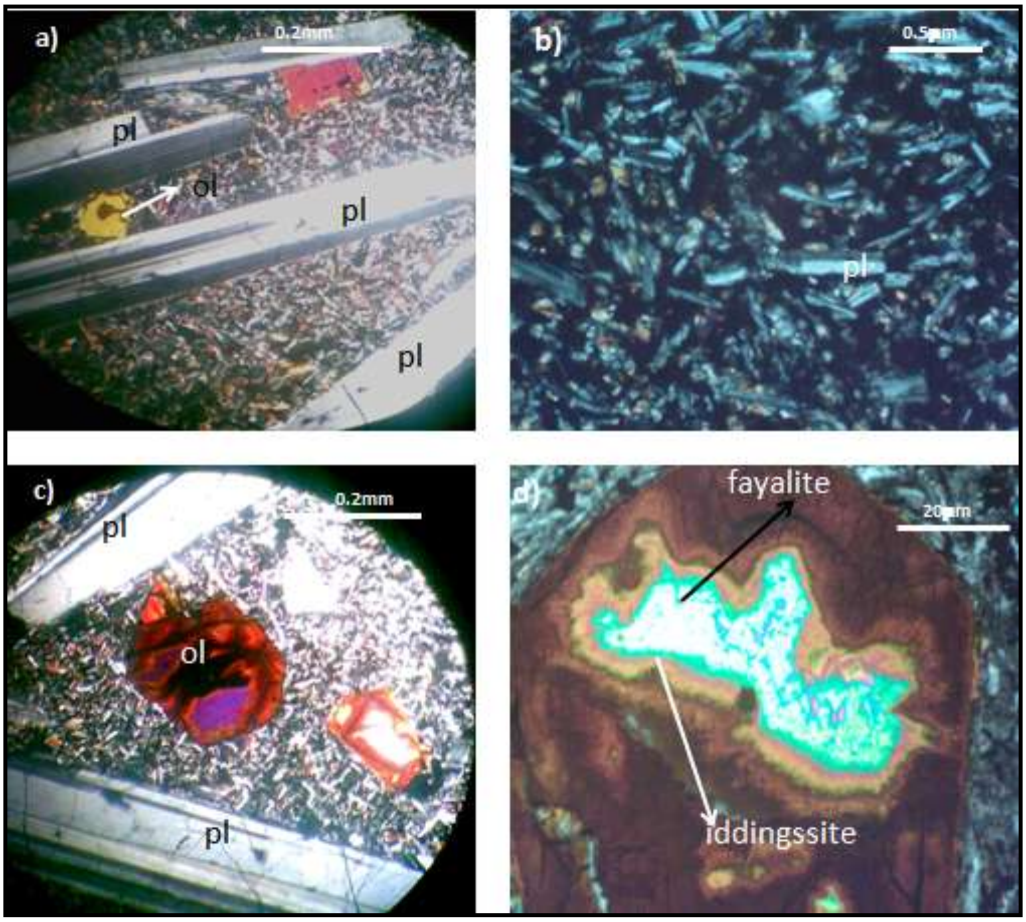

Figure 5-4 Rock sample(thinsection) as seen under petrographic microscope (cross-polarized view) of TB-AG-25 sample, a) Phenocrysts of plagioclase and olivine in micro lath groundmass under cross polarized light, x2.5 b) Micro laths of plagioclase under cross polarised light, x10, c) Phenocrysts of plagioclase and olivine in microlath plagioclase groundmass under crossed polarised light, x2.5, d) Magnified olivine crystal showing zonation of alteration, x20, Pl=plagioclase, Ol=olivine

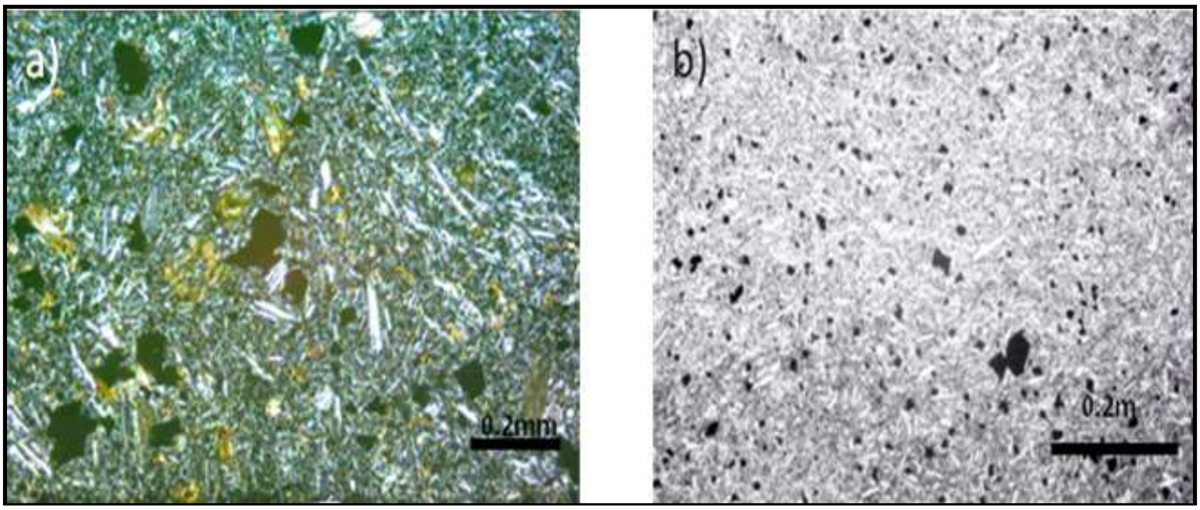

Figure 5-5 Microscopic photograph (TB-TS-1); a) Thin section under crossed nicol showing medium grained plagioclase and some pyroxene with opaque minerals, x20 b) Plain polarized light showing opaque and micro-laths of plagioclase feldspar, x10

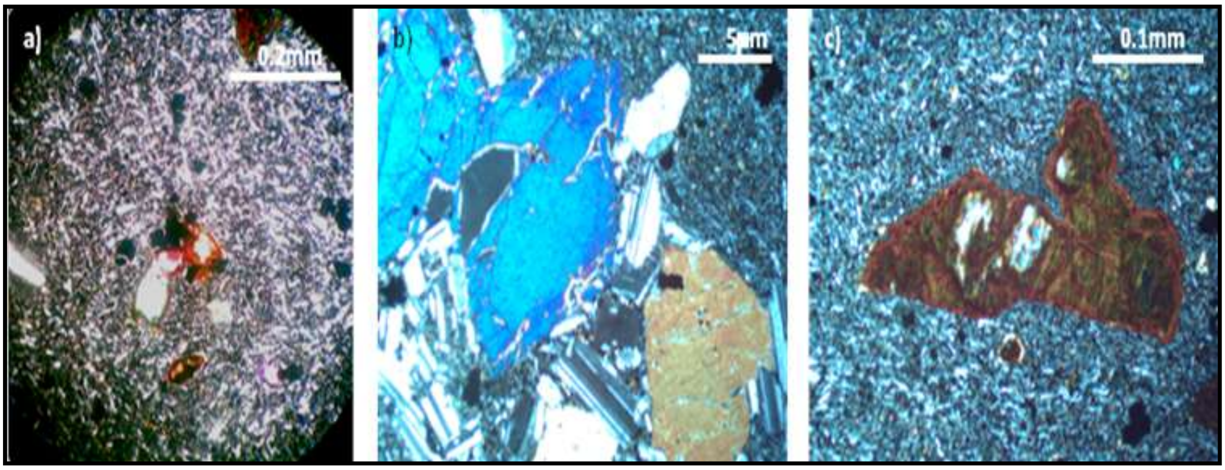

Figure 5-6 Microscopic photograph (TB-TS-23), a) General view of laths of plagioclase and opaque under cross polarised light, x2.5, b) Phenocrysts of pyroxene and plagioclase under cross polarized light, x10, c) Olivine phenocryst altered to iddingsite under crossed polarized light, x2.5

S.N	Sample number	Microscopic descriptions	Rock name (on Modal% basis)
1	TB-Ts-1	*It shows fluidal texture and is composed of plagioclase (40%), pyroxene (25%), opaque (10%), volcanic glass (10%) and olivine (5%). Small crystals of olivine, pyroxene and plagioclase are seen over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque. Opaque (Fe-oxide) minerals are abundant across the whole section of the thin section.*	Aphyric basalt
2	TB-Ts-5	*It shows fluidal texture and is composed of plagioclase (25%), pyroxene (20%), opaque (45%), zeolite (5%), and other accessories (7%). The groundmass which is composed of microlithic plagioclase, pyroxene, opaque and volcanic glass shows parallel alignment of flow texture. Volcanic glass shows beginning of divetrification to chalcedony and chlorite. Unfilled micro fractures and pores /voids/ filled by zeolite are seen across the section.*	Aphyric basalt
3	TB-Ts-6	*It shows fluidal texture and is composed of plagioclase (50%), pyroxene (15%) and opaque (30%). The groundmass is made up of micro-laths of plagioclase and some glass.*	Aphyric basalt
4	TB-Ts-10	*It shows fluidal texture and is composed of plagioclase (40%), pyroxene (35%), opaque (12%) and volcanic glass (10%). Some minor phenocrysts of pyroxene and plagioclase are seen over a ground mainly composed of microlithic plagioclase, pyroxene, opaque and volcanic glass that shows parallel alignment of flow texture.*	Aphyric basalt
5	TB-Ts-12	*It shows a fluidal texture. The microfabric is dominated by plagioclase (40%), Pyroxene (35%), opaque (Fe-oxides 12%), volcanic glass (10%). Besides, some minor phenocrysts of pyroxene and plagioclase are seen over a ground mass mainly composed of microlithic plagioclase, pyroxene, opaque and volcanic glass that shows parallel alignment of flow texture.*	Aphyric basalt
6	TB-Ts-15	*The texture is fluidal. It comprises of plagioclase (40%), pyroxene (30%), opaque/oxides (15%, devitrified volcanic glass (10%), zeolite (5%) and trace amounts of chlorite. The groundmass which is composed of microlithic plagioclase pyroxene, opaque and volcanic glass shows parallel alignment of flow texture. Volcanic glass shows beginning of devitrification to chalcedony and chlorite. Unfilled micro fractures and pores/voids filled by zeolite are seen across the section.*	*Aphyric basalt*
7	TB-Ts-16	*The texture is fluidal and microlithic texture. It comprises of plagioclase (40%), pyroxene (20%), opaque (Fe-oxide 15%), volcanic glass (7%), and zeolite5%). The groundmass is mainly composed of microlithic plagioclase, pyroxene, opaque and volcanic glass and shows parallel alignment of flow structures.*	*Aphyric basalt*
8	TB-Ts-20	*It is black in colour and very fine grained in texture with fluidal texture under the microscope. It comprises of some phenocrysts of lath plagioclase and pyroxene which are seen over a groundmass of microlithic plagioclase, pyroxene, opaque and volcanic glass. Microlithic plagioclase show parallel alignment of flow texture.*	Aphyric basalt

9	*TB-Ts-21*	*It shows porphyritic and fluidal structure and comprises of plagioclase (50%, pyroxene (30%), opaque (Fe-oxide 15%), olivine (5%). Phenocrysts of plagioclase and pyroxene are seen over a groundmass composed of plagioclase pyroxene, and opaque, laths of plagioclase shows parallel alignment of flow structure. Unfilled microstructures are seen across the section. Large crystals of olivine, plagioclase and pyroxene are seen as phenocrysts over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque.*	Porphyritic basalt
10	*TB-Ts-23*	*It is black in colour and very fine grained in texture. It consists of large crystals of olivine, plagioclase and pyroxene which are seen as phenocrysts over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque. Unfilled micro fractures and pores /voids/ are seen across the section. Some plagioclase crystals show zoning and subophitic texture.*	Porphyritic olivine basalt
11	TB-Ts-25	*Dark gray coloured and fine grained. It comprises of plagioclase (43%), pyroxene (35%), opaque/Fe-oxide (2%), olivine (5%), and volcanic glass (5%). Large tabular crystals of plagioclase, pyroxene and olivine are seen as phenocrysts over a groundmass composed of plagioclase, pyroxene, and opaque. Unfilled microfracture and plagioclase crystals show zoning and subophitic texture.*	Porphyritic olivine basalt.
12	TB-Ts-25R	*It is dark grey in colour and very fine grained and porphyritic in texture. It consists of large crystals of olivine; pyroxene and plagioclase are seen as phenocrysts over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque. Olivine crystals are oxidized /Weathered/.*	Porphyritic olivine basalt

Table 5-3 The microscopic description of the basaltic rocks from the study area (with Modal proportion)

As it has been said earlier, about 14 representative thin sections from pyroclastic rocks (ignimbrite, tuff, glassy rhyolite) were prepared and examined under a polarizing microscope (Figure 5-7 and 5-8). The detail descriptions of each thin section are available in appendix 1; however, the summarized descriptions are given below in Table 5-4.

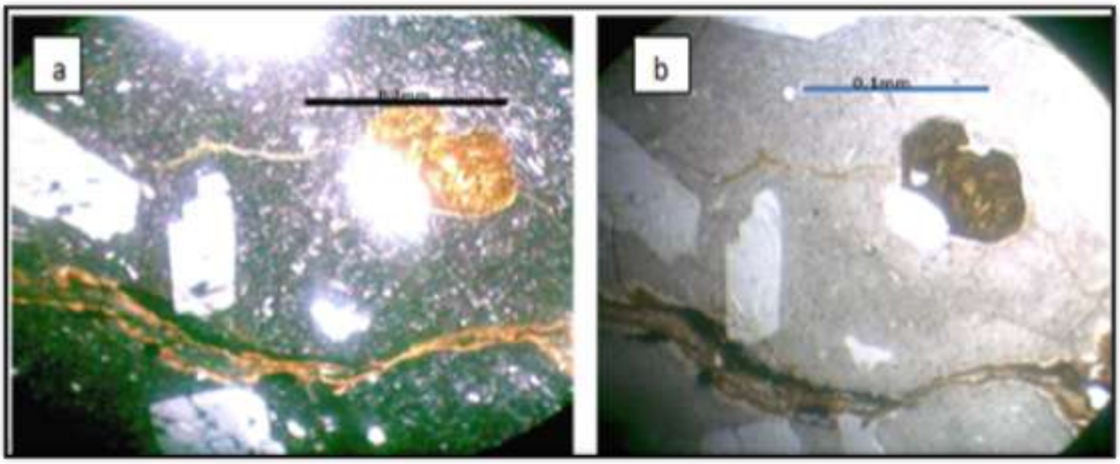

Figure 5-7 Microscopic photograph of thin section under crossed nicol, x10 (TB-TS-18),
a) Microfractures filled with secondary clay and opal mineral with phenocryst of plagioclase, b) Under plain polazised light with glassy groundmass, x10

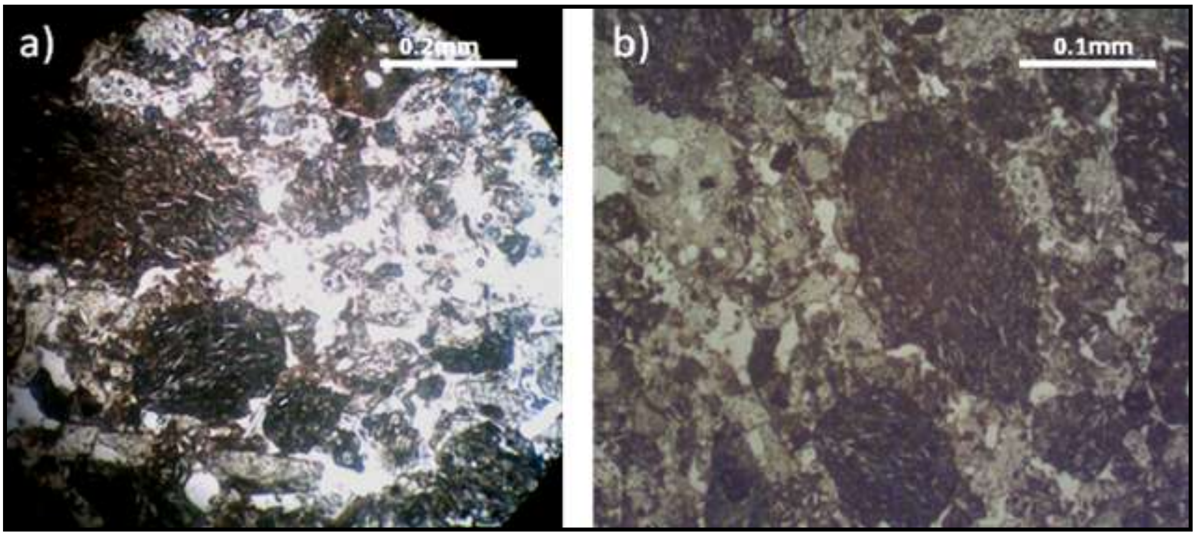

Figure 5-8 Microscopic photograph (TB-TS-19) a) Rock fragments and opaque in glassy groundmass under plane polarized light, x2.5, b) Rock fragment and some quartz in cross polarized light, x10

S.N	Sample number	Microscopic descriptions	Rocks Name
1	*TB-Ts-2*	*The texture is vitrophyric and is composed of volcanic glass (40%), rock fragments (25%), opaque (20%), sanidine (8%), and pyroxene (5%). Phenocryst of sanidine and quartz are seen over a glassy groundmass. Volcanic glass is devitrified to chalcedony.*	Ignimbrite
2	*TB-Ts-3*	*It shows vitrophyric texture and is composed of volcanic glass (45%), rock fragments (35%), quartz (10%), opaque (7%) and biotite (2%). Phenocrysts of sanidine, quartz and some biotite are assembled in a glassy groundmass with abundant rock fragments of pumice and others.*	Ignimbrite
3	*TB-Ts-4*	*The texture is vitrophyric and is composed of volcanic glass (40%), sanidine (30%), quartz (15%), opaque (10%) and accessories (5%). It comprises of skeletal quartz and phenocrysts of sanidine with abundant opaque (Fe-oxide) with devitrified glass. Micro factures and unfilled voids are seen across the thin section.*	Tuff
4	*TB-Ts-7*	*It shows vitrophyric texture and is composed of volcanic glass (30%), plagioclase (20%), opaque (20%), sanidine (10%), quartz (10%) and biotite (5%) in glassy groundmass.*	Glassy rhyolite
5	*TB-Ts-8*	*The texture is vitrophyric and is composed of volcanic glass (50%), rock fragments (20%), opaque (10%), sanidine (10%), and quartz (10%) in a glassy groundmass.*	Ignimbrite
6	*TB-Ts-9*	*It is with vitrophyric texture and is composed of volcanic glass (60%), rock fragments (20%), quartz (15%) and trace biotite.*	Ignimbrite
7	*TB-Ts-13*	*It shows vitrophyric texture and comprises of volcanic glass (50%), sanidine (15%), rock fragment (15%), and quartz (10%), opaque/Fe-oxide (5%) and plagioclase (5%). Some crystals of sanidine, quartz and rock fragments are seen over a glassy groundmass. The rock fragments are pumice and chalcedony.*	Tuff
8	*TB-Ts-14*	*The texture is vitrophyric. It comprises of volcanic glass (60%), rock fragments (20%), sanidine (10%), opaque (5%), quartz (5%), and plagioclase (2%), and trace pyroxenes. Large phenocrysts of quartz, plagioclase and sanidine are seen over a glassy groundmass. The rock fragments are of basalt, rhyolite and pumice.*	Ignimbrite
9	*TB-Ts-18*	*It shows vitrophyric texture and consists of volcanic glass (62%), sanidine (18%), quartz (10%), opaque/Fe-oxide (5%), pyroxene (5%), and trace amounts of apatite. Large crystals of sanidine, pyroxene and quartz are seen as phenocryst over a glassy groundmass. Unfilled microfractures are seen over the phenocryst and groundmass across the section.*	Glassy rhyolite

10	*TB-TS-19*	*It shows vitrophyric texture and consists of rock fragments (62%), volcanic glass (35%), sanidine (2%), opaque/Fe-oxide (1%) and trace amounts of plagioclase. Rock fragments are basalt; rhyolite and pumice are suspended over glassy groundmass.*	Lithic tuff
11	*TB-TS-22*	*It shows vitrophyric texture and comprise of volcanic glass (55%), chalcedony (10%), quartz (7%), rock fragments (3%), biotite (2%), opaque/Fe-oxide (2%) and hornblende (1%). Large phenocrysts of sanidine and quartz are seen as phenocrysts over a groundmass composed of volcanic glass and chalcedony. Unfilled voids, yellowish brown staining of oxidation and glass shards are seen across the section. Volcanic glass is devitrified to chalcedony.*	Ignimbrite
12	*TB-Ts-24*	*It shows vitrophyric texture and is comprises of volcanic glass (57%), sanidine (15%), rock fragment (10%), chalcedony (8%), quartz (7%), opaque/Fe-oxide (3%), trace amounts of biotite and hornblende. Phenocrysts of sanidine, rock fragment and quartz are seen over a groundmass composed of volcanic glass. The rock fragments are rhyolite and pumice. Volcanic glass is devitrified to chalcedony.*	Ignimbrite
13	*TB-TS-26*	*It shows vitrophyric texture and is composed of volcanic glass (53%), quartz (15%), sanidine (10%), rock fragment (5%), opaque (3%), hornblende (2%), and trace amounts of apatite. Phenocrysts of sanidine and quartz are seen over a glassy groundmass. Volcanic glass is devitrified to chalcedony. The rock fragments are rhyolite and pumice.*	Ignimbrite
14	*TB-TS-00*	*It shows vitrophyric texture and consists of volcanic glass (60%), sanidine (12%), quartz (8%), plagioclase (7%), opaque/Fe-oxide (5%), chalcedony (5%), pyroxene (3%) and trace amounts of hornblende and biotite. Phenocrysts of sanidine, plagioclase, and quartz are seen over a groundmass composed of volcanic glass. Unfilled and partially Fe-hydroxide and chalcedony filled fractures are seen across the sections.*	Glassy rhyolite

Table 5-4 The microscopic modal description of the pyroclastic rocks

5.2.1.2 Determination of Uniaxial Compressive Strength

Uniaxial Compressive Strength is one of the most important input parameters used in rock engineering (Sonmez et al., 2006) therefore, it is crucial to understand rock nature and rock behaviour. As has been said earlier the compressive strength test has been performed according to the standard UNIEN 1926:2006(European norm). The measuring equipment and the subsequent failure mode are shown in Figure 5-9. The measurements were conducted on cubic samples in three directions and the mean value was taken (Table 5-5 and Appendix 2).

The Uniaxial Compressive Strength values of the basalts ranges from 130MPa to 350MPa. The highest unconfined compressive strength is measured from the columnar basalt (TB-TS-12) which is aphyric-phyric lower basalt and the lowest is from the uppermost porphyritic basalt (TB-TS-25). Therefore, the lower basalt (columnar basalt) is very strong and could be used for structural loading and also the uppermost porphyritic basalt could be used as cladding and internal slabs for its visual attraction exhibited by the porphyritic nature. The Uniaxial Compressive Strength of the pyroclastic rocks varies from 7MPa to 146MPa. The lower value is measured from less compacted tuff and the highest value is from a strongly welded ignimbrite. The ignimbrites could be used as pavements and cobble stone for their high Uniaxial Compressive Strength (Figure 5-10 and Table 5-5) provided other properties are acceptable.

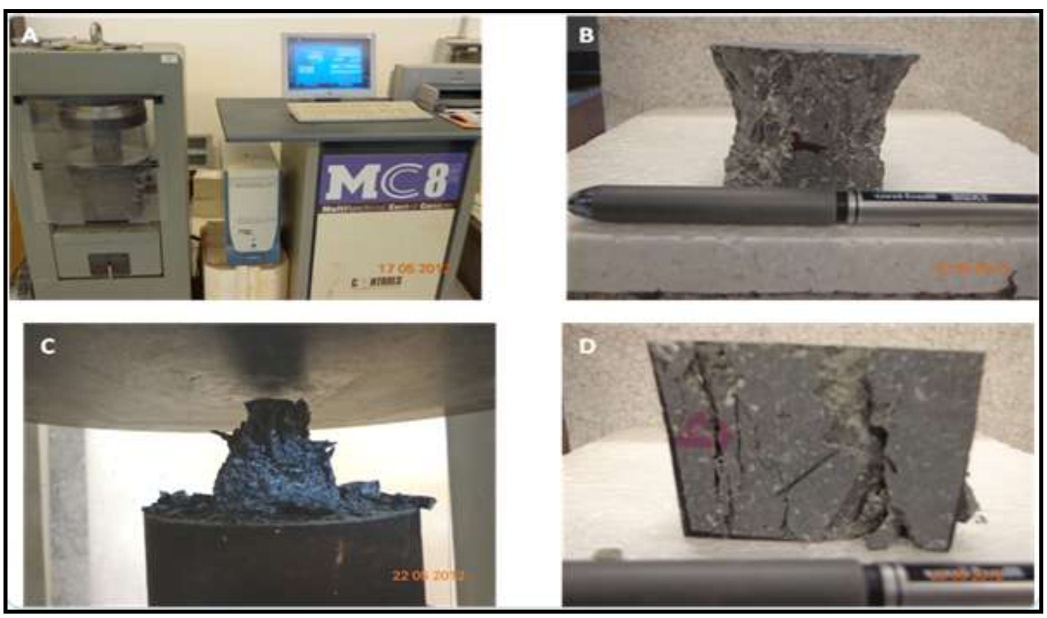

Figure 5-9 Uniaxial Compressive Strength measuring device and some of failure modes of the basaltic rock samples, A) Compression machine connected to a PC during uniaxial testing; C, B & D) Failure mechanisms

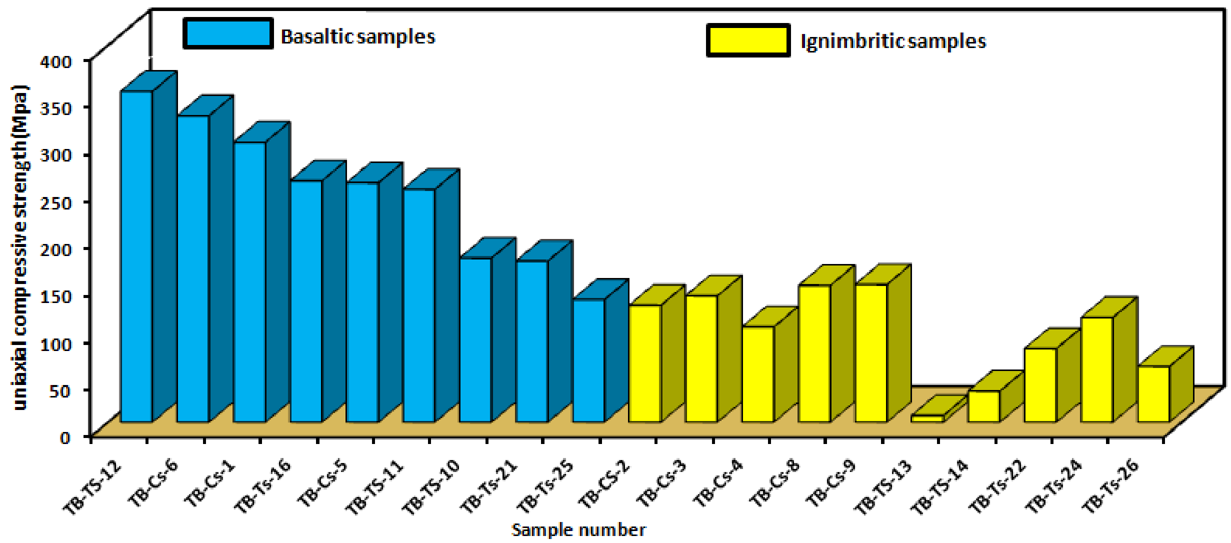

Figure 5-10 Bar chart showing the compressive strength of basaltic and pyroclastic/ignimbritic samples

Basaltic rock samples			**Pyroclastic/ignimbritic rock samples**		
Sample N.	Uniaxial Compressive Strength(MPa)	Engineering Classification, Anon(1979)	Sample N.	Uniaxial Compressive Strength(MPa)	Engineering Classification, Anon(1979)
TB-TS-12	351	Extremely strong	TB-CS-2	124	Very strong
TB-Cs-6	325	Extremely strong	TB-Cs-3	134	Very strong
TB-Cs-1	297	Extremely strong	TB-Cs-4	101	Strong
TB-Ts-16	256	Extremely strong	TB-Cs-8	145	Very strong
TB-Cs-5	254	Extremely strong	TB-Cs-9	146	Very strong
TB-TS-11	247	Extremely strong	TB-TS-13	7	Weak
TB-TS-10	174	Very strong	TB-TS-14	33	Moderately strong
TB-Ts-21	171	Very strong	TB-Ts-22	78	Strong
TB-Ts-25	130	Very strong	TB-Ts-24	111	Strong
			TB-Ts-26	59	Strong

Table 5-5 Uniaxial Compressive Strength of basaltic rock samples and pyroclastic/ignimbritic samples

The corresponding engineering classification by Anon (1979) shows the basaltic rocks are all corresponding to very strong to extremely strong while the pyroclastic rocks show a wide variety of strength from weak to very strong, dominantly strong to very strong.

5.2.1.3 Determination of abrasion resistance

The abrasion resistance was carried out on each lithotypes encountered in the project area. As well described in the geology section, the project area comprises of welded tuff/ignimbrite, aphyric basalt, basanite, trachybasalt and porphyritic basalt and the abrasion result of each lithotype is shown in Table 5-6.

Sample number	***Welded tuff (TB-CS-2)***	***Ignimbrite (TB-CS-9)***	***Aphyric basanite (TB-TB-16)***	***Aphyric basalt (TB-TS-5)***	***Phyric basalt (TB-Ts-25) (Upper most phyric basalt-trachytic)***	***Phyric basalt (TB-TS-23)***
Abrasion resistance (mm)	25.4	23.5	15.7	22.1	24.5	25.2

Table 5-6 Results of the abrasion resistance test

Standard value	**≤ 24mm intensive use**	**≤ 35mm Moderate**	**≤ 42mm Individual use**
Uses	▪ *public halls in stations, airports, shopping centers* ▪ *halls in apartment block with more than 30 housing units* ▪ *common rooms of office building with more than 50 employees* ▪ *floorings in supermarkets, etc*	▪ *common rooms of multifamily houses (with max. 30 housing units)* ▪ *common rooms of block offices (max. 50 employees)* ▪ *rooms with moderate commercial use*	▪ *all rooms in private housing units* ***Note*** *: in this category, the areas most susceptible to wear are the ones which are directly accessible from outside*

Table 5-7 EN14517 Standards and corresponding uses of tested materials

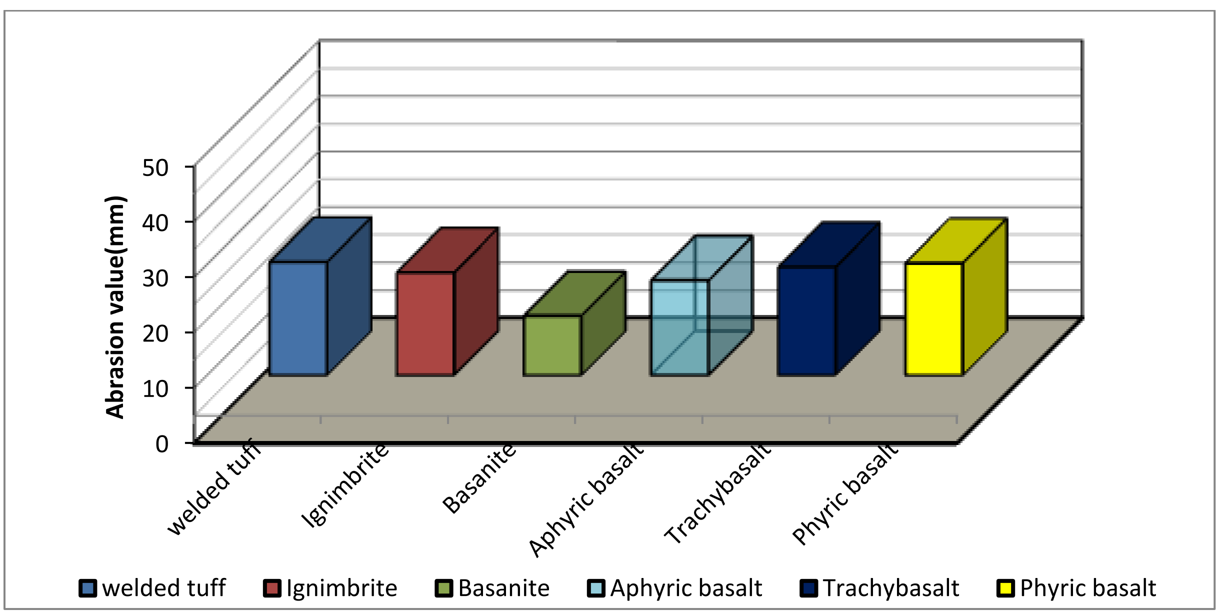

Figure 5-11 Bar chart showing the results of the abrasion test for the different rocks

Figure 5-12 The different lithotype abrasion test results

The wide wheel abrasion test (Capon wheel) is carried out by abrading the face of a sample which will be exposed in use with an abrasive material or wheel under standard conditions. The wear is determined as the width of the groove in the sample (Figure 5-11 and 5-12). According to the standards mentioned above (Table 5-7), the aphyric basalts, basanites and ignimbrites are good for intensive use while the tuff and phyric basalt fall in the category of moderate use as stated in Table 5-7.

Although the surface finish of a floor covering is a personal choice, there are some recommendations to be made. The polished finish is not recommended to use for floor coverings intended for frequent passage, like in buildings for common use as moderate and intensive (Table 5-7) unless they are made of durable rocks. Even for private houses it is not favorable using polished stone units in areas that are accessible from the outside (UNIEN 14157).

The reason for these recommendations is that a polished finishing turns rapidly dull in these areas where there is a frequent passage, so that after a certain time the difference between the passable and impassable becomes visible. In addition, it is not recommended to mix polished and honed surfaces in the same floor.

5.2.1.4 Determination of Point Load strength

The procedures and importance of the Point Load test is well explained in the methodology section (Chapter 4). The point load machine used in this test is state of the art product with smart pressure reader connected to the machine with hydraulic system (Figure 5-13).

$Is_{50} = F/De^2$………………………………………………………………… (*equ.5-1*)

where, F = Failure Load,   De= Equivalent core diameter

The above equation can be written also as below

$Is=4.F/\pi.D^2$ for cores,

$Is=F/W.D$ for blocks and irregular lumps, $W.D=A= (\pi/4)*De^2$, $De^2=D^2$ for diametral test,

but $De^2=4A/\pi$ for axial, block and lump tests, D=thickness of specimen, W-width of the sample, A-minimum cross-sectional area of a plane through the platen contact point

The IS_{50} should be corrected for size effects, with the following formula, Brook (1985) and the ISRM (1985), $IS_{50}=f\ (4.F/\pi.D^{2})$, where $f=\sqrt{De}/50$, is size correction factor

Figure 5-13 The Point Load Test machine used in this study

The samples for the Point Load Test were prepared almost in regular blocks and care was taken during the test when applying the pressure. The results of the Point Load Test are shown below in Table 5-8. The results are also corrected to Is_{50} using the above size correction factor.

Sample n.	W(mm)	D(mm)	P(N)	De^2(mm)	De(mm)	Is	f	IS_{50}(MPa)
TB-Cs-1	36	13	10720	596.18	24.42	17.98	0.70	12.57
TB-CS-2	27	12	3200	412.74	20.32	7.75	0.64	4.94
TB-Cs-3	27	11	3160	378.34	19.45	8.35	0.62	5.21
TB-Cs-4	25	11	2600	350.32	18.72	7.42	0.61	4.54
TB-Cs-5	27	11	5230	378.34	19.45	13.82	0.62	8.62
TB-Cs-6	27	13	9200	447.13	21.15	20.58	0.65	13.38
TB-Ts-7	28	12	6100	428.03	20.69	14.25	0.64	9.17
TB-Cs-8	26	13	4040	430.57	20.75	9.38	0.64	6.04
TB-Cs-9	26	13	4120	430.57	20.75	9.57	0.64	6.16
TB-Ts-10	24	18	5400	550.32	23.46	9.81	0.68	6.72
TB-Ts-11	32	12	7400	489.17	22.12	15.13	0.67	10.06
TB-Ts-12	27	18	13420	619.11	24.88	21.68	0.71	15.29
TB-TS-13	30	18	700	687.90	26.23	1.02	0.72	0.74
TB-Ts-14	27	18	2310	619.11	24.88	3.73	0.71	2.63
TB-Ts-16	28	17	9860	606.37	24.62	16.26	0.70	11.41
TB-TS-18	29	13	8700	480.25	21.91	18.12	0.66	11.99
TB-Ts-21	28	27	8120	963.06	31.03	8.43	0.79	6.64
TB-Ts-22	27	17	2100	584.71	24.18	3.59	0.70	2.50
TB-Ts-23	28	13	9700	463.69	21.53	20.92	0.66	13.73
TB-Ts-24	26	16	4580	529.94	23.02	8.64	0.68	5.86
TB-Ts-25	27	15	3700	515.92	22.71	7.17	0.67	4.83
TB-Ts-26	25	14	2300	445.86	21.12	5.16	0.65	3.35

Table 5-8 Point Load test results of the tested samples

The Point load index value (Is_{50}) ranges from 0.74MPa (loosely welded tuff) to 15.29MPa (compacted phyric basalt/basanite). The basaltic samples show higher values of Point Load Strength index as compared to the pyroclastic rocks (Figure 5-14). There is also a good relation between the measured Uniaxial Compressive Strength and the Point Load index test value (Figure 5-15).

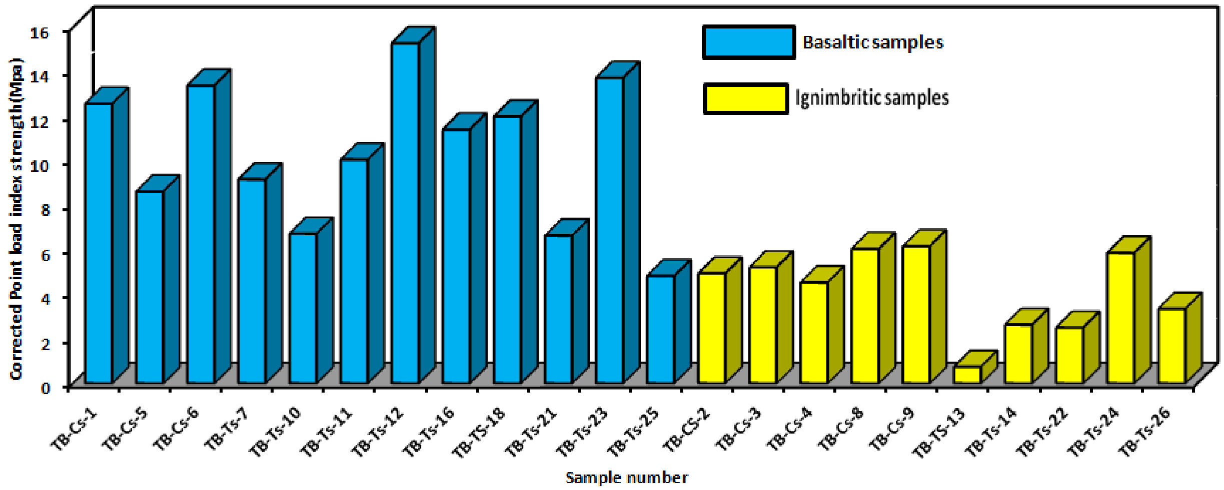

Figure 5-14 Bar chart showing the Point Load Strength index versus sample number

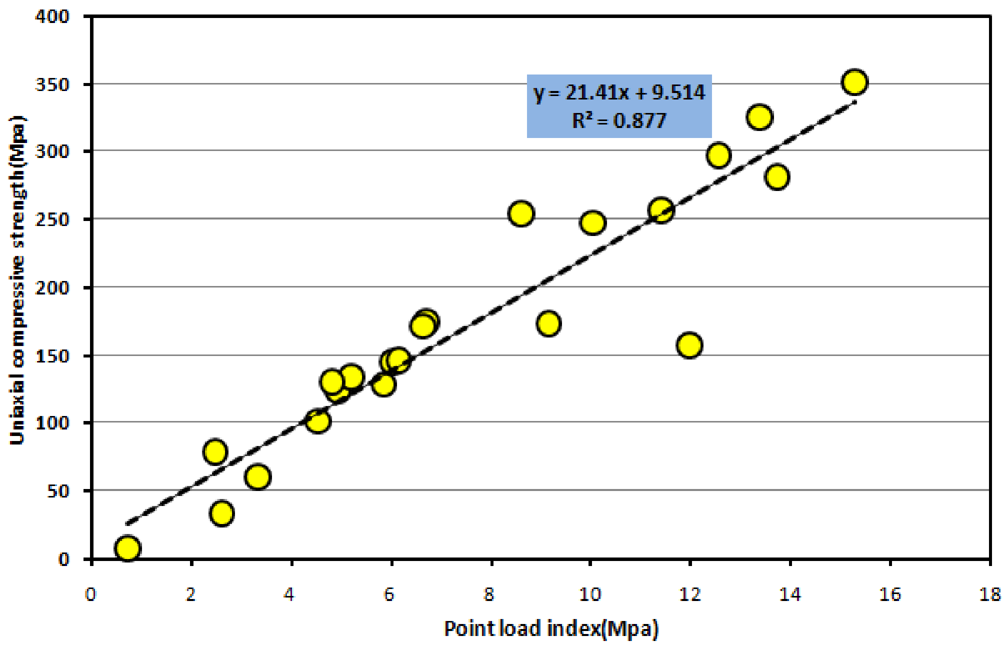

Figure 5-15 Chart showing good correlations of the Point Load and Uniaxial Compressive Strength

5.2.1.5 Determination of P-wave Velocity (Ultrasonic)

The *P*-wave Velocity of the intact rock was measured on cubic samples using the PUNDIT Mk V instrument designed with a high order of accuracy and stability (Figure 5-16). Three cube samples which have similar sides of 50mm*50mm*50mm were prepared for one test, so nine (9) measurements were made for a single test and the P-wave Velocity value was recorded (Table 5-9 and Appendix 3).

The average values of the ultrasound P-wave Velocity presented in the table 5-9 are calculated after measuring three specimens for each sample. The ultrasound P-wave Velocity of the basaltic samples varies from 4882 to 7015m/s. The higher values are recorded from the massive basalt samples (TB-Cs-1, aphyric basalt) while the values for the pyroclastic/Ignimbritic vary from 1554 to 4192 m/s (Table 5-9 and Figure 5-17).

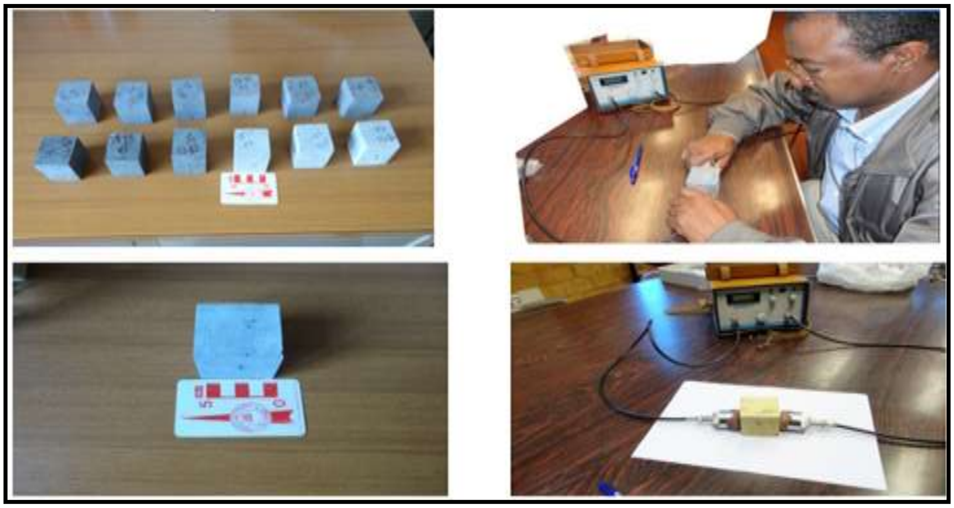

Figure 5-16 Preparation and measurement of Vp with Pundit Mk V

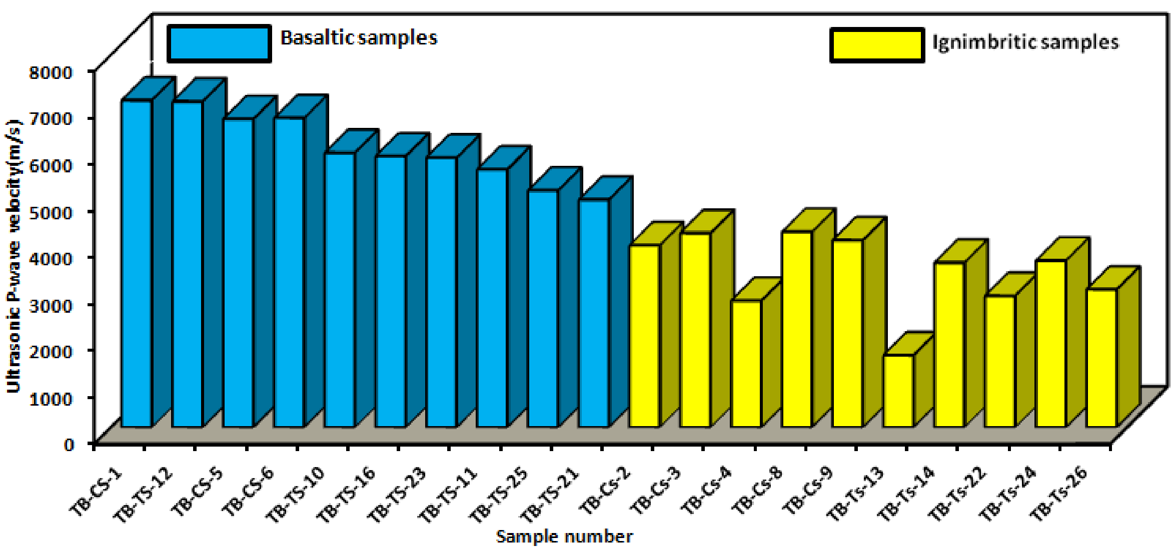

Figure 5-17 Bar chart showing the ultrasonic P-wave Velocity of basaltic and ignimbritic sample

Basaltic rock samples			Pyroclastic/ignimbritic samples		
Sample N.	Ultrasonic Velocity(m/s)	Engineering Classification, Anon(1979)	Sample N.	Ultrasonic Velocity(m/s)	Engineering Classification, Anon(1979)
TB-CS-1	7015.20	Very high	TB-Cs-2	3904.40	Mmoderate
TB-TS-12	6987.22	Very high	TB-Cs-3	4164.60	High
TB-CS-5	6611.10	Very high	TB-Cs-4	2712.20	Low
TB-CS-6	6635.20	Very high	TB-Cs-8	4192.30	High
TB-TS-10	5887.13	Very high	TB-Cs-9	4010.00	High
TB-TS-16	5815.60	Very high	TB-Ts-13	1544.00	Very low
TB-TS-23	5784.33	Very high	TB-Ts-14	3530.00	Moderate
TB-TS-11	5530.22	Very high	TB-Ts-22	2817.00	Low
TB-TS-25	5081.11	Very high	TB-Ts-24	3574.89	Moderate
TB-TS-21	4882.33	High	TB-Ts-26	2955.00	Low

Table 5-9 Engineering classification (Anon, 1979) of the Ultrasonic Velocity of basaltic and pyroclastic/ignimbritic samples

As it has been seen from the above engineering classification by Anon, 1979, the basaltic samples almost fall in the very high category while the pyroclastic rocks exhibited somewhat varied category from very low to high velocity ranges.

5. 2.1.6 Water absorption

Water absorption at atmospheric pressure

The water absorption at atmospheric pressure measured on the two groups of samples (both lithotypes, i.e. the basaltic and pyroclastic/ignimbritic), varies greatly (Table 5-10 and Table 5-11). The water absorption for the basaltic samples varies from (TB-TS-11, 0.33%) to (TB-TS-23, 1.08%), from aphyric and porphyritic basalt respectively (Figure 5-18). The water absorption of the pyroclastics/ignimbrite ranges from (TB-Cs-9, 4.92%) to (TB-Ts-13, 12.85%).

Sample N.	Water absorption (%)	Open porosity (%)	Bulk density(g/cc)	Real density (g/cc)	St.dev. (%)
TB-CS-1	0.42	1.23	2.94	3.0873	0.0054
TB-CS-5	0.89	2.54	2.84	2.9254	0.0064
TB-TS-10	0.62	1.82	2.91	3.0807	0.007
TB-TS-11	0.33	0.95	2.91	2.9692	0.0076
TB-TS-12	0.65	1.87	2.89	3.0779	0.0058
TB-TS-16	0.36	1.11	3.03	3.0679	0.0066
TB-TS-21	0.95	2.75	2.88	2.9172	0.0066
TB-TS-23	1.08	3.08	2.86	2.9809	0.0057
TB-TS-25	0.62	1.75	2.8	2.9363	0.007

Table 5-10 Physical properties of the basaltic samples determined by Helium UltraPycnometer-1000 in the Chemicals and Geological Sciences Department of Cagliari University

Sample n	Water absorption (%)	Open Porosity%	Bulk Density (g/cc)	Real Density (g/cc)	St.dev (%)
TB-Cs-2	6.01	13.59	2.26	2.6357	0.0069
TB-Cs-3*	6.37	10.71	2.34	-	-
TB-Cs-4*	8.4	16.75	2.32	-	-
TB-Cs-8*	5.36	10.6	2.37	-	-
TB-Cs-9*	4.92	11.33	2.21	-	-
Tb-TS-13*	12.85	24.13	1.88	-	-
Tb-TS-14	8.98	18.72	2.08	2.4089	0.006
TB-Ts-22	5.56	12.75	2.29	2.7485	0.0067
TB-Ts-24	10.29	20.81	2.02	2.7771	0.006
TB-Ts-26*	9.79	19.87	2.04	-	-

Table 5-11 Physical parameters of pyroclastic/ignimbritic samples as determined by Helium Ultrapycnometer 1000 in the Department of Chemical and Geological Sciences; samples with astrix are determined with immersion method in Ethiopia

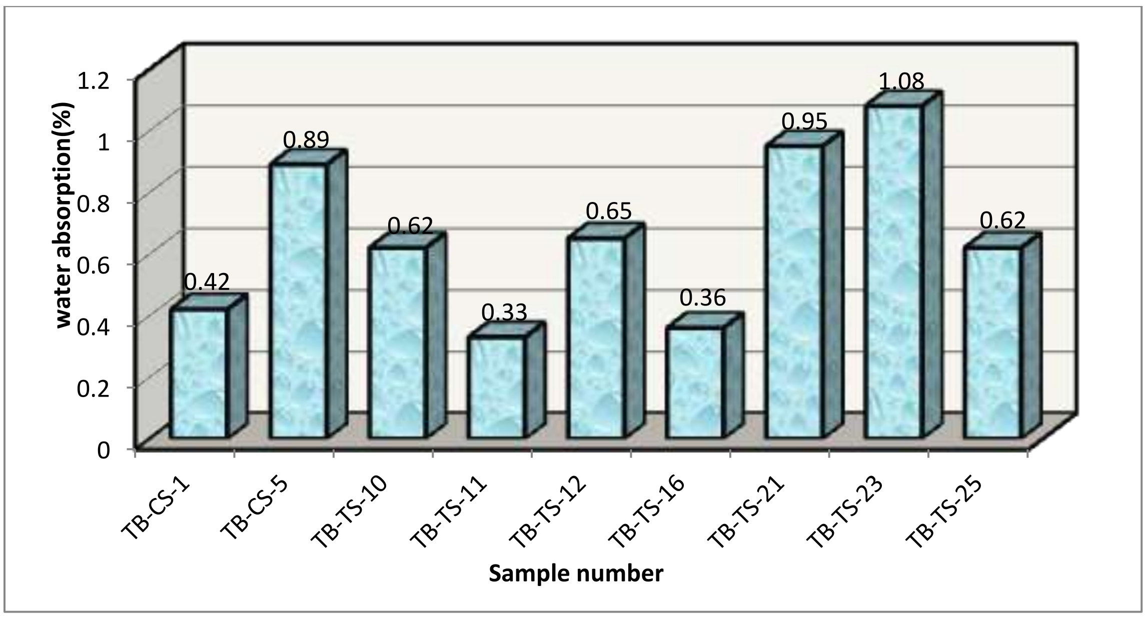

Figure 5-18 Bar graph showing the water absorption of the basaltic samples at atmospheric pressure

Water absorption coefficient by capillarity

The capillary suction was measured at the Department of Civil and Environmental Engineering and Architecture, University of Cagliari based on the UNIEN 1925: 1999. Dry samples were submerged in (3 ± 1) mm of water and the capillarity-rise absorption was measured in function of the time at various intervals. This test was measured on 9 samples, 4 basaltic samples and 5 pyroclastic/ignimbritic samples. The water absorption coefficient by capillarity is shown in Table 5-12 and Figure 5-19.

The coefficient of water absorption by capillarity is represented by the slope of the regression line and it can be calculated as**:**

$$\frac{Mi-Md}{A\sqrt{T}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(equ.5-2)}$$

where: **Md** mass of dried specimen, **Mi** successive masses of specimen during testing, **A** area of the immersed base of the specimen, **T** times from beginning of the test until the time in which the masses are measured.

Sample number	TB-Cs-1	TB-Cs-2	TB-Cs-3	TB-Cs-4	TB-Cs-5	TB-Cs-6	TB-Cs-7	TB-Cs-8	TB-Cs-9
water absorption by capillary coefficient, CC=(gm/m^{2}s$^{1/2}$)	1.19	27.56	2.26	12.42	1.01	1.32	3.36	31.27	29.53

Table 5-12 Results of water absorption coefficient by capillarity

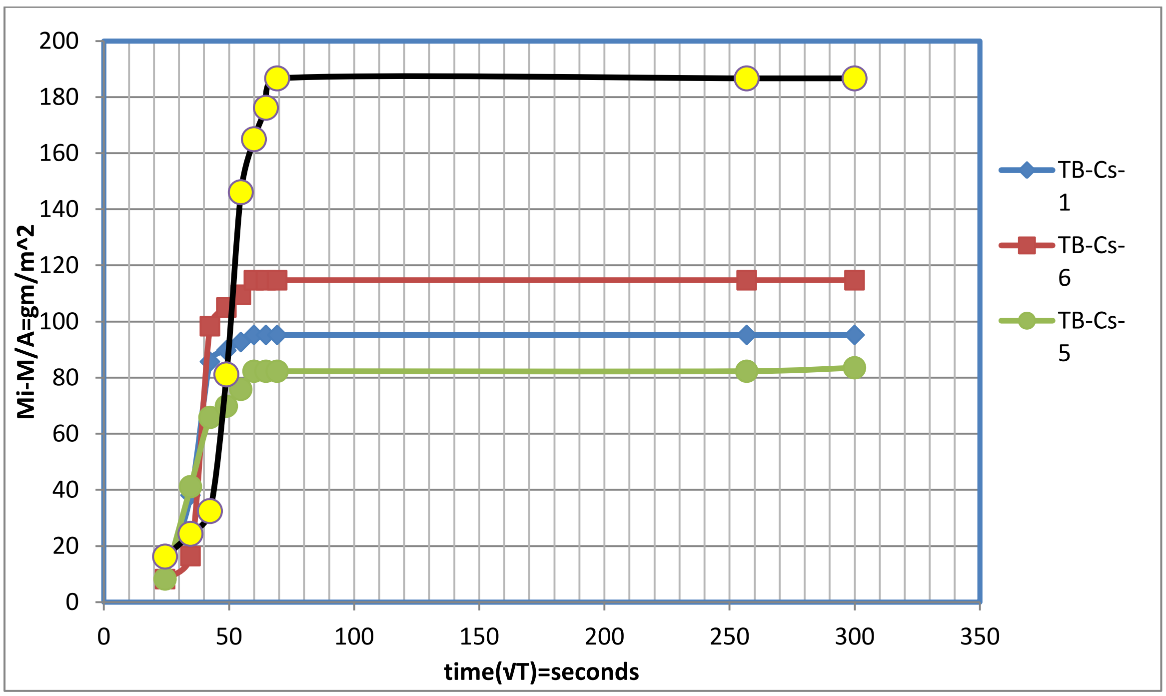

Figure 5-19 Chart showing the water absorption coefficient by capillarity (capillary curve) of some samples

The three basaltic samples (TB-Cs-1, TB-Cs-5, and TB-Cs-6) have almost a similar pattern and lower water absorption (g/m^2), while the pyroclastic/ignimbritic sample (TB-Cs-8) exhibits higher water absorption (g/m^2). It is considered that values above 100 g/m² are characteristic for stones with high capillarity absorption (UNIEN 1925). In this regard all the tested samples satisfy the UNIEN 1925 standards.

5.2.1.7 Total and open porosity

Open porosity

Porosity is probably the most important factor to material properties for many rocks, and there is hardly a physical property of rocks that is not influenced directly or indirectly by porosity.

Porosity is a fundamental property of stone which can have an influence on its durability. Many processes of alteration bring about an increase in porosity, while impregnation treatments which fill the pores have to decrease porosity. Therefore this test can be useful for the following:

- assessing the extent of some types of stone decay determining the extent to which the pore space to be filled by an impregnation treatment

The results of the open porosity for the different groups of tested samples are presented in Tables 5-13 and 5-14. The real density, the bulk density and the total and open porosity of the selected representative and freshly quarried samples are presented in the Table 5-13.

The pyroclastic/ignimbritic rock samples (TB-Cs-2, TB-Ts-22 and TB-Ts-24) show the highest average value of open and total porosity while the basaltic rock samples have relatively very low open and total porosity.

Sample N	Open porosity (%)	Bulk density(g/cc)	Real density(g/cc)	Total porosity (Nt %)	Engineering Classification of open porosity	
					Anon, 1979	Dearman, 1993
TB-Cs-1	1.23	2.94	3.09	4.77	Low	Extremely strong
TB-Cs-2	13.59	2.26	2.64	14.25	Medium	Very strong
TB-Cs-5	2.54	2.84	2.93	2.92	Low	Extremely strong
TB-Cs-7	2.85	2.93	3.09	5.08	Low	Very strong
TB-Ts-10	1.82	2.91	3.08	5.54	low	Very strong
TB-Ts-11	0.95	2.91	2.97	1.99	Very low	Very strong
TB-Ts-12	1.87	2.89	3.08	6.10	Low	Very strong
TB-Ts-16	1.11	3.03	3.07	1.24	Low	Very strong
TB-Ts-22	12.75	2.29	2.75	16.68	Medium	Strong
TB-Ts-23	3.08	2.86	2.98	4.06	Low	Very strong
TB-Ts-24	20.81	2.02	2.78	27.26	High	Strong
TB-Ts-25	1.75	2.80	2.94	4.64	Low	Very strong

Table 5-13 Total and open porosity of the selected samples

According to the engineering classification (Anon, 1979) most of the basaltic samples have low porosity while the pyroclastics/ignimbrite samples have medium to high porosity (TB-Cs-2, TB-TS-22 and TB-TS-24). Similarly, according to Dearman, 1993, strength classification based on porosity all of the samples fall within the range of strong to extremely strong (Table 5-14).

Porosity (%)	**Strength**	**Deformability**
0–5	Extremely strong	Very slightly deformable
5–10	Very strong	Very slightly deformable
10–20	Very strong	Slightly deformable
20–30	Strong	Slightly deformable
30–50	Strong	Moderately deformable
>50	Moderately strong	Very deformable

Table 5-14 Relationship between porosity, compressive strength and deformability of the tested basalt (modified after Turk and Dearman, 1983)

Rock density and water-absorbing capacity of any rock are influenced by its hardness, compactness, size and proportion of the pores, present minerals and mode of occurrence, grain size, degree of weathering and alteration of the rock, and in some cases the existence of microfractures within the rock.

The bulk density and real density of the samples were calculated with the formula indicated in the previous section. The bulk density of the pyroclastic/ignimbritic rock samples varies from 1.88g/cc (TB-Ts-13) to 2.37g/cc (TB-Cs-8) while the real density ranges from 2.4g/cc (TB-Ts-14) to 2.77g/cc (TB-Ts-24). In the same fashion, the bulk density of the basaltic samples ranges from 2.8g/cc (TB-Ts-25) to 3.03g/cc(TB-Ts-16) and the real density varies from 2.91g/cc (TB-Ts-210 to 3.087g/cc (TB-Cs-1) as indicated in Table 5-13.The relations of total porosity, bulk density, real density, open porosity are shown on Figure 5-20.

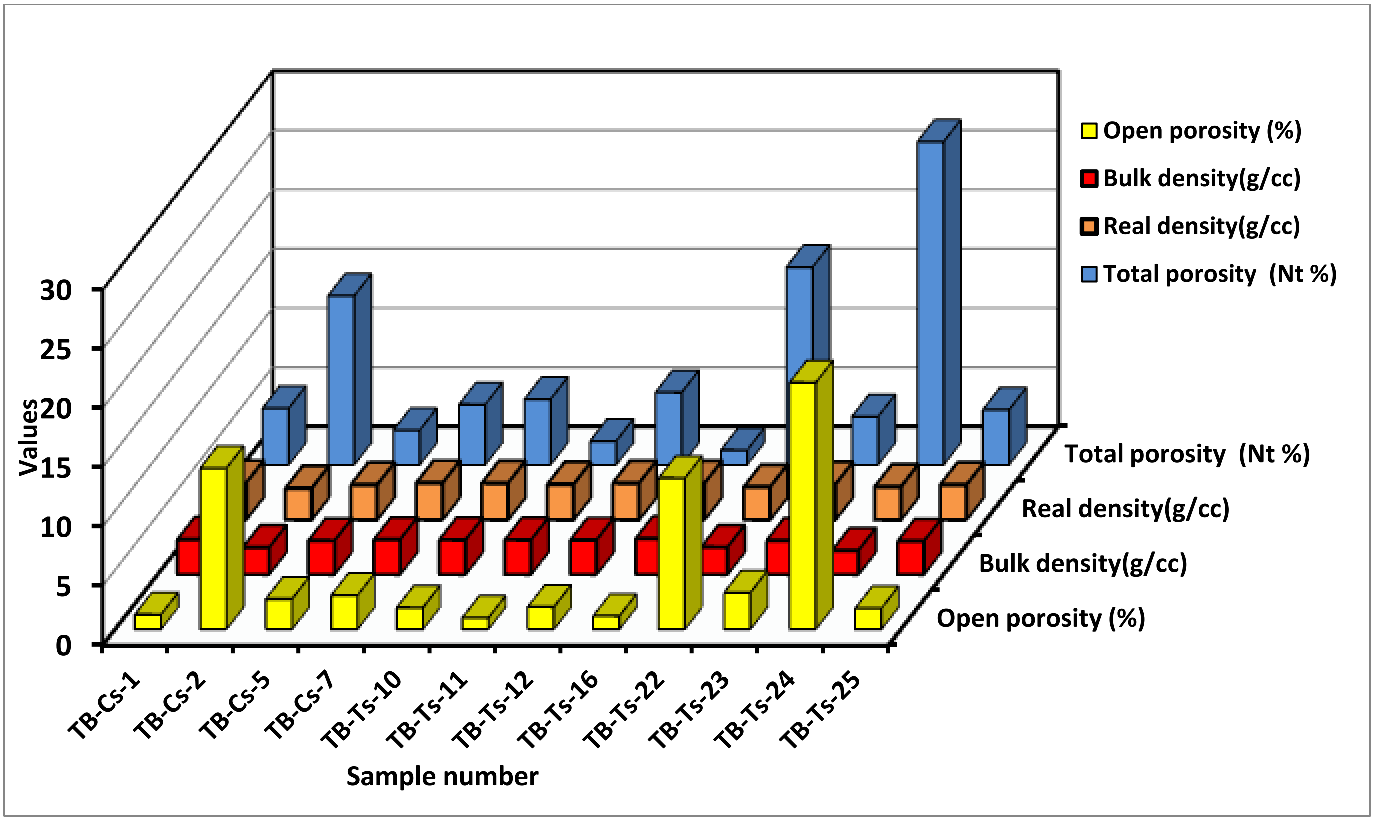

Figure 5-20 Bar chart showing the bulk density, open porosity, total porosity and real density of the basaltic samples

5.2.1.8 Dynamic elastic modulus (Young's), Ultrasonic P-wave Velocity and Uniaxial Compressive Strength

The Static Young's Modulus (E) is defined as the ratio of the axial stress to axial strain for a material subjected to uniaxial load (Neville 1997). While seismic wave velocity gives a physical measurement of the rock material, it is also used to estimate the Elastic Modulus of the rock material. From the theory of elasticity, compressional (or longitudinal) P-wave Velocity (Vp) is related to the Dynamic Elastic Modulus (Ed), and the density (ρ) of the material as, according to Pierce, 1989,

$$Vp = \sqrt{\frac{\mathrm{Ed}(1-\nu)}{\rho(1+\boldsymbol{v})(1-2\nu)}}$$ .... (*Equ.5-3*), Pierce, 1989

Solving equation 5-3 for Ed, it gives equation 5-4

$$\mathrm{Ed} = Vp^2\,\frac{[\boldsymbol{\rho}(\mathbf{1}+\boldsymbol{v})(\mathbf{1}-\mathbf{2}\boldsymbol{v})]}{(\mathbf{1}-\boldsymbol{v})}$$ .... *(Equ.5-4)*

where, Ed: Dynamic Young's Modulus, Vp: P-wave Velocity, ρ: density of the material and *v* is the Poisson Ratio taken from literature [for basaltic rocks as 0.15(0.1- 0.2)]. If ρ is in g/cm^3, and Vp is in km/s, then Ed is in GPa (10^9 N/m^2).

Similar to strength, Young's Modulus of rock materials varies widely with rock type. For extremely hard and strong rocks, Young's Modulus can be as high as 100GPa. Poisson's Ratio measures the ratio of lateral strain to axial strain, at linearly-elastic region.

The Elastic Modulus estimated by the above method is sometime termed as seismic modulus (also called Dynamic Modulus, but should not be mistaken as the modulus under dynamic compression). It is different from the modulus obtained by the Uniaxial Compression tests. The value of the Seismic Modulus is generally slightly higher than the Modulus determined from static compression tests.

This method offers two advantages over static measurements: i) it is a non-destructive tool and less expensive and can be performed in short time; ii) it can be performed in the field. However, the problem lies in the fact that static and dynamic elastic moduli slightly differ in values. This difference is explained by the presence of fractures, cracks, cavities, planes of weakness and foliation.

It is a general trend that a stronger rock material is also stiffer, i.e., higher elastic modulus is often associated with higher strength. There is reasonable correlation between Uniaxial Compressive Strength and Dynamic Elastic Modulus (Table 5-15 and Figure 5-21) for the current study. The Modulus Ratio (Uniaxial Compressive Strength versus Young's Modulus) also has shown that the tested samples clearly plotted in the volcanic rock modulus ratio region defining medium to high Modulus Ratio (Figure 5-22).

