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Granite By-Products for Inverted Pavement Technique

Learning scientific field of reference
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INDEX

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

As mentioned by Sardinia Region: "Sustainable Development is what satisfies present's needs without shattering those of future generations, thanks to smart use of environmental resources and without waists". This research aims to use a current resource available in high quantities in Sardinia to optimize the uses of the extracted materials and not to take just advantage of the Region. The mining activity in Sardinia, which is very important since ‘60s, during these years, has produced huge amounts of granite by-products. The ornamental use of granite is an important money source for Sardinia. Unfortunately, as the virgin material extracted must have high aesthetic qualities, many rock blocks are rejected. This research has the aim of making the most of the material stored in a quarry sites and of optimizing the uses of resource stone examined.

The target is the use of granite by-products as material with high mechanical featured to be used for road pavements, from the foundation to surface. This research gives you the opportunity to make the most of regional resources, to minimize the thickness of asphalt, reducing the maintenance and realization costs. This is a good start for the Island to make money of something easy to export.

Granite by-products will be used for the construction of innovative road pavement design. The Inverted Pavement Technique, studied and developed in South Africa since 1950, is going to be used for road infrastructure. In particular, I have focused the attention on the behavior of granular base layer. Thanks to this technique is actually possible to take advantage of mechanical features of base layer, creating base layers that assure high and long lasting performances with almost zero environmental costs. The Project is finalized to a sustainable design by using resources, considered as waste so far, present in the Sardinian Land and the minimal use of exhaustible and expensive row materials as asphalt layers.

The increasing costs of petrol products and their limited availability leaded to find alternative solutions to flexible infrastructure everywhere in the world.

Another target was to make sure that European and South African Regulation matched regarding granular aggregates. Through laboratory testing physical, chemical, and mechanical features of granite by-products were analyzed comparing to Dolerite, used in South Africa in the Inverted Pavement Technique.

KEY WORDS

Road Pavement Design, Inverted Pavement, Eco-Friendly Material, Green Public Procurement.

1. INTRODUCTION

The mining of granite for ornamental use is important for the economy of Sardinia since the ‘70s. There are more than 1900 active mines in Sardinia that produce 200 million cubic meters of granite by-products. The mining of granite and of the other stone materials is not only a source of growing perspectives, but also it determines a temporary and/or final alteration of the environment; actually, all the steps of the productive cycle, from the preliminary investigations to the most advanced phase, involve and change the environment causing a strong impact on it.

Right after the mining it was obtained a huge amount of waste materials stocked in areas of landscape and naturalistic importance as many mines are located on the mountains. (S. Portas, 2002). According to directive 75/442/CE the word “*waste*” is defined as follows: “*Any substance or object whose owner wants to get rid of or must get rid of*”.

In the chapter 1 of the same directive we find: “waste coming from prospecting, mining from mine or quarry as well as from chemical or physical treatment of the minerals”.

In the specific field of granite culture, the waste material is about 55% of the total inert mining. This is due to the fact that not all extracted blocks have excellent aesthetical features. They are actually ranked in first choice, second and third choice blocks and still waste blocks.

The effects on the environment are of different kind. One of the main permanent consequences is the landscape impact, due either to the mining and to the relative landfills left in place.

The placing of the quarry leavings always represents a problem inside the mining and for the community. With this research it is taken into consideration the possibility to use the wasted materials of the granite processing, which are nowadays out of market – but not for this reason without value – to build infrastructures and to reduce environmental exploitation.

We actually know that for the realization of an infrastructure besides the partial use of the materials in situ, most of the inert come from a quarry (F. Leuzzi, 2009) .

The total length of ANAS roads in Sardinia is 2.924,649 km (Anas source) and they are all flexible infrastructures.

The 2015 maintenance plan foresees 31 extraordinary maintenance projects and 11 new constructions. The total cost of the works is Euro 726.884.407,34. The 60% of the costs is given by the supplying of building materials. It takes 30.000 tons of inert for one kilometer of road. The majority of the inerts comes from the exploitation of mines, the remaining part comes from the construction site. This research aims to characterize, from the structural point of view, the granite by-products coming from quarry so that it is considerably reduced the amount of virgin aggregates extracted.

Granite by-products stocked in quarry will be used to build layers of the infrastructure, not a basic “flexible” or “rigid” infrastructure. It has been taken into consideration the Inverted Pavement technique developed in South Africa, characterized by a sub-base layer in cement mix, a granular base layer and a thin surface layer of hot mix asphalt.

The “secrets” of the success of these pavement are the high quality, abundantly available, crushed material used for the base and sub-base and the high levels of compaction achieved (Molenaar, 2009).

The goal of this research is to investigate on the theoretical and experimental aspects of the best use and performances of granular layers mainly regarding the regional situation. Sardinia has the ideal candidates such as granite by-product and marble for the production of innovative materials with high and low cost performances.

South Africa has developed the Inverted Pavement technique in the ‘70s and it keeps on studying this technology according to the continuous growing of the axial loads that burden on to the infrastructure. The study of flexible pavements has grown considerably from 1978 to 1994, thanks to the introduction of new machinery such as HVS (Heavy Vehicle Simulator) that allowed to perform simulations of the loading onto the flexible pavements to improve some of their characteristics. The building methodologies of South Africa highlight the importance of having a good structural support of the foundation materials and from all the layers made of granular or stabilized material. The infrastructure is usually characterized of a sub-base layer with a thickness of 150 - 300 mm in stabilized cement mix, on top of which is built a very rigid layer of unbound granular mix, of 150 mm thickness, compacted to obtain high density through the Slushing process. This rigid layer is now covered by an hot mix asphalt of low thickness (40-50 mm). The N1 highway in the northern Pretoria is an example of the efficiency of South African highways created with the Inverted Pavement technique 23 years ago and it is nowadays in use and in good conditions.

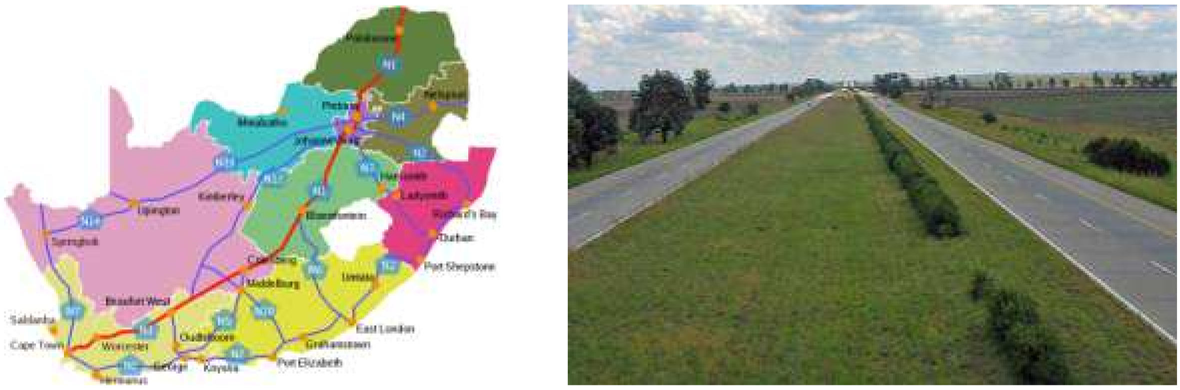


Figure 1 National Route 1

This study gives considerable importance to the mechanical behavior of granular mix.
Granular mix is a mixture of grains, not only of stone origin, which has growing performances related to energy and compaction pressures. In South Africa the material used is a result of crushed Dolerite rock available in high quantities, which mechanical characteristics have been studied with laboratory tests according the Technical Recommendation for Highway (TRH). The results of the material used in South Africa have been compared to those of the same tests made for granite by-products. The study was carried analyzing first of all the different types of South-African flexible and semi-rigid pavements according to the pavement catalog (TRH, 1996), and also testing the stress status attached to each layer of the pavement. Secondly, it was analyzed the chemical, physical, mechanical and mineralogical characteristics of Dolerite. Afterwards, we explored the mechanical and mineralogical characteristics and the particle size range specifics for the creation of the unbound granular mix base layer. The efficient use of granite by-products makes interesting this study as well as the economic savings coming from the low thickness of the hot mix asphalt and the growing of the useful life foreseen for the infrastructure. It is not enough to have excellent mechanical and grain size characteristics of the material to obtain an artfully base layers. Machinery used and the steps for the making of the layers cover remarkable importance. The use of the Inverted Pavement technique is nowadays a cutting edge method in the modern South African pavements.

2. MINING

Sardinia represents the tenth region in Italy for the number of enterprises and the eleventh for the number of people serving as mining. Veneto, Tuscany and Lombardy are the three most important regions of Italy. In 2001, according to the census, the 4,4% of Italian enterprises and the 4,1 of the occupants of this sector were placed in Sardinia, with a majority in the city of Sassari, Nuoro and Cagliari. Sardinia is characterized by the presence of two important districts acknowledged by the Region: the Granite of Gallura and the Marble of Orosei, in which are centered the mines and the majority of the ornamental stone companies. (Structural Analysis: mining and working stones, 2006). The mining and working areas of the ornamental stones of Sardinia is mainly consisted of small and micro enterprises, the 84% has less than ten workers and the 15,7% has between 10 and 49 employees. Furthermore, the business with more than 50 workers are very few: only one company in 2004 and two companies in 2005. In 2005 the employment of mining area and stone working area was of 2.592 units and the revenue was 144 millions of Euros.

Commercial companies linked to mining and stone working enterprises are also placed in Sardinia followed by a minor number of companies with stores in other Italian regions (and particularly in the main stone districts of Verona and Massa Carrara).

In 2004 the most of the companies working in Sardinia works only on the transformation of the ornamental stone and it does not have personal caves and it buys raw materials on the market. It belongs to this category of company 308 enterprises, equal to 74,9% of the total. The next important companies are those who carry either mining and transformation activity. We are talking about 60 companies with a revenue of 58,6 millions of Euros.

There are different types of cultivation, not only linked to mining and geological aspects, but also linked to local morphological conditions. In Sardinia the mining of rocks for ornamental use is carried basically on "open air cultivation", that inevitably causes a permanent change of the sites and an impact on the local eco system and environment.

The Regional Law 30/89 set the mining and the cave life schedule.

This law foresees the planning of the mining and at the same time the recovery of the areas at the end of the cultivation. With the directives of the European Union CE91/156, 91/689 and 94/62, which govern the waste sector, Italian Government has issued a D.Lgs. 15th February 1997 with title "Waste Management". The purpose of this Decree is to ensure, through a careful waste management, a high protection of the environment. From this, arises the need of introducing new techniques and new building methodologies able to reduce the amount of waste materials. From here it also comes the need to reduce the exploitation of the environment as well as the use of natural materials coming from the new mines. In the Figure 2 Active and closed Caves and Mines. It is possible to identify the percentage of closed, active, closing and decommissioned mines until 2007.

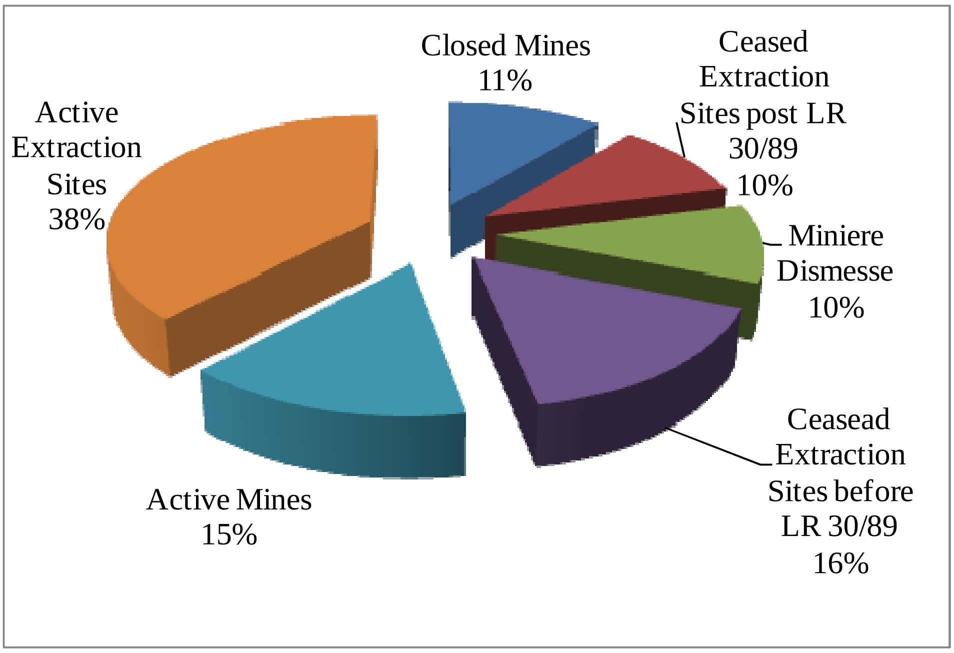


Figure 2 Active and ceased Caves and Mines.

3. ITALIAN REGULATION FOR MINING

Mining is regulated by the “Regio Decreto” n. 1443/1927 that is the main source of the Italian rules concerning the mining. Such Decree sorts the use of the minerals establishing two different working categories:

- the first category, called mine, is about the cultivation and research of mineral substances of strategic importance and of unavailable heritage of the Country whose practice is under concession;
- the second category, called cave, is about the cultivation of materials that belong to the owners of the lands and they are allowed to exploit them under the authorization or concession of the government.

With the regional law n. 30 of 1989 without a public framework law, Regions prepared a regulatory and administrative system of planning, authorizing and checking. Even though this system is miscellaneous and uneven on the national territory, it certainly limited the environmental and hydrogeological destruction that could have been caused by the messy exploitation of caves. The regional law 30/89 sets in the Regional Plan of Mining (PRAE), the tool of the sector programming and the operational reference. The PRAE, planned by Department of Industry, has not been presented in the regional Council for the main approval yet; without the approval it applies the so called "Piano Stralcio" approved in regional Council on 30th June 1993 and published on the BURAS n.29 on 28th July 1993. Sardinian Region has, according its own statute (L. Cost. 26th February 1948, n. 3), legislative power on mineral and thermal waters and power on patrimonial and state property law of mines, caves and salterns and therefore it provided to rule the mining trough Law n.30 of the 7th June 1989 and amended. In this law there are different groups of materials according to the intended use:

- ornamental rocks (marbles, granites, alabasters, slates, limestones, travertines, trachites, basalts, porphyry, etc.) to be used to produce blocks, plates and related;
- materials for industrial use (marls, limestones, dolomites, diatomaceous earth, siliceous sands, earth colors, clays, peats, etc.) ;
- materials for civil works and buildings (sands, gravels, granulates, blocks, etc.).

Caves can be “ornamental”, “industrial” and “civil” according to this selection of groups referring to the main destination or origin. The litotype, depending on the characteristics, can give place to different kind of caves. One deposit can be given license for multiple destinations (according to the fact that one cave could give its only product different uses).

The license for cultivation activity is ruled by Title IV, art.19 of the above mentioned Regional Law.

The application for the license must be equipped with the cultivation project including the description of the geological characteristics of the concerned lands, the description of the preparing, mining and restoration steps. The application must also include the description of the landfill sites (ruled by D.Lgs. 117/2008) and the illustrative paper of the main elements of operations (estimated duration time, annual production, estimated yield, employment, possible arrangement in vertical order).

The cultivation project has to define preventively the amount and the type of materials produced and refused (making the “extraction waste” according to D.Lgs. 117/2008).

To release the license it must be acquired the necessary clearance such as environmental, forest, archeological permission and all control procedures.

With the entry of the D.Lgs. 30th May 2008, n. 117, Directive 2006/21/CE relating the waste management of mine industry, there are new specific rules to ensure environmental and sanitary protection of the waste coming from the prospecting, the mining, the treating and stacking of mineral sources and from cave exploitation.

This topic is not included in the application of part IV of D.Lgs. 3rd April 2006, n. 152, according to art. 185 and application field of D.Lgs. 13th January 2003, n. 36 as foreseen by paragraph 6 of art. 2 of D.Lgs. 117/2008. The Decree is part of the special rules of the mining sector as per R.D. 29th July 1927, n. 1443, and the relating safety rules of D.P.R. 09th April 1959, n. 128 and from D.Lgs. 624/1996 in tune with special European directives.

The D.Lgs. 117/2008 sets the procedures and necessary actions to prevent or reduce as much as possible negative impacts on the environment, in particular for water, air, land, flora, fauna and risks for human health coming from the management of waste produced by mining industries.

It is important to know that this law is limited to rule the management of wastes coming from the inside of the sites and in the facilities with a limit on the application.

Whether the managing of waste is done outside the site or outside the facility, it will automatically be covered by part IV of D.Lgs. 152/2006.

All other kind of waste that are not specific of mines are excluded from application of the law even if originally coming from the normal mining activity and they are subject to general discipline of waste management of part IV of D.Lgs.152/2006.

One of the news inserted in D.Lgs. 117/2008 is the "Plan of management of wastes" which is an integral part of cultivation project to achieve the license.

The Waste Management Plan aims to:

- prevent or reduce the dangerousness of production of waste coming from mining, previously when planning properly either the mining and treating methods foreseeing to possibly relocate the wastes in the same landfills created by the excavation; the choices of the project must be technically achievable and sustainable from the economical and environmental point of view;
- stimulate the recovery of wastes by possible recycling or salvaging always according to the law and if it does not involve a problem in the environment;
- ensure the secure short and long-term disposal of wastes planning, during the design phase, the waste management either during the mining and after the end.

The 10th August 2010 it was issued regulation nr. 161 laying the rules on the using of lands and rocks for mining which defines excavation material as "working residuals of stone materials" (marble, granite, stones, etc.) also not related to the creation of works and not containing dangerous substances (such as flocculant with acrylamide or polyacrylamide). It is also specified that such materials of result may be used to replace virgin materials coming from cave if a Using Plan was expected.

The Using Plan must include:

- requirement of material which is originated by a production process whose main purpose is not the production of it (DLgs. 152/2006);
- production site, deposit and future use;
- place in the territory;
- prescribe possible industrial treatments useful to improve the characteristics of the by-product.

According to these characteristics the body responsible (ARPA) gives an opinion about the use of the by-products.

4. GRANITE BY-PRODUCTS

Granite is one of the most popular building materials. It has been used for thousands of years in both interior and exterior applications. Granite dimension stone is used in buildings, bridges, paving, monuments and many other exterior projects. Indoors, polished granite slabs and tiles are used in countertops, tile floors, stair treads and many other design elements. Granite is a prestige material, used in projects to produce impressions of elegance and quality.

The blocks classified as top quality will produce slabs that present no flaws or discontinuities that might diminish exploitation possibilities and aesthetic quality. Blocks classified as of inferior quality do exhibit some discontinuity or flaw but may be exploited so as to obtain an acceptable economic return. Here, the transformation equipment available is important in determining the minimum size of the blocks. Finally, the part of the bank considered not to be exploitable is that which incorporates such a quantity of discontinuities that it is not possible to extract even minimally sized blocks. (J. Taboada, 1999).

The ornamental rock processing industry uses large amounts of rocks in a wide variety of finished products (e.g. granite, marble, slate, gneiss, quartzite, etc.). As a result, this industry produces worldwide huge amounts of by-products. In Brazil, in 2007 about 1.8 million tons of waste was generated every year (A. J. Souza, 2010). During the years it was observed how the environment has changed after the mining. As shown in the Figure 3, fronts are always wider, without vegetation and visible from far away. At the same time hills are covered by waste barren materials from mining and the work of blocks.

Sardinia has an area of 24090 km², 25% of which is granite. The mining of granite has great importance for Sardinian economy tank to the exportation of granite blocks.

Figure 3 Example of “open air” mining and stocking of extracted blocks.

One of the effects of mining is the waste production of granite by products and low quality blocks. During the years it was produced a considerable amount of inert material stored in the landfills of each cave. Even though this material preserves the qualities of the subgrade it can only be discarded because of its aesthetic defects or due to the inappropriate size of the blocks to be worked for ornamental use. In Sardinia there are 40 million cubic meters of stored inerts to which are added 1,5 million of cubic meters more each year of mining.

Figure 4 Cava Usai and Punta Molentis, in Villasimius.

Granite by-products preserve the same chemical, physical, mechanical characteristics of the rocks whence they are extracted but they must comply with technical standards foreseen by UNI EN 13285, UNI EN 14688-1, UNI EN 13242 and UNI 11531 to be used for building infrastructure. To obtain the CE marking they must meet standards UNI EN 13242 and DM 11/04/2007 and to achieve the environmental approval they must meet requirements of DM 5/02/1998 and DM 5205/2003.

Sardinia has a natural heritage of great value and decisions taken regarding the intended use of the territory cover an important role particularly along the coasts where there are sundry natural reserves Figure 4.

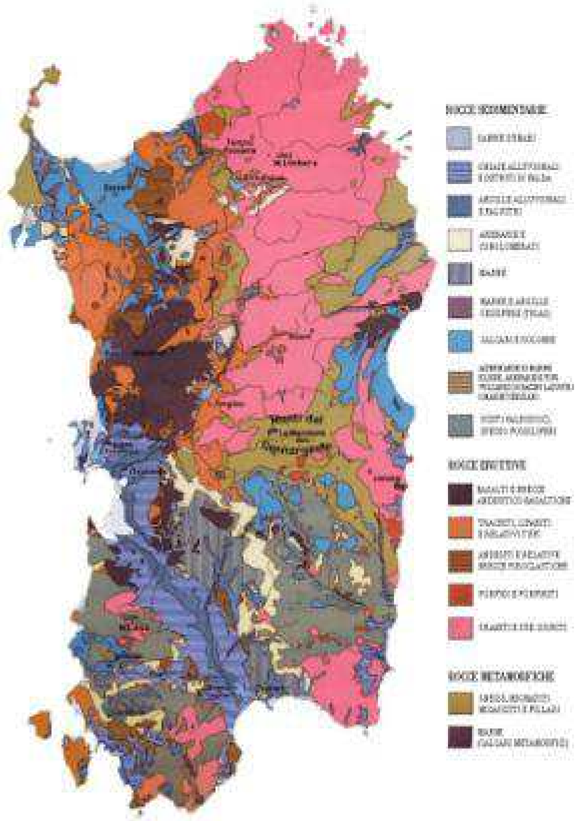


Figure 5 Extracted minerals in Sardinia

In the Figure 5 is the geological map of Sardinia. The mining of ornamental stones covers the 50,6% of the mining of non-energy regional minerals and it is one of the mining carried in the territory (Movimprese 2005). The plan is to study the compatibility of granite by-products stored in each extraction site in Sardinia to build infrastructure. These aim to minimize the environmental impact thanks to the use of wasted materials and the reduction of non-renewable sources such as bitumen to realize the asphalt layer.

With the chart below (Figure 6) it is possible to understand how the percentage of aggregates extracted covers the 49% of the total inerts produced for the infrastructures only.

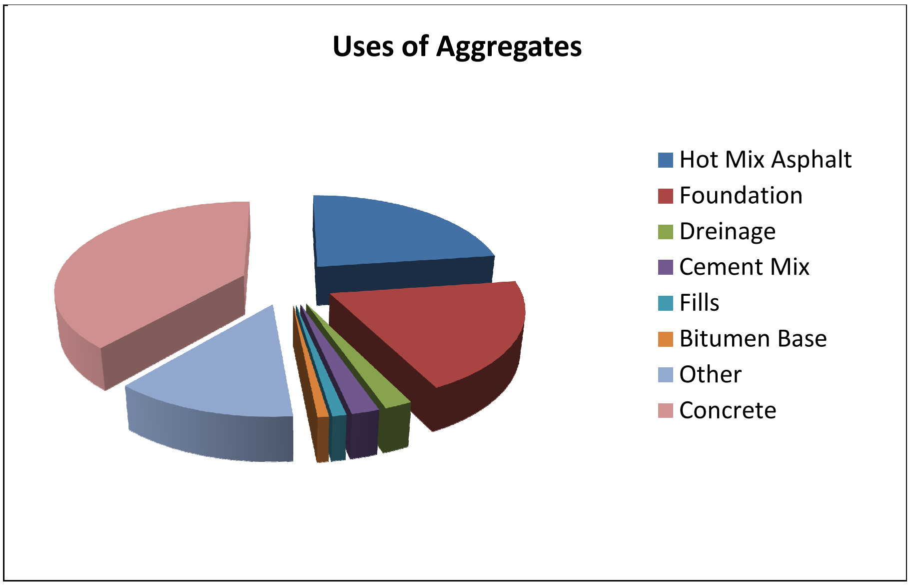


Figure 6 Percent division of natural aggregates produced between 2009 and 2013.

The distribution in the territory of the ornamental stones extraction sites is almost equable and this makes the costs of the transportation of the inert from the cave to the infrastructure site considerably reduced. When the main intent was reached, that was the sustainable infrastructure built by minimizing the use of non-renewable sources and by optimizing the use of material considered as waste, there have been different obstacles among which:

- difficulties on how to find advice of each cave because quarryman are not willing to give information regarding the production and material waste data;
- difficulties on the performance evaluation of granite by-product as the high number of granite types (11 different kinds of granite) makes it hard to select the right material in each cave;
- low sustainable expenses from privates and public administration;

The Sardinia Region with resolution n°22/19 of 22nd May 2012 issued the guide lines for the application of ecological public outgoings in work contracts with title: “Use of Granite and Marble by-products for the Infrastructure Trades”.

5. ENVIRONMENTAL SUSTAINABILITY

The environmental sustainability is the ability to ensure the long last of the environmental functions, such as: source of natural resources, receiver of waste and pollution, supplier of necessary conditions for the maintenance of life. Concepts of sustainability were first introduced with Brundtland report (Brundtland, 1983), which researched a balance between economic development and life quality through the correct exploitation of natural resources.

After the first oil crisis of the Seventy's it was developed a new way to build, aiming to save the remaining natural resources. The use of sustainable resources becomes the main target together with the topics about the pollution, that concerns our planet with its consequences, climate changes, greenhouse effect etc. This new way of thinking and interacting with the environment has had a great impact on the market that studied and developed new technologies.

In Italy in 2002 the Resolution CIPE 57/08/2002 introduced the "Environmental Impact Evaluation" as a valuation tool for every single building work. Whilst the principle of sustainable development in the engineering design was introduced with D. Lgs. 4/2008 and renewed then by the D.P.R. 207/2010, these rules foresee that during the planning phase it must be given considerable importance to the atmospheric and water aspects, to eco-system evaluation, to the entity of the noise and vibrations produced, as well as the change of the soil and subsoil. An infrastructure that covers all analysis fields must interact and incorporate with the environmental contest, becoming an input of economic development for the territory. Infrastructures are basic for the modern society as well as they were since the beginning of Roman Empire, they connected Rome with suburban lands encouraging commerce and the meeting with new cultures.

The VII Program of action for the environment between 2014 and 2020 of European Union is called: "Living well inside the limits of our planet". The file sets the concept of "life cycle" as basis of strategic choices for sustainable use of the resources, prevention and wastes recycling. The Community Directive 98/08/CE sets the target of the recycling of inert wastes to be achieved before 2020, equal to 70% of the total amount of wastes produced.

5.1. GREEN PUBLIC PROCUREMENT (GPP)

The Green Public Procurement introduced, thanks to the book "Green Book about the politics produced" in February 2001, is the whole of environmental considerations regarding the expenses procedures of Public Administration. In Europe the Directive 2004/81/CE of 31st March 2004 inserts the "environmental" variable as a standard for the evaluation of the offer. In Italy the Green Public Procurement is not compulsory, though there are rules that urge to insert it according to specific requirements and targets for the purchasing and using of certain products. In Sardinia it was enacted the "Guide lines for the ecological public purchases in the work contracts: the use of by-products from marble and granite caves to build infrastructures".

With the Regional Resolution 37/16 of 30th July 2009 Sardinia has set its own politics about the Green Public Procurement that represents the mean for a sustainable development aimed at reviewing the public administration expenses. The Green Public Procurement encourages the use of goods and services that involve less and less natural resources, the production of waste, pollutant emissions, danger and risks for the environmental health and use of nonrenewable sources. This politics involves the adoption of a method to plan and realize interventions by respecting the life cycle of used materials, aiming to reduce as much as possible the environmental impacts and to ensure at the same time the safety of the infrastructure. This policy is willing to ensure the health of workers and users as well as the quality of the intervention regarding the territorial context.

The choice of materials and technologies to apply to infrastructures has to be made considering those environmentally friendly products that meet several requirements such as:

- Hygiene and health safety: material must be free from pollutant and harmful emissions either during production, while using it and during removal;
- Durability: that is the ability of maintaining over time its own physical features and performance, but also the adaptability and easiness of maintenance;
- Environmental friendliness: the product has to come from plentiful raw materials; it must have low Energy consumption related to transportation, but most products have to encourage traditions and experience of local handicraft and industry to protect formal aspects and choice of materials that are going to characterize the identity of the territory;
- Endurance: that is the ability to bear with stress without damages or breakage, either during the implementation and during the work life.

The target pursued in this research is to work on granite by-products, by the chemical mechanical and physical point of view to make use of them on infrastructures, ensuring:

- Full respect of the rules foreseen by the Regulations;
- To give an economic value a material considered so far just a processing waste and therefore stored in huge garbage dump, which produces first of all a storage cost and it represents an uneconomic use of the territory;
- To give a new profitability to existing mines;

- To avoid the opening of new extraction sites which disfigure the environment.

It is clear how the creation of a road requires large movements of soil not only for the basic layout of the solid road but also for the reclamation of the substratum, shallow layer and improvement of foundations. (F. Leuzzi, 2009).

Stone materials, coming from ornamental work process, allow to make them more desirable for other markets such as infrastructure field. As foreseen by the last regulations on "Use of excavation soils and rocks", it is necessary to examine granite by-products by the chemical and physical point of view to establish their compliance. At the end of the examination, every mine will be able to draw up its own "Using Plan" as foreseen by DM 10th August 2010 n°161.

6. USE OF INERTS IN ROAD FIELD

To create infrastructures we must consider some Specials as:

- Consiglio Nazionale delle Ricerche (CNR) regulations;
- HIGHWAYS FOR ITALY (AUTOSTRADE PER L'ITALIA): maintenance and construction of pavements – technical regulations for contract performances;
- Ministry of Infrastructure and Transport (Ministero delle Infrastrutture e dei Trasporti) "Capitolato Speciale d'Appalto Tipo per Lavori Stradali";

6.1. CNR REGULATION FOR AGGREGATES

Inerts are the most conspicuous part of the materials employed in the road engineering. Their origin, their provenience and their mechanical properties can be different and for this reason they must be monitored constantly with extreme attention. Depending on the use in the building of the various layers of the superstructure, the stone aggregates must have different geometric, physical-chemical and mechanical features. Depending on the size of granules, we can distinguish aggregates, in a conventional way, in three classes with a decreasing size: granulated or crushed, sands, filler. It is always necessary to monitor the inert clearing, above all if is considered the use with any alloying. The checks that are required concern:

- granulometry;
- shape;
- angularity;
- resistance to chipping;

- resistance to consumption by friction;
- resistance to abradibility;
- freezing;
- alterability.

