UNIVERSITY OF CAGLIARI

PhD School in Civil Engineering and Architecture

PhD in Structural Engineering

XXIV CYCLE

New Building Materials in Structural Engineering

"Structural Concretes made with Coarse and Fine Recycled Aggregates"

PhD Student
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PhD School in Civil Engineering and Architecture

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XXIV CICLO

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Tutor: Prof. Ing. Luisa Pani

SSD : ICAR 09: Tecnica delle Costruzioni

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Introduction

With more than three tons per head, per year, concrete is the most important and widespread material used in construction worldwide.
The Italian code allows the use of waste produced by construction and demolition (C&D) operations to produce recycled aggregates.
The great interest, both technical-economic and environmental aroused by this subject has in recent years and all over the world led to a noteworthy increase in experimental and theoretical studies on recycled materials resulting from the construction sector and, in particular, on recycled aggregates.
The possibility of utilizing recycled aggregate is a very good solution to the problem of C&D waste and at the same time it reduces quarrying operations and limits the use of natural aggregates.
The Italian ministerial decree of 14 January 2008 containing technical regulations for construction works, together with UNI EN 12620 and UNI 8520-2 standards concerning structural materials now allows a limited replacement percentage of only coarse recycled aggregates (sizes above 4 mm), to produce structural recycled concrete, if previously recycled aggregates used were identified, selected and tested following the same regulations.

In this scenario, the research activities described herein were developed with the final purposes of:

I. Characterizing “real” coarse and fine recycled aggregates derived from construction and demolition waste by only concrete, randomly taken (without the knowledge of mechanical properties, shape, age and condition) from an authorised class A storage site located around Cagliari in Sardinia. This characterization was performed to determine their performance, compliance with the Italian code and the best experimental practice for the production and use in structural concrete. Furthermore the characterization of recycled aggregates by means of their shape, sizes, density, structure, strength, permeability and resistance to freezing and thawing cycles, directly leads to CE+2 certification, which is not present in Sardinia at the moment.

II. Analyzing different concrete mixtures made with different replacement percentages of fine and coarse and only coarse recycled aggregates in place of the natural ones to create a product having good properties during production, transport and implementation, with good compatibility with all devices and machines employed in concrete plants. The intention is to use recycled aggregates produced exclusively by concrete, coming from authorized class A storage sites, immediately after their release from the crusher and to optimize the mix design of the recycled concrete and the relative packaging procedure.

III. Determining the mechanical properties of recycled concrete made with different replacement percentages of coarse and fine and only coarse recycled aggregates and comparing them with ordinary concrete to measure the gap in performance and evaluating their use in structural concrete.

IV. Reviewing and examining the scientific scenario in the determination of mechanical properties of the transition zone (ITZ) between aggregates and cement mortar to analyse its influence on strength features of recycled concrete. Some possible uses of numerical simulation of problems in approaching this issue will be provided. In particular, this part of the work was carried out at the University of East Paris “Marne la Vallèe”.

Chapter 1. State of the art

1.1 ENVIRONMENTAL SUSTAINABILITY

Sustainable development and environmental protection are today sensitive issues all around the world due to increasing energy consumption and the decrease in non-renewable natural resources. The correct definition of “sustainable development” is: the possibility of satisfying present-day needs without preventing future generations from satisfying theirs [1].

Problems connected with the environment and the large amounts of wastes produced by construction and demolition (C&D) year by year, makes it indispensable to find innovative solutions for the disposal or reuse of recyclable materials. This must be the main interest in all operations and of all those operating in the construction sector.

Many European country such as Denmark, The Netherlands, Belgium and Germany have been studying for many years the issue of recycling of construction and demolition wastes. Those countries have laws that impose their reuse.

The recycling of wastes resulting from C&D operations means a decrease in the use of natural materials destined to finish during the next decades, and also an important saving of money in consideration of the costs connected with their disposal and a certain escalation in the number of unauthorized dumps.

In Italy alone, the civil construction work produce 40 million tons of wastes per year, which is an enormous amount of material that must be disposed of but which, by performing the necessary operations, could become recyclable, thus helping the economy and facilitating the creation of new jobs. A noteworthy problem in the situation of our country is that there is no real way of quantifying C&D wastes. Also it’s very complicated to make an accurate “census” of the active recycled sites throughout the nation [2-3].

Another important limiting factor is that there are always much perplexity about the use of recycled materials in buildings; this fact is linked to the idea that recycled materials are somehow inferior in quality and mechanical properties than ordinary ones.

In Sardinia for example, there is no construction company equipped to demolish buildings selectively, therefore wastes coming from C&D procedures arrive at the storage site with no selection or separation, and are crushed in this way.