Sample number	Ultrasonic Velocity(m/s)	Uniaxial Compressive Strength(MPa)	Elastic-Dynamic Modulus(GPa)	Bulk Density(g/cc)	Open porosity (%)
TB-Cs-1	7015	297	129	2.81	1.23
TB-Cs-2	3904	124	32	2.26	13.39
TB-Cs-3	4165	134	38	2.34	10.71
TB-Cs-4	2712	101	16	2.32	16.75
TB-Cs-5	6611	254	120	2.93	2.54
TB-Cs-6	6635	325	125	3.04	0.83
TB-Cs-7	6055	173	95	2.76	2.85
TB-Cs-8	4192	145	39	2.37	10.6
TB-Cs-9	4010	146	33	2.21	11.33
TB-TS-10	5887	174	93	2.87	1.81
TB-TS-11	5530	247	81	2.85	0.93
TB-TS-12	6987	351	129	2.82	1.86
TB-TS-13	1544	7	4	1.88	24.13
TB-TS-14	3530	33	24	2.08	18.72
TB-Ts-16	5816	256	92	2.91	1.11
TB-Ts-18	5321	157	75	2.84	2.54
TB-Ts-21	4882	171	64	2.88	2.75
TB-Ts-22	2817	78	17	2.29	12.75
TB-Ts-23	5784	281	89	2.86	3.08
TB-Ts-24	3575	128	24	2.02	20.81
TB-Ts-25	5081	130	71	2.94	1.75
TB-Ts-26	2955	60	16	2.04	19.87

Table 5-15 The Elastic Dynamic Modulus and other physical and mechanical properties of the studied samples

Several attempts have been made to correlate Static (E) and Dynamic (Ed) Moduli for rocks. The simplest of these empirical relations is proposed by Lydon and Balendran (Neville, 1997),

$$E = 0.83\,Ed$$

and also according to Christaras, 1995,

$$E=-3.16+1.05Ed$$

However, another empirical relationship for rock’s elastic moduli was proposed by Swamy and Bandyopadhyay and is now accepted as part of British testing standard BS8110 Part2:

$$E = 1.25Ed - 19$$

where both units of E and Ed are in GPa.

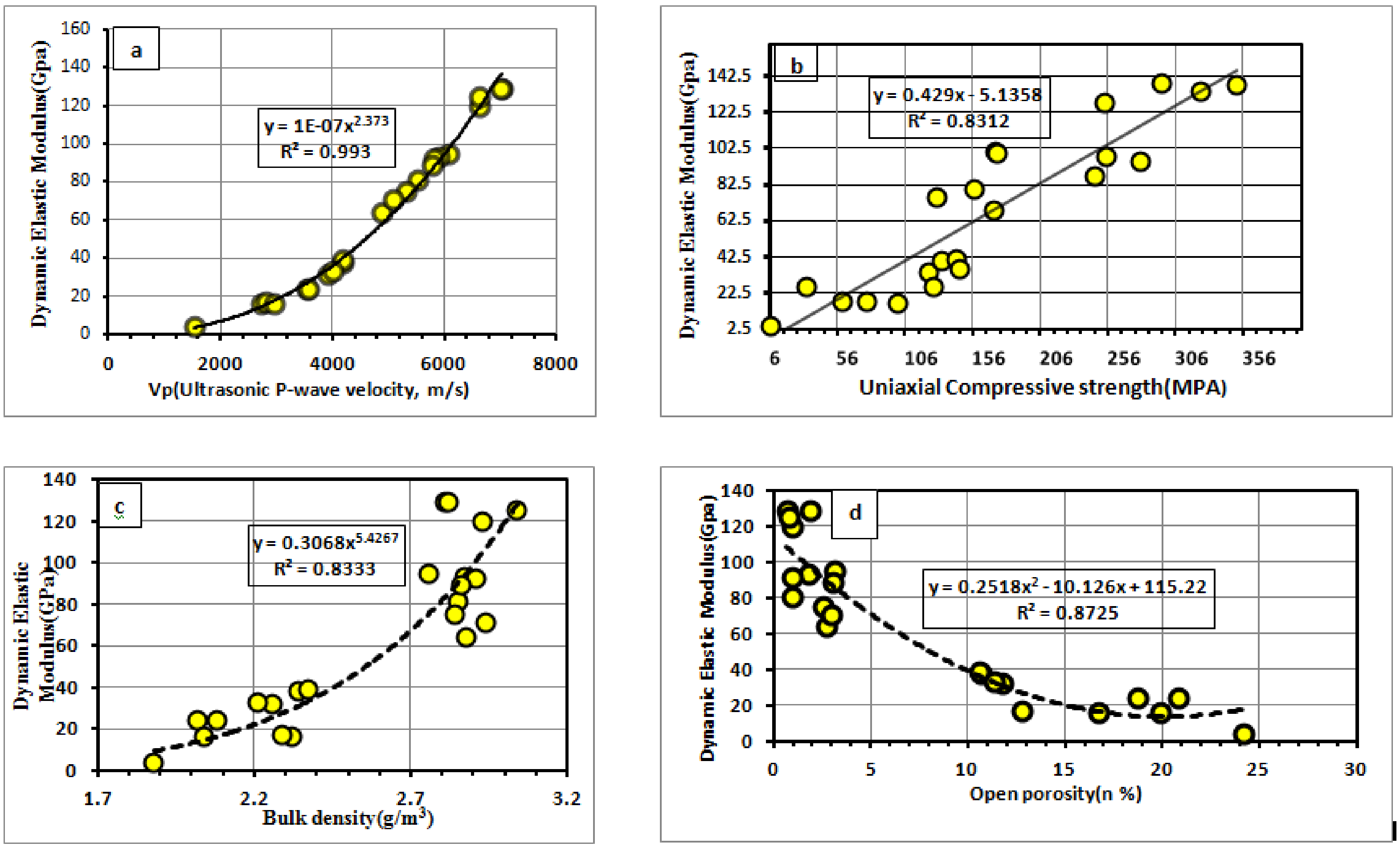

Figure 5-21 Chart showing the Dynamic Modulus of Elasticity with other physical and mechanical properties, a)Vp (P-wave Velocity) versus Dynamic Elasticity Modulus, b) Uniaxial Compressive Strength versus Dynamic Elasticity Modulus, c) Bulk Density versus Dynamic Elasticity Modulus and d) Open porosity versus Dynamic Elasticity Modulus

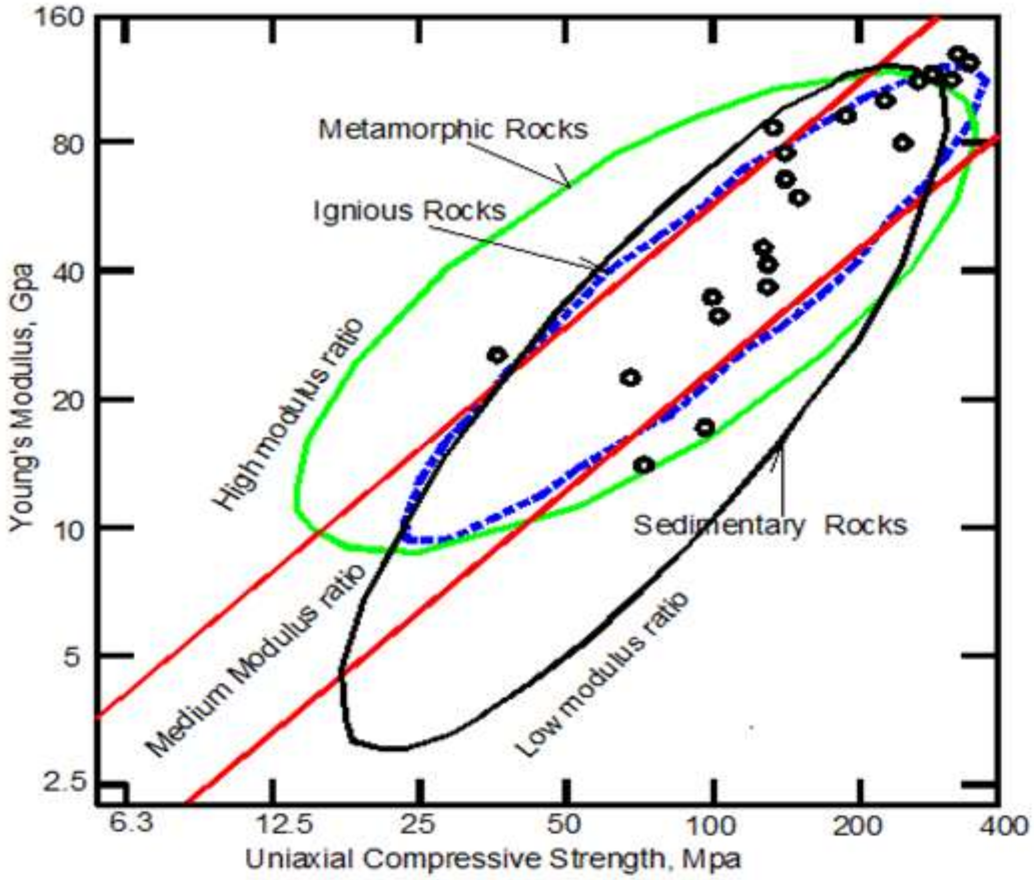

Figure 5-22 Chart showing Modulus ratio (Uniaxial Compressive Strength versus Young's Modulus)

5.2.1.9 Pore shape determination

It is well known that the strength and deformability of the so called "intact rock" are influenced both by pores and fissures. Fissures and microcracks are distinguished from spherical pores by their narrow, elongated shape and their high length-to-width ratios, typically of the order of 10^3(Walsh and Brace, 1966 as cited in Kelsall, et al., 1998). In addition, as a consequence of their shape, microcracks and fissures are further distinguished from pores by their compressibility and preferred orientation. Therefore, the effects of cracks and fissures are quite distinct from the effects of spherical pores, which are relatively noncompressible and which do not have preferred orientation.

Cavities in low porosity rocks are usually in the form of cracks, which are situated along cleavages in the minerals or at grain boundaries (Bourges, 2006). A simple approach to separate porosity of pores from porosity of cracks is to calculate the Quality Index (QI). Tourenq and Fourmaintraux (1971) have described the calculation of the quality index. Indeed the authors proposed a method to quantify the discontinuities in rocks. Also Goodman (1986), proposed this method to index degree of fissuring in rocks. Fourmaintraux (1975) also proposed a method of distinguishing fissured and porous rocks based on the relationship between P-wave Velocity and porosity. Fissured rocks can also be distinguished according to the effect of water saturation on P-wave Velocity. According to Tourenq et al (1971), saturation can increase the P-wave Velocity by as much as three times in fissured rocks, while it has little effect in porous rocks. In the present study, it is tried to characterize porosity of pores and porosity of cracks or fissures of the Tarmaber basaltic rocks using the P-wave velocity. It is based on the comparison of the measured ultrasonic velocity and theoretical ultrasonic velocity values of the rocks; which lead to the Quality Index definition, with equation (5-5).

$$\boldsymbol{QI}\% = \frac{\boldsymbol{Vp}}{\sum_i \boldsymbol{Ai.Vpi}} * \mathbf{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (equ.5\text{-}5)$$

where,

QI: Quality Index 0 < QI < 100 % (maximum quality)

Vp: measured ultrasonic velocity (P-waves, m/s)

ΣAiVpi: theoretical ultrasonic velocity (P-waves, m/s),

The theoretical ultrasonic Velocity is calculated from the velocity of each mineral contained in the rock and its concentration. Tourenq and Fourmaintraux (1971) demonstrated also that the Quality Index could be expressed as equation 5-6:

QI% = $(1-\alpha N_p-\beta N_F)*100$... *(equ.5-6)*

With:

NP: porosity of pore, NF: porosity of cracks; α, β: experimental coefficients

The authors defined two equations 5-7 and 5-8

QI = 100 – 22 NF for rocks containing only cracks (pore porosity NP = 0) (equ.5-7)

QI = 100 – 1.6 NP for rocks containing only pores (crack porosity NF = 0) (equ.5-8)

Le Berre (1975) showed that the porosity of cracks should have a larger importance and transformed the equation 5-7 and 5-8

QI = 100 – 47 NF

QI = 100 – 1.32 NP

The corrected relation of the porosity of cracks NF and of pore NP is illustrated in the Figure 5-23. All the constants are derived from experimental coefficients. Indeed, the authors determined the equation and the constants from the representation of diversified lithotypes in the diagram porosity Nt vs. Quality Index QI%.

Looking at the diagram (Figure 5-23), values of NF and NP present two limits clearly drawn; NF is necessary below 2% (NF < 2%), while NP must be below 75% (NP < 75%) to result QI% above zero.

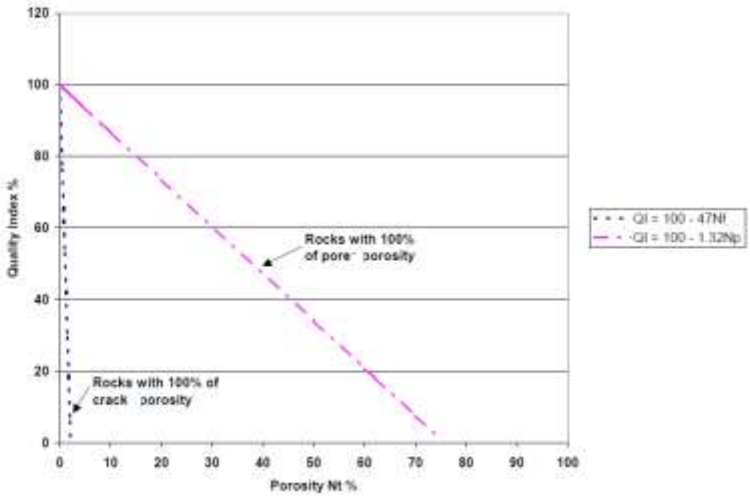

Figure 5-23 Corrected relation of the porosity of cracks and of pore (after Le Berre 1975)

The Quality Index, QI%

For the aphyric basalt, porphyritic basalt, ignimbrite and rhyolitic glass, the following theoretical P-wave Velocity values were taken from the literature (Gebrande, 1982; Goodman, 1990) to calculate the theoretical velocity and QI:

Quartz: 6050 m/s, **plagioclase/feldspar**: 6250 m/s, **Pyroxene:** 6200m/s, **Olivine:** 8400m/s, **Volcanic glass:** 5720m/s and the mineral composition of the rocks were determined on microscopic view/thin section study and it is shown below for each lithology:

1. Porphyritic basalt: 55 % plagioclase; 30 % pyroxene; 15% olivine
2. Aphyric basalt: 50% plagioclase; 35 % pyroxene; 15 % olivine
3. Rhyolitic glass: 60% glass; 20% feldspar; 20 % quartz
4. Ignimbrite: 35% glass, 18 % feldspar; 45 % quartz; minor other accessories

The theoretical ultrasonic P-wave Velocity is calculated from the velocity of each mineral contained in the rock and its concentration, for example,

Ignimbrite ($Ai.Vi_P$) =35%*5720m/s + 18%*6250m/s +45%*6050m/s=5850m/s

Then QI for ignimbrite= $Vp/AiVi_P$=3800/5850, in such a way the Quality Index is formulated as below for the major rock units in the studied area: Vp is the measured velocity of the bulk material which is directly measured according to the normal standards of P-wave Velocity measurement on the rock sample.

Rock type	**Measured Vp (m/s)**	**Theoretical Vp(m/s) = $\sum_i Ai.Vpi$**	**QI (%) = $\frac{Vp}{\sum_i Ai.Vpi} * 100$**
Porphyritic basalt	5500	6557	83%
Aphyric basalt	6000	6555	91%
Rhyolitic glass	4200	6475	64%
Ignimbrite	3800	5850	64%

The aphyric and phyric basalts have a higher Quality Index than the ignimbrites and rhyolitic glass. It shows that the basaltic rocks may have fewer discontinuities in their structure. Hence these two rocks may be quite entirely characterized by a porosity of cracks as they are close to crack porosity line. While the ignimbrite shows a relatively lower Quality Index and could be characterized by pore porosity as it is close to the pore porosity line (Figure 5-24).

In general, Quality Index (QI %) is obtained by non-destructive method and indicates the discontinuities in the stone and therefore is seen as an important variable. Pore shape can also be determined when QI is displayed versus the total porosity. The higher value of QI indicates that crack porosity dominates while lower value shows pore porosity is prevailing.

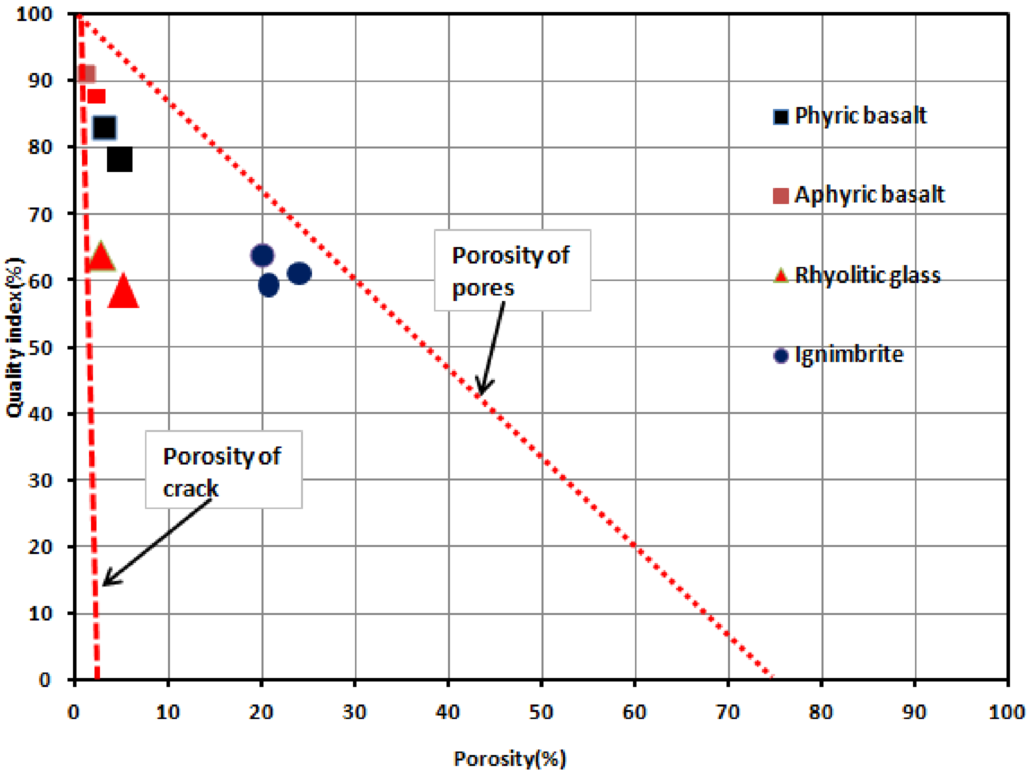

Figure 5-24 Corrected relation of the porosity of cracks and of pore of the phyric basalt, aphyric basalt, rhyolitic glass and ignimbrite

5.3 Simple regression analysis of physical and mechanical properties

An attempt has been made in the present study to correlate Uniaxial Compressive Strength, ultrasonic Velocity, bulk density, open porosity and water absorption of the volcanic rocks of the study area considering its greater applicability in the project area where resources for costly laboratory testing is limited and even laboratories are far from easy access.

The data in Table 5-16 were analysed using the method of least squares regression. Linear, logarithmic, exponential and power curve fitting approximations were tried and the best approximation equation with highest correlation coefficient was determined for each regression.

A number of researchers have studied the relation between different physical and mechanical properties of rock materials and have reported that the P-wave Velocity is closely related to physical and mechanical properties (Smorodinov et al. 1970). Inoue and Ohomi (1981) investigated the relation between Uniaxial Compressive Strength and P-wave Velocity of soft rocks and reported very poor correlation between them.

Relation between density and P-wave Velocity was given by Gaviglio (1989). Kahraman (2001a) correlated P-wave Velocity with the number of joints and Schmidt hammer rebound number and found a strong influence of the joint density on P-wave Velocity; he also reported that the evaluated Uniaxial Compressive Strength using Schmidt Hammer rebound number and P-wave Velocity.

Sample Number	Uniaxial Compressive Strength (MPa)	Ultrasonic Velocity (m/s)	Schmidt Hammer Rebound Value(H_R)	Open porosity (N%)	Wtabs (%)	Bulk density (g/cc)
TB-Cs-1	297	7015	53	1.23	0.12	2.81
TB-Cs-2	124	3904	36	13.39	5.78	2.26
TB-Cs-3	134	4165	40	10.71	6.37	2.34
TB-Cs-4	101	2712	31	16.75	8.4	2.32
TB-Cs-5	254	6611	49	2.54	0.26	2.93
TB-Cs-6	325	6635	52	0.83	0.21	3.04
TB-Cs-7	173	6055	48	2.85	1.23	2.76
TB-Cs-8	145	4192	38	10.6	5.36	2.37
TB-Cs-9	146	4010	29	11.33	4.92	2.21
TB-TS-10	174	5887	54	1.81	0.63	2.87
TB-TS-11	247	5530	43	0.93	0.33	2.85
TB-TS-12	351	6987	53	1.86	0.66	2.82
TB-TS-13	7	1544	21	24.13	12.85	1.88
TB-TS-14	33	3530	35	18.72	8.98	2.08

TB-Ts-16	256	5816	50	1.11	0.33	2.91
TB-Ts-18	157	5321	42	2.54	0.89	2.84
TB-Ts-21	171	4882	40	2.75	0.95	2.88
TB-Ts-22	78	2817	35	12.75	5.56	2.29
TB-Ts-23	281	5784	49	3.08	1.08	2.86
TB-Ts-24	128	3575	44	20.81	10.29	2.02
TB-Ts-25	130	5081	47	1.75	2.94	2.94
TB-Ts-26	60	2955	28	19.87	9.79	2.04
Mean	**171**	**4773**	**41.68**	**8.18**	**4.00**	**2.56**
Max	**351**	**7015**	**54.00**	**24.13**	**12.85**	**3.04**
Min	**7**	**1544**	**21.00**	**0.69**	**0.12**	**1.88**
SD	**93.78**	**1536.55**	**9.25**	**7.80**	**4.02**	**0.37**
V	**8794.61**	**2360981.46**	**85.56**	**60.91**	**16.13**	**0.14**
N	**22**	**22**	**22**	**22**	**22**	**22**

Table 5-16 The physical and mechanical characterization results of the sample

The data were analyzed with simple ordinary least squares analysis. The objective was to see if there is best fit between the physical and mechanical properties. The Uniaxial Compressive Strength has the lowest correlating coefficient of 0.731 with open porosity, while other properties have relatively higher correlation coefficient (Table 5-17).

No.	**Related parameters**	**Regression equation**	**R^2 value**
1	Ultrasonic Velocity(Vp)- Uniaxial Compressive Strength(UCS)	$Ucs = 0.055Vp - 92.75$	$R^2 = 0.822$
2	Uniaxial Compressive Strength (UCS)-Open porosity (N %)	$N\% = 30.58e^{-0.01Ucs}$	$R^2 = 0.731$
3	Uniaxial Compressive Strength (UCS)-Water absorption (W_{tabs}%)	$Wtabs\% = 19.11e^{-0.01ucs}$	$R^2 = 0.751$
4	Ultrasonic velocity-open porosity (N %)	$N\% = -0.004Vp + 30.40$	$R^2 = 0.84$
5	Ultrasonic Velocity (Vp)-Water absorption (W_{tabs}%)	$w_{tabs}\% = -0.002Vp + 15.42$	$R^2 = 0.84$
6	Ultrasonic Velocity-Bulk density(ρb)	$\rho b = 1.666e^{9E-05Vp}$	$R^2 = 0.785$

Table 5-17 Regression equations and corresponding R^2 of the various physical and mechanical properties

The results for physical and mechanical properties of the samples were analyzed using the methods of least square regression technique. The equation of regression, best fit line and coefficient of determination were calculated for each physical and mechanical property.

The correlation coefficient values for ultrasonic P-wave Velocity (Vp) vs. Uniaxial Compressive Strength (UCS), UCS vs. Open porosity (N%), Vp vs. N%, Vp vs. Water absorption(W_{tabs}%), Vp vs. bulk density (ρb), are 0.82, 0.73, 0.75, 0.83, 0.84, 0.78, respectively, as shown in Table 5-17 and Figure 5-25. Comparatively a little weak correlation coefficient was found for UCS Vs. N% and Vp vs. Water absorption as compared with the other physical and mechanical properties.

N	Parameters	Student t-test value	
		Calculated value	**Tabulated value**
1	Ultrasonic P-wave Velocity (Vp)- Uniaxial Compressive Strength (UCS)	14.02	1.682
2	Uniaxial Compressive Strength (UCS)-Open porosity (N %)	8.14	1.682
3	Uniaxial Compressive Strength (UCS)-Water absorption (w_{tabs}%)	8.36	1.682
4	Ultrasonic P-wave Velocity (Vp)-Open porosity (N %)	14.55	1.682
5	Ultrasonic P-wave Velocity (Vp)-Water absorption (w_{tabs}%)	14.56	1.682
6	Ultrasonic P-wave Velocity (Vp)-Bulk density(ρb)	14.56	1.682

Table 5-18 The calculated and tabulated values of the t-test

The significance of R^2-values can be determined by the *t*-test, assuming that both variables are normally distributed and the observations are chosen randomly. The test compares the computed *t*-value with a tabulated value. In simple terms, the *t*-test compares the actual difference between two means in relation to the variation in the data.

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{S_1{}^2}{N_1} + \frac{S_2{}^2}{N_2}}}$$ .... (*equ.5-9)*

where,
$\bar{x}_1$ is the mean of first data set, S_1^2 is the standard deviation of first data set
$\bar{x}_2$ is the mean of second data set; S_2^2 is the standard deviation of second data set
N_1 is the number of elements in the first data set; N_2 is the number of elements in the second data set

The value for the *t*-test is positive, when the first mean is larger than the second and t value is negative if it is lower. Once the *t* value is computed, it is then compared with the tabulated value. If the computed value is larger than the tabulated one, then it indicates strong and significant correlation. To test the significance, one needs to set a risk level or called the alpha level. In most cases, the “rule of thumb” is to set at 95% confidence interval. Since a 95%

confidence level was chosen in this test, a corresponding critical *t*-value 1.682 is obtained, taking the Degree of Freedom (DF) as n_1-1 + n_2-1=42 (Table 5-18).

For the t-test results it can be concluded that there is a real correlation between Vp vs. UCS, UCS vs. open porosity (N %), Vp vs. N%, Vp vs. Water absorption (wtabs %), Vp vs. ρb of physical and mechanical properties and this relations could be used in the future in the study area.

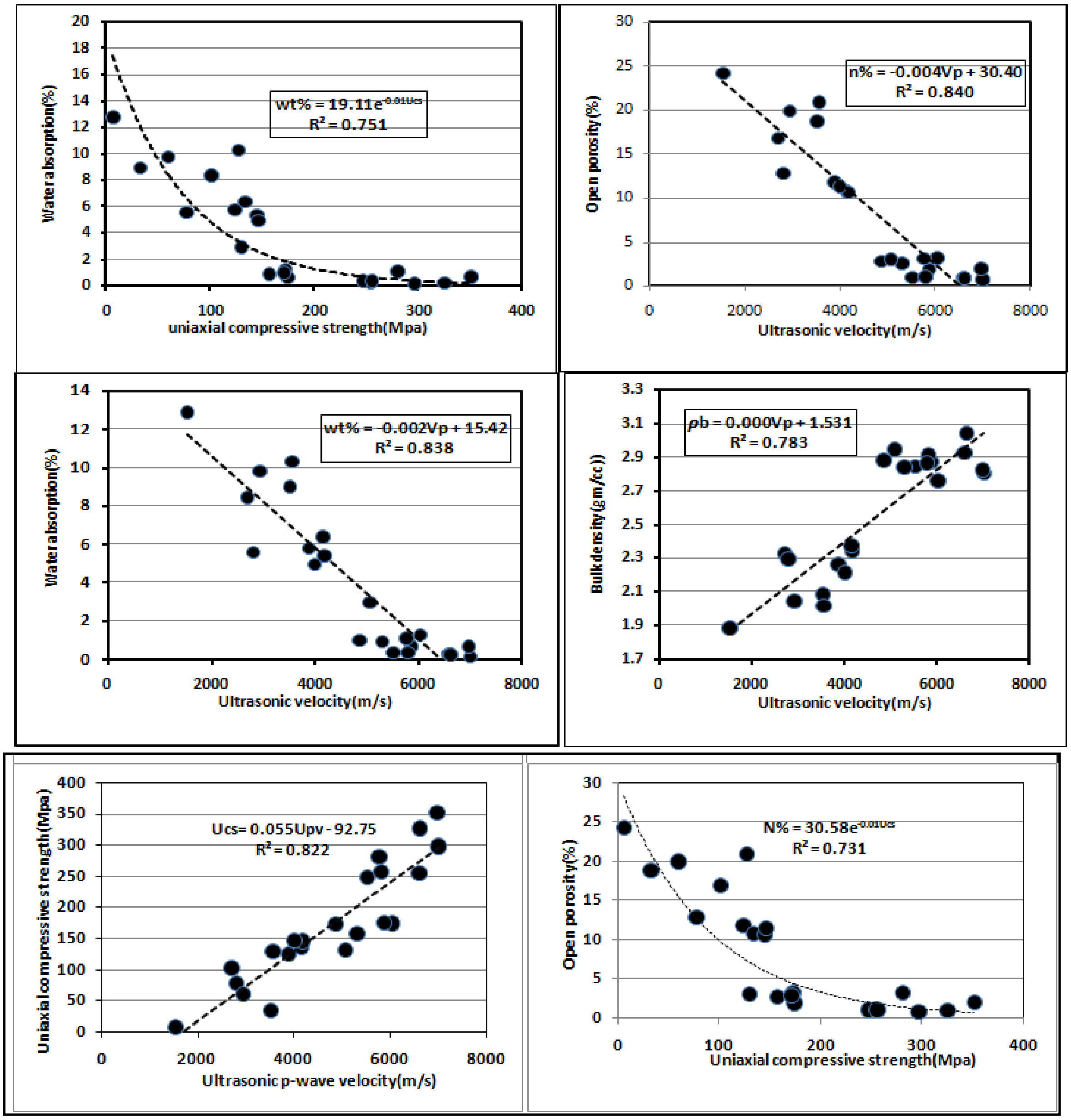

Figure 5-25 Correlation chart between the various physical and mechanical properties

In all the above cases, calculated value of *t*-test is higher than the tabulated value and hence they all have significantly strong correlation among themselves and this may be used for prediction of parameters one from the other as laboratory test expenses are too high and even the availability is far limited like in the project area.

According to literature, the relation between porosity and Uniaxial Compressive Strength was studied by Kossev (1970) and Smorodinov et al. (1970) on quartzitic and magmatic rocks of Egypt. The higher the porosity the lower the strength and both relations are exponential with a correlation factor of around 0.8. The decrease in compressive strength with increasing porosity was also illustrated on limestone of the Nile Valley, Egypt, in an exponential regression (Sayed et al., 1999). The same author demonstrated the positive relation between strength and apparent density, i.e. an increase in the compressive strength shows an increasing in apparent density.

5.4 Anisotropy

Many rocks outcropped on earth's surface show well defined fabric elements in the form of bedding, stratification, foliation, fissuring or jointing. In general, these rocks have properties (physical, dynamic, mechanical, hydraulic) that vary with direction and are said to be inherently *anisotropic*. Anisotropy can be found at different scales in a rock mass ranging from intact specimens to the entire rock mass.

In general, intact rocks are not too strongly anisotropic compared to other engineering materials. Worotnicki (1993) classified anisotropic rocks into four groups:

- Quartzofeldspathic rocks (*e.g.* granites; quartz and arkose sandstones, granulates and gneisses),
- Basic/lithic rocks (*e.g.* basic igneous rocks such as basalt; lithic and greywacke sandstones and amphibolites),
- Pelitic (clay) and pelitic (micas) rocks (e.g. mudstones, slates, phyllites, and schists),
- Carbonate rocks (*e.g.* limestones, marbles and dolomites),

Worotnicki (1993) concluded that quartzofeldspathic and basic/lithic(basalts and pyroclastics) rocks show low degrees of anisotropy ratio less than 1.3 for about 70% of the rock samples analyzed and less than 1.5 in about 80%.

Generally anisotropy is one of the factors that affect the behaviour of rocks. The properties of such rocks vary with direction. In general, rocks have some degrees of anisotropy and isotropic rocks are rarely found in nature (Kwasniewski, 1993). The rock anisotropy is mainly due to the presence of foliation, cleavage, schistosity, joints, micro and macro fissures and bedding plane (Al-Harti, 1998).There are several forms of anisotropy with various degrees of complexity. It is therefore only the simplest form of anisotropy, transverse isotropy, to be considered here. Igneous rocks are more isotropic in nature than sedimentary and metamorphic rocks (Ramamurthy, 1993; Goodman, 1986), whereas metamorphic rocks are mostly anisotropic. Rocks such as slates, shales, phyllites and gneisses have anisotropic behaviour.

5.4.1 Uniaxial compressive strength

Many authors (Goodman, 1986; Sing *et al*., 2001; Ramamurthy, 1993; Ramamurthy *et al*., 1988; as cited in Goshtasbi et al., 2005) have studied the anisotropic behaviour of rocks such as shales, slates, sandstones, gneisses, phyllites, etc. Hence the anisotropy ratio for Uniaxial Compressive Strength may be assessed with the following formula (Singh et al.1989).

$$Rc = \sigma c_{max} / \sigma c_{min} \quad \text{.........} \quad (equ.5\text{-}10)$$

Where ***Rc*** is anisotropy ratio, **σcmax** is maximum strength and **σcmin** is minimum strength.

In view of the above, the samples collected and tested for Uniaxial Compressive Strength were also checked for anisotropy with the above equation. If the value (the ratio) is close to unity it is said quasi-isotropic, and very low or higher than unity indicates anisotropy (ISRM, 1989). With regard to this, out of the total samples tested, 80% of the samples show anisotropy ratio less than 1.1(nearly unity) and only 10% of the samples show slightly higher value than unity (1.1-1.4) and this shows that the rocks in the studied area are quasi-isotropic.

In summary, the anisotropy ratio which is the ratio between the maximum compressive strength to the minimum strength, can directly describe the ratio between the strength of rock materials (intact rock) to the shear strength of the discontinuity. Therefore, the anisotropy ratio increases with either the increase of compressive strength of the intact material or decreases of the shear strength of the discontinuities and vice versa.

5.4.2 Ultrasonic P-wave Velocity

The anisotropy of the P-wave Velocity is computed from the maximum velocity of the sample along the expected flow layering and the minimum velocity, which is to be perpendicular to the assumed flow layering. In the basaltic rock samples identifying flow layering is very difficult as the sample size is very small, but in the pyroclastic/ignimbritic it is relatively possible to identify the lithic layering direction and banding. These values enabled anisotropy coefficient *k* to be determined using the relation by Živor et al. 2011 and Ivankina et al. 2005:

$$K\,\% = [(Vp_{max} - Vp_{min})/Vp_{mean}]*100 \quad \text{.........} \quad (equ.5\text{-}11)$$

Where *Vpmean* is the mean value determined from both velocities *Vpmax* and *Vpmin*. The values of the anisotropy coefficient of longitudinal waves of the samples are practically low (1-10%). The basaltic samples (90%) exhibited very low anisotropy ratio (k%, 0.8-2.7%) while the pyroclastic samples show relatively higher values of anisotropy ratio (k%, 2-10%). However, in both cases, the basaltic and pyroclastic rocks could be regarded as quasi isotropic. This indicates that the laboratory P-wave measurement was least affected by anisotropy because the samples represent intact rock material and hence flow banding or microfractures are less encountered.

5.5 Chemical test results

5.5.1 X-Ray Diffraction (XRD)

Due to some technical problems only few samples were subjected to XRD analysis in Cagliari University and Ethiopian Geological Survey. The analysed samples were prepared from basaltic rocks aiming to reveal deleterious constituents towards concrete mix. In doing so, zeolite and some chalcedony and iron hydro-oxides are detected in the basaltic samples and glassy rhyolites. The zeolite minerals were detected in two samples collected from columnar basalts. The detected zeolite minerals are further identified to be heulandite and laumonite which are both regarded as reactive zeolite species (Figure 5-26), the former with Na^+ cation capable of releasing the cation to the cement paste facilitating Alkali Silica Reactivity to take place and the latter one known for its volume change on wetting and drying.

The XRD analysis also confirmed that the feldspar groups that dominate the Tarmaber formation are “Plagioclase feldspar” or “ Soda-Lime” group comprising of sodium aluminium silicate and calcium aluminium silicate mainly including albite (Na-feldspar), anorthite (Ca-feldspar), with intermediate andesine (Na-Ca feldspar) and labradorite (Na-Ca feldspar). This result is supported by XRF major oxide analysis plotted as K_2O versus Na_2O suggesting the sodium affinity of Tarmaber formation.

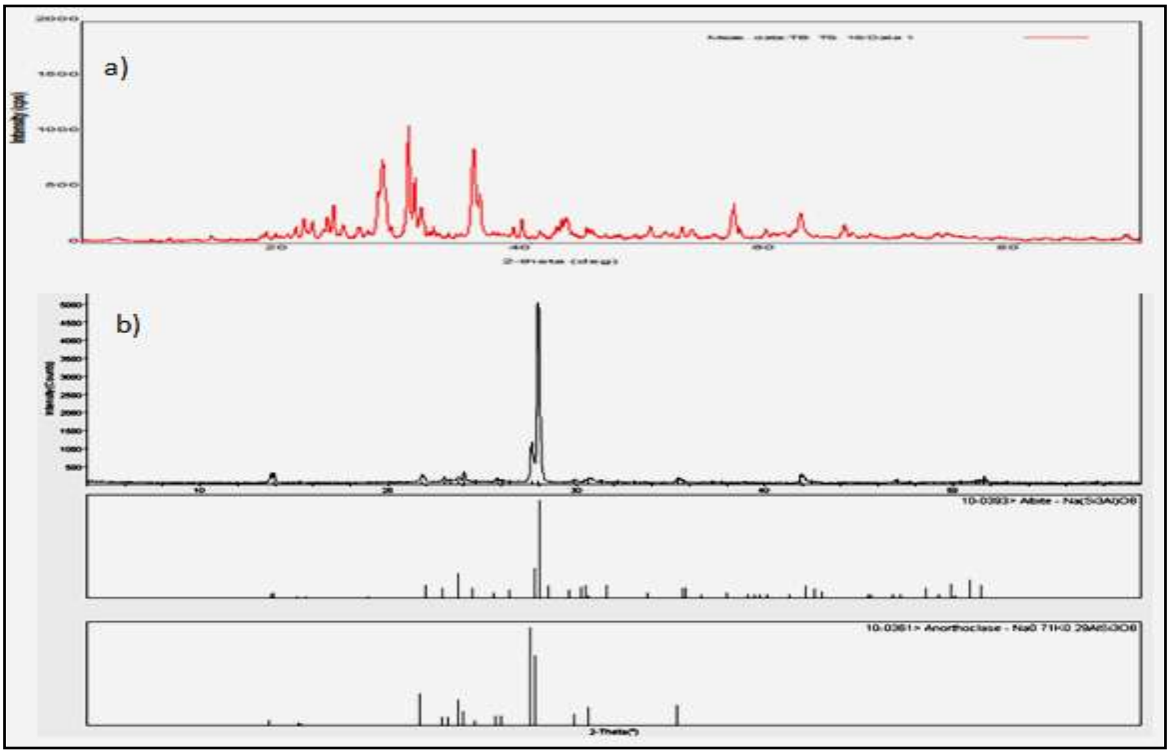

Figure 5-26 XRD pattern of, a) Zeolite from basaltic samples (TB-Ts-16) and, b) Anorthoclase and albite from basaltic sample (TB-Ts-18)

5.6 Durability assessement of the basalts and pyroclastics as dimensionstone

The durability of a stone is the measure of its ability to resist weathering and so to retain its original size, shape, strength and appearance over an extensive period of time (Bell, 1980). It is necessary to recognise that every rock type once put in service will be liable to change in appearance and undergo at least some decays.

Therefore, what is durability? Webster Dictionary defines durable as follows:

Durable: *lasting or enduring: holding out well against wear or any destructive change.* If so, for what period of time must a material or a component last to be considered durable? The period of time will vary depending on the purpose of the building, and is defined as the service life. Hence, the definition of durability becomes: *The ability of a building or any of its components to perform its required functions over the intended period of time (Kuhnel et al., 1994).*

Durability is not an inherent property of a building material or building component in most cases. It relates to the particular use of a material, in a particular environment. A material that is durable in a particular environment may not be durable in a different environment, or for a different use in the same environment. The durability of construction materials is decisive for the lifetime of engineering structures and monuments. It is an erroneous presumption that stone will survive ages. The tendency to degradation is a function of many variables (Kuhnel et al., 1994). The first is the internal variables in the specific rock itself and the second group comprises external conditions to which the rock is exposed. In the destructive action, biota, and, especially micro-organisms join the physical and chemical external forces.

The third group of variables include features induced by handling (mining, transport and processing). Such features are often not considered, powerful blasting and crushing are responsible for generation of inner, sub-microscopic discontinuities (fissures and fractures) that become open in time and enhance the deterioration. It is assumed that the rock in place is in equilibrium with the environment. Extraction and relocations of the rock to a site of utilization initiate accommodation processes begin. The greater the difference between conditions at sites of origin and use, the faster rock degradation proceeds. The physical and chemical stability and reactivity of rock forming phases is the second side of the coin. Therefore, durability is a complex function of internal and external features.

There are several approaches suggested by numerous authors and guidance (BRE, BS, UNIEN, and AASHTO). Within the frame of this thesis, water absorption, porosity, saturation coefficient and compressive strength, petrographic examination, salt crystallization methods are discussed regarding the durability of the building stone/dimension stone. These parameters are interpreted to be an indicator of easily disintegration upon exposure to atmospheric effects. Saturation coefficient (S) of a stone is the ratio between the natural capacity of a stone to absorb water after complete immersion under atmospheric pressure for a definite time, and its total volume of the pores that is accessible to water (Table 5-19). It was first developed as a rapid frost resistance test on the theory that because water expands by approximately 10% on freezing, a stone must have at least 10% of its pore space empty to be able to accommodate the expansion.

Saturation coefficient depends on the pore structure (pore size and pore size distribution). A stone with a very high saturation coefficient may be deteriorated by some alteration processes, for instance the freezing of water.

Sample n.	Water absorption (%)	Open porosity (%)	Saturation Coefficient S	Uniaxial Compressive Strength(MPa)
TB-Cs-1	0.42	1.23	0.34	297
TB-Cs-5	0.89	2.54	0.35	254
TB-TS-10	0.63	1.82	0.35	174
TB-TS-11	0.33	0.95	0.35	247

TB-TS-12	0.66	1.87	0.35	351
TB-Ts-16	0.33	0.8	0.41	256
TB-Ts-21	0.95	2.75	0.35	171
TB-Ts-23	1.08	3.08	0.35	281
TB-Ts-25	0.62	1.75	0.35	130
Average	**0.66**	**1.87**		**240**

Table 5-19 Basaltic samples saturation coefficient

S = (water absorption /effective porosity)

A rock with very high saturation coefficient may be deteriorated by freeze-thaw activity (RILEM, 1980). Therefore, this value is an indicator to evaluate the durability of the stone in freeze-thaw situation. The value of saturation coefficient can mostly vary between 0.4 and 0.95 (BRE, 1983). A saturation coefficient greater than 0.8, indicates low durability “susceptible to frost activity” (Hirschwald in Schaffer, 1972).

S<0.75 weathering and frost resistant

0.75-0.85 moderately resistant

> 0.90 not weathering and frost resistant

However, many stones have saturation coefficients within the range of 0.66 to 0.77. In this range, the saturation coefficient gives an unreliable guide (Anon, 1975). As has been seen above (Table 5-20), the saturation coefficient of the basaltic samples ranges from 0.34 to 0.41 which is very good (high resistance to freeze/thaw), while the pyroclastic/ignimbrite rocks show 0.44 to 0.59, which are a bit higher than the basaltic rocks (Table 5-20). However, still the pyroclastic rocks show weathering and frost resistance.

Sample n.	Water absorption (%)	Open porosity (%)	Saturation Coefficient S	Uniaxial Compressive Strength (MPa)
TB-Cs-2	6.01	13.59	0.44	124
TB-Cs-3	6.37	10.71	0.59	134
TB-Cs-4	8.4	16.75	0.50	101
TB-Cs-8	5.36	10.6	0.51	145
TB-Cs-9	4.92	11.33	0.43	146
Tb-TS-13	12.85	24.13	0.53	7
Tb-TS-14	8.98	18.72	0.48	33
TB-Ts-22	5.56	12.75	0.44	78
TB-Ts-24	10.29	20.81	0.49	111
TB-Ts-26	9.79	19.87	0.49	59
Average	**7.853**	**15.93**		**94**

Table 5-20 Pyroclastic/ignimbritic samples saturation coefficient

To assess durability, Bell (1988) explained that a measurement of porosity does not serve as an adequate indicator of durability, as it does not provide information on the distribution of pores within the stone. For Bell the saturation coefficient, or Hirschwald coefficient, linked with pore size distribution are the main factors required to assess durability. In any case, the saturation coefficients of both the basaltic and pyroclastic rocks are very low, even though the pyroclastic rocks show a bit higher values than the basaltic rocks. However, fine-grained rocks that have over 5% absorbed water are often very susceptible to frost damage, whereas those containing less than 5% are very durable (Bell, 1986).

Even so, building stones that are cut from igneous rocks generally suffer negligible decay in climate changes, some basalt which had smectitic clay within microfractures have proved exceptional in this respect in that they have deteriorated rapidly, crumbling after about 5 years of exposure (Bell, 1986).

In addition to the above mentioned classification, another assessment of durability regarding the strength of the ignimbrites and basaltic rocks depending on various authors is presented in Figure 27 and it is revealed that the average strength value of the basaltic rocks ranging from 130MPa to 351MPa (mean, 249MPa) is in the range corresponding to strong to extremely strong in each of the classification schemes. While the average compressive strength of the ignimbritic samples is 94MPa which corresponds to medium strong to strong in all classification schemes.

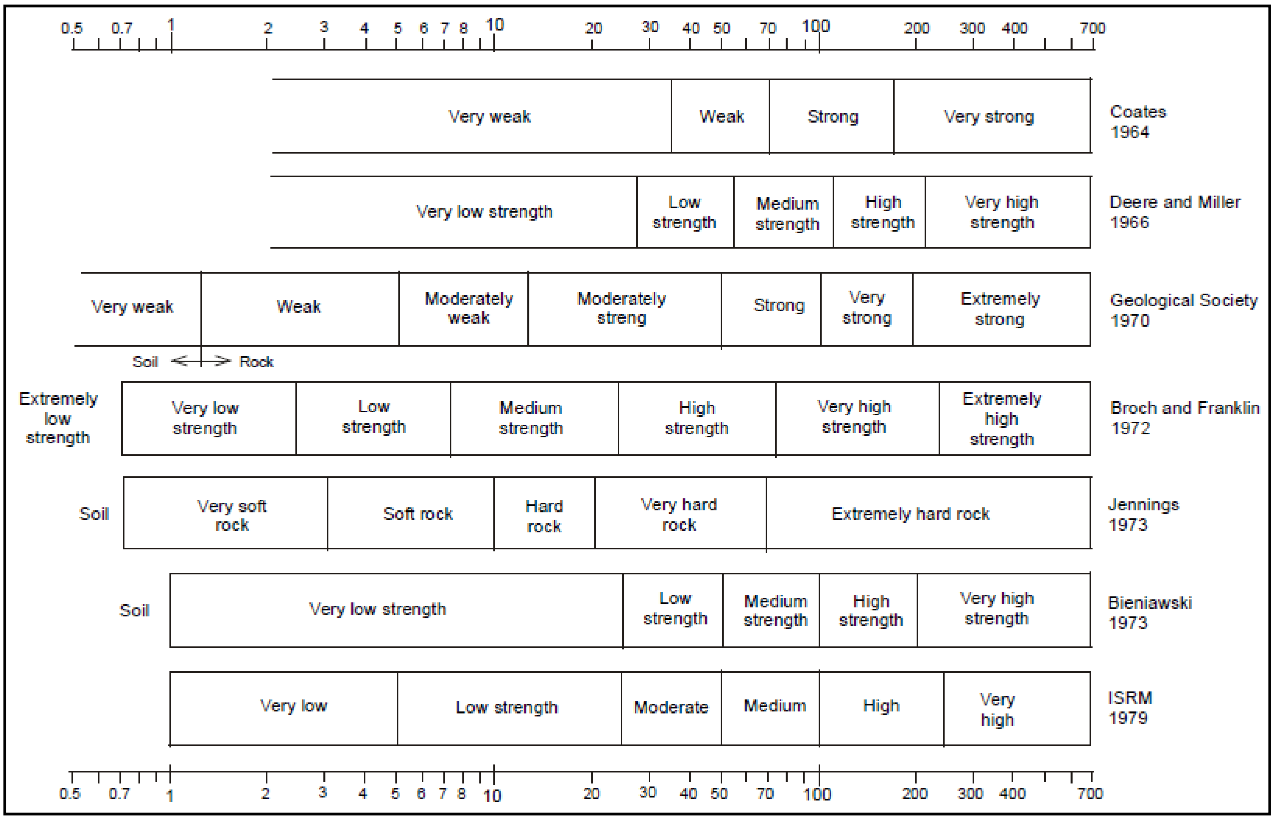

Figure 5-27 *Classifications of rock material strength (from Bieniawski, 1984, as cited in Palmstrom, 1995)*

However, extreme values of properties such as very low relative density and Uniaxial Compressive Strength (such as 1.88 g/cc, 7MPa, of sample TB-Ts-13-pyroclastic layer) or high porosity (such as 24.13 %, TB-Ts-13) give an indication of the sensitivity of this unit and its susceptibility to reduction in its strength and stiffness especially of the pyroclastic rocks.

Petrographic examination

Petrographic examinations could be helpful technique to recognise: the presence of potentially unstable constituents such as zeolite, clay or clay like minerals that may undergo volume changes on wetting and drying and micro-brecciated (fractured) rocks or the presence of particularly weak veins or seams. Petrographic examinations were carried out according to UNIEN 12407: 2000. In anyway, for a proposed building stone a starting point for evaluation of its durability; petrographic examination is paramount important in that it could lead to select which other tests will be relevant to be performed next. The petrographic sampling location and other sample references are shown on Figure 5-28.

The petrographic examination of the pyroclastics/ignimbrites proved the presence of high proportion of volcanic glass, some opaque (Fe-oxide) and microfractures as described above in section 5.2.1.1(Table 5-4). In addition, also the basaltic samples exhibit high abundance of opaque (Fe-oxides) and trace amounts of zeolite but no any clay mineral is seen in all the thin sections.

Salt crystallization

Salt crystallization as durability test especially for a porous building stone, has often been used to assess the susceptibility of the rock to frost action and is somewhat arguable. First of all, according to the Building Research Enterprise (BRE) salt crystallization test is mainly used for selective rocks without any further explanation why other rock types are not tested with it. The durability of the rocks is evaluated by the quantity of the weight loss that occurs after the total number of cycles. In this regard, the salt crystallization test is not useful for the pyroclastics/ignimbrites and basalts as these rocks are with low porosity and high strength.

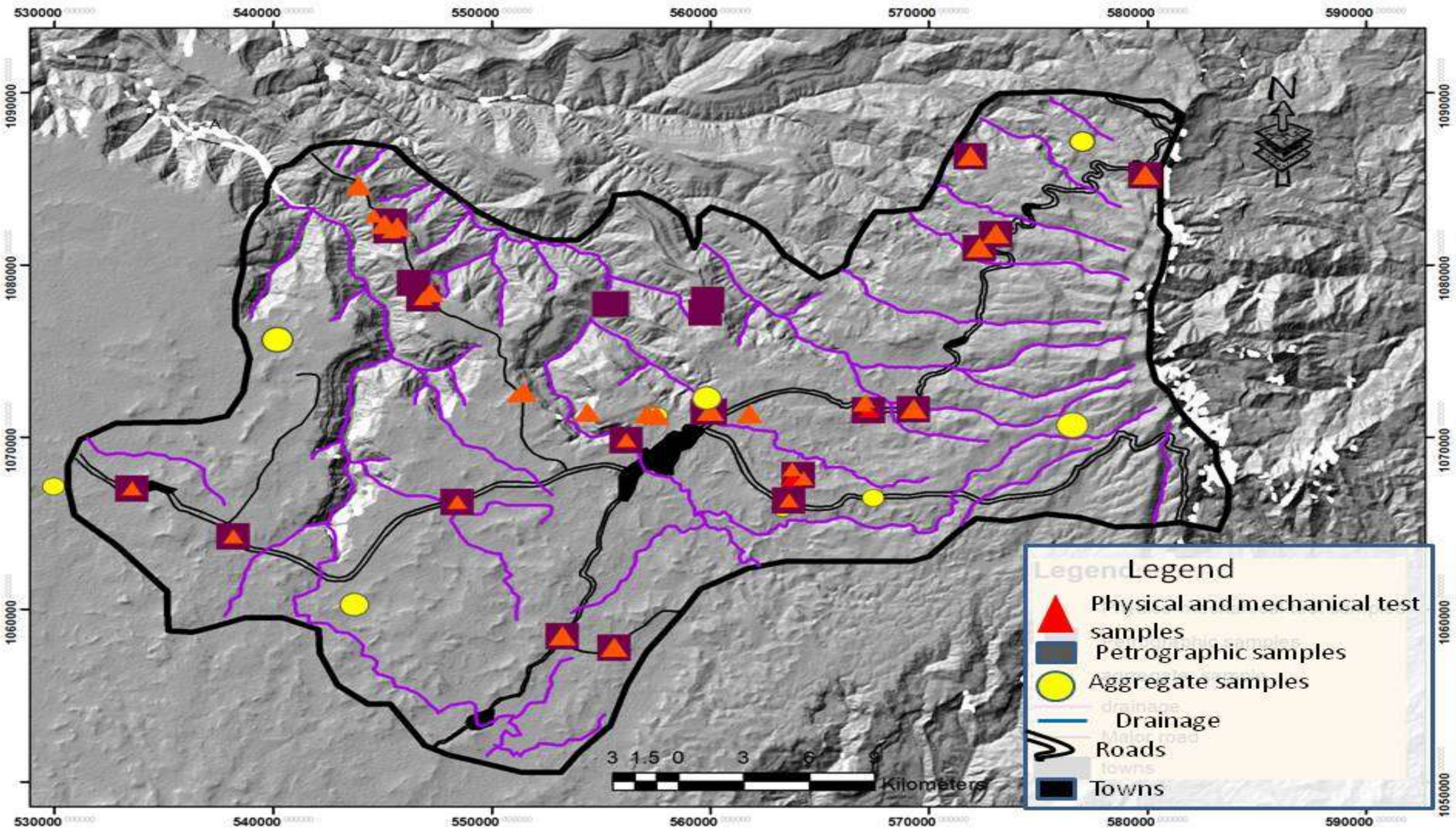

Figure 5-28 Sampling location (UCS,Vp, thin section, aggregate etc) on hill shade basemap

CHAPTER SIX

6. Geoengineering evaluation for crushed coarse aggregate tests and results

6.1 Introduction

The delicate balance between sustainable development and needs of the society for the development of the infrastructure means, among others, a meaningful usage of available natural resources. Infrastructures like roads, railways, and houses, etc. require huge amounts of construction materials. Aggregates are the most widely used geomaterials (25 billion tons exploited annually, USGS, 2010) and represent critical raw materials used in current building sector.

The aggregates used in concrete mix have to meet a number of specifications with regard to mechanical performance, durability, chemical stability, Alkali Silica Reactivity, gradation, shape, surface texture, and the presence of harmful materials. Several standard tests are employed to ensure aggregates qualify those specifications. However, petrographic examination, despite being qualitative in nature, remains the most valuable test for predicting the overall performance of concrete aggregates in any control test, and in service, as well (Be rube, 2001).

Literature review reveals that no attempt has been witnessed in Ethiopia which has shown the evidence of aggregate characterization, technique to achieve this target and mapping of aggregate resources (Karstaedt and Wondafrash, 1986). It is, therefore, crucial that a rigorous effort should be carried out for characterization of aggregates serving the construction industry; by integrating all possible sources affecting their performance in concrete and other related construction materials.

The present study, hence, would not only resolve the issue of regional aggregate resource quality, but would also possess the potential to resolve major drawbacks regarding construction problems arising from aggregates in the construction industry specifically around the study area as a model. Throughout the world, basaltic rocks are used extensively as engineering materials including as aggregates for Portland cement concrete and asphaltic concrete mix, rock fill for dams and breakwaters, material for railroad ballast and highway base courses (Goodman,1993). Barksdale (1991) states that, "rock is broken or crushed when a force is applied with sufficient energy to disrupt internal bonds or planes of weakness that exist within the rock." For quarried aggregates, the crushing process begins with the blast that turns solid rock into particles of a size range that can be accepted by the primary crusher.

Prediction of aggregate characteristics before placement and starting the construction activity can indicate the un-expected happening and can prevent the post construction material problems. In this regard, keeping in view of other construction material requirements, aggregate sampling and testing is a paramount importance to make the construction workable and long-lasting. The construction industry needs to move toward material laboratories in order to ensure quality and establish adequate confidence regarding the material used to satisfy given requirement and quality during the service life. Quality assurance of materials, therefore, as a first step needs testing of materials on the basis of specifications that should ensure and increase the confidence regarding fitness for the purpose of product and services.

Aggregate characterization imply the process of identification of source, evaluation of aggregate properties and designation of material sources so as to generate engineering properties of construction materials that can be utilized for instant reference in construction industry as needed. The essential requirements of an aggregate for concrete are that it remains stable within the concrete in the particular environment throughout the design life of the concrete. In Ethiopia, the assessment of aggregate quality in both new and established aggregate deposits is not generally justified in view of the well established characteristics for most aggregate sources, in most cases; new aggregate sources are opened and used without any characterization. Quality should, nevertheless, be confirmed by independent testing and periodic recheck. The aggregate characterstics which affect the properties of the fresh concrete are those which are under the control of the aggregate product. Properties such as the particle size and shape are influenced by selective crushing and the use of the appropriate type of crusher for the particular rock type. In addition, it should be free from fines and clay to reduce the water requirement of the produced concrete structure.

The preliminary need of the aggregates is its inherent durability against natural and man created disturbances. The aggregate provide volume, stability, resistance to weathering and other physical properties to the building and road structures. There are common issues in construction related to characteristic of material such as; suitable aggregate gradation, shape, density and source. Deterioration of construction aggregates loses the durability requirement and progressive performance of structure.

Concrete may be defined as a mixture of water, cement or binder, and aggregate, where the water and cement or binder forms the paste and the aggregate forms as inert filler. In absolute volume terms the aggregate amounts to 65-75% of the volume of concrete and is, therefore, the major constituent (Figure 6-1). The aggregate type and volume influences the properties of concrete, its mix proportions and its economy. So, characterization of aggregate source/parent rocks is a prerequisite before starting production from any deposit.

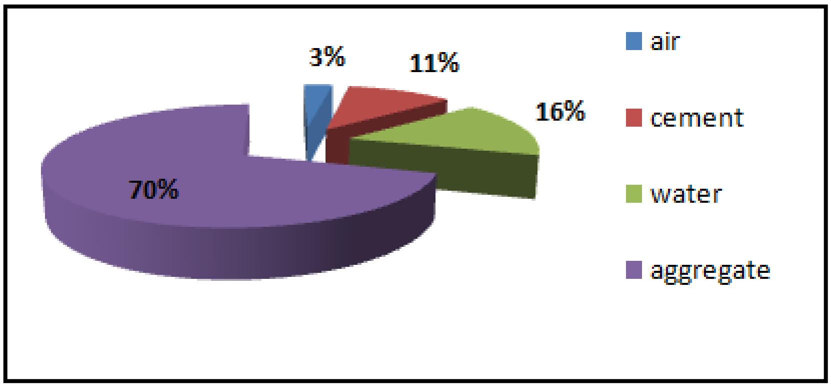

Figure 6-1 Concrete ingredients by volume

The performance of aggregates depends on a number of factors (Smith and Collis, 1993; Fookes et al., 1988; Kandhal et al., 2000; Neville, 2000) that can be evaluated by appropriate aggregate tests indicated in published literatures on road and building codes to assure quality. The engineering properties of aggregates are directly related to the performance of mortar, concrete and unbound and bound pavement (Smith and Collis, 1993; Neville, 1993). Durable and strong aggregates are normally preferred because they can resist abrasion and disintegration, make an excellent bond with cementing materials, are resistant to rapid impacts and are sound (BS: 812).

Therefore, this chapter deals with the engineering properties of crushed rock aggregates and data represented here are related to the samples collected from quarries and natural outcrops from the studied area.

The sets of engineering tests for evaluation of aggregate in relation to its behaviour in asphalt and cement concrete mix could be identified and conducted according to UNIEN, AASHTO, ASTM and BS standards (Dhir et al., 1971; Akbulut et al., 2006). The list of selected tests for the current study are: Flakiness Index; Elongation Index; Los Angeles Abrasion Value (LAAV), Specific gravity and Water absorption; Bulk density, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Alkali Silica Reactivity (ASR), Ten Percent Fines Value (TFV), Sodium Sulphate Soundness Value (SSSV), Water soluble chloride and Water

soluble sulphate to mention some. The samples utilized for conducting these tests, however, remained confined to crushed aggregates obtained from existing quarries and outcrops.
The physical and mechanical properties like specific gravity, Porosity, Thermal behaviour, Compressive strength, Tensile strength, and the chemical properties of an aggregate are attributed to the parent material. The shape, size and surface texture which are essential for concrete workability and bond characteristics between the aggregate and cement paste are, however, attributes of the mode of production and nature of the parent rock. The strength and durability parameters of the produced concrete structure may also be affected by any change in the water demand during production. The aggregate producer, however, usually have little control over aggregate properties such as strength, particle density and water absorption although these on occasions may be of some importance and be limited in concrete structure specifications. In general, processing may have some effect but, most of these properties remain essentially the same as the parent rock (Smith and Collins, 1986).

It is, therefore, essential to understand the mechanical, physical and chemical properties of aggregate and its modes of production in an effort to produce the required quality of concrete. The studied basalt samples were broken into smaller pieces by hammer. Standard (10-14 mm) and nominal (6.3-10 mm) size aggregate fractions were prepared from the smaller pieces using a laboratory mini jaw crusher. The aggregate tests undertaken included Percentage of fines, Flakiness index and Elongation index, Specific gravity, potential Alkali Silica Reactivity (ASR), Water absorption, Uncompacted bulk density, Aggregate Impact Value, Aggregate Crushing Value, Los Angeles Abrasion Value, Na_2SO_4 Soundness Value, Water soluble Chloride content and Water soluble Sulphate content. These tests were performed in accordance with AASHTO, ASTM and BS Standards. Each test was performed at least two or three times.

The samples were numbered by using prefixes "**TB-TS**"- for Tarmaber basalt-intact rock samples and '**TB-AG'**-for Tarmaber basalt-aggregates.

6.2 Engineering Properties of Aggregates

The performance of aggregates in concrete depends on their mineralogical and petrographic characteristics. Before concrete is produced and through its service life, aggregates may be exposed to mechanical, physical, and chemical stresses, which they must resist. They have then to satisfy a number of specifications, with standard tests used to control compliance.

In service behaviour of natural aggregates depends on different characteristics (BS: 812) and published literature indicates that a wide range of tests have been devised to describe the materials and determine their potential value (Smith and Collis, 1993; Neville, 2000) as construction materials. These tests are assumed to predict the future in service performance of the aggregates. Most require some physical or mechanical attribute of the material, while a few investigates particular chemical characteristics (BS: 812). The aggregate quality is determined by its physical, mechanical and chemical properties or overall combination of these three parameters. In cement and asphalt concrete, petrographic analysis of aggregates is to determine its behaviour in different environmental conditions (Neville, 1995). Following its engineering properties based on physical, mechanical and chemical tests are performed to predict the expected behaviour of various basaltic units identified in the study area. All the test results are shown in Table 6-3 and compared to the different specifications.

6.2.1 Physical properties of aggregates

The physical properties of aggregates stem from the inherent properties of the parent rock and predict as to how an aggregate would perform in construction. The commonly measured physical/mechanical aggregate properties (BS: 812; Smith and Collis, 1999) are surface texture, toughness, abrasion resistance, durability and soundness, particle shape, cleanliness and deleterious materials and specific gravity. Toughness and wearing resistance is determined by Los Angeles abrasion, Aggregate Crushing, Aggregate Impact and Soundness tests.

6.2.1.1 Flakiness index and Elongation index

The shape of aggregate is an important characteristic since it affects the workability of concrete. The shape of the aggregate is partly very much influenced by the type of crusher and the reduction ratio, i.e., the ratio of the size of material fed into crusher to the size of the finished product (Shetty, 1982). Particle shape and size distribution influence the water content necessary to obtain a mix of suitable resistance, and then by affecting the compressive strength, drying shrinkage and durability of the resulting concrete.

During aggregate production, the rock breaks into an assemblage of particles of different shapes, of which four categories are identified in BS specifications: cuboidal, elongate, flaky and flaky-elongated. A flaky particle is one in which the smallest dimension is a maximum of 0.6 times the mean sieve size. An elongated particle is one whose maximum dimension is greater than 1.8 times its mean dimension (BS 812: Part 105-1). The flakiness and elongation indices were determined according to the procedures given by BS 812: Part 105-1-2. The results are given in Table 6-1. As it has been seen in this table, the Flakiness index and Elongation index of the basalt aggregate ranges from 15% to 43% and 15% and 38% respectively. The maximum and minimum Flakiness index values are obtained from TB-AG-10 and TB-AG-01, respectively. The Elongation index is highest for TB-AG-03 and lowest for TB-AG-02 (Table 6-1 and Figure 6-2).

The presence of flaky and elongated aggregate particles beyond specified limits increases the degradation of mixes (Britton, 1968). Flaky and elongated aggregate particles may break during construction and under traffic load.

Sample N.	Flakiness Index (%)	Elongation Index (%)	Remarks
TB-AG-01	15	21	
TB-AG-02	23	15	
TB-AG-03	37	38	Glassy rhyolite
TB-AG-04	22	19	
AG-05	24	16	
AG-06	27	23	
AG-07	27	25	
AG-08	-	-	Not done
AG-09	21	19	
AG-10	43	36	Glassy rhyolite
AG-11	29	25	

Table 6-1 The Flakiness and elongation index values of the tested samples

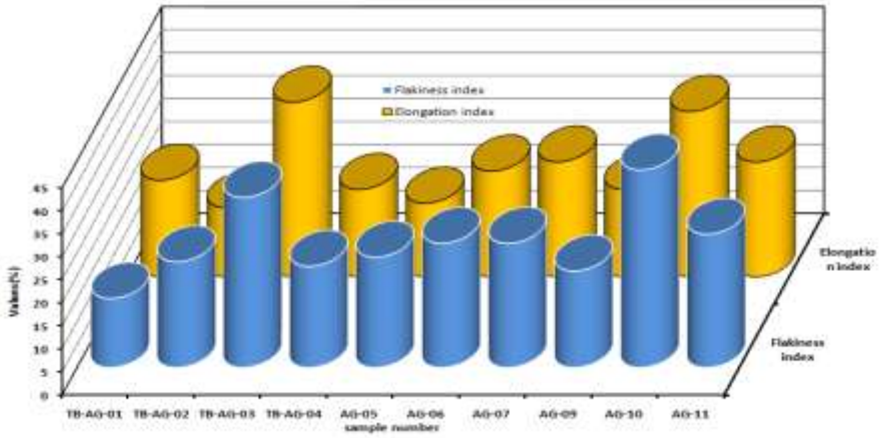

Figure 6-2 Graph showing the Flakiness and Elongation index

6.2.1.2 Specific gravity (relative density), water absorption and bulk density

There is generally a direct positive relationship between high specific gravity and high strength of aggregates (Kandhal and Lee, 1970; Neville, 1973, 2000).