6.1.1. GRANULOMETRIC RULES

For the base layer the granulometry which is allowed is that into the granulometric melt of reference, based on the connections between the minimum diameter of inert (d) and maximum diameter of inert (D). The melts of reference are two and are distinguished based on the maximum diameter of inert. In the first case reported in the Figure 7, the maximum diameter of inert is 71 mm; in the second granulometric melt, reported in the Figure 8, the maximum diameter of inert is 30 mm.

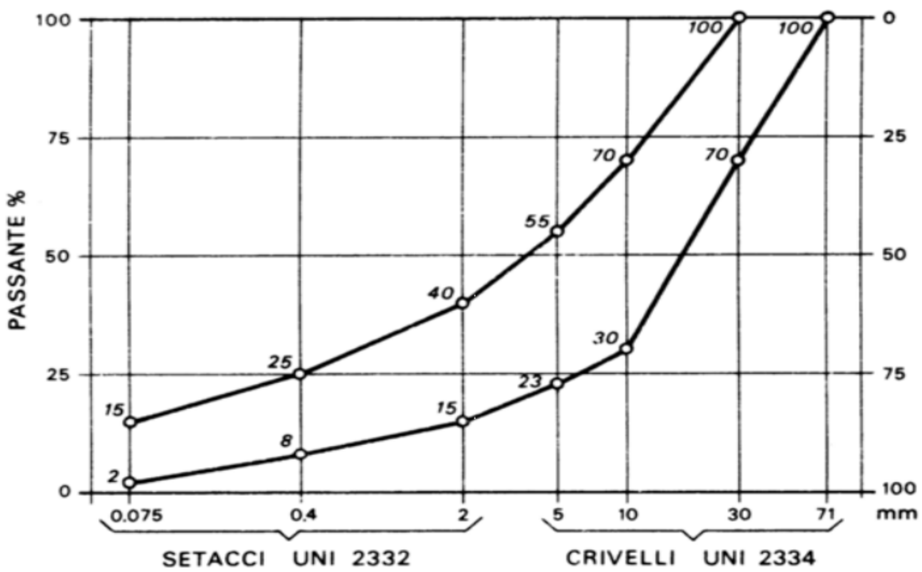


Figure 7 Grading Curves for Foundation Layer

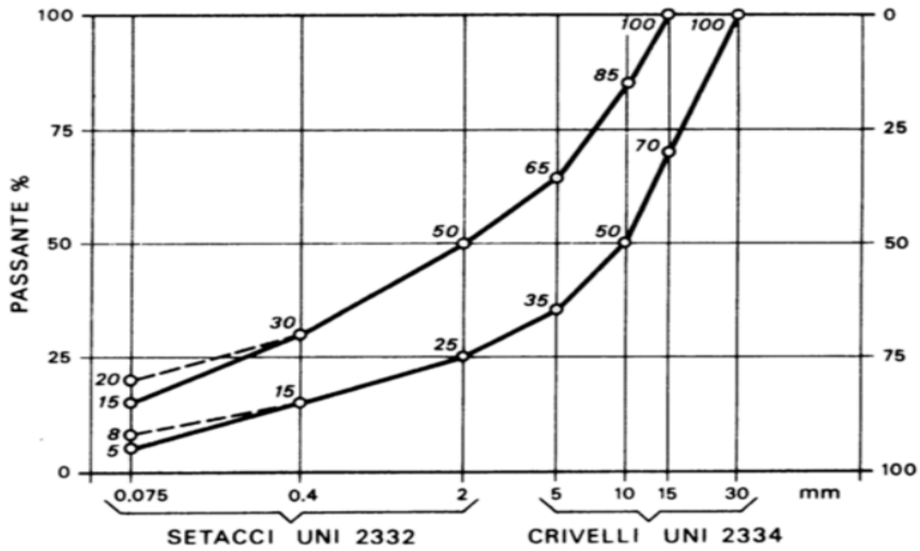


Figure 8 Grading Curves for Foundation Layer with maximum Aggregates 30 mm

The grading of the granular mixture has a remarkable importance, because, despite imposing a rather narrow grading melt, the mixture conduct is somewhat different. For this reason, CNR, on the rules about cemented blends, proposed two grading melts to use for two different kinds of cemented blends: the type A1 with narrow melt and the type A2 with wide melt. The curve of type 1 provides some higher values of thickening and resistance to compression; instead, the curves of type 2 generate, the contents of alloying being equal, better resistances to curve. About cemented blends that are used as layers of sub-base, the grading melts of reference are those reported in the Figure 9 and in the Figure 10:

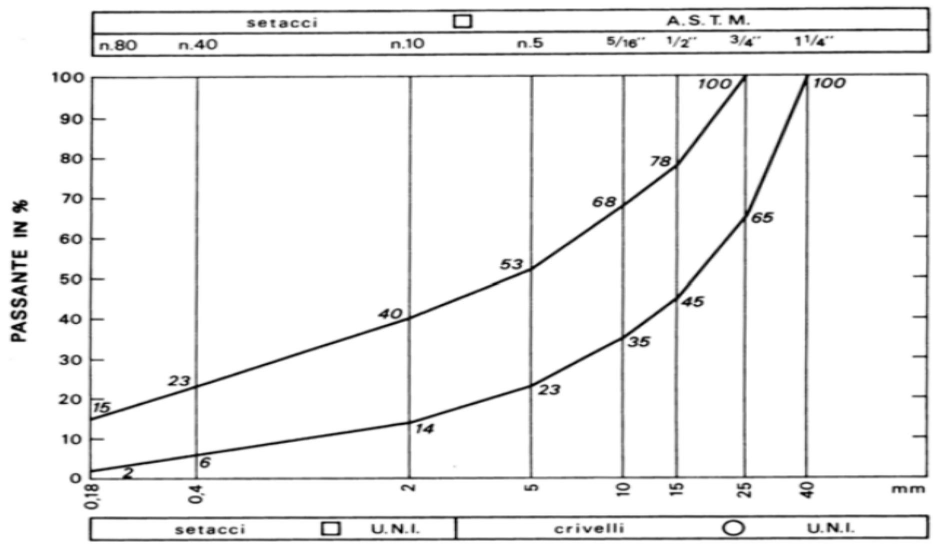


Figure 9 Grading Curves for cement mix A1

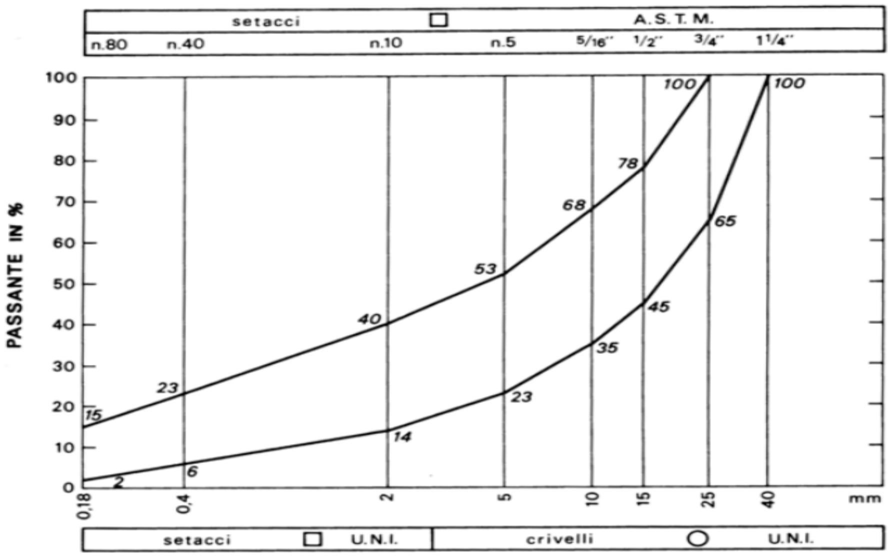


Figure 10 Grading curves for cement mix A2

About the base layers with not alloyed granular mixture, they are some blends completely alike to those described for the base layers with granular mixture. Obviously, being layers nearer to the traffic action, are ordered narrowest granulometric melts and a control of resistance of elements, through the *Los Angeles test* that must have a coefficient minor of 25-30 %. The rules of plasticity and of minimum resistance CBR of 80 must be kept, above all if surface layers alloyed by bitumen will have a thickness minor of 10 cm.

6.1.2. THE SHAPE INDEX

The shape of material is determined using sieves and sifters with elongated gaps or rod sieves. Elements, exposed to vibration, pass through gaps placing themselves according to the minor of three sizes L (length), G (width), E (thickness). The shape coefficient is given by the division between the volume of the single element ($V_{elemento}$) and the volume of sphere (V_{sfera}) that has, as a diameter, the size bigger than the element itself, as reported in the formula:

$$C_f = \frac{V_{elemento}}{V_{sfera}(d : \max L, G, E)}$$

The angularity of material increases the resistance to the inert cut. It is determined by the division between the elements with sharp edges E_{viviv} (crushed elements) and those round (E_{tond}), as reported in the formula:

$$C_{sp} = \frac{E_{viviv}}{E_{tond.}}$$

6.1.3. RESISTANCE TO CHIPPING AND TO FRICTION

Resistance to chipping is evaluated through the *Deval test*, whereas, resistance to consumption by friction is evaluated through the *Los Angeles test*. The first one is done inserting material (about 50 pieces of stone chippings) into a keyed cylinder tilted of 30° towards the horizontal side that is made rotate for 10.000 turns. At the end, is removed the dust produced through washing on a sieve of 2 mm. The result of the test is the *coefficient by Deval*, namely the percentage of dust compared to the initial weight of sample. The second test consists in inserting a specific predetermined quantity of granulometric mixture into a hollow cylinder, that has a prominence. Into the cylinder, there are some steel spheres according to the quantity of aggregate; cylinder is made rotate. At the end of the test, it is possible to measure the quantity of material that must pass through a sieve of 1.7 mm. Through this test, it is possible to measure the modification of the original granulometry, given to the chipping of material, both by friction between particles and by the impact against metal spheres. This test will be developed in the next chapters.

6.1.4. RESISTANCE TO ABRADIBILITY

Resistance to abradibility is measured through the *CPA test* (Coefficient de Polissage Accéléré). You must glue a layer of the material, that must be evacuate, on some metal laminas, that, then, are placed out of a metal wheel. This wheel is made rotate in very close contact with a pneumatic, thanks to the presence of water and of an abrasive mixture, composed of dust of emery and sand. After six hours, are extracted laminas and on the material, that is present on them, is done a test through the skid test. The division with the value obtained of the not treated sample, through the skid test, is the measure of abradibility of the mixture of inert tested. Through this test, it is possible to evaluate the reduction of microscopic roughness of material.

6.2. HIGHWAY STANDARDS FOR ITALY

6.2.1. FOUNDATION LAYER

Highways for Italy ("Autostrade per l'Italia") foresees several instructions starting from the foundation layer to choose the suitable materials for the creation of an unbound foundation layer.

"Highways for Italy" "Autostrade per l'Italia" defines the foundation as follows: "The foundation is made of a mix of granulometrically stabilized soils; the granular fraction of this mixture (kept in sieve UNI 2 mm) may be formed by gravels, crashed, quarry debris, wastes or other suitable materials as well. The foundation will be made of suitable filler material or made of materials that will have to be corrected with proper machinery in fixed mixing system or other systems".

The inerts used must be qualified according to directory 89/106/CEE on the building products. The inerts will have the following requirements:

- Aggregate does not have to be flattened, washy, lenticular or bigger than 71mm;
- Granulometry (standard UNI EN 933-1) must be included in the grading of the chart Table 1 below and it has to have a continuous and flat trend, practically accordant to those of the limit curves:

Table 1 Grain size grading per foundation layer

UNI EN 933-1	mm	Total Passing %
Sieve	40	95-100
Sieve	31.5	75-100
Sieve	16	53-80
Sieve	8	36-66
Sieve	6.3	31-61
Sieve	2	16-39
Sieve	0.5	8-23
Sieve	0.063	3-10

- The relation between the sieve passing UNI 0,075 mm and the sieve passing UNI 0,4 mm is lower than 2/3;
- Weight loss at Los Angeles test is lower than 30%;
- The equivalent of sand measured on the fraction under passing sieve UNI 0,2 mm is between 25-65;
- CBR lift index after four days of imbibition in water (carried on passing sieve UNI 25 mm) is not lower than 50.

After the lying of the layer it is evaluated the performance of the foundation through the assessment of the Real Dynamic Elastic Modulus that must be greater than or equal to the project value and anyway higher than 185 MPa.

6.2.2. SUB-BASE LAYER

Concerning the sub-base layer in cement mix the inerts will have to be qualified according to directive 89/106/CEE on the building products. Gravels and sands from cave or river can be used with an overall percentage of crushed, understood as inert that do not have any round face, from 30 to 60% of weight of the total inerts.

They must respect the following requirements:

- Aggregates not bigger than 40mm, neither flattened nor stretched, nor lenticular;
- Granulometry must be included in the grading of the chart (Table 2) below and it has to have a continuous and flat trend:

Table 2 Grain size grading per subbase layer

UNI EN 933-1	mm	Total passing percentage
Sieve	31.5	100-100
Sieve	20	70-87
Sieve	16	62-77
Sieve	10	46-61
Sieve	6.3	35-48
Sieve	4	28-40
Sieve	2	18-30
Sieve	0.5	9-19
Sieve	0,25	7-16
Sieve	0.063	5-10

- Weight loss at Los Angeles Test non higher than 30% in weight;
- Equivalent in sand between 30 and 60;
- Plasticity index equal to zero.

After the lying of the layer it is evaluated the performance of the sub-base layer through the assessment of the Real Dynamic Elastic Modulus that will be calculated through BACAN program.

6.2.3. BASE LAYER

“Highways for Italy” foresees a bound base layer of bitumen for flexible pavements and a cement mix for rigid pavement.

Inerts must be qualified according to Directive 89/106/CEE on building products. The Granulometry must be included in the grading of the chart Table 3 below.

Table 3 Grain size grading per bound base layer

UNI EN 933-1	mm	Total passing percentage
Sieve	63	100-100
Sieve	31,5	90-100
Sieve	20	71-98
Sieve	10	49-80
Sieve	6,3	39-69
Sieve	4	30-59
Sieve	2	120-40
Sieve	0.5	10-22
Sieve	0,25	7-17
Sieve	0,063	4-8

Inerts must meet the following requirements:

- Percentage of crushed in the inert mixture higher than 2mm greater than 65%;
- Percentage of crushed in the inert mixture lower than 2mm greater than 60%;
- Weight loss from Los Angeles Test lower than 30%;
- Sensitivity to frost (directive UNI EN 1097-2) lower than or equal to 2%;
- Coefficient of imbibition (directive CNR file IV/1953) lower than or equal to 0,015;
- Coefficient of shape (directive UNI EN 933-4) lower than or equal to 10;
- Coefficient of flattening (directive UNI EN 933-3) lower than or equal to 10;
- Equivalent in sand (directive UNI EN 933-8) must be higher than or equal to 70%.

6.3. MINISTRY OF INFRASTRUCTURE AND TRANSPORT– TECHNICAL STANDARDS OF PERFORMANCE

6.3.1. QUALIFICATION OF MATERIALS FOR ROAD EMBANKMENT

Natural dissolved materials may be result of decomposition of the formation of lands and stone rocks in the area where the project foresees the development of the solid road in trench, that is the mining of lent caves. The foundation of the infrastructure will have to guarantee the stability of the superstructure, the Deformation Modulus (called "compressibility" as well) Md, set on the laying base (reclaimed or natural) according to directory CNR 146/92, at the first loading cycle, in the range between 0,05÷0,15 N/mm^2 , it mustn't be lower than :

- 15 N/mm^2 (minimum value to allow the correct compaction of layers above) when distance from foundation to the support layer is higher than 2,00 m;
- 20 N/mm^2, when distance from foundation to support layer is included between 1,00 and 2,00 m;
- 30 N/mm^2, when distance from foundation to support layer is included between 0,50 and 1,00 m;

For distances lower than 0.50 m it is applied requirements for the sub-base.

6.3.2. FOUNDATION LAYER

The coarse aggregate could be made of elements obtained by the massive crush of rocks from cave or alluvial, from natural elements with sharp edge or rounded. Such elements could have different origin as long as requirements of the Table 4 are satisfied:

Table 4 Coarse aggregate characteristics

MAIN HIGHWAYS AND HIGHROADS			
Quality Indicators			Layer
Parameter	*Directive*	*Unit of measure*	Foundation
Los Angeles	UNI EN 1097/2	%	≤ 30
Micro Deval umida	CNR 109/85	%	-
Amount of crashed	-	%	≥ 60
Maximum dmension	UNI EN 933/1	*Mm*	63
Sensitivity to frost	CNR 80/80	%	≤ 20
(*) Not Suitable material save from exceptional cases			

Fine aggregate must be constituted by natural elements or crashed that have characteristics resumed in the Table 5.

Table 5 Characteristics of fine aggregate

MAIN HIGHWAYS AND HIGHROADS			
Passing Sieve UNI n. 5			
Quality Indicators			Layer
Parameter	*Directive*	Unit of measure	Foundation
Equivalent in sand	CNR 27/72	%	≥ 50
Plasticity Index	CNR-UNI 10014	%	N.P.
Liquid Limit	CNR-UNI 10014	%	≤ 25
Passing to 0.075	CNR 75/80	%	≤ 6

The mix of aggregates to be used for the granular mix must have a granular composition between the grading of the Table 6:

Table 6 Granulometry grading per Foundation Layer

Sieve series UNI		Passing (%)	
Sieve	70	100	-
Sieve	30	70 - 100	100
Sieve	15	-	70 - 100
Sieve	10	30 - 70	50 - 85
Sieve	5	23 - 55	35 - 65
Sieve	2	15 - 40	25 - 50
Sieve	0.4	8 - 25	15 - 30
Sieve	0.075	2 - 15	5 - 15

The CBR bearing ratio (CNR-UNI 10009) after four days of water imbibition (performed on passing sieve UNI 25 mm material) does not have to be lower than the value obtained for the pavement calculation and anyway not lower than 30. Therefore, it is required that this condition is evaluated in a range of ±2% according to optimum humidity of compaction.

The **resilient modulus (M_R)** of the mixture must be the one set in the pavement project and it is determined by applying the standard AASHTO T294 or another methodology suggested by the designer.

The **deformation modulus (M_d)** of the layer must be the one inserted in the pavement project and it is determined by applying the standard CNR 146/92.

The **reaction module (k)** of the layer must be the one inserted in the calculation of the pavement and it is determined by applying the standard CNR 92/83.

The different components, particularly the sands, must be without organic, soluble, friable and alterable materials at all.

6.3.3. SUB-BASE LAYER IN CEMENT MIX

The cement mix is made of a mixture of virgin stone aggregates (granular mix) processed with an hydraulic binder (cement). After an adequate time of seasoning, the mixture has to have a long-lasting mechanical resistance through the tests performed on specimens of given shape, also in the presence of water and ice.

The **coarse aggregate** must be made of elements obtained by the crushing of stone rocks, natural roundish elements, roundish crushed elements and natural sharpened elements. Such elements may have different petrographic origin as long as each type of them meets the requirements indicated in the Table 7:

Table 7 Characteristics of coarse aggregate

Parameter	*Standard*	*Unit of measure*	*Value*
Los Angeles	CNR 34/73	*%*	≤ 30
Amount of crushed	-	*%*	≥ 30
Maximum dimention	CNR 23/71	*mm*	40
Sensitivity to frost	CNR 80/80	*%*	≤ 30
Passing Sieve 0.075	CNR 75/80	*%*	≤ 1
Content of:			
- Rocks reacting with cement alkalis		*%*	≤ 1

The **fine aggregate** must be made of natural or crushed elements that have the following characteristics (Table 8):

Table 8 Characteristics of fine aggregate

Parameter	*Standard*	*Unit of measure*	*Value*
Equivalent in sand	CNR 27/72	*%*	≥ 30; ≤ 60
Liquid Limit	CNR-UNI 10014	*%*	≤ 25
Plasticity index	CNR-UNI 10014	*%*	NP
Content of:			
-Schistose, alterated, soft rocks	CNR 104/84	*%*	≤1
-Sulphatic or degradable rocks	CNR 104/84	*%*	≤1
- Rocks reacting with cement alkalis	CNR 104/84	*%*	≤1

The mix of aggregates (granular mix) to be used for the creation of the cement mix must have a granular composition according to the grading in the Table 9.

Table 9 Grading for the subbase layer in cement mix

UNI Sieve series		*Main Highways and Highroads*	*Secondary Highroadsand Urban Road*	*District urban and Local urbans Roads*
		Passing (%)		
Sieve	40	100	100	
Sieve	30	80 - 100	-	
Sieve	25	72 - 90	65 - 100	
Sieve	15	53 - 70	45 - 78	
Sieve	10	40 - 55	35 - 68	
Sieve	5	28 - 40	23 - 53	
Sieve	2	18 - 30	14 - 40	
Sieve	0.4	8 - 18	6 - 23	
Sieve	0.18	6 - 14	2 - 15	
Sieve	0.075	5 - 10	-	

6.3.4. BASE LAYER

The base layer of Italian Infrastructures is made of hot mix asphalt if the street is of flexible kind or it is made of concrete slabs if the street is of rigid kind. The characteristics of the aggregates to be used in this layer are therefore linked to resistance and adherence type expected either by the hot mix asphalt and by concrete.

6.3.4.1. Hot Mix Asphalt Base Layer

Characteristics required by the Hot mix Asphalt are resumed in the Table 10:

Table 10 Hot mix Asphalt Base Layer – Coarse Aggregate

MAIN HIGHWAYS AND HIGHROADS					
UNI n. 5 Sieve keeping					
Quality Indicators			Layers		
Parameter	*Standard*	*Unit of measure*	Base	Binder	Surfacing
Los Angeles (□)	CNR 34/73	*%*	≤ 25	≤ 25	≤ 20
Micro Deval humid (□)	CNR 109/85	*%*	≤ 20	≤ 20	≤ 15
Amount of crashed	-	*%*	≥ 90	≥ 90	100
Max Dimension	CNR 23/71	*mm*	40	30	20
Sensitivity to frost	CNR 80/80	*%*	≤ 30	≤ 30	≤ 30
Spogliamento	CNR 138/92	*%*	≤ 5	≤ 5	0
Passing at 0.075	CNR 75/80	*%*	≤ 1	≤ 1	≤ 1

Flakiness Index	CNR 95/84	%		≤ 25	≤ 20
Porosity	CNR 65/78	%		≤ 1,5	≤ 1,5
CLA	CNR 140/92	%			≥ 42
(□) One of the values of Los Angeles and Micro Deval Humid tests could be higher (up to two points) than the indicated limit as long as their sum is lower than or equal to the limit values indicated.					

The content of **fine aggregate** must be of natural and crushed elements.

According to the type of street, the fine aggregates for traditional hot mix asphalt must meet the requirements in the Table 11:

Table 11 Characteristics of fine aggregate for hot mix asphalt base layers

MAIN HIGHWAYS AND HIGHROADS					
UNI n. 5 Passing Sieve					
Quality Indicators			Layers		
Parameter	*Standard*	Unit of measure	Base	Binder	Surfacing
Sand Equivalent	CNR 27/72	%	≥ 50	≥ 60	≥ 80
Plasticity Index	CNR-UNI 10014	%	N.P.		
Liquid Limit	CNR-UNI 10014	%	≤ 25		
Passing at 0.075	CNR 75/80	%		≤ 2	≤ 2
Amount of crashed	CNR 109/85	%		≥ 50	≥ 70

The **filler**, passing sieve 0,075 mm, comes from the fine fraction of aggregates or it may be consisting of rock dust, preferably calcareous, from cement, hydrated lime, hydraulic lime, asphalt dust or flying ashes. Anyway it must meet the requirements resumed in the Table 12:

Table 12 Filler Characteristics

ALL ROADS			
Filler			
Quality Indicators			Layer
Parameter	*Standard*	Unit of measure	Base Binder Surfacing
Stripping	CNR 138/92	%	≤ 5
Passing to 0.18	CNR 23/71	%	100
Passing to 0.075	CNR 75/80	%	≥ 80
Plasticity Index	CNR-UNI 10014		N.P.
Rigden Gaps	CNR 123/88	%	30-45
Stiffening Power Relation filler/asphalt = 1,5	CNR 122/88	ΔPA	≥ 5

6.3.4.2. Concrete Base Layer

Aggregates are components of concrete characterized by entire or crushed stone elements. These stone elements may be artificial or natural and they are of proper size and shape for the making of the concrete. According to the category they are used in, aggregates must meet the basic characteristics foreseen by standard UNI 8520-97, prospectus 1, part 2.

7. ITALIAN PAVEMENT CLASSIFICATION

The Italian Highway Code sets out a rigorous classification of road types according to their technical and functional features. Roads are classified in different categories:

- **A =** a freeway is a dual carriageway with at least two lanes for each direction, paved shoulder on the right, no cross-traffic and no at-grade intersections. Speed Limit is 130 km/h
- **B =** a main inter-urban road is a dual carriageway with at least two lanes for each direction, paved shoulder on the right, no cross-traffic and no at-grade intersections. Speed Limit is 110 km/h.
- **C =** a secondary inter-urban road is a single carriageway road. Speed Limit is 90 km/h.
- **D =** a urban freeway is a dual carriageway urban road with sidewalk. Speed Limit is 70 km/h.
- **E =** a urban district road is a single carriageway urban road with sidewalk, this kind of road travels across an urban area. Speed Limit is 50 km/h.
- **F =** a local road is a urban road without sidewalk. Speed Limit is 50 km/h.

The Italian Regulations provided a pavement design catalogue that you can see in the Figure 11 and in the Figure 12 in function of:

- Resilient Modulus of Sub-grade;
- Number of commercial vehicles;
- Different Base: hot mix asphalt or cement mix.

Italian pavement is designed according to 120 kN axle allowing a maximum of 45 million vehicles in the heavy load lane.

In this research, I have studied the possible application of Inverted Pavement technique as Category A Freeways, for heavy traffic.

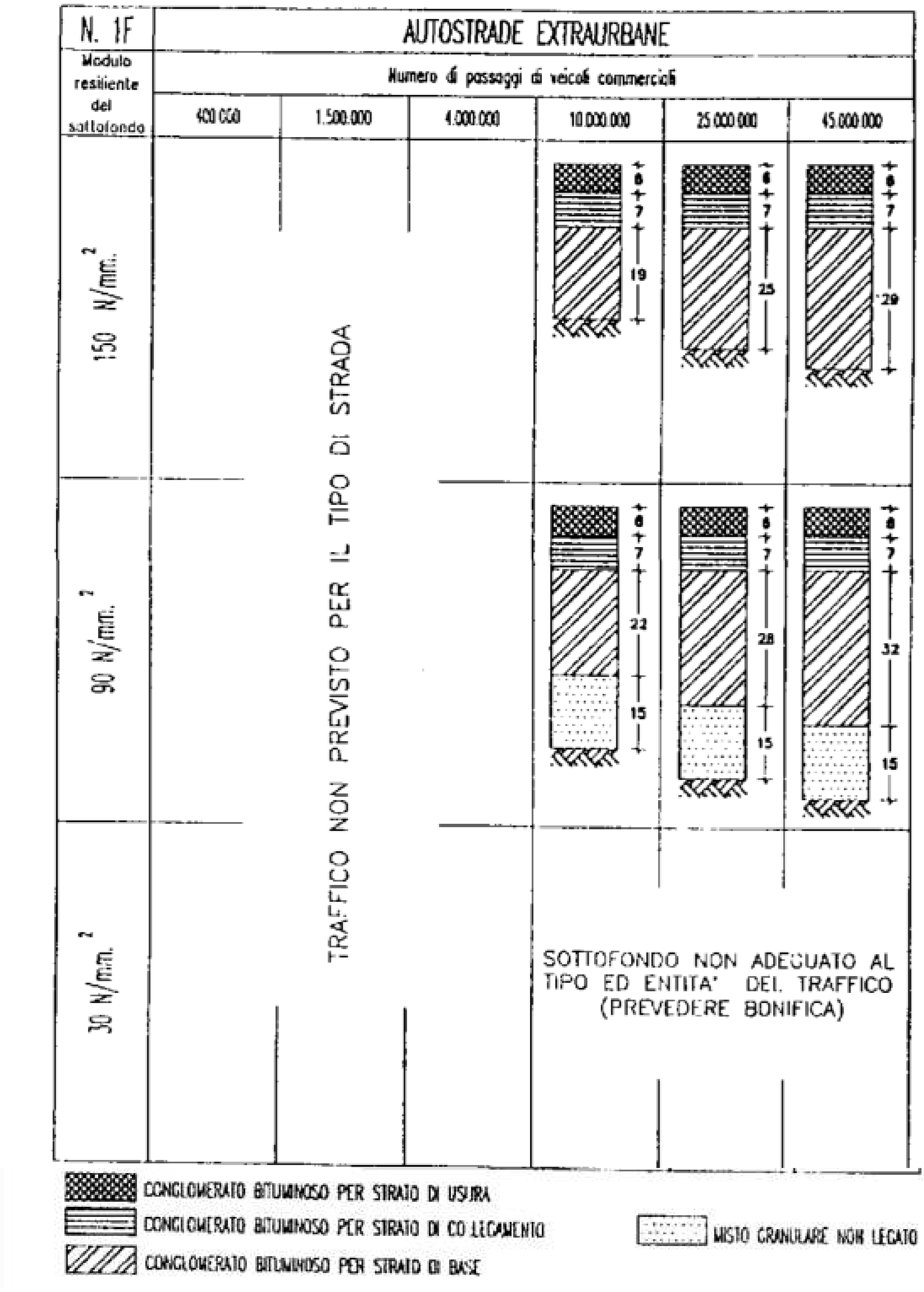


Figure 11 Italian Catalogue for Freeways with hot mix asphalt base layer. (CNR, 1995)

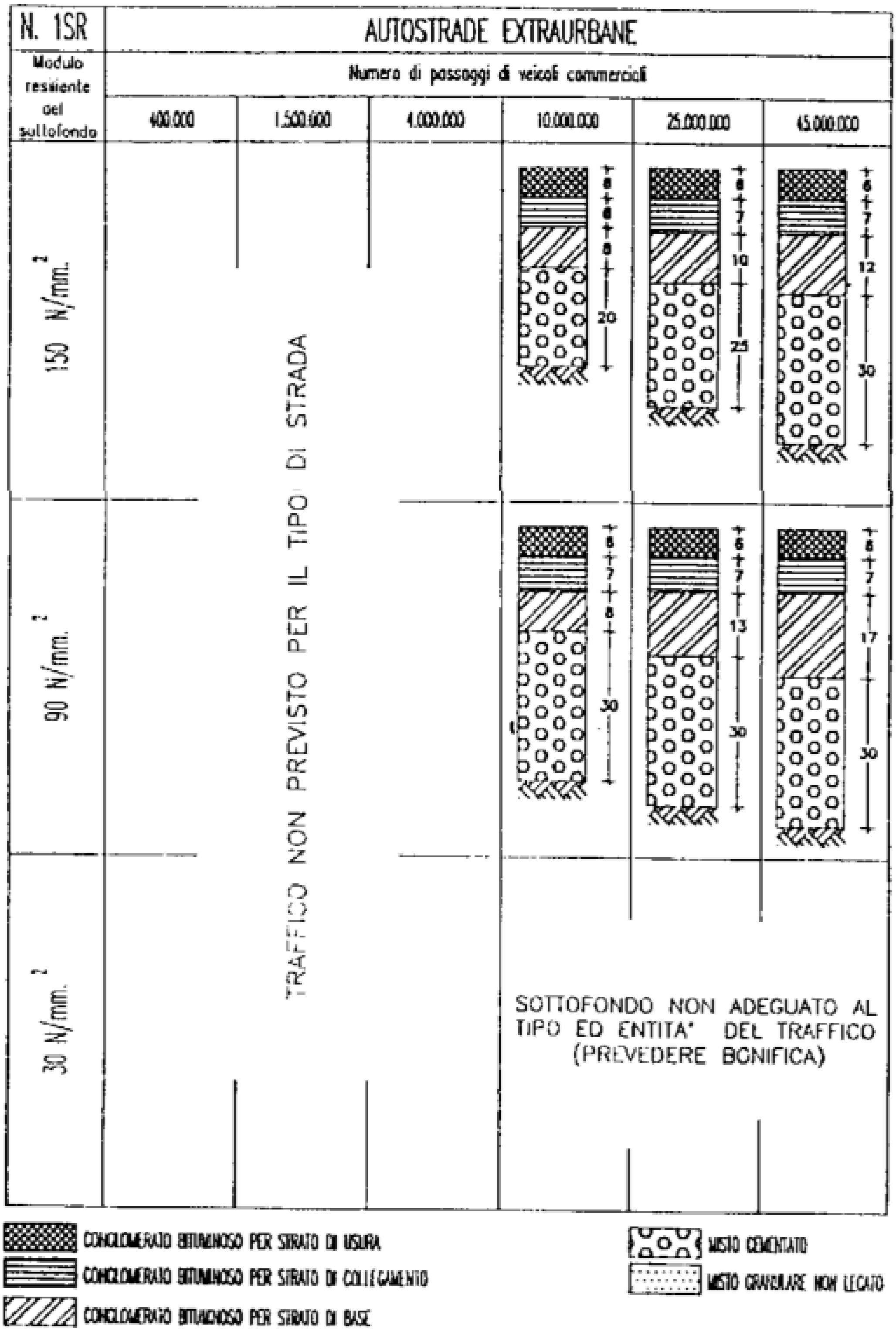


Figure 12 Italian Catalogue for Freeways with cement mix base layer.