Table 1 presents the percentage of solid wastes derived from C&D and the recycled percentage at present. In Italy, 30% of all wastes come from the demolition of civil buildings; of this, only 10% is recycled while 90% is abandoned at storage sites.

The situation is critical: in comparison to the other European countries, Italy is far behind. Denmark is a virtuous case: between 25% and 50% of wastes are connected to C&D and more or less 80% are recycled before the final abatement [4].

These wastes are primarily composed of concrete, sand, wood, metals, glass, production wastes, bitumen, plastic, paper, etc., and the composition varies greatly depending on the location of the storage site in the country. An interesting projection [5] estimated that 75% of total debris in the European Union is composed of waste produced by the demolition of concrete.

Country	C&D wastes (%)	Recycled from C&D (%)
Australia	**44**	**51**
Brazil	**15**	**8**
Denmark	**25-50**	**80**
Finland	**14**	**40**
France	**25**	**20-30**
Germany	**19**	**40-60**
Hong Kong	**38**	**N.I**
Japan	**36**	**65**
Italy	**30**	**10**
Netherlands	**26**	**75**
Norway	**30**	**7**
Spain	**70**	**17**
United Kingdom	**More than 50**	**40**
United States	**29**	**25**

Table 1 - Percentages of solid wastes from C&D operations (2007)

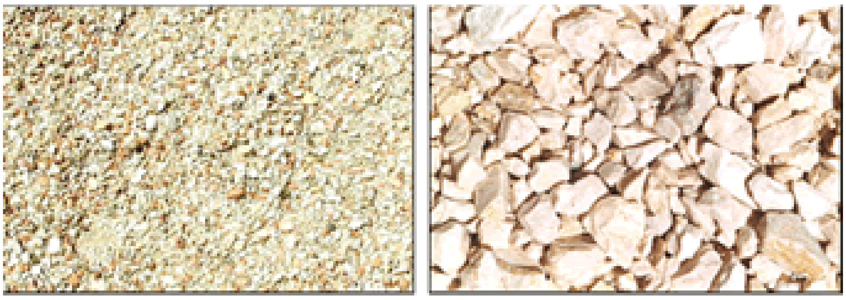

Fig.1 – Fine and coarse natural aggregate

Fig. 2 – Fine and coarse recycled aggregate derived from demolition waste

Wastes produced by C&D operations are numerous and very heterogeneous. The first and second (MPS) materials obtained from homogeneous wastes are usually better than those derived from a heterogeneous mix of products. To facilitate the recycling of building materials it would be desirable to adopt only demolition techniques producing homogeneous wastes. This strategy, usually called “selective demolition”, is still not widespread due to the higher costs and longer times connected with the operations even though this allows better separation of the materials and the elimination of useless substances and the pollutants. What occurs in the real case is that the economy and speed of the process are the most important factors so there is no attention paid to the reuse of the material and the selection and handling of demolition products [10].

The regulations only specify the devices that must be employed in crushing of the wastes but there are no any particular specifications on the type of the site. This generates some confusion and not the right situation to facilitate recycling operations.

At present, C&D wastes are used to create recycled aggregates often employed in the field of civil engineering mostly for roads and in the production of non-structural concrete.

1.2 RECYCLED AGGREGATES

Recycled aggregates come directly from construction and demolition wastes (C&D). They occur as different kinds of rock elements covered by a layer of cement mortar.

When the concrete undergoes the crushing step, all the mortar that is not attached to the aggregates is completely broken into very thin elements that could be removed during sieving.

In the last few years many research projects have focused on different applications employing the recycled aggregates and the results obtained have been very promising [11-13].

The studies performed analysed many useful fundamental parameters used to characterize the behaviour of the recycled aggregates. These parameters are listed below with a brief description, definition and their influence:

Density

The recycled aggregates occur in small elements covered by a layer of mortar. The mortar is more porous than the natural rock so it is clear that the density of the recycled aggregates is lower than the natural ones.

This reduction in density is greater for the fine recycled aggregates due to the presence of a larger amount of mortar. For the fine aggregates the mortar may be between 30 and 65% of the total mass, while in the recycled coarse ones it rarely exceeds 40% [14-20].

The main tendency of the standard (UNI EN 12620: 2008) is to control the percentage of mortar in the recycled aggregates by means of a critical value of density that must be complied with.

Water absorption

The layer of mortar on the recycled aggregate’s surfaces directly causes a decrease in density and a greater capacity to absorb water than the natural aggregates.

In particular, water absorption of the coarse recycled aggregates (from 4 to 32 mm) can vary by 4 to 9% and is found to be independent of the quality of the original concrete. The situation is different for fine recycled aggregates which can reach 12%. Water absorption for natural aggregates is between 0.5 and 2.5 percent [14-20].