The specific gravity of the basaltic units was determined using AASHTO: T-85 standards and the value ranges from 2.61 to 3.0. The plagioclase phyric basalt yields the highest specific gravity due to massive and compact nature as well as the presence of magnetite/ilmenite. The results are shown in Table 6-2. This property, according to ASTM: C29 and 127, AASHTO: T-85 standards give an idea of strength of rocks.

Water absorption is an indirect measure of the permeability of an aggregate, which, in turn can relate to other physical characteristics such as mechanical strength, shrinkage and to its general durability potential (Collis and Fox, 1985). It could be also related to mechanical strength, soundness and durability (Smith and Collis, 1993; Neville, 2000). Aggregate having high water absorption are more porous in nature and are generally considered unsuitable unless they are found to be acceptable based on other properties such as strength, impact and hardness tests (Schmidt and Graf, 1972). A study conducted in 1995 by Pigeon and Pleau suggested that a limit of 2 percent be placed on the water absorption of coarse aggregates to prevent freezing and thawing damage from occurring.

In general, less absorptive aggregates often tend to be more resistant to mechanical forces and to weathering. Low absorption value might reasonably be considered as less than 1% and it is imperative to clarify that water absorption limits should not be imposed unless it has been established, for a particular material that it relates closely to some other undesirable property. Although an aggregate may satisfy water absorption limit there is no guarantee that problems with concrete will not occur (Smith and Collis, 1993). However, BS 812: and ASTM C127, C128, state that the upper limit for concrete aggregate water absorption should not be greater than two percent (<2-2.5%).

Limits on aggregate water absorption values have also been suggested to identify low shrinkage aggregates, 0.5 and 1.5% for fine and coarse aggregates, respectively (Barbaei and Purvis, 1994). The currently studied samples water absorption values ranges from 0.6% to 2.3% (Table 6-2). The minimum value of the water absorption was determined in the basanitic/aphyric and massive basalt rocks which are dense and fine-grained (0.6%) while the maximum water absorption is measured from glassy rhyolite (2.3%). All the basaltic samples water absorption is below 2% with the exception of one sample (Figure 6-2).

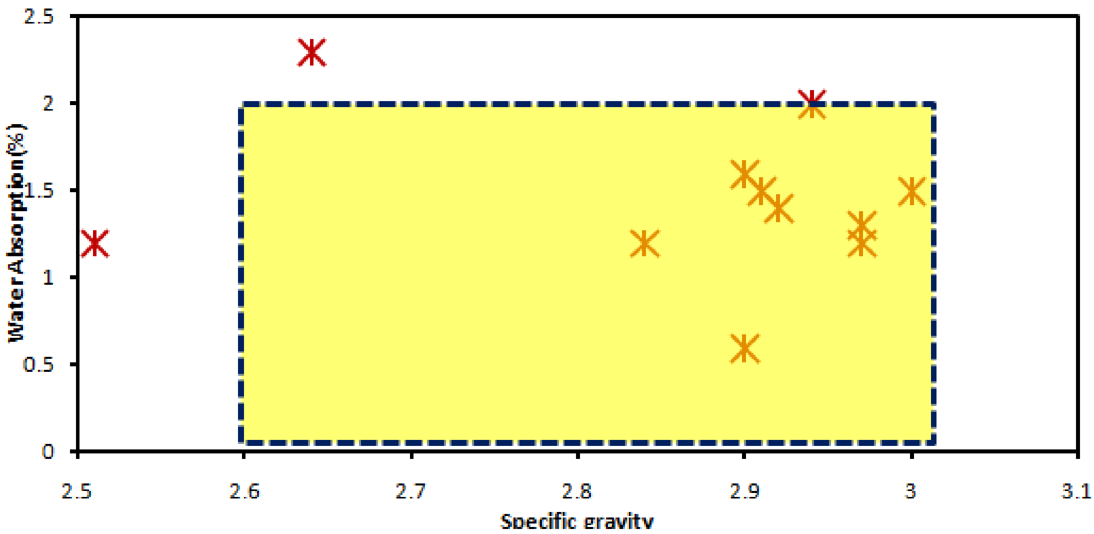

Figure 6-3 Water absorption (%) versus specific gravity

As shown in the above graph, except two samples, the rest samples fall within the acceptable limit marked by the dashed blue line rectangle according to ASTM: C29 and 127, AASHTO: T-85, BS : 812 standards.

It should be noted that if the aggregates are dry, they absorb water from the mixing water and thus affect the workability and, on the other hand, if the aggregates contain surface moisture they contribute extra water to the mix and thereby increase the water/cement ratio. Both these conditions are harmful for the quality of concrete. In making quality concrete, it is very essential that corrective measures should be taken both for absorption and free moisture so that the water/cement ratio is kept as exactly as per the design (Shetty, 1982, as cited in Denamo, 1995). Therefore, in calculating or measuring quantities for concrete mix it is important to know the state at which the aggregate is used (Abayneh, 1992, as cited in Denamo, 1995).

Some aggregates are porous and absorptive. Porosity and absorption of aggregate will affect the water/cement ratio and hence the workability of concrete. The porosity of aggregate will also affect the durability of concrete when the concrete is subjected to freezing and thawing and also when the concrete is subjected to chemically aggressive liquids (Shetty, 1982).

Sample Number	Specific gravity	Water absorption (%)	Uncompacted bulk density(kg/m^3)
TB-AG-01	2.91	1.5	1449
TB-AG-02	2.90	0.6	1449
Tb-AG-03	2.51	1.2	1347
TB-AG-04	3.00	1.5	1549
AG-05	2.84	1.2	-
AG-06	2.94	2	-
AG-07	2.97	1.3	-
AG-08	2.64	2.3	-
AG-09	2.92	1.4	-
AG-10	2.90	1.6	-
AG-11	2.97	1.2	-

Table 6-2 Laboratory test results of specific gravity and water absorption of the studied samples

The uncompacted bulk densities of the basalt aggregate were also determined in accordance with AASHTO: T-19. Uncompacted bulk density ranges from 1347kg/m^3 to1549kg/m^3. The basalt belonging to the olivine phyric uppermost layer shows the highest value while TB-AG-03 which is glassy rhyolite has shown the lowest value (Table 6-2 and Figure 6-3). The bulk density of an aggregate also takes into account the effects of voids present in the aggregate at a given degree of compaction (Waqa, 2004).

Tests	Sample number											Standards used for evaluation (ASTM, UNIEN, AASHTO and BS)
	TB-AG-01	TB-AG-02	TB-AG-03	TB-AG-04	AG-05	AG-06	AG-07	AG-08	AG-09	AG-10	AG-11	
Los Angeles Abrasion test	17%	15%	30%	16%	18%	16%	19%	12%	16%	16%	16%	<35%, UNI EN 12620: 1998
Aggregate crushing value	20%	22%	36%	21%	15%	14%	15%	10%	18%	17%	14%	<25%, (BS 812:part 110:1990
Aggregate impact value	18%	17%	32%	19%	14%	14%	14%	15%	15%	13%	15%	<25%, BS 812: Part 112:1990
Ten percent fine value	200KN	180KN	110KN	190KN	ND	ND	ND	ND	ND	ND	ND	>160KN, BS 812: 1990
Sodium sulphate soundness test	1%	1%	2%	3%	1%	1%	1%	10%	2%	1%	1%	<10% for general purpose , *ASTM C-88*
Water absorption	1.5%	0.6%	1.2%	1.5%	1.2 %	2%	1.3%	2.3%	1.4%	1.2%	1.6%	<2% BS 812: ASTM C127,128
Bulk density	1449kg/m3	1449kg/m3	1347kg/m3	1549kg/m3	ND	ND	ND	ND	ND	ND	ND	1200-1800kg/m^3, BS 812 : Part 1 (1975)
Specific gravity	2.91	2.9	2.51	3	2.84	2.94	2.97	2.64	2.92	2.90	2.97	>2.61, BS : 812
Flakiness index	15%	23%	37%	22%	24%	27%	27%	ND	21%	43%	29%	<25 % BS 812: Part 105
Elongation index	21%	15%	38%	19%	16	23	25	ND	19	36	25	<25% for general purpose, BS 812: Part 105
Water soluble chloride	69ppm	79 ppm	125 ppm	79 ppm	ND							<400 PPM, BS 812, Part 117
Water soluble sulphate	41 ppm	25 ppm	41 ppm	27 ppm	ND							<3000PPM, BS 812, part 118

Table 6-3 Test results as compared with standard specifications

6.2.2 Mechanical properties

The mechanical tests provide parameters for strength and durability of rock aggregates (Aitcin and Mehta, 1990; Neville, 2006). The available standards (BS, ASTM, AASHTO, and UNIEN) require that the rock aggregate should not disintegrate during mixing or compaction. In the present study, strength and durability of the basaltic aggregates were tested (Table 6-4) through the procedures and limits defined by the parameter such as Aggregate Impact Value (AIV), Aggregate Crushing Value (ACV), Los Angeles Abrasion Value (LAAV), Ten Percent Fines Value (TFV) and Soundness test by Sodium Sulphate Soundness Value (SSSV) to mention a few.

Sample N.	Los Angeles Abrasion Value (LAAV)	Aggregate Crushing Value (ACV)	Aggregate Impact Value (AIV)
TB-AG-01	17	20	18
TB-AG-02	15	22	17
TB-AG-03	30	36	32
TB-AG-04	16	21	19
AG-05	18	15	14
AG-06	16	14	14
AG-07	19	15	14
AG-08	12	10	15
AG-09	16	18	15
AG-10	16	17	13
AG-11	16	14	15

Table 6-4 Laboratory values of mechanical properties of the tested aggregates (LAAV, ACV and AIV)

6.2.2.1 Strength

Aggregate strength needs to be assessed for aggregates that are to be used in high strength concrete, but not for normal strength due to the fact that the strength of concrete is generally controlled by the strength of the hydrated cement matrix rather than the aggregate in normal strength concretes. There are currently no AASHTO or ASTM testing methods to determine aggregate strength directly. However, the British Aggregate Crushing Value test has been used extensively to determine the relative strength of graded concrete aggregates. This test consists of applying a load to an aggregate sample in a steel cylinder for 10 minutes. After the 10 minute loading period the sample is analyzed for changes in gradation and a value is determined. Although the aggregate crushing value test may provide insight into the strength of the aggregate it may not always reflect the strength of the concrete in which the aggregate is placed. The aggregate impact value and the aggregate crushing value tests do not measure strength in the sense of compressive strength in intact rocks; rather they are indices of the resistance to pulverisation over a prescribed interval or sequence of loading (Collis and Fox, 1985).

When cement paste of good quality is provided and its bond with the aggregate is satisfactory, then the mechanical properties of the rock or aggregate will influence the strength of the concrete. Therefore, it can be concluded that while strong aggregates cannot make strong concrete, for making strong concrete, strong aggregates are essential requirement (Shetty, 1982). Assessment of strength of the aggregate is made by using a sample of bulk aggregate in a standardized manner. This test is known as Aggregate *Crushing Value test*. Aggregate Crushing Value gives a relative measure of the resistance of an aggregate sample to crushing under gradually applied compressive load (Shetty, 1982).
During strength evaluation of the Tarmaber basalts, all the various subunits are considered for the test. The strength evaluation considers both Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) and also the Uniaxial Compressive Strength. In general, these properties normally depend on the inherent properties in particular and on the particle shape (flakiness index) of the parent rocks (Monteiro, 1993).

Aggregate Impact Value and Aggregate Crushing Value

Toughness is the property of aggregates to resist impact against moving loads. These tests are included in British Standards for measurement of the mechanical properties of crushed rock aggregates, including the Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) tests (BS 812: Part 112 and BS 812: Part 110), respectively. The Aggregate Impact Value test was stated to have the following advantages: it requires a small sample; it requires less expensive portable equipment; and samples may be tested in a wet condition (Kandhal, 1998).

As it has been seen in Figure 6-4, the Aggregate Crushing Value and the Aggregate Impact Value show a linear relationship (with R^2=0.85) indicating these properties are important mechanical properties of the aggregate characterization as far as this study is concerned. Furthermore, except a single sample, the rest samples fall within the range specified by BS 812: Part 112 and BS 812: Part 110, as marked by blue broken line rectangle.

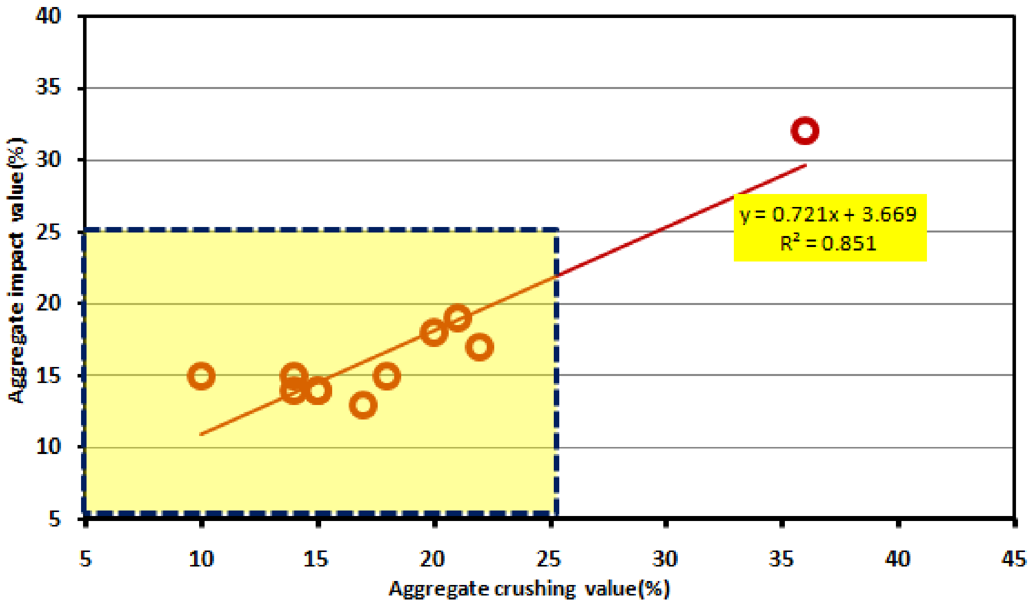

Figure 6-4 Aggregate impact value versus aggregate crushing value (%)

Apart from testing aggregate with respect to its crushing value and impact resistance, testing the aggregate with respect to its resistance to wear is an important test for aggregate to be used for road constructions, ware house floors and pavement constructions.

In these tests, samples ranging in size from 10 to 14 mm are subjected to shock and static load. The proportion of material passing BS 2.36mm sieve after loading is calculated as a percentage of the original sample weight, and expressed as the aggregate impact and aggregate crushing values for shock and static loading, respectively.

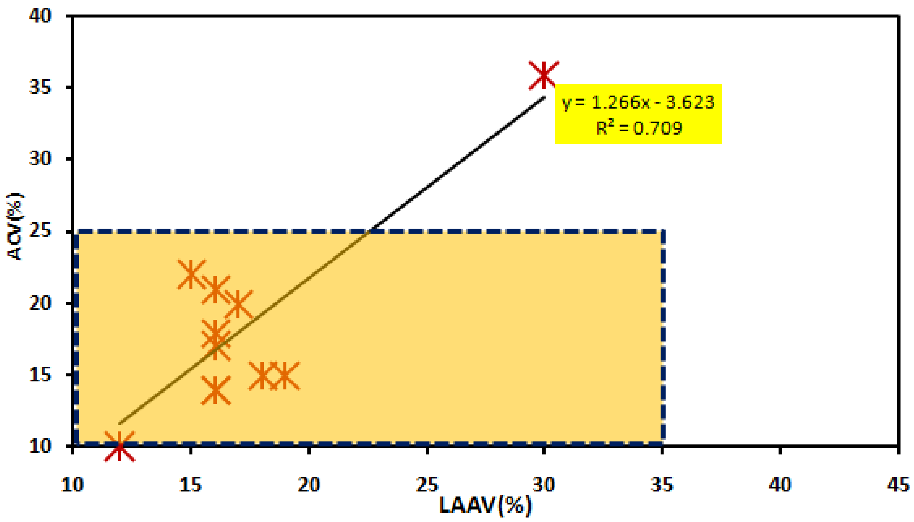

Figure 6-5 LAAV (loss %) versus ACV (%), samples falling in the accepted limits

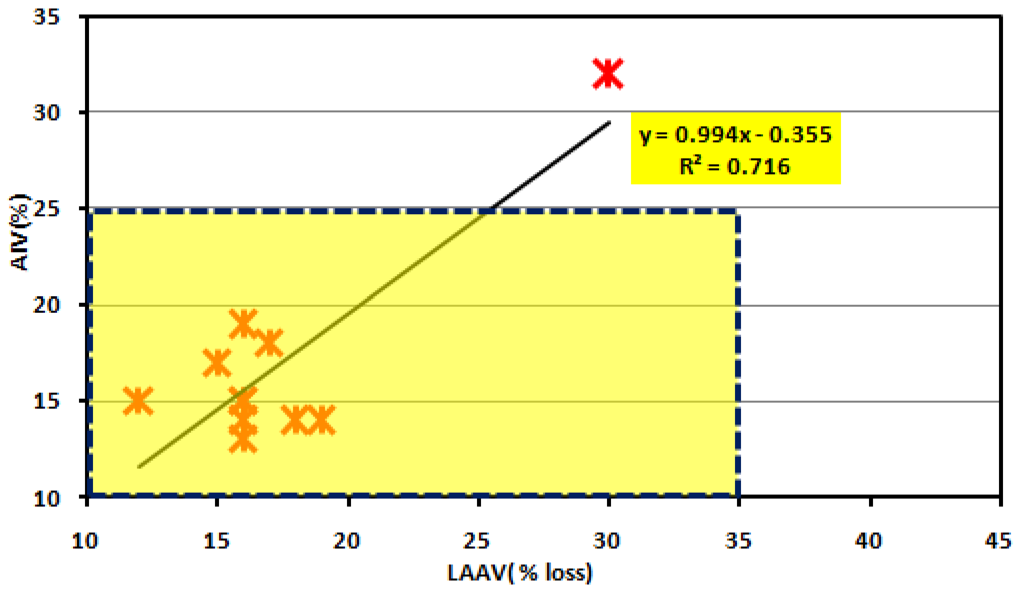

Figure 6-6 LAAV (% loss) versus AIV (%)

In the current study, the Aggregate Crushing Value ranges from 10% to 36% while the aggregate impact value ranges from 13% to 32%. The samples collected from the basanitic basalt and phyric basalt which are dense and fine-grained show the highest strength both in terms of aggregate impact and crushing values. The olivine phyric basalts and rhyolitic glass show the lowest strength (Table 6-4 and Figure 6-5). As depicted in Figure 6-5, the graph presents the relationship between Los Angeles Abrasion and Aggregate Crushing Values. The dashed blue line rectangle represents the range for which all Los Angeles abrasion values will lie for Aggregate Crushing Value of less than 25% and Figure 6-6 represents Los Angeles abrasion value versus Aggregate Impact Value and the dashed broken line rectangle shows those samples which fulfill the two specifications. In this regard, the aggregate crushing and impact values; the lower the value the better the strength and the higher the value the weak is the aggregate. Therefore, almost all the samples satisfy BS 812:1990 specifications to be used as aggregate for concrete mix except a single sample (TB-AG-03) as far as LAAV is concerned. Various authors refer to a positive correlation between the Los Angeles Abrasion and both Aggregate Crushing Value and Aggregate Impact Value, i.e., good correlation as shown in Figure 6-4 and proposed the use of only one method to determine the abrasion and impact resistance of aggregates, i.e., by Los Angeles method. The three tests LAAV, ACV and AIV are shown with a bar graph to see the ACV and AIV for the different rock type aggregates (Figure 6-7).

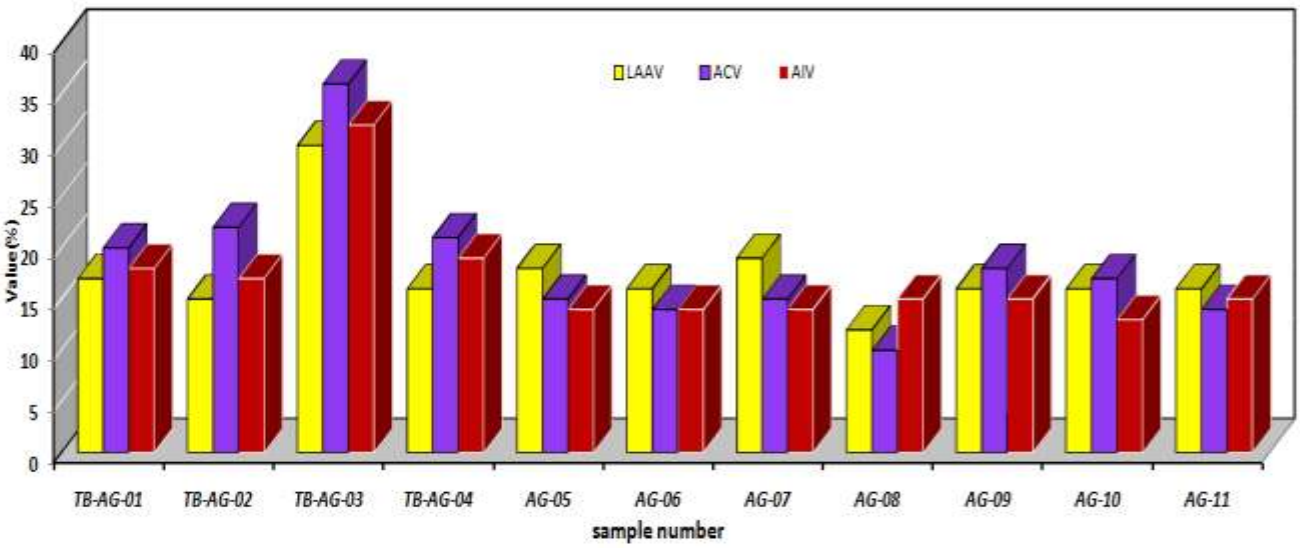

Figure 6-7 ACV, AIV and LAAV of the Tarmaber basalt test results

6.2.2.2 Durability of aggregates

Since aggregates make up the bulk of concrete, any lack of durability of the aggregate will have disastrous consequences for the concrete. If there are durability problems, special screening tests may be required, routinely to avoid problematic aggregates, or special measures must be taken to counteract the effects of undesirable aggregates. The latter approach will become more important in the future as deposits of high-quality aggregates are worked out and more marginal material is brought into use (Sidney and Young, 1981). Aggregates should be hard and should not contain materials that are likely to decompose or change in volume when exposed to extreme weather conditions. Examples of undesirable materials are lignite or coal, pyrite and lumps of clay.

The resistance to wear or decay defines durability of the material that is an important requirement of rock aggregates (Fookes and Collis, 1975). Similarly, the aggregate may be resistant to weathering conditions (Fookes et al., 1988). Durability tests are defined for this research work in terms of Los Angeles Abrasion value (LAAV) and Sodium Sulphate Soundness Value, and Uniaxial Compressive Strength, secondary mineral index and petrographic weathering index of the aggregate source rocks.

Los Angeles Abrasion Value (LAAV) and Sodium Sulphate Soundness Value (SSSV)

The abrasion resistance of an aggregate can be tested using the Los Angeles abrasion machine where the aggregates are rotated with steel balls in a drum and the mass loss is measured after a given time (Waqa, 2004). The test consists of placing an aggregate sample in a steel drum along with 6-12 steel spheres weighing approximately 420 g each. The steel drum is then rotated for 500 revolutions. A steel shelf within the drum lifts and drops the aggregate and steel spheres with each revolution. Following the completion of the 500 revolutions the resulting sample is dry sieved to determine the amount of degradation that occurred during the test. The overall stability of concrete aggregates may be defined as the ability of individual particles to retain their integrity and not to suffer any physical, mechanical and chemical changes, which could adversely affect the properties or performance of concrete in either engineering or aesthetic respects (Collis and Fox, 1985).

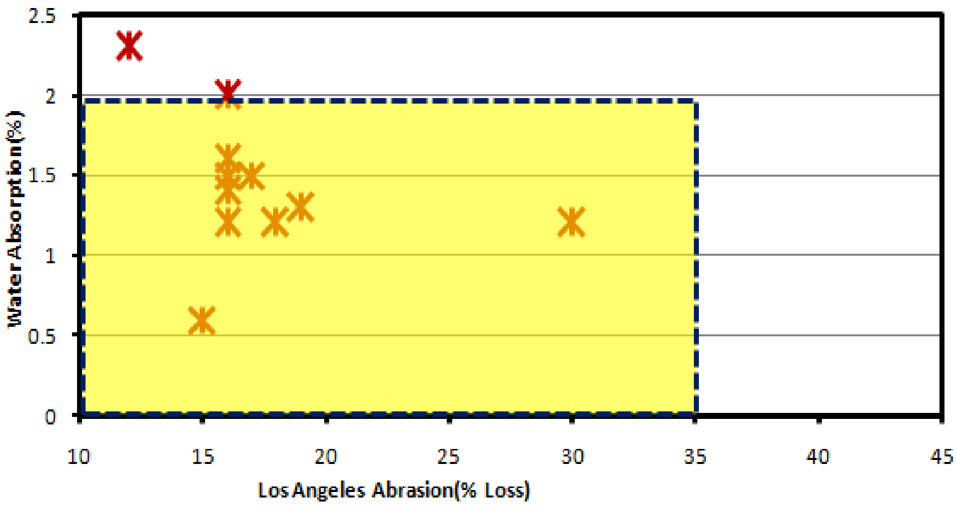

Figure 6-8 Water absorption (%) versus Los Angeles Abrasion Value (% loss)

As depicted in Figure 6-8, the graph presents the relationship between L.A. Abrasion and water absorption. The dashed blue line rectangle represents the range for which all L.A. Abrasion Values (35%) will lie for water absorption of less than 2%.

As demonstrated, aggregate with absorption value of less than 2% have a L.A. Abrasion Value of less than 30%, which is substantially lower than the 35% loss failure criterion used by AASHTO: T-96 and AASHTO: T-104, respectively.

Some aggregates with satisfactory values from the standard strength tests deteriorate with time. Thus, LAAV test is a measure of degradation of mineral aggregates of standard gradings resulting from a combination of actions including abrasion, impact and grinding in a rotating steel drum containing the prescribed numbers of steel balls. The test has been widely used as an indicator of the relative quality of competence of various sources of aggregates. The test can only be used with coarse, dry aggregate. Unsounded aggregates are those that show significant volume changes, resulting in the deterioration of concrete when subjected to different environmental conditions (Waqa, 2004). On the other hand, to be able to resist abrasion, an aggregate has to be hard, dense, strong and free from soft particles.

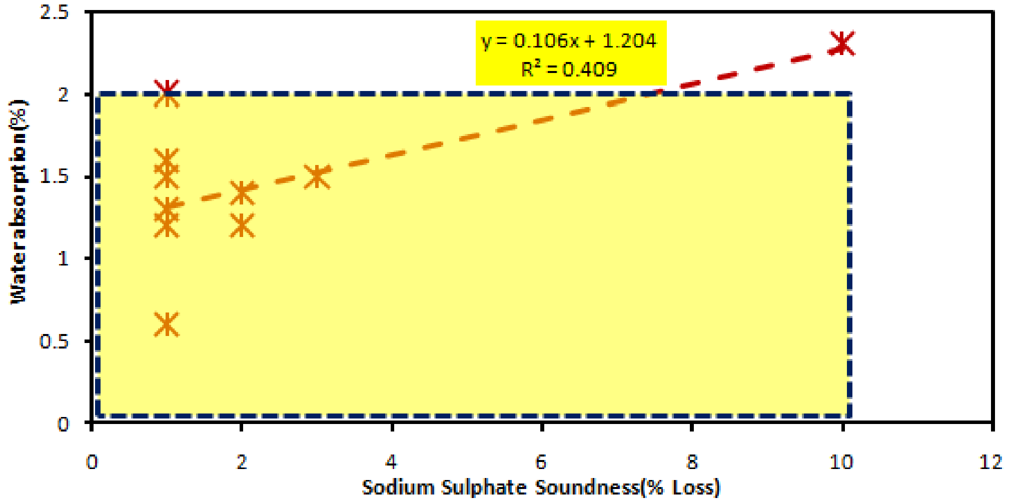

Figure 6-9 water absorption versus sodium sulphate soundness value (% loss)

The graph on Figure 6-9 shows that almost all the studied samples tested for water absorption and Sodium sulphate soundness fall in the specified range marked by broken line rectangle according to AASHTO: T-104.

The LAAV and Sodium Sulphate Soundness of aggregates were determined on the Tarmaber basaltic aggregate samples according to AASHTO: T-96 and AASHTO: T-104 respectively. The data are shown in Table 6-5 for these parameters.

Sample N.	***LAAV (%)***	***SSSV (%)***	***Water absorption (%)***	***Remark***
TB-AG-01	17	1	1.5	
TB-AG-02	15	1	0.6	
TB-AG-03	30	2	1.2	Glassy rhyolite
TB-AG-04	16	3	3	
AG-05	18	1	1.2	
AG-06	16	1	2	
AG-07	19	1	1.3	
AG-08	12	10	2.3	Glassy rhyolite
AG-09	16	2	1.4	
AG-10	16	1	1.2	
AG-11	16	1	1.6	

Table 6-5 Laboratory values of LAAV, SSSV and water absorption (%) of the Tarmaber basalt

The aggregates of the Tarmaber basalts are highly sound as compared to the above standards or BS standards. Generally, the LAAV ranges from 12-30% which indicates these aggregate samples are highly sound with regard to above considered standards (Table 6-5). Specifically, the LAAV of the aphyric basalt (TB-AG-02, 12% and AG-08, 15%), porphyritic basalt (TB-AG-01, 17% and AG-05, 18%) and aphyric-porphyritic basalt (TB-AG-04, AG-06, AG-09 and AG-10, 16%) indicate that these basaltic rocks are not only strong but also possess superior resistance to abrasive action. This result has confirmed the relatively high durability of the rock, which signifies that the rock can be used for high stress applications such as road and runway constructions (Figure 6-10).

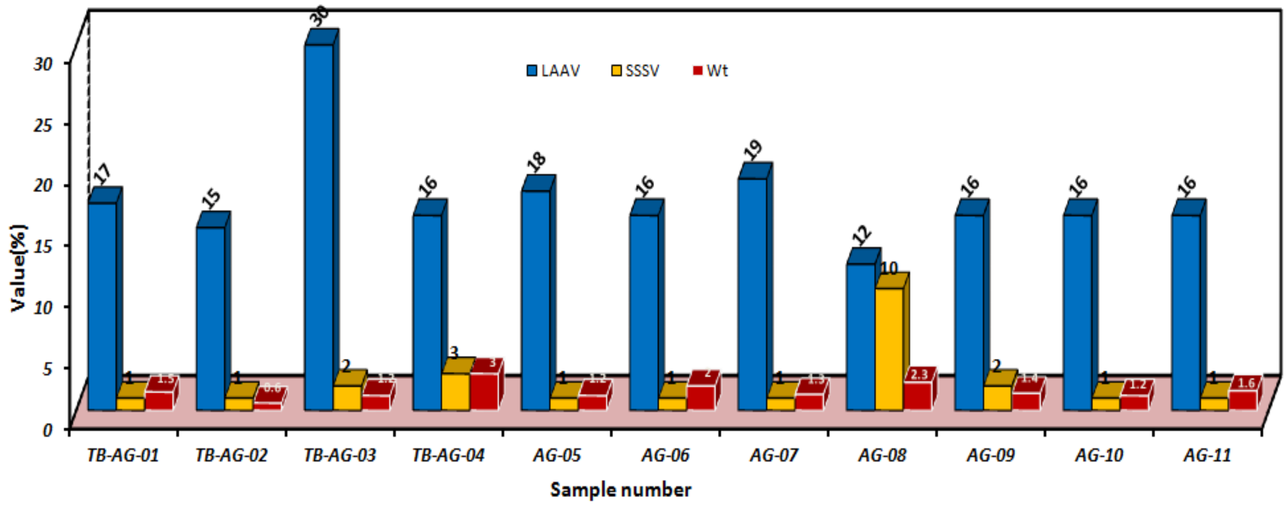

Figure 6-10 LAAV, SSSV and Water absorption (%) of the Tarmaber basaltic samples

The sodium sulphate soundness test evaluates the resistance of aggregate particles to degradation and disintegration that occurs due to crystallization of salts within pores and interstices of particles (Wu et al., 1988). The Sulfate soundness test is one of the most widely used tests for the prediction of freezing and thawing durability of aggregates. Freezing and thawing cycles are simulated by immersing the aggregate in a sulphate solution, drying the aggregate, and then reimmersing the aggregate in the sulfate solution. Expansive forces are created when the sulfate crystals in the aggregate pores are re-hydrated. The salt expansion simulates the forces that are created when water freezes in aggregate pores. The ranges of mass loss allowed in specifications vary from agency to agency with the type of sulfate used. Typical limits are 10 and 18 percent loss for sodium and magnesium sulfate, respectively.

However, recent studies on aggregates for use in unbound base and asphalt and Portland cement concrete pavements (Saeed et al, 2001; Kandhal and Parker, 1998) recommend that only the magnesium sulfate test be used due to the fact that it provides more precise values than the sodium sulfate, a statistic that is acknowledged in the ASTM and AASHTO test methods. However, in both cases, sulfate soundness tests do not address the condition where aggregate particles have a high porosity and permeability, which can cause fracturing of the Portland cement paste or add/cause stripping of asphalt cement. The sulfate soundness test has come under scrutiny because of its lack of precision. As an alternative, a study by Harman et al (1970) suggests that specific gravity and water absorption may serve as better indicators of aggregate soundness than the sulphate soundness test.

Unfortunately, for the current study, sodium sulphate soundness test is carried out according to AASHTO: T-104. All the samples have shown very good results ranging from 1% to 3%; only a single sample from a rhyolitic glass has shown 10%. The results of the sodium sulphate soundness test are quite good according to the AASHTO and BS specifications (Table 6-5).

Secondary mineral rating index

Fookes et al., (1988) stressed, by restating the opinion of 'numerous authors (e.g. Weinert 1964, 1968; Wylde 1976, 1977; Fookes 1980), that it is weathering in geological time which dictates the durability of crushed and uncrushed rock material in engineering time'.

The secondary mineral rating system of Cole and Sandy (1980) represents an attempt to quantify mineralogy and texture in relation to durability and was specifically developed to assess basalts for use as road aggregate. The secondary mineral rating *(Rsm)* is given by:

$$R_{sm} = [\sum(P.M)]T \qquad \text{(equ.6-1)}$$

where **P** is the percentage of secondary minerals present in the rock, **M** is the rating for a particular secondary mineral, and **T** is a textural rating for the rock (Table 6-6). Cole and Sandy (1980) suggested a critical value for Rsm of 140, above which the rock could be regarded as unusable.

a) Mineral ratings

Mineral ratings(M)		
	M	***Mineral***
Least deleterious	2	Calcite, white micas (muscovite and sericite)
	3	Kandites, chlorites, vermiculites, zeolites, hydrous micas (including illites), brown micas (phlogopite and biotite)
	5	Swelling chlorite
Most deleterious	10	Iddingsite (a mixture of chlorite, vermiculite

		and smectite)

b) Texture ratings

Texture ratings(T)

	T	***Mineral***
Least deleterious	0.3	Partial alteration of phenocrysts (up to 50%)
	0.3	Incomplete vesicle filling (up to 50%)
	0.4	Complete alteration of phenocrysts (more than 50%), e.g. iddingsite after olivine
	0.5	Homogeneous scattered distribution in matrix
	0.6	Large irregular matrix patches (1 to 5 mm) including filled vesicles
	0.7	Irregular matrix patches, minor interconnections
	1.0	Irregular partly connected patches in the matrix
Most deleterious	2.0	Fine interconnected vein networks or patches (0 to 30 mm apart)

Table 6-6 Secondary mineral rating system (after Cole and Sandy 1980)

Based on the above table, for some of the basaltic samples which show some slight alterations, secondary mineral rating index was calculated and it is found to be low, as suggested by Cole and Sandy, values above 140 are unstable or non durable. One important thing is that, the secondary mineral index rating takes into account chemical alteration and mechanical fracturing of minerals which form the bases of most classification of weathering. It therefore would appear that the value of 140 suggested by Cole and Sandy to distinguish unsuitable (non durable) material is too high. Subsequently, Tugul and Gurpiner (1997a) introduced **a petrographical weathering index** (Ipw) based on the proportion of weathered minerals in a basalt, as stated in the following formula,

Ipw= Wp/(1-Wp)... *(equ.6-2)*

where, Wp is the percentage of weathered/altered minerals

It can be seen from Table 6-7 that all the basaltic samples could be grouped under fresh (unaltered) according to petrographic weathering index after Tugrul and Grupinar (1979a).

Sample number	***Type of secondary Mineral identified***	***Percentage (Modal analysis)***	***Secondary Mineral Index (Rsm)***	***Petrographic Index (Ipw)***
TB-Cs-1	Iddingsite	5%	20	0.04(F)
TB-Cs-5	Zeolite	5%	4.5	0.04(F)
TB-Ts-10	-	-	-	-
TB-Ts-11	-	-	-	-

TB-Ts-12	-	-	-	-
TB-Ts-16	Zeolite	5%	4.5	0.04(F)
TB-Ts-21	Iddingsite	5%	20	0.04(F)
TB-Ts-23	Iddingsite	5%	20	0.04(F)
TB-Ts-25	Iddingsite	5%	20	0.04(F)
TB-Ts-25R	Iddingsite	7%	35	0.075(F)

Table 6-7 Percentage of altered minerals, secondary minerals ratings and petrographic weathering index of the various basaltic samples, where, F=Fresh

Actually, according to megascopic observation, the basaltic samples have shown no alterations and weathering evidence in hand specimen. Some basalt is susceptible to rapid weathering (Bell and Jemmy, 2000). The factors that are responsible for causing rapid disintegration of basalts include swelling and shrinking of smectitic clay minerals on hydration and dehydration respectively, and swelling and shrinking of certain species of zeolites. Deuteric alterations of primary minerals by hot gases and fluids from a magmatic source migrating through rocks give rise to the formation of secondary clay minerals. The primary rock minerals that tend to undergo the most deuteric alterations are olivine (Table 6-7), pyroxene and biotite when present in basalts. The texture of the rock influences the degree of disintegration and how rapidly it occurs in that it governs the access of water to suspect minerals.

6.2.3 Chemical properties

The occurrence of sulphates, chlorides, alkali cat-ions (Sodium and Potassium), reactive quartz varieties, metallic oxides and sulphides and organic matter pose serious problems in the use of aggregates specially in concrete (BS:812; ASTM: C 33; ASTM: C 289). The present study gives high concern and carried out detail investigation regarding Alkali Silica Reactivity (ASR) since it is the primary concern for failure of concrete structures in the study area. Therefore, detail petrographic examination and alkali silica reactivity tests are performed according to UNIEN: 124070 and ASTM: C 289, respectively.

6.2.3.1 Alkali Silica Reactivity (ASR)

It is imperative to highlight the inevitable reaction that happens in concrete between certain aggregates and alkali hydroxides derived from the concrete mix. Some aggregates used in concrete contain certain amount of silica, making them susceptible to this reaction if a critical amount of reactive silica is present.

Alkali-Silica Reaction (ASR) is a deleterious chemical reaction between the alkali hydroxides from the concrete pore solution and the silica of reactive aggregate in concrete and cement paste or mortar. It produces expansive gels and causes cracking of aggregate and paste, sometimes resulting in major structural problems which could lead to extensive maintenance, repair and even demolition of affected civil structures in extreme cases.

The phenomena occur everywhere and in all types of structures (such as dams, bridges, roads, buildings, breakwaters). In damaged structures, the consequences of ASR become noticeable after a period which could be as short as 2-5 years (Leming, 1996). During a latent time, the reaction takes place in the concrete without causing structural problems. The latent time can last more than five to ten years. One of the main concerns for the owners of these ASR-damaged structures is to know whether the reaction is almost finished or if many years of swelling still remain.

The history of the ASR dates back in 1935, when Holde explored the reactions between cements and certain aggregates (in Comby-Peyrot, 2006), and in l939, Thomas Stanton (1940) and co-workers at the California Department of Transport discovered that unexplained cracking in concrete that had been occurring in the USA for over two decades was caused by certain aggregates reacting with cement alkalis. They named this phenomenon Alkali-Aggregate Reaction (AAR). The initial work of Stanton was quickly expanded by other workers (Mielenz and Witte, 1948) at major US agencies such as the Bureau of Reclamation and the US Army Corps of Engineers. Stanton T., described the nature of the components of ASR and observed the dislocation in the structures. Later in, 1941, the hydraulic structure **"Parker Dam" (USA)** was first identified as affected by alkali aggregate reaction (Corneille et al. 1991). Afterwards, many structures were gradually found to be affected by this harmful reaction and understating the nature and chemical processes of the ASR become clear in which as a result different tests were developed.

In 1985, a report from International Commission of Large Dams(ICOLD) summarized the damage to dams caused by alkali-aggregate reaction, which involved 24 structures in USA, 5 dams in France, 3 dams in Spain, 2 in India, 2 in Brazil, 3 in Italy and so on (Corneille et al. 1991). Another published report (Charlwood 2009) gives statistical data on the dams damaged by AAR (Figure 6-11). The published papers also in alkali-silica reaction are increasing for the last three decades.

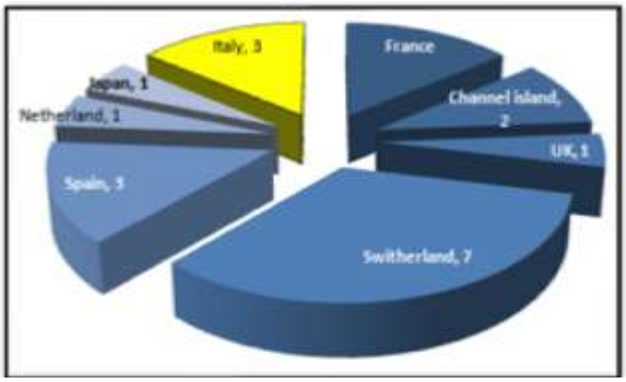

Figure 6-11 Dams damaged by AAR attack (as cited in Charlwood 2009)

Considering the high complexity of ASR, which refers to the chemical processes, the materials and the mechanical consequences, this thesis only, assesses the general aspects of ASR from different standpoints and the causes that result ASR in the studied area by performing detail petrographic examinations and chemical tests for detection of potential reactivity of the aggregates. Firstly, the type and mechanism of the ASR reaction is presented and the factors affecting the reaction are described, secondly, the detection methods and sample results shall be discussed.

The **Alkali–Aggregate Reaction** is a general, but relatively vague, expression which can lead to confusion. Actually, it is recommended to refer to a more precise definition such as one of the following:

- Alkali–Silica Reaction (ASR, the focus of this research);
- Alkali–Silicate Reaction
- Alkali–Carbonate Reaction

The Alkali–Silica Reaction is the most common form of alkali–aggregate reaction while the two other types are less common and will not be dealt with hereafter in this research. The following are factors which promote the alkali aggregate reaction:

- reactive type of aggregate
- high alkali content in cement
- availability of moisture
- optimum temperature conditions

For preventing damage and failure, the most efficient practice is to identify the susceptibility of an aggregate to the Alkali-Silica Reaction (ASR) before using it in concrete mix. Alkali-Silica Reaction (ASR) is a reaction that takes place between the reactive silica contained in aggregates and the alkalis in the cement paste. For the reaction to take place in concrete, three conditions must exist: high pH, moisture, and reactive silica. The different types of silica available in aggregates react with the hydroxyl ions found in the pore solution of the concrete structure. The silica, now in solution, reacts with the sodium (Na^+) and potassium (K^+) alkalis to form a volumetrically unstable alkali silica gel. Once the gel is created, it starts absorbing water and expands to a greater volume than that of the reacted materials. Water absorbed by the gel can be water not used in the hydration reaction of the cement, free water from rain, snowmelt, tides, rivers, or water condensed from air moisture (Farny, 1998). In general, the reaction can be viewed as a two-step process (Farny, 1996):

Step 1:

Silica + Alkali ⟶ Alkali-silica gel (sodium silicate)

SiO_2 + 2NaOH + H_2O ⟶ $Na_2SiO_3.2H_2O$ (2KOH can replace 2NaOH)

Step 2:

Gel reaction product + water ⟶ expansion

Since the gel is restrained by the surrounding mortar, an osmotic pressure is generated by the swelling. Once that pressure is larger than the tensile strength of the concrete, cracks occur leading to additional water migration or absorption and additional gel swelling (ACI 221, 1998).

Various forms of silica or silicon oxide tetrahedron may be found in natural aggregates. A crystalline silicate structure is formed by the repetition of the silicon tetrahedron in an oriented three-dimensional space (Prezzi et al. 1997). Quartz (SiO_2) is an example of completely crystalline silica where the different tetrahedral are linked by oxygen ions. Each oxygen ion is bonded to two silicones in order to achieve electrical neutrality (Figure 6-12).

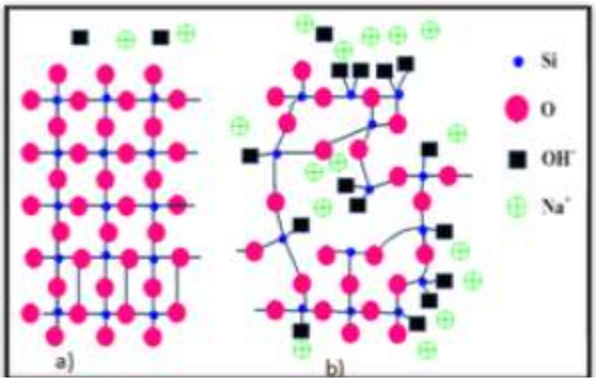

Figure 6-12 Attack of alkali solution on silica lattice, a) Ordered/well crystallized, and b) Disordered/poorly crystallized silica

A complete tetrahedron cannot form on the surface of a crystalline structure. The bonds between oxygen and silicon are broken on the surface resulting in negative charges that are unsatisfied (Prezzi et al. 1997). Such structures are chemically and mechanically stable, impermeable, and react only on the surface (Leming 1996). Amorphous silicates (non-crystalline) are also formed by a combination of the silicon tetrahedron with the exception that the tetrahedral are arranged in a random three dimensional network without forming a regular structure (Prezzi et al. 1997). As a result, amorphous silica is more porous, has a large surface area, and as a consequence, is very reactive. The more amorphous the silica is, the more reactive it becomes. Certain volcanic aggregates, for example, contain glassy materials formed by the rapid cooling of melted silica that prevents it from crystallizing and renders it very reactive (Leming 1996). In addition to the degree of crystallization of silica, the amount of energy stored in the crystal structure also affects the reactivity of an aggregate. Some silica structures might contain large amounts of strain energy caused by heat and pressure usually termed as strained structure.

Aggregates having such contents of silica are more likely to be responsive to deleterious alkali-silica reactions. However, the rate of reaction is much slower than that of aggregates containing amorphous silica. Metamorphic aggregates containing strained quartz are an example of such aggregates (Leming, 1996).

ASR requires a minimum relative humidity in the concrete. Internal relative humidity will vary with the environment of the structure and will influence the amount of protection required against ASR. Testing has indicated that where a concrete undergoing ASR is kept moist, the reaction will proceed continuously. Moisture may be derived from high atmospheric humidity, proximity to waterways, retained water, or exposure to groundwater or runoff that drains over or ponds on the concrete surface.

ASR cracking is caused by tension generated by expansion of the internal concrete rather than by reaction of the 75-100mm surface layer of concrete. Thus it is the moisture condition of the internal concrete that must be considered. The moisture content of internal concrete in elements with large cross section is less sensitive to wetting and drying of the surface than is the internal concrete in smaller elements.

Some aggregates contain crystalline silica formed by very fine crystals having very large surface areas. These types of aggregates, such as chert, are prone to ASR (Leming 1996). The amount of silica contained in aggregates also affects their reactivity (ACI 221, 1998).

In a low humidity environment, the internal portions of concrete can dry out. Reports from various countries (Stark, 1985) indicate that even under desert conditions, internal moisture loss is slow and concrete members with large cross sections may retain high levels of internal moisture for more than twenty years. This indicates that although concrete not exposed to external moisture sources is at low risk from ASR, it cannot be assumed that such concrete will dry sufficiently to prevent the reaction. Bad quality concretes that are less dense and more porous will dry more rapidly and will be less prone to ASR than higher quality concretes in a dry environment. In view of this, in the central parts of Ethiopia, temperature is mild and rainfall is bimodal and heavy. This climate allows the outer concrete to dry for some time but leaves sufficient moisture inside the concrete for ASR to proceed.

One of the most aggressive environments in which ASR can proceed is hot, dry conditions during the day and cold conditions at night where the temperature drops below the dew point and water condenses on the exposed surfaces (Fookes, 1980). These conditions accelerate ASR, and if salts are also deposited on these surfaces, rapid disintegration of the concrete may occur due to combined expansion from ASR and penetration of chloride causing corrosion of reinforcement.

An interesting feature of ASR is that expansion, which depends on the amount of reactive silica in the aggregate, usually shows a maximum value at some intermediate proportion of the type of reactive silica (Figure 6-13). At low levels of reactive silica increasing the amount increases the expansion, but at some amount the expansion peaks, and at high levels of reactive silica increasing the amount decreases the expansion. This is termed a pessimum effect, because expansion is greatest, or pessimum, at this intermediate proportion of reactive silica. For some reactive constituents (opal) the pessimum occurs at a very low proportion, perhaps only a few percent, and decreases sharply at higher levels. For other reactive constituents (chert) the pessimum occurs at around 50% and decreases only gradually at higher levels. Glass does not usually show a pessimum, expansion increases even up to 100% glass (ACI, 221. 1998).

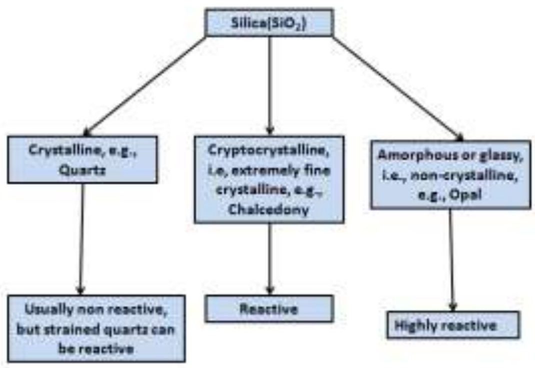

Figure 6-13 Quartz family that is non-reactive and reactive

Aggregates containing the following amounts of silica are susceptible to ASR (ACI 221, 1998).

- opal: more than 5%
- chert and chalcedony: more than 50%
- strained or microcrystalline quartz: more than 5%
- natural volcanic glasses, no limit

Identifying the susceptibility of aggregates towards Alkali-Silica Reactivity (ASR), before using as a concrete mix is one of the most efficient practice for minimizing damage and failure of civil structures due to reactive aggregates. Several tests have been developed for identifying aggregates subjected to ASR, but each has its limitations, some takes more than a year to see the result. Since considering the relatively short time available for the present study, the quick and accelerated chemical testing and petrographic examination are selected. The chemical test method (ASTM, C-289) known as the "Quick chemical test" or the "Mielenz test" (Mielenz and Benton, 1958), has been found to be a satisfactory initial method for determining the potential reactivity of aggregates derived from volcanic rocks. This test categorises aggregates as "**Innocuous**", "**Potentially Deleterious**" or "**Deleterious**". For this test (chemical test) nine different samples from active quarries of basalt and outcrops used as aggregate sources were sampled in the studied area (Table 6-8). So, according to this test, aggregate collected from one big and active quarry site used for a multimillion dollar road project is found to be reactive (potentially deleterious, TB-AG-03, Figure 6-14).

Potential Reactivity of Aggregates		
Sample N.	***Dissolved Silica by the Gravimetric method $S_c(SiO_2)$ in millimole per liter***	***Reduction in Alkalinity R_c in millimoles per liter***
TB-AG-01	46	260
TB-AG-02	47	235
TB-AG-03	380	136
TB-AG-04	95	367
AG-05	154	134
AG-06	96	220
AG-07	38	330
AG-08	48	240
AG-09	56	265

Table 6-8 Chemical test results using ASTM C 289 test method

This method consists of reducing the aggregate source to 150 to 300 μm particles and then immersing it in a 1M NaOH solution at 80^0C for 24 hours. The solution is then filtered and analyzed for the content of dissolved silica (Sc) and the Reduction in alkalinity (Rc) both of which are plotted on a standard graph defining areas of innocuous, deleterious, and potentially reactive aggregates.

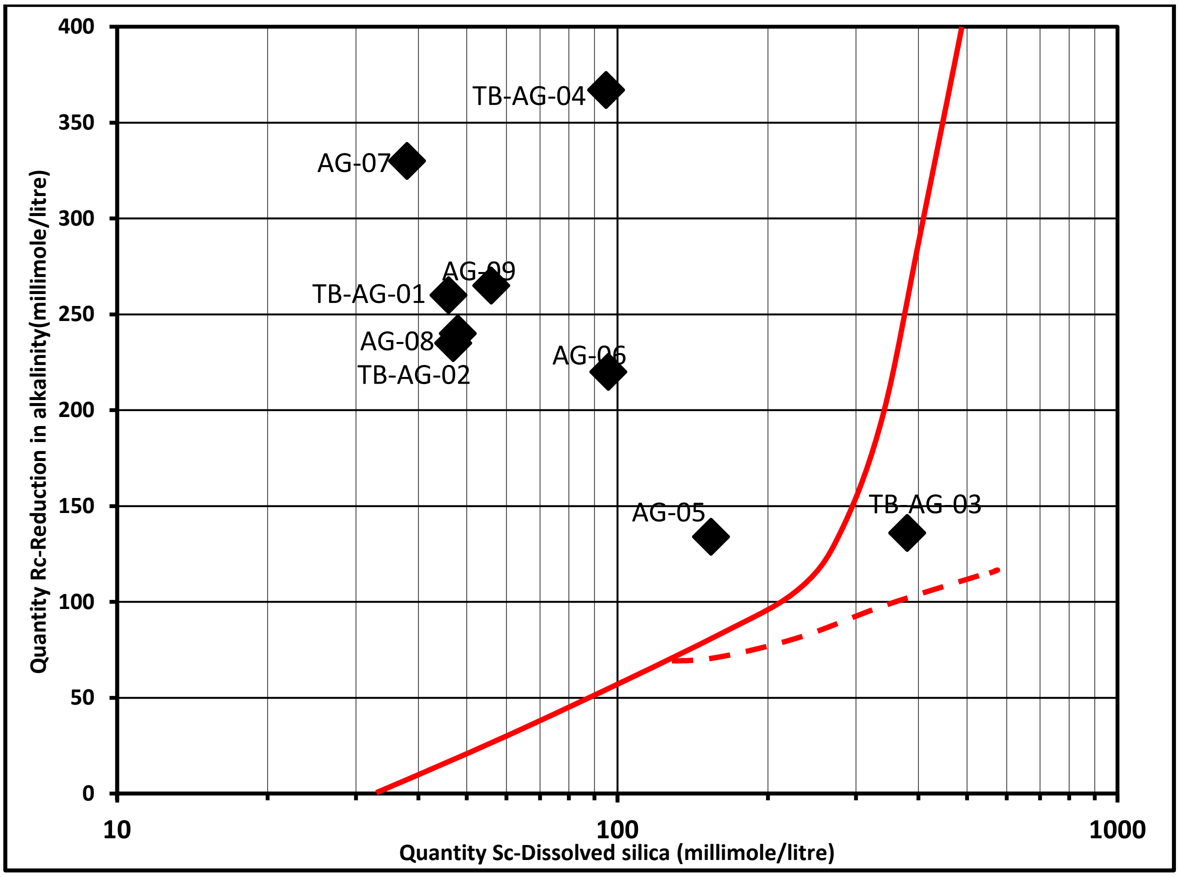

Figure 6-14 Samples plotted on Mielenz standard graph with illustration of division between Innocuous and deleterious aggregates on the basis of reduction in Alkalinity test (ASTM C289)

However, there are some critics on this test that many aggregates are not adequately identified using this test. The poor performance of this testing method can be blamed on; 1) the interference of minerals such as calcium, magnesium, silicates, gypsum, zeolites, clay minerals, organic matter, or iron oxides, 2) the crushing and preparation of the aggregates especially with aggregates containing microcrystalline quartz. However, sample preparation to the required size fraction and detailed petrographic examination could improve the test result.

In the current studied area different structures have been affected with the ASR. A recently built highway (3-6 years old) is showing signs of alkali silica reaction pattern and some buildings also are seen affected by these phenomena (Figure 6-15).

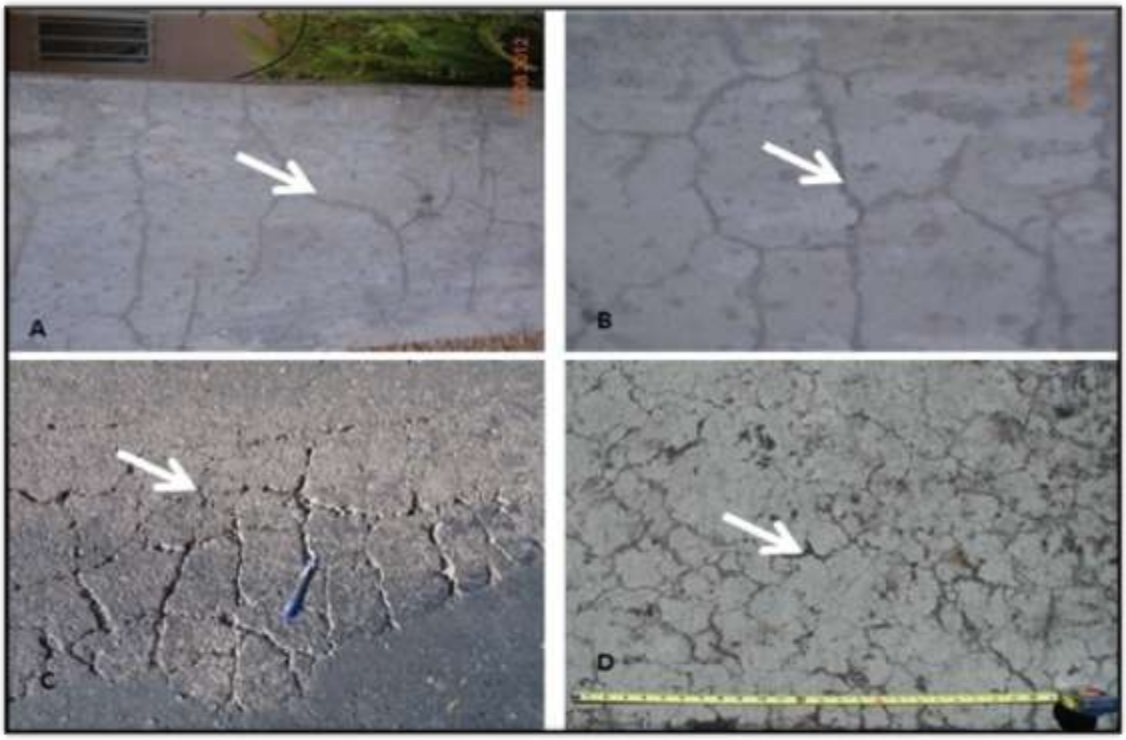

Figure 6-15 Alkali Silica Reaction affected structures (A-D); the effect of Alkali Silica Reaction is well developed in the study area

The development of Alkali Silica Reaction could result in total or partial damage of civil structures by reducing the concrete compressive strength, tensile/flexural strength, shear strength and elastic modulus.

Mitigation and prevention of ASR

There are several mechanisms by which ASR could be mitigated and prevented. The first and easy way is not to use reactive aggregates. The second one is to use low alkali content cement (0.6% Na_2O) and the third is limiting the alkali content of the cement mix when aggregates are found to be indicative of reactivity and the fourth method is very rare and costly choice is using supplementary cementing material which could hinder the process of ASR. These supplementary materials are by themselves high costly and needs another processing system. The supplementary systems are lithium nitrate (Lithia glass, soda lime) and silica fume.

6.2.3.2 Petrographic Examination

Petrographic examination, despite being qualitative in nature, remains the most valuable test for predicting the overall performance of concrete aggregates in any control test, and in service, as well.

Petrographic testing is a microscopic examination that evaluate the aggregate material (French, 1991) and is used to examine the Alkali-Aggregate-Reaction (AAR) risk in aggregates which remains to be one of the major cause of damage in concrete (Lopez-Buendia et al., 2006).The petrographic examination, therefore, includes the description and systematic classification of rock and studying thin sections by means of petrographic microscope. It is arguable that to use any natural rock material for an engineering purpose without knowledge of the rock type is to take the same risk of unforeseen problems which can arise where any unknown material is used in construction. It is equally true; however, that knowledge of the rock type, or types, within an aggregate cannot itself be used to judge the suitability of that aggregate for its intended purpose. Hammersley (1989) noted that the petrography of a rock mass, involving field inspection, can be of value in any assessment of its potential suitability for use as aggregate.

Petrographic examination of aggregates in particular uses include:

- an aid in developing appropriate testing regimes;
- assistance in the interpretation of other test results;
- assessment of aggregate performance where there is no standard or reliable performance test;
- detection of potentially deleterious substances, the more common including:
    - porous and frost susceptible particles;
    - weak or soft particles, or coatings;
    - rock types susceptible to shrinkage and swelling;
    - certain occurrences of salts and other soluble minerals;
    - forms of silica or carbonate which may be alkali-reactive in concrete;
    - coal, lignite and other organic matter;
    - pyrite and other metallic contaminants;
    - mica; etc

A detailed petrographic examination is particularly important where a new aggregate source is being developed. The petrological examination of the constituents of the aggregate particles is an essential preliminary to their use in any region where the quality of the aggregate is unknown or little known.

Generally, identification of the constituent materials in an aggregate may assist in characterizing its engineering properties, but identification alone cannot provide the sole basis for predicting behaviour of aggregates in service. Aggregates of any type or combination of types may perform well or poorly in service depending upon the exposure to which the concrete is subjected, the physical and chemical properties of the matrix in which they are embedded their physical condition at the time they are used, and other factors. Constituents that may occur only in minor amounts in the aggregate may or may not decisively influence its performance. The petrographic examination, therefore, included the description and systematic classification of rocks and studying thin sections by means of microscope.

Examining thin sections of aggregates using an optical microscope is helpful in detecting potentially reactive minerals that could cause damage. These minerals include opal, cristobalite, tridymite, volcanic glass, chert, chalcedony, and microcrystalline quartz (Dolar-Mantuani 1983). Information from petrographic analysis could aid in determining which accelerated testing method should be used to further evaluate the Alkali-Silica Reactivity of an aggregate. The petrographic description of 11 basaltic samples from outcrops and existing quarries of Tarmaber formation were studied under a polarizing microscope based on the UNIEN 12407: 2007(European norm). The complete descriptions of these thin-sections are found on appendix 1.

In doing so, on some of the studied thin-sections it was possible to identify some deleterious components which also later confirmed by XRD analysis. Some typical microscopic photos of the thin-sections are depicted (Figure 6-16, 6-17, 6-18 and 6-19).