The term flexible pavement is derived by the fact that the total pavement structure deflects, or flexes, under loading. A flexible pavement structure is typically composed of several layers of material. Each layer receives the loads from the above layer, spreads this load, then passes on these loads to the next layer below. The typical flexible pavement structure consisting of the surface course underlying base, foundation and sub-grade that are usually in situ aggregates. Each of these layers contributes to structural support and drainage. The surface course is the stiffest and contributes the most to pavement strength. The underlying layers are less stiff but are still important to pavement strength as well as drainage and frost protection. A typical structural design results in a series of layers that gradually decrease in material quality with depth (A. Montuschi, 2012). As you can see in the Figure 13 the Young's Modulus decrease from the top to the sub-grade, this is the section that I have compared with Inverted Base Pavement.

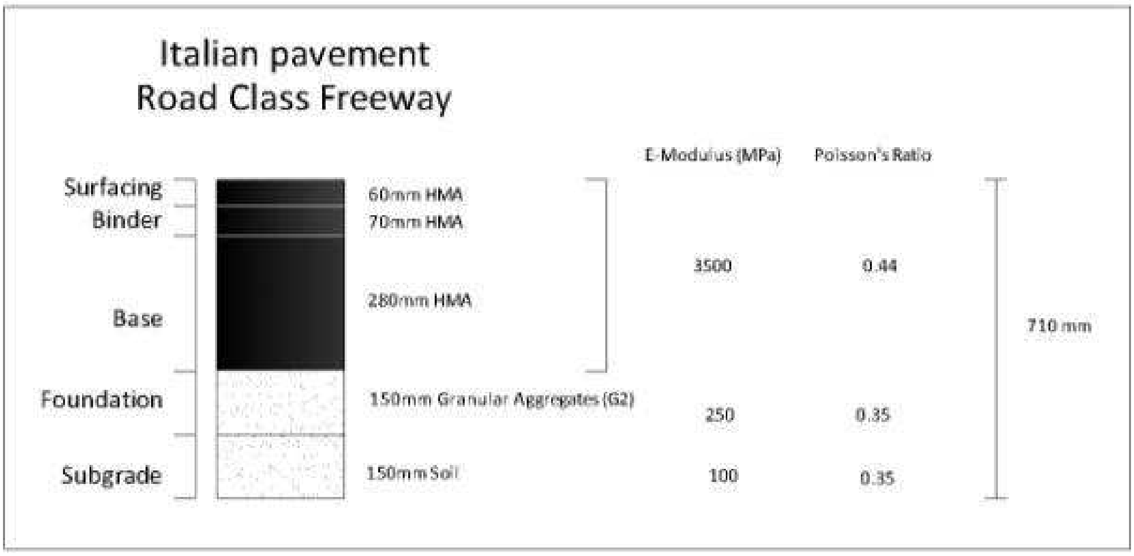


Figure 13 Italian Pavement Design for Road Class Freeway

8. SOUTH AFRICAN ROAD PAVEMENT CLASSIFICATION

South African road authority has a number of road categories to suit the different levels of service. Each road categories will necessitate certain geometrical and structural standards to ensure that the service objectives of the road can be met and maintained throughout its analysis period. Roads Categories are classified with a letter from A to D, as shown in the Table 13 from high performance to low performance. (DOT, 1996)

Table 13 South African Road Categories (DOT, 1996)

	ROAD CATEGORY			
	A	**B**	**C**	**D**
Description	Major interurban Freeways and major rural roads	Interurban collectors and rural roads	Lightly trafficked rural roads, strategic roads	Rural access roads
Importance	Very important	important	Less important	Less important
Service Level	Very high level service	High level of service	Moderate level of service	Moderate to low level of service

In South Africa the standard axle load is 80 kN. However, the legally permissible axle load is 88 kN (DOT, 1996)

In the Pavement Design Catalogue, pavements are divided into ten different classes, namely ES0.003 to ES100, covering extremely light traffic to extremely heavy traffic. There are a different catalogue in function of climate conditions, in particular there are three climatic regions: dry region, moderate regions and wet regions; and also in function of kind of base layer that could be: granular aggregates, hot mix asphalt base and cemented base. I am interesting in granular base layer and in the Figure 14 and in the Figure 15 I have reported the inverted pavement catalogue.

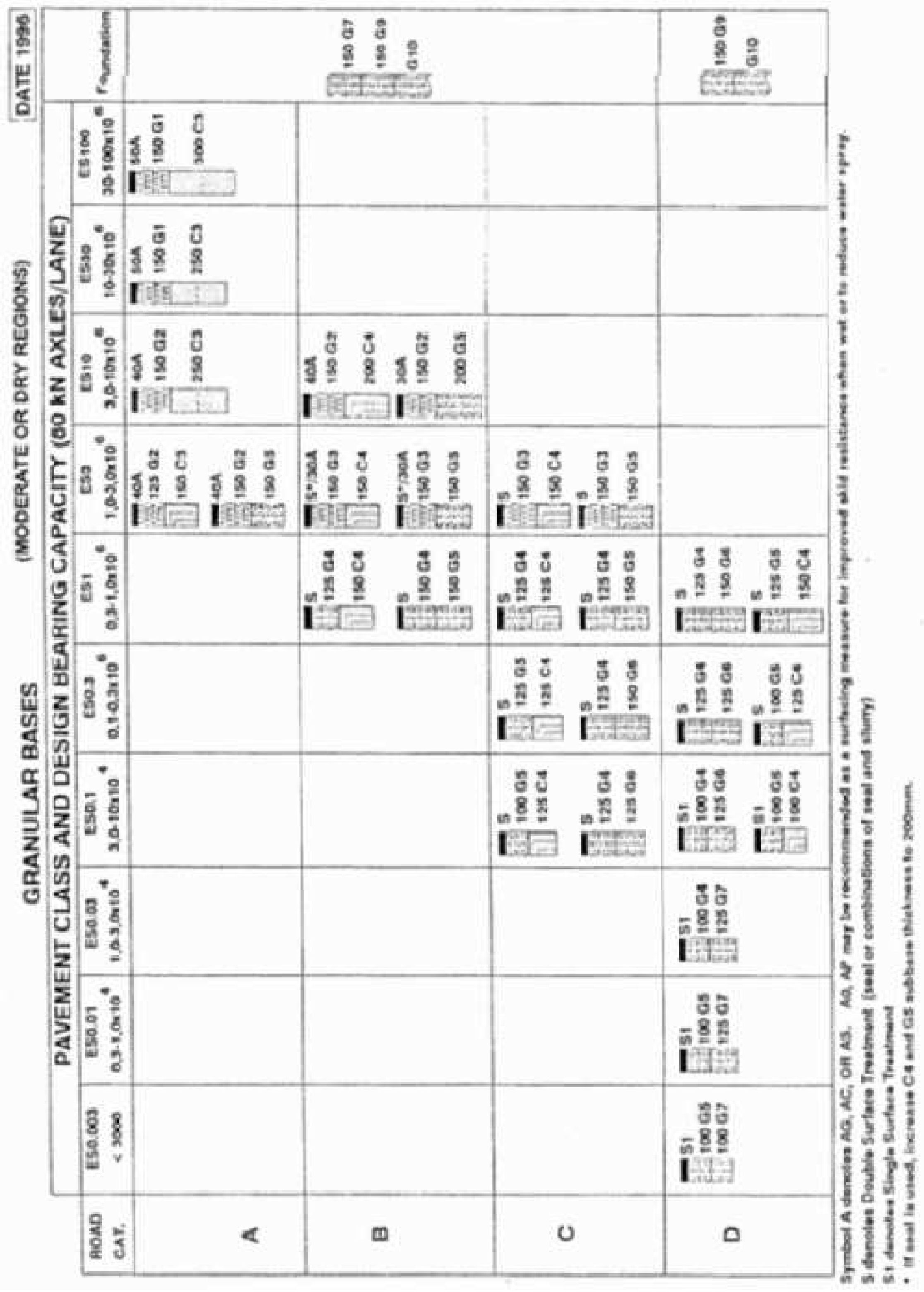
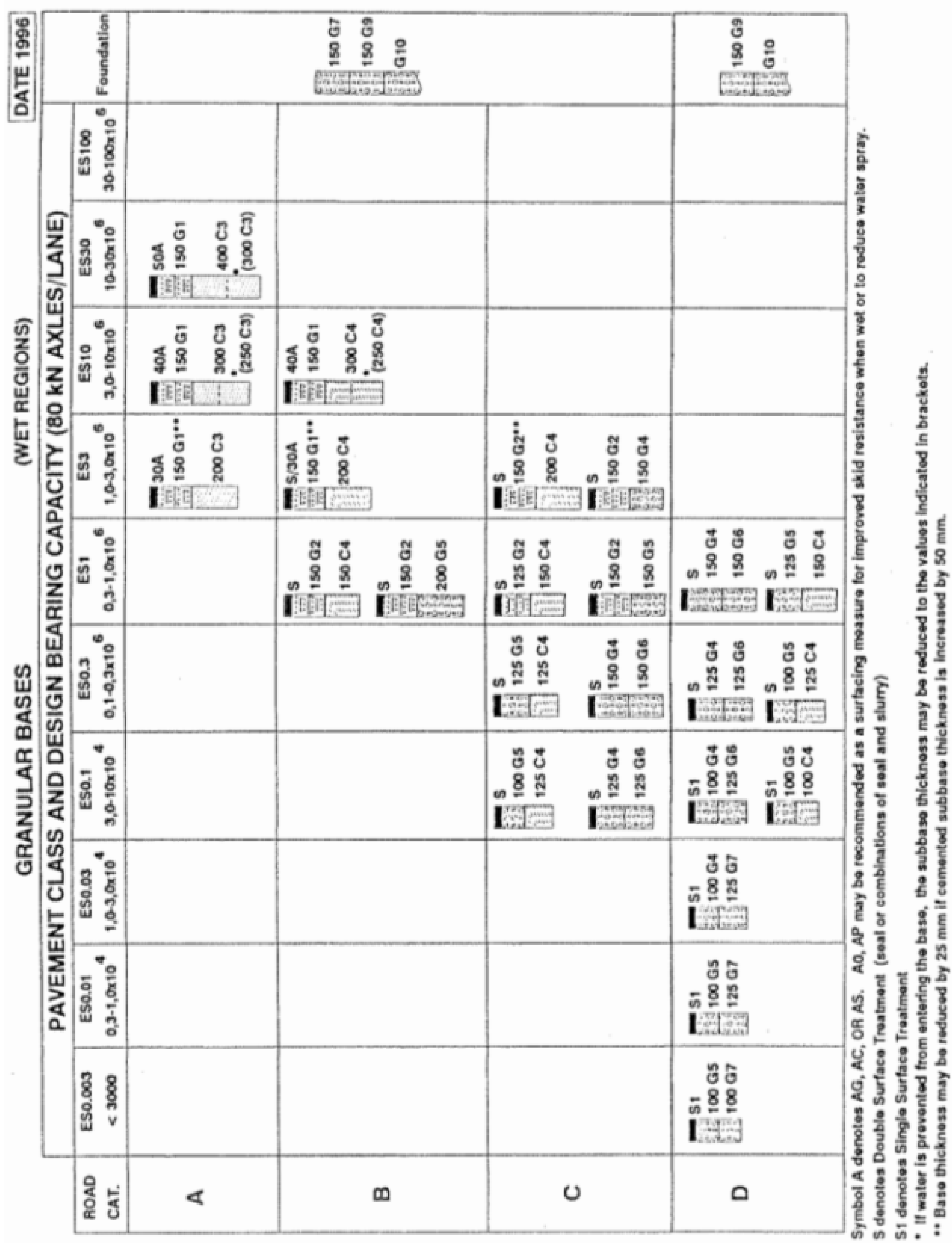


Figure 14 Structural Design for flexible pavement in moderate and dry region



GRANULAR BASES (WET REGIONS) DATE 1996

PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)

ROAD CAT.	ES0.003 < 3000	ES0.01 0,3-1,0x10^4	ES0.03 1,0-3,0x10^4	ES0.1 3,0-10x10^4	ES0.3 0,1-0,3x10^6	ES1 0,3-1,0x10^6	ES3 1,0-3,0x10^6	ES10 3,0-10x10^6	ES30 10-30x10^6	ES100 30-100x10^6	Foundation
A							30A 150 G1** 200 C3	40A 150 G1 300 C3 * (250 C3)	50A 150 G1 400 C3 * (300 C3)		150 G7 150 G9 G10
B						S 150 G2 150 C4 S 150 G2 200 G5	S/30A 150 G1** 200 C4	40A 150 G1 300 C4 * (250 C4)			
C				S 100 G5 125 C4 S 125 G4 125 G6	S 125 G5 125 C4 S 150 G4 150 G6	S 125 G2 150 C4 S 150 G2 150 G5	S 150 G2** 200 C4 S 150 G2 150 G4				
D	S1 100 G5 100 G7	S1 100 G5 125 G7	S1 100 G4 125 G7	S1 100 G4 125 G6 S1 100 G5 100 C4	S 125 G4 125 G6 S 100 G5 125 C4	S 150 G4 150 G6 S 125 G5 150 C4					150 G9 G10

Symbol A denotes AG, AC, OR AS. A0, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray.

S denotes Double Surface Treatment (seal or combinations of seal and slurry)

S1 denotes Single Surface Treatment

* If water is prevented from entering the base, the subbase thickness may be reduced to the values indicated in brackets.

** Base thickness may be reduced by 25 mm if cemented subbase thickness is increased by 50 mm.

Figure 15 Structural Design for flexible pavement for wet region

As you can see in the Figure 14 and in the Figure 15 it is possible to use inverted pavement technique for different road category and for different entity of traffic.

In this research, I have focused the attention just on road freeways classified into category A and in particular for heavy traffic class ES30, and I have analyzed the catalogue for dry region. This kind of structure are design for 25 years useful life. In the Figure 16 I have reported the pavement design that I have considered.

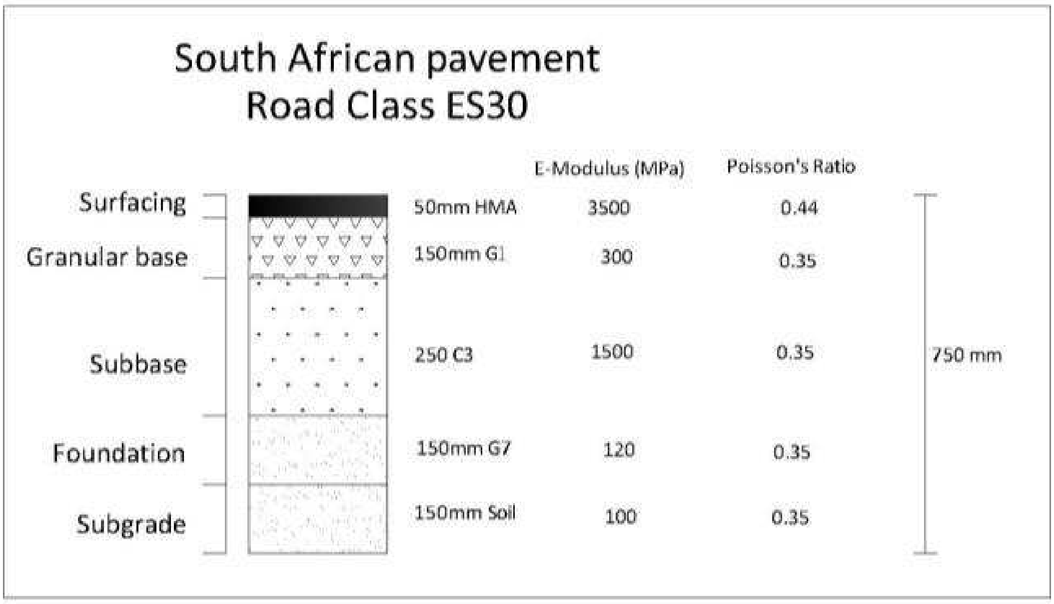


Figure 16 South African Design for Freeways in Dry Region with traffic category ES30.

9. LITERATURE REVIEW

9.1. SOUTH AFRICAN EXPERIENCE

Inverted Pavement systems represent an innovative pavement technology developed in South Africa in the 1970. The motivation behind expanding the use of inverted pavement system is more than initial cost savings, although that is crucial in these economic times. Doing more with less also means using designs which have reduced life cycle cost and which are sustainable. (Buchanan, 2010) Pavements in developing countries do have only thin asphalt surfacing, and as a consequence the granular base and sub-base layers provide the bulk of the bearing capacity.

During '80s and '90s pavements have been tested with the Heavy Vehicle Simulator that has allowed us to better study the behavior of the pavement at higher cycles load (Jooste & Sampson, July 2005). The effectiveness of this construction technique is largely entrusted to the bearing capacity of the base layer made of mixed granular unbound. Road Infrastructure made according to the technique of the Inverted Pavement, which provides a foundation in mixed concrete, a base layer of high stiffness and load-bearing capacity, put in work with super- compaction techniques and a final layer of hot mix asphalt very thin. In the Figure 17 it is possible to observe a pattern of paving made with the technique of the Inverted Pavement.

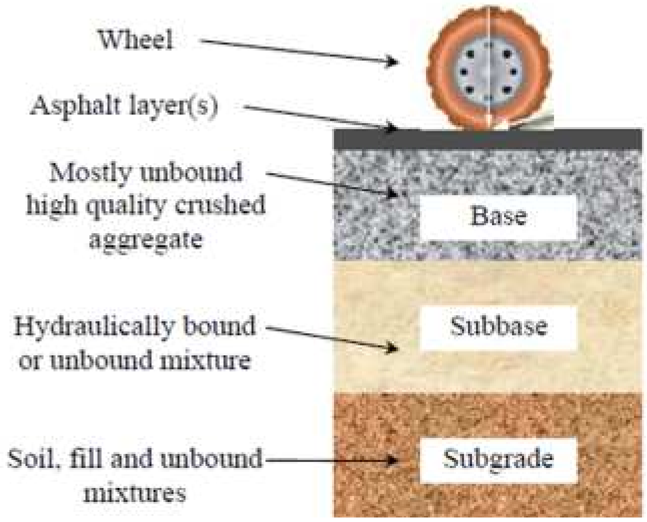


Figure 17 Inverted Pavement Design (Araya, 2011)

It is apparent from the Figure 17 the reduced thickness of the asphalt layer, which varies between 3 and 5 cm. This layer is not entrusted any load capacity. Inverted base pavements with thin asphalt layers were found to be particularly susceptible to shear loading at the pavement surface due to the high tensile strains in the asphalt layer. (Santamarina & Papadopoulus, 2014)

While the base layer in granular mix of high quality, has a thickness of 15 cm and has the job of distributing the loads to the underlying layers. The high stiffness and durability of the base layer of the infrastructure is obtained thanks to the use of a rock, which Dolerite with excellent physical-mechanical performance (Kleyn & Bergh, 2008). This technique allows to reduce the costs related to the thickness of the layers with hot mix asphalt, South Africa has reported a 20-25% cost savings compared with conventional hot mix asphalt pavements, that in our country are of the order of 15-20 cm, but it is particularly important the fact that the granular mixture that we will use are granites by-products deriving from stockpile at the extraction sites of stone material for ornamental use, therefore, you should reduce the extraction of virgin rock, thereby conserving our landscapes.

9.2. CONSTRUCTION PROCEDURES OF INVERTED PAVEMENT BASE LAYER

An inverted base pavement is a pavement structure that consists of an unbound aggregate base between a stiff cement-treated foundation layer and a thin asphalt cover.

Constructing a G1 Crushed Stone base layer is a very exacting process and the specifications must be stringently applied if it is to perform as expected and be a cost-effective option. The major expert of Inverted Pavement Technique in South Africa is Edward Kleyn. He have studied and monitored the realization process for years and he has reported a step by step process:

Step 1: The importance of accepting only in-specification G1 material on site cannot be over-stressed – it can mean the difference between getting the job done cost-effectively and going bankrupt. Inspect the target grading from the crusher for compliance with the specification for the project (or COLTO) before ordering. Suggest and negotiate corrections to the crushing plant manager timely before ordering. Inspect each batch of crushed material delivered for compliance with the target grading and other specifications agreed upon, before acceptance. Stockpile the material from the crusher onto a prepared site from which it can be reloaded without the danger of being contaminated/degraded, or stockpile it directly onto the road.

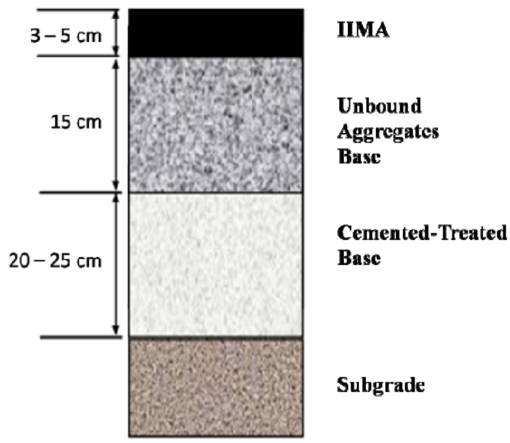


Figure 18 Inverted Pavement Structure

Step 2: Provide a clean, dampened and well stabilized and leveled subbase as anvil upon which to construct the G1 basecourse – keeping in mind that a G1 layer requires copious amounts of water and high compaction energy to compact and interlock. A poorly leveled and rough subbase surface will encourage segregation of the aggregate during placing of the material and affect the slush-interlocking process adversely, even to the point of impossibility. Note: It is strongly recommended that a G1 test section, prepared similarly to the pavement under construction, be laid to familiarize one with the material from and the most suitable compaction process for, the particular crusher/rock source and ultimately to demonstrate competence.

Step 3: Calculate the spacing of the truck loads to be stockpiled in the middle of the road on the subbase according to the truck load volume to achieve the compacted layer thickness. Avoid using varying truck sizes, which will cause varying dump spacing and material movement which may cause aggregate segregation and layer thickness variation. If possible have the aggregate being transported damp to inhibit segregation during loading, transportation and dumping. Do not hose it down with a stream of water, either in the main stockpile or on the truck, since this will certainly cause segregation of the fines and lengthen the on-site mixing process and/or complicate the final slush-compaction process. Just dampen the material enough to cause the fines to adhere to the larger aggregate. Visually inspect the material for obvious grading non-conformity and deleterious content.

Step 4: Moisten the stockpiled aggregate again one day prior (at least 12 hours) to constructing the layer, if it has dried out in the mean time, once more taking care not to induce segregation of the fines. This is done by only slightly flattening the aggregate dumps with a motor grader such that a watering truck can just drive over the dumps at crawling speed to moisten the material to below, but as close as possible to, optimum moisture content (OMC). Check visually that the fines are not washed off from the larger aggregate.

Step 5: Spreading of the damp material on the day of construction is done with a motor grader by gently taking successive fully laden blade-sized loads off the stockpiles on the subbase across the full width of the available subbase. The material must not be disturbed unnecessarily – rather place it in close proximity to the stockpile from which it was cut. Do not storm into the dump and try to flatten it in one fell swoop. This will only succeed in segregating the material. If the spread material appears to be too dry it may be moistened and mixed-in to the full depth of the layer and with the grader blade sweeping the surface of the subbase. (Do not use a disc harrow for this purpose since it will tend to segregate the material as well as damage the subbase.) If the material starts deforming under compaction, it usually is too wet. Let it dry out sufficiently before continuing. If the moisture content is just right, the material may be placed as soon as possible. This is done at an even pace (≈ 8km/hr) to the correct thickness, allowing for a bulking factor of 1,4 to 1,5, as well as a small windrow of material on one side of the road for unforeseen layer thickness correction purposes.

Note: The OMC of G1 material usually lies between 4% and 6%. A very low OMC indicates a lack of fines in the mix, which means that the final slush-compaction process will be difficult to accomplish, whereas a very high OMC indicates excessive fines, which will lengthen the slush-compaction process because of the additional fines that will have to be extracted to achieve proper interlock. (Keep in mind that the OMC of a material is roller/compaction equipment sensitive.)

Step 6: The layer can now be shaped according to the specification by motor grader. Depressions may be corrected by mixing in additional material. If the shortage of material occurs over a short distance (< 15m), Crushed Stone material may be spread on the area with the ripper teeth of a motor grader and mixed in thoroughly. If the depression is longer than about 15m it is advisable to remix all the material over a distance of at least 100m after the additional material has been added. Excess material may be removed similarly. Be careful not to contaminate the G1 material with the shoulder material where it consists of normal gravel. All layer thickness corrections must be done in this phase, before any compaction is done.

Step 7: The compaction process must start as soon as the layer thickness and shape is to specification. To avoid rolling the layer out of shape, always initiate the process with the first pass on the outer edge of the layer and move successively with each pass towards the centre line or highest point of the cross section. When initiating the compaction process with a vibratory roller, do the first pass in “static” mode. This can be followed by two passes with the vibration at relatively low frequency and high amplitude at a speed of 3 to 4 km/hour.

Step 8: Do any layer/shape corrections at this point before it is too firmly compacted. Initiate the first cut at the windrow on the side of the road and always with the grader blade fully laden with the graded material. The layer must be shaped again to specification. Apply the vibratory roller (Figure 19) again for two passes at a speed of 4 to 6 km/hour, but this time at a relatively high frequency and low amplitude. Hereafter, the layer should have the correct elevation/thickness and shape and be stable enough to receive its final “windrow fines distribution cut”, if necessary. A visually even, well-graded, appearance will enhance the slushing process.

Figure 19 Vibratory Roller

Step 9: The layer should now be rolled with a heavy pneumatic-tired roller (upwards of 17 m ton) in combination with heavy static steel-tired rollers, shown in the Figure 20 and in the Figure 21 . Ensure that the moisture content is correct for the equipment used. It is important to lead with the driven wheel/s of the roller, especially initially, to avoid the formation of a compaction negating “bow wave” of material in front of the roller-drum.

Figure 20 Heavy Pneumatic-Tired Roller

Figure 21 Steel-Tired Rollers

Step 10: Rolling must continue until the layer exhibits no (or very little) movement under the wheels of a heavy roller, before the slushing process may begin. At this stage the density of the G1 material should be in the order of 85% of SRD/ARD. If the slushing process is started too early the layer will become unstable and even expel the larger (sandy) fines, which will further complicate and delay the slushing process.

Step 11: The slushing process can commence immediately when the layer is stable enough, or delayed for a day or two to dry out and regain stability. However, do not let the layer dry out unnecessarily before starting with the slushing since this might delay the onset of the actual slushing action itself. Basically the slushing process is initiated by thoroughly wetting and rolling 40 to 60m sections of the layer at a time (depending on the number of rollers available) with heavy static rollers. The water must be applied at the highest points of the cross section or gradient and utilized as it runs down to the lower points. Keep in mind that using relatively light rollers can result in only the upper part of the layer being properly slushed. The fines (< 0.075 mm!) expelled must be broomed to areas deficient in fines, and eventually off the road. Finally all slush-fines must be removed from the road with heavy duty hand brooms or light mechanical brooms before it dries out and hardens to a crust. Take care not to overdo the brooming and so loosen/destroy the aggregate mosaic.

Step 12: If one keeps in mind what the slushing action is supposed to accomplish it will not be difficult to monitor the process and observe when the goal has been achieved. Hence, look out for the following indicators:

- Slight movement of the layer under the rollers might be observed at the onset but should decrease and stop as soon as the air bubbles and fines start being expelled.
- Observe that air bubbles will appear on the surface as soon as the slushing process takes hold – indicating that the aggregate is being moved closer together, expelling the air from the voids in the matrix. This phenomenon will cease during the final stages of the slushing process. As you can see in the Figure 22:

Figure 22 Fines appearing on the surface

- Similarly, observe that fines (creamy in nature) will start appearing on the surface and should be broomed to the side of the road or to coarser areas. Keep just enough slush on the road to assist with the slushing process. A sign that the slushing process has been completed and should be stopped is when the slush being expelled clears up until it is mainly water. If this indicator is ignored, sandy textured fines (the fraction above the minus 0.075mm) usually starts being expelled.

As the aggregate becomes more interlocked the surface will increasingly exhibit a densely knitted aggregate mosaic with a minimum of fines being visible in between particles.

Step 13: After the above has been done the layer should be allowed to dry out somewhat for about 12 hours and no traffic should be allowed on it. The layer can then receive its final "dry roll" to bed the surface aggregate even better since, although not visible, the aggregate particles will be slightly raised because of the excess water around and under the aggregate which should now have evaporated.

Step 14: Density/quality control should be done within 24 hours when the material is still damp (moisture content of about 50% OMC in the upper portion of the layer) and the possibility of disturbance minimized. COLTO adopted density control by nuclear apparatus, mainly because the possibility of disturbing the compacted aggregate matrix is less than when excavating a sand replacement hole. This is a moot point since both have their pros and cons.

(It delivers an “indicator” with which to “engineer”, pretty much the same as any other material specification and quality control measure (Kleyn, Successful G1 Crushed Stone BaseCourse Construction, 2012).
At the base of the success of Inverted Pavement there are some qualities of stone materials that were used and sediment and compaction techniques.