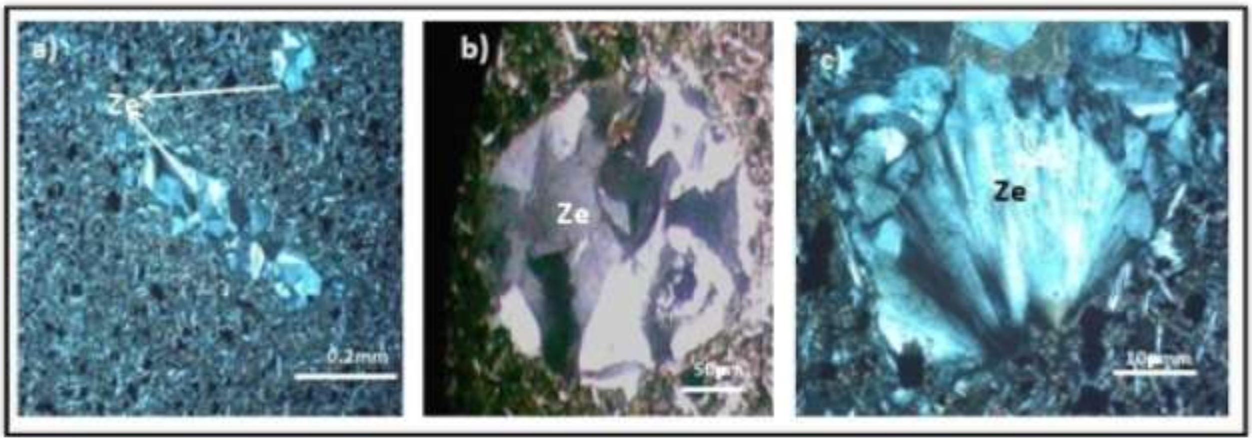

Figure 6-16 Rock sample as seen under petrographic microscope (cross-polarized view) showing zeolite mineral from sample number TB-TS-15(a, b) and TB-TS-16(c), Ze-zeolite in plagioclase lath and iron oxide in glassy ground mass

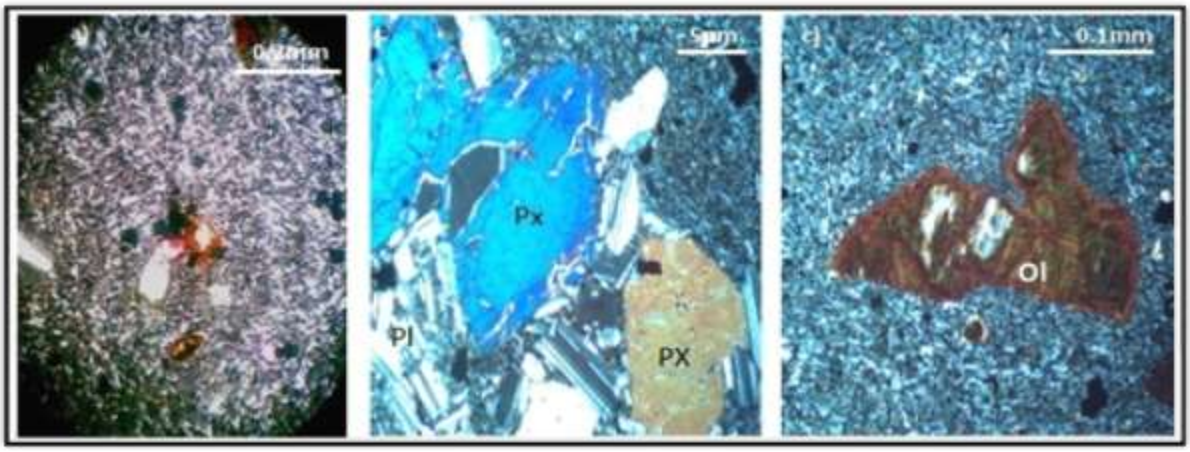

Figure 6-17 Rock sample as seen under petrographic microscope (cross-polarized view), a) General view of laths of plagioclase and opaque under cross polarised light, x2.5, b) Phenocrysts of pyroxene and plagioclase under cross polarised light, x10, c) Olivine phenocryst changing to iddingsite under crossed polarised light, x2.5, Px=pyroxene, Pl=plagioclase, Ol=olivine/iddingsite

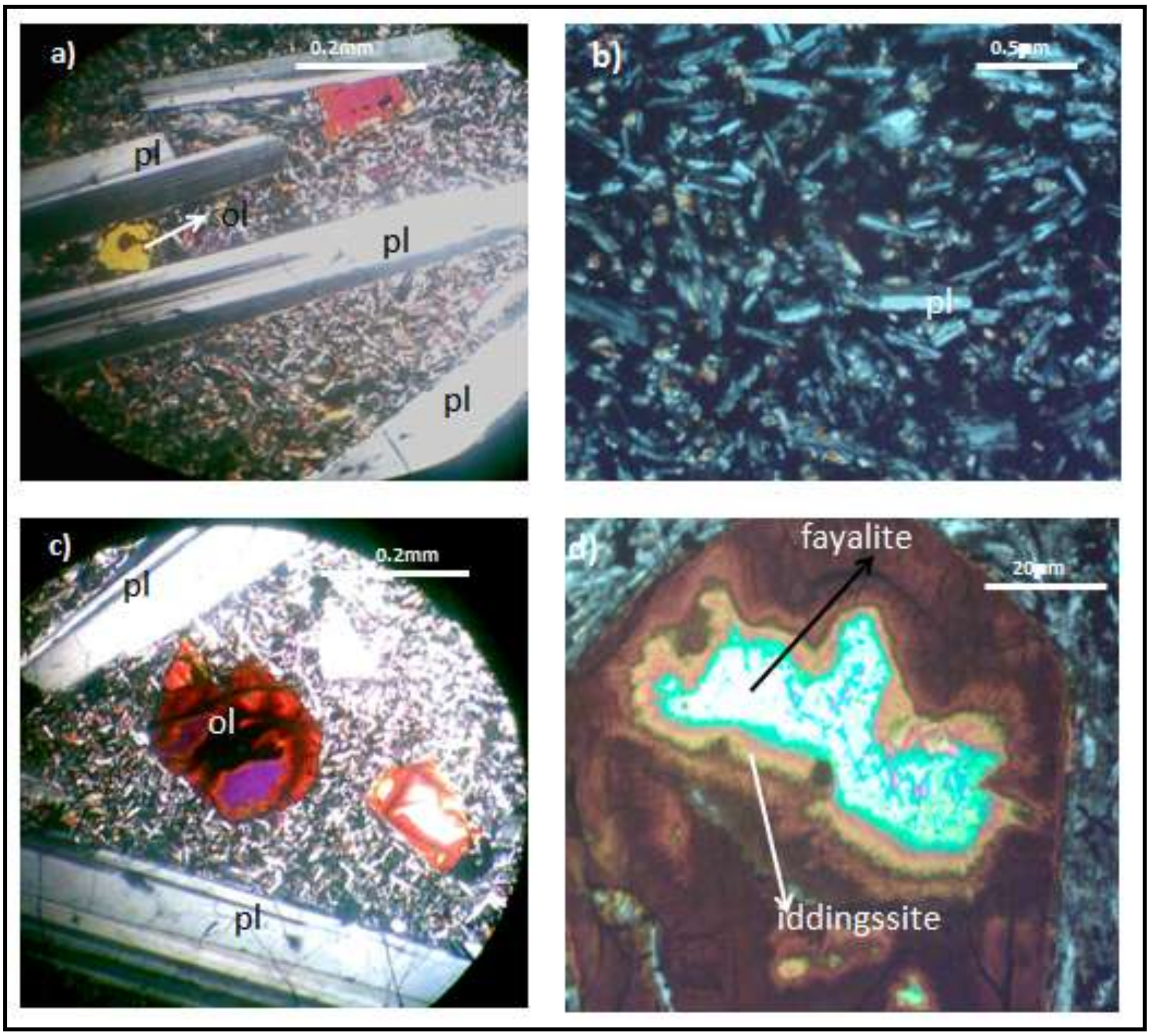

Figure 6-18 Rock sample as seen under petrographic microscope (cross-polarized view), a) Phenocrysts of plagioclase and olivine in micro lath groundmass under cross polarized light, x2.5 b) Micro laths of plagioclase under cross polarised light, x10, c) Phenocrysts of plagioclase and olivine in micro lath plagioclase groundmass under crossed polarised light, x2.5, d) Magnified olivine crystal showing zonation of alteration, x20, Pl=plagioclase, Ol=olivine

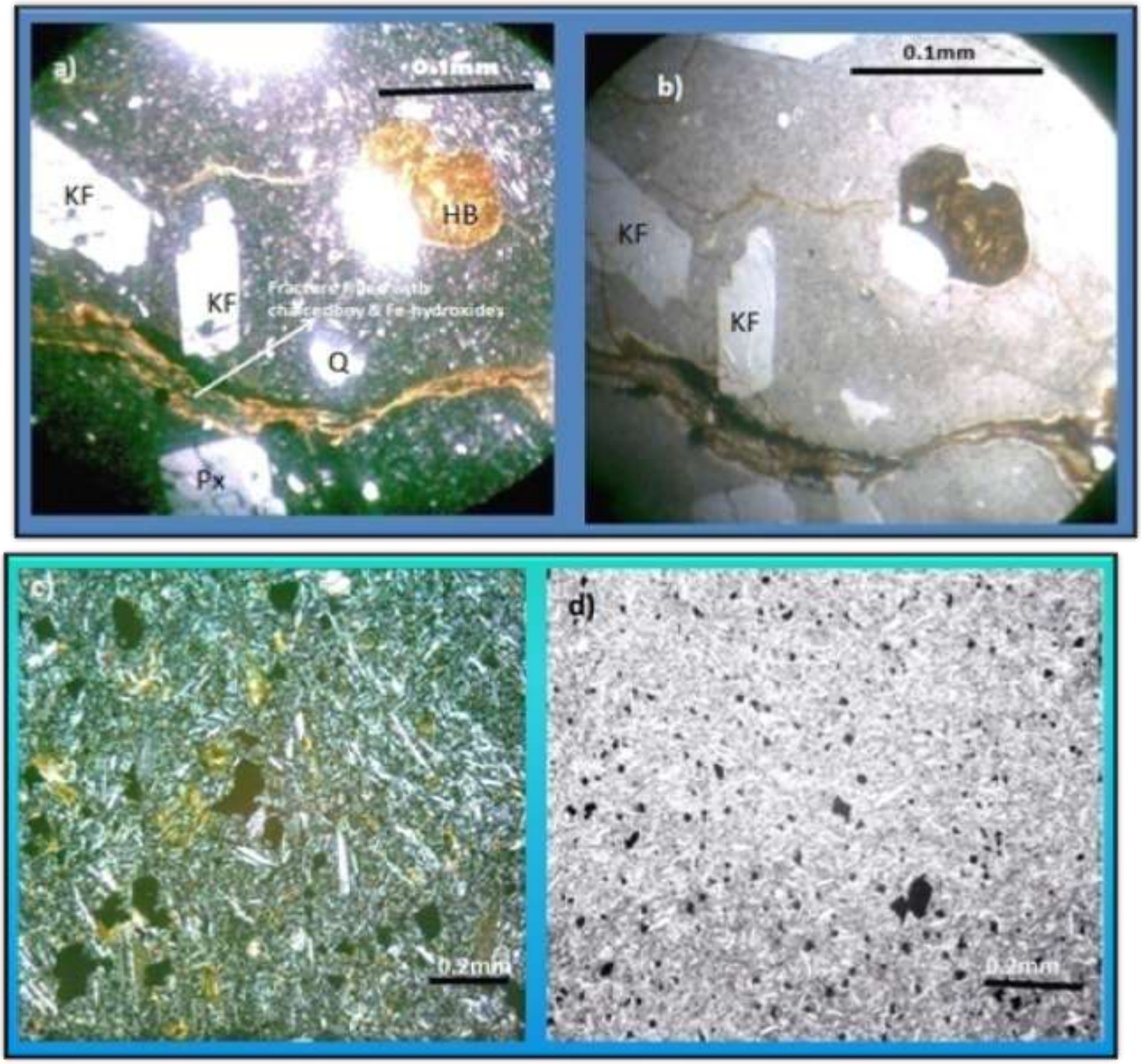

Figure 6-19 Rock sample as seen under petrographic mcroscope (cross-polarized view), a)Thin section under crossed nicol, x10, micro fractures filled with secondary clay and opal/chalcedony mineral with phenocryst of plagioclase, b) Under plain polarised light with glassy groundmass, x10, c) Thin section under crossed nicol showing medium grained plagioclase and some pyroxene with opaque minerals, x20 d) Plain polarised light showing opaque and micro laths of plagioclase feldspar, x10(KF=k-feldspar, HB=hornblende, Q=quartz, Px=pyroxene)

6.2.4 Deleterious constituents

The concrete aggregate should be free from impurities and deleterious substances that are likely to interfere with the process of hydration and result in prevention of effective bond between the aggregate and matrix. These impurities sometimes reduce the durability of the aggregates. Coarse aggregate stacked in the open and unused for long time may contain moss and mud in the lower level of the stack. The deleterious constituents are organic matter, chloride sulphate, metallic oxides, clay minerals, zeolite group minerals and are discussed the proceeding sections below.

6.2.4.1 Organic matter, chloride and sulphate contents

Aggregates should be clean and free from organic impurities: aggregate containing organic materials make poor concrete. Organic matter is regarded as deleterious in aggregates destined for use in cement concrete (Kandhal et al., 1998). However, organic matter in volcanic aggregates (basalts) is practically negligible and no test is conducted regarding organic matter. Chloride and sulphate content beyond the threshold values in the aggregate are deleterious in cement concrete (Lee, 1987; BS: 812). While the sulphate and chloride contents in the currently studied aggregates do not affect significantly the durability of the aggregates since their content is very negligible (Table 6-9).

Sample N.	Water soluble chloride content in ppm(parts per million)	Water soluble sulphate content in ppm (parts per million)
TB-AG-01	69	41
TB-AG-02	79	25
TB-AG-03	125	41
TB-AG-04	79	27

Table 6-9 Water soluble chloride and sulphate tested according to BS 1377

6.2.4.2 Metallic oxides and sulphides/other impurities

Certain metallic compounds can seriously affect the setting rate of concrete, even when present in only trace amounts (Lea, 1970), which can occur in some natural sources. Thus knowledge of the source geology could be of value in assessing the likelihood of retardation problems on this account, also whether the cause of any difficulties is likely to be general throughout a deposit or local concentrations effect.

Pyrite (iron sulphide)

Iron pyrite (pyrite or iron sulphide) is another naturally occurring contaminant in some aggregate deposits. Some forms of iron sulphide are able to oxidize, with the resultant expansion, when situated at or near concrete surfaces. This activity thus leads to the development of surface defects with considerable attendant staining of the surface by iron oxide. The surface deterioration is usually, of no structural or durability significance, but visually unattractive appearance.

Clay minerals

The term "clay" refers to natural material composed of particles in a specific size range less than 2μm (0.002 mm). Mineralogically, clay refers to a group of layered silicate minerals including the clay-micas (illites), the kaolin group, very finely divided chlorites, and the swelling clays-smectite including montmorillonites. Members of several groups, particularly micas, chlorites, and vermiculites, occur both in the clay-size range and in larger sizes. Some clays are made up of alternating layers of two or more clay groups. Random, regular, or both types of interlayering are known. If smectite is a significant constituent in such mixtures, then fairly large volume changes may occur with wetting and drying.

Clay minerals are hydrous aluminium, magnesium, and iron silicates that may contain calcium, magnesium, potassium, sodium and other exchangeable cations. They are formed by alteration and weathering of other silicates and volcanic glass. They are found disseminated in pockets and in altered and weathered igneous rocks.

Most aggregate particles composed of, or containing large proportions of clay minerals are soft and, because of the large internal surface area of the constituents, they are porous. Some of these aggregates will disintegrate when wetted. Rocks, in which swelling clay minerals (smectite) are present as a continuous phase or matrix such as in some altered volcanic rocks, may slake in water or may disintegrate in the concrete mixer. Rocks of this type are unsuitable for use as aggregates. Rocks having these properties less well developed will abrade considerably during mixing, releasing clay, and raising the water requirement of the concrete containing them. When such rocks are present in hardened concrete, the concrete will manifest greater volume change on wetting and drying than similar concrete containing non-swelling aggregate. However, no clay minerals are detected in all the aggregate samples using petrographic and XRD analysis in the current study. So, the adverse effect of clay minerals in the aggregate of the currently studied source area (Tarmaber basalt) is far remote as far as careful aggregate production is practiced.

Zeolites

The zeolite minerals are a large group of hydrated aluminium silicates of the alkali and alkaline earth elements which are soft and usually white or light coloured. They are formed as a secondary filling in cavities or fissures in igneous rocks, or within the rock itself as a product of hydrothermal alteration of original minerals, especially feldspars. Some zeolites, particularly ***heulandite, natrolite,*** and ***laumontite***, reportedly produce deleterious effects in concrete, the first two having been reported to raise the alkali content in concrete by releasing alkalis through cation exchange and thus increasing alkali reactivity when alkali-reactive aggregate constituents are present. Laumontite and its partially dehydrated variety *leonhardite* are notable for their substantial volume change with wetting and drying.

In the current study area, using both petrographic and XRD study it was possible to identify zeolite minerals in two aggregate samples collected from an active quarry and an outcrop of columnar basalt. The XRD analysis identified heulandites, a zeolite mineral group with a cat ion of Na+ and also determined its concentration to be 3.3% by volume. The petrographic investigation also clearly identifies a zeolite mineral in fine grained basalt as a phenocryst as shown below in the Figure 6-20.

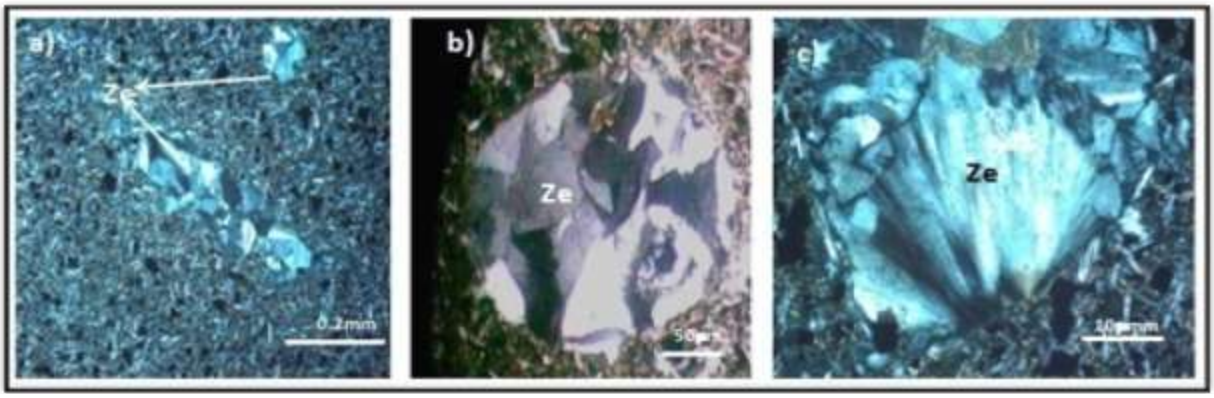

Figure 6-20 Rock sample as seen under petrographic microscope (cross-polarized view) showing zeolite mineral from sample number TB-TS-15(a, b) and TB-TS-16(c); Ze=zeolite in plagioclase lath and iron oxide in glassy ground mass

Iron Oxide Minerals, Anhydrous and Hydrous

There are two common iron oxide minerals: (*1*) Black, magnetic: *magnetite* (Fe_3O_4), and (*2*) red or reddish when powdered: *hematite* (Fe_2O_3); and one common hydrous oxide mineral, brown or yellowish: *goethite* (FeO (OH)). Another common iron-bearing mineral is black, weakly magnetic, *ilmenite* ($FeTiO_3$). Magnetite and ilmenite are important accessory minerals in many dark igneous rocks. Hematite is commonly found as an accessory mineral in other types of rocks. Limonite, the brown weathering product of iron-bearing minerals, is a field name for several varieties of hydrous iron oxide minerals including goethite; it frequently contains adsorbed water, and various impurities such as colloidal or crystalline silica, clay minerals, and organic matter. The presence of substantial amounts of soft iron-oxide minerals in concrete aggregate can colour concrete various shades of yellow or brown. Sometime hematite ores are used as heavy aggregates. In view of this, the basaltic samples showed various proportions of opaque (Fe-oxides). According to petrographic modal analysis(Figure 6-21), the samples which show high proportions of Fe-oxides are TB-CS-5 (45%), TB-CS-6(30%), TB-TS-12(12%), TB-TS-16(18%), and TB-TS-21(15%).

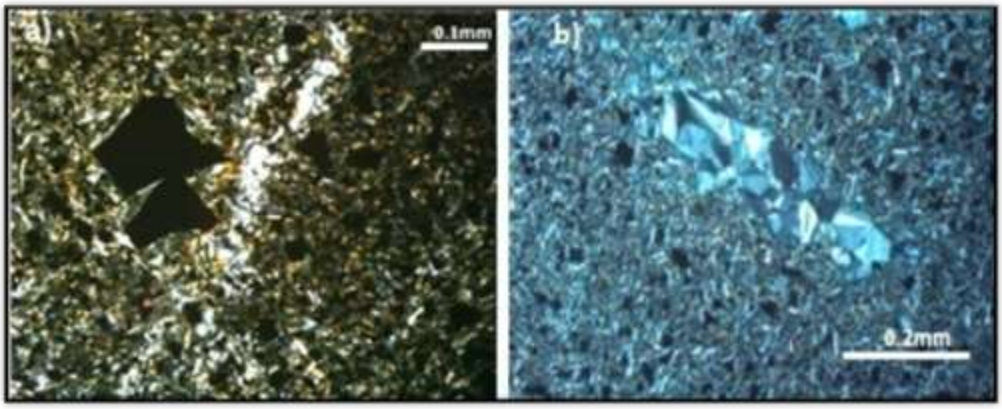

Figure 6-21 Rock sample as seen under petrographic microscope (cross-polarized view) of some of the thin section samples showing opaque in crossed nicol, 2x (Fe-oxide: black colour) concentration

CHAPTER SEVEN

7. Aggregate and dimension stone quarry and its environmental impacts

Quarrying activity plays a role of strategic importance in the national economy of every country, even though, the scale of importance varies with the resource availability and developmental status of the country. By securing a supply of construction mineral raw materials, such activity promotes the development of a country. The most common uses of aggregates are closely related to the construction sector: e.g. they can be used either without a difficult manufacturing process, as in road filling, railway ballast or armorstones, or they can be used in the production of high quality materials such as ready-mixed concrete (made of 65-75% aggregates), pre-cast products, etc. Consequently, the resources of aggregates are used in the implementation of all built-up environments, in particular: housing (building of new homes) and civil engineering structures (hospitals, schools, bridges and flood protection), roads, railways which each of them consumed high amount of aggregates.

Construction aggregates are in fact essential and valuable resources for the economic and social development of mankind (Badino et al., 2007), but they must be produced and used according to Sustainable Development Principles (SDP). Aggregates quarrying provide necessary raw materials for infrastructure and civil development; however, mining and/or quarrying operations have a non-zero environmental impact. So, quarrying and post-quarrying activities should always target the mitigation of potential environmental and/or social impacts. The primary objectives of good quarry practice are the safe, efficient and profitable extraction of the maximum usable material from the minimum area of land while causing the minimum environmental and social disturbance and resulting in beneficial final restoration and land-uses. Generally, quarrying is known as one of the human activities since ancient times with more important impact on environment, and generates strong opposition and conflict with local communities. Though it is similar to and classified under mining, construction stone quarrying is a bit different. Various agents of forces could shape the earth's surface, and there is a great force of man's invented industries that can alter gradually the different landforms. Quarrying is one of them, and it is also one industry that booms here in Ethiopia in the last ten years and seems continuing in the future as this country is in construction boom and economical and social development. Its different impacts which can affect people and the environment itself also will continue.

The aggregate industry is presently facing a growing, public awareness in relation to the environmental profile of its activities. Important areas of concern are: a) The non-renewable character of the natural resources, especially in regions facing a coming shortage of adequate local materials, b)The environmental impact on neighbourhood and of the quarrying and of the materials transport related to the quarrying activities, c) Land use conflicts between quarrying and e.g. agriculture, recreation, building sites, archaeology - especially in densely populated regions, d) lack of sustainability in production, characterized by inferior mass balance (i.e. high percentages of e.g. surplus fines to be deposited) and a high energy consumption needed per ton aggregate produced.

These questions in the relation between the aggregate industry and its surrounding society will by far be determinant for the industry's survival. In the future it seems that, only those companies and branches which can earn their public acceptance from an active use of environmental parameters in their planning and execution of own activities, will survive. Currently, Ethiopia is upgrading its environmental authority to ministry level with multi disciplined professional and necessary technology to monitor the environmental impacts generated from various industries, one of which is dimension stone and aggregate quarry.

The real challenge here is to merge the environmental issues with the industrial ones; to create industrial plants, which are at the same time environmentally friendly and economically profitable, which integrate quarrying and industrial production, and finally–for which there exist plans for restoration and area use after quarrying period is completed.

*Figure 7-1*Natural attractive scenery in the studied area

7.1 Impacts of construction stone quarry sites on environment

Quarries are opened for production of construction materials such as selected materials for roads construction, dimension stones for buildings, gravel, aggregates, ceramic and cement raw materials, etc (Skoytes and Hussey, CP/44/74). The quarries´ negative reputation comes from the years from 1980-1990 of last century, when the lack of regulations in the quarrying brought important environmental and landscape damage, due to lack of restoring quarrying activities. Consequently the Ethiopian government was forced to adopt environmental restorations legislation after closure of quarries for the first time in 1992. And subsequently environmental protection authority of Ethiopia was established in 2005.

Hence, restoring quarrying in fact was not compulsory and in some cases not even considered before the aforementioned authority was legally established, even today, it is not accomplished very well even though strong words are written on the legislation. However, it seems, the situation radically changed since the beginning of the 2000s, when the new federal law was issued and the establishment of the environmental protection in ministerial level in 2011. In this law, environmental impact evaluation was rendered compulsory, and also environmentally sustainable planning and management of quarry operations and products are given due concern. For Ethiopia, it seems it is the beginning to think about environmental protections since we are now feeling the effects and we need to implement the new legislation aggressively to save our natural resources of the country. The new regulation brought the obligation of quarries restoration, thus helping to reduce negative environmental impacts of quarrying.

Focusing on the environmental impacts, it can provide direct damage to people by inhaling dust, and listening loud sounds. Indirect effects can cause different calamities such as landslides and flash floods. Thus, it is appropriate that certain laws and standards must be implemented to mitigate the impacts. Air pollution is one of the major effects of quarrying. Dust is the most common and the most extensive air pollutant from a quarry. It has different origins in a quarry site such as mechanical handling operations that include crushing and grading process; haulage with which is related to the vehicle, and the nature and condition of the way; blasting; additional manufacturing operations and wind blow from paved areas, stockpiles etc.

Quarrying generates significant amount of noise in its different activities. It starts from the starting phase such as establishment of roads to the site, construction of buildings and facilities. In some instances the next process involves the exposing of the valuable rock or mineral by using scraping equipments to remove the top soil and other layers. The excavation of the mineral contributes more noise than by use of machinery to transport the materials and sometimes having processing plants to crush and grade the materials.

Damage to biodiversity is also imminent by which the natural habitat as well as the species it support is destroyed. There's no helping that the habitat can be destroyed, but when the quarry closes it must be ensured that the site will be fully restored at the end of the activity.

Obviously, creating the pits or quarries requires the removal of virtually all natural vegetation, top soil and subsoil to reach the aggregate underneath. Not only does this lead to a loss of existing animal wildlife, it also leads to a huge loss of biodiversity as plants and habitats are destroyed. Moreover, adjacent eco-systems are affected by noise, dust, pollution and contaminated water.

One of the negative environmental impacts that aggregate production plants have on the environment and on the inhabitants dwelling nearby are the dust that resulted while crushing the aggregate (Figure 7-1 and 7-2).

Figure 7-2 Active quarry showing dust produced by a process of aggregate production in one of the biggest aggregate production plants in Ethiopia

Figure 7-3 Plate showing abandoned quarry site which destroyed large part of forest area in the present studied area

Most of the materials used in the building of cities have natural origin. In obtaining these materials there are a number of active and abandoned quarries which change the natural topography. Generally, before, the 1980, quarry was not backed by reclamation mainly because there was no restoration clause prior to the enactment of the Ethiopian environmental protection authority. The environmental impacts of aggregate and dimension stone quarrying are mainly altered landscape, unused large excavations, subsidence, derelict work sites with compacted and diluted soils and changes in vegetation cover. However, unlike metallic mining, aggregate quarrying does not cause chemical hazardous and contamination and in most cases declared to be safe practice provided that all environmental protection guidelines are implemented adequately.

Abandoned quarries are left open and some of them becoming ponds, or domestic waste is dumped to them which become favourable place for insect breeding (Figure 7-3). Unless old quarries are filled and planted with trees it would be difficult to avoid their hazardous consequences (kebede and Tadesse, 1990).

Figure 7-4 Coarse aggregate crushing plants have effect on nearby inhabitants, schools, hospitals, factories etc. especially when they are located within cities

Figure 7-5 Dimension stone quarry in the studied area, A) Ponds created due to poor drainage system and displacement of the fertile black cotton soil, B) Selected material quarry affecting farm land

Failure to strictly follow proper environmental restoration practice may result in the following unwanted effects (environmental impacts) of aggregate quarrying (according to Ethiopian environmental legislation).

- ponds developed in a quarry can serve as breeding ground for water born disease and mosquitoes,
- land slide and land fall,
- production of dust,
- affecting farm land or cause land use change,
- overburden disposal accumulation,
- the vertical cliffs can cause death to animals and human life,

Figure 7-6 Aggregate quarry impacts, a) Abandoned quarry, b) Abandoned selected material quarry creating ponds, reported by the local people, 2 children were died by drowning in the pond, c) Adjacent streams polluted with sediments and suspended materials, d) Stockpiles on grasslands creating land use problem.

7.2 Mitigation methods

Mining/quarry designers must consider the effects of mine/quarry on its surroundings. Engineering alternatives have to be judged according to their environmental influence. After a plan is accepted, the consequences on the environment have to be monitored. Construction materials producers and communities should as a minimum recognize environmental restoration as a high priority, notably during the authorization process and through the development and execution of environmental managing systems.

The environmental impact that aggregate production quarries have, is drawing the attention of the public in the recent years. Some of the measures to be taken are listed below (Ethiopian environmental legislations):-

- Restoration of the completed overburden disposal areas by cultivating and seeding, and tree planting;

- Abandoned quarries should be cultivated and seeded and trees planted
- Adopt the safest quarry opening method
- Eliminate hazardous high walls; by shooting down the high walls and cover by soil and re-vegetation
- Establish appropriate quarry drainage system
- Rehabilitate quarries and refill irregular and level surfaces around quarry site
- Revegetation is an integral part of reclamation activities. The reasons for this are that revegetation is the most effective and economic method of stabilising the soil against erosion assists in re-establishing biodiversity in the reclaimed area and helps improve visual impacts.

The extraction activity of aggregates from quarries and pits may disturb local communities in various ways and many citizens do not support quarrying in part because they do not recognize the dependence of society on rock as construction materials. Authorities, industry and society must cooperate at the regional and local planning levels for sustainable aggregate extraction to be successful. To ensure the sustainable management and supply of aggregate resources, each of the relevant stakeholders (authorities, industry and society) must accept certain responsibilities.

The ultimate goal of mineral resource policies is not to limit the quantities extracted, thus affecting economic policies and resulting in a shortage of aggregates on the market, but rather to make a proper assessment of requirements in advance in order to plan amounts, methods and mining sites.

The lack of a more "holistic" perspective, both when considering different sources of aggregates and when assessing the impacts of a possible scenario, reduces the possibility to achieve resource effective use at minimal environmental impacts. A more harmonised approach is thus highly desirable, and achievable also by adopting the recent environmental legislation, however this seems far remote in the current ill implementation of the new legislation in Ethiopia.

The aggregates demand should be calculated on a regional and national basis, however calculating the national demand is usually a good approach since it gives more space to optimization of resources production.

CHAPTER EIGHT

8. Discussion of results

The samples collected from the different parts of the project area representing the various geological units have been subjected to various physical, chemical and mechanical tests to identify their potential utilization as raw materials in the production of coarse aggregate and building stone (ashlar, cobble stone and others).

Hence, the field and laboratory works were being compiled and compared together to reveal the engineering performance of the studied volcanic rocks in terms of building stone and coarse aggregates suitability.

8.1 Utilization of the Tarmaber formation as building stone and aggregates

8.1.1 Crushed aggregate for concrete

The Tarmaber basaltic rock shows a variety of textural and mineralogical characteristics which might affect their physical and mechanical properties as well as their use as construction materials. The rock material and aggregate properties of the basalts were compared with the various standards and evaluated for their suitability for different end uses.
The pyroclastic/ignimbrites are traditionally used as ashlars, cobble stone, structural loading, fencing and facades, etc in the studied area. The physical and mechanical properties of these rocks do not warrant for standard uses, especially with regard to their high water absorption, high porosity and low abrasion resistance; however, their good uniaxial compressive strength and high ultrasonic velocity highlight the possibility of using in local level, such as multi family residence houses, block offices with limited number of employees and small business offices as internal pavements, wall claddings and decorations.

The physical property especially water absorption is found to be a useful property in assessing durability of the various rocks used as building stone and concrete aggregates. It has been shown that rocks with water absorption values greater than 2% are subject to freeze-thaw damage, however, this is not a big problem in the study area since it is located in tropical regions.

According to the test results of the studied samples, the water absorption ranges from 0.6-2.3% which is very low (<2%). The open porosity is also very important in rock strength, for which it reduces the durability of the rock material (Goodman, 1989; Bell, 1998). According to the engineering classifications (Anon, 1979), the open porosity of the currently studied samples is classified as low (1-5%), implying these rocks could be used as aggregate for various applications. Regarding the Uuniaxial Compressive Strength values, it is a useful property both for building stone and aggregates selection. The strength of a rock is an intrinsic characteristic, but the effective strength of an aggregate particle is modified by its shape and size (Ramsay et al., 1974).

Even though it is not directly related, the Uniaxial Compressive Strength of concrete mainly depends on the strength of the aggregates. Smith and Collis (1986) indicated that the rock material used for concrete should be unweathered and with high strength. Furthermore, according to Dearman (1991), the Uniaxial Compressive Strength of the parent rock should be higher than 35MPa for concrete aggregate production. However, Lorenz et al. 2003, stated that for aggregate production by crushing, parent rocks should have Uniaxial Compressive Strength greater than 60MPa. In any case, all the studied basaltic samples are quite suitable for concrete aggregate production in both regards since the uniaxial compressive strength of the studied basaltic samples ranges from 130MPa to 350MPa. According to BS: 812 part 105, the Flakiness Index of crushed stone aggregate should be a maximum of 25%; in this case most of the samples meet the mentioned requirements. Basalts having high specific gravity are used for production of special concrete even though they create workability problem.

In addition, the aggregates water absorption is an important property in determining mixing ratios. Therefore, aggregate with low water absorption values are in high demand for quality concrete manufacturing. As indicated by Fookes, 1980, high strength concrete can be made with rock of low water absorption (<2%). However, in accordance to BS 812:8007 and ASTM C-127-88, aggregate water absorption value should be less than 3% and 2.5%, respectively. In both standards, the studied basaltic samples are suitable for high strength concrete production considering their water absorption. In this regard, the aggregate water absorption value of the aphyric dense basalt (TB-AG-02, 0.6%) is lower than the other basaltic units indicating superior quality of this unit.

According to BS 812: Part 1, the uncompacted bulk density of normal aggregate should be between 1200-1800kg/m^3; therefore, the studied basaltic samples are well suitable in reference to the above standards. The olivine-plagioclase phyric basalt sample from the uppermost basaltic layer has shown the highest bulk density (TB-AG-04, 1549kg/m^3). The results obtained for Aggregate Impact Value and Aggregate Crushing Value tests are mainly affected by inherent geological factors namely, petrology, petrography, and fabric (Ramsay et al., 1974). A high crushing value indicates a weak, potentially nondurable material and Fookes, 1984, stated that Aggregate Impact Value and Aggregate Crushing Value should be less than 25%. However, BS 812: Part 110 (1990) recommends that crushing value should be maximum 30% of its weight. In this case except one sample, almost all studied samples meet the mentioned specification. The variation in Aggregate Impact and Crushing Values can be attributed to the influence of aggregate particle shape and geological features such as: bulk composition, grain size, texture and weathering (Fookes, 1986).

According to Smith and Collis, 2001, aggregate in the Los Angeles abrasion test suffers a combination of attrition and impact, with the latter probably more significant. As a result, Los Angeles Abrasion Values are influenced by the same geological and clast features, which affect Aggregate Crushing Value and Aggregate Impact Value. The Los Angeles Abrasion Value of the studied samples ranges from 12% to 30%, while UNIEN and AASHTO T-89 states the maximum allowable value is 35% up to 40%. Therefore, the studied samples have shown superior quality interms of Los Angeles Abrasion test results.

As defined by Smith and Collis, 1993, the durability of aggregate is the capability of individual particles to maintain their integrity and resistance against the deterioration of physical, mechanical or chemical changes to an extent which could adversely affect the properties or performance of concrete. **Soundness and the resistance to abrasion**, apart from **Alkali Silica Reactivity**, are probably the most common properties of rock that need to be addressed in order to maintain the integrity of the concrete mix.

According to ASTM C 33-86 (1986), sodium sulphate soundness values for coarse aggregates should be less than 10%. The Soundness values of the studied basalt aggregate samples have shown extra superior quality, except a single sample. Regarding the Alkali Silica potential reactivity, most samples fall in the “Innocuous” field which means non reactive while a sample (TB-AG-03) is found to be “Potentially Reactive” according to the quick chemical test (ASTM, C-89), and subsequently the sample was subjected to detail petrographic examination and XRD analysis which later confirmed the presence of deleterious quartz variety.

Rock petrography is important in determining the physical and chemical characteristics of the material that have a bearing on the performance of the material in its intended use. Thin sections were prepared from rock samples obtained from aggregate sources that can potentially be developed into quarries and from active quarries. Petrographic microscope was used to study these thin sections. Rock features like minerals present and their mode of occurrence, grain size, approximate percentage composition of each mineral and texture have been highlighted. Detail petrographic examination of the samples under a polarising microscope reveals the presence of cryptocrystalline quartz (chert/opaline) silica, zeolite, ilmenit/magnetite and high proportion of glass in some of the studied samples.

The interaction of various minerals and alkali hydroxides in a concrete mix has also been critically studied. The presence of silica-bearing components in some of the samples was reviewed, due to the possibility of long-term reaction within the concrete if they are used as sources of aggregates for construction. These two groups of minerals (reactive quartz and zeolite), if present in certain proportion in a concrete mix, can cause swelling and cracking of the concrete. The expansion causes misalignment of structures and can threaten structural integrity. Cracking can lead to reinforcement corrosion and other durability problems.

Aggregates are major constituents of Portland cement concrete and in general the coarse aggregate constitutes about 65-75% by volume and 70-85% by weight of concrete. Cement shrinks on drying, if the aggregate is strong, the amount of shrinkage is minimized and the cement–aggregate bond is good (Bell, 1986).

The quality and characteristics of aggregates and cement paste as well as paste aggregate bond influence the properties of concrete (Neville, 2000). Published literatures (ACI committee 318, 1989; Ramsay, 1974) indicates that in-service behaviour of concrete depends on properties like water cement ratio, porosity, bond strength in compression, freeze-thaw and abrasion resistance. However, petrographic properties coupled with engineering properties of aggregates are the prime features that control the strength and durability of concrete. The important parameters of coarse aggregate are its shape, texture and maximum size that affects the properties of fresh and hardened concrete. Surface texture, mineralogy and shape affect the bond between the aggregate and cement paste and the stress level where micro-cracking initiates (Aitcin, 1990).

Concrete is more workable when smooth and rounded aggregate is used instead of rough, angular or elongated aggregate (Young, 1981). Crushed stone produces much more angular and elongated aggregates which have a higher surface-to-volume ratio, better bond characteristics but require more cement paste to produce a workable mixture (Neville, 2000). The currently studied aggregate comprising of Tarmaber basalt is angular and irregular in shape. The surface texture of aggregate may be complex but can be either considered smooth or rough. Smooth surface improves workability, whereas rough textured surface leads to a stronger bond between the paste and the aggregate there by creating a higher shearing strength. The surface texture also depends on the mineralogy of the aggregate (Smith and Collis, 1983). The Tarmaber basalt crushed aggregate exhibits rough texture due to the occurrence of various coarse and medium size minerals such as plagioclase and pyroxene. The contribution of different types of coarse aggregate to concrete strength has been reviewed by Aitcin, 1990 and this study indicates that petrographical and mineralogical characterstics of coarse aggregate control the strength of concrete. The minerals of the aggregates must be tough and fine grained in order to produce durable and sturdy concrete (Johansen and Anderson, 1989). As far as durability/strength of concrete is concerned, the rough texture of Tarmaber basalt aggregates will be good in developing an excellent bond between aggregate and cement paste due to its rough surface texture.

Petrographically, it was not so simple to identify deleterious constituents except some types, however, XRD analysis on selected samples show insignificant amounts of zeolite which has been also identified during the thin section study. Such insignificant amounts of zeolite may not trigger deleterious alkali silica reaction due to the low percentage. The glassy rhyolite is rich in volcanic glass and cryptocrystalline quartz (chert/opaline silica) as has been discussed previously. These are highly deleterious if used with ordinary Portland cement in concrete aggregate.

The use of larger maximum size of aggregate particles influences the strength. This is because larger aggregate particles have less specific surface area and the aggregate paste bond strength is reduced due to which compressive strength of concrete is reduced (Cook, 1989; Zia et al., 1993). The use of larger aggregate particle reduces the volume of paste providing restraint to volume changes of the paste. This concentrates more stress in the paste initiating microcracks prior to application of load. It may therefore, be concluded that smaller size aggregate produce high strength (Cook, 1989). According to Cook (1989), it is clear that aggregate for use in concrete must range from fine to coarse size (10mm to 25mm) for best performance and durability. Alexander and Addis (1992) studied the influence of aggregates and interfacial bond on the mechanical properties of high strength concrete, using different aggregate and indicated that basaltic aggregates make a better bond with cement paste as compared to all others. As far as physical properties are concerned, the tested Tarmaber basalt aggregate samples fall within the acceptable ranges as compared to various time honoured standards.

Mechanical properties like impact value, crushing value, Los Angeles value, and soundness are important parameters. Aggregate impact value is nearly the same for all rock samples except sample TB-AG-03 which is 32% (rhyolitic glass) while others ranges from 12% to 19%. This implies that basaltic rocks are definitely better in mechanical strength than the rhyolitic glass. Aggregate crushing Values and Impact Values are the basic strength parameters that are given in chapter 6 and Table 6-3.

As has been discussed earlier, ordinary Portland cement by volume contains about 60-70% coarse aggregate and is considered as manmade artificial rocks. The strength of concrete is considered to depend on rocks aggregates and its paste (Neville, 2000).

Besides, the occurrence of deleterious minerals and ASR potential aggregates can result in onset of Alkali Silica Reaction in cement concrete in the absence of proper measures. It may lead for unacceptable expansion in structures. The Evaluation of the ASR potential is carried out in the present study using petrographic examination (UNIEN 124070:2000) and quick chemical test (ASTM C289).

In order to develop relationships between the various physical and mechanical properties like water absorption, Unconfined Compression Strength (UCS), ultrasonic P-wave velocity, porosity, Schmidt hammer rebound number, bulk density, simple regression analyses have been used. Regression analysis is normally used to create a mathematical model that can be used to predict the values of a dependent variable based upon the values of an independent variable. Different curve fitting relationships, such as linear, exponential, logarithmic, polynomial, and power, were used to analyze the relationship between a dependent and independent variable. The curve fitting relationships produce a coefficient of determination R^2. The coefficient of determination is the measure of the proportion of variability on one variable that can be accounted for variability on the other variable. In this regard some of the physical and mechanical properties were found to have good correlation coefficients which could be used to predict the unknown from the known easily available low cost property of the rocks in the study area.

For the aggregate producer, the concrete aggregates are end products, while, for the concrete manufacturer or for the contractor, the aggregates are raw materials to be used for mix designs and successful concrete production. In order to optimize the aggregate-concrete chain, one has to know the aggregate quality characteristics that dominate different concrete properties.

Securing the suitable type of aggregate for concrete mix starts from selection of a suitable source that can be used for production of aggregates, which satisfy standard requirements and then follows the production process of aggregates. Finally, transporting the product to the place where, the different ingredients are mixed and concrete is produced becomes the last part of the process.

Generally, two types of aggregates are used for concrete production in Ethiopia; coarse aggregates and fine aggregates. Crushed rock aggregate is used as coarse aggregate and river sand is used in most cases as fine aggregate. Since aggregates are directly, without their chemical composition being altered through the production process, used for concrete production it is important to take proper care while processing and handling them. In addition, it is important for the concrete producer to be aware of the influence of the properties of aggregates on concrete.

The physical properties like specific gravity, porosity, thermal, and chemical properties of aggregate are attributed to the parent rock. However, the shape and surface texture of natural aggregates are attributed to the mode of production in some extents. It is, therefore, very important to give due attention to the source and mode of production of concrete aggregates.

Of the different properties of aggregate; Specific gravity, Unit weights, Surface moisture, Porosity and absorption, gradation, maximum sizes are those which influence the property of the concrete significantly. In addition, physical properties which include shape, texture, and strength are also important parameters that affect the final product, the concrete. Furthermore, aggregate particle shape and texture have decisive influence in the property of concrete. Crushed and angular aggregates are good for strong concrete production but they require more water for workability than gravel and smooth surfaced aggregates.

It is now recognized that for many conditions, the most significant property of concrete is its durability. There are many aspects of concrete durability, and practically all are influenced by the properties of the aggregate. These include Alkali-Aggregate Reaction which in turn is controlled by selection of non-reactive aggregates, use of low alkali cement, use of corrective admixtures such as pozzolanas and controlling the void space in concrete.

The other important property of aggregates with regard to durability is soundness. According to all the tests in this study, the soundness values of all the rock samples have been found to satisfy the requirements set by the various standards. This is an indication that the rocks in the study area are suitable potential sources for production of concrete aggregates.

With the same token, deleterious substances can also attribute to the durability of concrete. Unless concrete aggregates are free from impurities and deleterious substances, the durability of the concrete is in question. This is the very reason why aggregates should be tested and washed before they are used for concrete production. Furthermore, production process of aggregates has significant effect on the property of the aggregates which also influence the chattels of the final product i.e., the concrete.

The environmental impact that aggregate production plants have is drawing the attention of the public in the recent years in Ethiopia. In addition, the relation between the aggregate industry and its surrounding society will be determinant for the industry’s survival potential. Some of the environmental impacts of aggregate production are: formation of ponds, formation of high vertical cliffs, dust production, affecting land cause and land change, sound and vibration on the neighbouring inhabitants which in the long run shall bring about health problems.

Although mineral aggregates generally have a low unit value, their large consumption makes them one of the most valuable mineral resources in terms of total annual production. Ethiopian aggregates resources are large, although not necessarily at or near the locations where needed. Also, competing land-use and environmental restrictions further limit the quantity of available resources, recently. Access and quality requirements for some uses, are additional factors.

There is little sign of using recycling of demolition concrete and asphalt, especially in large urban and industrial areas. However, this activity is not so far well practiced in Ethiopia and it seems also far remote since urbanization and industrialization remain always at its infancy in Ethiopia.

Currently, basalt is the preferred rock type, and is quarried in several parts of Ethiopia which are mostly unweathered. Basalts of Miocene age are exposed in north western central highland volcanic plateaux of Ethiopia covering extensive part of the plateaux. The massive basalt variety from lava flows is used for road construction and concrete aggregate, whereas scoria is used for decorative and drainage applications. Some, however, is suitable only for low-grade products because of the presence of deleterious accessory minerals or glass as discussed in the previous chapters.

Dense, unweathered basaltic rocks are crushed for concrete aggregate, sealing chip, ballast, and base course aggregate. The more rubble and vesicular varieties of lava and scoria have been used for lightweight aggregate, absorbent drainage systems, and temporary road making. However, the need for physical and mechanical characterization of the parent rocks is a must do if one needs to produce high grade aggregate from the basalts since there are various flow layers of basalts in the volcanic province of Ethiopia with diverse chemical, physical and mechanical properties.

8.2 Economic potential of the Tarmaber formation/basalts

Markets for aggregate are strongly dependent on population density and resulting demand for building and highway construction. Transport costs are a major part of the end price and therefore a next-door source is preferable in any case. However, where smaller quantities of higher-quality aggregates are required, or there is no suitable local source, a higher unit price may be acceptable and material can be transported to greater distances. So, these factors may determine the quality level of an acceptable aggregate and the distance it can be transported to an area devoid of any suitable aggregate source rock.

The availability of different types of transportation also has a major impact on the location of production. Quarries located on, or near major transportation routes are often able to reduce transport costs and be competitive in some markets. Truck haulage is the most common mode of transporting aggregate and is the preferred choice for distances up to 50 km (Tony, 1991). Rail haulage is often used for intermediate distances of 50 km to 100 km, when producers have access to rail connections and stockpiles can be maintained in close proximity to mineral consumers.

In Ethiopia, truck haulage is almost the only form of transport used for aggregate; however railway transport is evident in the near future in Ethiopia. Currently there are huge railway projects running in the country of which one of them is passing via the currently studied area to the capital city.

Currently Ethiopia is one of the fast growing developing countries in Africa. It is expanding its civil infrastructures. These infrastructures include highways, motor ways, power plant projects, housing schemes and lining of irrigation channels etc.

In view of these booming infrastructures; Ethiopia needs enormous quantities of high quality rocks construction material (dimension stone and aggregate) to cater the needs of the construction industry in the coming decades. Aggregates are the basic ingredients in the manufacturing of asphaltic and cement concrete (Smith and Collis, 1993). In general, aggregates for construction in Ethiopia, are derived from outcrops by crushing and screening. Published literatures (Aitcin, 1991; Neville, 2000) indicated that a rock used in producing aggregate must possess high strength so that the produced aggregate can contribute to long lasting strength and durability of infrastructures. Throughout the studied area, it has been observed that the aggregate deposits are being exploited without keeping in view of their optimal economic end use. In order to conserve and ensure proper use of resources of aggregates, a proper characterization of different rock formation as crushed aggregate source; must be carried out to match their properties with end uses to avoid using high grade resources where lower quality materials satisfy end use.

In many cases (Barksdale, 1991; Neville, 2000) the mode of extraction of raw materials and method of processing may play an important role in the quality improvement of coarse crushed aggregates. As described earlier the AASHTO, ASTM, UNIEN and BS standards have been followed in the present studies to evaluate the aggregate test results.

CHAPTER NINE

9. Conclusions

The focus of new construction has shifted inescapably from the developed to the developing world in recent decades, and this trend will continue well into the present century. While restrictions on aggregate usage for minimizing environmental damage and other issues may become increasingly strict in the developed world, restrictions of the same severity may not always apply to the developing world, at least not initially. This reflects the urgent need in the majority of the world for adequate housing, transportation, health and education facilities, and so on. While such needs remain paramount, aggregate production will be required to meet those needs.

Many different naturally available geomaterials are used for different purposes after subjecting them to certain modifications and changes. The dearth of commonly used geomaterials (granite, marble, etc) and the increasing demand have led to a profound and new search, which resulted in the use of BASALT“a naturally occurring rock as a construction material.”

In this work all the available geochemical, geological, physical, mechanical and petrographical data from the literature, field observation, intensive laboratory works have been compiled and synthesised to draw the following conclusions, since a better understanding of the engineering properties of rocks can provide a base for a more rational approach to use these rocks in civil engineering works.

Understanding of physical and mechanical properties can be useful both for initial selection and for diagnosis of the deterioration processes of building stone. We do not need only laboratory measurements of physical properties but also observations on the rocks in-situ are most important.

The construction industry needs to move toward material laboratories in order to ensure quality and establish adequate confidence regarding the material used to satisfy given requirement and quality during the service life. Quality assurance of materials, therefore, as a first step needs testing of materials on the basis of specifications that should ensure and increase the confidence regarding fitness for the purpose of product and services.

Turning to the main topic under discussion, during the early Cenozoic, extrusion of flood lavas occurred from fissures and centres and covered the greatest part of the Mesozoic sedimentary rocks and some deeply weathered basements of Ethiopia. The earliest and most extensive group of volcanics termed as Flood Basalt (FB) are estimated to cover about 600,000km^2 in the central part of Ethiopia. These flood basalts have been divided into two groups, the Ashange group and post Ashange group which contain Aiba and Alaji fissural volcanism. The fissural Alaji volcanism is followed by central type volcanism which built up large shield volcanoes named Tarmaber central type volcanic rocks (Tarmaber formation/Megezez subdivision). However, recent classification approach by various workers based on TiO_2 content, the Ethiopian continental flood and shield basalts are grouped into three magma types: two high Ti group and one low Ti group. The current study focuses on the central type (Shield volcano) of Tarmaber formation (high Ti group) basalts and associated subordinate pyroclastics (ignimbrite). This study deals with the geology, geochemistry and engineering geology properties of dimension stone and crushed stone aggregates extracted from the Tarmaber formation (Megezez subdivision) in the studied area. The rock types exposed in the project area belong to the Tarmaber formation/Megezez subdivision.

The Tarmaber formation/Megezez subdivision in the studied area is made up of phyric basalt, minor basanites, trachybasalt, aphyric basalt, ignimbrite, rhyolitic glass and tuff. Mineralogically, the mafic rock suite includes plagioclase (andesine, albite), pyroxene, opaque/Fe-oxides, olivine, while the felsic suites is predominantly ignimbrites, rhyolitic glass and tuff. The ignimbrites are composed of quartz, sanidine, and rock fragments and glass. The ignimbrites and tuffs are found interbedded with the basalts from bottom to top. Chemical analysis (XRF) was carried out to determine the mineral composition and to understand the nature and degree of alterations of the various rock units of the Tarmaber formations/Megezez subdivision.

Geochemically, the Tarmaber formation represents alkaline to sub alkaline bimodal mafic - felsic associations. Slightly depleted of K_2O and enrichment of Na_2O occurred in the mafic units. In addition, silica undersaturated rocks both in (modal and Norm) composition are observed. The mafic rocks are also low in MgO (<7%) and low Mg # (<60), high P_2O_5 and TiO_2 which might represent highly evolved magma from deep mantle sources. The lack of calc-alkaline rocks (andesite, dacite and rhyolite) suites in the Tarmaber formation suggests that the volcanic rocks are unrelated to subduction tectonic setting and probably it could be related to intraplate/anorogenic volcanism from a deep mantle plume source.

The physical and mechanical properties (porosity, density, uniaxial compressive strength, ultrasonic velocity, point load index, water absorption, abrasion resistance etc) of the basaltic and pyroclastic (ignimbrite) rocks indicated these rocks could be used as cobble stone, masonry stone and slabs for sidewalks. The ignimbrites/welded tuffs are the more preferred varieties for cobble stone and masonry even though the water absorption and porosity is a bit higher than the specified limits. The basalts are also very good building stones as far as physical and mechanical properties are concerned except the excessive hardness which might require special equipment to produce required size dimension stone.

Regarding aggregate properties, every rock unit has its own properties depending upon its mineralogical and textural characteristics. Flakiness and Elongation indice are generally considered to be an inherent property of the rock itself depending mainly upon its mineralogy, texture and structure; and partly on the crushing methodology/techniques. The Flakiness index ranges from 15% to 43% while the elongation index ranges from 15% to 38%. However, most samples fall in the range from 15% to 25% which meet the BS 812: part 105 specifications as concrete aggregate.

Aggregate Crushing, aggregate Impact and Los Angeles Abrasion Values are the basic strength parameters to evaluate the strength and durability of the aggregate. Aggregate crushing and impact values of the various basaltic rock samples ranges from 15% to 22% and 13% to 19% respectively. These values are good for surface concrete aggregate construction. The ACV and AIV of the rhyolitic glass ranges from 32% to 36% respectively and might be used for base course in unbound pavement since BS 812: part 110 and 112 restricts ACV and AIV to be less than 25% for concrete aggregate mix. The Los Angeles Abrasion Value is good for all tested samples (<35%, UNIEN 12620).

The minimum values of ACV, AIV, and LAAV are obtained from aphyric and columnar basalts which are dense and compact on visual inspections. In regards to the use of these basaltic rocks in concretes, they can be used in the construction of roads and buildings by virtue of the excellent engineering properties and petrographic characteristics.

Petrographic quantitative (modal) analyses of aggregates, specifically dedicated to the determination of ASR susceptible phases, have been carried out according to the UNIEN 12704:2000. These were integrated with X-Ray Florescence Spectroscopy (XRF), and X-Ray Powder Diffraction (XRPD) analyses and the quick chemical test (ASTM C289), coupled with geological field observation to scrutiny the ASR of basaltic units. As a result, most samples plot in the "Innocuous "field which means non reactive, while the rhyolitic glass is found to be "Potentially Reactive", according to the quick chemical test (ASTM C289) and the detailed petrographic examination (UNIEN 12070). Therefore, it is concluded that rather than identifying specific rock types as characteristically as nonreactive and others reactive, ASR test on each rock types should be carried out.

As stated by Smith and Collis, 1993, the durability of aggregate is the ability of individual particles to retain their integrity and not to suffer physical, mechanical or chemical changes to an extent which could adversely affect the properties or performance of concrete. Soundness and the resistance to abrasion, apart from Alkali Silica Reactivity, are probably the most common properties of rock that need to be addressed in order to maintain the integrity of the concrete mix. Hence, according to ASTM C 33-86 (1986), Sodium Sulphate Soundness Values for coarse aggregates should be less than 10%. In this regard, the Sodium Sulphate Soundness Values of the basalt aggregates show extraordinary superior quality with respect to the standard limits specified in ASTM C 33-86.

The extensive occurrence of ignimbrite, basalt, trachybasalt and rhyolitic glass can be used for local construction purposes like masonry, cobble stone and sidewalks. During the construction of Addis Ababa-Debresina asphalt road in the years 2008-2010, many quarries were opened in the currently studied area (now some are abandoned) to produce sub base and base course and crushed basalt aggregates and to unearth selected materials. However, some of the crushed aggregate source rocks are now found to be alkali reactive potential and low quality in terms of physical and mechanical properties.

Specifically, the aphyric basalts can be used as crushed aggregate (gravel and sand size fractions) for concrete mix in large sized buildings, bridges and roads. Also, the phyric basalt in rare cases and large volume of ignimbrite slabs are used by the local people for the construction of houses, fences and other masonry works and this trend should continue also in the future. The rhyolitic glass and ignimbrite are used locally as a building material since these rocks are easily cut and shaped. Sufficient and good quality ignimbrites which can be used as masonry are exposed particularly in the vicinity of Debrebirhan and Chacha towns. There are a number of existing quarries exploiting ignimbrite rocks for masonry used in the construction of buildings, bridges, culverts and other engineering structures. These existing ignimbrite quarries are sufficient, good quality, workable and accessible.

Coarse crushing of basalt rocks to the size of gravel is needed for raw materials for road construction and there are a number of crushers producing all sizes of aggregates in the study area, some are active and others are out of function. Larger sizes are also important for foundations and structural loading. Fresh, very strong to strong basalt is found in sufficient quantity and good quality for crushed aggregate production. Such rocks are well exposed at different parts of the studied area forming high relief hills, a resistant upper scarp zone and lower valley slopes. Several active and abandoned basalt quarries are found in the various parts of the studied area. The rock is easily workable due to systematic three/four sets of columnar jointings.

The current research presents a conceptual framework which puts forwarded a vision for aggregates characterization typical to the studied area (Figure 9-1). It integrates two major facets of characterization namely the aggregate source and the basic properties obtained through physical and engineering testing. The above two facets are linked with application side where the standards come in place to define suitability of the aggregate for a given application such as concrete, asphalt etc. The output of the characterization is an aggregate resource which can provide future resource reference of the Tarmaber basalt for ready utilization in the context of Ethiopian construction industry. It may be concluded that the current research would provide results which would be highly beneficial to the construction industry in Ethiopia.

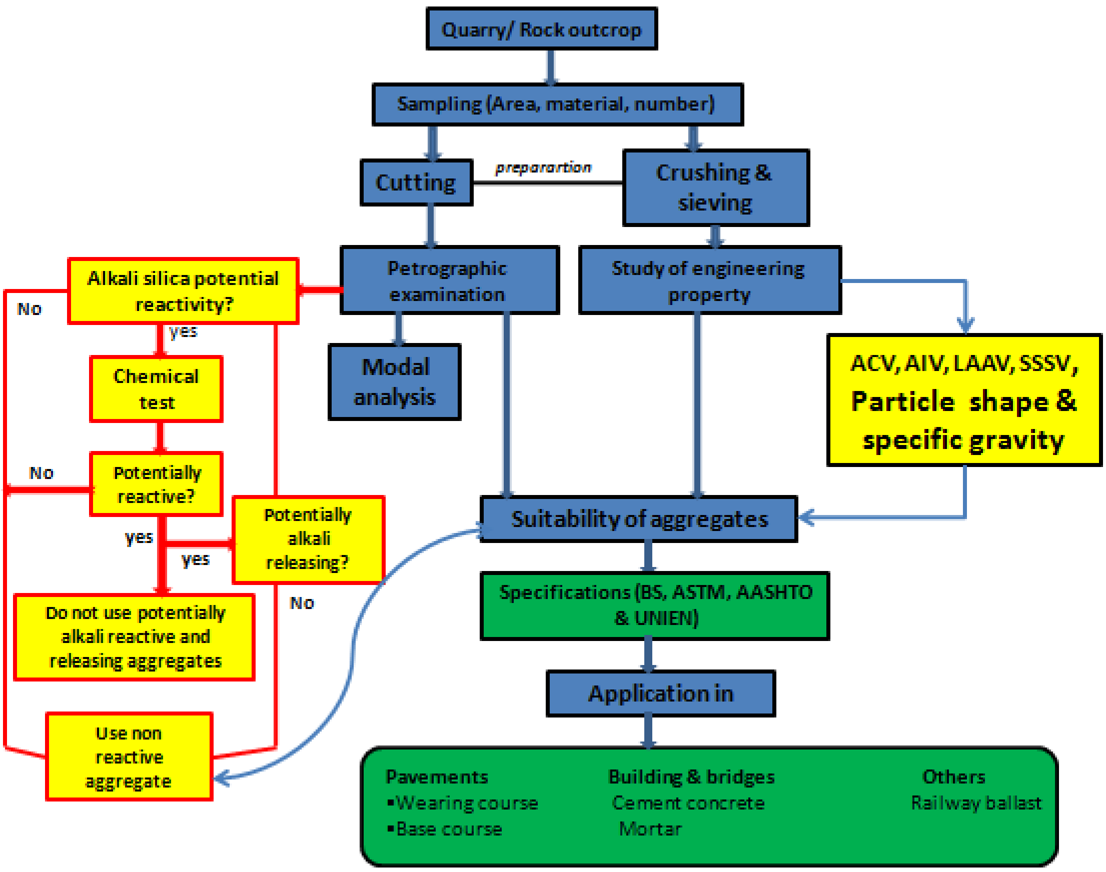

Figure 9-1 Conceptual framework for aggregate characterization of the Tarmaber formation

Crushed stones are the main types of natural aggregates produced and used in Ethiopia. The high demand of aggregates, production facilities without planning and insufficient investigations, the lack of good quality aggregate and urban development, force the construction sector on the evaluation of further potential aggregate sources. It should be highlighted, however, that most quarry concessioners are reluctant to implement best practice codes when that reduces their profit. This is due to the fact that most companies do not have management vision and do not consult modern management practices. In Ethiopia, and also in many other African countries, most crushed aggregate producers are ignorant of sustainable practices and environmental conscience: for this reason areas of environmental protection are usually seen as developmental barriers.

Mining of rocks usually results in environmental degradation, this can be reduced by incorporating Environmental Impact Assessment (EIA) report to include land restoration at each phase of the life cycle of the quarry/mining. However, in the case of natural aggregates production, different environmental impacts can be associated with quarrying and subsequent use. In addition, a complex set of direct and indirect issues must be taken into account.

Dimension stone mining, by the very nature of the requirements for the final product is a clean industry from a polluting point of view. However, the visual impacts are often significant, given that many deposits are situated in hills or mountains.

Coarse aggregate constitutes a major part of Portland cement concrete and is therefore a major determinant of its performance. A classification system for coarse aggregate would provide a systematic means for identification of aggregates, which could be used in the selection of aggregates for different design and construction combinations.

The ultimate goal of the above characterization scheme (Figure 9-1) is to optimize the selection of coarse aggregate to be used in concrete mix. The backbone of a system to classify coarse aggregates is based on keying on a few significant properties of coarse aggregates which affect performance with relevancy to the geographical location.

In synthesis, rapidly growing population, increasing industrialization and the need of better housing and other infrastructures in Ethiopia have resulted in intensive building and construction activity in recent years. Crushed stone, sand and gravel are the main types of natural aggregate used in this country mainly in the regional capital cities. In this work, the properties of aggregates produced in the studied area and as would be quarry sites were studied and compared to the various specifications used in the construction industry.

After reviewing the literature and examining how different countries manage geomaterials testing and characterization, it was clear that there is a lack of unified procedures and guidelines. Different countries have adopted different aggregate testing procedures that best fit their needs. It was noticed that there is a great interest in for a unified testing procedures capable of predicting the potential drawbacks of geomaterials. It also seemed that ASTM, AASHTO, UNIEN and BS and modifications or combinations of these procedures are becoming more and more popular and more trusted in giving accurate results.

9.1 Recommendations for future work

So far, the studied area basalts and ignimbrites have been used as construction material both for aggregate and dimension stone/cut stone without any physical and mechanical characterization. This leads to failure of the engineering structures before the design life. The present study identified important physical, chemical and mechanical properties of the

Tarmaber formation in general. However, the following recommendations are given for future consideration:

- Prior to opening an aggregate quarry, it is necessary to conduct adequate physical and mechanical characterization of the rocks to be quarried for the intended purpose.
- There is an incorrect thought that assumes all basaltic rocks are considered as excellent source of aggregates for concrete and asphalt mix; however this is totally wrong, instead attention should be focused on the mineral constituents of the rocks to identify deleterious components
- Quarry sites should be selected systematically and should be properly rehabilitated after mining. This calls for strict and sustainable controlling system by concerned body
- Material laboratories equipped with known standards capable of carrying out the required quality investigation should be established in Ethiopia
- Aggregate identification, quarrying, storage and handling should be done professionally
- It is highly recommended to carry out ASR tests for the various volcanic rocks used in the aggregate industry and necessary to establish the pessimum proportion of each rock type used as aggregate in the Ethiopian volcanic rocks
- The glassy rhyolites and ignimbrites should be utilized only as masonry and cobble stone. It is observed that the glassy rhyolites are used as aggregate in concrete mix. This practice should be avoided as the glassy rhyolite is found to be Alkali Silica Reactive

Since aggregates and cement are non-renewable resources there is no means to reuse them unless they are recycled which of course is a technology that Ethiopia cannot afford to have currently. Therefore, in construction projects and ready-mixed concrete production plants, care should be taken to avoid wastage of concrete making materials as much as possible.

Part II: Sardinian Project area

CHAPTER TEN

10.Generalities

10.1 General background

In Sardinia, in fact stone is the most used natural material in masonry and, from a building point of view; it is the major element that characterizes Sardinian rural building, because of the countless varieties which could be found (Atzeni, 2003).

Basalt produced in Sardinia for architectural and ornamental purposes is obtained by quarrying of stone deposits or mining of huge underground erratic boulders which are cut and extracted with mechanical equipments. Most often, the local extraction companies handle the whole production chain, from the quarry to the finished products. The island's basalt resources are virtually inexhaustible, as a large portion of Sardinia is made up, we might say, of a single extended basalt effusion, with varying degrees of fracturing. The basalts of Sardinia are used for the production of dimension stone and aggregate in light of the excellent technical properties.

Today, the basalt industry of Sardinia proudly carries forward the ancient tradition. Fabrication, mostly done in house by the quarries themselves, is constantly growing through the adoption of state of the art technology and methods. Enabling the local producers of basalt dimension and ornamental stone to meet the most diverse design and installation requirements is utmost important.

As basalt is an extensive igneous rock, mostly it is emplaced by intraplate volcanism, in plate spreading contexts, by means of effusive eruptions with scarce explosive activity. The magma coming from the earth's interior, has a very small gas content, high temperature (1100-1300^{0}c) and low viscosity (runny lava). Some basalt has porphyritic texture, i.e. it comprises of both large crystals (phenocryst) that formed underground and has a well defined shape and microcrystals that formed on the surface, set in a consistent glass matrix. Macroscopically, basalt can be vesicular, due to the presence of gas bubbles in the lava, and to their subsequent degassing at atmospheric pressure, or it can be compact.

Extensive areas of Sardinia have been covered by large volumes of basalt and andesite rocks. Examples are the 'Giare', table lands such as those of Gesturi or Nurri and other large plateaux including Campeda, central Sardinia. Among others Plio-Quaternary basalt rich area on the island are Montiferro, Logudoro, and the Gulf of Orosei, Abbasanta, Borore and Guspini districts.

The current commercially, exploited Sardinian basalt is produced by extensive volcanic activity in the Pliocene and Pleistocene epochs (5-0.1Myr) after the opening of the Campidano plain and Tyrrhenian Sea rift.

For many decades now, the dimension stone sector (quarrying and working) has been one of the most important industries in Sardinia and will continue to be also in the future. The major commercial stone types on the island in terms of produced quantities and those with practically inexhaustible supply are in door: granite, marble, basalt and pyroclastic rocks. Granite and marble are mostly quarried in well defined areas of central and north-eastern Sardinia, while basalt and pyroclastic rocks quarries are mostly located over a large area in central western Sardinia **(*www.lapideisardi.it)***.

The dry laying without the help of binder or mortars, a typical characteristic of stone masonry in premodern Sardinia, would surprise nobody if we consider the skill that the Sardinian builders have shown to possess in this type of building since remote times (Atzeni, 2003). It is worth mentioning here about the Nuraghi as far as we talk stone works in Sardinia. A large number of the Nuraghi are built of large irregular blocks of basalt in most parts of the Island, Sardinia. The Nuraghi are a very well-known Sardinian symbol. It is actually its most representative monument, which recalls its millenary history. Its construction is quite impressive. It can reach 20m, of height. The most important Nuraghes can even count 15 interconnected towers. These constructions were built by the dry-stone technique ("pietra a secco"), without any cohesive material. So, it seems unbelievable that they have survived completely up to our times. They represent a real prehistoric architectural jewel and document the high developmental level reached by the bronze civilization and is mostly made from basaltic rock slip.The hundreds of Nuraghi spread in the regional territory and still perfectly preserved, are good witnesses of this fact (Fig.10-1).

In fact stone is the most used natural material in masonry and, from a building point of view, it is the major element that characterizes Sardinian rural building. A thorough study of

Sardinian historic events indicates that Sardinian building shows many similarities and convergences with other Mediterranean areas despite its strong local character, and it has rooted its origins in the distant past (Atzeni, 2003).