9.2.1. COMPACTION TECHNIQUE DEVELOPMENT

Compaction of soils has been used for as long as mankind had the need to improve the properties of the soil. Properties such as strength and bearing capacity increase with compaction, while the compressibility and permeability reduce. The earliest road builders did not understand the principles of modern day soil mechanics; instinctively they applied mechanical compaction to improve the properties of soils to be used for road construction purposes. In this regard, compaction, through history, has proven to be one of the key processes in road construction. (L. J. Ebels, 2004)
From the turn of the 19^{th} century the developments in compaction equipment accelerated. Below a brief summary of the important developments is given (Schwartz, 1984):

- By 1920 the sheepfoot roller, shown in the Figure 23, had been developed to a size, which is now termed ‘light’. The mass was in the range of between 6,000 and 10,000 lbs (2.7 - 4.5 ton) and footprint pressure in the range of 60 to 100 psi (414 - 690 kPa);

Figure 23 Sheepfoot Roller

- By the late 1920's, the flat wheel steamrollers, shown in the Figure 24, had been converted to internal combustion engines and had reached masses of up to 30 tons;

Figure 24 Flat Wheel Steamrollers

- During the 1930s small rubber tired roller of 6 to 8 tons, often called the wobble wheel roller (Figure 25), came into use for compacting thin layers of base course and for smoothing and knitting the surfaces of compacted layers;

Figure 25 Wobble Wheel Roller

- The present day 'heavy' sheepfoot rollers were developed in the 1930s for the highway and earth dam construction. The roller had a mass of up to 30,000 lbs (13.6 tons) and could be used at footprint pressures of 300 to 600 psi (2070 to 4140 kPa). Subsequent developments in sheepfoot rollers have been concerned more with the shape of the foot and mechanical developments rather than the size of the roller;

- Compaction by vibratory and dynamic techniques was developed in Germany during the 1930s. A self-propelled caterpillar type vibrating plate compactor with a total mass of 25 tons was developed as early as 1933. The developments in Germany produced the so-called ‘frog’ tamper just before World War II;
- During the Second World War the technology required for airfield pavements resulted in the development of ‘heavy’ compaction equipment. During 1943-1944 the U.S. Army Corps of Engineers developed several rubber tired rollers equipped with 24 tires capable of being loaded up to 100 tons;
- The first self-propelled and tractor towed vibratory rollers were constructed during the 1940s. Since the Second World War the most significant development has been in the field of vibratory compaction. At present vibrating rollers feature very prominent in road construction and they are very effective in producing high density pavement layers.

The development of devices and techniques of compaction carries on still today, because it is one of the most important factors for the establishment of pavements performances. Depending on the ease through which it is possible to produce the raw material in a mine, the cost for compaction is about 10% of the total cost of the material used for the base layer, that includes provision of granular mixture in a construction site, chipping, transportation and machineries for working. The increase, of about 10%, in the costs for the realization of layer, compensates considerably the framework in terms of increase of resistance to break and of increase of useful life. A pioneering work in the mechanic of lands happened during 1930s through the introduction of the *CBR test*, the *Proctor test*, and then of the *AASHO test*, that gave information about the real increase of the resistance of not alloyed materials, after the compaction process. Proctor, a field engineer for the Bureau of Waterworks and Supply in Los Angeles in California, conducted a research into the relationships between density of soil, the compaction energy and the moisture content. Proctor published a series of four articles in the Engineering News Record concerning soil compaction in 1933. In these articles he introduced his so-called Proctor curve, the relation between moisture content and maximum dry density, which formed the basis of the Bureau’s compaction control procedures and which is still in use today. Due to the simplicity of the equipment and procedure the Proctor test became widely used. The American Association of State Highway Officials (AASHO) adopted the Proctor test and redefined it as the ‘AASHO standard laboratory method of test for the compaction and density of soil’ in their Standard Specification published in 1942. Another very important milestone in understanding the behavior of soils was the development of the triaxial test by Casagrande, also during the early 1930s. This test was developed to assess the shear strength of soils more accurately.

The effect of compaction on the bearing capacity of a granular material is clearly shown in the Figure 26 by the relationship between the CBR and the density to which the material is compacted:

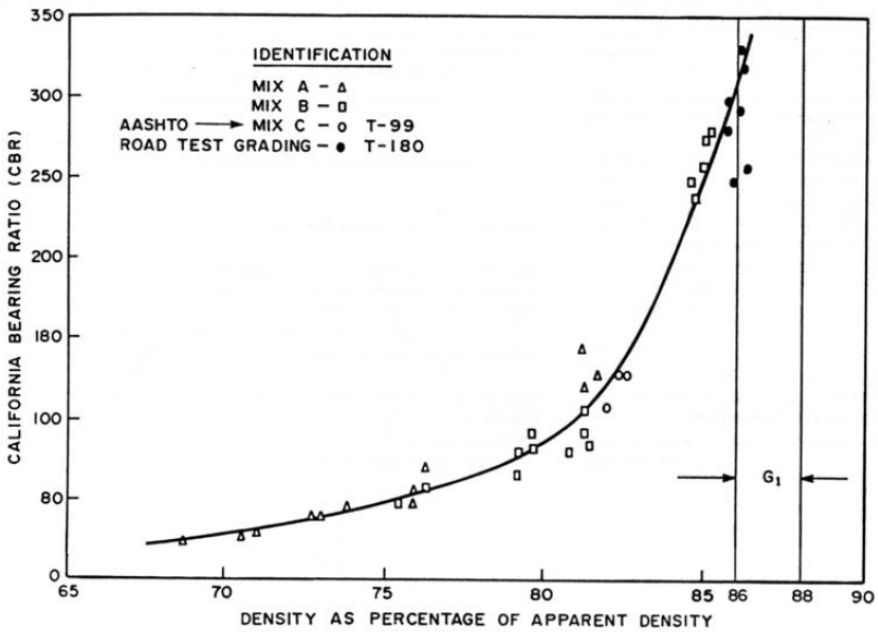


Figure 26 CBR vs. density of G1 crushed stone (Semmelink, 1988)

It is important to note that for crushed stone the increase in shear strength as indicated by the CBR test is more rapid as the maximum achievable density is approached.

The G1 crushed stone base layer is probably one of the vital layers in modern day high quality pavements in South Africa. (L. J. Ebels, 2004)

The effect and the entity of compaction must not be underestimated, because, with quite low costs, compaction increases the bearing capability of layer, increasing very much the useful life of superstructure.

9.3. MORGAN COUNTY TEST SECTION

In the spring of 1999, Georgia Department Of Transport (GDOT) engineers became familiar with IP technology while attending an international transportation symposium in South Africa and this experience was followed by the construction of 244 meters of an Inverted Pavement test section at the Lafarge Morgan County (E.L. Dwane, 2012).

Based on the success of the Morgan County Project, and due to the rising cost of asphalt cement, in 2008 Georgia Department Of Transport decided to fund and build its own Inverted Pavement test section on the South LaGrange Loop in Troup County. This project, hereafter referred to as the LaGrange Bypass Project.

The road test section was constructed at a quarry owned by Lafarge North America in Morgan County, in Georgia, 60 miles east of Atlanta. The road test section contains the following sections:

- first section: 300 meters of traditional haul road; prepared sub-grade with minimum CBR of 5.1 cm of Granular Aggregate sub-base, 15.2 cm of surge stone, 20.3 cm Granular Aggregate Base, and topped with 7.6 cm of HMA;
- second section: 400-ft (120-m) length of inverted pavement with a South African base; prepared sub-grade 5,1 cm of unbound granular aggregates; 20,3 cm of granular aggregates with 4% to 5% cement by volume; 15,2 cm of unbound granular aggregates base and 7,6 cm of hot mix asphalt;
- third section: 400-ft length of inverted pavement with a Georgia base; prepared sub-grade 5,1 cm of unbound granular aggregates; 20,3 cm of granular aggregates with 4% to 5% cement by volume; 15,2 cm of unbound granular aggregates base and 7,6 cm of hot mix asphalt;

The only difference between the South African Section and Georgia Section is the slushing process that was used just in south African section (R.G. Terrel, 2002). The material used in the UAB layer for all three sections is classified by the GDOT 1993 Specifications as Group II - slag, gravel, granitic and gneissic rocks, quartzite, synthetic aggregate, or any combination thereof. In the Figure 27 we can see the design of Inverted Pavement test section.

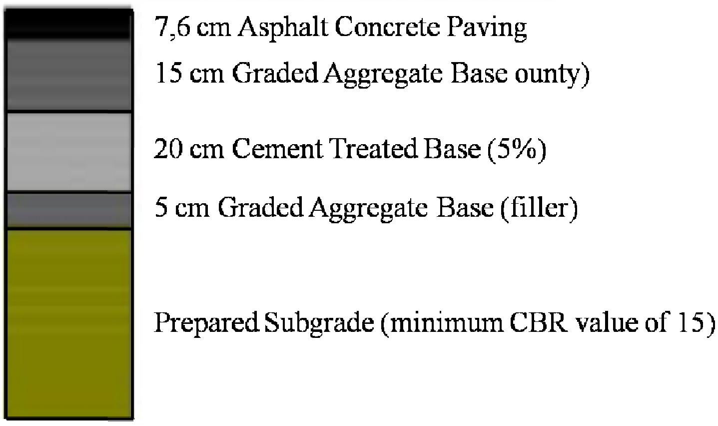


Figure 27 Morgan County Inverted Pavement Test Section

Actually the test section is not really conform to South African road catalogue, in fact in Morgan County test section the HMA layer is more than five centimeters.

After 13 years the total ESAL's per one month are 1.255.733,10. Rutting measurements were made in 2003 and 2006 for each section. The rutting observed in the two inverted pavement sections was insignificant; however, minor and major rutting was found within the conventional section. Annual inspections continue to perform well with no rutting or cracking being observed (E.L. Dwane, 2012).

It was found that the Georgia section was as good as the South African section, but that the traditional section was the stiffest.

9.4. LAGRANGE TEST SECTION

A full-scale field study was conducted in LaGrange, Georgia. The laboratory and field studies conducted as part of this project advance both the current state of knowledge on the behavior of inverted base pavement systems and the state of the practice in terms of construction processes and quality assurance. The test section build in 2009 is part of an industrial parkway intended to serve the growing car manufacturing industry in south-west Georgia. The inverted base pavement test section is a two-lane 1036 meters long stretch of the south LaGrange loop. The inverted base pavement was designed as you can see in the Figure 28 using empirical guidelines from the South African experience. The sub-base mix contained 4% cement by weight and was compacted to 98% of Proctor (Cortes, 2010). The aggregate used for base layer is granite.

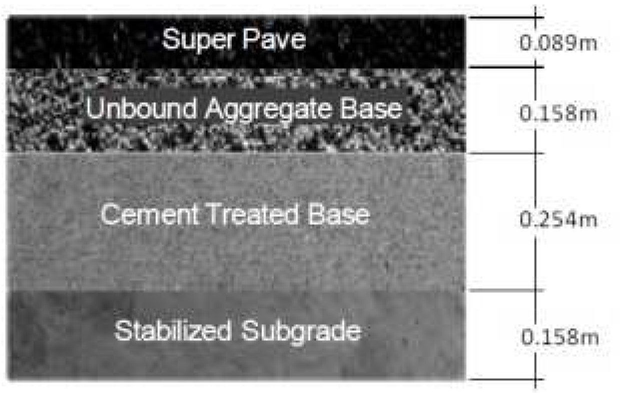


Figure 28 LaGrange Inverted Pavement Design

Also in this test section the HMA layer is 8,9 cm against 5 cm of South African Catalogue.

10. MATERIALS

The geology of base course aggregates is an important aspect which can influence the performance of aggregates in pavement and the engineering properties of aggregates can be assessed if the type of the source rock is known as the rocks are classified based on their mineralogy, grain size, and texture. The type of the rock along with a petrographic description provides a sound foundation to judge the engineering properties of the source rocks. The type of the source rocks can be identified by the microscopic investigation of the rock by making thin sections. (Higgins, 2000) Thin sections can be inspected under the electron microscope to identify various types of minerals present in the rock. The strength of aggregates is dependent on the shape of grains, arrangement of grains, and the cementitious nature of the abundant mineral found in the matrix of the aggregate. The Inverted Pavement was developed in South Africa in 1970 and the material used to build up the structure is Dolerite.

10.1. DOLERITE MINERALOGY

Dolerite is one of the most abundant natural rocks, available in South Africa, used to build up road infrastructure. Doleritic intrusions in Natal and adjoining areas of South Africa are very numerous, and are associated with the break-up of Gondwana which took place some 187 to 155 million years ago. These dolerites (Figure 29) generally possessed high or very high strength and densities, and corresponding low or very low porosities. (F.G. Bell, 1998) Dolerite is a basic crystalline igneous rock that essentially minerals are plagioclase feldspar and pyroxene, which together constitute between about 60% and 80% of the total rock composition. The accessory minerals are quartz, orthoclase, chlorite and magnetite. Quartz, orthoclase and chlorite may comprise 20% to 40% of the rock while the magnetite composition may be 2% to 3%. (Leaman, 1973)

Figure 29 Dolerite from Kwazulu Natal

The hardness of dolerite and its propensity for producing insufficient fines implies that sometimes the gravel material cannot easily be broken down even by aggressive grid rolling (E. G. Kleyn, 2008). Unfortunately, in Sardinia and in Italy we do not have this kind of rock, therefore I have investigated the possible use of granite by-products to replace a base layer of inverted pavement section.

10.2. GRANITE MINERALOGY

The granitoids of Sardinia represent a geological resource of great economic relevance, providing for the most part the Italian export of siliceous ornamental stones. A large part of the Sardinia production comes from the Gallura region, where granite quarrying is known from the roman age, and where from the early 1960s, modern granite extraction supplied national and international ornamental stones markets. (S. Tocco, 2007)

The most confirmed definition is that of officious igneous rock, namely rock with volcanic origin: it is possible to think to the liquid lava, that, not being able to come out from the depths of the Earth, became slowly cold into the Earth crust. During its very long transformation process (called metamorphic), the mineral impurities – present as granules or as sedimentary layers into the lava flows – they are moved and crystallized again because of the pressure and warmth effect. These processes created a hard, solid and strong material, but with very beautiful veining able to satisfy the most refined aesthetic tastes. Impurities as clay, loam, sand, iron oxide and flint nodules, generated the various colors of granite, from white to light grey to pink to yellowish wholesale, seldom to green. The basic components of this rock are quartz and potassium feldspar (orthoclase, microcline), plagioclase (albite, oligoclase), mica, biotite. Instead, the accessory minerals are magnetite, apatite, pyrite, zircon, ortite, tourmaline and those accidental are mica, muscovite, orneblenda, pyroxene, garnet. (A. Mottana, 1987)

From the commercial point of view, "granite" represents a wide class of rocks also more different from the petrographic-classifying point of view, including officious and effusive igneous rocks, sedimentary and metamorphic rock. The granites of Sardinia represent the Sardinian Hercynian batholit that emerges from North to South, mainly in the East side and in a subordinate way in the South-West side of the Island, occupying an area of about 6000 km². (U. Sanna, 2009)

The granite is the most spread rock of the Earth crust, given that it is present in the big Scandinavian, Canadian, Russian, Brazilian and African. In Italy is very peculiar the granite of Novara, a part of a massif between metamorphic rocks of the "series of the Lakes" from the Lago D'Orta to the Lago Maggiore, and of Sardinia. (W.S. Mackenzie, 1994)

As you can see in the Figure 30 the terrestrial Earth surface is covered by 64% sediments, 13% metamorphics, 7% plutonics, and 6% volcanic. *Acid plutonics* represent plutonic rocks containing quartz, Granites and their relatives are grouped in this class in particular, but also quartz-diorites and quartz-monzonites. (Hartmann & Moosdorf, 2012)

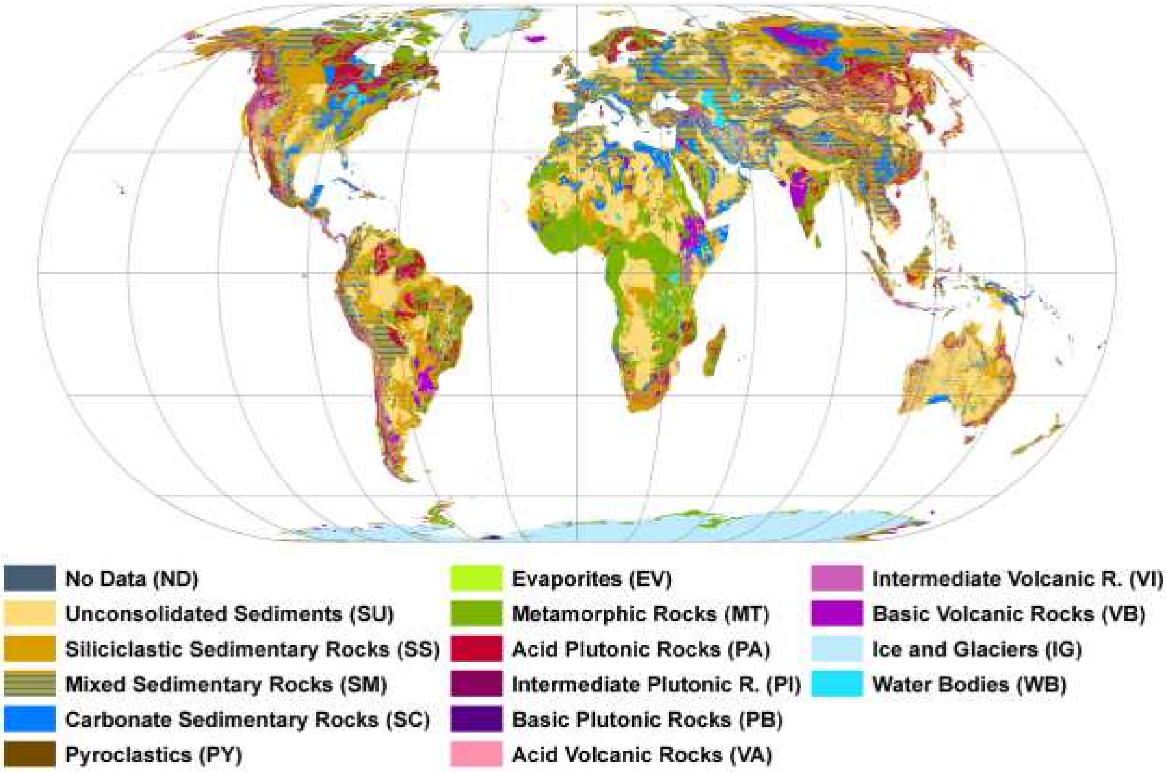


Figure 30 The New Lithological map database GLiM (Hartmann & Moosdorf, 2012)

The stone materials have ever been used in the building and architectural field, above all for the building of the wrought ashlars or as an ornamental stone. The Ancient Roman population used them a lot and created an important transport network from the mines of the territory of Gallura towards the ports of Lazio. (U. Sanna, 2009).

The branch of ornamental rocks is characterized by the production of granites, marbles, trachites, tuffs and basalts. Are exported in Italy and abroad rough blocks or sheets produced in specific factories. The granite of Gallura and the marble of Orosei represent two among four industrial districts of Sardinia. The branch of granite stands at the second position in the World, after China. (Bonioli, 2002)

The peculiarity of rocks, extracted for ornamental use, implicates that only materials of first choice can be input in the market and, so, the production of high quantities of wastes. From the point of view of the visual impression, the main problems is that concerning the placement of landfills. (Bordicchia, A.De. Martini, & Tocco, 2002)

The environmental costs of these activities have been large excavation and huge volumes of waste materials. Regional laws and regulation dispose the recovery and rehabilitation of dismissed quarries, and the reuse of rock wastes.

If the production of wastes will be always unvaried, in the next ten years, we can suppose that will be produced 4 millions of cubic meters of rocks situated as a landfill, that would be add to two hundred millions of cubic meters amassed until now in the landfills. (S. Portas, 2002)

It is necessary to remember that there are eleven typologies of granite that are different, one another, not only for color and granularity of minerals, but also for the chemical- physical mechanical features. For proving that, it is possible to notice, in the Table 14, the different values of resistance by compression of granite coming from the various mining sites of Sardinia.

Table 14 Resistance by compression of granite from various mining sites of Sardinia (U. Sanna, 2009)

City	Compression Resistance (MPa)	Weight (Kg/m³)
Benetutti, Nule	105	2710
Buddusò	110	2700
Mamoiada, a	105	2660
Mamoiada, b	150	2760
Nuoro, a	110	2620
Nuoro, b	140	2760
Oliena	145	2760
Orgosolo, a	130	2700
Orgosolo, b	135	2650
Orune, a	140	2670
Orune, b	140	2660
Sarule	90	2760
Tiana	70	2740

From the Table 14 it is possible to notice that the range of resistance by compression oscillates from 70MPa to 145 MPa, whereas seem more homogeneous the values relative to the specific weight, that oscillate from 2620 to 2760 Kg/m³.

11. METHODOLOGY AND PROCEDURES

11.1. CHARACTERIZATION OF GRANITE FROM CALANGIANUS QUARRY

In this Research I have analyzed granite derived from Calangianus quarry Figure 31, derived from the north of Sardinia. This kind of Granite is "Ghiandone" because there are big mineral particles in the matrix.

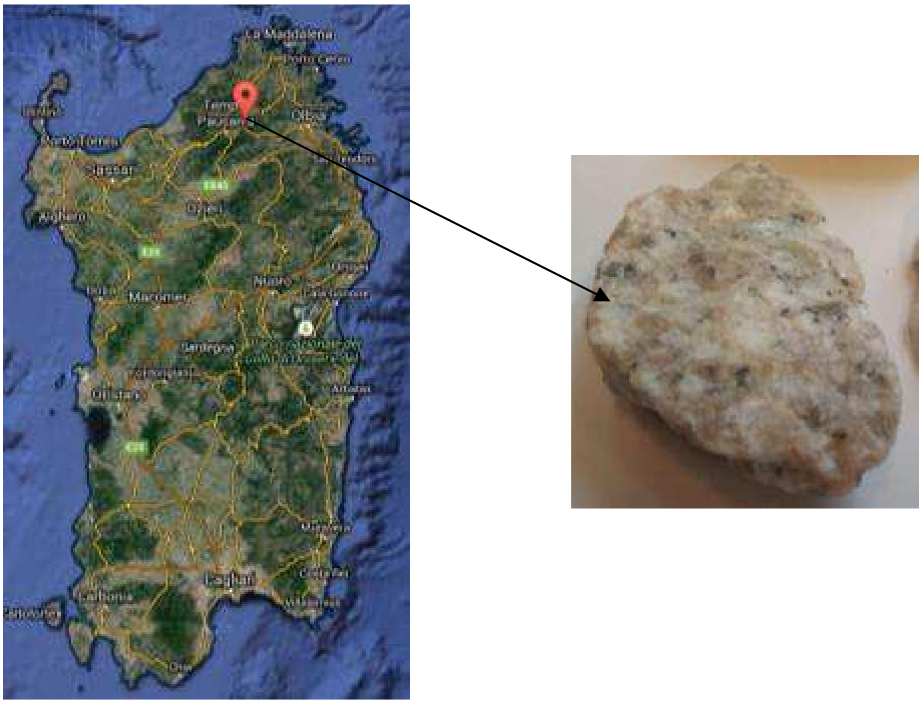


Figure 31 Granite Ghiandone from Calangianus Quarry

11.1.1. PETROGRAPHIC ANALISYS

Petrographic analysis has three main purposes: that of removing the risks concerning the use of aggregates of poor quality; that of allowing the use of local materials easily available, suggesting the ways of compensating the inadequate quality through the use of alloying or through other expedients; that of finding a scale of reference for comparing the materials of different origins and for making possible a choice. Indeed, intrusions of minerals, as micas, talcosi and clay schist, calcite crystals and feldspars, can forecast an inadequate resistance to compression of aggregate, a feature that, in the road field, has a fundamental importance. Above all, in granites, resistance to compression decreases considerably when the sizes of elements decrease. Instead, for resistance to impact, it needs to consider that aggregates, that are full of quarzite elements, have a greater resistance to compression, but less about resistance to impact. (Ferrari & Giannini, 2007)

The petrographic classification and the quantitative analysis are done examining, through the polarized optical microscope by pulsed light, the relative thin section, namely a rock layer, conveniently cut and with a thickness of about 25 μm, glued on a slide things-holder and covered on the upper part by a slide things-cover. In the petrographic microscope, a polarized light beam of a determined orientation, after having crossed the thin section, reaches another polarized filter, swiveling it too. Microscope, in addition to supplying an increased image of the minerals present in the section, situated on a rotating table, allows to observe a series of optical features, thanks to which it is possible to do the identification of them. The growth is produced by two systems of lenses (objective and ocular). Objective is composed of a series of lenses that produce a first extension; this image is further enlarged by ocular. The petrographic microscope allows the optical identification of minerals; it allows to characterize sizes and shape of the components of the sample analyzed (minerals, fossils, etc.) and to do standard procedures of analysis of samples and quality controls. The Axio Zeiss is a polarized microscope, linear and motorized for examinations in orthoscopy and conoscopy, by pulsed and reflected light. The blowup of objectives are: 2,5x, 10x, 20x, 40x, 50x, whereas, the ocular used has a growth of 10x.

The petrographic analysis allowed to classify the material as: Granite is an igneous intrusive acid rock with a granular structure and texture holocrystalline distinctly inequigranulare for the presence of large crystals euedrali (= with proper form) or sub-euedrali of K-feldspar, in sizes up to centimetric. The quartz (Qz) is abundant in individuals plurimillimetrici always anhedral (= without proper form). The high quartz content in clasts and matrix cement of the aggregate source rock sandstones give the material high strength; the K-Feldspar (K-Fel) is present in the phase Ortoclasio, with the presence inside of abundant interlocking pertitici (i.e. with small elements of Na-Feldspar); individuals are frequently affected by incipient alteration in sericite (Ser) and clay minerals (kaolinite: Kao). There is, and also the relatively abundant plagioclase (Pl), with large elements often zoned, a composition oligoclasico-andesinica; the only mafic mineral present is the biotite (Bt), present in individuals and aggregates of individuals lamellar and frequently altered in chlorite (Chl) or oxides of iron (Fe ox). Overall, the petrographic characteristics, textural and compositional, the rock can be classified as a monzogranito.

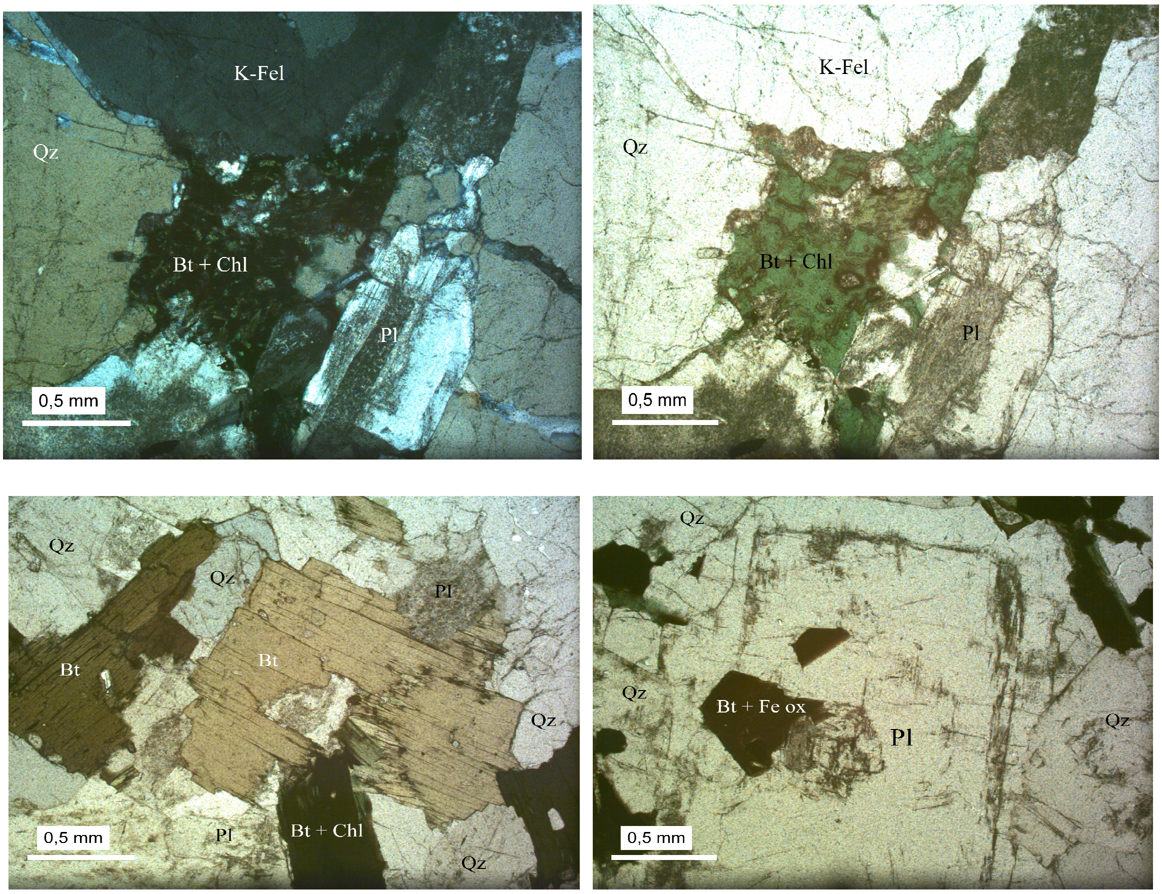


Figure 32 Granite by-products thin section**.**

11.1.2. CHEMICAL TEST

In order to verify the potential use of this granite, specific tests were conducted according to Italian regulations. To measure the chemical composition of the granite the Inductively Coupled Plasma with Optical Emission Spectrometry (ICP- OES) technique was used, the instrument was a Perkin Elmer Optima 7000 DV ICP-OES Figure 33.


Figure 33 ICP-OES Perkin Elmer Optima 7000 DV

The ICP was developed for Optical Emission Spectrometry (OES) in the middle of the 1960s. This system is based on the emission of photons from atoms and ions that have been excited by radiofrequency (RF) induced argon plasma using one of a variety of nebulizers or sample introduction techniques. Liquid and gas samples may be injected directly into the instrument, while solid samples require extraction or acid digestion so that the analyses will be present in a solution. To perform the measurements the granite by-products were reduced to a granular size of 0.063 mm.

In the Table 15 are reported the average chemical compositions of granite by-product samples in comparison with Dolerite commonly use in South Africa.

Table 15 Chemical Composition of Granite by-products in comparison with Dolerite

Component	Granite (%)	Dolerite (%)
SiO_2	67,1	49,95
Al_2O_3	8,28	12,78
TiO_2	0,31	3,51
MgO	0,46	6,59
MnO	0,07	0,20
CaO	2,86	9,70
Na_2O	4,34	2,52
K_2O	6,19	0,91
P_2O_5	0,08	0,29
SO_3	0,03	---
Fe_2O_3	3,31	13,12
LOI	---	---
Tot.	100,95	99,57

The two materials have silicon dioxide and aluminum oxide as main chemical component, even if with slightly different values. Granite has 67,1% of silicon dioxide while Dolerite has 49,9%; again Granite only has 8,28% of aluminum oxide while Dolerite has 12,78%. Sodium oxide and manganese oxide, present with low percentage, have same values in both rocks. Main differences can be notices in the amount of magnesium, calcium, potassium and iron oxide with 8%. The histogram of the Figure 34 shows in percentages the results of chemical tests carried for the two different rocks.

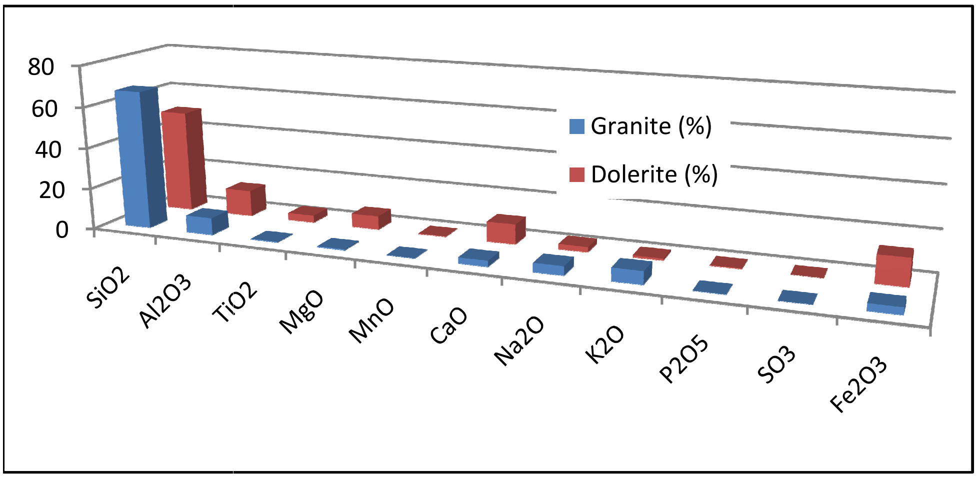


Figure 34 Parallel on the chemical analysis of Granite and Dolerite.

The final test performed in this phase consisted on determining the specific gravity of the aggregates (Figure 35).

Figure 35 Specific gravity weighing apparatus

The UNI EN 1097-6 specification was used performing hydrostatic weighing on aggregates with particle size between 63 mm and 31.5 mm, while the vacuum Pycnometer Figure 36 was used to measure aggregates with size ranging from 31.5 mm to 0.063 mm.

The tests conducted gave values between 2.2 – 2.8 g/cm^3.

Figure 36 Vacuum Pycnometer

Unfortunately, chemical tests are not enough to decide if these materials are suitable or not therefore physical-mechanical characteristics such as thickness, porosity, compressive strength, water absorption percentage and Los Angeles test have been analyzed.

11.2. THE IMPORTANCE OF GRADING

Unbound granular base derives its high stability from particle interlock and inter-particle friction. Gradation has a profound effect on material performance. But the question is: what is the best gradation? This is a complicated question, the answer to which will vary depending upon the material. It might be reasonable to believe that the best gradation is one that produces the maximum density. This would involve a particle arrangement where smaller particles are packed between the larger particles, which reduces the void space between particles. This creates more particle-to-particle contact. Therefore, although it may not be the "best" aggregate gradation, a maximum density gradation does provide a common reference. A widely used equation to describe a maximum density gradation was developed by Fuller and Thompson in 1907. Their basic equation is:

$$P = \left(\frac{d}{D}\right)^n$$

where: P = % finer than the sieve

d = aggregate size being considered

D = maximum aggregate size to be used

n = parameter which adjusts curve for fineness or coarseness (for maximum particle density n ≈ 0.5 according to Fuller and Thompson)

In the Figure 37 we can see the parallelism between the Fuller curves and the G1 grading curves for base layer.

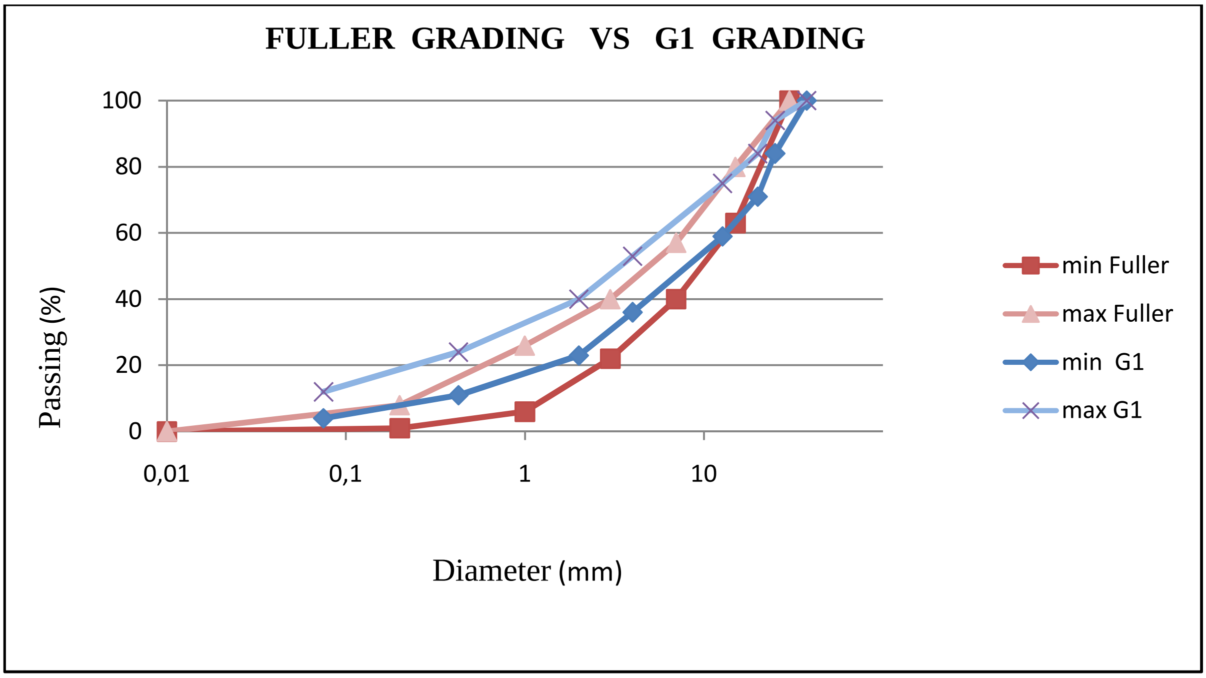


Figure 37 Comparison between Fuller grading curves and G1 base layer grading curves

Soil gradation is very important to geotechnical engineering. It is an indicator of engineering properties such as compressibility, shear strength, and hydraulic conductivity. To obtain a good matrix with need to have a clear amount of fines. So, knowledge of the amount of the percentage fines and the gradation of the coarse particles is useful in making a choice of material for base courses of highways.

Base layers, constructed with crushed stone, must possess high resistance to deformation in order to withstand the high pressure imposed upon them. The functions of a base layer are prevention of pumping, drainage, prevention of volume change of sub-grade, increased structural capacity and expedition of construction. To accomplish these functions high density and stability are required.

Hussain have studied in 2012 the correlation between repeated triaxial test on three different grading curves: course graded (CG), medium graded (MG), fines graded (FG), as shown in the Figure 38. He made triaxial test drained (DR) and un-drained (UD).

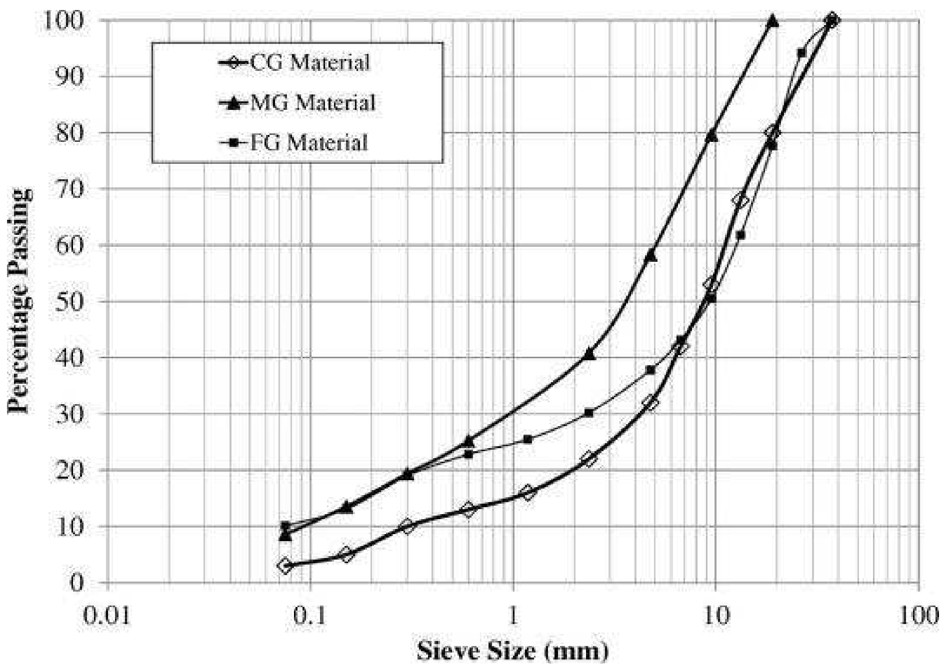


Figure 38 Different grading curves used by Hussein experiment

It is observed in the Figure 39 that under drained conditions, the fine graded material displayed higher permanent deformation for all the stress states. In addition to that, it fails during stress state 5. At lower stress states (below stress state 5) it appears that the medium graded material has lower permanent deformation if compared to the coarse graded material. However, at the high stress state, the ultimate deformation of the medium grade material is more significant than the coarse graded material.

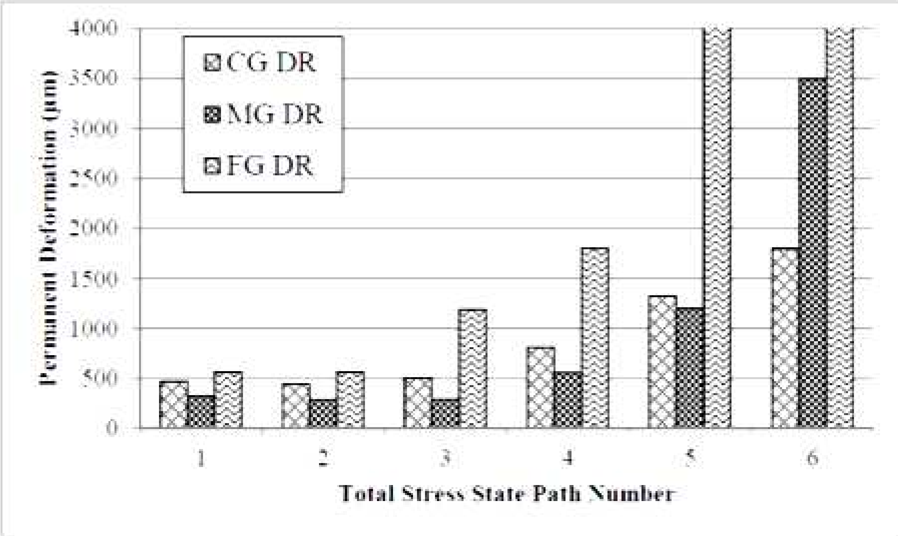


Figure 39 Comparing Material Performance varying stress States- Drained Conditions

The un-drained conditions in the Figure 40 displayed different trends. Firstly, in all stress states, the coarse graded material displayed the lower deformation. Medium graded material had the highest deformation at lower stress states. The fine graded material displayed significant increased rates of deformation at stress state 3 and failed during stress state 4. (Hussain, 2012)

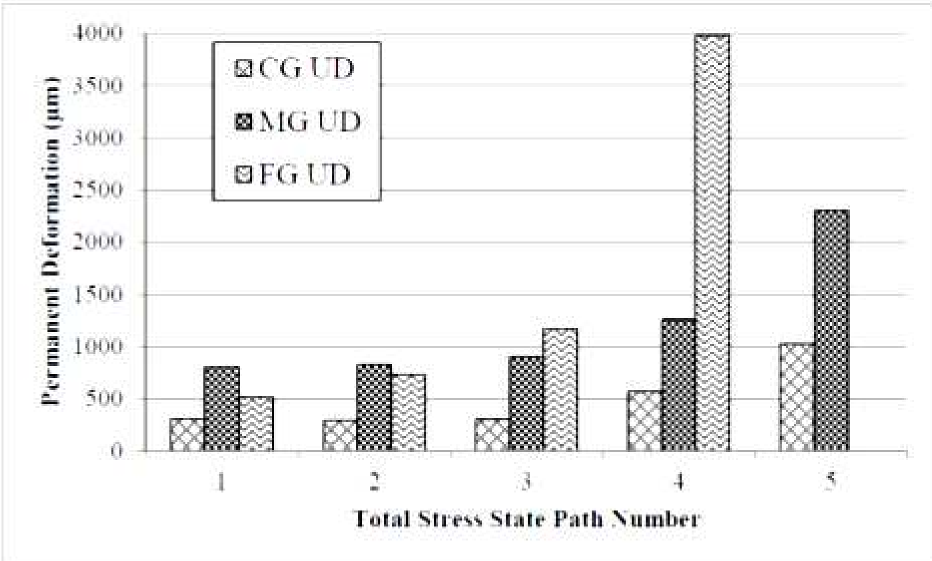


Figure 40 Comparing Material Performance varying stress States Un-Drained Conditions

An aggregate with little or no fines content (Figure 41 a) gains stability from grain-to-grain contact. An aggregate that contains no fines usually has a relatively low density but is pervious and not frost susceptible. However, this material is difficult to handle during construction because of its non-cohesive nature. An aggregate that contains sufficient fines to fill all voids between the aggregate grains will still gain its strength from grain-to-grain contact but has increased shear resistance (Figure 41 b). Its density is high and its permeability is low. This material moderately difficult to compact but is ideal from the standpoint of stability. As shown in the Figure 41 c, material that contains a great amount of fines has no grain-to-grain contact and the aggregate merely ‘float’ in the soil. Its density is low; it is practically impervious and it is frost susceptible. In addition, the stability of this type of material is greatly affected by adverse water conditions. (E. J. Yoder, 1975)

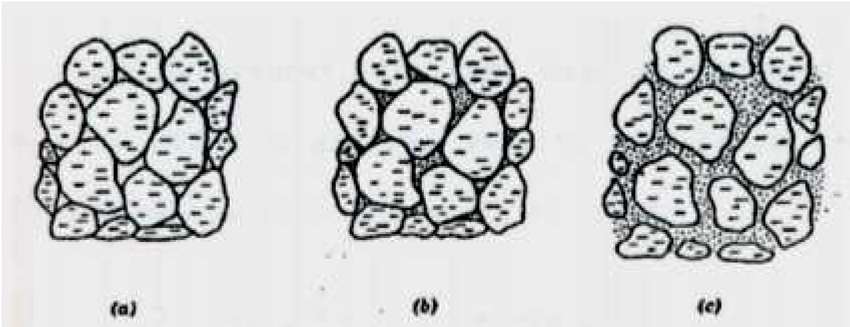


Figure 41 Coarse and fines particles distribution

The profound effect of the Gravel-to-Sand (G/S) ratio on the peak deviator stress at failure (or shear strength behavior) can also be interpreted from the particle packing and porosity characteristics acquired by different relative concentrations of gravel and sand size particles. Aggregate base/granular materials, in essence, are mixtures of the gravel fractions, sand fractions and fines. Coarse aggregate grains can be deemed to enclose a void space in which finer sand particles fill; whereas the fines (passing No. 200 sieve or smaller than 0.075 mm) basically fill the void space created by the sand particles. The Figure 41 a indicates the packing state resulting in the largest G/S ratio as almost no sand grains to occupy a portion of the voids between the coarse aggregate particles. Mixtures at this state develop shear or permanent deformation resistance primarily by friction resistance between gravel size particles and may not be very stable depending on the grading of the gravel-size particle distribution. G/S ratio decreases when more sand fractions exist until an optimal packing configuration is reached at the ideal state shown in the Figure 41 b. This ideal state means the voids between the gravel size particles are completely occupied by the bulk volume of the sand grains, developing the condition of minimum porosity. The minimum porosity of the mixture can be theoretically interpreted as the boundary between a gravel-controlled and a sand-controlled mixture. The phase diagram analysis of the Figure 41 b can also derive that the minimum porosity of the mixture is the product of the porosity of each individual fraction with the same specific gravity assumed for all fractions. After that, if sand fractions keep increasing (or G/S ratio decreases), then packing conditions will dictate gravel (or coarse) particles to “float” in the sand-fine matrix and have trivial control over shear strength behavior of the mixture (Figure 41 c). (Y. Xiao, 2012)

The increase in permanent deformation with an increase in saturation can be explained by the lubrication of the aggregates, and the development of pore water pressure within the materials that can then result in a reduction in effective stress. The lubrication of the aggregates helps the grains to rotate and to slide against each other that then cause further compaction. Moreover, the fine particles in the material become plastic further helping the deformation process. The increase in saturation creates pore water pressure in the material which reduces the effective stress, which is responsible for the strength of the specimen. Hence, when the stress is higher on the materials, the material becomes weak at higher saturation levels resulting in greater permanent deformation. The Coarse Grading (CG) material showed relatively less deformation at saturated un-drained conditions than saturated drained conditions for the first five stress states. The permanent deformation of Fines Grading (FG) material at saturated drained and saturated un-drained conditions was the same until the third stress state. For the rest of the stress states the FG material showed greater permanent deformation with increasing saturation. The Medium Grading (MG) materials showed higher deformation at saturated un-drained condition than the saturated drained condition at all stress states. (Hussain, 2012)

If we want to obtain a grain skeleton with a high bearing capacity, obviously cubical grains with a rough surface are to be preferred. Although the grain size distribution (grading) is of great importance, one other aspect related to construction must always be taken in mind, and that is compaction. Compaction is crucial to obtain a grain skeleton with high bearing capacity. The sieve curve also yields information about the amount of fine material which is present in the soil.

The Importance of grading was investigated and the conclusions are: high gravel content levels of more than 15–20% by volume act as a supporting framework, thus protecting the fine earth considerably from compaction, and they also increase precompression stress substantially. For these soils with higher gravel content, at least, consideration should be given to gravel content when assessing their susceptibility to compaction damage. Failure to do so could otherwise result in miscalculations of mechanical load capacity. On the other hand, in soils with low gravel contents of less than 10% by volume, the gravel effect of reducing compaction requires somewhat less consideration. With regard to the impact of a gravel shape on precompression stress, no clear conclusions can be drawn from these experiments. Here there appears to be considerable interdependency with the texture of the fine earth, and future investigations should aim to shed light on this. (J. Rucknagel, 2013)

In the Figure 42 we can see the optimum gradation of Dolerite for Inverted Pavement base layer.

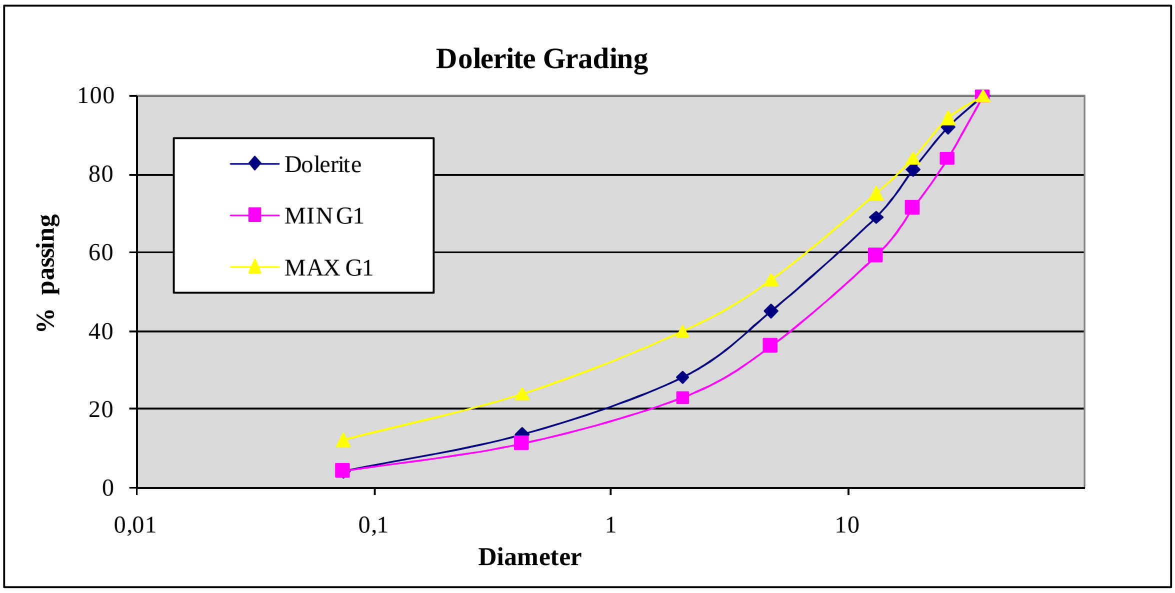


Figure 42 Dolerite grading for base layer

The test section made in La Grange and in Morgan County, were made with granite deriving from two different quarry. The LaGrange Aggregates as medium-grained granitic gneiss, interspersed with layers of amphibolite gneiss. The granitic gneiss takes on a more pink hue in some areas of the pit, due to an increased amount of pink orthoclase (potassium-rich) feldspar in the rock. Other areas have a more grey/white color, because there is less orthoclase feldspar in the rock and more white/clear plagioclase (potassium-depleted) feldspar in the rock. The general orientation of the foliation in the pit is N60°E, 22°W and it is most easily noted in the eastern area of the pit. The interface between the amphibolite gneiss and granitic gneiss corresponds with this foliation. The presence of the two distinct rock compositions with very different specific gravities creates a challenge when certain areas of the pit are being mined. Vulcan sometimes has to blend different shots of material in order to maintain a consistent specific gravity in the final product. Mafic intrusions (high specific gravity) were noted on the northern wall of the pit, cross-cutting the foliation in a ribbon-like manner. The intrusions were no more than 2 feet wide in any section, and the composition of the intrusions was difficult to ascertain due to their location. It is not expected that Vulcan will encounter these intrusions in their mining plan anytime in the near future.

The grading used is perfectly inside to G1 curves, as you can see in the Figure 43.

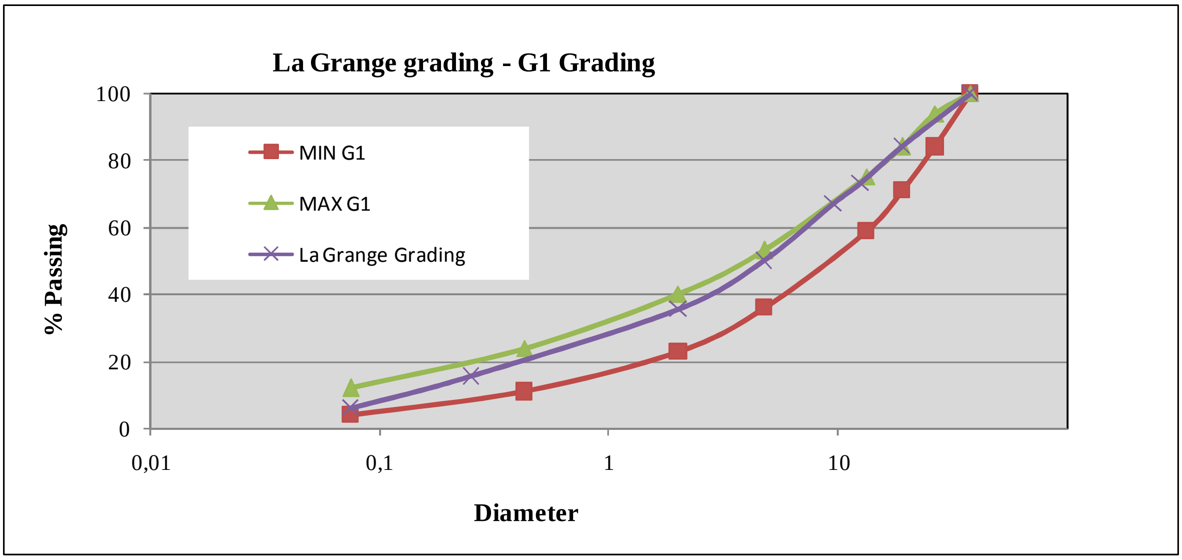


Figure 43 La Grange Grading for base layer

Morgan County was the first Inverted Pavement test section made in Georgia State, it is the entrance road of a Lafarge quarry and the material used for base layer derive from the same quarry. The Unbound Aggregates Base layer is classified by the GDOT 1993 Specifications as Group II – slag, gravel, granitic and gneissic rocks, quartzite, synthetic aggregate, or any combination thereof. (R.G. Terrel, 2002) In the Figure 44 below can we see the grading used for base layer.

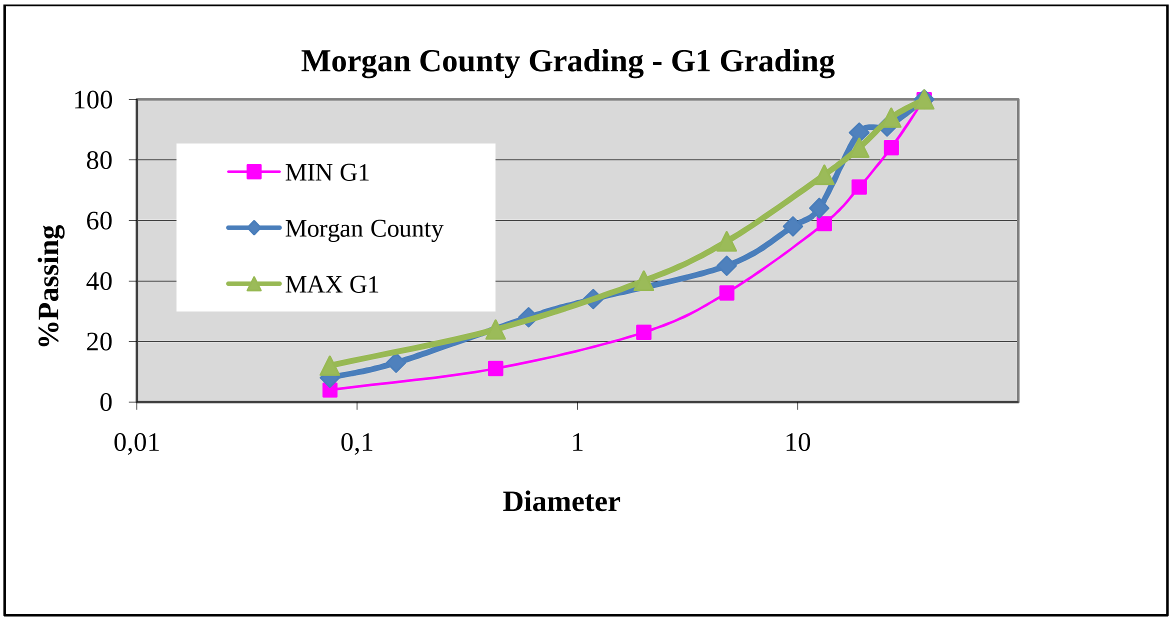


Figure 44 Morgan County grading for base layer

Granite is an igneous intrusive acid rock with a granular structure, the rock that I have analyzed can be classified as a monzogranite.

The fines present in these aggregates are non-expanding and non-plastic. In the Figure 45 we can see the Granite Grading used for Inverted Pavement base layer.

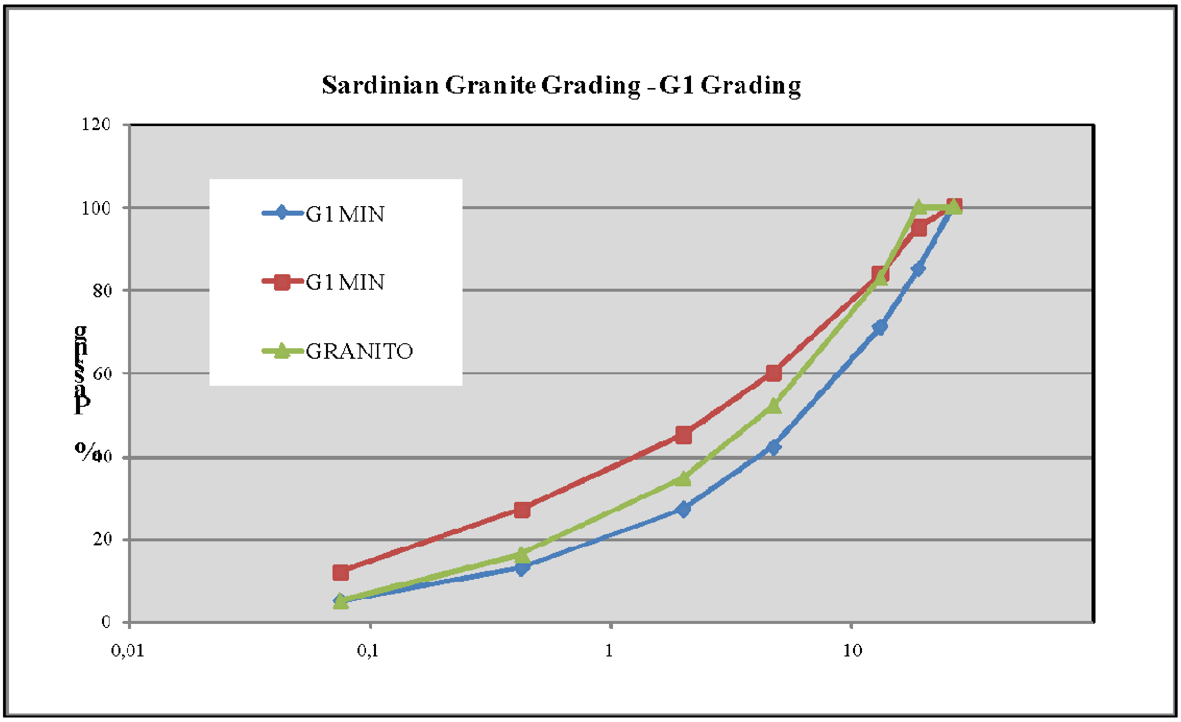


Figure 45 Sardinian Granite grading for base layer

11.3. ENVIRONMENTAL CHARACTERIZATION OF DIGGING MATERIALS

The environmental characterization is made for verifying the existence of environmental quality requisites considered "By-products". To evaluate the possibility of using granite by-products for road construction purposes was important to evaluate if such material were environmental compatible. In order to do some tests to evaluate the permissible concentrations of elemental species in the aggregate or their leachates had to be carried out. The Italian legislation and regulation on this type of matters, that in this last years and months have been changing quite rapidly, have to deal with the LG.D. n.152/2006 and the D.M. n. 161/2012. The LG.D. n.152/2006 the so called “Environmental Code” this Legislative Decree gives the guide lines on which proceeding to use to perform the tests and the list of elements with the maximum permissible concentration. In 2012 D.M. n. 161/2012 was introduced. In this new Decree there is the possibility of performing tests on elements not present in the list if there is a doubt that the site from which the aggregates are extracted has been subjected to possible industrial activities or other activities that could have contaminated the site. In the Table 16 I have reported the results of leachates test.