The production chain of Sardinian stone sector comprises quarrying companies, stone fabricators, and companies that both quarry and fabricate. In the past, the Sardinian stone industry mostly focused on quarrying activity, but over the last several decades, modern fabrication and finishing plants have been setup and have expanded steadily. Today, the dimension stone companies of Sardinia process primary blocks. These companies are using state of the art technology to cut blocks and slabs and to manufacture finished products which are marketed and appreciated globally***(http//www/lapideisardi.it)*.**The Sardinian basalts are used in different forms such as, cobblestone, curb stone, flooring slabs, square tiles, setts, flagstone and paving tiles. Basalt paved surfaces are to be found in the largest and most beautiful cities in the world, including those with very cold climates and long periods of frost, giving proof of this stone's excellent physical and mechanical properties. A wide range of paving elements in Sardinian basalt are available, both sawn and split faced. They all have very high breaking, compressive and wearing resistance. The Sardinian basalts were used as masonry stone, historically, ***cantonetti***, or brick-sized blocks, were among the earliest types of basalt building stone. The blocks used in the early centuries of the second millennium to build the beautiful churches of ***Giudicati*** period can trace their origin back to the well squared ashlars, square or rectangular used in the top courses of the ancient ***Nuraghi*** and Sacred Wells. Today, basalt is the building stone of choice not only for beautiful restoration projects, but also increasingly for new buildings where this very resistant versatile stone can be used for the entire structure or just for the facade. Sardinian basalt has excellent technical properties, which ensure the durability of its surface finishes. Its shades of colour range from light to very dark gray or black, from wine red to dark red, and can be arranged in appealing combinations (Figure 10-2). *(Regione Autonoma della Sardegna, Progetto Pilota-Innovazione e tecnologia nel settore lapideo, 2013).*

Figure 10-1 The ancient amazing Nuraghi and churches were built of basalts

Figure 10-2 The modern use of basaltic rocks in Sardinia

10.2 Location

The studied area is located in the central part of the Sardinian island, 175km north of Cagliari city. It represents the Altopiano di Abbasanta and Campeda stretched from Abbasanta to Borore (Figure 10-3).

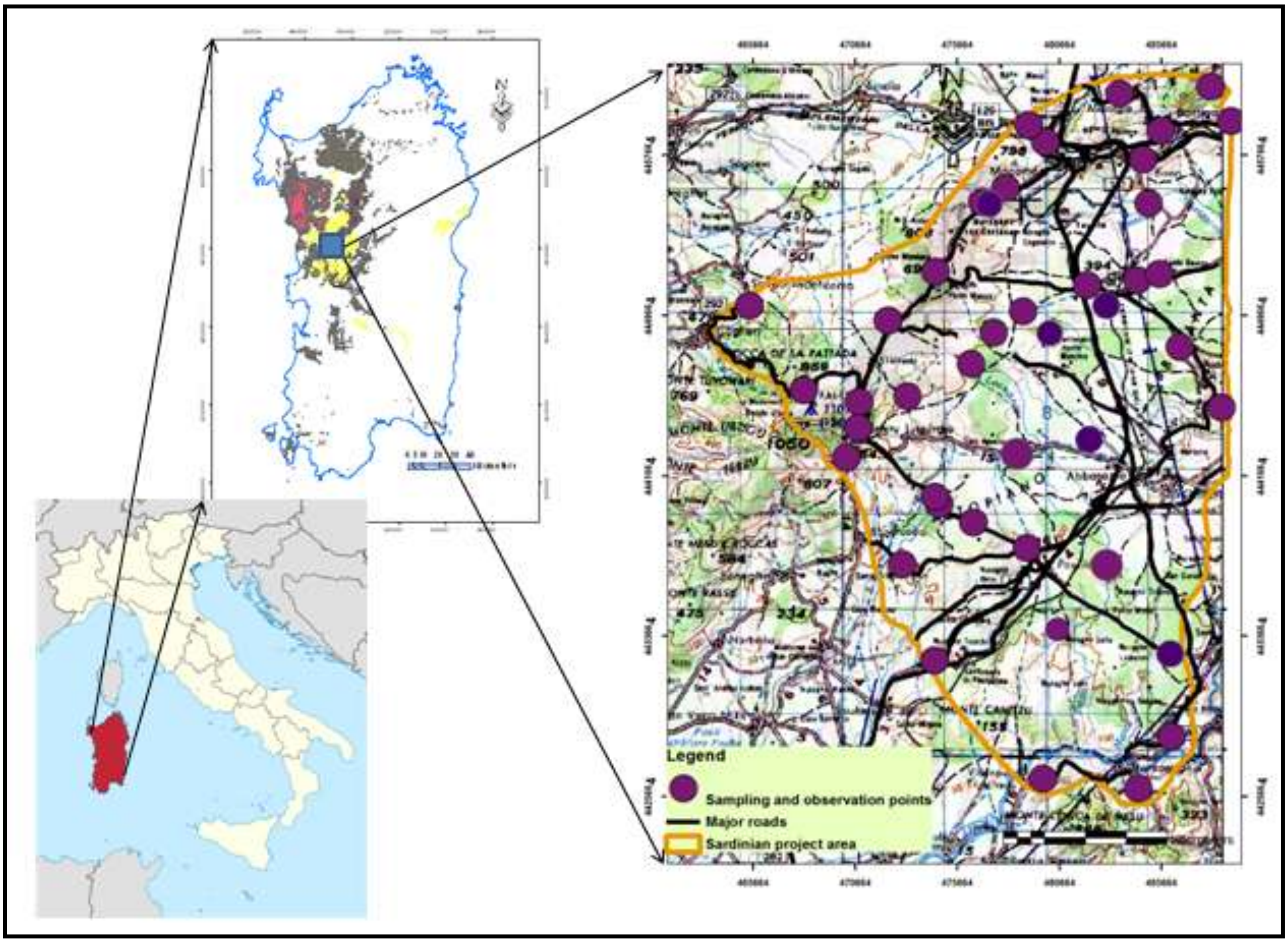

Figure 10-3 Location map of the study area

CHAPTER ELEVEN

11. General geology and landscape

11.1 Landscape

11.1.1 Physiography of the study area

Sardinia is the second largest island in the Mediterranean Sea with a territory of 24,089.89 square kilometres (ISTAT, 2001) which is slightly smaller than Sicily but with longer coastline. The island exhibits low topographic relief dominated by rocky peaks of granite, basalt, trachyte, andesite, pyroclastics and others.

Sardinia hardly seems to be the 'isola Montana' it is claimed to be; only 18% of the island exceeds the altitude of 600 m above sea level and only some isolated peaks reach an altitude over 1,200 m above sea level, as e.g. the Monte Linas (1,236 m) in the Iglesiente massif of west central Sardinia. Exceptionally, the Punta La Marmora in the Gennargentu massif of eastern central Sardinia rises to 1,834 m above sea level, thus constituting the highest peak on the island. The mean altitude of Sardinia is only 334 m above sea level and half of the island lies even below 300 m. From a geomorphologic point of view, as much as 86% of Sardinia must be classified as hilly to mountainous land, while only 13% of the island can claim a genuinely mountainous relief (Pracchi, 1971, as cited in Brigaglia, 1987).

The Sardinian relief is dominated by relatively level highlands that give it a characteristic horizontal appearance, which has often puzzled visitors approaching the island. A 19th century traveller for instance remarked that 'Sardinia, compared with the peaks of Corsica and the gigantic Etna, appears at the horizon as a vast blue plain located in the centre of the Mediterranean' (Pasquin Valéry, 1835, as cited in Le Lannou, 1979).

The impact of the Sardinian relief, however, stems from a dramatic fragmentation of the landscape caused by deep gorges, high uprising ridges and steep cliffs that dissect the highland plateaus into distinct tablelands and smaller plateaus (Le Lannou, 1979).

Although there are very few high mountains, Sardinia is in fact a mountainous region, characterized by much-eroded high plains and plateaux and by steep and abrupt slopes. About twenty percent of the island is comprised of low-lying plains with adjacent terraces to about

200m a.s.l, the largest of which is the Campidano of Cagliari extending for some 110 km from the Gulf of Cagliari to the Gulf of Oristano.

The relief reflects the solid geology and seismic history of the island. The Alpine orogenesis of the Tertiary period created the present relief. There is a system of semi-rifts arranged on a north-south axis which have been affected by several cycles of volcanic activity when basaltic lavas filled the shallow valleys and which have been eroded to create plateaux known as Giare. From geomorphologic point of view, the island can be divided into three sections: the eastern sector has the most variation in relief and includes the **Limbara** and **Gennargentu** mountains; the central area is characterized by broad basaltic lava flows, and the Palaeozoic rocks of the west (Vogiatzakis *et al.* 2005).

11.1.2 Climate, Vegetation and land use

The coastal region of the southwest (Sulcis) and the southern 25 km of the Campidano are plagued by a semi-arid subtropical climate, with less than 500 mm of rainfall per year; to the interior of Sulcis and the Campidano and along the southern coast to the mouth of the Flumendosa as well as on the plain of Orosei runs a band of subtropical climate up to about 10 km wide, with 500 to 700 mm of rainfall per year. Except for two small, moist regions with more than 1100 mm of rainfall per year, much of the remainder of the island -- the western half, the north, and the eastern coastal area -- is temperate to warm, with 500 to 800 mm of rainfall per year and an average annual temperature of 15° to 16.9° C. The remainder is sub-humid, with average temperatures of 11° to 15° C and 800 to 1200 mm of rainfall per year **(***www.usd.edu/~clehmann/erp/Sardinia/geograph.htm***).**

Vegetation communities are typical Mediterranean associations such as forests of various oaks and pines, including extensive cork oak forests, maquis comprising wild olive, lentisk (**Pistacia lentiscus**), juniper, myrtle, and garrigue. Shrubs dominate above the treeline at 800m (Vogiatzakis, 2006).

Agriculture is much diversified which includes viticulture, horticulture and tree crops such as fruit and olives along with sheep farming and cereal cultivation. Therefore most of the study area is serving as pasture land with some plots of olive tree.

11.2 General geology

The geological record of Sardinia, reconstructed through the analysis of the outcropping lithotypes and the correlations with other areas of central and western Mediterranean basin, distinguishes it from the remainder Italian territory and explains why its 24,000 km^2 of territory retain substantial traces of almost all geological ages, offering a sampling of wide range of rocks of valuable varieties (Graziella Marras, 2010).

With very few exceptions (Cioni et al., 1982; Di Battistini et al., 1990; Montanini et al., 1994), up to a few years ago the Sardinian magmatism (~32-0.1 Ma) was excluded from detailed geochemical and petrological investigations, the only scientific papers being mostly confined to the 1970s (Lustrino et al., 2001). From the second half of the 1990s an increasing number of data and interpretations of Sardinian volcanic rocks became available for the scientific community (Morra et al., 1994, 1997; Brotzu, 1997; Lustrino et al., 1996, 2000, 2002; Gasperini et al., 2000). From these studies, a complex petrological scenario became clear, and a large number of hypotheses have been proposed in order to explain two points: 1) the origin of the igneous activity in relation with the Alpine geodynamics, and 2) the origin of the modification that affected the mantle sources of these magmas (as cited in Lustrino et al, 2004a).

The island of Sardinia records two distinct volcanic phases during Oligocene-Miocene and Plio-Pleistocene times. These phases produced magmas with completely different petrographic, volcanological and geochemical characteristics. The Oligocene-Miocene volcanic products (32-15 Ma; Araña et al., 1974; Savelli et al., 1979; Montigny et al., 1981; Beccaluva et al., 1985; Morra et al., 1994; Lecca et al., 1997) are subalkaline, with serial affi nity going from tholeiitic to calcalkaline, and subduction related signatures (Morra et al., 1994, 1997; Brotzu et al., 1997a). On the other hand, the Plio-Pleistocene volcanic rocks (~5-0.1 Ma) are mildly to strongly alkaline (mostly Sodic) to subalkaline (with tholeiitic affinity), with peculiar within-plate geochemical signatures (Figure 11-1, Lustrino et al., 1996, 2000, 2002).

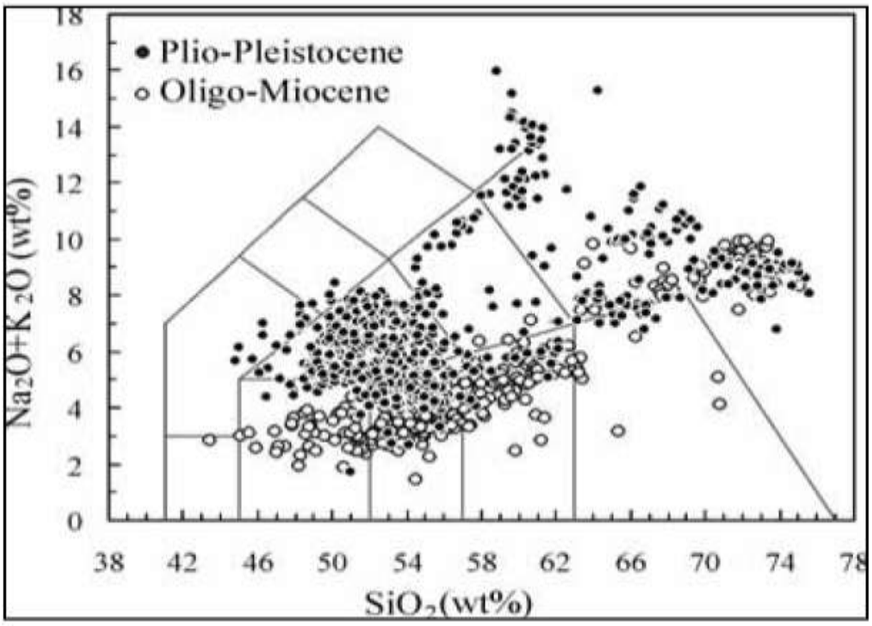

Figure 11-1 SiO_2 vs. Na_2O+K_2O (TAS) diagram (Le Maitre, 2002) of Oligo-Miocene and Plio-Pleistocene volcanic rocks of Sardinia (Lustrino et al. 2004)

The Cenozoic-Quaternary magmatic evolution of Sardinia (the Oligo-Miocene orogenic volcanic cycle followed by Plio-Quaternary anorogenic volcanism) is a common feature throughout the entire circum-Mediterranean area and has its counterparts in many other circum-Mediterranean igneous provinces (Figure 11-2, Lustrino et al., 2004).

Today, the Oligo-Miocene and the Plio-Pleistocene Sardinian volcanic rocks belong to the well-studied Cenozoic European Volcanic Province for which a large set of chemical data is currently available (Wilson and Downes, 1991; Pécskay et al., 1995; Liotard et al., 1999; Jung and Hoernes, 2000; Wedepohl, 2000; Bogaard and Wörner, 2003; Lustrino, 2003, as cited in Lustrino et al, 2007). However, a very limited and still poorly known Eocene (62 to 61Ma) igneous activity with emplacement of a few lamprophric dikes has been discovered by borehole drillings in southwest Sardinia (Maccioni and Marchi, 1994).

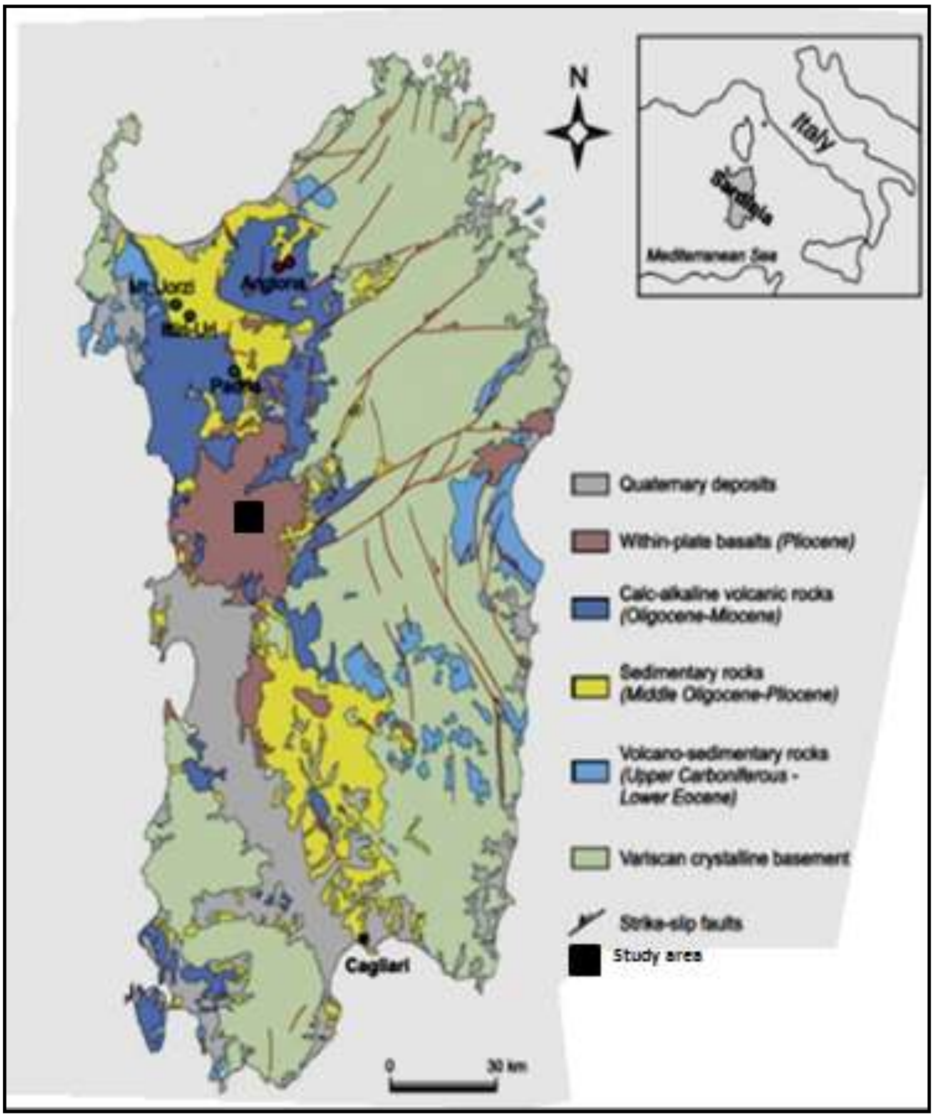

Figure 11-2 Simplified geological map of Sardinia (adapted from Carmignani et al. 2001)

11.2.1 Oligo-Miocene volcanic rocks of Sardinia

During Mesozoic and Early Cenozoic, there were intermittent transgression and regression periods which resulted in the deposition of huge amounts of carbonates as the case of Jurassic limestone plateaux.

However, in the Middle Cenozoic new tectonic events occurred, mainly extensional ones that generated the Sardinian rift; the volcanic phase accompanied with this tectonics led to the emplacement of mainly calc-alkaline volcanic rocks represented by rhyolite, ignimbrite and andesitic-dacite and minor trachytes.

The Oligo-Miocene magmatism is concentrated in western Sardinia along a graben structure known as ***Fossa Sarda*** where as the Plio-Quaternary volcanism is scattered across the island (Figure 11-3). The Oligo-Miocene igneous rocks are mostly calc-alkaline in composition with minor arc tholeiites. Dacites to rhyolitic lavas and ignimbrites are more abundant than andesites and basalts. The Oligo-Miocene rocks have typical arc signatures with low TiO_2 contents (Lustrino et al. 2004a).The orogenic magmatic cycles ended at about 15Ma, when the Tyrrhenian Sea started to open. Successively, Sardinia was subjected to a late Miocene to Pliocene tectonic uplift, followed by a Plio-Quaternary extensional phase and by a new cycle of volcanic activity from about 5 to 0.1Ma that exhibits intraplate signatures (Beccaluva et al.1985a; Lustrino et al, 2004a).

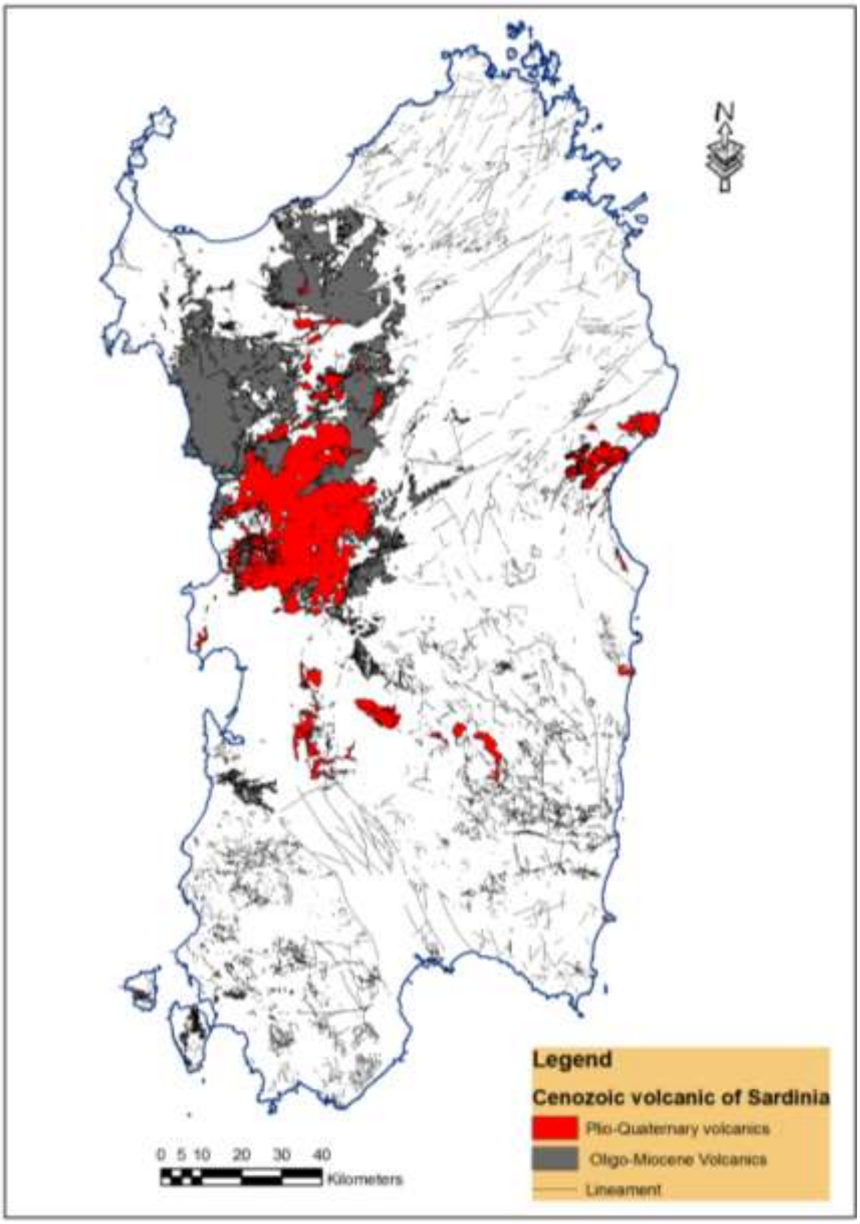

Figure 11-3 Oligo-Miocene volcanic rocks along the Fossa Sarda graben and the scattered Plio-Quaternary rocks of Sardinia

11.2.2 The Plio-Quaternary volcanic rocks of Sardinia

The late Cenozoic Era marks the end of the crustal movements; and after some period of quiescence, however, there is the beginning of a new reactivation phase (which lasted from the late Tertiary and Early Quaternary, especially in central-southern Sardinia).

This tectonic has a within-plate character and is dominated by subalkaline to alkaline basic lavas and differentiated products (Beccaluva et al., 1989; Marchi et al., 2002). In another work, it is mentioned that the Plio-Quaternary volcanic rocks from Sardinia covers a surface area of about 2200km^2 (Lustrino, 1999).

Unlike the Oligo-Miocene orogenic volcanic rocks, which outcrop only along the western side of the island, the Plio-Quaternary volcanics occur both in the eastern and western sectors of Sardinia. This magmatism developed after a pause of about 10Ma after the end of the previous orogenic magmatism (Lustrino et al., 2004b).

The activity is mainly located along normal faults related to the coeval opening of the back-arc Tyrrhenian Sea, interpreted as the middle-Miocene to recent-version of the Oligocene Provencal Basin. In some cases, the vents reactivated Oligo-Miocene magmatic conduits (e.g., at Mt. Arci). The Campidano graben, which crosscuts the island in its southwestern part and which partially overlaps the Oligo-Miocene ***Fossa Sarda***, is the clearest structural evidence of such tensile stresses during the geodynamic evolution of the western Mediterranean Sea. The development of magmatic activity only after the rifting processes, and the lithospheric thickness of about 70 km (Panza, 1984), indicate a strong crustal control on the genesis of this magmatism, being unlikely a mantle plume involvement in the genesis of Plio-Pleistocene volcanic rocks of Sardinia.

Most of the Plio-Quaternary volcanic rocks of Sardinia are basic to intermediate in composition with mildy alkaline; evolved compositions are relatively scarce but make up a significant part of some volcanic complexes (Lustrino, 2007). Subalkaline (tholeiitic) rocks are less abundant than the mildy alkaline types and are mostly basaltic andesites.

Generally, the Plio-Quaternary volcanism of Sardinia is represented mainly by basaltic lava fields with a few large volcanic complexes. From north to south the most important volcanic districts of eastern Sardinia are Orosei-Dorgali and S. Pietro Baunei districts, Rio Girone and Capo Ferrato (Figure 11-4). The most important volcanic districts of central-western Sardinia are **Lugudoro, Campeda-Planargia-Abbasanta-Paulilatino, Montiferro**, **Oristano Gulf, Mt. Arci, Gerrei and Guspini** areas. Published representative geochemical analysis of the Plio-Quaternary volcanic rocks of Sardinia showed that most volcanic rocks range from basic to intermediate (i.e., 45 to 58 wt% SiO_2, as cited in Lustrino et al., 2007). The compositional range of the Plio-Quaternary volcanic rocks of Sardinia is shown in the Total Alkali Silica (TAS) diagram (Figure 11-1). As it has been stated in a number of publications (Lustrino, as cited in Lustrino et al., 2007), the Sardinian volcanic rocks have variable TiO_2 (1.2-3.4 wt %), Al_2O_3 (13.4-18.2 wt %), Na_2O (2.5-5.8 wt %), and K_2O (0.4-3.3 wt %) contents.

The relatively high silica content of Sardinian Plio-Quaternary volcanic rocks could be related to the orthopyroxene rich compositions of mantle sources, as proposed by Lustrino (2005). The orthopyroxene rich compositions of mantle sources of the Sardinian mafic rocks are possibly related to partial melting of the lower crustal lithologies recycled within the mantle by delamination and /or detachment of the deeper crust portions (Lustrino, 2005).

In summary, the major element analysis of Sardinian igneous rocks reflect the superimposed effect of variable degrees of partial melting coupled with variable extents of fractional crystallization processes. The relatively high SiO_2 and the low CaO content of the Sardinian volcanic rocks provide constraints on their mantle sources. Sardinian lavas cannot be related to derivation from a depleted mantle source because their low CaO content should be accompanied by lower contents of lithophile elements like Al_2O_3, Na_2O and K_2O, these depletions are not seen in the composition of the Sardinian lavas. The major element composition of the Sardinian Plio-Quaternary volcanic rocks (in particular their high SiO_2 and Al_2O_3 values and the lower CaO and Fe_2O_3 values) requires derivation from comparatively orthopyroxene-rich lithospheric mantle sources.

In general, the Plio-Pleistocene volcanic rocks of Sardinia have mainly mafic to intermediate composition; differentiated products (both SiO_2 oversaturated and undersaturated) occur as well (Di Battistini et al., 1990; Montanini et al., 1994; Lustrino et al., 1996, 2000, 2002, 2003). Both alkaline (basanite, alkali basalt, hawaiite, mugearite, benmoreite, trachyte and phonolite) and subalkaline types (tholeiitic basalt to rhyolite) are present (Figure11-1). The alkaline rocks are mildly-to-strongly alkaline, mainly with sodic affinity, although some slightly potassic types are also found (Lustrino et al., 1996). The subalkaline rocks are less primitive than their alkaline counterparts and show a tholeiitic character (Lustrino, 1999; Lustrino et al., 2002).

The peculiarity of the great majority of Sardinian Plio-Pleistocene volcanic rocks (>99% of outcrops) is their "transitional" character between typical within-plate anorogenic products and sub-duction modified compositions (Di Battistini et al., 1990; Lustrino et al., 1996, 2000, 2002).

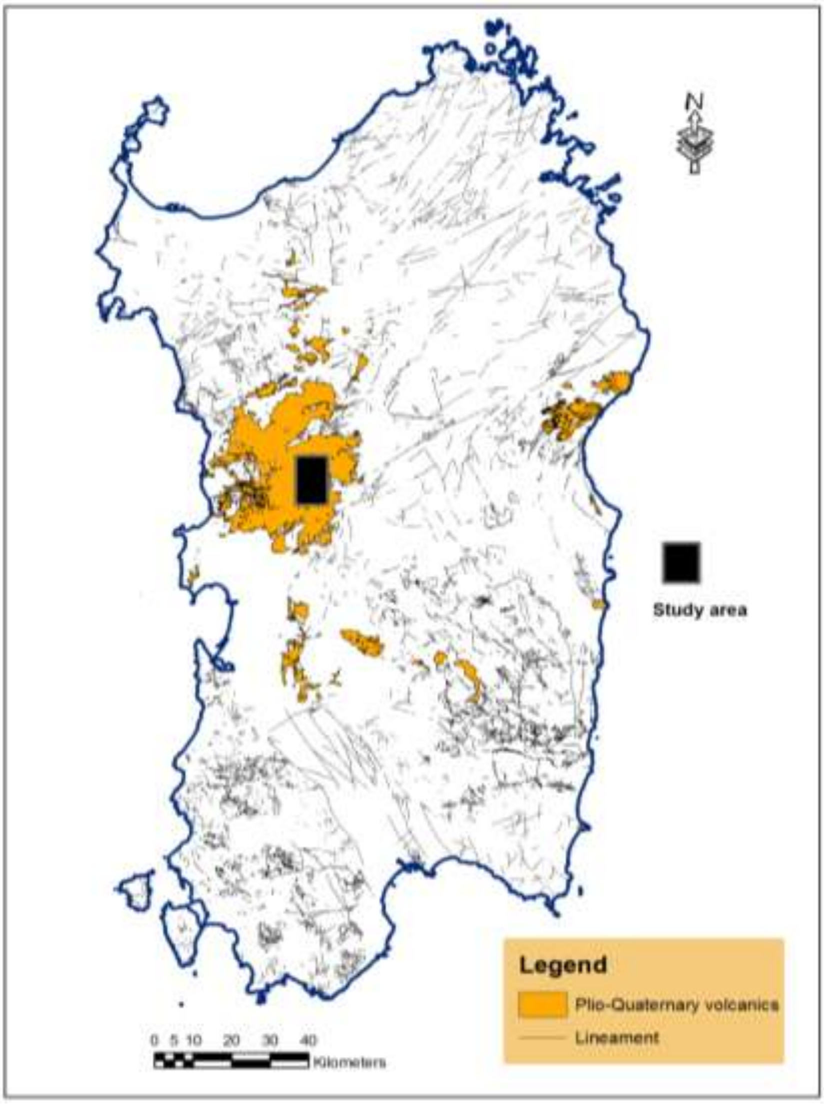

Figure 11-4 Major outcrops of Plio-Quaternary volcanic rocks of Sardinia (extracted from geological map of Sardinia, Geoportale Sardinia)

11.3 Regional stratigraphy

The geological structure of Sardinia is the result of several tectono-magmatic processes that begun with the Late Paleozoic compressional tectonics that led to the consumption of large oceanic masses (Paleo-Tethys) and the amalgamation of continental plates into the supercontinent Pangea (tectono-magmatic phase locally ascribed to the Hercynian Orogeny (Compagnoni et al.,1989). The back-bone of this island is made up of plutonic and metamorphic rocks related to the shortening of the Hercynian Orogeny and the following relaxation tectonics that led to a disruption of the recently amalgamated super-continent. During the Carboniferous-Permian, Sardinia (and Corsica) experienced abundant production of calc-alkaline to high-K calcalkaline granitic-granodioritic magmatism (Tommasini *et al.*, 1995) plus minor gabbroic-tonalitic and volcanic activity (calcalkaline to sodic alkaline dykes), partially coeval with, or pre-dating continental rifting that dismembered Pangea (Lustrino, 2000).

The Oligocene-Aquitanian tectonics of Sardinia is dominated by N-S trending normal faults (present-day coordinates) bounding a graben system that cut through pre-Alpine basement Sardinia from North to South for a total length of about 220 km and an average width of 50 km (Cherchi *et al.*, 2008). The Sardinian Trough (also known as ***Fossa Sarda***) is filled by up to 2km of Upper Oligocene syn-rift (mainly non-marine sediments followed by fluvial-deltaic sediments, marls and silts) and Burdigalian-Messinian post-rift (marine marlsilt successions) deposits (Cherchi *et al.*, 2008, and references therein). Starting from the Pliocene a new, NW-SE trending graben developed in SW Sardinia (Campidano graben; e.g., Balia *et al.*, 1991), partially overlapping the southern sector of the ***Fossa Sarda*.**

11.4 Regional tectonics

In general, the Italian area is characterized by strong areal and temporal variability of tectonic and magmatic signatures. This variability affects also the entire Central-Western Mediterranean and challenges the applicability of classical plate tectonics models (Lustrino *et al.*, 2011). Italy is a tectonically and magmatologically active region, as testified by the distribution of earthquakes and igneous activity.

Magmatism is rather controlled by lithospheric scale discontinuities, as clearly evidenced by the roughly linear alignment of the Cenozoic igneous rocks of the Alps, and by active geodynamic processes, as observed in Sardinia, Sicily, along the Italian peninsula, the south-eastern Mediterranean and the Sicily Channel.

The Sardinian Oligo-Miocene rift crosses all of Sardinia's 220km on N-S trend, while the Plio-Quaternary graben of Campidano is superimposed on the south western part of the Oligo-Miocene graben but in an oblique NW-SE direction.

The Plio-Quaternary graben corresponds to entirely different event, which affected the central and western Mediterranean area. Detailed structural analysis indicated that the Oligo-Miocene rift appears as a typical rift edge. The Paleozoic basement of Sardinia, sometimes including its Mesozoic and Eocene cover is down faulted by a succession of tilted blocks (Cherchi, 1982, Figure 11-5).

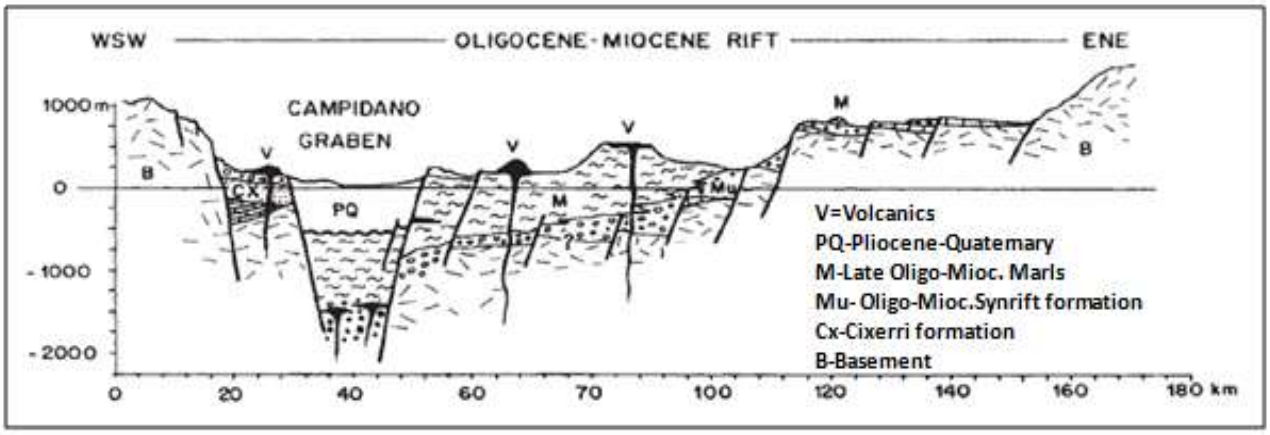

Figure 11-5 Schematic geologic cross-section through the Oligo-Miocene rift of Sardinia with the super imposed Plio-Quaternary Campidano graben (Cherchi, 1982)

The Sardinian Oligo-Miocene rift has been filled by Oligo-Miocene continental to marine sediments. Volcanic rocks occurring from the late Oligocene to middle Miocene (Cherchi, 1982) are believed to be the products of the volcanic arc linked with the subduction process. The Plio-Quaternary Campidano graben is a NW-SE trending superimposed graben structure filled with thick continental sediments.

From tectonic point of view, the Plio-Quaternary volcanic rocks of Sardinia are anorogenic magmatism as the part of Mediterranean region while the Oligo-Miocene volcanic is orogenic ones, but some time the latter predates the former (Lustrino et al., 2004a, b). Orogenic magmatism is mainly associated with oceanic lithosphere subduction or continent-continent collisions and anorogenic magmatism is to imply a geodynamic setting far away from contemporaneous subduction zones. According to (Wilson and Bianchini, 1999) orogenic and anorogenic magmas could be effectively discriminated using combinations of trace elements.

11.5 Local geological setting of the study area

The project area is located in the northwestern central Sardinia, Altopiano di Abbasanta and AltoPiano di Campeda. It is relatively the highland part of the Island covered with Plio-Quaternary mildly alkaline basalt and subalkaline volcanic rocks.

The Plio-Quaternary volcanic of alkaline to subalkaline rocks forms the ***Altopiano di Abbasanta stretched from Paulilatino-Abbasanta-Borore to Maccomer*** areas. These Plateaux covered with Plio-Quaternary formation (about 3.2-2Ma, Lustrino et al. 2004a) comprises of alkaline and tholeiitic (basaltic andesite) to Na-alkaline mafic to intermediate lava flows (trachybasalt) covering large area (Beccaluva et al. 1977; Lustrino et al. 2004a).

From the regional geological map of Sardinia (Carmignai et al.2001), the study area geology is depicted as 'Basalti di Plateau' which includes alkaline basalts, trachybasalts, basaltic andesite, some phonolites and basanites. However, in the extreme north and south of the study area, pyroclastic of volcano di Ottana were observed, in addition, on the southern, eastern and western parts of the study area Pleistocene continental deposits are also encountered (Figure 11-11).

The dominant rock units in the current studied area as observed in the field at outcrop scale and examined under petrographic microscope (thin section) are, porphyritic olivine basalt, vesicular olivine basalt, andesitic basalt and aphyric basalt with olivine and plagioclase phenocrysts in all cases being the frequent ones. The olivine phenocrysts are in most cases slightly oxidized and iddingsized indicating some degree of weathering pattern and deuteric alteration respectively.

The detail geological description of the studied area according to field observation and petrographic study is given below considering only the "Basalti di Plateau" as this work is mainly aimed at towards the study of these basaltic rock's physical and mechanical properties. The detail geological descriptions are given as follows.

11.5.1 Basalts (vesicular-porphyritic basalt)

This basalt (Vesicular and porphyritic) is the most abundant rock in the current study area. It is observed along the Paulilatino-Abbasanta-Borore area and also on the road from Macomer to Sindia, and near Santa Maria di Corte along Cuglieri road. In most localities it is only slightly weathered on the surface with few mms weathering crust (Figure 11-6). The thin section study of this unit exhibit fluidal and porphyritic texture and comprises of plagioclase (55%), pyroxene (29%), olivine (8%), opaque (5%) and volcanic glass (3%). Some large crystals of olivine (2-5mm) are seen over the groundmass as phenocrysts (Figure 11-7). The groundmass is mainly composed of lath plagioclase, anhedral pyroxene, olivine and opaque (Fe-oxides). While the vesicular varieties of this unit exhibits similar textural pattern but comprises of more opaque constituents. It shows fluidal and porphyritic texture and comprises of plagioclase (50%), pyroxene (29%), olivine (8%), opaque (20%) and volcanic glass (3%). Phenocrysts of olivine are seen over the groundmass. The groundmass is mainly composed of lath plagioclase, pyroxene and olivine. Lath plagioclases show parallel alignment of flow texture. Phenocrysts of olivine are oxidized. Unfilled empty voids are also seen across the section.

Figure 11-6 Outcrops of the alkaline basalt, a) Porphyritic basalt near Borore village, b) Vesicular basalt c/Jointed basalt in an old quarry, d) Massive slightly weathered basalt north of Abbasanta village

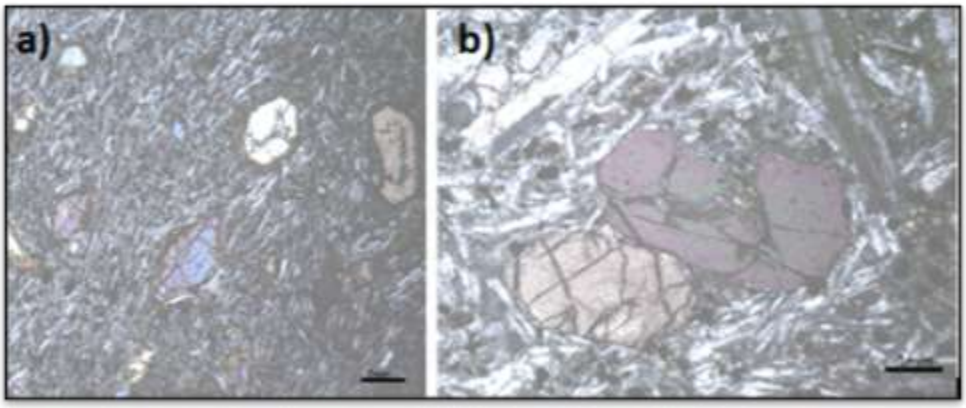

Figure 11-7 Microscopic photograph of the porphyritic basalt under crossed nicol, a) Euhedral phenocrysts of olivine within plagioclase laths groundmass, x10, b) Phenocrysts of olivine and plagioclase

11.5.2 Andesitic basalt

This unit is encountered north of Bortigali village and in some parts of the Paulilatino plain area. It is light to dark brown in colour and fine grained. In some parts of the visited area, it forms flat topography and in others subdued hills and ridges were observed. Weathering phenomena are diverse near Paulilatino village; it is only surfacially weathered up to few mms deep while in other localities it is found moderately to highly weathered (Figure 11-8).

The thin section study of this unit reveals that it is composed of plagioclase (67%), pyroxene (20%), olivine (10%) and opaque (3%). Phenocrysts of olivine and plagioclase are seen over the groundmass. The groundmass is mainly composed of lath plagioclase, anhedral pyroxene, olivine, volcanic glass and opaque (Fe- oxides). Lath plagioclases show parallel alignment of flow texture. Most of the olivine phenocrysts are oxidized at their rims (iddingsized). The overall thin section appears to show fluidal texture (Figure 11-9).

Figure 11-8 Outcrop of the andesitic basalt near Bortigali village

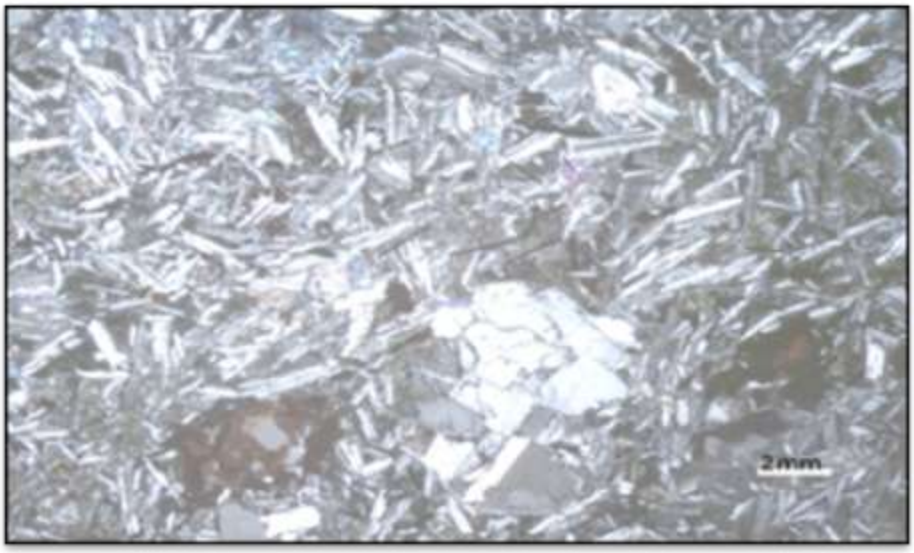

Figure 11-9 Microscopic photo under crossed nicol, x10, showing the andesitic rocks with abundant laths of plagioclase and rare olivine phenocrysts which are oxidized

11.5.3 Trachybasalt

The trachybasalt covers small portion in the study area. It is only encountered northwest of Macomer village and east of Bortigali village on the road to Silanus. The outcrops are very small and highly weathered (Figure 11-10). The thin section study shows fluidal/trachytic texture and comprises of plagioclase (50%), pyroxene (20%), olivine (10%), opaque (12%) and volcanic glass (8%). Groundmass of lath plagioclases and very fine anhedral pyroxene shows parallel alignment of fluidal /trachytic texture. Some phenocrysts of euhedral olivine are suspended over the groundmass.

Figure 11-10 The plate above shows, at the bottom olivine porphyritic basalt overlain by a trachybasalt

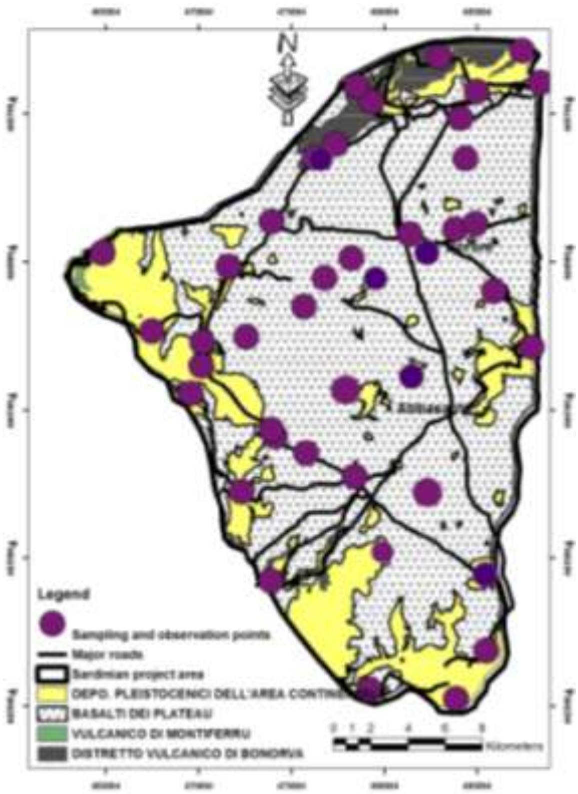

Figure 11-11 Schematic geological map of the studied area

CHAPTER TWELVE

12. Geo-engineering characterization results for dimension stone/cut stone

12.1 In-situ investigation results

12.1.1 Schmidt hammer

The procedures and principles of Schmidt hammer test are well described in part one of this thesis (Part I and Chapter 4). The Schmidt hammer rebound values on the blocks of the selected rocks in the study area are presented in the Table 12-1 and Figure 12-1. The Schmidt hammer rebound values are higher for the more compact units such as the aphyric basalt and phyric andesitic basalts (Abs-05, Abs-24, Abs-28, Abs-32 and Abs-41). Generally, the Sardinian Plio-Quaternary basalts exhibit relatively uniform Schmidt hammer rebound number which ranges from 20 to 42. The lower Schmidt hammer rebound number is recorded from samples Abs-10, Abs-11 and Abs-12 which are vesicular variety of basalts. Since the Schmidt hammer is influenced by the hardness of the constituent minerals of a rock, it does not consider empty cavity, i.e. empty cavities tend to reduce the rebound number.

Sample n.	Coordinates (WGS84)		Average Schmidt hammer rebound value
	X (Eastings)	Y(Northings)	
abs-02	479163	4459156	36
abs-04	474592	4451836	30
abs-05	472263	4449407	42
abs-10	482009	4451171	22
abs-11	484478	4451409	20
abs-12	485566	4451712	32
abs-13	493325	4454564	34
abs-15	489056	4459345	32
abs-16	488064	4461078	36
abs-18	479068	4438054	34
abs-19	476444	4439328	30
abs-21	474570	4440596	28
abs-24	474527	4432439	40
Abs-27	464281	4488920	38
abs-28	465472	4450148	32
abs-32	486153	4428642	38
abs-39	478014	4456015	38
abs-41	484752	4457422	40

Table 12-1 Average Schmidt hammer rebound value of Sardinian Plio-Quaternary basalt (studied area)

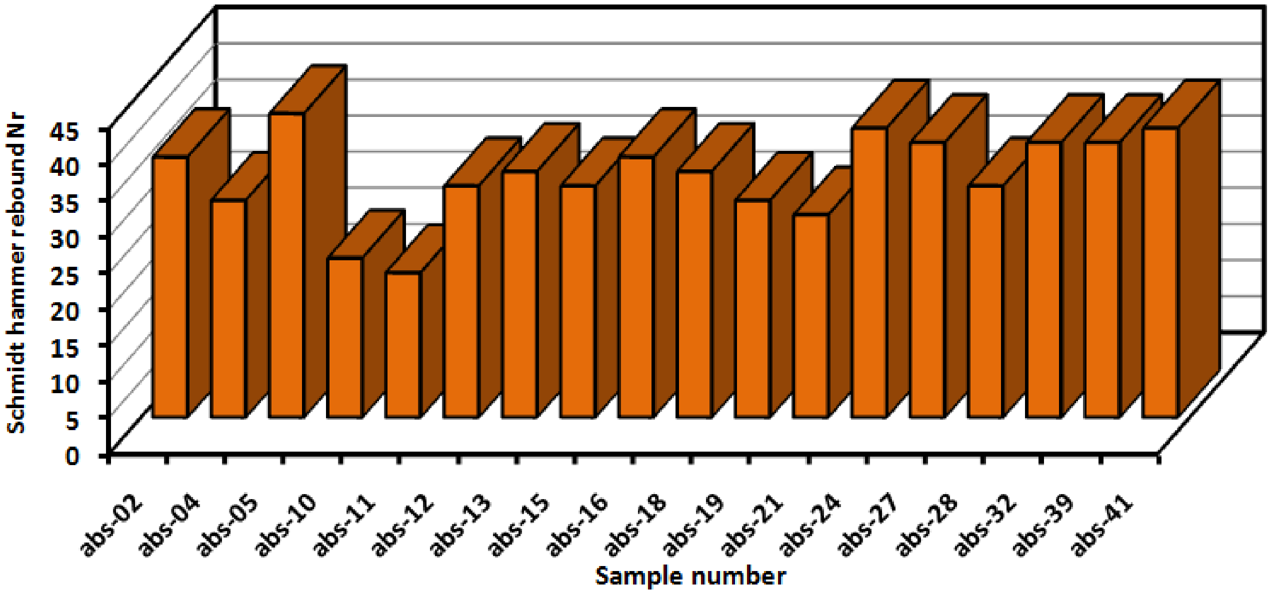

Figure 12-1 Bar chart showing Schmidt hammer rebound number vs sample number

12.1.2 Rock Quality Designation (RQD)

When no core is available, but discontinuity traces are visible in surface exposures or exploration adits, Palmström (1982) suggested that the *RQD* may be estimated from the number of discontinuities per unit volume. The various relationships for calculation of RQD are already well described in part I of this thesis (Part I, chapter 4).

It has been suggested that RQD is a directionally dependent parameter and its value may change significantly, depending upon the borehole orientation. The use of the volumetric joint count can be quite useful in reducing this directional dependence. In the context of this thesis, the most important use of *RQD* is to calculate the block size. Due to the significant of the joint number (Jn) in rock masses, for each rock type the block size were calculated and presented as ratio RQD/Jn. The block size is an extremely important parameter in rock mass behaviour (Barton, 1990, ISRM, 1978).

The quotient ***RQD*/J*n***, representing the structure of the rock mass, is a crude measure of the block or particle size, with the two extreme values (100/0.5 and 10/20) differing by a factor of 400. If the quotient is interpreted in units of centimetres, the extreme 'particle sizes' of 200 to 0.5 cm are seen to be crude but fairly realistic approximations (Palmstron, 1982). Probably the largest blocks should be several times this size and the smallest fragments less than half the size. Block size in this thesis is used as a common expression for the degree of jointing, density of joints, block volume, and joint spacing only.

In the studied rocks, the ratio RQD/Jn directly reflects the smallest block size exhibited by andesitic basalt and the largest size is shown by vesicular and trachybasalt units. The RQD/Jn parameter was utilized to give an abstraction about the crude block sizes of the examined rock mass. The higher RQD/Jn values, the more massive rock and can be used as slabs, hence RQD/Jn can be taken as a primary criterion for the quarrying method. In other words, the small RQD/Jn is preferred for crushed stone (Table 12-2 & Figure 12-2).

Rock type	**Texture**	**RQD**	**Joint set**	**Jn**	**RQD/Jn**
Porphyritic olivine basalt	Dark to dark bluish coloured, fine to medium grained, with phenocrysts of olivine and plagioclase, slightly weathered and less jointed	95	2	4	23.75
Vesicular basalt	Dark coloured, fine grained, rare joints and with abundant vesicles (25%), less weathered	98	2	4	24.5
Trachybasalt	Light gray to dark coloured, slightly weathered and rarely jointed	98	2	4	24.5
Andesitic basalt	Light gray, gray coloured, jointed and slightly weathered	92.2	2	4	23.05

Table 12-2 Results of field descriptions and values of RQD/Jn of major rock units of the study area

The quotient (RQD/Jn) varies from 23 to 24 (Table 12-2 and Figure 12-2). The relatively higher values are observed from the vesicular and trachybasalts indicating the massive nature of these rocks. Hence these rocks have high potential to be used as pavements and slabs as far as other necessary physical and mechanical properties meet the required specifications.

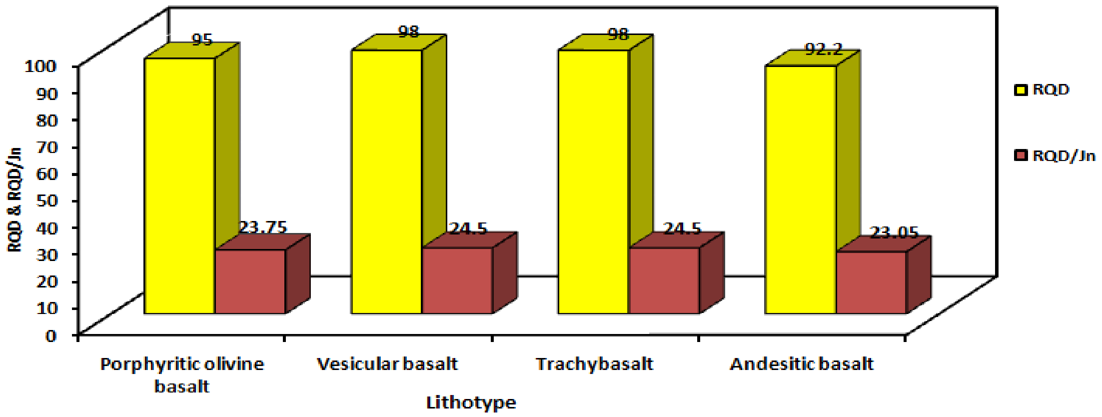

Figure 12-2 Bar graph showing the RQD and RQD/Jn of the studied samples

12.2 Laboratory analysis results

To determine the physical and mechanical properties of the various rocks found in the studied area, small block samples were collected directly from the outcrop with due care for the laboratory tests. The most difficult work was the sample preparation following the different standards. At this stage cutting, polishing and grinding to comply with various test standards was the difficult part of this study. We were looking for different laboratory facilities to reduce the big blocks into cm size cubes. Therefore, the sample preparation stage was not as such simple. However, it was managed to prepare appropriate samples from these carefully collected blocks in line with norms stated in UNIEN, BS and ASTM standards for bulk density, real density, open porosity, Uniaxial Compressive Strength, Point Load and P-wave Velocity measurements (Figure 12-3).

The physical properties to be determined includes apparent density, specific gravity, water absorption, porosity, real density, degree of saturation, petrographic examinations while the mechanical properties include Schmidt hummer rebound hardness test, Point Load Strength index, ultrasonic velocity and Uniaxial Compressive Strength. These laboratory measured values enable to classify the studied Sardinian Abbasanta-Borore basalt into various rock strength classes.

Figure 12-3 The process of sample preparation for the various physical and mechanical tests

12.2.1 Physical and mechanical test results

12.2.1.1 Petrographic examination

Fourteen (14) thin sections were prepared from the various rock units to study the mineralogical constituents and identify deleterious components towards using as construction material (dimension stone and aggregates) in the context of this research. In doing so, these thin section samples were studied using petrographic microscope in DIGITA (Dipartimento di Geoingegneria e Tecnologie Ambientali). The thin sections were prepared and described in accordance with UNIEN 12407:2007 standard. Most of the studied thin section samples are found to be porphyritic olivine basalt; vesicular olivine basalt, andesitic basalt and only few are trachybasalts. The vesicular olivine basalts and some of the porphyritic basalts are observed to be slightly weathered in that most of the olivine phenocrysts are transformed to iddingsite. Iddingsite is an alteration product of olivine due to deuteric or hydrothermal effects. A sample (Abs-13) which is porphyritic olivine basalt, exhibits trace amounts of chalcedony and zeolite minerals as secondary development in the vesicles of the basaltic rocks when examined at high magnification (x40); later XRD analysis of this sample confirmed the presence of cristobalite rather than chalcedony, may be due to the close similarities of the two minerals under microscopic view. The summarized description of the studied thin section samples is given in Table 12-3 and Appendix 1.

SAMPLE N.	CONCISE MICROSCOPIC DESCRIPTION OF THIN-SECTION SAMPLES	ROCK NAME
Abs-02	*It exhibits porphyritic texture and comprises of plagioclase (55%), pyroxene (20%), olivine (15%) and opaque (10%). The ground mass is mainly composed of lath plagioclase, anhedral pyroxene, olivine and opaque (Fe- oxides). Some phenocrysts of olivine and plagioclase are seen over the groundmass. Unfilled/empty fractures and veins are also seen across the section.*	*Porphyritic olivine basalt*
Abs-04	*It shows porphyritic texture and is composed of plagioclase (46%), pyroxene (32%), olivine (10%), opaque (5%) and volcanic glass (7%). Phenocrysts of olivine and plagioclase are seen over the groundmass mainly composed of lath plagioclase, anhedral pyroxene, olivine, volcanic glass and opaque (Fe-oxides). Lath plagioclases show parallel alignment of flow texture*	*Porphyritic olivine basalt*
Abs-10	*It shows vesicular texture and is composed of plagioclase (67%), pyroxene (20%), olivine (10%) and opaque (3%). The groundmass is vesiculated and mainly composed of lath plagioclase, anhedral pyroxene, olivine, volcanic glass and opaque (Fe- oxides). Most of the olivine grains are strongly oxidized*	*Vesicular andesitic basalt*
Abs-11	*It exhibits fluidal and porphyritic texture and comprises of plagioclase (45%), pyroxene (29%), olivine (8%), opaque (15%) and volcanic glass (3%). Some large crystals of olivine are seen over the ground mass as phenocrysts. The ground mass is mainly composed of lath plagioclase, pyroxene and olivine. Lath plagioclases show parallel alignment of flow texture. Phenocrysts of olivine are oxidized. Some*	*Vesicular olivine basalt*

	unfilled empty voids are also seen across the section	
Abs-12	*It shows porphyritic texture and comprises of plagioclase (45%), pyroxene (25%), olivine (15%), opaque (10%) and volcanic glass (5%). Phenocrysts of olivine and some plagioclase are seen over the groundmass that is mainly composed of lath plagioclase, anhedral pyroxene and opaque (Fe-oxides). Olivine phenocrysts are iddingsized. Empty voids /vesicles/ are also seen across the section*	*Porphyritic olivine basalt*
Abs-13	*It shows intergranular texture and comprises of plagioclase (49%), pyroxene (35%), olivine (10%), opaque (3%), chalcedony (2%), and chlorite (1%), and trace amounts of zeolite. The groundmass is mainly composed of lath plagioclase, anhedral pyroxene, olivine and opaque (Fe- oxides). Intergranular space between plagioclase is occupied by pyroxenes. Unfilled/ empty/ vesicles are seen across the section. Some of the vesicles are rimmed by chalcedony, some are partially filled by zeolite*	*Olivine basalt*
Abs-15	*It shows fluidal/trachytic texture and comprises of plagioclase (50%), pyroxene (20%), olivine (10%), opaque (12%) and volcanic glass (8%). Groundmass of lath plagioclases and very fine anhedral pyroxene shows parallel alignment of fluidal /trachytic/ texture. Some phenocrysts of euhedral olivine are suspended over the ground mass*	*Trachy- basalt*
Abs-16	*It exhibits fluidal texture and comprises of plagioclase (67%), pyroxene (20%), olivine (10%) and opaque (3%). Phenocrysts of olivine and plagioclase are seen*	*Andesitic basalt*

	over the groundmass mainly composed of lath plagioclase, anhedral pyroxene, olivine, volcanic glass and opaque (Fe- oxides). Lath plagioclases show parallel alignment of flow texture. Olivine is oxidized at its rim (iddingsized)	
Abs-41	*It shows porphyritic texture and comprises of plagioclase (47%), pyroxene (30%), olivine (5%), opaque (10%) and volcanic glass (5%). Large phenocrysts of olivine, pyroxene and plagioclase are grown over the groundmass mainly composed of lath plagioclase, anhedral pyroxene, volcanic glass and opaque (Fe- oxides). Olivine phenocrysts are iddingsized*	*Porphyritic olivine basalt*
Abs-18	*It shows vesicular texture and consists of plagioclase (65%), pyroxene (20%), olivine (12%), and opaque (3%). Groundmass is vesiculated and mainly composed of lath plagioclase, anhedral pyroxene, olivine and opaque (Fe- oxides). Most of the olivine grains are oxidized*	*Vesicular andesite*
Abs-21	*It exhibits porphyritic texture and comprises of plagioclase (50%), pyroxene (23%), olivine (15%), opaque (7%) and volcanic glass (5%). Phenocrysts of olivine and some plagioclase are seen over the groundmass that is mainly composed of lath plagioclase, anhedral pyroxene and opaque (Fe-oxides). Olivine phenocrysts are iddingsized. Empty voids /vesicles/ are also seen across the section*	*Porphyritic olivine basalt*
Abs-28	*It shows porphyritic texture and consists of plagioclase (50%), pyroxene (29%), olivine (7%), opaque (10%) and volcanic glass (5%). Phenocrysts of olivine are*	*Porphyritic olivine basalt*

	grown over the groundmass mainly composed of lath plagioclase, anhedral pyroxene, volcanic glass and opaque (Fe- oxides). Unfilled/empty/vein is seen across the section	
Abs-32	*It exhibits porphyritic texture and comprises of plagioclase (55%), pyroxene (20%), olivine (10%), opaque/Fe-oxide (5%), and volcanic glass (10%). Phenocrysts of olivine are seen over the groundmass of lath plagioclase, anhedral pyroxene, and volcanic glass and opaque/Fe-oxide are also observed. Voids/vesicles are also seen across the section*	*Andesitic basalt*
Abs-17	*It shows porphyritic texture and consists of large phenocrysts of olivine (10%); pyroxene (30%) and plagioclase (42%) phenocrysts which are grown over the groundmass of mainly lath plagioclase, anhedral pyroxene, volcanic glass (7%) and opaque/Fe-oxide (8%). Olivine phenocrysts are iddingsized.*	*Porphyritic olivine basalt*

Table 12-3 Summarized microscopic description of thin sections from the studied area

12.2.1.2 Determination of Uniaxial Compressive Strength (UCS)

In the Sardinian project area, 18 cubic samples were prepared in DIGITA and at the Department of Chemical and Geological Sciences, University of Cagliari. For each sample a minimum of 3 cubes with 50mm*50mm*50mm dimension were prepared and tested using a compressive machine in the Department of Civil and Environmental Engineering and Architecture (Figure 12-4). The compressive machine is connected to a PC in which the applied force is controlled so that the load increment is made very gradual until failure is recorded. The maximum Uniaxial Compressive Strength recorded was **177MPa** and the minimum was **35MPa** (Table 12-4, 12-5 & Figure 12-5). The maximum Uniaxial Compressive Strength was measured from a fine grained, massive trachybasalt while the minimum was from vesicular andesitic basalt. Almost more than 70% of the samples give values greater than 100 MPa. According to the engineering classification by Anon, 1976; 57% of the samples fall within the range of strong (>50MPa), 2% moderately strong (>15MPa) and 33% very strong (>120MPa). Dimension stone requires strength usually excessive, hardness and workability to be considered for the various uses. For usual building purposes, Uniaxial Compressive Strength of 35MPa (Bell, 2005) is satisfactory and the strength of most rocks used for building stone is well in excess of this value. In certain instances tensile strength is important, for example, tensile stresses may be generated in a stone subjected to ground movements. However, the tensile strength of a rock or more particularly its resistance to bending is a fraction of its Uniaxial Compressive Strength. The Uniaxial Compressive Strength and the Schmidt hammer rebound value show relatively good correlations with correlation factor R^2=0.76(Figure 12-6).