Table 16 Leachate test results

MINERALE	CONCENTRATION	
	Limit (mg/l)	Granite by-products (mg/l)
Rame	0,05	0,006
Cromo	0,05	0
Cadmio	0,005	0,001
Zinco	3	0
Piombo	0,05	0
Arsenico	0,05	0
Cobalto	0,25	0,001
Selenio	0,01	0,004
Bario	1	0
Berillio	0,01	0
Antimonio	1	0,003
Vanadio	0,25	0,002
Tallio	1	0,003
Nichel	0,01	0

As I have supposed all value are inside of limit concentration values. All results are shown in the Figure 46.

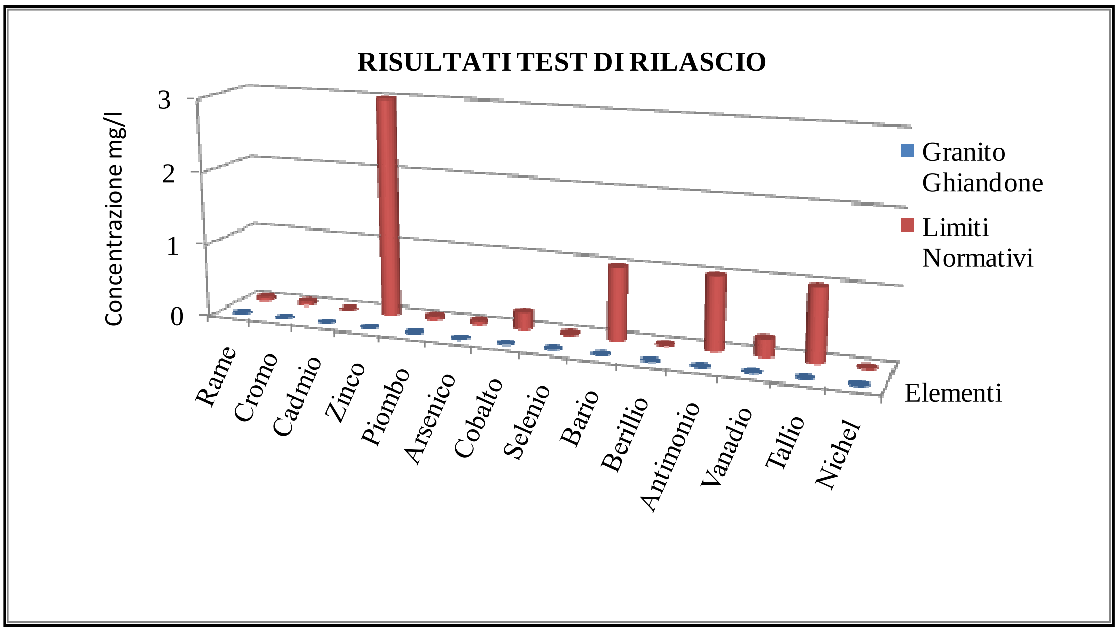


Figure 46 Histogram of Leachate test results

At this step the material has all the potential features to be used as a base layer for Inverted Pavement Structure.

12. PHYSICAL - MECHANICAL TEST

Sardinian granite by-products were characterized to verify the possible application for the construction of granular base layers following South African standards.

According to South African Technical Recommendations for Highways (TRH) 14, the aggregates used for base layer must have a specific grading depending on the nominal maximum size of passing the 37.5 mm sieve or 26.5 mm one and physical properties. TRH 14 specifications are aimed to evaluate aggregate quality and compaction properties. In the Catalogue of designs the materials are indicated by means of a code G1 to G10 which refer to materials with certain defined properties, as you can see in the Table 17.

Table 17 Aggregates classification for Base Layer

CODE	MATERIAL
G1, G2, G3	Graded crushed stone
G4, G5, G6	Natural Gravel
G7, G8, G9, G10	Gravel Soil

Graded Crushed Stone (G1) meets the quality and the grading requirements mentioned below and it is generally derived from the crushing of solid not weathered quarried rock, clean rock from mine rock dumps or clean boulders. It is placed at near saturation moisture content; the field density is usually specified as a percentage of the apparent density (AD) of the all in material and expressed as relative compaction (RC) for G1 material. For G2 and G3 materials the field density is expressed as a percentage of modified AASHTO density. Slushing is usually carried out to obtain the required density for a G1 material.

Grade Crushed Stone (G2 and G3) that I obtained by crushing rock, boulders or coarse gravel-Provided, it conforms to the specified requirements; the crushed material may include natural fines not derived from crushing the parent rock. (State of Road Authorities, 1985)

In the Case of graded crushed stone G1, a faulty grading may be adjusted only by the addition of crusher sand or other stone fractions obtained from the crushing of the parent rock. The materials for base layer should comply with the grading envelopes shows in the Table 18:

Table 18 Grading of graded crushed Stone, soil and natural gravel.

Sieve size (mm)	Percentage passing by mass G1-G2- G3	
	Nominal Maximum size of aggregate (mm)	
	37,5	26,5
37,5	100	100
26,5	84-94	100
19,0	71-84	85-95
13,2	59-75	71-84

4,75	36-53	42-60
2,00	23-40	27-45
0,425	11-24	13-27
0,075	4-12	5-12

There are different Atterberg Limits for every material, as shown in the Table 19.

Table 19 Atterberg Limits for graded crushed stone, natural gravel.

PROPERTY	MATERIAL TYPE	
	G1	G2, G3, G4
Liquid Limit (max)	25	25
Plasticity Index (max)	4	6
Linear Shrinkage % (max)	4	3

Other tests as Flakiness Index, 10% Fines Aggregate Crushing Test (FACT), Aggregate Crushing Value (ACV) that I will explain in the following chapter are required for classified aggregate as suitable for G1 layer. All this limit values are shown in the Table 20.

Table 20 Limit test values for G1 material

TEST	LIMIT VALUES
10% FACT	110 kN
ACV	29 %
Flakiness Index	35%

12.1. ATTERBERG LIMIT

For knowing the susceptibility to water by a land, that must be used in a pavement, we use the Limits by Atterberg: liquidness limit, plasticity limit and limit receding. Atterberg limit tests were performed according to CNR-UNI 10014 (CNR-UNI 10014, 1969). The liquidness limit has been determined through the "spoon by Casagrande" - the so-called in Italian "cucchiaio di Casagrande" - a bowl that is again and again lifted and made fall from a height determined by the regulations. Put the material on the "spoon", you must realizes a crack in the middle of it, through a standard grooving utensil, such that the material is divided in two identical fractions, as you can see in the Figure 47:

Figure 47 Test by Casagrande for liquid limit value

So, you count the bumps necessary to the parts of the land in order to make them stay in close contact, for a length of at least 13 mm; weighing the specimen before and after the drying into the oven, you can obtain its contents of water. You must repeat this procedure three times varying the contents of water. Taking note of these three results, so obtained on a semi-logarithmic diagram, contents of water-logarithm of the number of bumps, and marking the straight line that better rounds off them, you can obtain the contents of water corresponding to the closing of the crack in 25 bumps, that is called liquid limit. The plastic limit is the moisture content that defines where the soil changes from a semi-solid to a plastic. It is determined, creating by hand through rolling on a glass sheet, some stick of land with a thickness of 3,2 mm; at the plasticity in the sample of land, are created some cracks caused to the receding of the land itself. As you can see in the Figure below:

Figure 48 Determination of Plastic limit

As soon as they begin to crack, you can measure their contents of water, indicated in percentage, that, for definition, is equal to the plastic limit. You can obtain the Index of Plasticity by the formula shows below:

$$\text{Plasticity Index} = \text{Liquid Limit} - \text{Plastic Limit}$$

The test shows that granite by-products resulted non plastic.

12.2. FLAKINESS INDEX

The geometrical irregularities of aggregate particle are of great importance for the behavior of the aggregates. The grain shape of aggregates influences the material gradation obtained by sieving. The grain shape is one of many important parameters influencing the response of unbound aggregates (Uthus, Hoff, & Horvli, 2005) The flakiness index is defined as the total weight of the material passing the various thickness gauges, expressed as a percentage of the total weight of the sample with the sieve analysis. Flaky and elongated particles are considered undesirable for base coarse construction as they may cause weakness with possibilities of braking down under heavy loads.

Figure 49 Flakiness Index Apparatus

The Flakiness Index was calculated with the following formula:

$$\text{Flakiness Index} = (A/B) \times 100$$

where:

A= Total mass of Aggregate pass slots

B= Mass of test sample

A low flakiness index is desired because it indicates cubical-shaped aggregates.

Figure 50 Flakiness Index Test

As reported in the Table 21 the flakiness index values that have been measured for granite by-products are:

Table 21 Flakiness Index test results

Sample	Mass of Test Sample kg	Mass Passing kg	Flakiness Index %
1	7,5	0,46	6,10
2	7,5	0,50	7,00
3	7,5	0,54	6,96

All these value are inside the limit.

12.3. DRY DENSITY AND OPTIMUM MOISTURE CONTENT

The optimum water content and dry density depend on the soil composition and the amount of compact energy used. The moisture-density relationship of a soil is a graph of dry density versus water content, for a given compact effort. The data points obtained from compacting several samples at different water contents form a smooth curve, called the compaction curve, which is used to obtain the optimum water content and maximum dry density. The test was measured performing modified Proctor test using UNI-EN 13286-2 specifications (UNI-EN 13286-2, 2010).

In the Modified Proctor Test the soil is compacted by a 4 kg hammer falling a distance of 45 cm, and uses five equal layers of soil and each layer is subjected to 25 drops of the hammer. The compaction mold has 15 cm of height and it has 15 cm of diameter. The graphical relationship between dry density and moisture content are shown in the Figure 51.

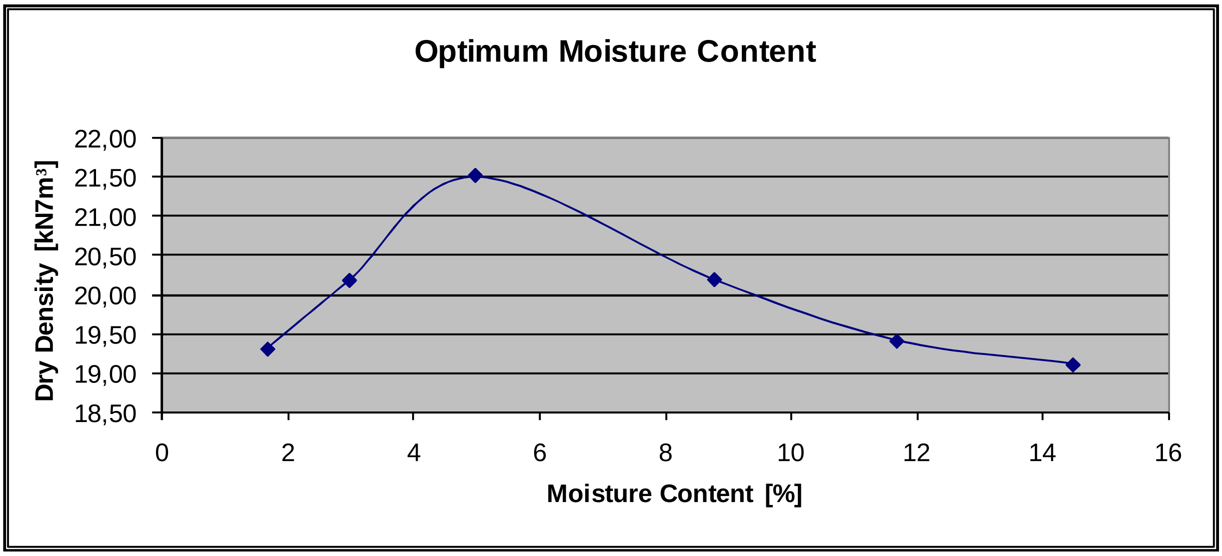


Figure 51 Moisture - Density relationship for granite by-products

From this chart is it possible to obtain the peak points of the compaction curve determining optimum water content as 5,5 % and the related dry density is 21,50 kN/m³.

12.4. LOS ANGELES ABRASION TEST

Los Angeles abrasion test was performed using UNI EN 1097-2 specifications (UNI-EN 1097-2, 2010). The road aggregates should be hard enough to resist abrasion. Resistance to abrasion of aggregate is determined in laboratory by Los Angeles test machine. The principle of Los Angeles abrasion test is to produce abrasive action by the use of standard steel balls which when mixed with aggregates and rotated in a drum for specific number of revolutions also cause impact on aggregates. The percentage wear of the aggregates due to rubbing with steel balls is determined and is known as Los Angeles Abrasion Value.

In the Figure 52 Los Angeles Machine consists of a hollow steel cylinder, closed at both the ends with an internal diameter of 700 mm and long 500 mm and capable of rotating about its horizontal axis. Abrasive charge is characterized by steel balls, approximately 48mm in diameter and each weighing between 390 to 445g; six to twelve balls are required.

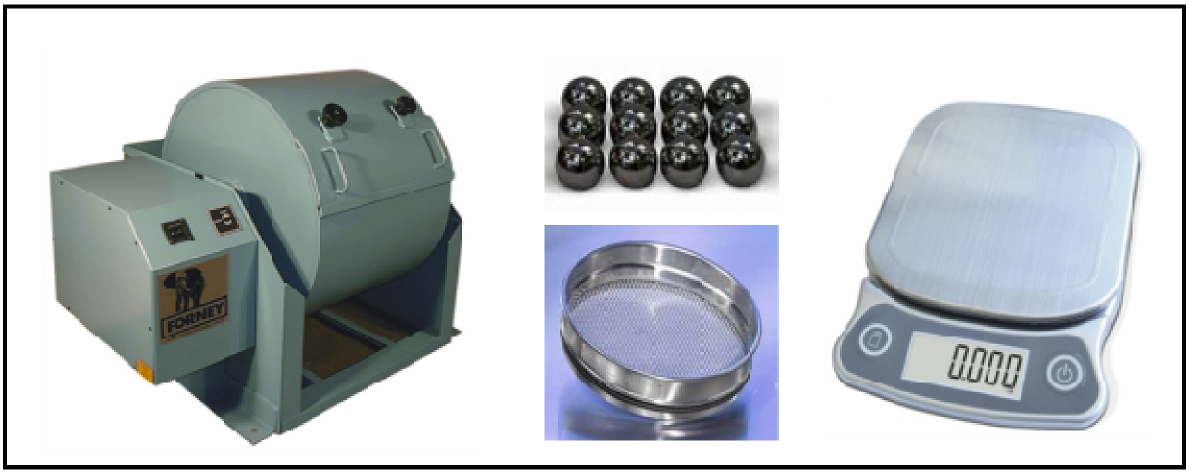


Figure 52 Los Angeles Abrasion Test Equipment

12.4.1. TEST PROCEDURES

The test sample consists of clean aggregates dried in oven at 105° – 110°C. Select the grading to be used in the test such that it conforms to the grading to be used in construction. Take 5 kg of sample. Choose the abrasive charge depending on grading of aggregates, in my test for A grading I have used 12 balls. Place the aggregates and abrasive charge on the cylinder and fix the cover. After being subjected to the rotating drum, the weight of aggregate that is retained on the 1.60 mm sieve is subtracted from the original weight to obtain a percentage of the total aggregate weight that has broken down and passed through the 1.60 mm sieve.
The Los Angeles Coefficient LA is calculated by the formula:

$$\mathbf{LA} = \left(\frac{5000 - m}{50}\right) \quad \textbf{UNI-EN 1097-2: 2010}$$

m: is the amount of aggregate in grams retained on the 1.6 mm sieve after fragmentation
As reported in the Table 22, the average Los Angeles abrasion values that have been measured for granite by-products and for Dolerite are respectively:

Table 22 Los Angeles Abrasion Test Medium Values

Material	Los Angeles Abrasion Value (%)
Granite by-Products	28,5
Dolerite	15

12.5. AGGREGATE CRUSHING VALUE (ACV)

The aggregate crushing value gives a relative measure of the resistance of an aggregate crushing under gradually applied compressive load. To achieve a high quality of pavement, aggregates possessing low aggregate crushing value should be preferred. ACV test was

performed using South African Technical Methods for Highway number one (TMH1). South African regulations defined ACV as: "*The ACV of an aggregate is the mass of material, expressed as a percentage of the test sample, which is crushed finer than a 3,35 mm sieve when a sample of aggregate passing the 19,00 mm and retained on the 13,20 mm sieve is subjected to crushing under a gradually applied compressive load of 400 kN*".
The ACV apparatus shown in the Figure 53 consists of an open-ended steel cylinder of 150 mm nominal diameter with plunger and base plate; a metal tamping rod 16 mm in diameter and 450 mm to 600 mm long; a compression testing machine capable of applying a load of 400 kN and which can be operated at a uniform rate of loading so that this load is reached in 10 minutes. The aggregates size for this test is the passing 19,00 mm and retained 13,2 mm.

Figure 53 Equipment for Aggregate Crushing Value Test

This test is characterized by two step: one for dry aggregates and one for wet aggregates.
Aggregate crushing value (wet or dry) percentage (m/m) is calculated by the formula:

$$ACV=(B/A)x\ 100$$

Where:
A is the mass of the sample before test
B is the mass of fraction passing the 3,35 mm sieve

As reported in the Table 23 the average of ACV (dry) values that have been measured for granite by-products are:

Table 23 ACV dry test results on granite by-products

Sample	Weight sample (g)	Force (kN)	Passing 3,35 mm (g)	ACV dry
1	2042	400	714	34,97
2	1904	400	606	31,83
3	1980	400	657	33,18

As reported in the Table 24 the average of ACV (wet) values that have been measured for granite by-products are:

Table 24 ACV wet test results on granite by products

Sample	Weight sample (g)	Force (kN)	Passing 3,35 mm (g)	ACV wet
1	2032	400	656	32,28
2	1987	400	645	32,46
3	2054	400	670	32,62

The values reported in the Table 24 and in the Table 23 show some values that are slightly higher than the limit expected by the South African regulations, that corresponds with 29%.
The period of research happened in the Georgia Institute of Technology of Atlanta, allowed me to better study the conduct of granite. Indeed, the experimental sections of Inverted Pavement realized in Morgan County and in LaGrange, located in the Figure 54 were realized with granite.

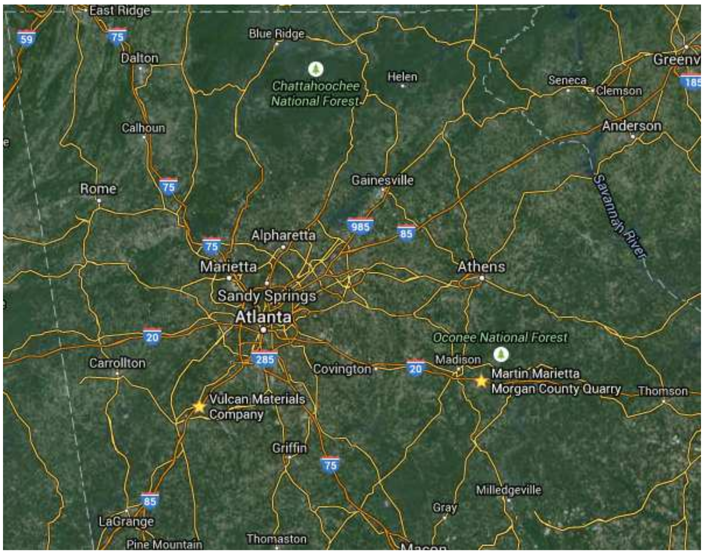


Figure 54 Volcan Quarry of LaGrange and Morgan County Quarry

The tests and the calculations made on the test sections show, as reported previously, that the granular blend basic layer realized with granite has excellent performances in terms of mechanical resistance. For confirming the goodness of the features of Sardinian granite, I did the laboratory tests ACV on the samples of granite used in the experimental sections. These two samples of granite, that are different both for coloring and for physical features, are reported in the Figure 55.

Figure 55 Granite deriving from Morgan County and LaGrange Quarry

The values obtained by the ACV, for the sample extracted in Morgan County, are reported in the Table 25 and in the Table 26.

Table 25 ACV wet test results on granite from Morgan County

Sample	Weight sample (g)	Force (kN)	Passing 3,35 mm (g)	ACV wet
1	1930,8	400	577,2	29,89
2	1847,7	400	582,7	31,53
3	1817,3	400	579,1	31,86

Table 26 ACV dry test results on granite from Morgan County

Sample	Weight sample (g)	Force (kN)	Passing 3,35 mm (g)	ACV dry
1	1802,2	400	538,1	29,85
2	1764,0	400	524,7	29,74
3	1824,4	400	539,6	29,57

The values obtained by the ACV, for the sample extracted in Lagrange, at Volcan quarry, are reported in the Table 27 and in the Table 28.

Table 27 ACV wet test results on granite from Volcan Quarry

Sample	Weight sample (g)	Force (kN)	Passing 3,35 mm (g)	ACV wet
1	1924,0	400	575,2	29,89
2	1985,2	400	585,9	29,51
3	1943,6	400	609,9	31,37

Table 28 ACV dry test results on granite from Volcan Quarry

Sample	Weight sample (g)	Force (kN)	Passing 3,35 mm (g)	ACV dry
1	1991,6	400	562,1	28,22
2	1872,6	400	529,5	28,27
3	1902,4	400	541,2	28,45

As you can see all value are out of limit except the result of ACV dry by Volcan quarry. This confirms that the test is not particularly indicative of the mechanical resistance of the aggregate to use. It would be opportune to improve the datum limit of the test, doing the test of the ACV for various materials, and giving a personalized value limit for each aggregate.

12.6. FINE AGGREGATE CRUSHING TEST (10%FACT)

When a road aggregate has been manufactured to a specified grading, it is stockpiled, loaded into trucks, transported, tipped, spread and compacted. If the aggregate is weak, some degradation may take place and result in a change in grading and/or the production of excessive and undesirable fines. Thus, an aggregate complying with a specification at the quarry may fail to do so when it is in the pavement. Granular base layers and surfacing are subjected to repeated loadings from truck tires and the stress at the contact points of aggregate particles can be quite high. These crushing tests can reveal aggregate properties subject to mechanical degradation of this form. The apparatus consists of a case hardened steel cylinder 154 mm diameter and 125 mm high together with a plunger which just fits inside the cylinder and a base plate. Other items are a steel tamping bar 16 mm diameter by 450-600 mm long and a metal measuring cylinder 115 mm diameter by 180 mm deep. Also required is a compression testing machine capable of applying a force of up to 500 kN and which can be operated to give a uniform rate of loading so that this force is reached in 10 minutes. We need three test specimen, each of mass about 3 kg, for each test dry and wet. All three samples are compacted with a different maximum force, that gives respectively a percentage of fines value:

a) of less than 7,5%

b) in the range 7,5 – 12,5%

c) of over 12,5%

I have plot the percentage so obtained against the forces, in kN, required for each, and from the resultant graph obtain the force that would give 10% fines.

The force required to give a percentage of fines in the range 7,5 – 12,5, calculate, as follows, a force that will required to produce 10% fines:

$$F = (14x)/ (y + 4)$$

Where:

F is the force required to produce 10% fines, kN

X is the force required to produced a percentage fines in the range 7,5- 12,5 as determined, (kN)

Y is the percentage of fines obtained with force X.

As reported in the Table 29 the 10% FACT (dry) values that have been measured for granite by-products are:

Table 29 10% FACT dry test results

N°	Weight sample (g)	Max force applied (kN)	Passing 2,36 mm (g)	Passing (%)	Note	10%FACT
1	2964	50	66	2,2	10mm in 10 min	
2	2779	116	221	8	15 mm in 10 min	135,3
3	2685	187	403	15	20 mm in 10 min	

As reported in the Table 30 the 10% FACT (wet) values that have been measured for granite by-products are:

Table 30 10% FACT wet test results

N°	Weight sample (g)	Max force applied (kN)	Passing 2,36 mm (g)	Passing (%)	Note	10%FACT
1	2827	75	188	6,7	10mm in 10 min	
2	2856	108	285,6	10	15 mm in 10 min	108
3	2789	162,06	362,57	13	20 mm in 10 min	

The values obtained by the test follow the limits expected by the South African regulations.

12.7. SOME TEST CONCLUSIONS

From the tests made until now, in accordance with the South African and Italian normative, emerges an only value out of range, that is that of the ACV. As previously explained, this test is a measurement of the resistance of the aggregate under the compaction load. A high number of this index implicates that, under compaction and so high compressions, material is inclined to crush, producing a lot of *fines particles* that passes through sieve, of 3,35 mm. However, this datum is not particularly negative, considered also the analyses on the material used in the test sections realized in Georgia, and so, we went on the simulations through software for understanding better the conduct of superstructure.

13. SOFTWARE SIMULATION USING MePADS

To verify the possibility of replacing the base layer of an Italian pavement structure, in this case study a road category A, with G1 to achieve reduction of thicknesses of the Hot Mix Asphalt layers, simulations were performed using MePADS software. The mechanical properties of granular bases are key design inputs for empirical pavement design methods as well as in mechanistic guidelines (AASHTO, 1993) (TRH, 1996).

MePADS is the electronic version of the current South African Mechanistic- Empirical Design and Analysis Methodology (SAMDM) (H.L. Theyse, 1996). The SAMDM is one of the few mechanistic-empirical (M-E) design methods that incorporate a methodology for evaluating the structural capacity of granular materials.

The software combines a stress-strain computational engine with pavement material models developed in South Africa. Pavement layers life is expressed in terms of the number of repetitions of an axle load until failure. Layer life is based on the typical linear-log damage functions obtained from experience and from the results of Heavy Vehicle Simulator (HVS) testing on the various pavement types carried out in South Africa since 1975. The South African design philosophy yield more cost-effective designs than those utilizing relatively thick asphalt layers on weaker granular layers. The saving on initial cost could be somewhere between 30 and 45 percent, depending on the traffic class and the quality of the sub-grade support (Du Plessis, Rust, Horak, Nokes, & Holland, 2008). Granular bases exhibit not linear, anisotropic, post peak softening behavior, yet design guidelines are based on the simplest assumptions (Clayton, 2011) (Dawson, Mundy, & Huhtala, 2000).

The structural analysis is done with a static, linear elastic multi layer analysis program. A few points related to the structural analysis, that will influence the design procedure, should be noted.

The model is based on the following assumptions:

- One with infinite thickness or more layers with a finite thicknesses and an infinite bottom layer;
- Homogeneous and isotropic layer material properties;
- Layers are extended to infinite in horizontal directions;
- Full friction at layer interfaces;
- No surface shearing forces;
- The materials are characterized by the Poisson’s ratio and modulus of elasticity.

The mechanistic-empirical method consists of two main modeling components, the primary pavement response model that calculates the elastic response of the pavement to loading and the damage models, that quantify the damage in all the pavement layers, gave certain elastic response parameters. The primary pavement response model used in most mechanistic-empirical design methods is a multi-layer, a linear elastic continuum mechanics model that requires Young’s modulus and Poisson’s ratio to characterize the resilient response of the materials found in each of the pavement layers. However, Young’s modulus and Poisson’s ratio are theoretical concepts that apply to perfectly elastic materials. The Young’s modulus that represents the “stiffness” of materials can only be approximated from experimental results and it is most often approximated by the resilient modulus for unbound granular material. The resilient modulus is a measure of the elastic recovery of a specimen of material given the repeated application and removal of an axial load under compressive stress conditions. Most road-building materials also exhibit stress-dependent and apparent anisotropic behavior. The magnitude of the resilient modulus therefore depends on the level of confinement of the material and differs under tensile and compressive stress conditions, not to mention the effect of density and saturation. Strictly speaking, there is no single resilient modulus value for a given unbound, granular material but rather an infinite range of possible values (Theyse, Beer, Maina, & Kennemeyer, 2011).

The software allows the user to set the level of a terminal rut, either 10 or 20 mm with empirical curves being available for either rut depth. Similarly reliability of the road design is preselected using the Road Category, and the Climatic Region options are Dry, Moderate or Wet.

A comparison of the results from PaveFEL in the linear-elastic mode compares well with multilayer linear-elastic programs such as MePADS (Bredenhann & Jenkins, 2004).

In order to perform the software simulation triaxial tests were performed to obtain Young’s modulus.

13.1. TRIAXIAL TEST

The triaxial test is one of the most versatile and widely performed geotechnical laboratory tests, allowing the shear strength and stiffness of soil and rock to be determined for use in geotechnical design. Advantages over simpler procedures, such as the direct shear test, include the ability to control specimen drainage and take measurements of pore water pressures. Primary parameters obtained from the test may include the angle of shearing resistance ϕ', cohesion c′, although other parameters such as the shear stiffness, compression index, and permeability may also be determined.

Triaxial test allowed to obtain the Young's modulus of G1 layer made with granite by-products, the Young's modulus is defined as the ratio of the tensile stress and the tensile strain. All test are made according to ASTM D2850 e D4767 procedures.

Triaxial compression test apparatus shown in the Figure 56, consists of a triaxial pressure chamber, cell supply system, loading system, together with load, displacement and volume change measurement devices. The specimen measure is 20 mm high and 100 mm of diameter, and it is vertically enclosed in a thin rubber membrane. The specimen is vertically enclosed with a thin rubber membrane and placed between two rigid ends inside a pressure chamber. The upper plate can move vertically and apply vertical stresses to the specimen. The axial strain/stress of the sample is controlled through the movement of this vertical axis. Also, the confining pressure is controlled by the water pressure surrounding the sample in the pressure chamber. The volume change of the sample is also controlled by measuring the exact volume of moving water.

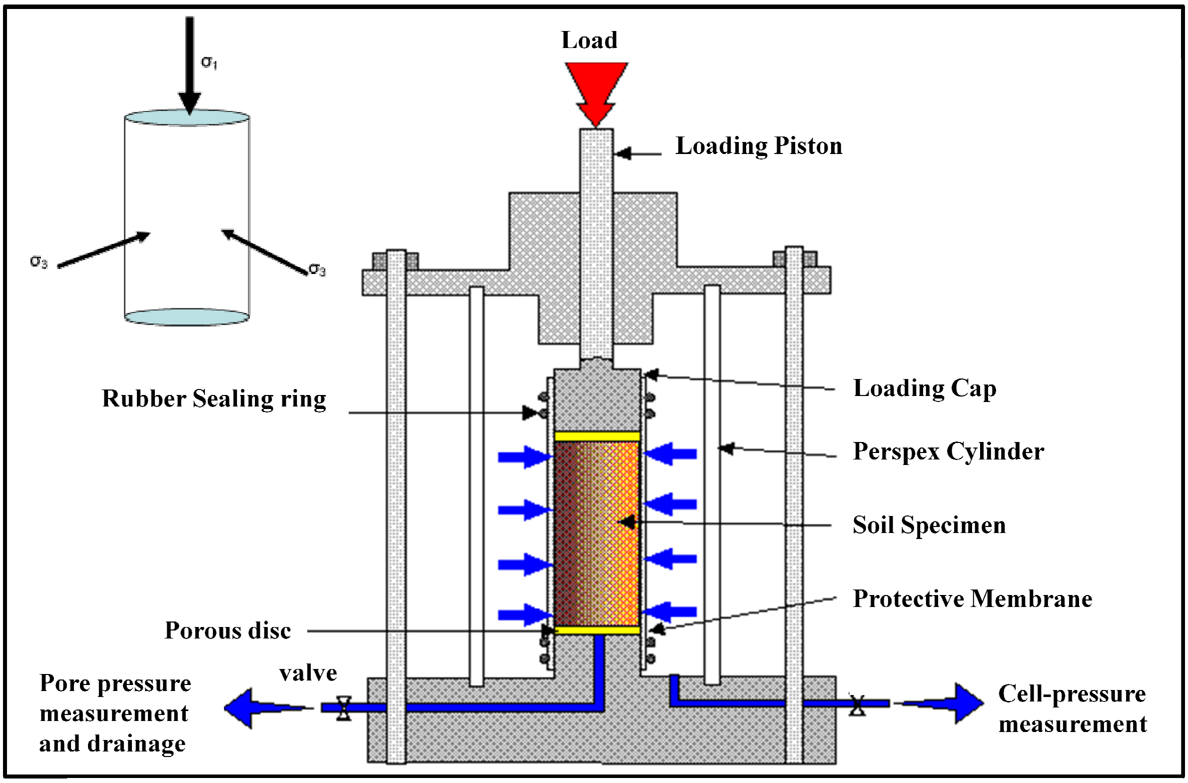


Figure 56 Triaxial apparatus

All triaxial test, consolidated drained, shown in the Figure 58, Figure 59, Figure 60 are made by using all grading for G1 Base Layer. All samples were compacted with Modified Proctor procedures, and at optimum moisture content that is around 5,5 %.

The cell pressure was calculated with the Multi-layered elastic model of Boussinesq. A layered elastic model can compute stresses, strains and deflections at any point in a pavement structure resulting from the application of a surface load. Layered elastic models assume that each pavement structural layer is homogeneous, isotropic, and linearly elastic. In other words, it is the same everywhere and will rebound to its original form once the load is removed.

The layered elastic approach works with relatively simple mathematical models and thus, requires some basic assumptions. These assumptions are:

- Pavement layers extend infinitely in the horizontal direction.
- The bottom layer (usually the sub-grade) extends infinitely downward.
- Materials are not stressed beyond their elastic ranges.

A layered elastic model requires a minimum number of inputs to adequately characterize a pavement structure and its response to loading. These inputs are:

- Material properties of each layer
- Pavement layer thicknesses

- Loading conditions

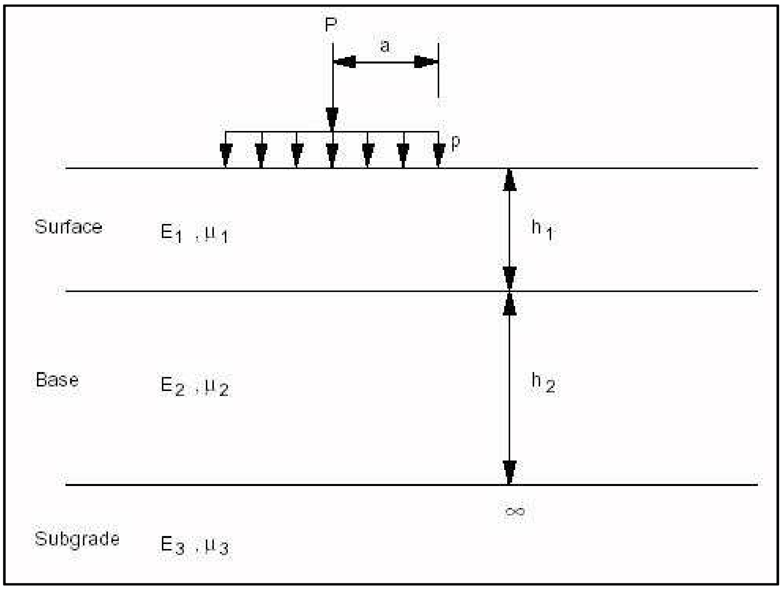


Figure 57 Multi-layered Elastic Model scheme.

The outputs of a layered elastic model are the stresses, strains, and deflections in the pavement:

- Stress: The intensity of internally distributed forces experienced within the pavement structure at various points. Stress has units of force per unit area;
- Strain: The unit displacement due to stress, usually expressed as a ratio of the change in dimension to the original dimension ;
- Deflection: The linear change in a dimension. Deflection is expressed in units of length.

The use of a layered elastic analysis computer program will allow one to calculate the theoretical stresses, strains, and deflections anywhere in a pavement structure (Interactive, 2008).

The tests were performed with hydrostatic pressure of the cell equal to 100-250-350 kPa. This value was chosen based on the calculations performed with the Boussinesq theory, according to which, considering the various types of load provided in the Italian rules and applying such loads statically.

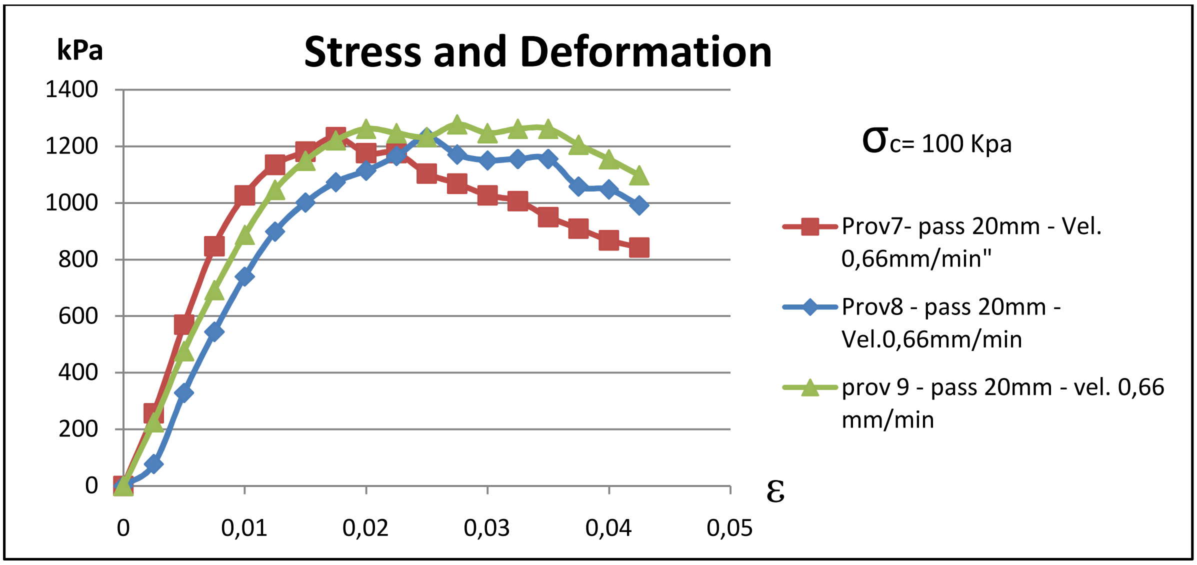


Figure 58 Triaxial test diagram with 100 kPa Confinement Pressure

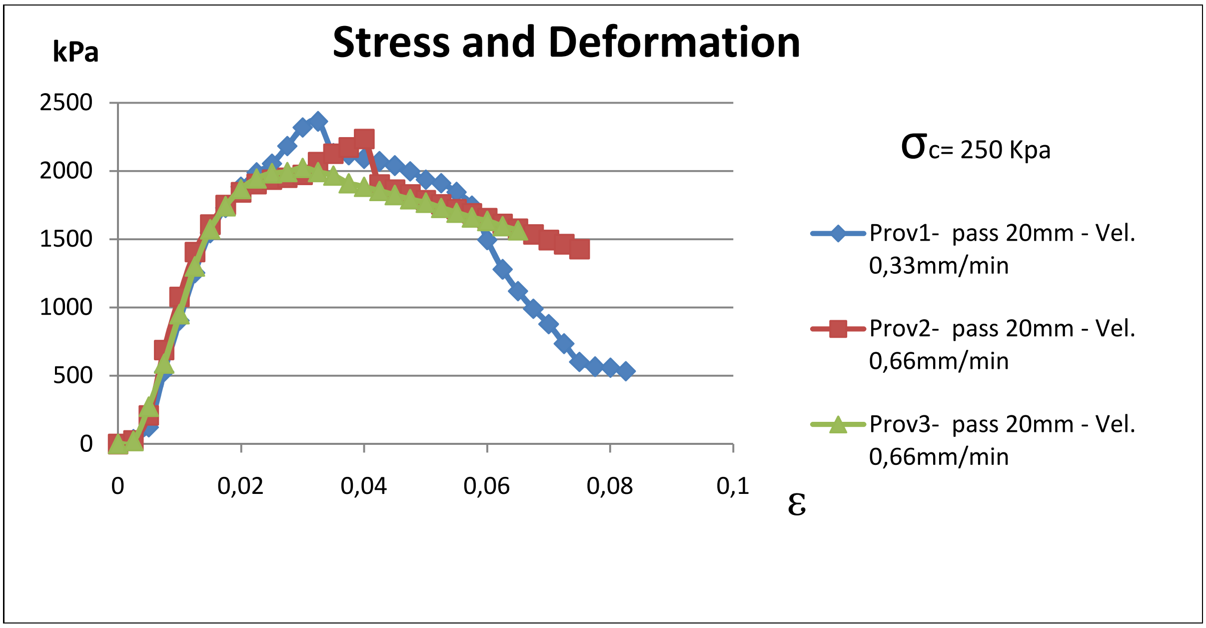


Figure 59 Triaxial test diagram with 250 kPa Confinement Pressure

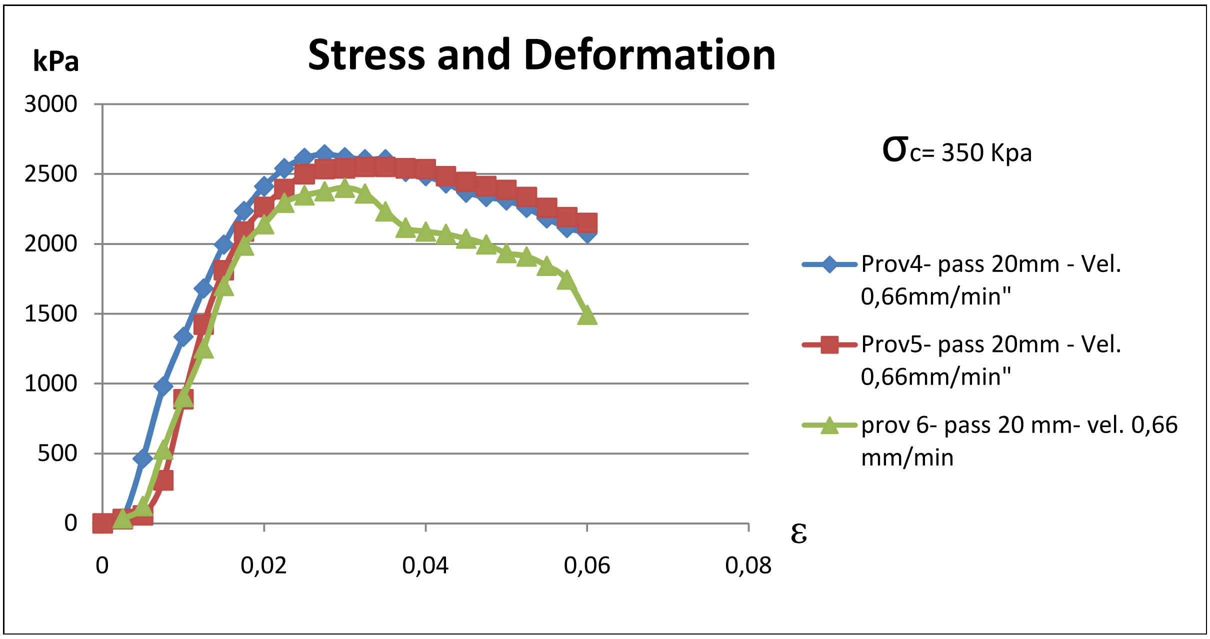


Figure 60 Triaxial test diagram with 350 kPa Confinement Pressure

After having did the tests, through an analysis of the results, we calculated the Young's Modulus of each sample. The values obtained are reported in the Table 31:

Table 31 Triaxial test consolidated Drained of Granite by-products

Sample n°	Confinement Pressure kPa	Density g/cm³	Young's Modulus MPa
1	100	2,28	102,69
2	100	2,25	88,31
3	100	2,32	88,78
4	250	2,21	150,68
5	250	2,26	159,50
6	250	2,19	136,92
7	350	2,21	162,59
8	350	2,26	182,10
9	350	2,22	150,17

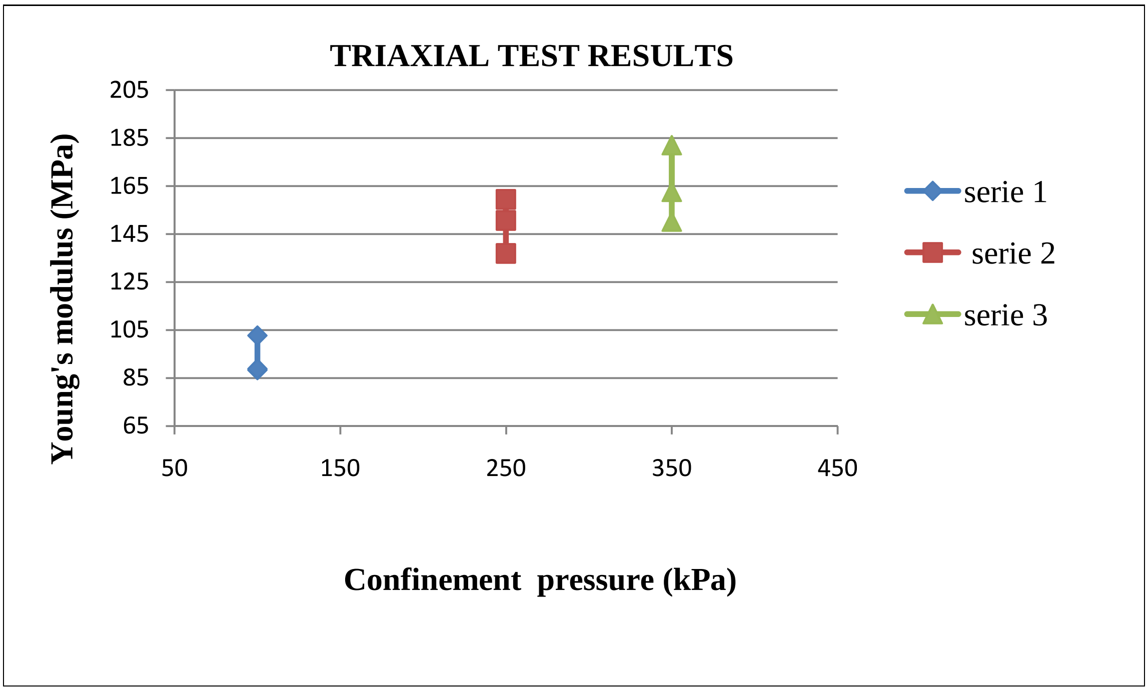


Figure 61 Young’s modulus obtain from triaxial test

As you can see in the Figure 61 the Young’s modulus values change in function of the confinement pressure. The pressure that we can have in real conditions is closed to 250kPa, and for that value the range for Young’s modulus is between 137-160 MPa.

These are the values obtained compacting the sample through the Proctor compactor, namely a pestle of 4,53 kg, 25 bumps per layer, material compacted in three layers. The values of elastic modulus obtained by Dolerite for the layer of G1, are obtained after a compaction in situ and followed by the Slushing Process, of which I will talk about then. The applicability of laboratory values to in situ conditions is questionable (Puppala, 2008).

13.2. MePADS SIMULATIONS

The simulation was made considering some fixed values, such as:

- Tire pressure 520 kPa
- a twin standard axle of 12 tons
- Road traffic range ES30 (30.000.000 millions of passages of standard axles)
- moderate climate
- road class A (highways, freeways)
- terminal rut 20 mm

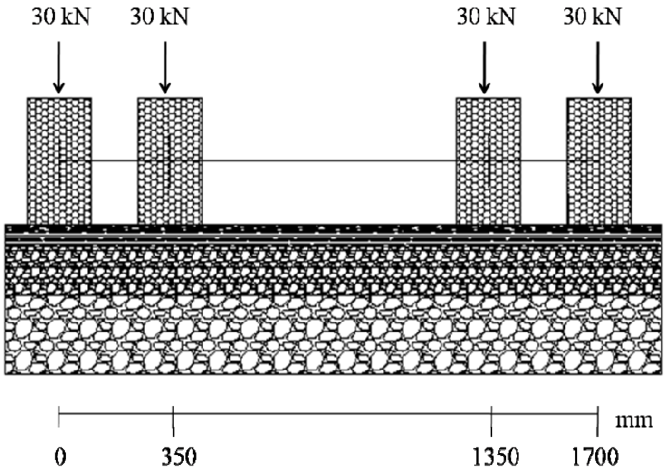


Figure 62 Scheme of the Infrastructure and Load distribution for software simulation

In the Figure 62 I have reported the scheme of Load distribution that I have used for all software simulation.

13.2.1. SOUTH AFRICAN INVERTED PAVEMENT

The first simulation was made on South African pavement structure, but using Italian standard axles. In the Figure 63 I have reported the software screen video about infrastructure characteristics, there are 5 layers from foundation up to hot mix asphalt layers with their relative depth, Young's modulus, Poisson's ratio, etc.

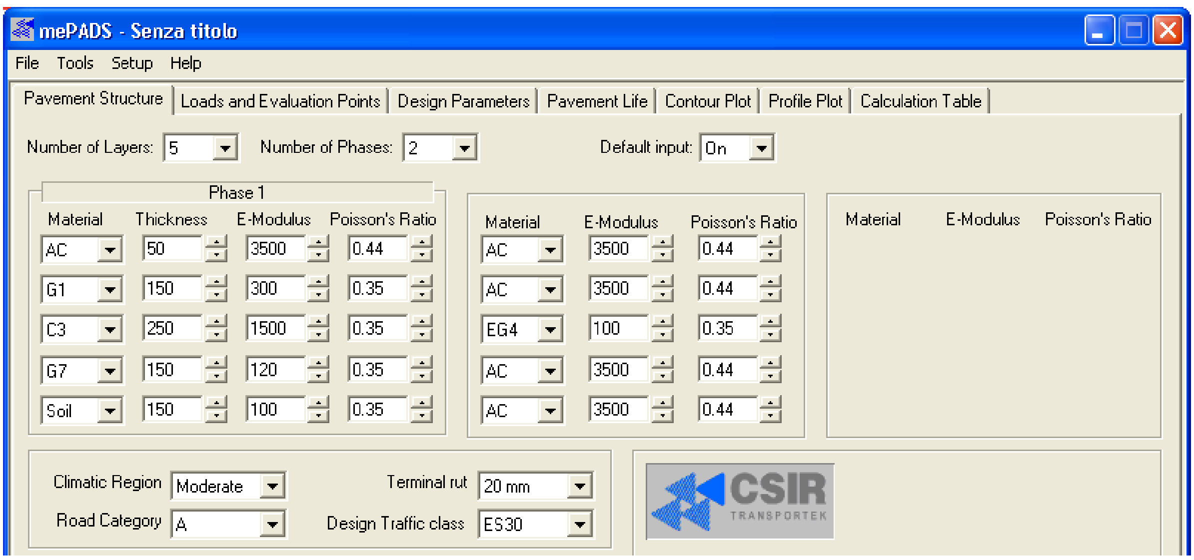


Figure 63 MePads Screen Video with South African Inverted pavement layers and relative values.

In the Figure 64 are shown the normal strain values: the maximum normal strain is in the base layer with 0.000912 value, on top and in the sub-base layer the normal strain values are very low.

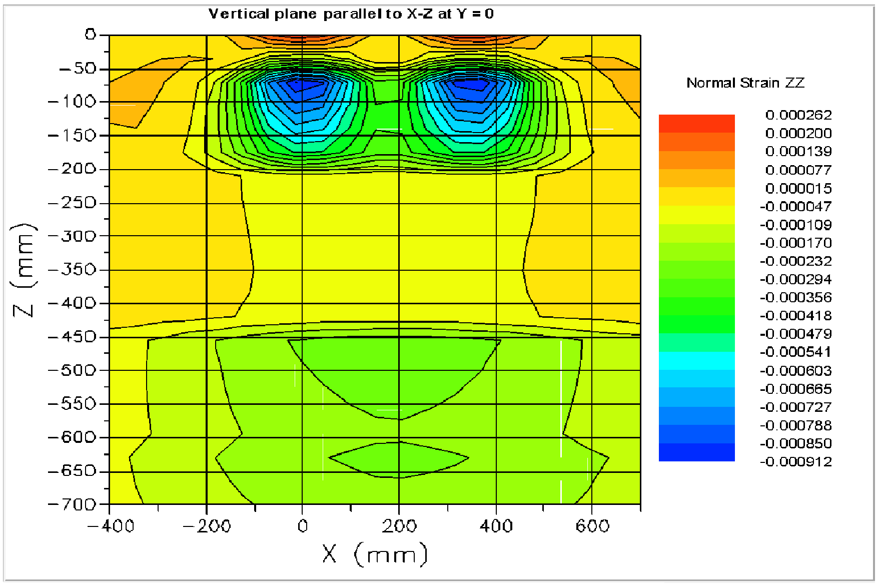


Figure 64 Trend of Normal Strain in a vertical plane of South African Inverted Pavement

Under these traffic load the maximum vertical Displacement is 0,25 mm and decrease very quickly in the base layer, the sub-base is characterized just from 0,15 mm of maximum displacement, as you can see in the Figure 65.

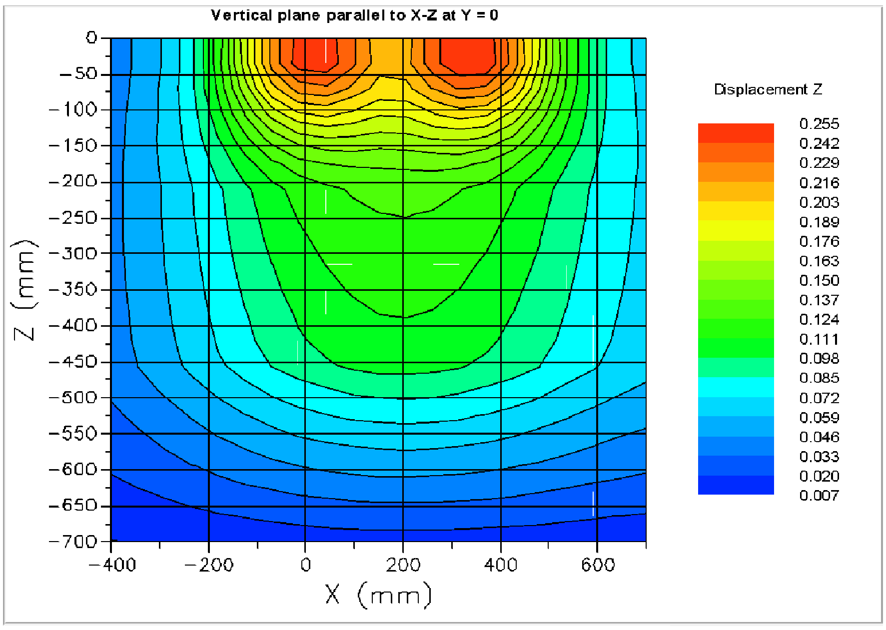


Figure 65 Trend of Displacement in a vertical plane of South African Inverted Pavement

13.2.2. ITALIAN FLEXIBLE PAVEMENT

The second simulation was made on Italian flexible pavement structure. In the Figure 66 and in the Figure 67 I have reported the software screen video about infrastructure characteristics, there are 5 layers from foundation up to hot mix asphalt layers.

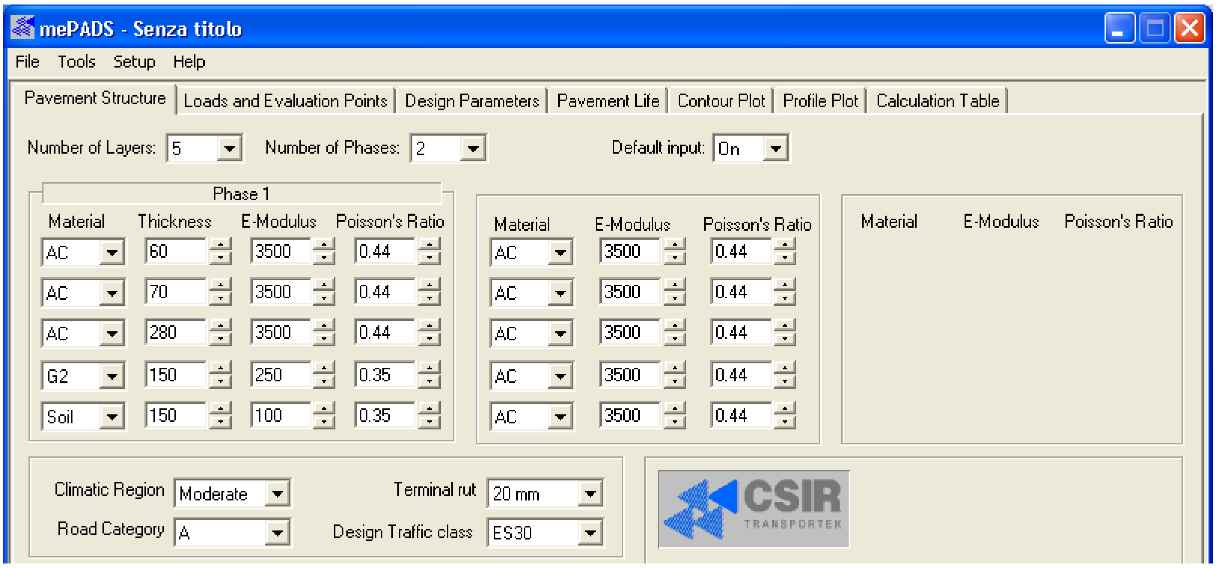


Figure 66 MePads Screen Video with Italian Flexible pavement layers and relative values

In the figure below we can see that the most important normal strain values are in the sub-grade and in the foundation layers. The maximum value for normal strain is 0.000263.

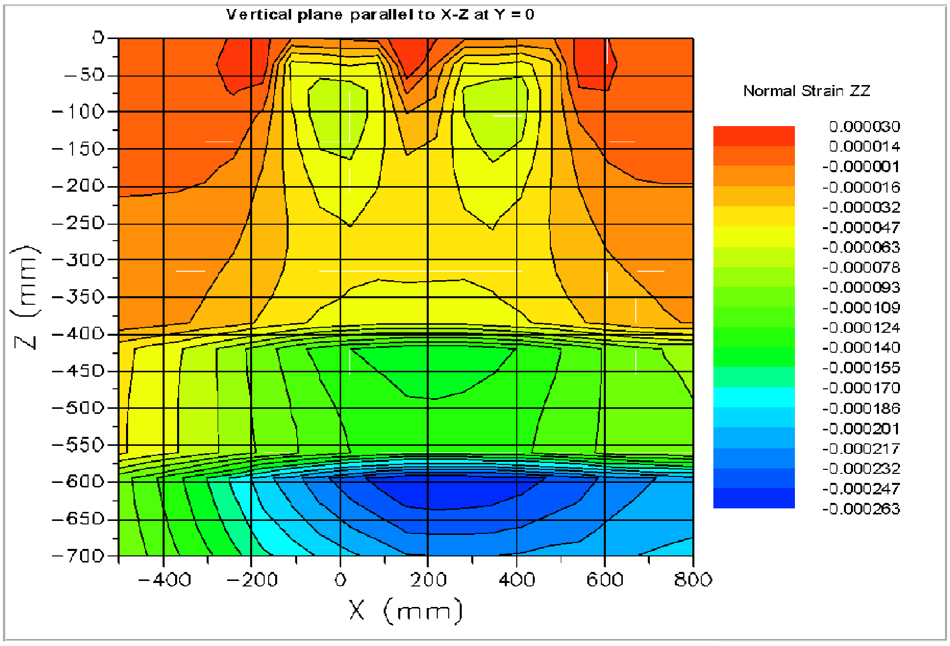


Figure 67 Trend of Normal Strain in a vertical plane of Italian Flexible Pavement

And the maximum vertical displacement is registered on surface and on base layer, the values are between 0,079 mm and 0,067 mm, as shown in the Figure 68.

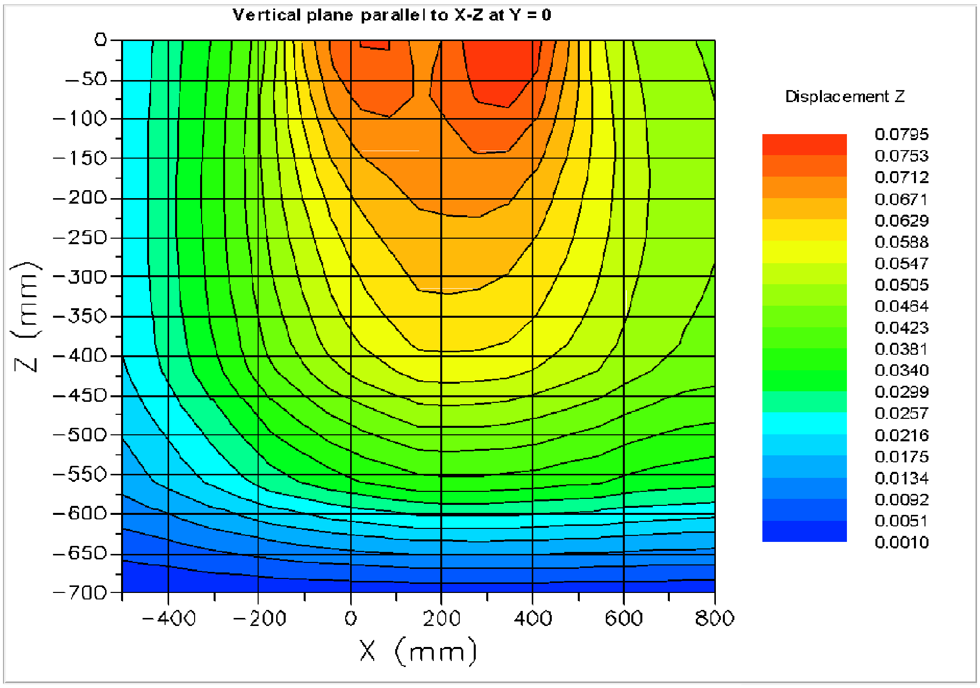


Figure 68 Trend of Displacement in a vertical plane of Italian Flexible Pavement

13.2.3. MORGAN COUNTY INVERTED PAVEMENT TEST SECTION

The third simulation was made on Georgia Inverted Pavement test section of Morgan County, that was build up in 2003. In the Figure 69, Figure 70, Figure 71, I have reported the software screen video about infrastructure characteristics: there are 5 layers from foundation with minimum CBR 15, 5 cm graded aggregates (characterized as G2), 20 cm cement mix, 15 cm of granular base G1 with Young’s modulus 200 MPa and 7,6 cm of Asphalt concrete.