Figure 12-4 Determination of Uniaxial Compressive Strength and ultrasonic Velocity in the laboratory

Sample N.	***Compressive strength (MPa)***	***Mean***	***Standard Deviation***	***Megascopic/handspecimen descriptions***
Abs-02	141			Fine to medium grained, dark coloured, with rare phenocrysts of plagioclase and pyroxene-it is porphyritic olivine basalt
	114.6			
	131	128.86	13.32	
Abs-04	123.9			Fine to medium grained, dark gray coloured, slightly weathered on the surface-It is porphyritic olivine basalt
	53.7			
	58.8	78.8	39.14	
Abs-05	179			Dark coloured, fine grained, It is aphyric basalt
	167.2			
	154.2	166.8	12.40	
Abs-10	37.2			Fine grained, light gray to dark coloured, vesicular basalt with undifferentiated secondary minerals
	36.2			
	32.9	35.43	2.25	
Abs-11	37.8			Light gray, fine to medium grained, extensive outcrop, less vesiculated, vesicular basalt
	23.1			
	49.1	36.66	13.03	
Abs-12	75.0			Dark coloured, fine grained, porphyritc olivine basalt
	71.2			
	58.7	68.3	8.52	
Abs-13	91.4			Dark grey coloured, fine to medium grained, olivine basalt
	78.3			
	116.3	95.33	19.30	
Abs-15	80.8			Dark grey coloured, fine to medium grained, Trachybasalt
	96.2			
	92.1	89.7	7.97	
Abs-16	101.5			Light grey coloured, fine to medium grained, slightly massive, slightly weathered and jointed andesitic basalt
	149.8			
	145.6	132.3	26.75	
Abs-18	66.8			Dark coloured, fine grained, very hard on hammering, It is massive and slightly vesiculated basalt
	133.4			
	75.6	91.93	36.17	
Abs-19	104			Dark coloured, fine to medium grained, highly jointed, basalt-trachyte
	104.1			
	98.9	102.33	2.97	
Abs-21	58.8			Light grey coloured, fine to medium grained, slightly massive, slightly weathered and jointed
	102.7			
	86.1	82.53	22.16	
Abs-24	195.8			It is light grey coloured, fine grained, massive and dense trachybasalt
	164.7			
	171.8	177.43	16.29	
Abs-27	97.6			Light grey, fine grained, massive trachyphonolite
	83.8			
	101.2	94.2	9.18	

Abs-28	134.3			Dark gray coloured, fine to medium grained, with phenocrysts of plagioclase and pyroxene, porphyritic basalt
	98.2			
	121.3	117.93	18.28	
Abs-32	188			Highly weathered and fractured, porphyritic basalt
	172			
	119.1	159.7	36.05	
Abs-39	101.4			Light gray coloured, fine to medium grained, jointed trachybasalt
	96.2			
	80.9	92.83	10.65	
Abs-41	131.2			Light gray coloured fine grained, massive trachybasalt
	130			
	134.6	131.93	2.38	

Table 12-4 Measured values of Uniaxial Compressive Strength and description of samples

Sample N.	Uniaxial Compressive strength(MPa)	Engineering Classification(Anon, 1979)
abs-02	129	Very strong
abs-04	59	Strong
abs-05	167	Very strong
abs-10	35	Moderately strong
abs-11	40	Moderately strong
abs-12	68	Strong
abs-13	95	Strong
abs-15	89	Strong
abs-16	132	Very strong
abs-18	92	Strong
abs-19	102	Strong
abs-21	96	Strong
abs-24	177	Very strong
abs-27	94	Strong
abs-28	118	Strong
abs-32	160	Very strong
abs-39	93	Strong
abs-41	132	Very strong

Table 12-5 Average Uniaxial Compressive Strength and engineering classification

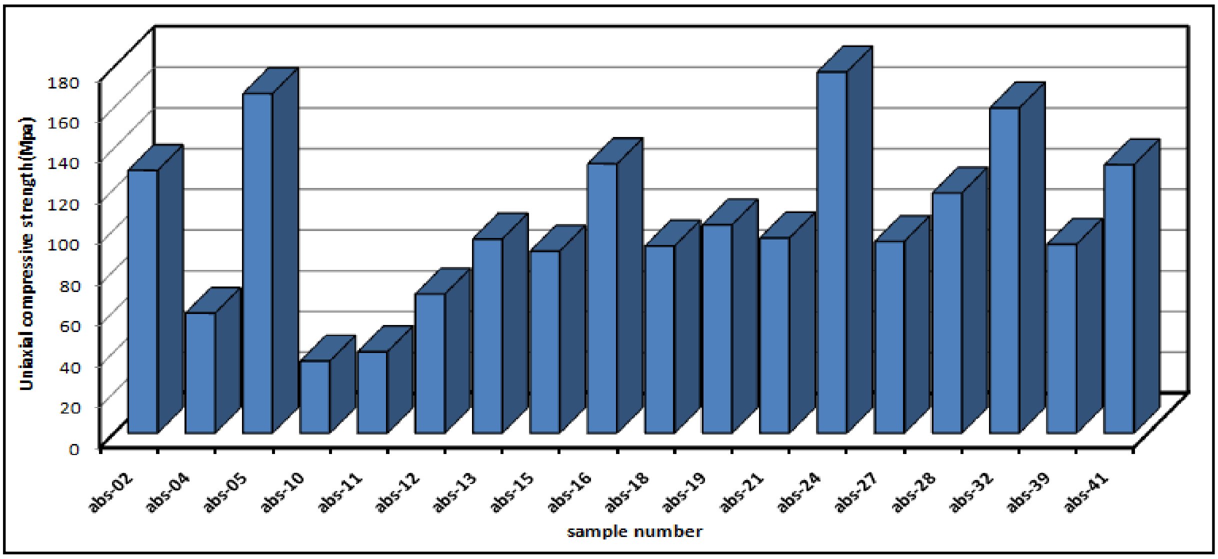

Figure 12-5 Bar graph showing the Uniaxial Compressive Strength of the studied samples

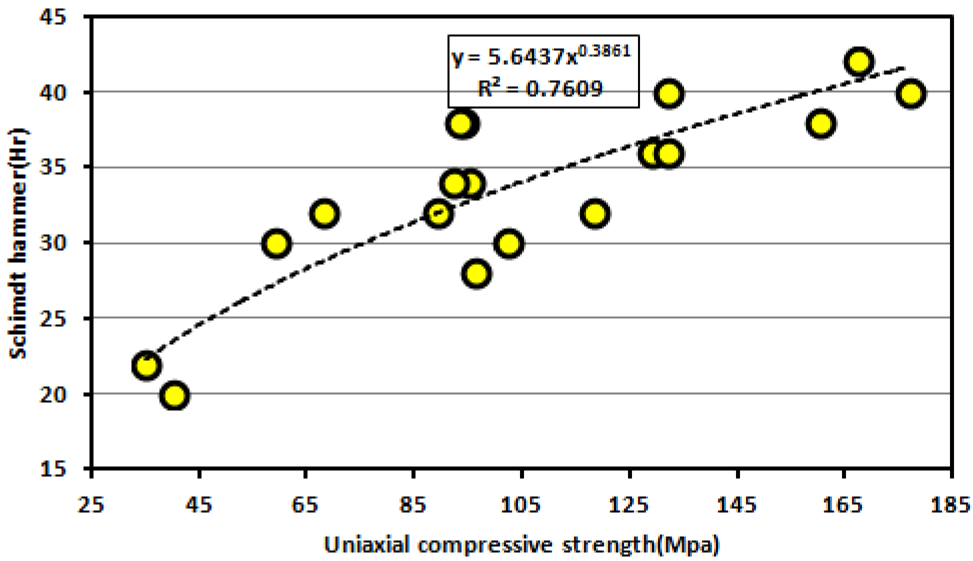

Figure 12-6 Chart showing correlation of Uniaxial Compressive Strength versus Schmidt hammer rebound number

12.2.1.3 Determination of Ultrasonic Velocity (P-wave Velocity)

The P-wave Velocity of intact rock was measured on cubic samples using the PUNDIT Mk V instrument designed with a high order of accuracy and stability. Three cube samples which have similar sides of 50mm*50mm*50mm were prepared for one test, so that 9 measurements were made for a single test and average P-wave Velocity value was recorded (Table 12-6).

The Ultrasonic Velocity measurements of 18 samples are given on Table 12-6. As it has been seen from the Table 12-6 and Figure 12-7, the maximum ultrasonic Velocity is 6066 m/s from fine grained massive trachybasalt (Abs-24), while the lowest value is 4143m/s from a vesicular basalt (Abs-10). These values are in good agreement with the Uniaxial Compressive

Strength of the studied samples. P-wave Ultrasonic Velocity is a good characteristic of the mechanical properties of hard rocks and soft rocks, and could be classified semi-quantitatively (Anon, 1979).

Generally, the Ultrasonic Velocity of the Plio-Quaternary Abbasanta-Borore basalts show relatively uniform values indicating the less fractured and weathered nature of these volcanic rocks. Rocks with high porosity and tectonic fracture yields low ultrasonic velocity as compared to the massive and fine-grained ones. According to the engineering classification by Anon, 1976, 50% of the samples are classified as high and the rest 50% are very high ultrasonic velocity (Table 12-7). The ultrasonic P-wave Velocity shows relatively good correlation with the Uniaxial Compressive Strength with $R^2 = 0.73$(Figure 12-8).

Sample n.	***Measuring faces***	***Vp (m/s)***	***Mean value***	***St.dev***	***Brief geological descriptions***
Abs-02	a-a1	4863.95	5265.5	357.99	Fine to medium grained, dark coloured, with rare phenocrysts of plagioclase and pyroxene-It is porphyritic olivine basalt
	b-b1	5313.41			
	c-c1	5571.36			
Abs-04	a-a1	4540.64	4670.9	135.61	Fine to medium grained, dark gray coloured, slightly weathered on the surface-It is porphyritic olivine basalt
	b-b1	4811.32			
	c-c1	4660.93			
Abs-05	a-a1	5585.26	5472.7	98.08	Dark coloured, fine grained, It is aphyric basalt
	b-b1	5405.44			
	c-c1	5427.46			
Abs-10	a-a1	4016.87	4142.7	109.17	Fine grained, light gray to dark coloured, vesicular basalt with undifferentiated secondary minerals
	b-b1	4198.91			
	c-c1	4212.31			
Abs-11	a-a1	4621.49	4812.4	171.92	Light gray, fine to medium grained, extensive outcrop, less vesiculated, vesicular basalt
	b-b1	4861.05			
	c-c1	4954.90			
Abs-12	a-a1	4771.19	4967.3	359.20	Dark coloured, fine grained, porphyritic olivine basalt
	b-b1	5381.94			
	c-c1	4748.97			
Abs-13	a-a1	5088.83	5285.5	170.35	Dark grey coloured, fine to medium grained, olivine basalt
	b-b1	5382.74			
	c-c1	5385.05			
Abs-15	a-a1	5132.29	5374.0	378.82	Dark grey coloured, fine to medium grained, trachybasalt
	b-b1	5810.62			
	c-c1	5179.18			

Abs-16	a-a1	4886.07	4721.6	142.55	Light grey coloured, fine to medium grained, slightly massive, slightly weathered and jointed andesitic basalt
	b-b1	4645.17			
	c-c1	4633.54			
Abs-18	a-a1	5262.06	5209.3	63.69	Dark coloured, fine grained, very hard on hammering, It is massive and slightly vesiculated basalt
	b-b1	5227.35			
	c-c1	5138.56			
Abs-19	a-a1	4763.98	4763.0	28.32	Dark coloured, fine to medium grained, highly jointed, basalt-trachyte
	b-b1	4790.89			
	c-c1	4734.27			
Abs-21	a-a1	4777.13	4869.9	80.48	Light grey coloured, fine to medium grained, slightly massive, slightly weathered and jointed
	b-b1	4913.02			
	c-c1	4919.77			
Abs-24	a-a1	6072.69	6066.0	6.25	It is light grey coloured, fine grained, massive and dense trachybasalt
	b-b1	6065.04			
	c-c1	6060.30			
Abs-27	a-a1	4934.95	4940.0	24.17	Light grey, fine grained, massive trachyphonolite
	b-b1	4918.78			
	c-c1	4966.32			
Abs-28	a-a1	5162.12	4885.0	241.87	Dark gray coloured, fine to medium grained, with phenocrysts of plagioclase and pyroxene, porphyritic basalt
	b-b1	4715.96			
	c-c1	4777.11			
Abs-32	a-a1	5766.17	5662.2	91.35	Highly weathered and fractured, porphyritic basalt
	b-b1	5594.46			
	c-c1	5626.23			
Abs-39	a-a1	5049.79	5011.7	80.99	Light gray coloured, fine to medium grained, jointed trachybasalt
	b-b1	4918.78			
	c-c1	5066.79			
Abs-41	a-a1	5539.37	5377.4	140.60	Light gray coloured fine grained, massive trachybasalt
	b-b1	5307.05			
	c-c1	5286.00			

Table 12-6 Average P-wave Velocity of the studied basaltic samples from Sardinian project area as determined in the laboratory

Sample N.	Ultrasonic P-wave Velocity(m/s)	Engineering classification (Anon,1976)
abs-02	5266	Very high
abs-04	4671	high
abs-05	5473	Very high
abs-10	4143	High
abs-11	4612	High
abs-12	4968	High
abs-13	5286	Very high
abs-15	5374	Very high
abs-16	4722	High
abs-18	5209	Very high
abs-19	4763	High
abs-21	4870	High
abs-24	6066	Very high
abs-27	4940	High
abs-28	4885	High
abs-32	5662	Very high
abs-39	5012	Very high
abs-41	5377	Very high

Table 12-7 The engineering classification according to Anon 1979, of the average Ultrasonic P-wave Velocity of the studied Sardinian samples

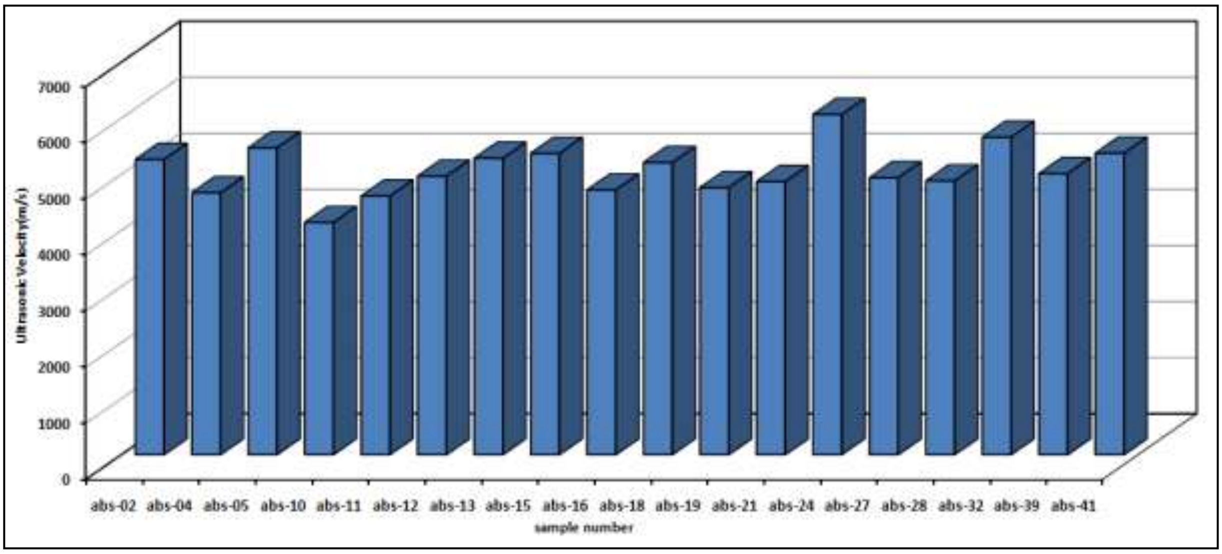

Figure 12-7 Bar chart showing the Ultrasonic Velocity of the studied Sardinian samples

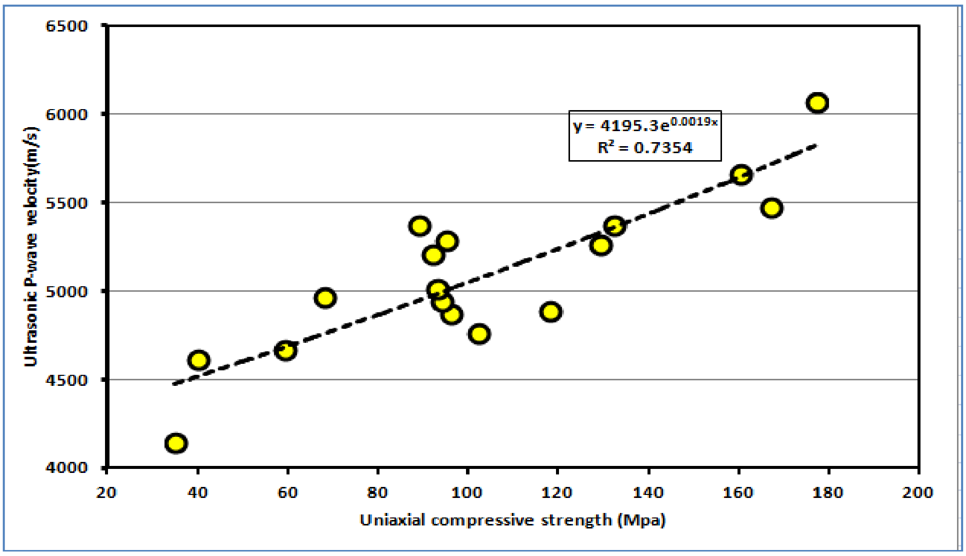

Figure 12-8 Chart showing correlation of Uniaxial Compressive Strength vs P-wave Velocity

12.2.1.4 Point Load index test

The test is performed according to the procedure of Brook (1985) and ISRM (1985).The Point Load Test involves compressing of a rock sample between conical steel platens until failure occurs, in which the point load test allows the determination of the uncorrected point load strength index (Is),which can be derived from (equ.3-1) as follows:

$$Is=F/(De)^2 = \pi F/4A = \pi F/4*D*W \text{ .... (Equ.3-1)}$$

where: Is = uncorrected Point Load Strength index, F = Force at failure (breaking load)

De=Equivalent core diameter which is given by (1) De=D for the diametral test, and

(2) De= √4A/π for the axial, block or irregular lump tests (refer part I of this thesis for diagrammatic representation), A=D*W; where A is the minimum cross sectional area of a plane through the platen contact points, D is the thickness of specimen and W is width of specimen. The Is must be corrected to the standard equivalent diameter of 50mm, as follows:

$$Is_{(50)} = f*(F/(De)^2) = f*Is \text{ .... (Equ.3-2)}$$

Brook (1985) and ISRM (1985)

Where, $Is_{(50)}$ =Point Load Strength index of a specimen of 50mm diameter,

$f = (De/50)^{0.45}$ = Size correction factor.

Early studies by Broch and Franklin (1972) and Bieniawski (1975) conducted on hard, strong rocks found that the relationship between UCS and the strength index (Is) could be expressed as: $UCS=K*Is_{(50)} =24*Is_{(50)}$; where K is the index of strength conversion factor.

The point load index value of the study area ranges from 1.98 to 7.05MPa (Table 12-8 & Figure 12-9) represented by samples (Abs-10) and (Abs-24) respectively. According to the classification by Franklin & Broch, 1972, 35% of the tested samples are high strength and 65% are very high strength.

The Point Load index is a crude strength characteristic measured in the absence of uniaxial compressive strength. However, it gives some clues and help to deduct Uniaxial Compressive Strength owing to its simple and quick method and it does not need intensive sample preparation. It could be also carried out right at the spot in the field and reduces sample transport cost.

Sample N.	W(mm)	D(mm)	P(N)	De^2(mm)	De(mm	Is	fc	Is_{50}(MPa)
Abs-02	20.4	74	11600	1923.06	43.85	6.03	0.94	5.65
Abs-04	50	57	11400	3630.57	60.25	3.14	1.10	3.45
Abs-05	50	43	17180	2738.85	52.33	6.27	1.02	6.42
Abs-10	110.3	90.1	16700	12659.91	112.52	1.32	1.50	1.98
Abs-11	72	64	11340	5870.06	76.62	1.93	1.24	2.39
Abs-12	65	88	21000	7286.62	85.36	2.88	1.31	3.77
Abs-13	40	42	6700	2140.13	46.26	3.13	0.96	3.01
Abs-15	80	50	16800	5095.54	71.38	3.30	1.19	3.94
Abs-16	100.75	50.4	34700	6468.54	80.43	5.36	1.27	6.80
Abs-18	20.4	100.5	14230	2611.72	51.10	5.45	1.01	5.51
Abs-19	155	54	26000	10662.42	103.26	2.44	1.44	3.50
Abs-21	54	32	6800	2201.27	46.92	3.09	0.97	2.99
Abs-24	60	70	31200	5350.32	73.15	5.83	1.21	7.05
Abs-27	100.5	60.8	15300	7783.95	88.23	1.97	1.33	2.61
Abs-28	50	34	11700	2165.61	46.54	5.40	0.96	5.21
Abs-32	110.5	40.4	27500	5686.88	75.41	4.84	1.23	5.94
Abs-39	150.4	50.3	22860	9637.10	98.17	2.37	1.40	3.32
Abs-41	80.5	60.9	21300	6245.16	79.03	3.41	1.26	4.29

Table 12-8 The Point Load index test results of the studied samples

In general, the Point Load Test is intended as an index test for the strength classification of rock materials, but it may also be widely used to predict other material strength properties with which it is correlated. It is an attractive alternative method, since it can provide similar data at a lower cost and its ease of testing and portable nature of the equipment allow for the possible use in the field. Many research works had been conducted to acknowledge with regard to Point Load index and has resulted in widely used Point Load index and other parameters. In this study the correlation of Point Load index values with the Uniaxial Compressive Strength gives (R^2=0.71) which is relatively good value (Figure 12-10).

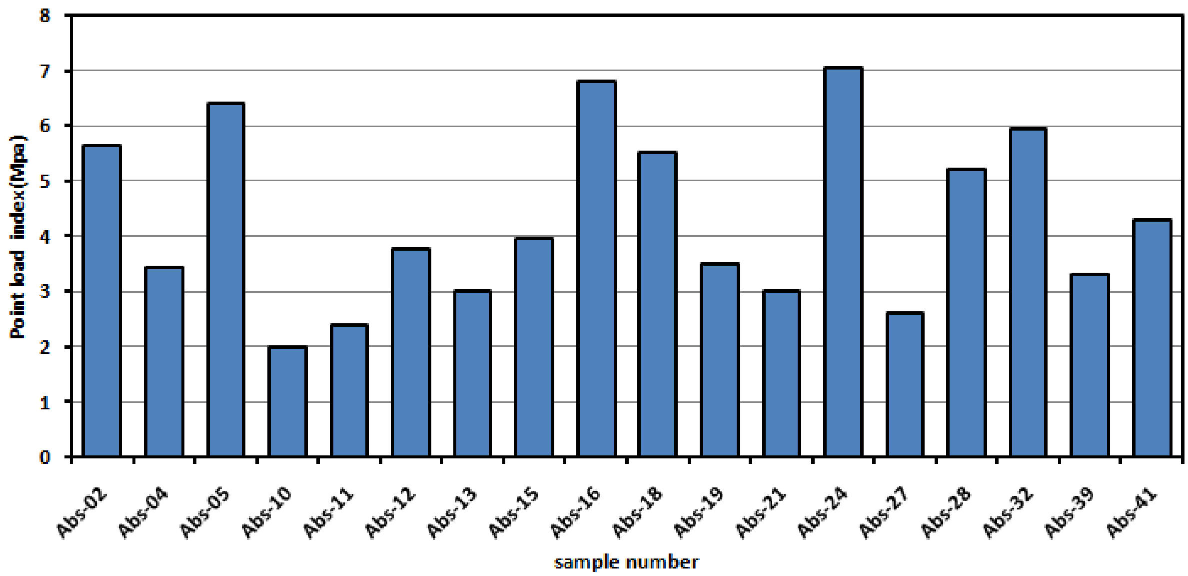

Figure 12-9 Bar chart showing the Point Load index of the tested samples **(Is $_{(50)}$)** in MPa

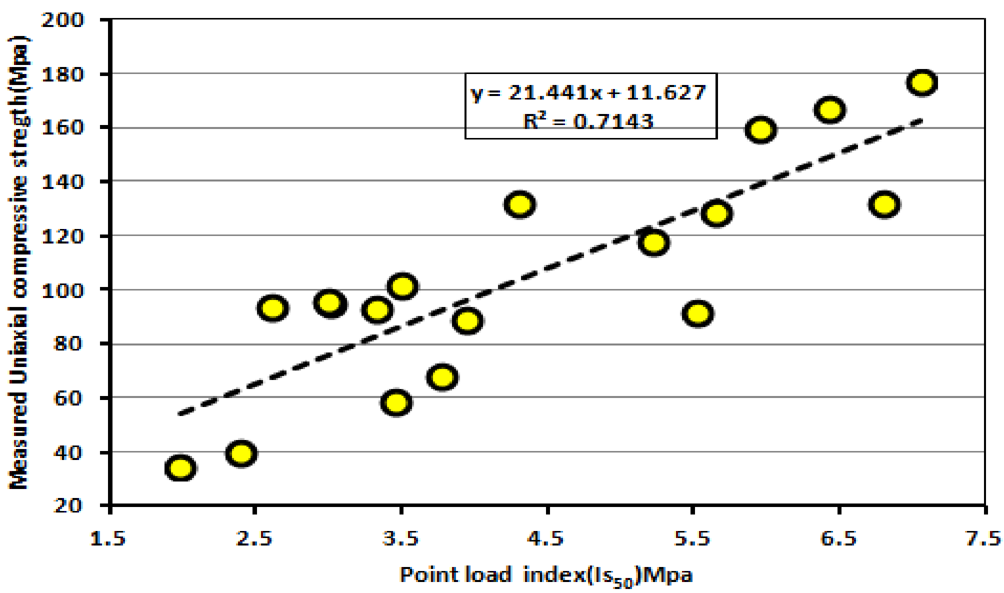

Figure 12-10 Graph showing the correlation of measured Uniaxial Compressive Strength vs Point Load index

12.2.1.5 Determination of abrasion resistance

The abrasion resistance was carried out on each lithotypes encountered in the project area. As it has been well described in the geology section, the project area comprises of vesicular basalt, porphyritic basalt, andesitic basalt and trachybasalt and the abrasion test result of each lithotype is shown on Table 12-9 and Figure 12-11.

Sample number	***Vesicular basalt (Abs-18)***	***Andesitic basalt (Abs-32)***	***Trachybasalt (Abs-15)***	***Porphyritic basalt (Abs-21)***
Abrasion resistance (mm)	23.6	21.8	19.4	22.7

Table 12-9 Results of the abrasion resistance test of the studied samples

Standard value	**≤ 24mm intensive use**	**≤ 35mm Moderate**	**≤ 42mm Individual use**
Uses	▪ *public halls in stations, airports, shopping centers* ▪ *halls in apartment block with more than 30 housing units* ▪ *common rooms of office building with more than 50 employees* ▪ *floorings in supermarkets, etc*	▪ *common rooms of multifamily houses (with max. 30 housing units)* ▪ *common rooms of block offices (max. 50 employees)* ▪ *rooms with moderate commercial use*	▪ *all rooms in private housing units* ***Note*** *: in this category, the areas most susceptible to wear are the ones which are directly accessible from outside*

Table 12-10 EN14517 standards and corresponding uses/application area

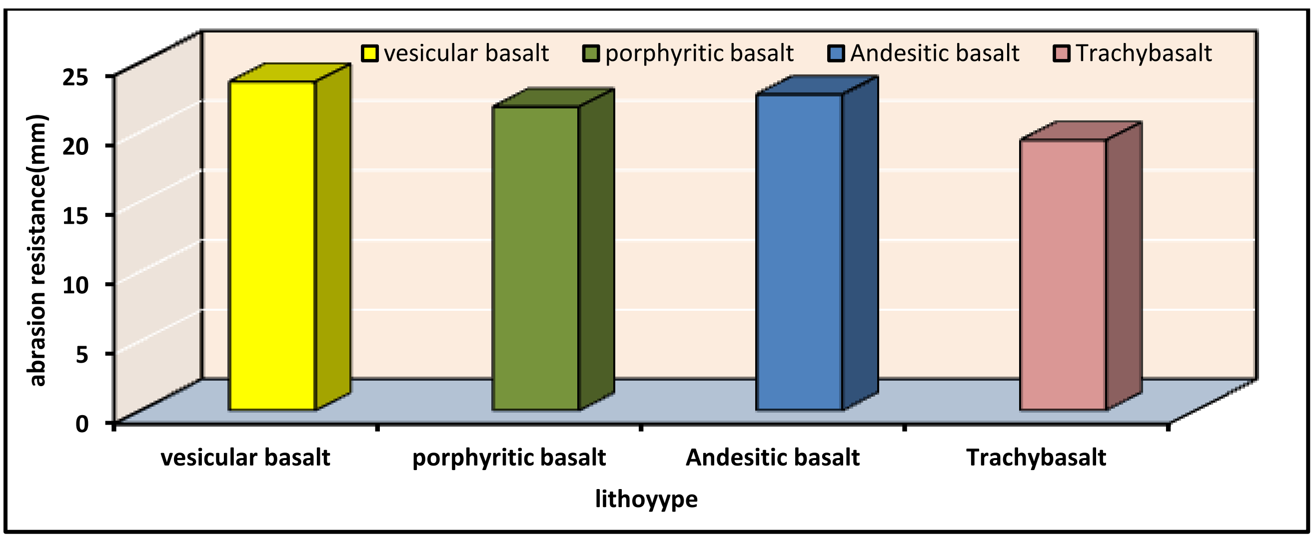

Figure 12-11 Bar chart showing the results of the abrasion test for the different studied samples

Figure 12-12 The different lithotype abrasion test result patterns (grooves made by the abrasion Capon wheel)

The wide wheel abrasion test (Capon wheel) is carried out by abrading the face of a sample which will be exposed in use with an abrasive material or wheel under standard conditions. The wear is determined as the width of the groove in the sample (Figure 12-12). According to the standards mentioned on Table 12-9, all the lithotypes are fit for intensive public use with the vesicular basalt being marginal probably it could better be used for small business office floors with limited public access.

Although the surface finish of a floor covering is a personal choice, there are some recommendations to be made. The polished finish is not recommended to use for floor coverings intended for frequent passage, like in buildings for common use (moderate and intensive, Table 3-9*)* unless they are made of durable granite. Even for private houses it is not favorable using polished stone units in areas that are accessible from the outside (EN 14157). The reason for these recommendations is that a polished finishing turns rapidly dull in these areas where there is a frequent passage, so that after a certain time the difference between the passable and impassable becomes visible. In addition, it is not recommended to mix polished and honed surfaces in the same floor. Hardness as far as building stone is concerned is a factor of small consequence. The exception to this is, if a stone is likely to be subjected to continual wear such as in the case of steps or pavings.

12.2.1.6 Water absorption and bulk density

Water absorption at atmospheric pressure

The scope of this method is to determine the water absorption of the natural stone samples by immersion in water at atmospheric pressure. The procedure of the measurement is based on the EN 13755: 2001.

The specimens were cubic of about 50 mm *50mm*50mm. They were dried to constant mass at the temperature of (70 ± 5) ºC. Their dry mass *md* was measured. The samples were placed in a tank on special supports and then tap water was added until the specimens were completely immersed to a depth of (25 ± 5) mm of water. In each certain interval of time which was initially very short and later longer, the specimens were taken out of the water, quickly wiped with a damp cloth and then weighted within 1 min to an accuracy of 0.01g (*mi*). After the measurement, the specimens were immediately immersed again in water to continue the test up to constant mass of specimens. The result of water absorption at each interval was expressed as a percentage to the nearest 0.1 % by the following equation:

$$Ai = \frac{mi - md}{md} * 100 \ldots\ldots\ldots\ldots\ldots\ldots \text{(equ.3-3)}$$

The mass of the last weighing is the saturated one *ms* and based on this, the total water absorption at atmospheric pressure *wtabs%* after immersion was calculated by the aforementioned equation replacing *Ai* with *wtabs* and *mi* with *ms*.

Bulk density and real density

The bulk density and real density are calculated with the below formula for each sample, ρw being the density of water taken as 0.98g/cc, at 20^{0}C (UNIEN 1936:2007)

$$\rho b = \frac{Md}{Ms - Md}(\rho w) \ldots\ldots\ldots\ldots\ldots\ldots \text{(Equ.3-4)}$$

$$\rho r = \frac{md}{md - mh} \ldots\ldots\ldots\ldots\ldots\ldots (equ.3-5)$$

where, ρr realdensity, mh submerged/suspendedmass

The water absorption at atmospheric pressure measured on three specimens for each sample is presented on Table 12-11 and Figure 12-13. The Sardinian Plio-Quaternary basaltic rocks water absorption varies greatly. The water absorption for the basaltic samples varies from (Abs-24, 0.24%) to (Abs-10, 4.71%), from strongly compacted trachybasalt and porphyritic vesicular basalt respectively. The bulk density and real density are also showing variations, the bulk density varies from 2.06g/cc to 2.7g/cc while the real density ranges from 2.33g/cc to 2.85g/cc.

sample N.	**wtabs (%)**	**Bulk density(ρb) g/cc**	**Real density(ρr) g/cc**
abs-02	1.34	2.66	2.82
abs-04	1.21	2.7	2.85
abs-05	1.22	2.64	2.78
abs-10	4.71	2.06	2.33
abs-11	4.64	2.18	2.48
abs-12	1.64	2.49	2.65
abs-13	1.14	2.57	2.7
abs-15	1.05	2.69	2.82
abs-16	2.05	2.38	2.56
abs-18	2.33	2.5	2.71
abs-19	0.87	2.63	2.75
abs-21	2.82	2.53	2.78
abs-24	0.24	2.67	2.74
abs-27	3.83	2.2	2.45
abs-28	2.52	2.56	2.8
abs-32	0.98	2.6	2.72
abs-39	1.44	2.38	2.52
abs-41	0.73	2.66	2.76

Table 12-11The wtabs %, ρd and ρr of the studied Sardinian basaltic samples

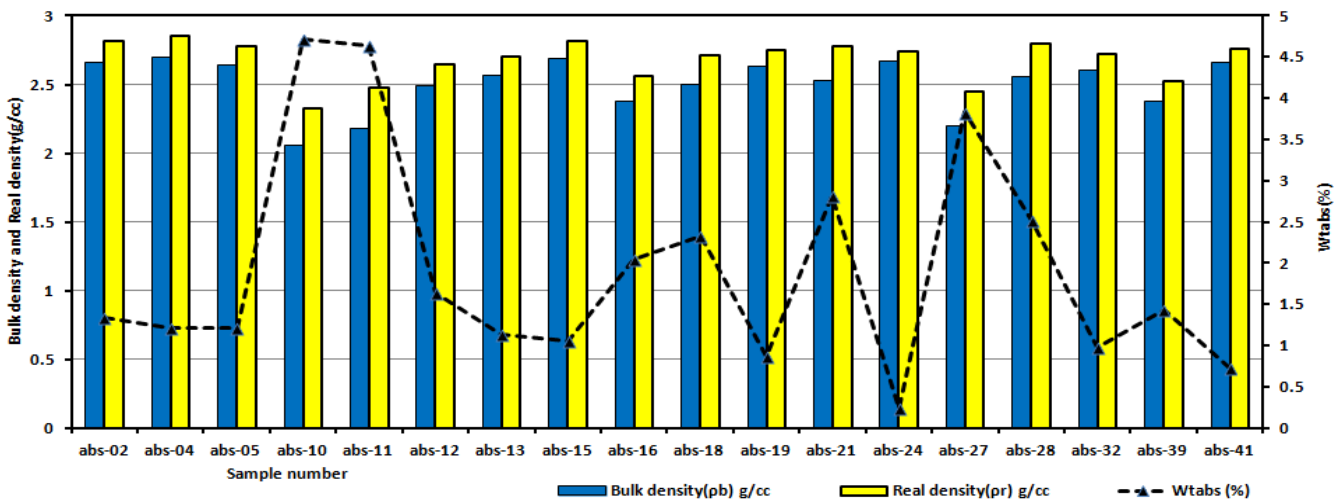

Figure 12-13 Bar chart showing the wtabs %, real and bulk density of the studied samples

12.2.1.7 Porosimetry

The goal of this measurement is to characterize the open porosity of the rock samples, determined by vacuum assisted water absorption. The method that was followed and it is described below is based on the UNIEN 1936: 2006 for natural stone. Under vacuum water can penetrate into pores with diameter larger than 100nm (Meyer et al. 1994, as cited in Theodoridou, 2009). The open porosity by vacuum assisted water immersion is defined by the difference between the mass of the given specimen of rock immersed in water under vacuum and the mass of the same specimen when dried, expressed in terms of the volume of the dry specimen.

The specimen was dried in a ventilated oven at (70 ± 5) ºC for 24 hours. The mass *md* of the dried specimen was measured. Right after the determination of the *md*, the specimen was immediately placed in a water tank. After a period of at least 2 hours, demineralised water was transferred from its initial tank into the tank in which the specimen was placed and the amount of water was sufficient to submerge the specimen, completely covering it with at least 20 mm water. The measurement of the wet mass *ms* took place after 24 hours. Before each weighing, the surface of the specimen was dried with a damp tissue so as to have water saturated surfaces. At that time, the specimen was also weighed while it was submerged in water, with a precision of at least 0.1% and this value is called *mh*.

Open porosity

The open porosity is the porosity which is easily accessible to water and was calculated with the formula:-

$$N = \frac{ms-md}{ms-mh} * 100 \quad \text{(Equ.3-6)}$$

Total open porosity

The total porosity is also calculated with the formula

$$Nt = 1 - \frac{\rho b}{\rho r} * 100\% \quad \text{(Equ.3-7)}$$

Where ρb is the bulk density and ρr is the real density, furthermore, on the basis of the results from the Helium gas ultrapycnometer, the real density ρr and the bulk density ρb of the specimens were calculated dividing the dry weight with the real volume and the bulk volume correspondingly: The values of the open and total porosity are given on Table 12-11.

$$\rho r = \frac{md}{Vr} \quad \textit{and} \quad \rho b = \frac{md}{Vb} \quad \text{(Equ.3-8)}$$

Sample number	Total porosity (%)	Open porosity (%)
abs-02	5.58	3.65
abs-04	5.26	3.32
abs-05	5.21	3.28
abs-10	11.7	9.89
abs-11	12.12	10.33
abs-12	6.09	4.17
abs-13	4.92	2.98
abs-15	4.83	2.89
abs-16	6.89	4.99
abs-18	7.83	5.95
abs-19	4.3	2.35
abs-21	9.11	7.26
abs-24	2.63	0.64
abs-27	10.42	8.59
abs-28	8.45	6.58
abs-32	4.55	2.6
abs-39	5.43	3.5
abs-41	3.95	1.69

Table 12-12 Values of Open and Total porosity

12.2.1.8 Dynamic Elastic Modulus (Young's), Ultrasonic P-wave Velocity & Uniaxial Compressive Strength

The Static Young's Modulus (**E**) is defined as the ratio of the axial stress to axial strain for a material subjected to uniaxial load (Neville, 1997). While seismic wave velocity gives a physical measurement of the rock material, it is also used to estimate the Elastic Modulus of the rock material. From the theory of elasticity, compressional (or longitudinal) P-wave Velocity (**V**p) is related to the Dynamic Elastic Modulus (Ed), and the density (ρ) of the material as, according to Pierce, 1989,

$$Vp = \sqrt{\frac{\mathrm{Ed}(1+\boldsymbol{v})}{\rho(1+\boldsymbol{v})(1-2\boldsymbol{v})}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equ.3-9), Pierce, 1989}$$

Solving equation 3-9 for Ed, it gives equation 3-10

$$E_d = Vp^2 \frac{[\boldsymbol{\rho}(\mathbf{1}+\boldsymbol{v})(\mathbf{1}-\mathbf{2}\boldsymbol{v})]}{(\mathbf{1}-\boldsymbol{v})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{(Equ.3-10)}$$

where, E_d: Dynamic Young's Modulus, Vp: P-wave velocity, ρ: density of the material and *v* is the Poisson Ratio taken from literature [for basaltic rocks as 0.15(0.1-0.2)]. If ρ is in g/cm^3, and Vp is in km/s, then Ed is in GPa (10^9 N/m^2).

Similar to strength, Young's Modulus of rock materials varies widely with rock type. For extremely hard and strong rocks, Young's Modulus can be as high as 100GPa. Poisson's Ratio measures the ratio of lateral strain to axial strain, at linearly-elastic region.

The Elastic Modulus estimated by the above method is sometime termed as seismic modulus (also called Dynamic Modulus, but should not be mistaken as the modulus under dynamic compression). It is different from the Modulus obtained by the uniaxial compression tests. The value of the Seismic Modulus is generally slightly higher than the modulus determined from static compression tests.

This method offers two advantages over static measurements: i) it is a non-destructive tool and less expensive and can be performed in short time; ii) it can be performed in the field. However, the problem lies in the fact that static and dynamic elastic moduli slightly differ in values. This difference is explained by the presence of fractures, cracks, cavities, planes of weakness and foliation.

It is a general trend that a stronger rock material is also stiffer, i.e., higher elastic modulus is often associated with higher strength. The lower Dynamic Young's Modulus (33GPa) is obtained from the lower Uniaxial Compressive Strength (Abs-10, 35MPa). There is reasonable correlation between Compressive Strength and Dynamic Elastic Modulus (Table 12-13 & Figure 12-14). The Modulus Ratio (Uniaxial Compressive Strength versus Young's Modulus) also has shown that the tested samples clearly plotted in the volcanic rock modulus ratio region defining medium to high modulus ratio (Figure 12-15).

sample n.	***Uniaxial Compressive Strength(MPa)***	**Bulk density(g/cc)**	***Ultrasonic Velocity(m/s)***	***Dynamic Young's Modulus(GPa)***	**Open porosity (%)**
abs-02	129	2.66	5266	69	3.65
abs-04	59	2.7	4671	55	3.32
abs-05	167	2.64	5473	74	3.28
abs-10	35	2.06	4143	33	9.89
abs-11	40	2.18	4612	43	10.33
abs-12	68	2.49	4968	57	4.17
abs-13	95	2.57	5286	67	2.98
abs-15	89	2.69	5374	73	2.89
abs-16	132	2.38	4722	49	4.99
abs-18	92	2.5	5209	63	5.95
abs-19	102	2.63	4763	56	2.35
abs-21	96	2.53	4870	56	7.26
abs-24	177	2.67	6066	92	0.64
abs-27	94	2.2	4940	50	8.59
abs-28	118	2.56	4885	57	6.58
abs-32	160	2.6	5662	78	2.6
abs-39	93	2.38	5012	56	3.5
abs-41	132	2.66	5377	72	1.99

Table 12-13 Dynamic Young's Modulus and other related physical and mechanical properties of the studied samples

Several attempts have been made to correlate Static (E) and Dynamic (Ed) Moduli for rocks.

The simplest of these empirical relations is proposed by Lydon and Balendran (as cited in Neville, 1997).

$$E = 0.83\ Ed$$

Another empirical relationship for concrete's elastic moduli was proposed by Swamy and

Bandyopadhyay and is now accepted as part of British Testing Standard BS: 8110 Part2:

$$E = 1.25Ed - 19$$

where both units of E and Ed are in GPa.

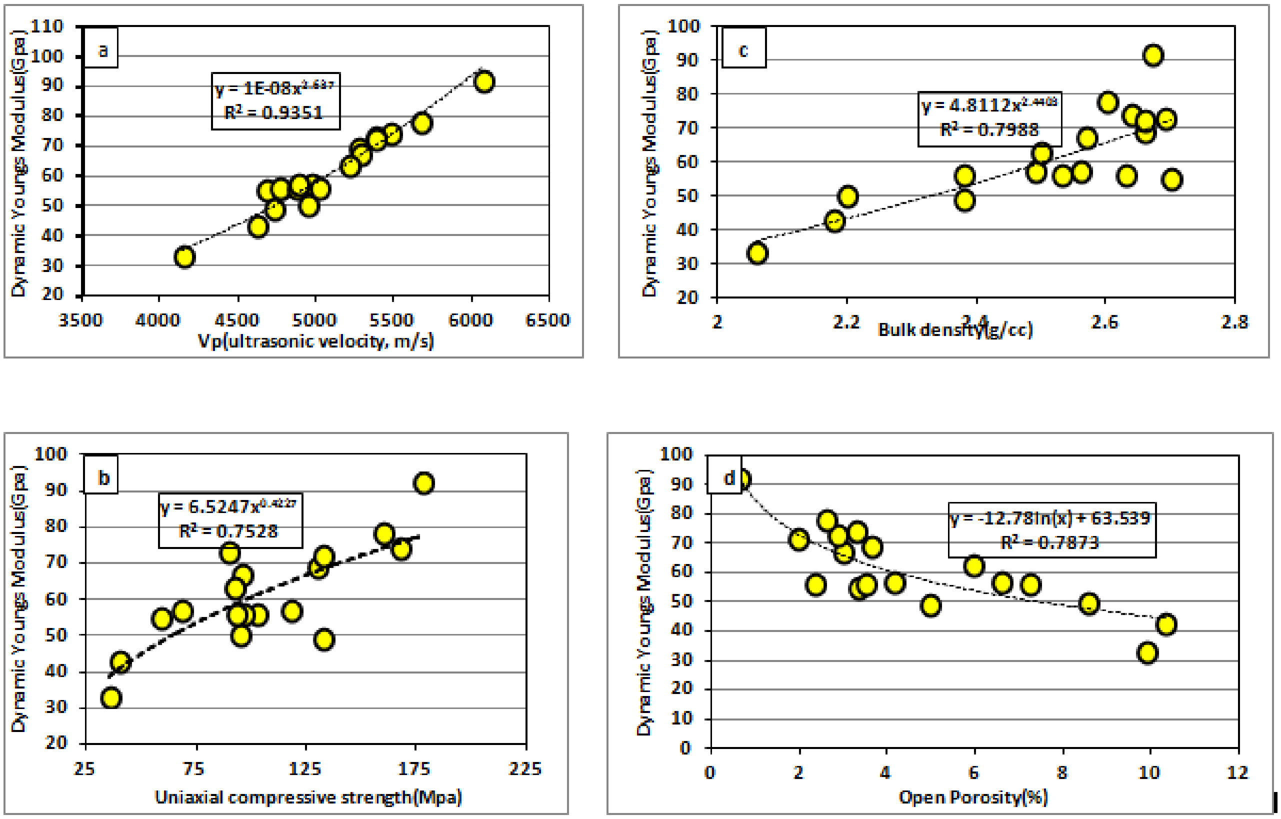

Figure 12-14 Graph showing the Dynamic Young's modulus and other physical and mechanical properties, a) Vp (P-wave velocity) versus Dynamic Young's Modulus, b) Uniaxial Compressive Strength versus Dynamic Young's Modulus, c) Bulk Density versus Dynamic Young's Modulus and d) Open porosity versus Dynamic Young's Modulus.

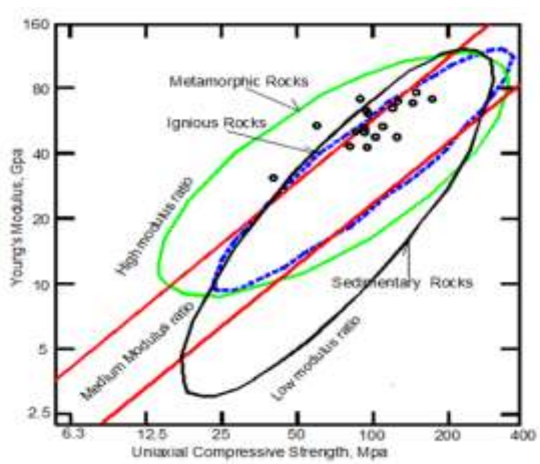

Figure 12-15 Chart showing Modulus ratio (Uniaxial Compressive Strength versus dynamic Young's Modulus)

12.2.1.9 Pore shape determination

Cavities in low porosity rocks are usually in the form of cracks, which are situated along cleavages in the minerals or at grain boundaries (Bourges, 2006). A simple approach to separate porosity of pores from porosity of cracks is to calculate the quality index. Tourenq and Fourmaintraux (1971) have described the calculation of the quality index. Indeed the authors proposed a method to quantify the discontinuities in rocks. It is based on the comparison of the measured ultrasonic velocity and theoretical ultrasonic velocity values and this lead to the Quality Index definition, with equation …:

$$\boldsymbol{QI}\% = \frac{\boldsymbol{Vp}}{\sum_i \boldsymbol{Ai.Vpi}} \quad \text{(Equ.3-11)}$$

where,

QI: Quality Index 0 < QI < 100 % (maximum quality)

Vp: measured ultrasonic velocity (P-wave) (m/s)

ΣAiVpi: theoretical ultrasonic velocity (P-wave)(m/s)

The theoretical ultrasonic Velocity is calculated from the velocity of each mineral contained in the rock and its concentration.

The Quality Index, QI%

As stated earlier there are four major lithotypes in the studied area and accordingly, the QI% is calculated for these lithotypes. For the porphyritic basalt, vesicular basalt, andesitic basalt and trachybasalt, the following theoretical P-wave Velocity values were taken from the literature (Gebrande, 1982; Goodman, 1990) to calculate the theoretical velocity and QI (Table 12-14):

Quartz: 6060 m/s, **plagioclase/feldspar**: 6250 m/s, **Pyroxene:** 6200m/s, **Olivine:** 8400m/s, **Volcanic glass:** 5720m/s, **magnetite/iron oxide:** 7400m/s and the mineral composition of the rocks were determined on microscopic view/thin section study of the Abbasanta-Borore basalts and it is shown below for each lithology (modal %):

1. Porphyritic basalt: 55 % plagioclase; 20 % pyroxene; 15% olivine, 15 % opaque
2. Vesicular basalt: 45% plagioclase; 30 % pyroxene; 8 % olivine, 15% opaque
3. Andesitic basalt: 67% plagioclase; 20% pyroxene; 10 % olivine
4. Trachybasalt: 50% plagioclase, 20 % pyroxene; 10 % olivine; 15% opaque

The theoretical ultrasonic velocity is calculated from the velocity of each mineral contained in the rock and its concentration, for example, Porphyritic basalt

$(Ai.Vi_P)$ =55%*6650m/s+20%*6200m/s+15%*6500m/s+15%*7400m/s=6777m/s

Then QI for porphyritic basalt= $Vp/AiVi_P$=5000/6777=73%

Similarly, the quality index for other lithologies is formulated as below,

Rock type	**Measured Vp(m/s)**	**Theoretical Vp (m/s)** $= \sum_i Ai.Vpi$	**QI (%)** $= \frac{Vp}{\sum_i Ai.Vpi}$	**Porosity (%)**
Porphyritic basalt	5000	6777	73	6.1
Vesicular basalt	4500	6490	69	10
Andesitic basalt	4900	6267	78	6.5
Trachybasalt	5100	6315	80	4.8

Table 12-14 Quality Index of the major rock units in the studied area

The porphyritic basalt, andesitic basalt and trachybasalt have relatively higher Quality Index than the vesicular basalt. It shows that these basaltic rocks (trachybasalt and andesitic basalt) may have fewer discontinuities in their structure. Hence these two rock units may be quite entirely characterized by a porosity of cracks as well as porosity of pores. While the vesicular basalt show a relatively lower Quality Index and could be characterized by pore porosity as it is relatively close to the pore porosity line (Figure 12-16).

In general, Quality Index (QI %) is obtained by non-destructive method and indicates the discontinuities in the rocks and therefore is seen as an important variable. Pore shape can also be determined when QI is displayed versus the total porosity. The higher value of QI indicates that crack porosity dominates while lower value shows pore porosity is prevailing.

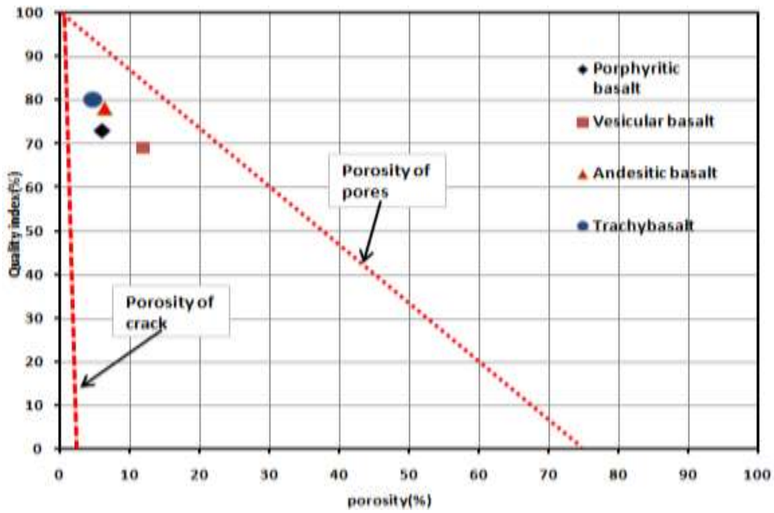

Figure 12-16 Corrected relation of the porosity of cracks and of pore of the porphyritic basalt, vesicular basalt, andesitic basalt and trachybasalt

12.3 Anisotropy

Generally anisotropy is one of the factors that affect the behaviour of rocks. The properties of such rocks vary with direction. In general, rocks have some degrees of anisotropy and isotropic rocks are rarely found in nature (Kwasniewski, 1993). The rock anisotropy is mainly due to the presence of foliation, cleavage, schistosity, joints, micro and macro fissures and bedding plane (Al-Harti, 1998).

Igneous rocks are more isotropic in nature than sedimentary and metamorphic rocks (Ramamurthy, 1993, 1993), whereas metamorphic rocks are mostly anisotropic. Rocks such as slates, shales, phyllites and gneisses have anisotropic behaviour.

12.3.1 Uniaxial Compressive Strength

Many researchers have studied the anisotropic behaviour of rocks such as shales, slates, sandstones, gneisses, phyllites, etc. Hence the anisotropy ratio for Uniaxial Compressive Strength is to be assessed with the following formula (Singh et al. 1989):

$$R_c = \sigma_{cmax}/\sigma_{cmin} \quad \text{(Equ.3-12)}$$

where ***Rc*** is anisotropy ratio, σ_{cmax} is the maximum strength and σ_{cmin} is the minimum strength. In view of equation (3-12), the samples collected and tested for Uniaxial Compressive Strength were also checked for anisotropy with the above formula. If the value (the ratio) is close to unity it is said quasi-isotropic, and very low or higher than unity indicates anisotropy (ISRM, 1989). In line with this, out of the total samples tested, 80% of the samples give almost unity, only 20% of the samples show slightly higher value than unity (1.48) with the exception of two samples resulting 2.12 & 2.3, and this shows that the rocks in the study area are quasi-isotropic with minor exceptions.

In summary, the anisotropy ratio which is the ratio between the maximum Uniaxial Compressive Strength to the minimum strength, can directly describe the ratio between the strength of rock materials (intact rock) to the shear strength of the discontinuity. Therefore, the anisotropy ratio increases with either the increase of compressive strength of the intact material or decreases of the shear strength of the discontinuities and vice versa.

12.3.2 Ultrasonic P-wave Velocity

The anisotropy of the P-wave Velocity is computed from the maximum velocity of the sample along the expected flow layering and the minimum velocity which has to be perpendicular to the assumed flow layering. In the basaltic rock samples; identifying flow layering is very difficult as the rock is massive and the sample size is very small. However, with the following equation, it is possible to assess anisotropy coefficient ***K*** to be determined using the relation by Živor, et al. (2011) and Ivankina et al. (2005):

K* % = [(*Vpmax* – *Vpmin*)/*Vpmean]100……………………………………….. (Equ.3-13)**

where ***Vpmean*** is the mean value determined from both velocities ***Vpmax*** and ***Vpmin*** *(*maximum & minimum ultrasonic velocity*)*. The values of the anisotropy coefficient of longitudinal waves of the study area, are practically low (0.2-9%) with the exception of 3 samples which give 12-13%, the average being 5.4%. Some basaltic samples exhibited very low anisotropy ratio (k%, 0.2-3%). However, in both cases, rocks of the studied area could be regarded as quasi isotropic regardless of the few exceptional results. This indicates that the laboratory P-wave Velocity measurement was least affected by anisotropy because the samples represent intact rock material and hence flow banding or microfractures are less encountered.

12.4 Durability assessement of the Abbasanta-Borore basalts

The durability of a stone is the measure of its ability to resist weathering and so to retain its original size, shape, strength and appearance over an extensive period of time (Bell, 1980). It is necessary to recognise that every rock type once put in service will be liable to change in appearance and undergo at least some decays.

If so, for what period of time must a material or a component last to be considered durable? The period of time will vary depending on the purpose of the building, and is defined as the service life.

There are several approaches suggested by numerous authors and guidance (BRE, BS, UNIEN, ASTM and AASHTO). Within the frame of this thesis, water absorption, porosity, saturation coefficient and uniaxial compressive strength, petrographic examination, salt crystallization methods are discussed regarding the durability of the building stone/dimension stone in the study area. These parameters are interpreted to be an indicator of easily disintegration upon exposure to atmospheric effects. Saturation coefficient (S) of a stone is the ratio between the natural capacity of a stone to absorb water after complete immersion under atmospheric pressure for a definite time, and its total volume of the pores that is accessible to water. It was first developed as a rapid frost resistance test on the theory that because water expands by approximately 10% on freezing, a stone must have at least 10% of its pore space empty to be able to accommodate the expansion.

Saturation coefficient depends on the pore structure (pore size and pore size distribution). A stone with a very high saturation coefficient may be deteriorated by some alteration processes, for instance the freezing of water.

Sample N.	**Wtabs (%)**	**Open porosity (%)**	**Saturation Coefficient S**	***Uniaxial Compressive Strength (MPa)***
abs-02	1.34	3.65	0.37	129
abs-04	1.21	3.32	0.36	59
abs-05	1.22	3.28	0.37	167
abs-10	4.71	9.89	0.48	35
abs-11	4.64	10.33	0.45	40
abs-12	1.64	4.17	0.39	68
abs-13	1.14	2.98	0.38	95
abs-15	1.05	2.89	0.36	89
abs-16	2.05	4.99	0.41	132
abs-18	2.33	5.95	0.39	92
abs-19	0.87	2.35	0.37	102
abs-21	2.82	7.26	0.39	96
abs-24	0.24	0.64	0.38	177
abs-27	3.83	8.59	0.45	94

abs-28	2.52	6.58	0.38	118
abs-32	0.98	2.6	0.38	160
abs-39	1.44	3.5	0.41	93
abs-41	0.73	1.99	0.37	132

Table 12-15 Saturation Coefficient of the studied samples

S = (water absorption /effective porosity)

A rock with very high saturation coefficient may be deteriorated by freeze-thaw activity (RILEM, 1980). Therefore, this value is an indicator to evaluate the durability of the stone in freeze-thaw situation. The value of saturation coefficient can mostly vary between 0.4 and 0.95 (BRE, 1983). A saturation coefficient greater than 0.8, indicates low durability "susceptible to frost activity" (Hirschwald in Schaffer, 1972).

S<0.75 weathering and frost resistant

0.75-0.85 moderately resistant

> 0.90 not weathering and frost resistant

However, many rocks have saturation coefficients within the range of 0.66 to 0.77. In this regard, the saturation coefficient gives an unreliable guide (Anon, 1975). As has been seen above (Table 12-15), the saturation coefficient of the studied samples ranges between 0.36 to 0.48 which is weathering and frost resistant.

Furthermore, to assess durability, Bell (1988) explained that a measurement of porosity does not serve as an adequate indicator of durability, as it does not provide information on the distribution of pores within the rock. For Bell the saturation coefficient, or Hirschwald coefficient, linked with pore size distribution are the main factors required to assess durability. In any case, the saturation coefficients of Abbasanta-Borore rocks are very low indicating high resistant to weathering and freeze-thawing. However, the response of a rock to weathering is directly related to its internal surface area and average pore size. Hence, coarse grained rocks generally weather more rapidly than fine grained ones. The degree of interlocking between component minerals also is a particularly important textural factor, since the more strongly a rock is bonded together, the greater is its resistance to weathering. The closeness of the interlocking of grains governs the porosity of rock. This, in turn, determines the amount of water it can hold and so the more porous the rock, the susceptible it is to chemical attack (Ordonez et al., 1997). The severity of the conditions to which a rock is exposed in a building is influenced by the nature of the environment and the degree to which this is affected by the features of, and the location within, the building itself. Hence, different zones can be recognized in terms of the protection afforded. If 60 years is taken as the design life of domestic buildings, then there are few stones that do not afford satisfactory performance if located in a sheltered position. Therefore durability needs to be taken into account when the stone is intended for longer life, for more exposed positions (e.g. string courses or copings) or for harsher environments (e.g. coastal situations). Exposure of stone to intense heating causes expansion of its component minerals with subsequent exfoliation at its surface. The most suspect rocks in this respect appear to be those that contain high proportion of quartz and alkali feldspars. Generally, finely textured rocks offer a higher degree of heat resistance than do coarse grained varieties (Bell, 2003).

Moisture in rocks is of great importance as a destructive agent and as a means of transporting salts. Most of the moisture present in rocks is derived by condensation from the atmosphere, from rain and from rising ground moisture. The latter contains more ions than rain water (Arnold, 1981 as cited in Bell, 2005).

Although, the rate of weathering of igneous rocks usually is slow, there are exceptions and once weathering penetrates a rock, the rate accelerates. Some basalt are deteriorated within a short period of time and Haskins and Bell (1995) commented on the rapid breakdown of basalts on exposure and attributed this to the presence of smectitic clay minerals formed by the deuteric alteration of primary minerals, the clay minerals swelling and shrinking on wetting and drying respectively.

In addition to the above mentioned classification, another assessment of durability regarding the strength of the samples depending on various researchers is presented in Figure 3-19 below and it is revealed that the average strength value of the currently studied rocks (Mean, 104MPa) is in the scale corresponding to medium to high strength rock in each of the classification schemes (Figure 12-17).

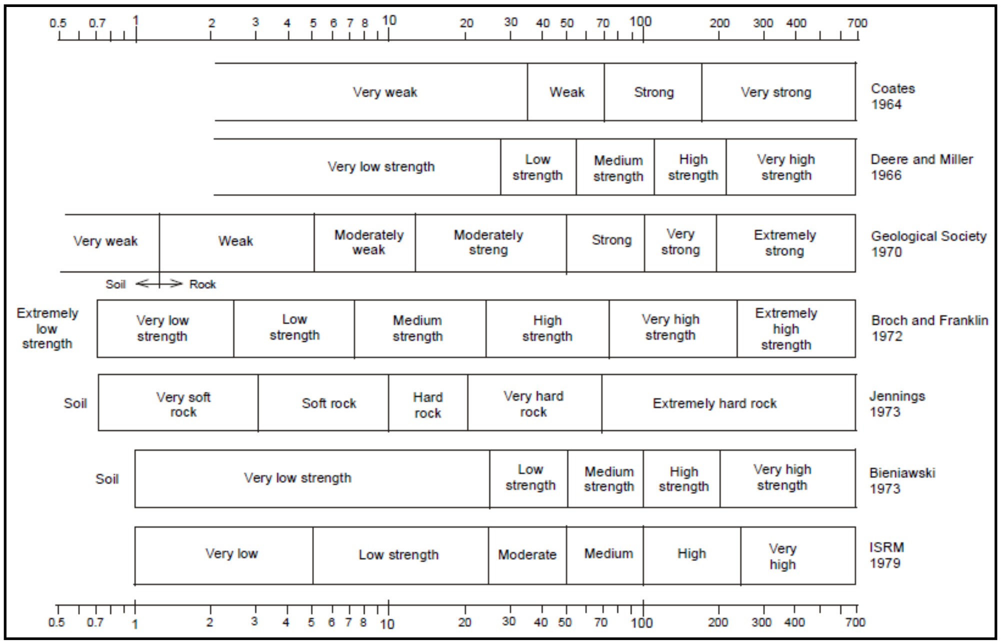

Figure 12-17 Classifications of rock material strength (from Bieniawski, 1984, as cited in Palmstrom A., 1995)

However, extreme values of properties of the vesicular basalt such as very low relative density and Uniaxial Compressive Strength (such as 2.06 g/cm^3, 35MPa, of sample Abs-10) and high porosity (such as 10 %, Abs-11) give an indication of the sensitivity of these units and its susceptibility to reduction in its strength and stiffness.

12.4.1 Petrographic examination

Petrographic examinations were carried out according to UNIEN 12407: 2000. For any proposed building stone a starting point for evaluation of its durability, petrographic examination is paramount important in that it could lead to select which tests will be relevant to be performed next to it.

The petrographic examination of samples collected from the study area evidenced the presence of high proportion of plagioclase, pyroxene, olivine, some opaque (Fe-oxide) and microfractures as described above in section 3.2.1.1. In addition, also some samples exhibit high abundance of opaque (Fe-oxides) and trace amounts of deleterious constituents including zeolite and chalcedony. However, further XRD analysis on selected samples confirmed the presence of cristobalite, montmorillonite and phlogopite, but was unable to quantify these harmful constituents towards using the basaltic rocks as construction material.

12.4.2 Secondary mineral rating index

The secondary mineral rating system of Cole & Sandy (1980) represents an attempt to quantify mineralogy and texture in relation to durability and was specifically developed to assess basalts for use as road aggregates. The secondary mineral rating *(Rsm)* is given by:

$$Rsm = [\sum (P.M)]\, T \qquad \text{(Equ.3-14)}$$

where **P** is the percentage of secondary minerals present in the rock, **M** is the rating for a particular secondary mineral, and **T** is a textural rating for the rock (Table 12-16). Cole & Sandy (1980) suggested a critical value for Rsm of 140, above which the rock could be regarded as unusable.

a) Mineral ratings

Mineral ratings(M)	*M*	*Mineral*
Least deleterious	2	Calcite, white micas (muscovite and sericite)
	3	Kandites, chlorites, vermiculites, zeolites, hydrous micas (including illites), brown micas (phlogopite and biotite)
	5	Swelling chlorite
Most deleterious	10	Iddingsite (a mixture of chlorite, vermiculite and smectite)

b) Texture ratings

Texture ratings(T)	*T*	*Mineral*
Least deleterious	0.3	Partial alteration of phenocrysts (up to 50%)
	0.3	Incomplete vesicle filling (up to 50%)
	0.4	Complete alteration of phenocrysts (more than 50%), e.g. iddingsite after olivine
	0.5	Homogeneous scattered distribution in matrix
	0.6	Large irregular matrix patches (1 to 5 mm) including filled vesicles
	0.7	Irregular matrix patches, minor interconnections
	1.0	Irregular partly connected patches in the matrix
Most deleterious	2.0	Fine interconnected vein networks or patches (0 to 30 mm apart)

Table 12-16 Secondary mineral rating system (after Cole and Sandy 1980)

Based on Table 12-16, for some of the basaltic samples which show some slight alterations, secondary mineral rating index was calculated and it is found to be low, as suggested by Cole and Sandy, values above 140 are unstable or non durable. One important thing is that, the secondary mineral index rating takes into account chemical alteration and mechanical fracturing of minerals which form the bases of most classification of weathering. It therefore would appear that the value of 140 suggested by Cole and Sandy to distinguish unsuitable (non durable) material is too high.

Subsequently, Tugul and Gurpiner (1997a) introduced **a petrographical weathering index** (Ipw) based on the proportion of weathered minerals in a basalt as follows,

Ipw= Wp/ (1-Wp)... *(Equ.3-15)*

where, Wp is the percentage of weathered/altered minerals

As it can be seen from Table 12-17 all the basaltic samples could be grouped under fresh (unaltered) or faintly altered according to petrographic weathering index (Table 12-16) after Tugrul & Grupinar (1979a).

Sample number	*Type of secondary Mineral identified*	*Percentage (modal analysis)*	*Secondary mineral index (Rsm)*	*Petrographic Index (Ipw)*
Abs-10	Iddingsite	10%	2.5	0.11(FA)
Abs-11	Iddingsite	8%	2	0.08(F)
Abs-12	iddingsite	15%	3.75	0.17(FA)
Abs-16	Iddingsite	10%	2.5	0.11(FA)
Abs-18	iddingsite	12%	3	0.14(FA)
Abs-21	Iddingsite	15%	3.75	0.17(FA)

Table 12-17 Percentage of altered minerals, secondary minerals ratings and petrographic weathering index of the various basaltic samples, where, F=Fresh, FA=Faintly altered, (after Tugrul & Grupiner 1997a)

Actually, according to megascopic observation, the basaltic samples show very slight alterations and weathering evidence in hand specimen. The locations of all samples and geological observation and documentation points are depicted on figure 12-18.

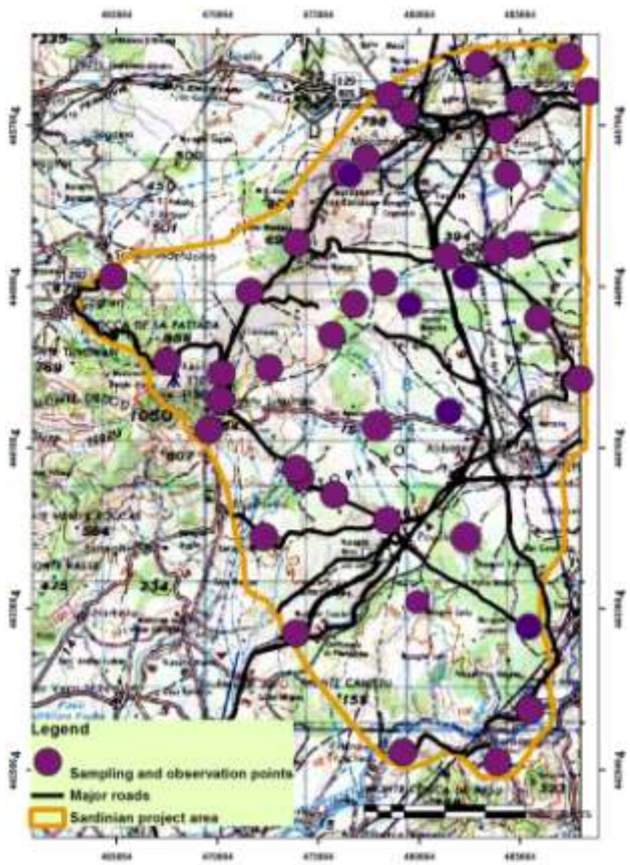

Figure 12-18 Sampling and observation points location map of the study area

CHAPTER THIRTEEN

13. Geoengineering evaluation for coarse crushed aggregate tests and results

13.1 Introduction

The last few years have been strongly marked by the continuing economic crisis in the world. The European Union has not escaped these problems, as is evident in the substantial decrease in production (supply) of aggregates during this time period. Hopefully, in the next few years the outlook will become more optimistic, primarily on the basis of renewed economic momentum, as well as faster societal development. In both scenarios (crisis and economic renewal) a need for different approaches to aggregates resources management and supply at all scales (from local, regional, and national to transnational) are needed.

Dimension stone and aggregates (that is crushed stone, sand and gravel) are an essential ingredient of the key building components that make up the residential, social and commercial infrastructure of modern European society. Europe currently needs some 3 billion tonnes of aggregates a year, equivalent to over 6 tonnes per capita (Tiess, 2011). The aggregates industry accounts for more than 22,000 production sites. Taking an EU average price of 7-8€/tonne, the aggregates sector represents a turnover of around €20-25 billion (Tiess, 2011).

The aggregates used in concrete mix have to meet a number of specifications with regard to mechanical performance, durability, chemical stability, alkali silica reactivity, gradation, shape, surface texture, and the presence of harmful materials. Several standard tests are employed to ensure aggregates qualify those specifications. However, petrographic examination, despite being qualitative in nature, remains the most valuable test for predicting the overall performance of concrete aggregates in any control test, and in service, as well (Berube, 2001).

Throughout the world, basaltic rocks are used extensively as engineering materials including as aggregates for Portland cement concrete and asphaltic concrete mix, rock fill for dams and breakwaters, material for railroad ballast and highway base courses (Goodman,1993).

Prediction of aggregate characteristics before placement and starting the construction activity can indicate the un-expected failure and can prevent the post construction material problems. In this regard, keeping in view other construction material requirements, aggregate sampling and testing is a paramount importance to make the construction workable and long-lasting. The construction industry needs to move toward material laboratories in order to ensure quality and establish adequate confidence regarding the material used to satisfy given requirement and quality during the service life. Quality assurance of materials, therefore, as a first step needs testing of materials on the basis of specifications that should ensure and increase the confidence regarding fitness for the purpose of product and services.

The preliminary need of the aggregates is its inherent durability against natural and man created disturbances. The aggregates provide volume, stability, resistance to weathering and other physical properties to the building and road structures. There are common issues in construction related to characteristics of material such as; suitable aggregate gradation, shape, density and source.

Crushed rock is produced for a number of purposes, the chief of which is for concrete and road aggregate. Concrete may be defined as a mixture of water, cement or binder, and aggregate, where the water and cement or binder forms the paste and the aggregate forms the inert filler. In absolute volume terms the aggregate amounts to 65-75% of the volume of concrete and is, therefore, the major constituent (Figure 13-1) and so its properties have a significant influence on the engineering behaviour of concrete. The aggregate type and volume influence the properties of concrete, its mix proportions and its economy. So, characterization of aggregate source/parent rocks is a prerequisite before to start production of aggregates from any quarry. Aggregate is divided into coarse and fine varieties, the former usually consists of rock material that passes the 37mm sieve and is retained on the 4.8mm mesh (Bell, 2003) and this is the focus of the current study.

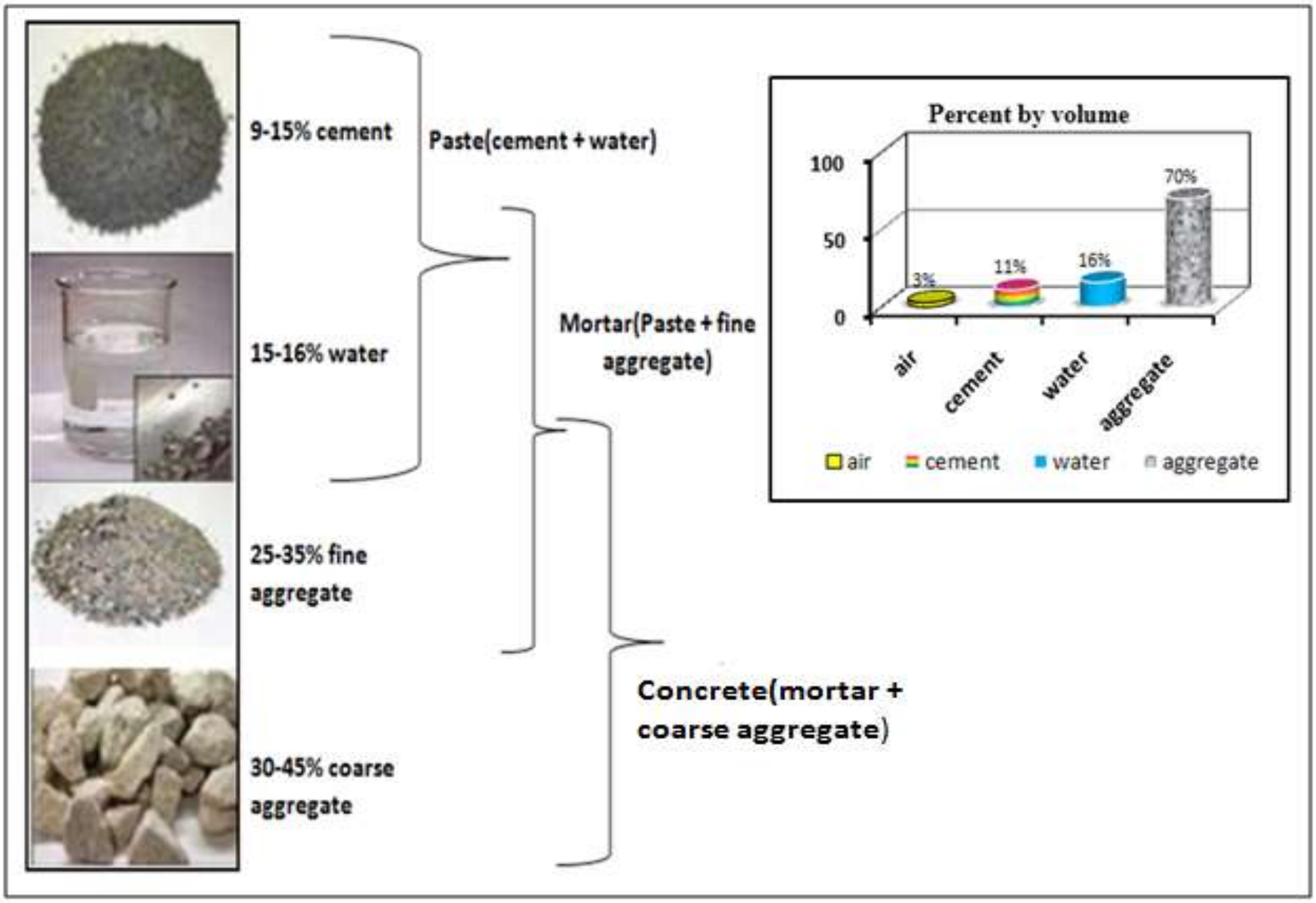

Figure 13-1 Concrete ingredients by volume

The performance of aggregates depends on a number of factors (Smith and Collis, 1993; Fookes et al., 1988, Hudson, 1999, Kandhal et al., 2000; Neville, 2000) that can be evaluated by appropriate aggregate tests indicated in published literature on road and building codes to assure quality. The engineering properties of aggregates are directly related to the performance of mortar, concrete and unbound and bound pavement (Smith & Collis, 1993; Neville, 1993). Durable and strong aggregates are normally preferred that can resist abrasion and disintegration, make an excellent bond with cementing materials, are resistant to rapid impacts and are sound (BS: 812).

Therefore, this chapter deals with the engineering properties of crushed coarse aggregates and data represented here relates to the samples collected from active quarries and natural outcrops of lithotypes mapped in the studied area.

The list of selected tests for the current study are as follows; Flakiness Index, Elongation Index, Los Angeles Abrasion Value (LAAV), Specific gravity and water absorption, bulk density, Aggregate Crushing Value (ACV) and Alkali Silica Reactivity (ASR). The samples utilized for conducting these tests, however, remained confined to crushed coarse aggregates obtained from existing active quarries and natural outcrops.

The physical and mechanical properties like specific gravity, porosity, thermal behaviour, compressive strength, tensile strength, and the chemical properties of an aggregate are attributed to the parent/source material. The shape, size and surface texture which are essential for concrete workability and bond characteristics between the aggregate and cement paste are, however, attributes of the mode of production and nature of the parent rock. The strength and durability parameters of the produced concrete structure may also be affected by any change in the water demand during production. The aggregate producer, however, usually have little control over aggregate properties such as strength, particle density and water absorption although these on occasions may be of some importance and be limited in concrete structure specifications. In general, processing may have some effect, but most of these properties remain essentially the same as the parent rock (Smith & Collins, 1986).

It is, therefore, essential to understand the mechanical, physical and chemical properties of aggregate and its modes of production in an effort to produce the required quality of concrete. The studied basalt samples were broken into smaller pieces by hammer. Standard (10-14 mm) and nominal (6.3-10 mm) size aggregate fractions were prepared from the smaller pieces using a laboratory mini jaw crusher. The aggregate tests undertaken included specific gravity, potential Alkali Silica Reactivity (ASR), Water absorption, Uncompacted bulk density, Aggregate Crushing Value and Los Angeles Abrasion Value. These tests were performed in accordance with AASHTO, ASTM and BS Standards. Each test was performed at least two or three times. The samples were numbered by using prefixes “AB-AG” for Abbasanta Basalt-Aggregates.

13.2 Engineering properties of aggregates

In service behaviour of natural aggregates depends on different characteristics (BS: 812) and published literature indicates that a wide range of tests have been devised to describe the materials and determine their potential value (Smith & Collis, 1993; Neville, 2000) as construction material. These tests are assumed to predict the future in service performance of the aggregates. Most require some physical or mechanical attribute of the material, while a few investigates particular chemical characteristics (BS: 812). The aggregate quality is determined by its physical, mechanical and chemical properties or overall combination of these three parameters. In cement and asphalt concrete, petrographic analysis of aggregates is carried out to determine its behaviour in different environmental conditions (Neville, 1995). Following is engineering properties based on physical, mechanical and chemical tests performed to predict the expected behaviour of the various basaltic units identified in the study area.

13.2.1 Physical properties of aggregates

The physical properties of aggregates stem from the inherent properties of the parent rock and predict as to how an aggregate would perform in construction. The commonly measured physical/mechanical aggregate properties (BS: 812; Smith & Collis, 1999; Roberts et al., 1996; Dunnby, 1983) are surface texture and specific gravity, water absorption and bulk density. Toughness and wearing resistance are determined by Los Angeles Abrasion and Aggregate Crushing tests. The size and shape of aggregate particles are important properties, and are governed by the type of crusher plant on the one hand and the fracture pattern of a rock mass on the other. These properties are termed Consensus properties of aggregates, because there is a wide agreement in their use and specified values. These properties are based on the criterion of traffic level and position within the pavement structure. Materials closer to the pavement surface requires strict Consensus properties as these are subjected to high traffic levels.

13.2.1.1 Specific gravity (relative density), water absorption and bulk density

There is generally a direct positive relationship between high specific gravity and high strength of aggregates (Kandhal and Lee, 1970, Neville, 1973, 2000). The specific gravity of the basaltic units was determined using ASTM: C29 &127; its value ranges from 2.26 to 2.71 for the oven dried samples and 2.33-2.75 for the saturated and surface dried samples (Table 13-1). The porphyritic olivine basalt and trachybasalt yield the highest specific gravity due to massive and compact nature as well as the presence of magnetite/ilmenite. The results are shown in the table below (Table 13-1). This property according to ASTM: C29 &127 gives an idea of the strength of rocks.

Sample Number	Oven dry specific gravity	Saturated and surface dry specific gravity	Water absorption (%)	Uncompacted bulk density(kg/m^3)
AB-AG-02	2.71	2.75	1.51	1230
AB-AG-11	2.26	2.33	3.11	990
AB-AG-12	2.56	2.61	1.85	1140
AB-AG-13	2.55	2.60	1.77	1180
AB-AG-18	2.61	2.67	2.23	1080
AB-AG-24	2.70	2.75	1.95	1210
AB-AG-28	2.67	2.74	2.36	1280
AB-AG-32	2.61	2.67	2.05	1250

Table 13-1 Laboratory test results of specific gravity and water absorption of Abbasanta-Borore basalts

Water absorption is an indirect measure of the permeability of an aggregate, which, in turn can relate to other physical characteristics such as mechanical strength, shrinkage and its general durability potential (Collis and Fox, 1985). It could be also related to mechanical strength, soundness and durability (Smith & Collis, 1993; Neville, 2000). “Aggregates having high water absorption are more porous in nature and are generally considered unsuitable unless they are found to be acceptable based on other properties such as strength, impact and hardness tests “(Schmidt and Graf, 1972). A study conducted in 1995 by Pigeon and Pleau suggested that a limit of 2 percent be placed on the water absorption of coarse aggregates to prevent freezing and thawing damage from occurring.

In general, less absorptive aggregates often tend to be more resistant to mechanical forces and to weathering. Low absorption value might reasonably be considered as less than 1% and it is imperative to clarify that water absorption limits should not be imposed unless it has been established, for a particular material, which it relates closely to some other undesirable property. Although an aggregate may satisfy water absorption limit, there is no guarantee that problems with concrete will not occur (Smith and Collis, 1993). However, BS 812: and ASTM C127, C128, state that the upper limit for concrete aggregate water absorption should not be greater than two (<2%).

The currently studied samples water absorption values range between 1.51 % and 3.11% (Table 13-1). The minimum value of the water absorption was determined in the porphyritic basalt which is dense and massive (1.51%) while the maximum water absorption is recorded from vesicular basalt (3.11%). The entire studied basaltic samples water absorption value is below 2% with the exception of 3 samples (Figure 13-2).

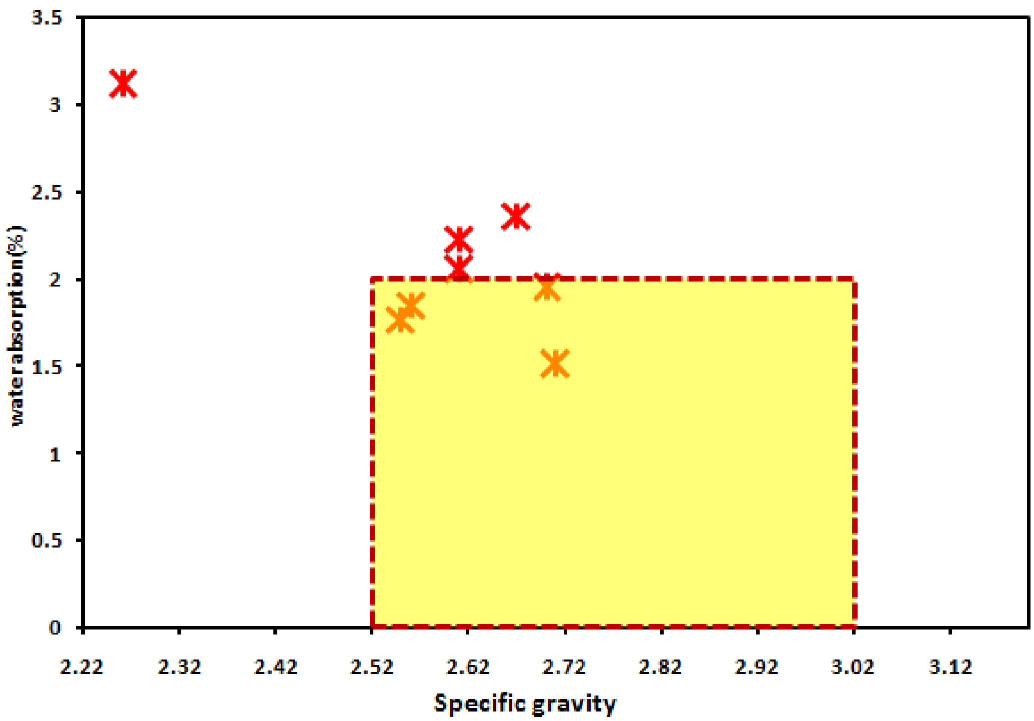

Figure 13-2 Graph showing water absorption (%) versus specific gravity

As shown in Figure 13-2, only 50% of the samples falls within the acceptable limit marked by the dashed red line rectangle according to ASTM: C29 & 127 and BS: 812.

It should be noted that if the aggregates are dry they absorb water from the mixing water and in doing so affect the workability and, on the other hand, if the aggregates contain surface moisture they contribute extra water to the mix and thereby increase the water/cement ratio. Both these conditions are harmful for the quality of concrete. In making quality concrete, it is very essential that corrective measures should be taken both for absorption and free moisture so that the water/cement ratio is kept as exactly as per the design (Shetty, 1982, as cited in Denamo, 1995). The water absorption of the vesicular basalt (AB-AG-11) is greater than any of the other samples (Figure 13-3) indicating this unit is not good as aggregate for concrete mix as far as the specific gravity and water absorption is considered.

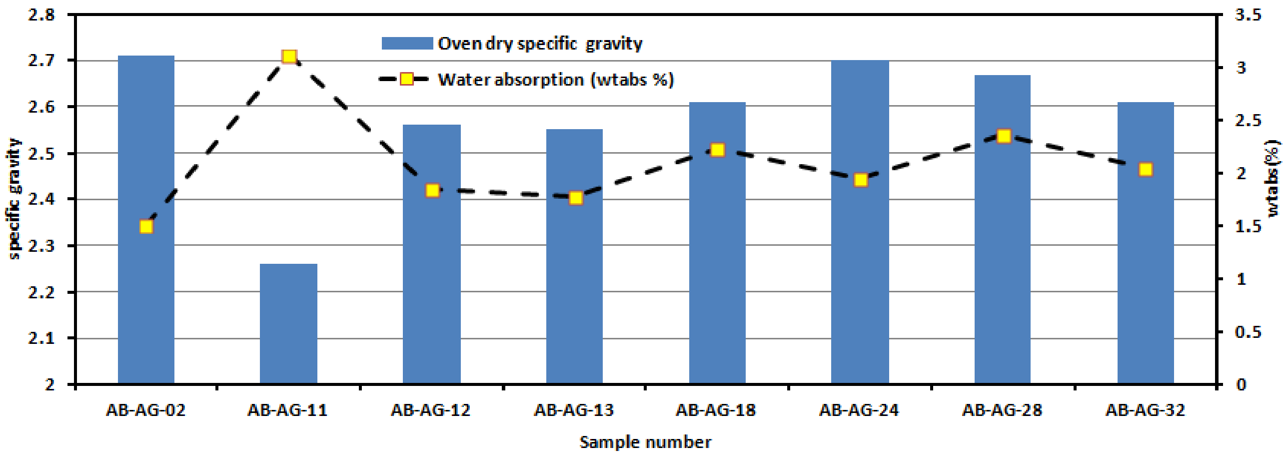

Figure 13-3 Bar chart showing water absorption, specific gravity versus sample number

Some aggregates are porous and absorptive. Porosity and absorption of aggregate will affect the water/cement ratio and hence the workability of concrete. The porosity of aggregates will also affect the durability of concrete when the concrete is subjected to freezing and thawing and also when the concrete is subjected to chemically aggressive liquids (Shetty, 1982).

The uncompacted bulk densities of the studied basalt aggregates were also determined in accordance with ASTM: C29 & 127. The basalt belonging to the trachybasalt and porphyritic basalt shows the highest value while the vesicular basalt shows the lowest value (Table 13-1). The uncompacted bulk density of an aggregate also takes into account the effects of voids present in the aggregate at a given degree of compaction (Waqa, 2004).

13.2.2 Mechanical properties

The aggregate properties, whose critical values are source specific, are often used by the producers to classify local sources of aggregates. The properties may be used as a source acceptance control and are relevant during the mix design process. The source aggregate properties are toughness (LAAV), deleterious materials, soundness and some other mechanical properties.

The mechanical property tests provide parameters for strength and durability of rock aggregates (Aitcin & Mehla, 1990; Neville, 2006). The available standards (UNIEN, BS, ASTM, AASHTO, etc) require that the rock aggregate should not disintegrate during mixing or compaction. In the current study, strength and durability of the basaltic aggregates were tested through the procedures and limits defined by the parameter such as Aggregate Crushing Value (ACV) and Los Angeles Abrasion Value (Table 13-2).

Sample N.	Los Angeles Abrasion Value (LAAV, %)	Aggregate Crushing Value (ACV, %)	Remarks
AB-AG-02	32	25	
AB-AG-11	33	46	Vesicular basalt
AB-AG-12	17	23	
AB-AG-13	31	22	
AB-AG-18	26	22	
AB-AG-24	26	19	
AB-AG-28	32	21	
AB-AG-32	17	20	

Table 13-2 Laboratory Values of the LAAV and ACV mechanical properties of aggregates

13.2.2.1 Strength

Aggregate strength needs to be assessed for aggregates that are to be used in high strength concrete, but not for normal strength due to the fact that the strength of concrete is generally controlled by the strength of the hydrated cement matrix rather than the aggregate in normal strength concretes. There are currently no AASHTO or ASTM testing methods to determine aggregate strength directly. However, the British Aggregate Crushing Value Test has been used extensively to determine the relative strength of graded concrete aggregates. This test consists of applying a load to an aggregate sample in a steel cylinder for 10 minutes. After the 10 minutes loading period, the sample is analyzed for changes in gradation and a value is determined. Although, the Aggregate Crushing Value test may provide insight into the strength of the aggregate it may not always reflect the strength of the concrete in which the aggregate is placed. The Aggregate Crushing Value does not measure strength in the sense of compressive strength in intact rocks; rather it is index of the resistance to pulverisation over a prescribed interval or sequence of loading (Collis and Fox, 1985).

When cement paste of good quality is provided and its bond with the aggregate is satisfactory, then the mechanical properties of the rock or aggregate will influence the strength of the concrete. Therefore, it can be concluded that while strong aggregates cannot make strong concrete, for making strong concrete, strong aggregates are essential requirement (Shetty, 1982).

Assessment of strength of the aggregate is made by using a sample of bulk aggregate in a standardized manner. This test is known as Aggregate *Crushing Value test*. Aggregate Crushing Value gives a relative measure of the resistance of an aggregate sample to crushing under gradually applied compressive load (Shetty, 1982).

During strength evaluation of the tested samples, all the various lithotypes are considered. The strength evaluation considers Aggregate Crushing Value (ACV) and also the Uniaxial Compressive strength in general. These properties normally depend on their inherent properties in particular and on the particle shape in general (Monteiro, 1993).

Aggregate Crushing Value

Toughness is the property of aggregates to resist impact against moving static loads. These tests are included in British Standards for measurement of the mechanical properties of crushed rock aggregates, designated as Aggregate Crushing Value (ACV) tests (BS 812: Part 110).

Apart from testing aggregate with respect to its crushing value, testing the aggregate with respect to its resistance to wear is an important test for aggregate to be used for road constructions, warehouse floors and pavement constructions.

In these tests, samples ranging in size from 10 to 14 mm are subjected to shock and static load. The proportion of material passing BS 2.36mm sieve after loading is calculated as a percentage of the original sample weight, and expressed as Aggregate Crushing Value for static loading.

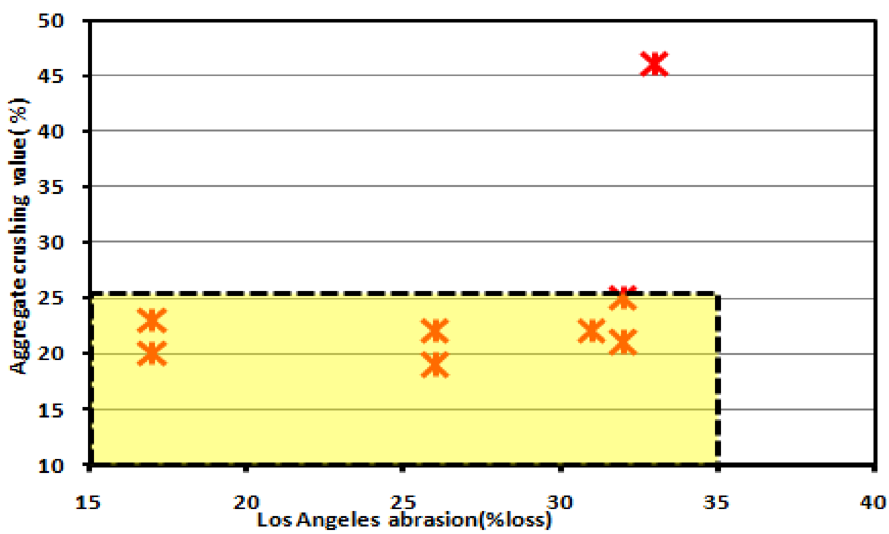

Figure 13-4 Graph showing the LAAV (loss %) versus ACV (%) and samples falling in the accepted limits

In the current study, the Aggregate Crushing Value ranges from 19 up to 46%. The samples collected from the vesicular basalt rendered exceptionally high Aggregate Crushing Value (46%) which is considered bad. The Aggregate Crushing Value should be less than 25% according to Bs specifications. The samples collected from trachytic basalt and porphyritic basalt showed very good results (19-20%) which both are dense and hard. As depicted in Figure 13-4, the graph presents the relationship between L.A. Abrasion and Aggregate Crushing Value. The dashed blue line rectangle represents the range for which all L.A. Abrasion Values will lie for Aggregate Crushing Value of less than 25%. The lower the value the better the strength and the higher the value the weak is the aggregate. Therefore, almost all the samples satisfy BS 812:1990 specifications to be used as concrete mix except a single sample (Abs-11) as far as LAAV and ACV is concerned (Figure 13-5).

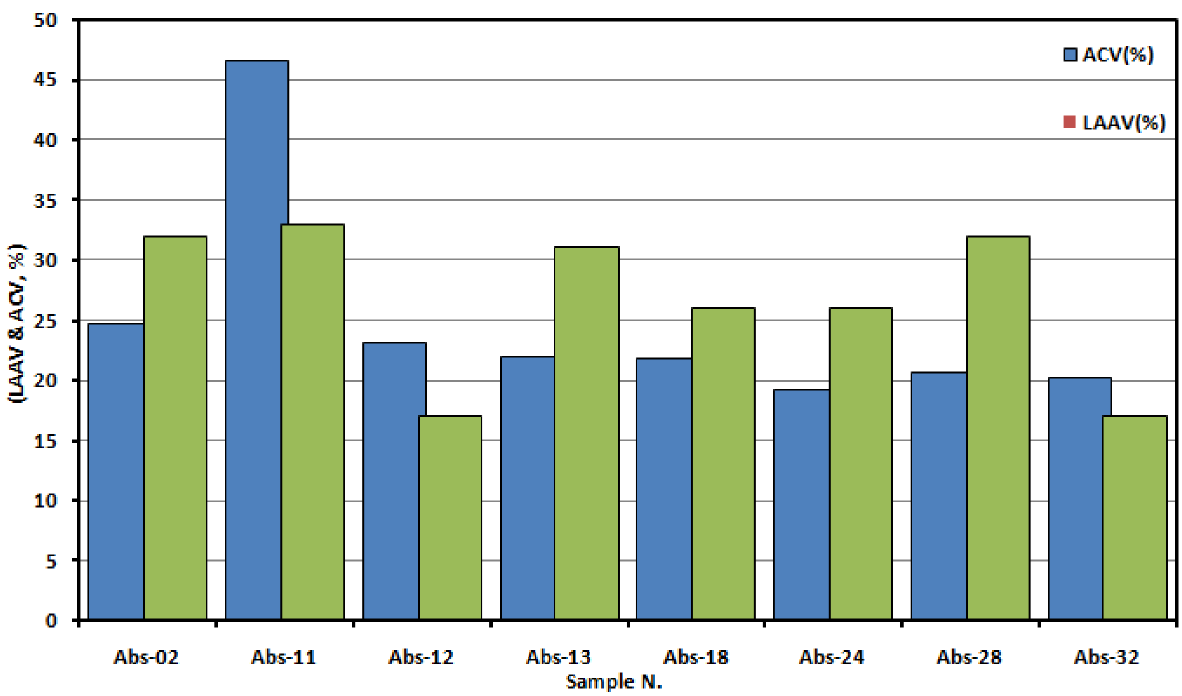

Figure 13-5 Bar charts showing the ACV & LAAV versus sample number of the studied samples

13.2.2.2 Durability of aggregates

Since aggregates make up the bulk of concrete, any lack of durability of the aggregate will have disastrous consequences for the concrete. If there are durability problems, special screening tests may be required, routinely to avoid problematic aggregates, or special measures must be taken to counteract the effects of undesirable aggregates. The latter approach will become more important in the future as deposits of high-quality aggregates are worked out and more marginal material is brought into use (Sidney & Young, 1981). Aggregates should be hard and should not contain materials that are likely to decompose or change in volume when exposed to weather. Examples of undesirable materials are coal, pyrite and lumps of clay.

It is the resistance to wear or decay which defines durability of the material that is an important requirement of rock aggregates (Fookes & Collis, 1975). Similarly, the aggregate may be resistant to weathering conditions (Fookes et al., 1988). Durability tests are defined for this research work in terms of Los Angeles Abrasion Value (LAAV) and Sodium Sulphate Soundness test, secondary mineral index and petrographic weathering index of the aggregate source rocks.

Los Angeles Abrasion Value (LAAV)

The test consists of placing an aggregate sample in a steel drum along with 6-12 steel spheres weighing approximately 420 g each. The steel drum is then rotated for 500 revolutions. A steel shelf within the drum lifts and drops the aggregate and steel spheres with each revolution. Following the completion of the 500 revolutions the resulting sample is dry sieved to determine the amount of degradation that occurred during the test (Figure 13-6). The overall stability of concrete aggregates may be defined as the ability of individual particles to retain their integrity and not to suffer any physical, mechanical and chemical changes, which could adversely affect the properties or performance of concrete in either engineering or aesthetic respects (Collis and Fox, 1985).

Figure 13-6 Photo showing the steps followed in Los Angeles Abrasion Value testing

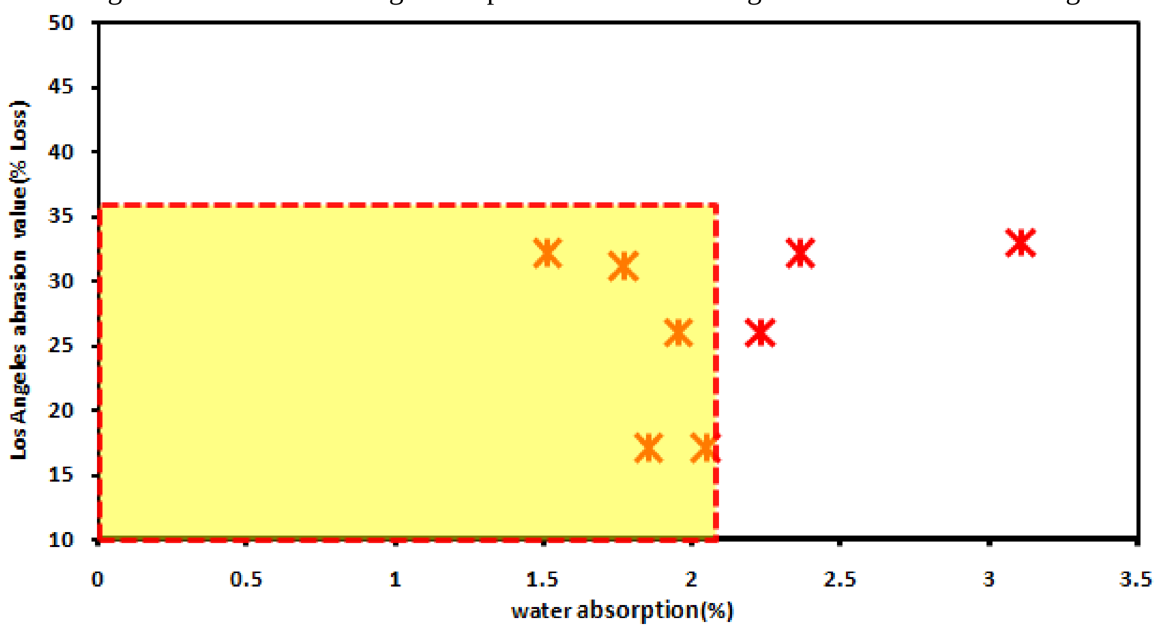

Figure 13-7 Water absorption versus Los Angeles Abrasion Value (% loss)

As depicted in Figure 13-7, the graph presents the relationship between L.A. abrasion and water absorption. The dashed red line rectangle represents the range for which all L.A. Abrasion Values (35%) will lie for water absorption of less than 2.1%. This demonstrates the high potential of the studied samples for coarse aggregate production in consideration of the L.A abrasion test and water absorption; however other relevant tests should also be verified according to the various standards and end uses. However, the L.A Abrasion is the most critical and important aggregate source property that should be considered in priority in the aggregate production.

Experience showed that, some aggregates with satisfactory values from the standard strength tests deteriorate with time. This LAAV test is a measure of degradation of mineral aggregates of standard grading resulting from a combination of actions including abrasion, impact and grinding in a rotating steel drum containing the prescribed numbers of steel balls. The test has been widely used as an indicator of the relative quality of competence of various sources of aggregates. The test can only be used with coarse, dry aggregate. Unsounded aggregates are those that show significant volume changes, resulting in the deterioration of concrete when subjected to different environmental conditions (Waqa, 2004). On the other hand, to be able to resist abrasion, an aggregate has to be hard, dense, strong and free from soft particles.

Sample N.	***LAAV (%)***	***Water absorption (%)***	***Remark***
AB-AG-02	32	1.51	
AB-AG-11	33	3.11	Vesiculated basalt
AB-AG-12	17	1.85	
AB-AG-13	31	1.77	
AB-AG-18	26	2.23	
AB-AG-24	26	1.95	
AB-AG-28	32	2.36	
AB-AG-32	17	2.05	

Table 13-3 Laboratory values of LAAV and Wtabs% of the studied basalt samples

Generally, the LAAV ranges from 17 to 33% which indicates these aggregate samples are moderately sound with regard to above considered standards (Table 4-3). Specifically, the LAAV of the porphyritic basalt (AB-AG-12 and AB-AG-32, 17%) indicates that these basaltic rocks are not only strong but also possess superior resistance to abrasive action. This result has confirmed the relatively high durability of the rock, which signifies that the rock can be used for high stress applications such as road and runway constructions (Figure 13-8).

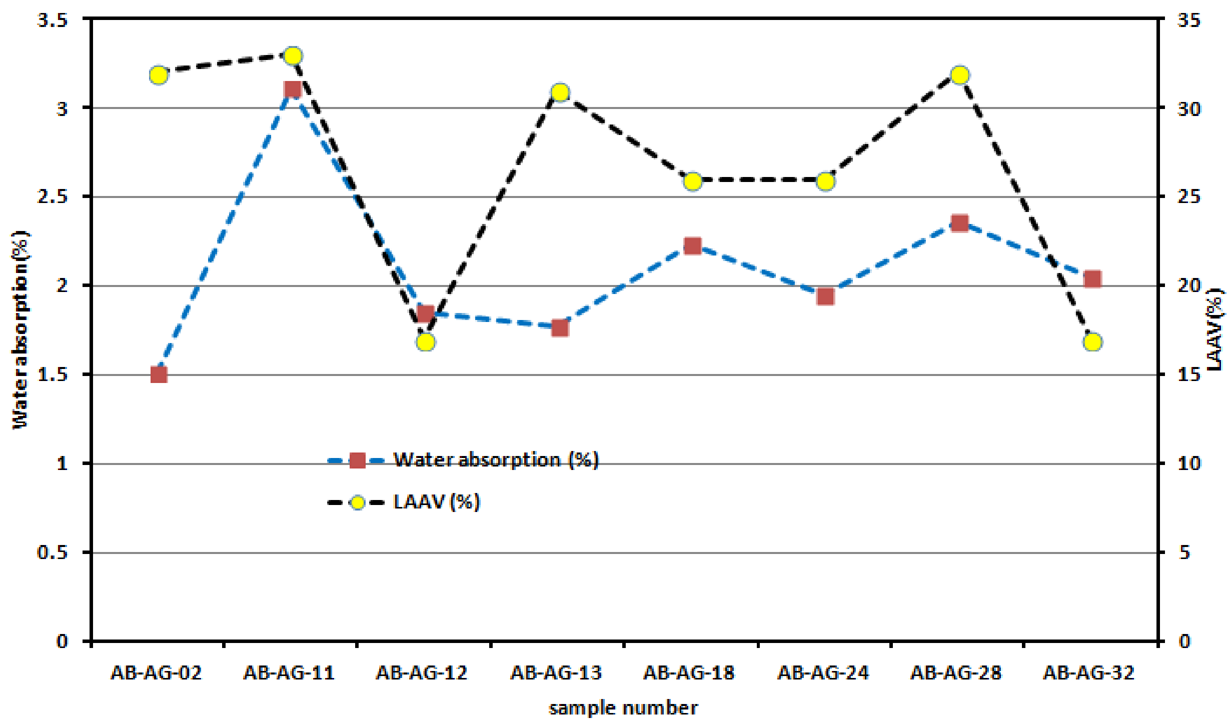

Figure 13-8 Line graph showing the LAAV (%) & Wtabs(%) versus sample number of the studied samples

13.2.3 Chemical properties

The occurrence of sulphates, chlorides, alkali cations (sodium and potassium), reactive quartz varieties, metallic oxides and sulphides and organic matter pose serious problems in the use of aggregates specially in concrete (BS:812, ASTM C 33, ASTM C 289). Therefore, for this reason detailed petrographic examination, XRD and Alkali Silica Reactivity tests are performed according to UNIEN 124070 and ASTM C 289, respectively.

13.2.3.1 X-Ray Diffraction (XRD)

The geometry of an X-ray diffractometer is such that the sample rotates in the path of the collimated X-ray beam at an angle θ while the X-ray detector is mounted on an arm to collect the diffracted X-rays and rotates at an angle of 2θ. For typical powder patterns, data is collected at 2θ from ~5° to 70°, angles that are preset in the X-ray scan.

X-ray powder diffraction is most widely used for the identification of unknown crystalline materials (e.g. minerals, inorganic compounds). Determination of unknown solids is critical to studies in geology, environmental science, material science, engineering and biology. However, in this study the main applications include:

- characterization of crystalline materials
- identification of fine-grained minerals such as clays and mixed layer clays that are difficult to determine optically

The advantages of X-Ray Diffraction are described by many authors, however, the most important advantages for the current study are:

- The powder diffraction method is determined by the exact atomic arrangement in a material
- Its substance in a mixture produces its own characteristic diffraction pattern independently of the others
- The X-ray diffraction pattern discloses the presence of a substance as that substance actually exists in the specimen
- Only a small amount of the material is required for the analyses
- The test is non-destructive on the prepared specimen

In this regard, some selected representative samples were subjected to XRD analysis in Cagliari University, Department of DIGITA. The analysed samples were prepared from basaltic rocks which are suspected of containing clay and other deleterious constituents during thin section study. In doing so, zeolite (analcime), montmorillonite and high temperature quartz (cristobalite) and some mica (phlogopite) were detected in some of the analysed basaltic samples. Clay mineral (montmorillonite) is also identified in one sample (Abs-12) which is porphyritic olivine basalt and in another sample (Abs-13) high temperature quartz (cristobalite) is identified (Figure 13-9). The zeolite and mica minerals were detected in one sample (Abs-28) collected from porphyritic olivine basalt (Figure 13-10).

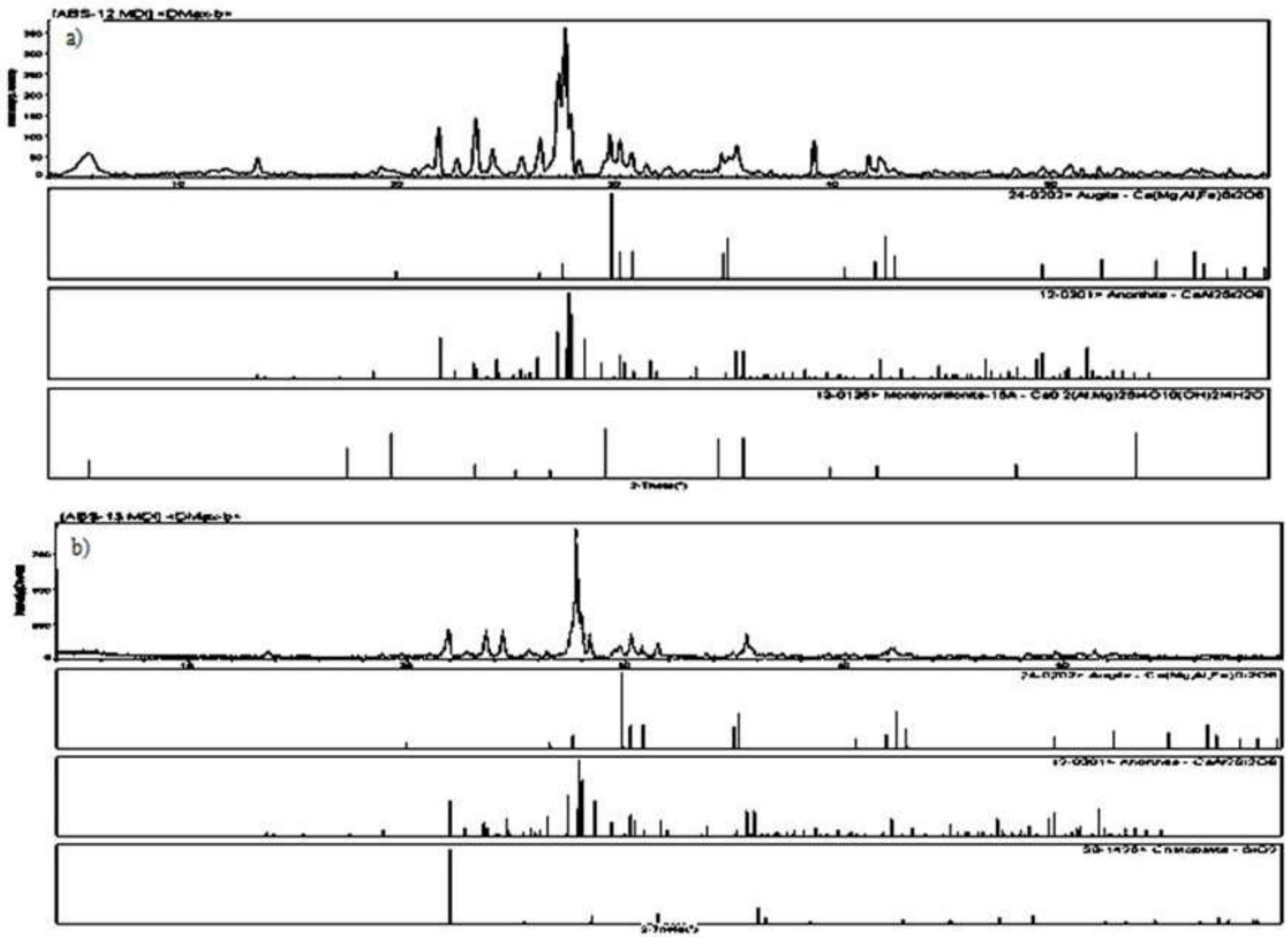

Figure 13-9 XRD analysis patterns of samples, a) Abs-12 and b) Abs-13

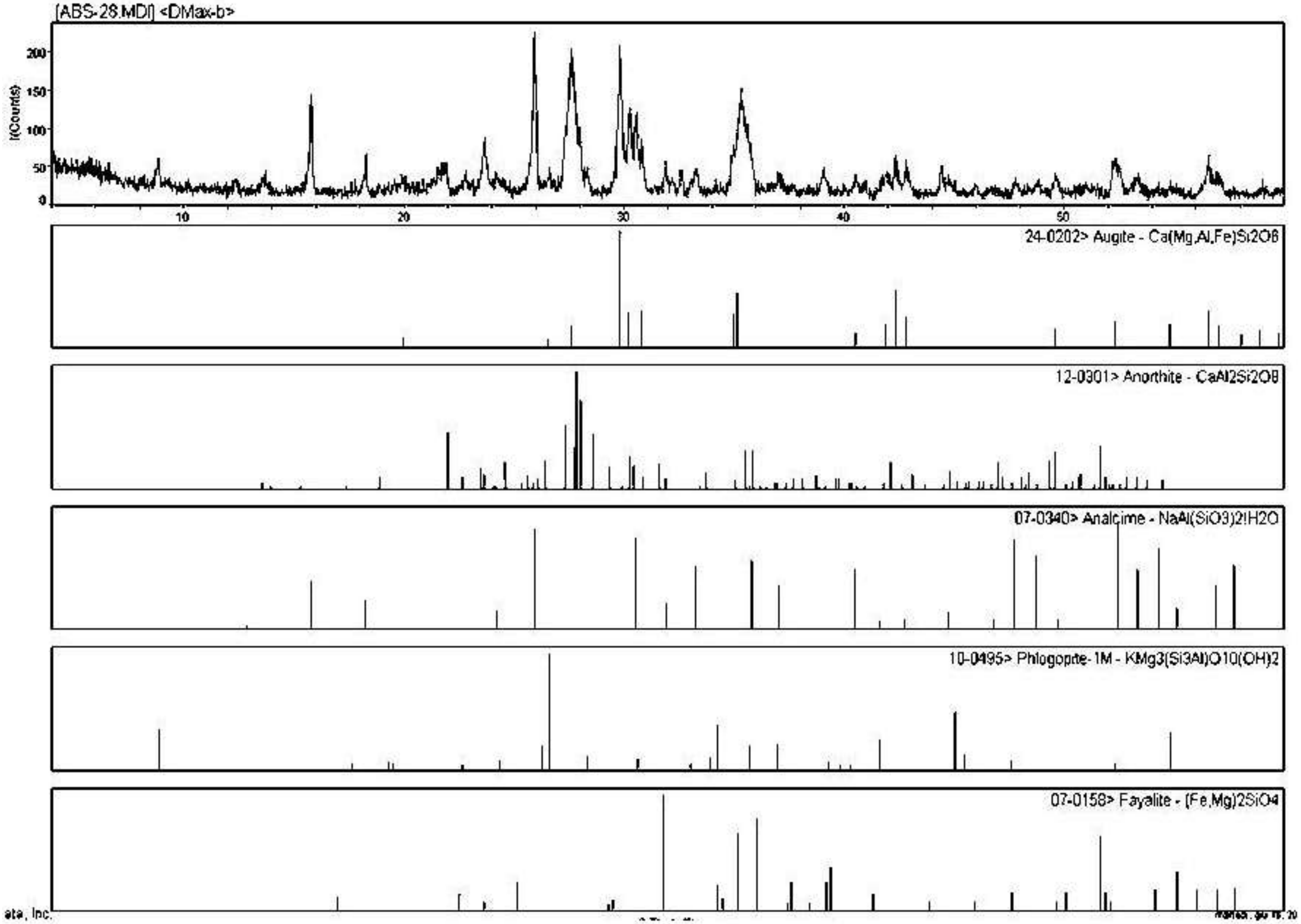

Figure 13-10 XRD analysis pattern of sample Abs-28

13.2.3.2 Alkali Silica Reactivity (ASR)

The concrete pore solution contains significant amounts of alkali hydroxides (NaOH, KOH); as a result, the pH is generally greater than 13.5. The aggregate particles in concrete are then subjected to a highly basic and alkaline environment where some mineral phases can produce significant deterioration as a result of deleterious chemical reactions commonly called alkali-aggregate reactions (AAR). Two types of AAR exist that differ fundamentally in the type of mineral phases and mechanisms involved: Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR).

Alkali-Silica Reaction is much more common and may be subdivided into two categories according to the type of reactive silica involved: ASR that occurs with poorly crystalline or metastable silica minerals, such as opal, tridymite, and cristobalite, and volcanic or artificial glasses, and ASR that occurs with quartz-bearing rocks. Alkali-Silica Reaction generates products of silico-calco-alkaline composition (gels and microcrystalline products). Concrete cracking and expansion result from the swelling, by absorption of solution of the hydrophilic gels produced at the periphery, throughout the whole volume (porous aggregates) or along pre-existing micro cracks in the aggregate particles. This causes the swelling of these particles, the application of excessive pressures on the adjacent cement paste, the creation of micro cracks in the cement paste, and concrete expansion. The pressures applied in the concrete may reach 6-7MPa, whereas the tensile strength is approximately 2-3MPa for ordinary concrete (Bérubé, 2001).

Italian reactive aggregates are related to the presence of microcrystalline and cryptocrystalline silica, generally defined as chert or flint, which is present in various sedimentary rocks, mostly carbonates, but also in siliciclastic rocks, and alluvial deposits derived from the erosion of the Alpine and Apennines mountain belts in the main land. However, in Sardinia, the strained quartz with undulatory extinction, mainly associated with metamorphic rocks and the amorphous glassy phase of volcanic rocks are also ASR susceptible, although to a much lesser extent. Local reports attest to widespread case histories of serious ASR damages in concrete structures in Italy (Berra, et al., 2011).

Aggregates containing certain forms of alkali-reactive silica, such as opaline silica, cryptocrystalline quartz and/or certain silicate minerals are known to cause severe damage to concrete structures owing to the development of expansive Alkali-Silica Reaction (ASR).

Several cases have been reported also in Italian structures in the last decades (Rossetti, 1981; Rossetti *et al*.1988; Baronio, 1984; Mancini *et al*., 1986; Berra, 1990; Giuseppetti *et al*., 2002, as cited in Berra, et al., 2011).

The petrographical analysis of the aggregates is generally the starting point, in order to establish their compositions and identify types and concentrations of any potentially reactive constituents in Italy. In Italy, aggregates are classified on the basis of the potential ASR susceptible phases present in their rock and six aggregate classes (Figure 13-11, from A to F) are found (Bera, et al., 2005).

Type of rock	ASR Susceptible phases in the rock	Aggregate Class
Carbonate rocks and carbonate sediments with significant content of chert or flint	Chert or flint	A
Carbonate rocks marlstones, gypsum and carbonate sediments without chert or flint	Rarely strained or microcrystalline quartz	B
Terrigenous rocks and alluvial sediments (clays, silts, sands and gravels)	Chert or flint, microcrystalline and/or strained quartz	C
Green and blue schists, gneisses, quartzites, phyllites and other metamorphic rocks	Microcrystalline and/or strained quartz	D
Granites, granodiorites, sienites, diorites, and other igneous intrusive rocks	Microcrystalline and/or strained quartz	E
Rhyolites, andesites, basalts, porphyries, and other igneous extrusive rocks	microcrystalline and/or strained quartz; amorphous glassy phase, tridymite and cristobalite	F

Figure 13-11 Classification of Italian aggregates based on the ASR susceptible phases present in the rock (after, Bera, et al., 2005)

According to Bera, et al., 2005, the reactivity of Italian aggregates is related to the presence of microcrystalline and cryptocrystalline silica, generally defined as chert or flint, which are present in various sedimentary rocks, mostly carbonates (aggregate class A), but also in siliciclastic rocks (aggregate class C), and alluvial deposits derived from the erosion of the Alpine and Apennines mountain belts in the main land. The amorphous phase of volcanic rocks, and strained quartz with undulatory extinction, mainly associated with metamorphic rocks (aggregate classes D, E and F), are also ASR susceptible, although to a much lesser extent.

ASR has been a matter of concern in Italy. Several investigations have been geared towards investigating the validity of accelerated testing procedures in predicting the reactivity of aggregates and the effectiveness of mitigation alternatives. The most recent work has been conducted by Berra, De Casa, and Mangialardi (1996) and Berra, Mangialardi, and Paolini (1994, as cited in ICAR, 2000).

Berra et al. (1996) used two Alkali-Reactive Aggregates to investigate the effectiveness of the ASTM C289 and C1260 test procedures in predicting the effects of using supplementary cementing materials (SCM), particularly, silica fume and fly ash.

Berra et al. (1994) investigated the use of ASTM C 1260 in assessing the effectiveness of fly ash and silica fume in reducing expansions caused by the Alkali Silica Reaction using fused quartz as a reactive aggregate. Results of the C1260 test were compared against the long-term results obtained from C227. A good correlation was found between the results of both tests. C1260 provided adequate minimum contents of fly ash and silica fume needed to prevent deleterious ASR expansions. For silica fume, it was found that the two tests provided comparable results when the expansion limits for C 1260 and C 227 were respectively 0.25% at 12 days and 0.10% at 1 year or alternatively, 0.15% at 14 days and 0.05% at 1 year. Results from both tests did not indicate that there is a relationship between the alkali content of the fly ash and its performance in reducing ASR expansions (Berra et al., 1994).

For the current study ASTM C289 and petrographic quantitative (Modal %) and qualitative analyses of aggregates, specifically dedicated to the determination of ASR susceptible phases, have been carried out according to the UNIEN 124070:2000 standards.

These were integrated with X-Ray Powder Diffraction (XRPD) analyses, coupled with geological data. Based on these results, the potential reactivity evaluation of each aggregate is assessed; the aim of this test is to provide a general overview of the potential Alkali-Silica Reaction risk of the Plio-Quaternary basalt aggregates of the studied area.

The analytical protocol adopted for the characterization of ASR susceptible phases in the aggregates consisted of petrographic examinations carried out through qualitative and quantitative (Modal) analyses on thin sections revealed that almost all the samples examined are found to be free from Alkali Silica Reactive constituents except a single sample.

In view of the above, the petrographic study was compared with XRPD mineralogical analysis, and these data are incorporated in rock classifications and mineralogical volume percentages.

Potential Reactivity of Aggregates		
Sample N.	***Dissolved Silica by the Gravimetric method $S_c(SiO_2)$ in millimole per liter***	***Reduction in Alkalinity R_c in millimoles per liter***
ABS-02	119	315
Abs-11	69	365
Abs-12	63	348
Abs-13	110	25
Abs-18	36	125
Abs-24	51	175
Abs-28	43	290
Abs-32	167	195

Table 13-4 Chemical test results using ASTM C 289 test method

The chemical test method (ASTM, C-289) known as the “Quick Chemical Test” or the “Mielenz test” (Mielenz and Benton, 1958), has been found to be a satisfactory initial method for determining the potential reactivity of aggregates derived from volcanic rocks. This test categorises aggregates as “**Innocuous**”, “**Potentially Deleterious**” or “**Deleterious**”. For this test (chemical test) eight different samples from active and old quarries of basalt and outcrops used as aggregates sources were sampled in the studied area (Table 13-4). So, according to this test, aggregate collected from an outcrop of olivine basalt (Abs-13) is found to be deleterious (Figure 13-12). This sample is further analysed in XRD and found to contain a high temperature quartz (cristobalite) confirming the result of the chemical test ASTM C289. Furthermore, petrographic examination also revealed the presence of chert/cristobalite, zeolite and chlorite in trace amounts in addition to the major rock forming minerals.

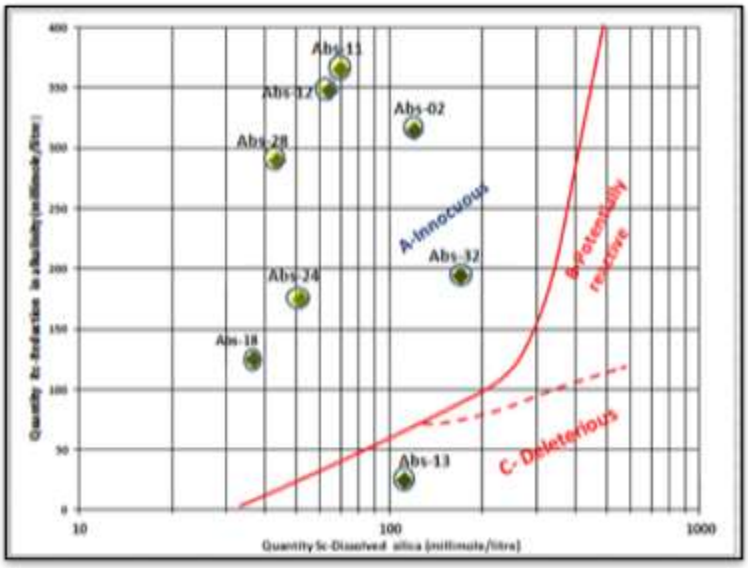

Figure 13-12 Samples plotted on Mielenz standard graph with illustration of division between Innocuous and deleterious aggregates on the basis of reduction in Alkalinity test (ASTM C289)

CHAPTER FOURTEEN

14. Dimension stone and aggregate quarrying environmental impacts

Quarrying activity is a key component of the GDP (Gross Domestic Product) of industrialized economies, since various productive sectors depend on it. The mining industry also plays a strategic role as an employment source. In particular, the extraction of aggregates (sand, gravel, and crushed stone) is closely related to the building sector. This chapter only highlights the relations between quarrying activity and the construction industry, and will focus on how quarrying activity could lead to environmental risks.

The most common uses of aggregates are closely related to the construction sector: e.g. they can be used either without a difficult manufacturing process, as in road filling, railway ballast or armour stones, or they can be used in the production of high quality materials such as ready-mixed concrete (made of 80% aggregates), pre-cast products, asphalt (made of 95% aggregates), etc. Consequently, the resources of aggregates are used in the implementation of all built-up environments according to European Aggregates Association (UEPG) in particular; 1) Construction of new resident houses, 2) Civil engineering structures (local hospitals, schools, bridges and flood protection, 3) infrastructures (roads and railways).

It should be pointed out that the building industry is a particularly complex sector, since it is closely linked to a number of other sectors of the economic system. In the European Union (EU) the aggregates industry is the largest non-energy extractive sector with an output of 2.3 billion cubic meters produced every year and 400,000 employees, including sub-contractors (UEPG, 2010).

Despite the world economic crisis that began in 2008, some recent data related to the construction sector in **EU27** confirm its economic key-role: it provided 9.9% of GDP (Gross Domestic Product) in 2009, and it is the biggest industrial employer in Europe, responsible for about 7.1% of Europe’s total employment and 29.1% of industrial employment according to European Construction Industry Federation (FIEC, 2010).

Concerns about the impact of quarrying are hardly new. Complaints about quarrying activities were voiced as far back as centuries ago. The issues of concern haven't changed over time – visual intrusion, damage to landscapes, traffic, smoke, noise, dust, damage to caves, loss of land, and deterioration in water quality. Quarrying is very much parts of local heritage and practice but most people in the area are only too well aware of the potentially negative impact of quarrying.

In general, the environment today has a higher political profile than ever before in the developed world, and protection of the environment has become a significant priority for society. The aggregate industry is an extractive industry, and aggregate resources cannot be obtained from the landscape without causing changes. Environmental disturbance caused by aggregate mining can be due to engineering activities carried out during aggregate extraction or processing. The most obvious impact is the conversion of land from undeveloped or agricultural status to an open pit or quarry.

This major impact may be accompanied by loss of habitat, noise, dust, vibrations, chemical spills, erosion, sedimentation, changes to the visual scene, and abandonment of the mined site without remedial action. Some of the impacts are short-lived, and most are easy to predict and easy to observe. Most impacts can be controlled, mitigated, or kept at tolerable levels.

Descriptions of common impacts are presented in Barksdale (1991) and Smith and Collis (2001),) to mention a few. Mining aggregate can lead to serious and obvious environmental impacts in some situations, but others are not obvious, particularly in geologic environments such as active stream channels, slide-prone areas, and karst areas. These environments are dynamic and respond rapidly to outside stimuli, including aggregate extraction. In these situations, aggregate mining may alter sensitive parts of the natural system at or near the site, and create serious environmental impacts.

In addition to landfill avoidance, recycled aggregates can be effectively turned into secondary products through recycling (Badino et al., 2007; Blengini and Garbarino, 2006; Sara et al., 2001; Tiruta-Barna et al., 2007). Recycled aggregates (RA) can be used in substitution or in mix with natural aggregates (NA) for several end-uses, thus saving non-renewable resources. In fact, the consumption of aggregates is closely related to the economic performance of a country, which is measured as Gross Domestic Product per capita (GDP/capita).

According to Reid et al. (2009), to avoid misleading conclusions, environmental impacts of mining activities should always be evaluated using site-specific data. According to Van Zyl (2005), mining environmental impacts are site specific and it is incorrect to assume that all mines or quarries or processing plants will impact the environment equally as land use and land change were felt contemporary by the activities of quarrying. Aggregate is mined from the earth, either dug out of pits or blasted out of quarries. This process has many significant environmental impacts.

From experience, creating the pits or quarries requires the removal of virtually all natural vegetation, top soil and subsoil to reach the aggregate underneath in most cases. Not only does this lead to a loss of existing animal wildlife, it also leads to a huge loss of biodiversity as plants and aquatic habitats are destroyed. Moreover, adjacent eco-systems are affected by noise, dust, pollution and contaminated water.

Pits and quarries disrupt the existing movement of surface water and groundwater; they interrupt natural water recharge and can lead to reduced quantity and quality of drinking water for residents and wildlife near or downstream from a quarry site. In the current study area, some old pits and quarries are not being properly rehabilitated (Figure 14-1).

Figure 14-1 Some of the old quarries which are not well restored in the studied area

Some countries classify pits and quarries as "interim uses of the land" and require 100% rehabilitation of pits and quarries. Clearly this requirement is not being met. Destroyed ecosystems and source water aquifers are irreplaceable. However, this is not an interim land use. The landscape is scared with destructive pits and quarries, and species of all kinds endure permanent negative impacts.

It is possible to conclude that the negative impacts from the quarry will not be significant, and that there is a compatibility with current land use. Thus with appropriate mitigation measures and management techniques the negative impacts could be reduced.

The main objective of mineral resource policies is not to limit the amounts extracted, thus affecting economic policies and resulting in a shortage of aggregates on the market, but rather to make a proper assessment of requirements in advance in order to plan amounts, methods and mining sites. Diverse complex solutions have been adopted in a number of European countries and may stimulate reflection and yield suggestions leading to adequate policies (Balletto, 2011). Among these we can point out the main two:

1) An environmental policy that is extremely strict with mining activity,

2) A policy oriented towards recycling (associated with exemptions and/or incentives) since one advantage of recycling is landfill avoidance, which implies saving of waste dump capacity, i.e. space: a very important and scarce resource nowadays in Italy (Balletto, 2011). By a more extensive use of recycled aggregates, greater environmental conservation and protection would be attained, reducing the extraction of natural aggregates and thus limiting the opening of new quarries.

As essential industries in today's environmentally aware society, it is vital that quarrying operations ensure that they achieve the best possible environmental management of their activities. Poor environmental management within the industry results not only in non-compliance of legislation, which might includes heavy fines, but also in poor public relations, loss of business, and loss and destruction of wildlife and habitats. Good environmental management in the industry can result in good publicity and public relations, increase in business, and the creation of habitats for a variety species.

So, understanding the essential role of the extractive industry and its contribution to society is an important part. It is equally important to recognise and increase understanding of the industries environmental impacts, both negative and positive, and understand management techniques to both mitigate in the former and enhance in the latter (Figure 14-2). Mining of aggregate might be acceptable in some environmentally sensitive areas, but should be conducted only after careful risk analysis, and then only with extreme prudence. Failure to do so can lead to serious, long-lasting, and irreversible environmental consequences, not only near the operation but also at locations some distance from the site.

Figure 14-2 Some active quarries in the project area with high damage to the environment

Dimension stone and aggregate quarrying might have environmental impacts; however the environmental impacts of dimension stone are generally not significant, are mainly of temporary duration, and can be effectively managed. There are no emissions besides those of the diesel powered earthmoving equipment utilised in its extraction and a small amount of blasting gases. Contamination of water resources is only likely in the event of petrochemical spillages from storage facilities and equipment, and these can largely be either prevented or cleaned up effectively. The major environmental impacts are of a visual nature, while in sensitive areas, habitat destruction and the destruction of archaeological heritage may become significant impacts.

Indeed, when it is the intention to merely blast and remove stone for its physical properties (ore mining), recovery can be almost 100% of the volume removed, while when the same stone is quarried with the intention of producing dimension stone blocks, recovery of saleable blocks is typically between 3% and 60%(Ashmole, et al.2008). This results in large quantities of waste rock which need to be disposed of, with resulting environmental implications.

The physical properties required of a successful dimension stone also have significant environmental implications – due to the requirement for inert materials which are not affected by weathering (and in today’s context, the effect of severe chemically polluted atmospheric environments), dimension stone residues are less harmful from a pollution point of view. Like natural aggregates, dimension stone is used in its natural state, and does not require concentration and extraction from an ore. It is these latter two processes that result in significant environmental impacts such as acid mines drainage and other toxic effects associated with many of the metal extraction industries (Drew, et al. 2002).

CHAPTER FIFTEEN

15. Discusion of results

The field and laboratory works were being compiled and compared together to reveal the engineering performance of the studied Plio-Quaternary volcanic rocks of Abbasanta-Borore area in terms of building stone and coarse aggregates suitability.

The Abbasanta-Borore Plio-Quaternary basaltic rocks exhibit diverse textural and mineralogical characteristics which could affect their physical and mechanical properties as well as their use as construction material. The rock material and aggregate properties of the basalts were compared with the various standard values and evaluated for their suitability for different applications (building stone, concrete aggregate, road wear and base course).

According to the currently studied test results of the aggregate samples, the water absorption ranges from 1.51 to 3.11% which is very low ($\leq$2.23%) with the exception of one sample. Only a sample (AB-AG-11) collected from vesicular olivine basalt has shown 3.11%. The open porosity is also very important in rock strength for which it reduces the durability of the rock material (Goodman, 1989; Bell, 1998). According to the engineering classifications (Anon, 1979) the open porosity of the studied samples is classified as low (1-5%) with the exception of a single sample. Regarding Uniaxial Compressive Strength values, it is a useful property both for building stone and aggregates. Even though, the strength of a rock is an intrinsic characteristic, the effective strength of an aggregate particle is modified by its shape and size (Ramsay et al., 1974).

Even though it is not directly related, the compressive strength of concrete mainly depends on the strength of the aggregates. Smith and Collis (1986) indicated that the rock material used for concrete should be unweathered and has to posses high strength. According to Dearman (1991), the Uniaxial Compressive Strength should be higher than 35MPa for concrete aggregate production and so, in this regard all the studied samples are quite suitable for concrete aggregate production.

According to BS 812: Part 1, uncompacted bulk density of normal aggregate should be between 1200-1800kg/m^3; therefore, 50% of the studied samples are below the acceptable limit. The olivine porphyritic (AB-AG-28) sample gives the highest bulk density. The results obtained for aggregate crushing value tests are mainly affected by inherent geological factors namely, petrology, petrography, and fabric (Ramsay et al., 1974). A high crushing value indicates a weak, potentially nondurable material (Fookes, 1984) and it is recommended that crushing value should be maximum 30% (BS 812: Part 110(1990) of its weight. The variation in aggregate crushing values of the different samples can be attributed to the influence of aggregate particle shape and geological features such as: bulk composition, grain size, texture and weathering (Fookes, 1986).

Regarding the Alkali Silica Potential Reactivity, most samples fall in the “Innocuous” field which means non reactive while a sample (Abs-13) is found to be “Reactive” according to the quick chemical test (ASTM C289).

Rock petrography is important in determining the physical and chemical characteristics of the material that have a bearing on the performance of the material in its intended use. Therefore, thin sections were prepared from rock samples that can potentially be developed into quarries and were studied under polarizing microscope. Rock features like minerals present and their mode of occurrence, grain size, approximate percentage composition of each mineral and texture have been highlighted. The detailed petrographic examination of the samples under a polarising microscope reveals the absence of deleterious constituents in most of the studied samples in a proportion which could harm the resulting concrete structure with the exception of few samples.