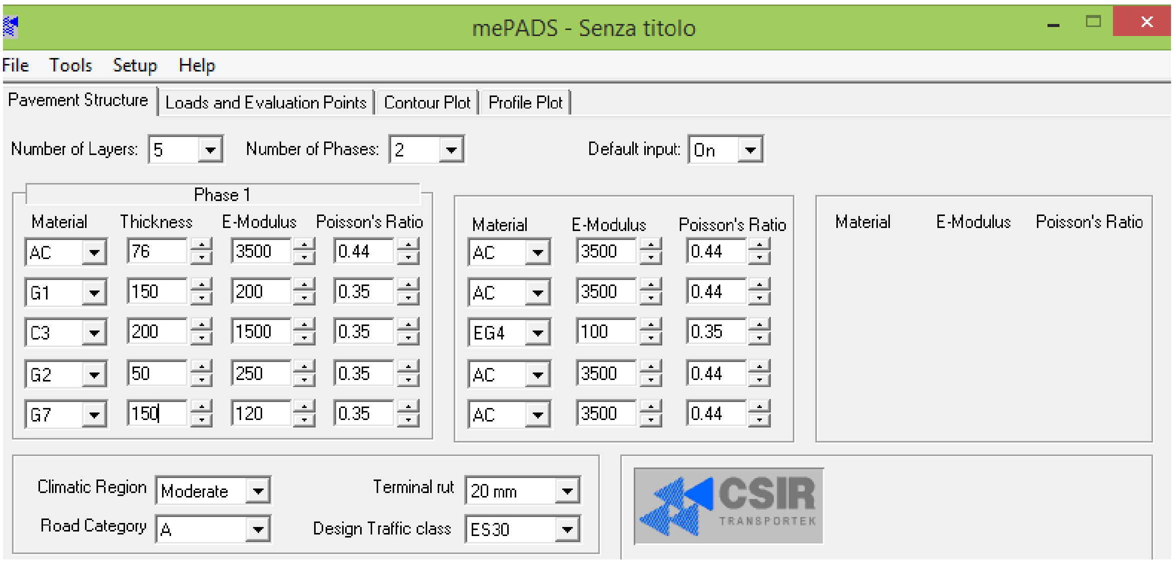


Figure 69 MePads Screen Video with Morgan County inverted pavement test section values.

The software simulation shows that the maximum displacement is 0,37 mm and in concentrated in the hot mix asphalt layer as shows in the Figure 70.

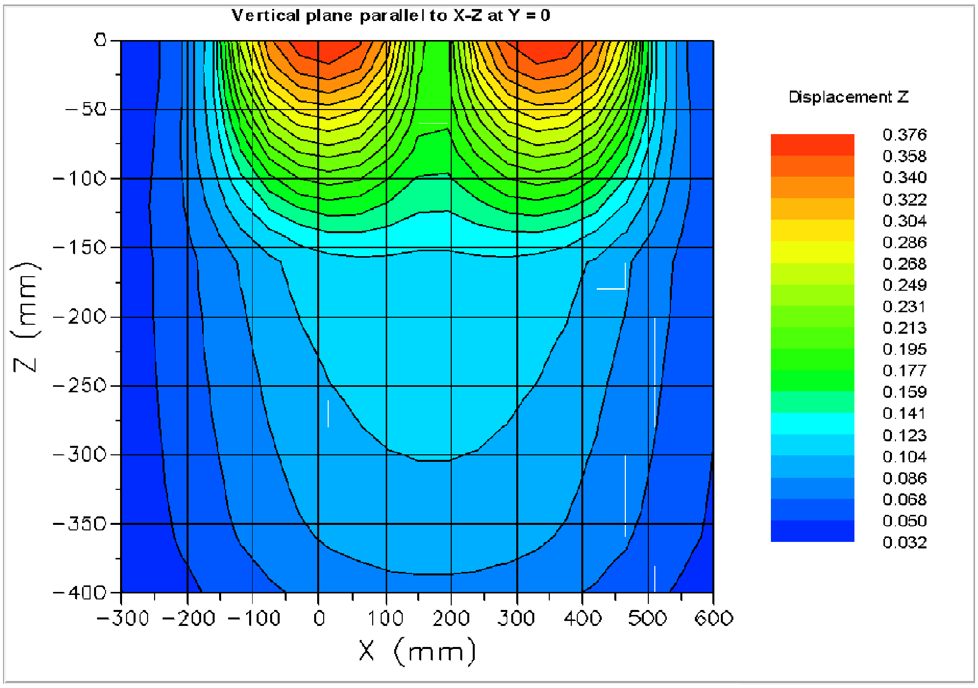


Figure 70 Trend of Displacement in a vertical plane of Morgan County test section

Also the maximum Normal Strain is registered in the same part of the infrastructure, the values are between 0.0015 and 0.0008 as reported in the Figure 71.

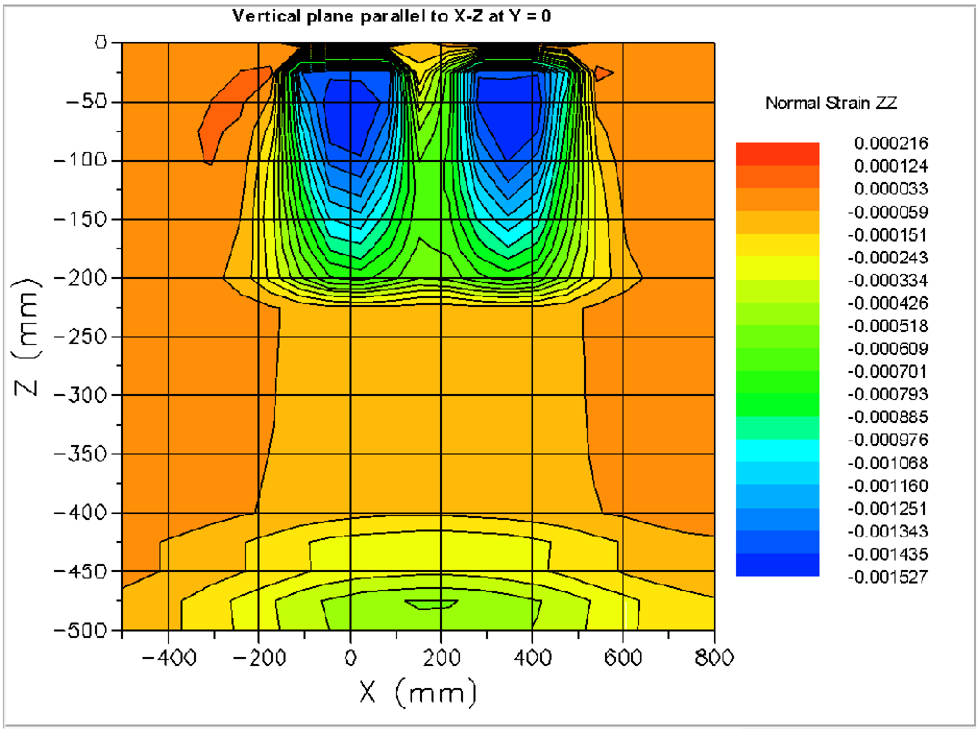


Figure 71 Trend of Normal Strain in a vertical plane of Morgan County test section.

13.2.4. LAGRANGE INVERTED PAVEMENT TEST SECTION

Another simulation was made on LaGrange inverted pavement test section, as you can see in the Figure 72 the test section is characterized of 150 cm of sub-grade (as G7), 25 cm of cement mix C3, 15 cm of G1 (but as shown in the test results the material is more close to G2) and 8,9 cm of Asphalt concrete.

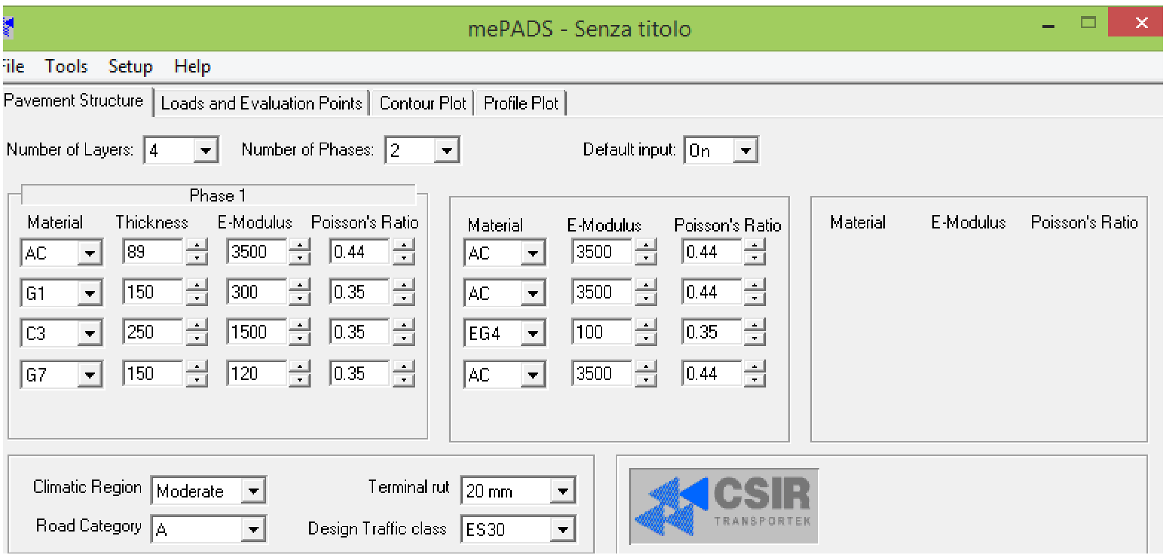


Figure 72 MePads Screen Video of LaGrange inverted pavement test section values

The software simulation reported that the normal strain maximum value is in the base layer and the values are around 0.0019 as shown in the Figure 73.

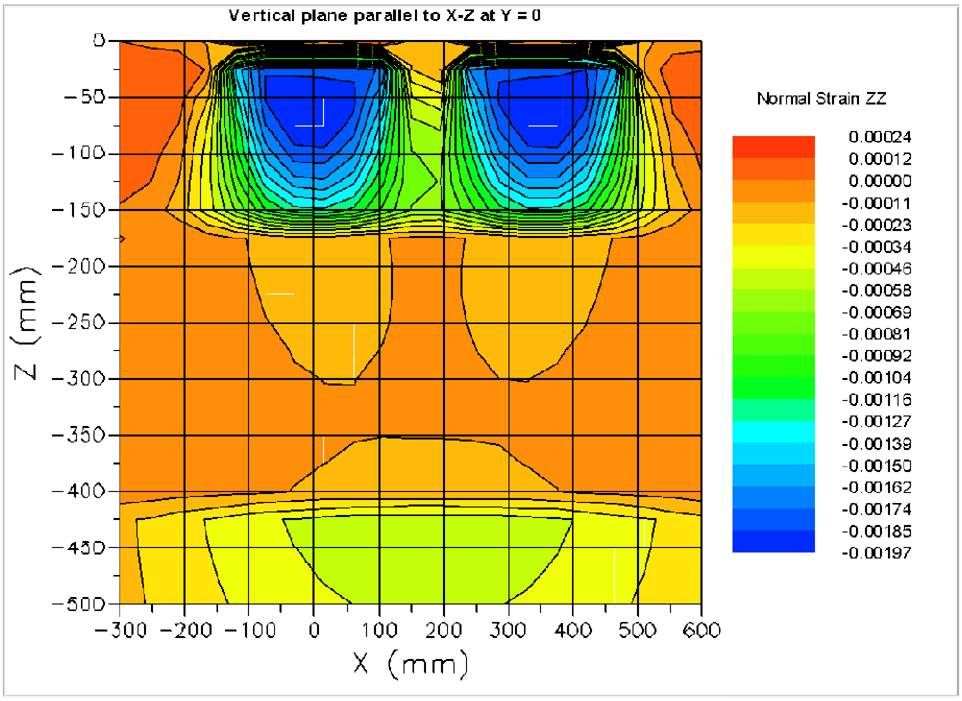


Figure 73 Trend of Normal Strain in a vertical plane of LaGrange test section

The Figure 74 shows the vertical displacement value, the highest value are in the hot mix asphalt layer and in the upper part of aggregate base layer, the values are around 0.32 mm.

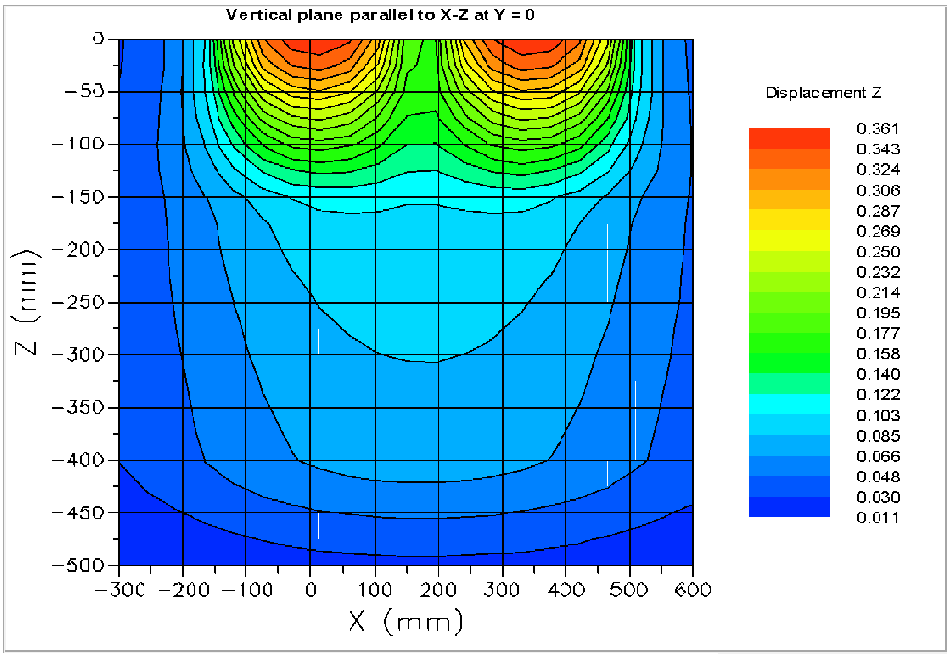


Figure 74 Trend of Displacement in a vertical plane of LaGrange test section

13.2.5. ITALIAN INVERTED PAVEMENT SIMULATION

The Italian inverted pavement simulation was made considering 7 cm hot mix asphalt surface, 150 granular base course with granite characterized as G1 with 200MPa Young's modulus, 250 cm of cement mix sub-base layer with 4% cement, 150 sub-grade classified as G2 and 150 cm foundation as G7.

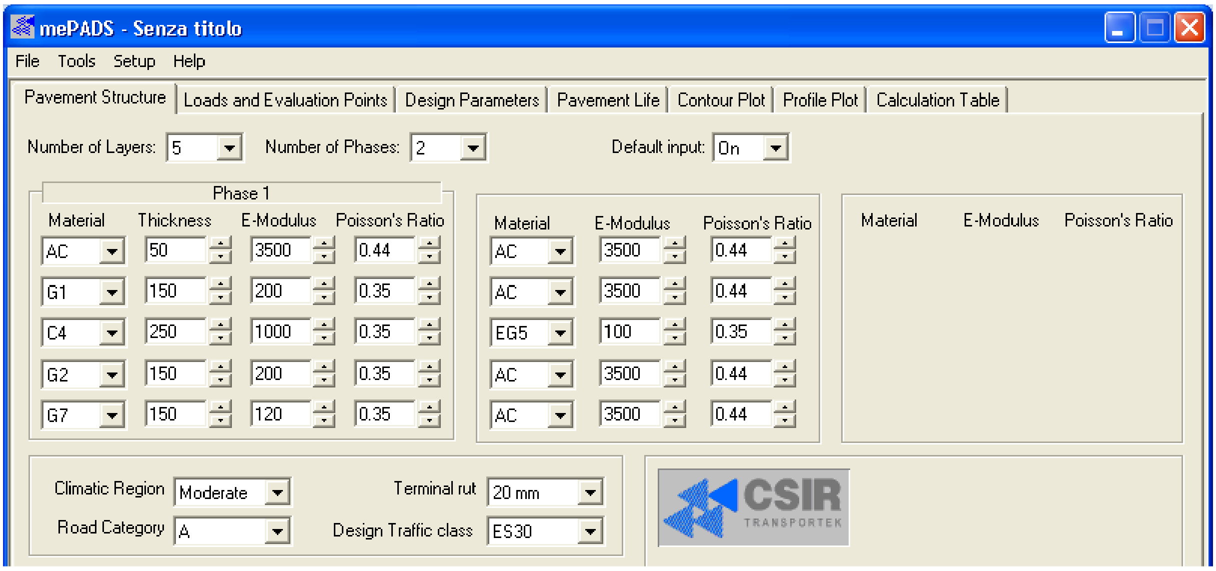


Figure 75 MePads Screen Video of Italian Inverted pavement simulation values

In the Figure 76 a trend of normal strain are shown, we can observed that the maximum value are in the hot mix asphalt layer and in the aggregates base layer, the sub-base registered just 0.000349 normal strain value.

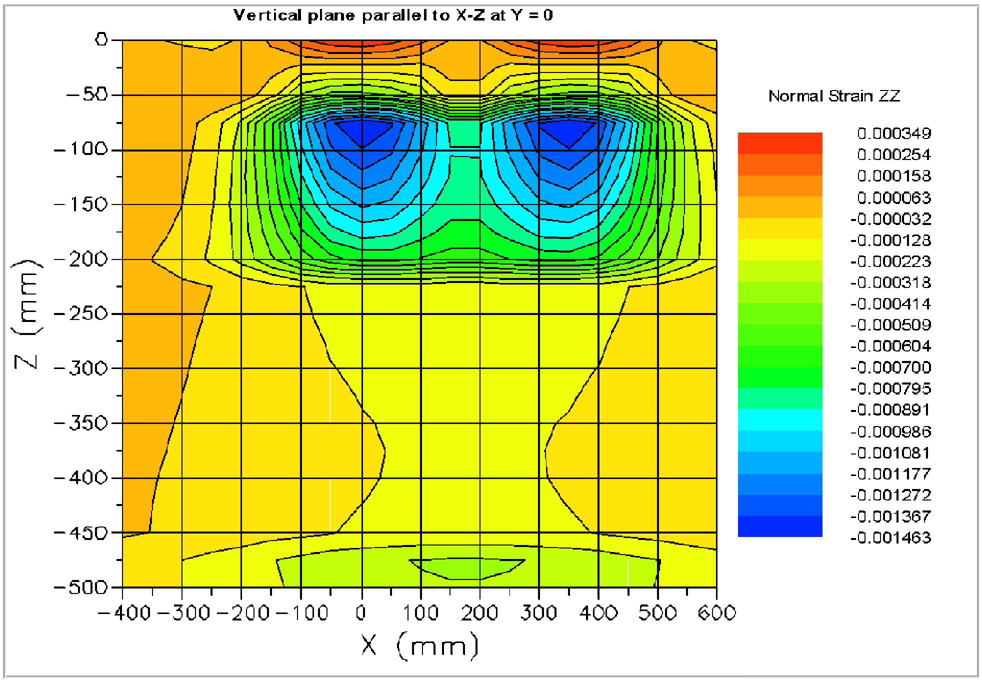


Figure 76 Trend of Normal strain in a vertical plane of Italian inverted pavement simulation

Also the maximum displacement are concentrated in the hot mix asphalt layer and in the aggregates base layer with value between 0.312 and 0.26 mm, as shown in the Figure 77.

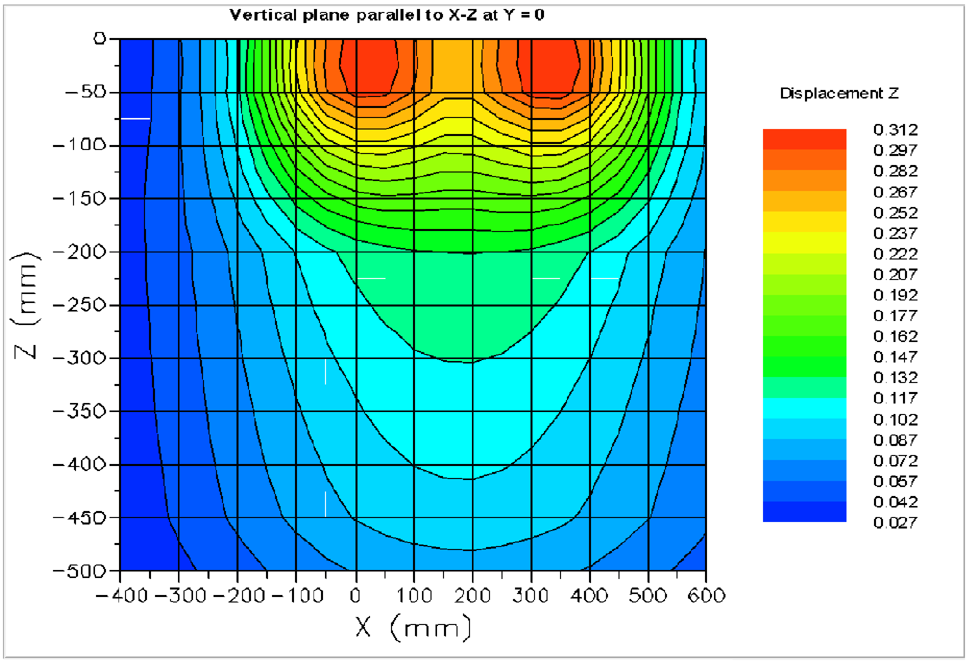


Figure 77 Trend of Displacement in a vertical plane of Italian inverted pavement simulation

13.3. SOME CONCLUSIONS ABOUT SOFTWARE SIMULATION

In this step we can obtain some conclusion about the maximum displacement and maximum normal strain value for all different kind of Inverted pavement (IP) structure. In the table below I have reported all value to comparing the different behavior.

Table 32 Comparison between every Inverted Pavement simulation values

	South African IP	Morgan County IP	LaGrange IP	Italian IP	Italian Flexible
Displacement (mm)	0,255	0,376	0,361	0,312	0,079
Normal Strain	0,000912	0,00152	0,00197	0,00146	0,000263
HMA layer (mm)	50	76	89	50	410

As you can see the results of South African Inverted Pavement are the best, although the Morgan County and LaGrange inverted pavement shows a very good behavior in term of software simulation and also in the real practice. The Italian inverted pavement shows a little bit higher values than the other one, but in term of savings of bitumen thickness layer is the best one. In fact the software simulation concerning the Italian inverted pavement is characterized by the thinner hot mix asphalt layer.
The difference between Italian Flexible and Italian Inverted pavement in terms of thickness of the hot mix asphalt layer is 36 cm.

14. ECONOMIC BENEFITS

Sardinia is characterized by a high landscape value given the variety of flora and fauna. The opening of mining sites of stone materials, and related ancillary areas to working lead to a prolonged and permanent impairment and disfigurement of the areas where this crop insists, despite measures to mitigate these fronts extraction, put in place according to the rules present in the D. Lgs. 3 April 2006, n.152, Environmental Regulations. the percentages of land use, on a total area of about 94,876 square meters, the excavation area is 34,285 square meters and 39,835 square meters area set up in landfill. As can be easily understood that the storage area of the materials placed in landfill from processing represent a footprint of 42% of the total area occupied by the extraction site (Pintus, 2011). These areas as well as representing a problem from the environmental point of view, in terms of disfigurement of the landscape, are characterized by a high financial price for companies extractors, in fact, in addition to the bulky surface must be paid time and money at the disposal of waste to landfill. The accumulation of the waste takes place according to the following deposition horizontal planes, whose interstices should be filled and each layer well compacted absolutely avoiding that they remain of the air chamber, which allows water to infiltrate, leading to erosion and consequent slope stability of the landfill. You have to pay more attention and care, interventions aimed at mitigating or restoring environmental impact of landfills, because, as the environmental impact report, are the most easily visible and value more the landscape. The proposed mitigation and environmental restoration of the quarry, allow you to operate the technical choices that minimize the degradation product on the territory. In this research the potential applications of granite by-products to be used in the road construction industry were taken into consideration evaluating the possibility of using such materials to recreate South African Inverted Pavement with super-compacted unbound granular layers known as G1. This with the aim of using this type of super-compacted material to replace the foundation layer of an Italian pavement structure to evaluate if this will bring benefits in terms of reduction of thickness of the HMA layers.

For better understanding the economic saving coming from the introduction of this new technology was made an analysis of the costs of the superstructure realization, using the price list of the ANAS, for each typology of superstructure simulated through MePads. The analysis shows the following economic results:

Table 33 Costs Analysis of Inverted Pavement

South African IP			
Layer	Depht (mm)	Price (euro/m^2)	Price x Depht
HMA	50	12,80	0,64
G1 Crushed Stone	150	4,60	0,69
C3 Cement Mix	250	6,20	1,55
G7	150	3,90	0,58
In situ Soil	150	2,60	0,39
		TOTALE EURO/M^2	**3,85**
Morgan County IP			
Layer	Depht (mm)	Price (euro)	Price x Depht
HMA	76	12,80	0,97
G1 Crushed Stone	150	4,60	0,69
C3 Cement Mix	200	6,20	1,24
G2	50	4,60	0,23
G7	150	3,90	0,58
		TOTALE EURO/M^2	**3,71**
LaGrange IP			
Layer	Depht (mm)	Price (euro)	Price x Depht
HMA	89	12,80	1,14

G1 Crushed Stone	150	4,60	0,69
C3 Cement Mix	250	6,20	1,55
G7	150	3,90	0,58
		TOTALE EURO/M^2	**3,96**
Italian IP			
Layer	Depht (mm)	Price (euro)	Price x Depht
HMA	50	12,80	0,64
G1 Crushed Stone	150	4,60	0,69
C4 Cement Mix	250	6,20	1,55
G2	150	4,60	0,69
G7	150	3,90	0,58
		TOTALE EURO/M^2	**4,15**
Italian Flexible Pavement			
Layer	Depht (mm)	Price (euro)	Price x Depht
HMA	410	12,80	5,24
G2 Crushed Stone	150	4,60	0,69
In Situ Soil	150	3,90	0,58
		TOTALE EURO/M^2	**6,51**

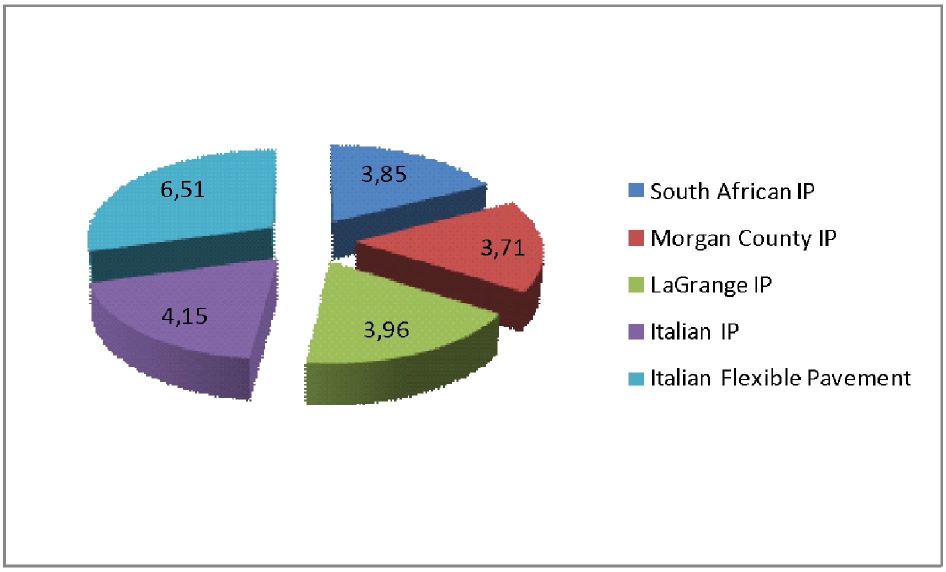


Figure 78 Economic Benefits using Inverted Pavement Technicque

It is easy to notice that from the Italian flexible paving to the Italian inverted pavement you would have a saving of 40%. A completely precautionary value, because I assumed that the mine sells the waste material at the same price of the waste material stocked at landfill.

The costs for the overall implementation of the superstructure are reduced by 40% with the method of inverted pavement, while reducing costs in the single-layer HMA is reduced by 75%.

15. CRITICAL DISCUSSION AND CONCLUSIONS

Considering the potential applications of granite by-products to be used in the road industry, it is possible to state that the test conducted on Sardinian granite by-products, deriving from the Calangianus, have shown that they can be considered a valid alternative to the aggregates that are currently used in South Africa for Inverted Pavement Technique. Focusing the attention on their use in the inverted pavement base layer, were considered all the points, from environmental compatibility to chemical-physical-mechanical features, up to the simulations to complete elements.

First of all, was considered the compatibility factor: the results obtained from the leaching tests proved that material is perfectly compatible to the road use. Indeed, all the values of concentration of minerals respect the normative values limit.

Secondly, were analyzed the chemical-physical features of granite scraps and were compared the results with those obtained on Dolerite. About chemical features it is inferred that the significant difference between two rocks is Ph: indeed, we have dolerite, that is a basic rock and granite, that is a acidic rock. From the physical point of view, results show values of density, porosity and water absorption that are almost alike. The greater differences were found in the value of Uniaxial Compressive Srenght, that for Dolerite is 40 MPa and for granite is 184 Mpa. This means that in the chipping phase, it will be necessary a bigger energy to obtain the desired sizes. Another significant difference was found in the value of the *Los Angeles test* that shows values of 14-15% for Dolerite and of 26-31% for Granite. A high value would indicate the potential of generation of dust, and break down during construction process. From the mechanical point of view, I made some specific tests required by the South African Regulations for inverted pavement. Regulations consider two tests of mechanical resistance, as *%FACT* and *ACV*, that are not considered by the Italian Regulations. From the point of view of *10%FACT*, granite follows perfectly the values limit that are required; instead, from the point of view of the *ACV test*, it showed values of 1-2% out of the normative limits. After these results, we paid attention to the problem of studying if in another town of the World was used the technique of Inverted Pavement through the use of rocks different to Dolerite. In the town of Atlanta, in the State of Georgia, I examined two test sections in the villages of Morgan County and LaGrange, realized respectively in 1999 and in 2009. It was possible to make some samples taking in two mines that supplied materials for the realization of the road superstructures. On the material that was extracted in the mine were made the tests of mechanical resistance and the results obtained by the ACV on the material used in Morgan County shows again some values out of the limit of 1-2%; instead, the values of ACV on the material used in LaGrange show some values out of the limit of about 1%. Values represent the evidence according to which the granite used in the test sections, despite not being in compliance with the limits required by the South African Regulations, has excellent results in situ, as well as I noticed.

The results obtained by the simulations done through MePADS software show again that the technology of Inverted Pavement allows to obtain high performances in terms of resistance to deformation, in spite of using a layer of bituminous melt of only 5-8 cm.

The economic benefit, in terms of saving of the raw materials used for the realization of the single superstructures examined, is obvious: it would be possible to save 40% for the realization of superstructure through a saving of not renewable raw materials, as the bituminous melt of 75%.

The values obtained thanks to laboratory tests, to software simulations and to the experience stabilized in other countries, does not give doubts on the excellent potentialities of granite by-products and of Inverted Pavement.

16. RECOMMENDATIONS FOR FURTHER RESEARCH

The results from this work cannot be used directly as guidelines to use Sardinian granite by-products for Inverted Pavement Technique. However, some results may be useful for further studies to validate the potential use of this material in the base layer.

It is necessary to remember that the granite that I analyzed is only one of eleven kinds present in the Sardinian territory, and so the physical-mechanical features could be different for other typologies of granite.

Future studies can validate the results that we obtained thanks to this research, through the building of a professional test section, open to traffic, and through a continuous monitoring of the bearing capacities of the superstructure and of the deformations, through not destructive measurement tools such as the Falling Weight Deflectometer.

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