The Abbasanta-Borore basalt crushed aggregate exhibits rough texture due to the occurrence of various coarse and medium size minerals such as plagioclase, pyroxene and amphibole. The contribution of different types of coarse aggregate to concrete strength has been published by Aitcin, 1990, who indicates that petrographical and mineralogical characteristics of coarse aggregates control the strength of concrete. The minerals of the aggregates must be tough and fine grained in order to produce durable and sturdy concrete (Johansen and Anderson, 1989). As far as durability/strength of concrete is concerned, the rough texture of Abbasanta-Borore basalt will be good in developing an excellent bond between aggregate and cement paste due to its rough surface texture.

Petrographically, it was not so simple to identify deleterious constituents except some constituents, however, XRD analysis on selected samples shows clay minerals, zeolite and some reactive quartz. Such insignificant amounts of zeolite may not trigger deleterious alkali silica reaction due to the low percentage. However, some basaltic samples were found to contain reactive quartz (chert/cristobalite) as it has been discussed previously. Chert/cristobalite is highly deleterious if used with ordinary Portland cement in concrete aggregate.

Alexander and Addis (1992) studied the influence of aggregates and interfacial bond on the mechanical properties of high strength concrete, using different aggregate and indicated that basaltic aggregates make a better bond with cement paste as compared to all others. As far as physical properties are concerned, the tested aggregate samples fall within the ranges as described by various time honoured standards even though there are few exceptions.

As it has been discussed earlier, concrete by volume contains about 65-75% coarse aggregate and is considered as manmade artificial rock. The strength of concrete is considered to depend on rock aggregates and its paste (Neville, 2000).

Besides, the occurrence of deleterious minerals with ASR potential in these rock groups can result in onset of alkali silica reaction in cement concrete in the absence of proper measures. It may lead for unacceptable expansion in structures. Evaluation of the ASR potential is carried out with petrographic test (UNIEN 124070:2000) and the quick chemical test (ASTM C289).

CHAPTER SIXTEEN

16. Conclusions

In this work all the available geochemical, geological, physical and mechanical and petrological data from the literature, field observation, and laboratory test have been compiled and synthesized to draw the best conclusion.

Understanding of physical and mechanical properties can be useful both for initial selection and for diagnosis of the deterioration processes of building stone. We do not need only laboratory measurements of physical properties but also observations on the rocks in-situ are most important.

In general, the present project area is covered by “Basalti di plateau”of Plio-Quaternary age which includes alkaline basalts, trachybasalts and basaltic andesite. Field observation and petrographic microscope (thin section) study indicates that the major rock units in the present study area include olivine basalt, vesicular olivine basalt, andesitic basalt, aphyric basalt with olivine and plagioclase phenocryts.

The physical and mechanical properties (porosity, density, uniaxial compressive strength, ultrasonic velocity, point load index, water absorption, abrasion resistance etc) of the basaltic rocks indicated that the studied rocks could be used as cobblestone, masonry stone and slabs for sidewalks. The basalts are very good building stones as far as physical and mechanical properties are concerned except the excessive hardness which might require special equipment to produce required size dimension. The Capon wheel abrasion resistance of the studied basalts ranges from 19.4 mm to 23.6mm. This result indicates that the tested rocks could be used for “intensive use” which includes public halls floor, airport shopping centre, halls in apartment blocks, common rooms of office buildings and floorings.

Regarding aggregate properties, every rock unit has its own properties depending upon its mineralogical and textural characteristics. Aggregate Crushing Value and Los Angeles Abrasion Value are the basic strength parameters to evaluate the strength and durability of the aggregate. Aggregate Crushing Value of the various basaltic rocks indicated high quality except the vesicular basalt (ACV, 46%). The Los Angeles Abrasion Value is also good for all rock types tested except the vesicular basalt which is relatively poor as compared to other units.

In regards to the use of the studied basaltic rocks as concrete aggregates, the tested rocks can be used in the construction of roads and buildings by virtue of excellent engineering properties and petrographic characteristics except the vesicular basalt, only considering the engineering properties.

Regarding the Alkali Silica Potential Reactivity, most samples plot in the “Innocuous”field which means non reactive while a sample (Abs-13) is found to be “Deleterous” according to the quick chemical test (ASTM C289). This sample represents the olivine bearing basalt and should not be used in concrete aggregate.

Petrographic quantitative (Modal) analyses of aggregates, specifically dedicated to the determination of ASR susceptible phases, have been carried out according to the UNIEN 12704:2000. These were integrated with X-Ray Powder Diffraction (XRPD) analyses and the quick chemical test (ASTM C289), coupled with geological field observation to scrutiny the ASR of the basaltic units. As a result, most samples plot in the “innocuous “field which means non reactive, while a single sample collected from olivine basalt is found to be “Deleterious” according to both the quick chemical test (ASTM C289) and the detail petrographic examination (UNIEN 12070:2000). In this regard, therefore, it is concluded that rather than identifying specific rock type characteristically as non reactive and reactive, ASR test on each rock types should be carried out.

As stated by Smith and Collis, 1993, the durability of aggregate is the ability of individual particles to retain their integrity and not to suffer physical, mechanical or chemical changes to an extent which could adversely affect the properties or performance of concrete. Soundness and resistance to abrasion, apart from Alkali Silica Reactivity, are probably the most common properties of rock that need to be addressed in order to maintain the integrity of the concrete mix.

Coarse crushing of basalt rocks to the size of gravel is needed for raw materials for road construction and there are some crushers producing all sizes of aggregates in the study area, some are active and others are out of function. Larger sizes are also important for foundations and structural loading. Few active and several abandoned basalt quarries are observed in the various parts of the studied area.

The current research presents the physical and mechanical properties of the basaltic rocks in the studied area to be used as source of dimension stone and coarse aggregates.

The environmental impacts of dimension stone are generally not significant, are mainly of temporary duration, and can be effectively managed. Natural aggregate/crushed stone from natural outcrops is less practiced types of natural aggregate source in Sardinia (Italy) probably due to environmental concern. It should be highlighted, however, that most quarry concessioners are cautious to implement best practice codes as observed in the field, unlike the Ethiopian quarry owners. However, most quarries in the study area are abandoned may be due to strict environmental regulations.

16.1 Recommendations for future work

The present study area is covered with Plio-Quaternary basaltic rocks and these rocks were sampled and tested in different laboratories to reveal the physical and mechanical properties. The laboratory test results indicated that the basaltic rocks could be used for various construction purposes, however, the trace amounts of deleterious constituents like reactive quartz, clay and zeolite should be quantitatively verified with further XRD analysis and also mortar bar method of Alkali Silica Reaction test should be done. It may be also necessary to conduct shallow core drilling to verify the depth continuity of the basaltic rocks both in quality and quantity.

CHAPTER 17

17.Comparison of the two sites (Ethiopian and Sardinian) basalts physical and mechanical properties

Basaltic rocks are among the most important sources of building stone (as ashlars, cobble stone, even as dimension stone) and crushed aggregate throughout the world. They are also the main types of crushed coarse aggregate sources in Ethiopia, for various construction activities. Also, in Sardinia, basalts are used for different construction purposes especially as cobble stone, site restorations, public walk areas and even as crushed coarse aggregates. One of the purposes of this research is to compare some of the engineering properties of basaltic rocks to determine whether similarities and differences occur between each of the different source countries, Ethiopia and Sardinia. This is particularly interesting given the distance between the two countries and the different processes that have occurred since the formation of these basaltic rocks (Figure 17-1).

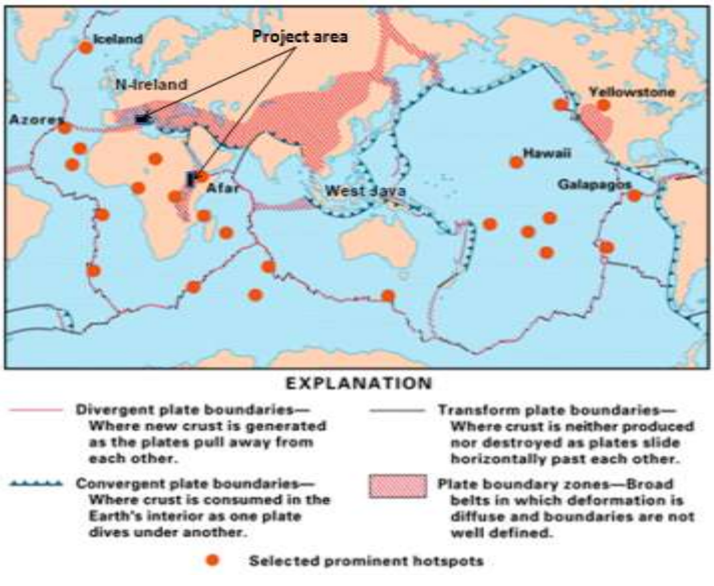

Figure 17-1 Plate boundaries of the earth's surface at present time and major hot spot locations (from USGS)

The Ethiopian volcanic successions lack rocks of intermediate composition (bulk rock chemistry: SiO_2, 52-63%) defining strong silica gap as observed in other volcanic areas and suggesting the bimodal volcanism nature of the Ethiopian volcanic suite in non subduction tectonic setting rather implying anorogenic magmatism probably connected to plume/hot spot source.

Geochemically, the Sardinian Plio-Quaternary volcanic rocks lack significant ultrabasic compositions (i.e., bulk rock silica SiO_2 composition <45% are less abundant, Lustrino et al., 2007). The Ethiopian Tarmaber formation bulk rock silica composition reaches as low as 40% and not greater than 51% while the Sardinian rocks reaches as high as 65% (andesitic). Intermediate rocks are totally absent in the Ethiopian Tarmaber formation. The Sardinian rock**s** show low CaO content, which only rarely reaches as high as 8.5% compared to the relatively higher 8-10% content of the basaltic rocks of Ethiopia. The Sardinian rocks have lower CaO/Al_2O_3 ratios (mostly <0.5) compared to the higher ratio of the Ethiopian basaltic rocks, mostly greater than 0.5. The Sardinian rocks are mostly silica saturated to silica oversaturated, with hypersthenes and/or quartz CIPW normative compositions. This result contrasts with the silica under-saturated and mild nepheline normative rocks of Ethiopia.

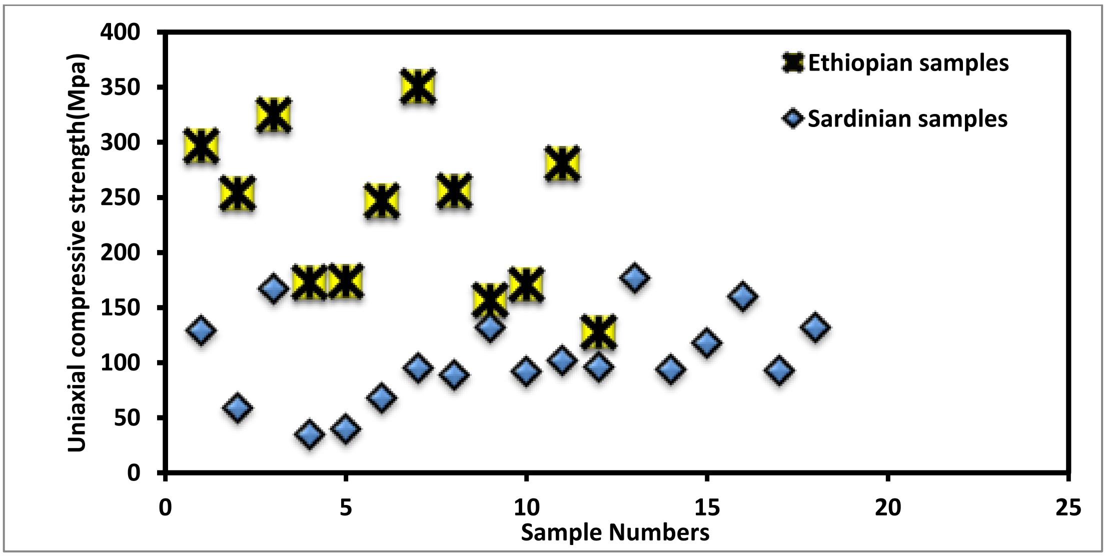

Figure 17-2 Uniaxial Compressive Strength of Ethiopian and Sardinian samples

As it has been seen from Figure 17-2, the Uniaxial Compressive Strength of the Ethiopian basaltic samples is higher than the Sardinian ones. The Ethiopian basaltic sample Uniaxial Compressive Strength reaches as high as 351MPa, while for the Sardinian basaltic samples maximum Uniaxial Compressive Strength is 177MPa. This difference could be explained with the difference in geological ages and the intensity of fracturing.

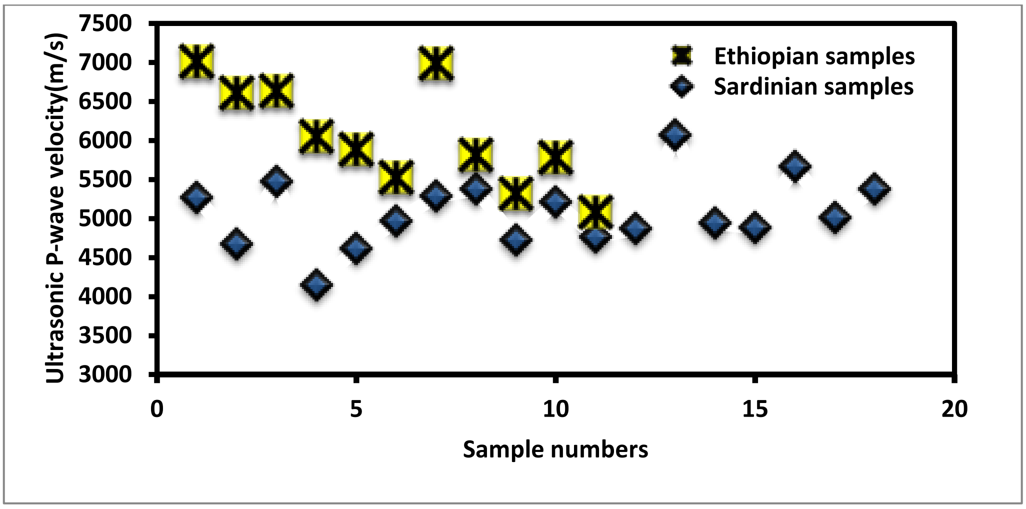

Figure 17-3 Ultrasonic P-wave Velocity of Ethiopian and Sardinian basaltic samples

Still as it has been seen from Figure 17-3, the Ethiopian samples show high ultrasonic P-wave Velocity as high as 7000m/s, while for the Sardinian samples maximum Ultrasonic p-wave Velocity is 6000m/s. The explanation might be similar to the Uniaxial Compressive Strength.

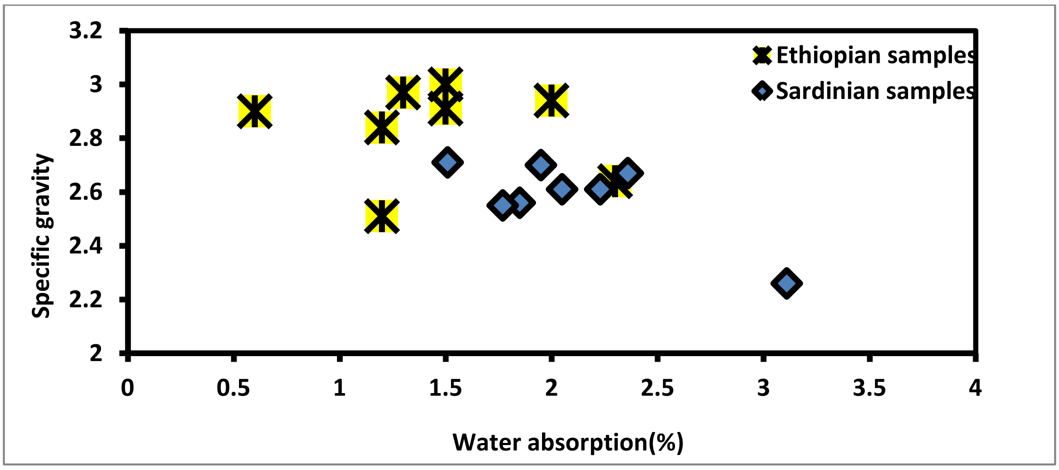

Figure 17-4 Relationship between water absorption and specific gravity determined on dry basis

It can be seen that the Ethiopian coarse aggregates are denser for a given water absorption than the Sardnian coarse aggregate (Figure 17-4). This relates to the predominant type of basaltic material found in each country i.e. the less dense andesitic nature basalt of the Sardinian and denser olivine and iron oxide/opaque rich basalts of Ethiopia. Good correlation exists between the two variables for the two aggregate sources i.e. specific gravity tends to increase as water absorption decreases. Only aggregates which have a water absorption value less than 3% are plotted here. It is interesting to note that the water absorption values for all the Sardinian basalt are above 1.5%, but for the Ethiopian basalts, water absorption values as low as 0.6 % are measured. This difference could be explained with the difference in geological age of the basalts. The relatively young basalts of Sardinia have a more open texture than the older Ethiopian basalts. Another factor affecting water absorption is the degree of alteration and intensity of fracturing. Typically the presence of altered minerals containing absorptive clays will result in lower densities and higher water absorptions. Indeed, the water absorption in some countries is used as a quick indicator of soundness, where water absorption values are greater than 2 % require a magnesium/sodium Sulphate Soundness test to be carried out.

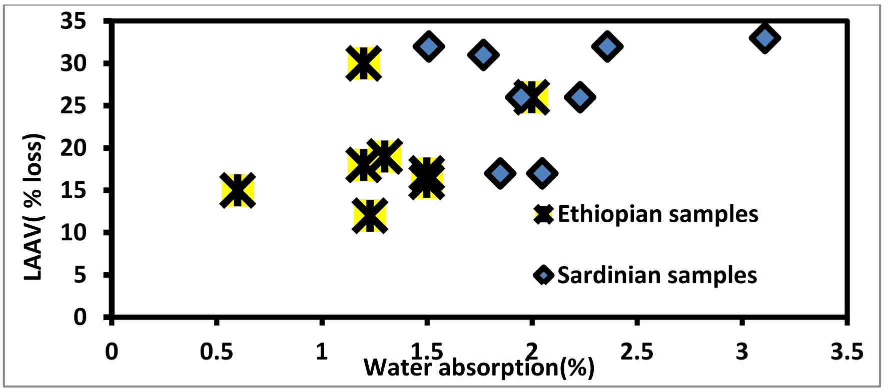

Figure 17-5 Relationship between Water absorption and Los Angeles Abrasion Value (% loss)

The LAAV of the coarse aggregates were determined using the AASHTO T-96, Grading ”B” method. Figure 17-5 shows the trend that increasing water absorption causes a decrease in the value of Los Angeles Abrasionvalue i.e. high water absorbing aggregates will suffer more degradation. This is related to the degree of alteration and fracturing where higher values of water absorption indicate a weathered unsound aggregate that is prone to degradation. For Sardinian basalts this also relates to vesicles and open texture, which result in a high water absorption value as well as a high LAA Value.

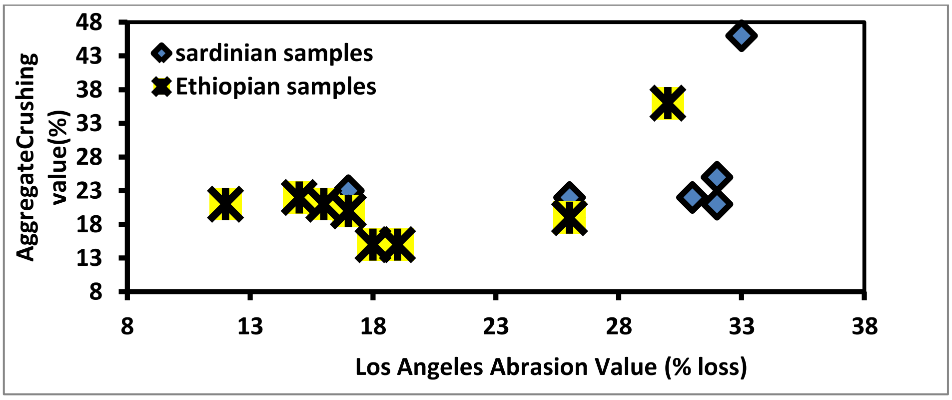

Figure 17-6 Relationship between Los Angeles Abrasion Value and Aggregate Crushing Value (% loss)

Figure 17-6 shows clearly that the Aggregate Crushing Value test results are relatively higher for Sardinian aggregates than Ethiopian aggregates for a given Los Angeles Abrasion Value. This confirms that the Ethiopian aggregate appears to be generally more resistant to static crushing than the Sardinian basalts. Although grouped under the engineering term “basaltic”, there are distinct differences within the specific types present in each of the countries considered in this study i.e. mainly andesitic basalt in Sardinia and alkaline basalt in Ethiopia.

In both countries the geological history of the basalts has influenced the aggregate properties. Sardinia on one hand and Ethiopia on the other hand have different climates at present i.e. Ethiopia is a tropical climate and Sardinia are regarded as relatively cold region. However, during the time of formation of these two basalts the climate for sure might not be similar to the present. Furthermore and more importantly, regional conditions (such as hydrothermal and tectonic activity) might have influenced the rock properties and alteration products in both countries.

Hence, correlation of physical and mechanical data indicates that the Ethiopian basalts are typically of higher density and resistant to static crushing than the Sardinian andesitic basalt. The difference in specific gravity values for aggregates from Sardinia on one hand and Ethiopia on the other hand is explained partly by the chemical composition of the material, but also by geological age, geological history and climate.

It is evident that individual sources of aggregate within rock type groupings do not perform in similar ways. A simple classification must therefore recognize that differences occur at a local level. Rather than use the collective terms such as basalt a much better level of immediate understanding would be achieved if knowledge of local problems and performance capability were available.

It is possible to conclude regarding the physical and mechanical properties of the Ethiopian and Sardinian basalts, that the Ethiopian samples show a relatively high degree of variability but better compliance to the various specifications while the Sardinian samples show relatively low variability but poor compliance to specifications.

Finally, the comparison of the results is revealing that different physical and mechanical trends are observed from rocks that are similar in basic mineralogical composition. This suggests that the relationships between physical and mechanical properties are often specific to rock type and occurrence.

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Appendices

Appendix 1: Microscopic examination results of some Ethiopian and Sardinian samples

Petrographic examination of natural stone
UNI EN 12407:2007

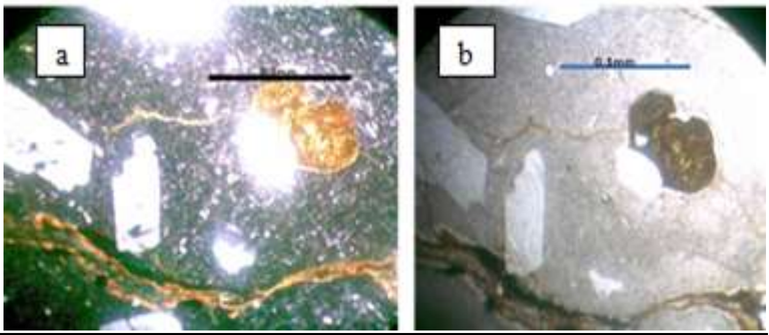
Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-00
Geological Classification	GLASSY RHYOLITE
Major minerals	Volcanic glass, Sanidine
Minor minerals	Quartz, chalcedony, opaque, biotite, hornblende
Textural features	Vitrophyric Texture

I) Hand specimen description: black coloured, fine grained and glassy in texture

II) Mineral composition

Mineral	Modal (%)	habit
Volcanic glass	60	-
Sandrine	12	Euhedral
Quartz	8	Anhedral
Plagioclase	7	Euhedral
Opaque (Fe-oxide)	5	Subhedral-Anhedral
Chalcedony	5	Radial
Pyroxene	3	Subhedrtal
Hornblende and biotite	Trace	Subhedral and platy

III) Textural descriptions/Notes: Phenocryst of sanidine, plagioclase and quartz are seen over a groundmass composed of volcanic glass. Unfilled and partially Fe-hydroxide and chalcedony filled fractures are seen across the section. Two generations of fracture systems are observed with cross-cutting relationship, both of which filled with secondary mineral. Trace amounts of mafic minerals (hornblende, biotite and pyroxene) are observed.



Thin section under crossed nicol, x10 a) microfractures filled with secondary clay and opal mineral with phenocryst of plagioclase, b) Under plain polarised light with glassy groundmass, x10

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-1
Geological Classification	Aphyric basalt
Major minerals	plagioclase, pyroxene, olivine
Minor minerals	Opaque(oxides)
Textural features	Fluidal texture

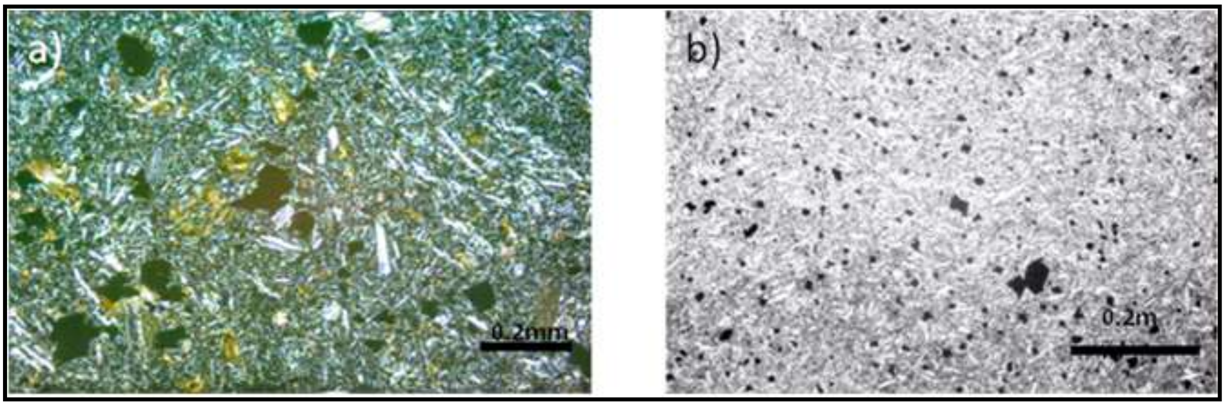
I) Hand specimen description: dark grey in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	40	Lath euhedral
Pyroxene	25	Anhedral
Opaque (Fe-oxide)	20	Subhedral-Anhedral
Volcanic glass	10	-
Olivine	5	Euhedral

III) Textural descriptions/Notes:-

Small crystals of olivine, pyroxene and plagioclase are seen over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque. Opaque (Fe-oxide) minerals are abundant across the whole section of the thin section.



Microscopic photograph, a) Thin section under crossed nicol showing medium grained plagioclase and some pyroxene with opaque minerals, X20 b) Plain polarised light showing opaque and microlaths of plagioclase feldspar, x10

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-4
Geological Classification	TUFF
Major minerals	Volcanic glass, rock fragments
Minor minerals	Biotite, opaque, quartz
Textural features	Vitrophyric

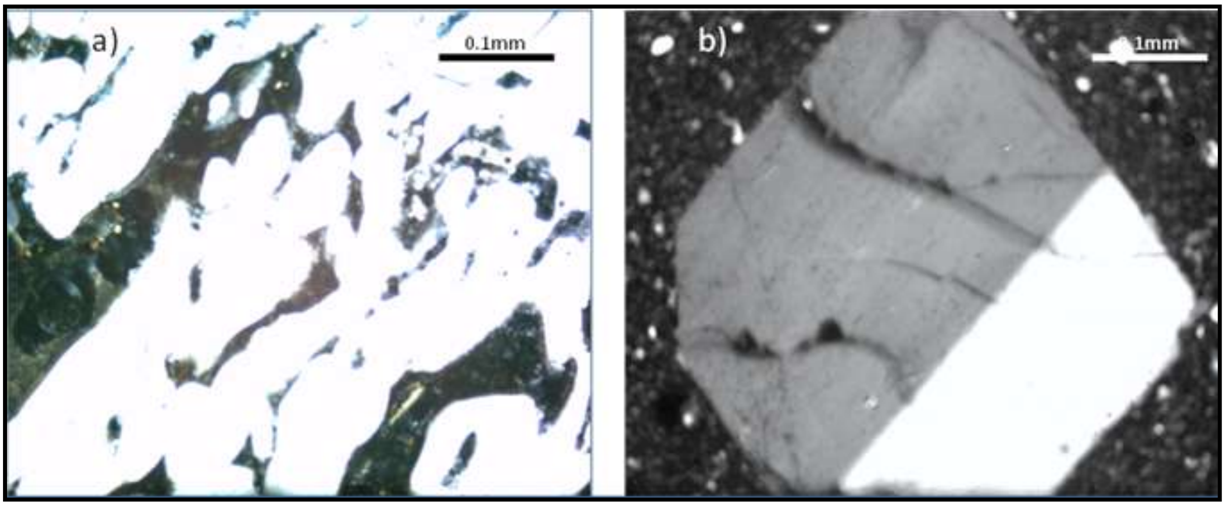
I) Hand specimen Description: light grey in colour and medium grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Volcanic glass	40	-
Sanidine	30	Euhedral
Quartz	15	Anhedral
Opaque (Fe-oxide)	10	Subhedral-Anhedral
Accessories	5	Euhedral

III) Textural dDescriptions/Notes:

It comprises of skeletal quartz and phenocrysts of sanidine with abundant opaque (Fe-oxide) with devitrified glass. Micro factures and unfilled voids are seen across the thin section.



Microscopic photographs: a) Chalcedonic quartz under plane polarized, x10 b) Phenocryst of sanidine in a glassy groundmass under crossed nicol, x10

UNI EN 12407:2007

Source of sample	Ethiopia, North Shea, near Debrebirhan
Sample number	TB-TS-5
Geological Classification	Basalt
Major minerals	Pyroxene, plagioclase, opaque
Minor minerals	Zeolite, other minerals
Textural features	Fluidal texture

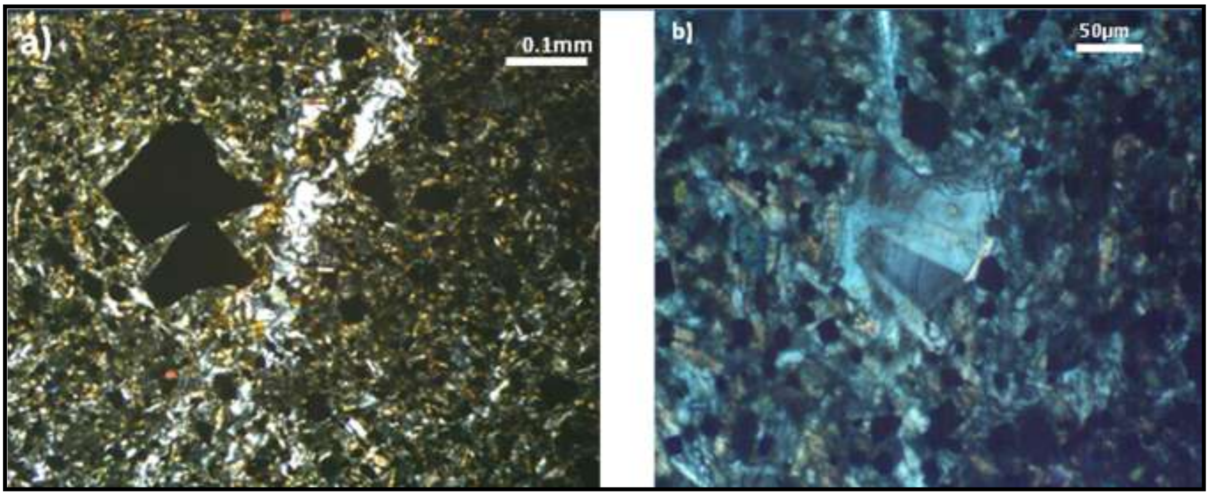
I) Hand specimen description: dark grey to black in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	25	Lath euhedral
Pyroxene	20	Anhedral
Opaque (Fe-oxide)	45	Subhedral-Anhedral
Zeolite	5	Anhedral
Other accessories	7	

***III) Textural descriptions /Notes**:-*

The groundmass which is composed of microlithic plagioclase, pyroxene, opaque and volcanic glass shows parallel alignment of flow texture. Volcanic glass shows beginning of divetrification to chalcedony and chlorite. Unfilled micro fractures and pores /voids/ filled by zeolite are seen across the section.



Microscopic photographs, a) Under crossed nicol, phenocryst of opaque crystal and aligned fracture filling zeolite with abundant fine opaque and microlithic plagioclase as a groundmass, b) Phenocryst of zeolite at the centre of view under crossed nicol, x20

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-7
Geological Classification	Glassy rhyolite
Major minerals	Volcanic glass, Sanidine
Minor minerals	Quartz, chalcedony, opaque, biotite, hornblende
Textural features	Vitrophyric Texture

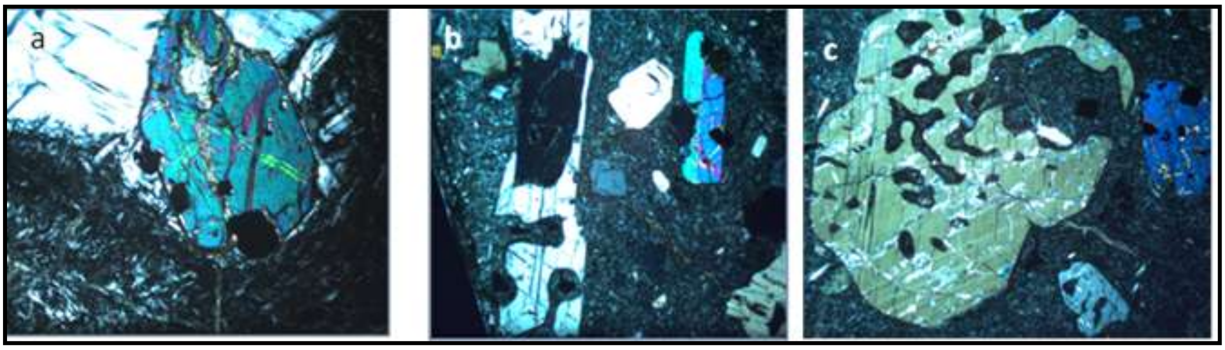
I) Hand specimen description: black coloured and glassy in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Volcanic glass	30	-
Sandrine	10	Euhedral
Quartz	10	Anhedral
Plagioclase	20	Euhedral
Opaque (Fe-oxide)	20	Subhedral-Anhedral
Pyroxene	20	Subhedrtal
Biotite	5	Platy

III) Textural descriptions/Notes:

Phenocryst of sanidine, plagioclase and quartz are seen over a groundmass composed of volcanic glass. Unfilled and partially Fe-hydroxide and chalcedony filled fractures are seen across the section.



Microscopic photographs,(a) Under crossed polarized light, phenocryst of olivine with Fe-oxide spot and on the upper right there is a pyroxene phenocryst in a glassy groundmass, x40 (b) Under crossed polarised light, phenocryst of plagioclase with muscovite on the surface another plagioclase on the right in fine grained groundmass, x40, (c) Skeletal phenocryst of plagioclase in glassy groundmass

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-15
Geological Classification	BASALT
Major minerals	Plagioclase, pyroxene, opaque, devitrified glass
Minor minerals	Zeolite, chlorite
Textural features	Fluidal texture

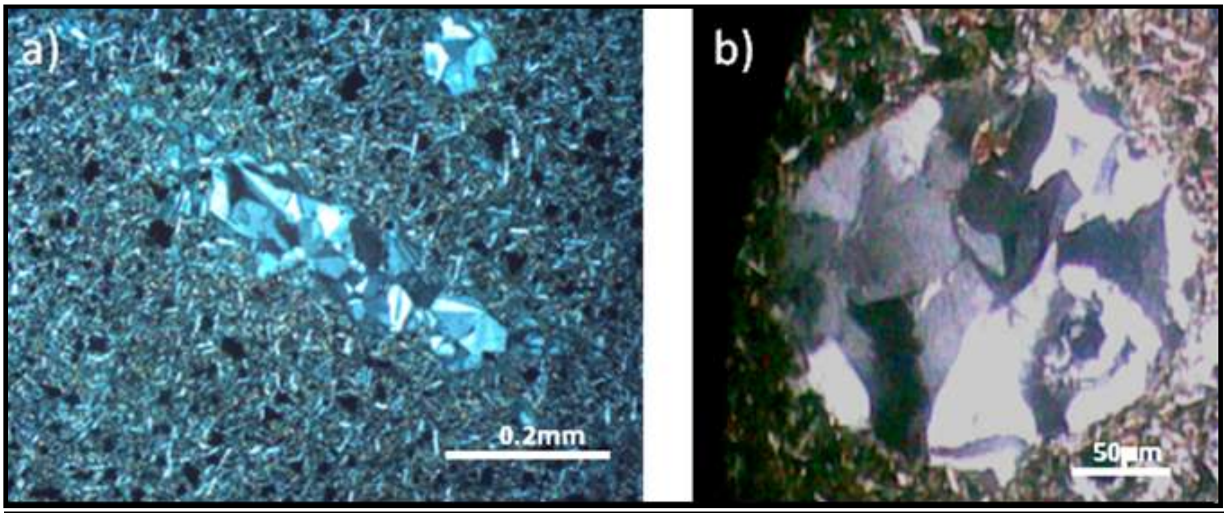
I) Hand specimen description: dark grey to black in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	40	Lath euhedral
Pyroxene	30	Anhedral
Opaque (Fe-oxide)	15	Subhedral-Anhedral
Devitrified Volcanic glass	10	-
Zeolite	5	Anhedral
Chlorite	Trace	Anhedral

III) Textural Descriptions/Notes:-

The groundmass which is composed of microlithic plagioclase, pyroxene, opaque and volcanic glass shows parallel alignment of flow texture. Volcanic glass shows beginning of devitrification to chalcedony and chlorite. Unfilled micro fractures and pores /voids/ filled by zeolite are seen across the section.



Microscopic photo, a) Under plane polarized light zeolite developed along cavities at centre of view and at the top, laths of plagioclase and opaque are dominant, x2.5 b) Magnified zeolite crystal under crossed polarized light, x10

UNIEN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-16
Geological Classification	Basalt
Major minerals	Plagioclase, pyroxene
Minor minerals	Opaque, volcanic glass, zeolite
Textural features	Fluidal and microllithic texture

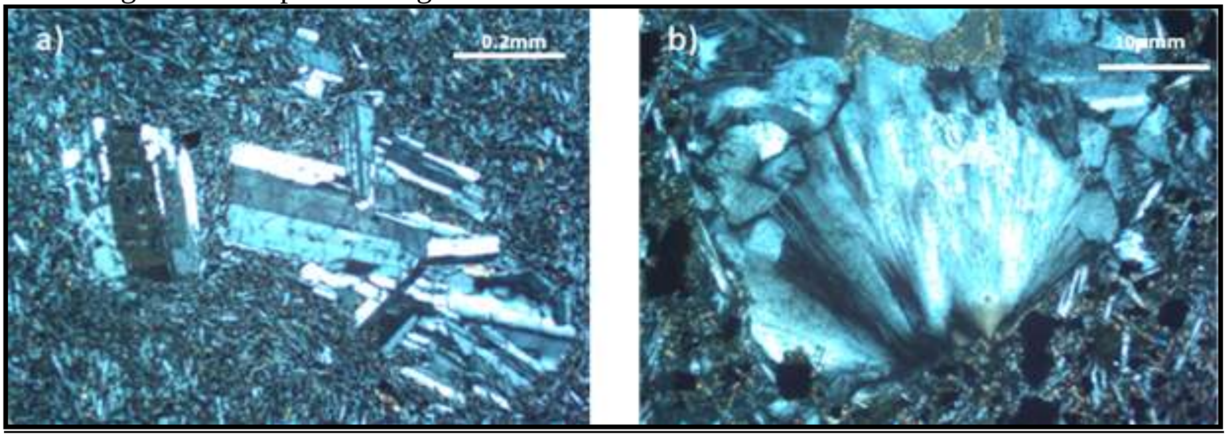
I) Hand specimen description: black in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	40	Lath euhedral
Pyroxene	30	Anhedral
Opaque (Fe-oxide)	18	Anhedral
Volcanic glass	7	-
Zeolite	5	Radial

III) Textural descriptions/Notes:

The ground which is mainly composed of microlithic plagioclase, pyroxene, opaque and volcanic glass shows parallel alignment of flow texture.



Microscopic photographs, a) Plagioclase phenocrysts on micro laths plagioclase as a groundmass under plane polarised, x 2.5, b) Magnified crystal of zeolite with radial texture, under crossed nicol, x20

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-18
Geological Classification	Rhyolitic glass
Major minerals	Volcanic glass, sanidine, quartz
Minor minerals	Opaque, pyroxene, apatite
Textural features	Vitrophyric texture

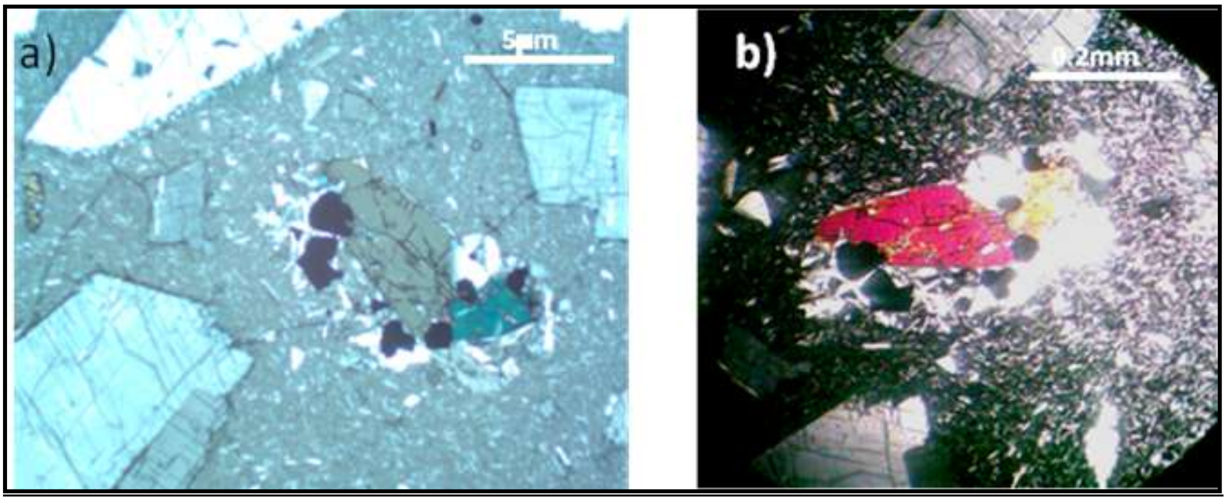
I) Hand specimen description: black coloured and glassy in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Volcanic glass	62	-
Sanidine	18	Euhedral
Quartz	10	Anhedral
Opaque (Fe-oxide)	5	Subhedral-Anhedral
Pyroxene	5	Subhedrtal
Apatite	Trace	Euhedral

III) Textural descriptions/Notes:

Large crystals of sanidine, pyroxene and quartz are seen as phenocryst over a glassy ground mass. Unfilled micro fractures are seen over the phenocrysts and groundmass across the section.



Microscopic photograph, a) Phenocrysts of sanidine and pyroxene in a glassy groundmass under Plane polarized light, x10, b) General view of the phenocryst and glassy groundmass under crossed polarized light, x2.5

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-23
Geological Classification	Porphyrithic olivine BASALT
Major minerals	Plagioclase, pyroxene
Minor minerals	Opaque, olivine, volcanic glass
Textural features	Porphyritic texture

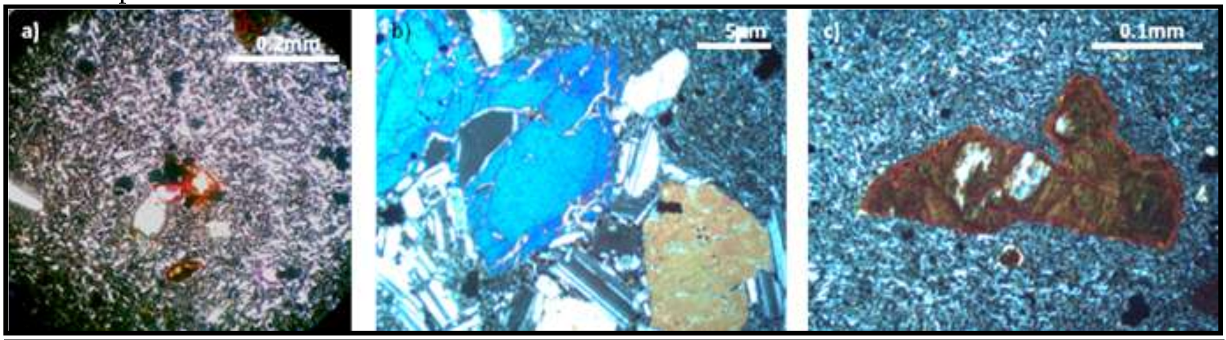
I) Hand specimen description: black in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	40	Lath euhedral
Pyroxene	30	Anhedral
Opaque (Fe-oxide)	15	Subhedral-Anhedral
Olivine	10	Euhedral
Volcanic glass	5	-

III) Textural descriptions/Notes:-

Large crystals of olivine, plagioclase and pyroxene are seen as phenocrysts over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque. Unfilled micro fractures and pores /voids/ are seen across the section. Some plagioclase crystals show zoning and subophitic texture.



Microscopic photograph, a) General view of laths of plagioclase and opaque under cross polarised light, x2.5, b) Phenocrysts of pyroxene and plagioclase under cross polarised light, x10, c) Olivine phenocryst changing to iddingsite under crossed polarised light, x2.5

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-25
Geological Classification	Porphyrithic olivine basalt
Major minerals	Plagioclase, pyroxene
Minor minerals	Opaque, olivine, volcanic glass
Textural features	Porphyritic texture

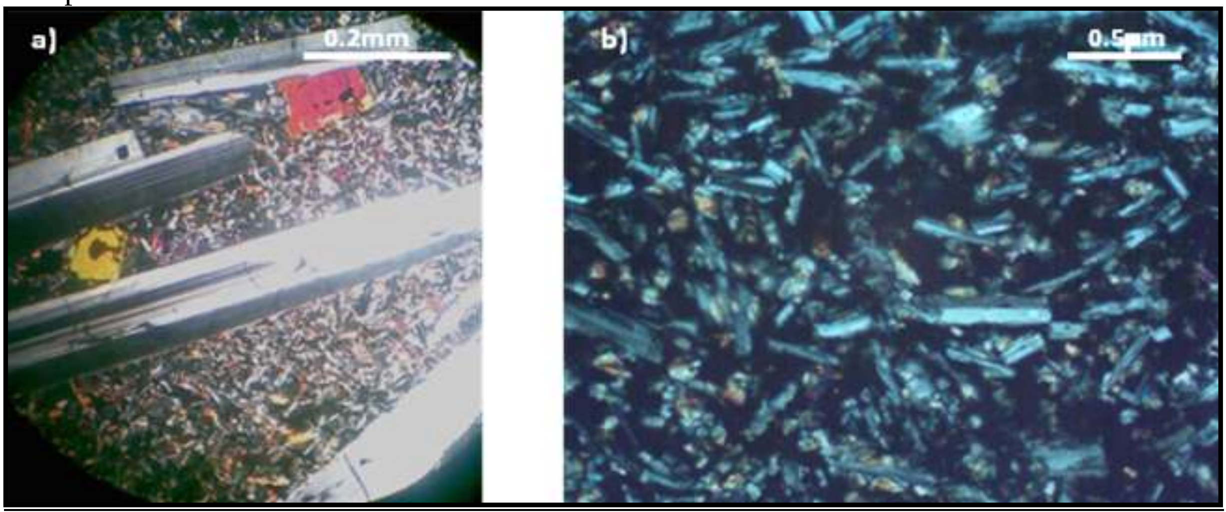
I) Hand specimen description: dark grey to black in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	43	Lath euhedral
Pyroxene	35	Anhedral
Opaque (Fe-oxide)	12	Subhedral-Anhedral
Olivine	5	Euhedral
Volcanic glass	5	-

III) Textural Ddescriptions/Notes:

Large tabular crystals of plagioclase, pyroxene and olivine are seen as phenocrysts over a groundmass composed of plagioclase, pyroxene, and opaque. Unfilled micro fractures and pores /voids/ are also seen across the section. Some plagioclase crystals show zoning and subophitic texture.



Microscopic photographs, a) Phenocrysts of plagioclase and olivine in microlath groundmass under cross polarized light, x2.5, b) Microlaths of plagioclase under cross polarised light, x10

UNI EN 12407:2007

Source of sample	Ethiopia, North Shewa, near Debrebirhan
Sample number	TB-TS-25R
Geological Classification	Porphyrithic olivine basalt
Major minerals	Plagioclase, pyroxene, opaque
Minor minerals	Volcanic glass, olivine
Textural features	Porphyritic texture

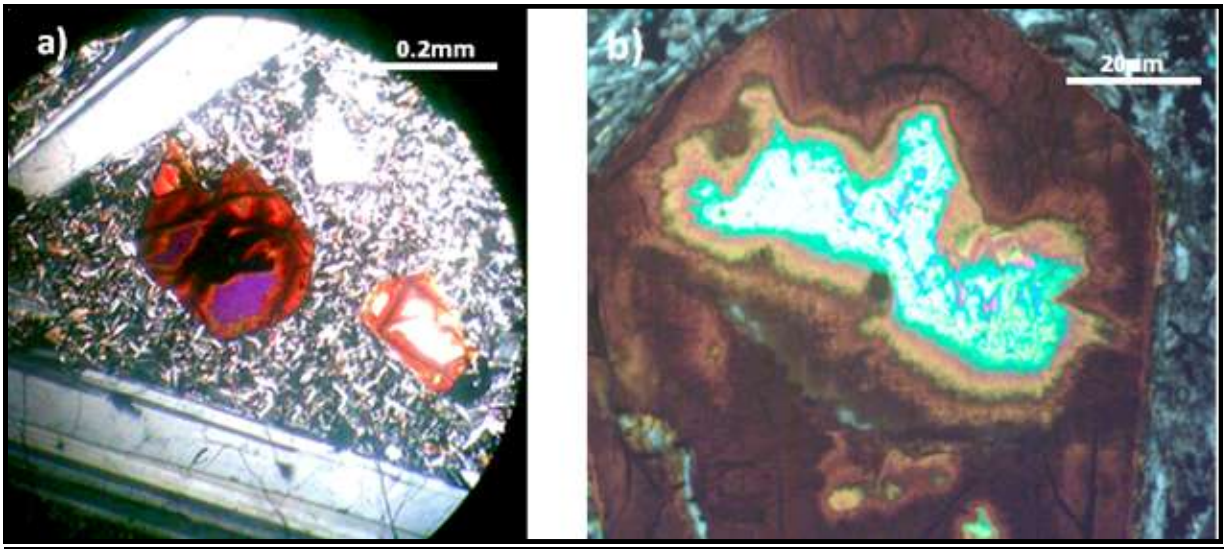
I) Hand specimen description: dark grey in colour and very fine grained in texture

II) Mineral composition

Mineral	Modal (%)	Habit
Plagioclase	40	Lath euhedral
Pyroxene	35	Anhedral
Opaque (Fe-oxide)	10	Subhedral-Anhedral
Volcanic glass	8	-
Olivine	7	Euhedral

III) Textural descriptions / Notes:

Big crystals of olivine, pyroxene and plagioclase are seen as phenocrysts over a groundmass composed of lath plagioclase, pyroxene, olivine, volcanic glass and opaque. Olivine crystals are oxidized /weathered/.



Microscopic photograph, a) Phenocrysts of plagioclase and olivine in micro lath plagioclase groundmass under crossed polarised light, x2.5, b)Magnified olivine crystal showing zonation of alteration

UNI EN 12407:2007

Source of sample	Sardinia, Abbasanta-Borore
Sample number	Abs-21
Geological Classification	Porphyrithic Olivine Basalt
Major minerals	plagioclase, pyroxene,
Minor minerals	Glass and olivine
Textural features	Porphyritic texture

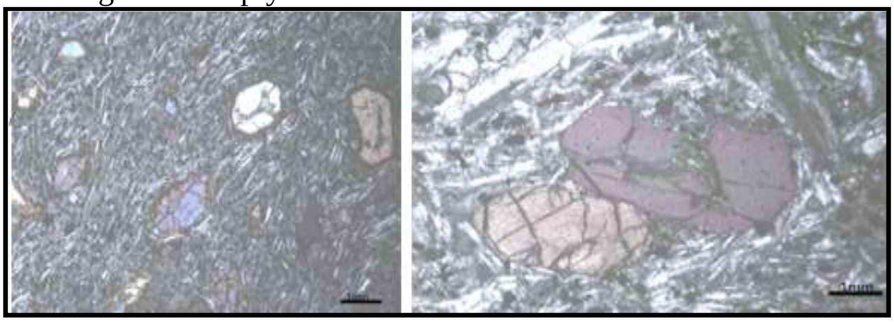
I) Hand specimen description: dark grey in colour and very fine grained in texture

II) Mineral composition

Mineral content	Modal Percent	Mineral Texture
Plagioclase	50	Lath
Pyroxene	23	Anhedral
Olivine	15	Euhdral-subhedral
Opaque (Fe-Oxide)	7	Anhedral
Volcanic glass	5	-

III) Textural Descriptions/Notes:

Phenocrysts of olivine and some plagioclase are seen over the groundmass that is mainly composed of lathe plagioclase, anhedral pyroxene and opaque (Fe- oxides). Olivine phenocrysts are idingsized. Empty voids /vesicles/ are also seen across the section.



Microscopic photograph of the porphyritic basalt under crossed nicol, a) Euhedral phenocrysts of olivine within plagioclase laths groundmass, x10, b) Phenocrysts of olivine and plagioclase

UNI EN 12407:2007

Source of sample	Sardinia, Abbasanta-Borore
Sample number	Abs-32
Geological Classification	Andesitic basalt
Major minerals	plagioclase, pyroxene,
Minor minerals	Glass and olivine
Textural features	Porphyritic texture

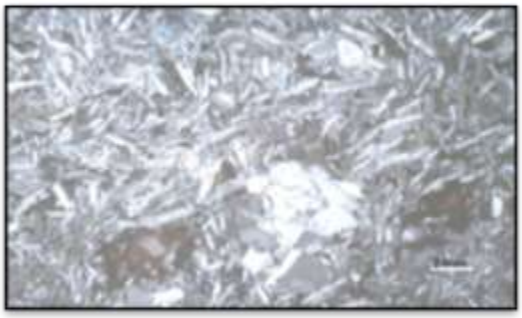
I) Hand specimen description: dark grey in colour and very fine grained in texture

II) Mineral composition

Mineral content	Modal Percent	Mineral Texture
Plagioclase	55	Lath
Pyroxene	20	Anhedral
Olivine	10	subhedral
Opaque (Fe-Oxide)	5	Anhedral
Volcanic glass	10	-

III) Textural Descriptions / Notes:

Phenocrysts of olivine are seen over the ground mass of lathe plagioclase, anhedral pyroxene, and volcanic glass and opaque (Fe- oxides). Some empty voids /vesicles/ are also seen across the section.



Microscopic photo under crossed nicol, x10, showing the andesitic rocks with abundant laths of plagioclase and rare olivine phenocrysts which are oxidized

Appendix 2: Uniaxial Compressive Strength of Ethiopian samples

Sample no	Compressive strength (MPa)	Mean	Standard Deviation	Remark
TB-TS-1	283.00	296	11.26	*APHYRIC BASALT: Dark coloured, fine-grained, compact and dense, with no fractures, massive and hard on hammering*
	303.00			
	302.00			
TB-TS-2	128.00	124.6	2.88	*IGNMBRITE: Light grey coloured, strongly welded ignimbrite with various lithic fragments (pumice, rhyolite, basalt)*
	123.00			
	123.00			
TB-TS-3	147.00	134.6	12.01	*IGNIMBRITE: Grey to light grey coloured, fine grained with rare lithic fragments, strongly welded*
	123.00			
	134.00			
TB-TS-4	90.00	101.33	22.27	*TUFF: Yellow to light yellow, coarse grained, quartz, rock fragments and glassy groundmass*
	127.00			
	87.00			
TB-TS-5	288.00	254.71	47.72	*APHYRIC BASALT: Dark coloured, fine grained, massive and unweathred*
	276.00			
	200.00			
TB-TS-6	347.00	325	24.89	*APHYRIC BASALT: Dark grey coloured, surfacially weathered, less jointed, slightly weathered on the surface*
	298.00			
	330.00			
TB-TS-7	215.00	172.33	13.12	*RHYOLITIC GLASS: Dark coloured, fine grained groundmass with phenocrysts of pyroxene and olivine*
	156.00			
	146.00			
TB-TS-8	170.00	144.0	22.71	*IGNIMBRITE: Light yellow to grey coloured, fine grained, strongly welded*
	128.00			
	134.00			
TB-TS-9	160.00	146.70	15.27	*IGNIMBRITE: Light yellow to grey, Fine grained, strongly compacted*
	130.00			
	150.00			
TB-TS-10	236.00	291.73	65.04	*BASALT: Dark coloured, fine grained, massive with slightly weathering surface, and jointed*
	363.20			
	276.00			
TB-TS-11	270.00	247.27	24.57	*BASALT: Dark coloured, fine grained, columnarly jointed*
	221.20			
	250.60			
TB-TS-12	400.00	351.33	54.78	*BASALT: Black in colour, fine grained, columnarly jointed, with rare phenocryst of pyroxene*
	292.00			
	362.00			
TB-TS-13	7.36	6.54	0.98	*TUFF: Pale yellowish grey, with yellowish brown staining, fine to medium grained, slightly to moderately*
	6.82			
	5.45			

				compacted
TB-TS-14	36.04	32.92	3.45	*IGNIMBRITE: Gray coloured fine grained with phenocrysts of plagioclase and sanidine which are seen over a glassy groundmass. The rock fragments are of basalt, rhyolite and pumice*
	29.20			
	33.52			
TB-TS-16	194.80	275.57	106.21	*APHYRIC BASALT: Black coloured, fine grained, columnar jointed, hard, unweathered*
	297.40			
	334.50			
TB-TS-18	124.20	157.03	28.48	*GLASSY RHYOLITE: Black collared, glassy appearance, extremely fine grained, jointed*
	171.70			
	175.20			
TB-TS-21	170.80	171.47	50.20	*APHYRIC BASALT: Black coloured with white spots, fine grained, massive and with rare phenocrysts of pyroxene and plagioclase*
	172.40			
	171.20			
TB-TS-22	74.28	77.75	4.13	*PHYRIC BASALT: Dark coloured, fine grained, massive and with phenocrysts of pyroxene and olivine*
	76.64			
	82.32			
TB-TS-23	361.80	280.77	92.10	*PHYRIC BASALT: Dark coloured, fine grained, massive and with phenocrysts of pyroxene and olivine*
	299.90			
	180.60			
TB-TS-24	123.09	127.60	34.38	*IGNIMBRITE: Light grey coloured, fine grained, strongly welded and compacted, with rare lithic fragments*
	163.68			
	96.04			
TB-TS-25	130.00	130.33	12.8	*PHYRIC BASALT: Dark to grey coloured, fine grained with phenocrysts of plagioclase, pyroxene and olivine, massive and hard*
	143.30			
	117.70			
TB-TS-26	65.66	59.98	12.47	*IGNIMBRITE: Light gray coloured, with abundant lithic fragments, moderately compacted*
	68.60			
	45.67			

Appendix 3 Ultrasonic sound speed measurements of Ethiopian samples

Sample n.	***Measuring direction***	***Vp (m/s)***	***Mean value***	***St.dev***	***Remark***
TB-TS-1	a-a1	6885.2	7015.2	128.86	*APHYRIC BASALT: Dark coloured, fine-grained, compact and dense, with no fractures, massive and hard on hammering*
	b-b1	7017.5			
	c-c1	7142.9			
TB-TS-2	a-a1	3596.5	3904.4	284.8	*IGNMBRITE: Light grey coloured, strongly welded ignimbrite with various lithic fragments (pumice, rhyolite, basalt)*
	b-b1	3958.3			
	c-c1	4158.4			
TB-TS-3	a-a1	4183.7	4164.6	115.83	*IGNIMBRITE: Grey to light grey coloured, fine grained with rare lithic fragments, strongly welded*
	b-b1	4040.4			
	c-c1	4269.7			
TB-TS-4	a-a1	2484.4	2712.20	210.16	*TUFF: Yellow to light yellow, coarse grained, quartz, rock fragments and glassy groundmass*
	b-b1	2753.6			
	c-c1	2898.6			
TB-TS-5	a-a1	6500	6611.1	96.24	*APHYRIC BASALT: Dark coloured, fine grained, massive and unweathred*
	b-b1	6666.7			
	c-c1	6666.7			
TB-TS-6	a-a1	6557.4	6635.2	232.48	*APHYRIC BASALT: Dark grey coloured, surfacially weathered, less jointed, slightly weathered on the surface*
	b-b1	6451.6			
	c-c1	6896.6			
TB-TS-7	a-a1	6250	6055.1	173.93	*RHYOLITIC GLASS: Dark coloured, fine grained groundmass with phenocrysts of pyroxene and olivine*
	b-b1	5915.5			
	c-c1	6000			
TB-TS-8	a-a1	3980.6	4192.3	188.83	*IGNIMBRITE: Light yellow to grey coloured, fine grained, strongly welded*
	b-b1	4252.9			
	c-c1	4343.4			
TB-TS-9	a-a1	4105.3	4010	227.86	*IGNIMBRITE: Light yellow to grey, Fine grained, strongly compacted*
	b-b1	4174.8			
	c-c1	3750			
TB-TS-10	a-a1	6002.6	5916	95.06	*BASALT: Dark coloured, fine grained, massive with slightly weathering surface, and jointed*
	b-b1	5931			
	c-c1	5814.3			
TB-TS-11	a-a1	5660	5562.6	118.29	*BASALT: Dark coloured, fine grained, columnarly jointed*
	b-b1	5597			
	c-c1	5431			
TB-TS-12	a-a1	5977	5984.6	60.19	*BASALT: Black in colour, fine grained, columnarly jointed, with rare phenocryst of pyroxene*
	b-b1	5928.6			
	c-c1	6048.3			
TB-TS-13	a-a1	1460.6	1545.1	113.14	*TUFF: Pale yellowish grey, with yellowish brown staining, fine to medium grained, slightly to moderately compacted*
	b-b1	1673.6			
	c-c1	1501			

TB-TS-14	a-a1	3506.3	3530.4	22.67	*IGNIMBRITE: Gray coloured fine grained with phenocrysts of plagioclase and sanidine which are seen over a glassy groundmass. The rock fragments are of basalt, rhyolite and pumice*
	b-b1	3551.3			
	c-c1	3533.6			
TB-TS-16	a-a1	5726.3	5815.5	80.76	*APHYRIC BASALT: Black coloured, fine grained, columnar jointed, hard, unweathered*
	b-b1	5883.6			
	c-c1	5836.67			
TB-TS-18	a-a1	5379	5340	51.67	*GLASSY RHYOLITE: Black collared, glassy appearance, extremely fine grained, jointed*
	b-b1	5264			
	c-c1	5377.33			
TB-TS-21	a-a1	4762.33	4882.3	106.73	*APHYRIC BASALT: Black coloured with white spots, fine grained, massive and with rare phenocrysts of pyroxene and plagioclase*
	b-b1	4966.67			
	c-c1	4918			
TB-TS-22	a-a1	2819	2816.3	37.52	*PHYRIC BASALT: Dark coloured, fine grained, massive and with phenocrysts of pyroxene and olivine*
	b-b1	2851			
	c-c1	2779			
TB-TS-23	a-a1	5791	5784	34.04	*PHYRIC BASALT: Dark coloured, fine grained, massive and with phenocrysts of pyroxene and olivine*
	b-b1	5747			
	c-c1	5814			
TB-TS-24	a-a1	3586	3541.3	40.80	*IGNIMBRITE: Light grey coloured, fine grained, strongly welded and compacted, with rare lithic fragments*
	b-b1	3532			
	c-c1	3506			
TB-TS-25	a-a1	5081	5081	201	*PHYRIC BASALT: Dark to grey coloured, fine grained with phenocrysts of plagioclase, pyroxene and olivine, massive and hard*
	b-b1	4880			
	c-c1	5282			
TB-TS-26	*a-a1*	*2935*	2954.6	*20.55*	*IGNIMBRITE: Light gray coloured, with abundant lithic fragments, moderately compacted*
	b-b1	2976			
	c-c1	2953			

Biography

Name: Tesfaye Asresahagne Engidasew

Date of birth: February, 1965

Education:

- Currently **PhD candidate** at the University of Cagliari, Italy, 2011-2014
- **M.Sc.** degree in Engineering geology from ITC/TUDelft, The Netherlands, 2004
- **B.SC.** degree in Geology, Addis Ababa University, Ethiopia, 1990

Some other relevant trainings:

- Modern techniques for Environmental and Sustainable Development of Earth Resources, ITC(The Netherlands)-Mekelle University joint sponsored, September, 2010
- Environmental and Health Safety Management in Mining Development of Investment Promotion Strategies for the Mining Sector Enforcing the Mining Licensing and Taxation Systems. Ministry of Mines and Energy, Addis Ababa, Ethiopia, 16 –18 May 2007.
- Small scale mine design and finance administration, UNDP, February-May, 1994

<u>**Key Qualification:**</u>

- Planned, co-ordinated and carried out engineering geological mapping of Dire Dawa Flood Control leaky dams at different sites
- Planned, co-ordinated and carried out engineering geological mapping of Abadir, Nura Era areas of Awash area for Awash flood control project
- Planned, and carried out geological mapping and exploration for gold and base metals in different parts of Adola Gold field (Ex-Ethioipan Mineral Resources Development Corporation) in southern Ethiopia
- Planned, co-ordinated and carried out geological mapping and gold, base metals, industrial materials detail exploration (Ezana-Ashantie Joint Venture share Company) in Tigray region
- Planned, co-ordinated and carried out geological mapping and detail exploration and mining of gemstones (Abay Natural Resources Development PLC) in North Shewa region
- Geological and hydrogeological mapping of Northern Addis Ababa(Sululta area)with the help of Satellite imagery and air photo)
- ETC., just to mention a few

Technical reports:

- Numerous unpublished technical reports, >25(in mineral exploration, engineering geology, hydrogeology, industrial and construction minerals)

Publications:

- **Engidasew, T. A. (2005).** Feasibility study for an underground opera hall in Cambrilles, Spain, Unpublished Master's degree thesis, ITC/TUDelft, The Netherlands
- **Engidasew, T. A., Fekeret, Y., Seifko, S., and Hack, R. (2005).** General purpose engineering geological map of Area 1, Coldejou, Spain. ITC/TUDelft, Engineering Geology section, The Netherlands
- **Engidasew, T. A. and Barbieri, G. (2013).** Geo-engineering evaluation of Tarmaber basalt rock mass for crushed stone aggregate and building stone/cut stone from Central Ethiopia (Journal of African Earth Science, Elsevier publisher, Peer-reviewed published, on line 12 December 2013)

- **Engidasew, T. A. and Barbieri, G. (2013).** Physical and mechanical characterization of Tarmaber basalt rockmass for crushed coarse aggregate production in central Ethiopia, IAEG, (Springer-Verlag publisher, IAEG, abstract accepted, manuscript under review)

Full Conference Proceedings

Engidasew, T. A. and Barbieri, G. (2013). Geo-engineering evaluation of Tarmaber basalt rockmass for building stone/cut stone and crushed stone aggregate from Central Ethiopia, Colloquium of African Geology (CAG), January 2013