Presence of polluting elements

The presence of pollutants is common in recycled aggregates because of the composition of the materials and the addition of particular substances during the manufacturing process.

This undesired material includes: gypsum, asphalt, glass, aluminium, organic materials, tiles, bricks, chloride, etc.

All pollutants are very important because their elimination is a key factor in producing a good result since they cause a decrease in the mechanical properties of the concrete.

Different international researches have shown that the mechanical properties of concrete are not affected when the aggregates are degraded by window glass, although an excessive amount of glass could create some problems due to the reaction between alkali-aggregate.

The presence of bitumen can impact significantly on compressive mechanical behaviour.

Some organic elements can slow down the hydration process of cement or increase the instability of the concrete when submitted to dry/wet cycles; varnishes for example can facilitate the extra inclusion of air inside the concrete, thus leading to a decrease in mechanical features.

Traces of vegetable soil and clayey fractions are completely unacceptable in a very similar way as that encountered for natural aggregates. These kinds of argillaceous materials act to reduce adhesion phenomena between the matrix and the aggregate, thus reducing compressive strength.

Difficulty in controlling the mix water

Due to strong absorption, the recycled aggregates require a long time to reach the saturation surface dry point. The kind/class of aggregates influences the speed of water absorption and the time required may consistently vary, especially in the next step after mixing. This situation makes it difficult to control the workability and verification of the effective water/concrete ratio.

Many research projects and international studies have theorized an increased need for concrete (due to the larger amounts of water required) when recycled aggregates are employed instead of natural ones. To avoid this inconvenience, other authors [14-20] introduce an extra step when recycled aggregates are used, that is, their pre-saturation.

The production of fine aggregates and fresh concrete workability

The mortar attached to recycled aggregates reduces density and increases water absorption, thus causing the most important reasons for damage of recycled concrete: a little control of production of fine fractions, generated by the crumbling of the old cement mortar. This phenomenon modifies the original particle size distribution and workability.

For this reason most studies on this topic suggest not to employ fine recycled aggregates (< 2 mm) because they have a larger percentage of mortar than coarse ones, or eventually to insert a step where the aggregates alone are pre-mixed in the concrete mixer for five minutes. Using this solution the workability of the fresh concrete notably improves.

1.3 RECYCLED CONCRETE

In the last few years the interest in concrete recycling operations has increased rapidly due to the continuous increase in the volume of concrete demolitions.

Moreover, the low availability of natural aggregates has determined a rise in their cost which is bound to increase year by year.

Notwithstanding all these facts, there is still a distrust in the potential and use of recycled materials. Engineers and construction companies usually prefer to apply a conservative approach through the use of “standard” building materials.

1.3.1 PROPERTIES OF FRESH AND HARDENED CONCRETE

The mechanical properties of recycled concrete are usually worse than natural ones. This relation is clearly dependent on the replacement percentage of recycled aggregates instead of on the natural elements. Indeed, the characteristics of concrete change if coarse and fine aggregates are used together instead of just coarse ones.

The elastic modulus also changes: the minor stiffness of recycled aggregates is usually linked to a minor elastic modulus compared to natural concrete [26-38].

Considering fresh recycled concrete, the presence of mortar on the aggregates, their texture and absorption ability determines a greater need for water than in ordinary concrete.

The workability of concrete made with recycled aggregates strongly depends on the free water inside the mixture and on the initial humidity status of the aggregates.

When employing dry recycled aggregates with a high replacement percentage, the original workability of the recycled concrete is equal or sometimes even better than the ordinary exemplars, thanks to the large amount of free water and the greater absorption, while workability at 30 minutes is actually lower than that of natural concrete.

When recycled aggregates in the sutured surface dry condition are used (SSD) the workability at 5 and 30 minutes is comparable to the value obtained for natural concrete [39].

These are very good reasons to recommend a water check for the mix of recycled concrete. Pre-saturation of the aggregates to limit losses in workability is a key factor.

1.4 RECYCLED AGGREGATES NORMATIVE AND CE MARKING

To study and elaborate on the employment possibility of the recycled aggregates in the concrete production and for exactly define their properties, during the 1976 the “RILEM” starts a research that performed a first report in 1993 to clarify the state of the art and the techniques used in the production of new concrete using recycled aggregates derived from structural demolitions (RILEM TC 121, 1993).

The “Direttiva 99/31/CE” of 26 April 1999, more precisely in the “art. 2 letter. e” was the first to introduce the definition of inert waste.

In Europe since 2002, the EN 12620 normative is valid. It specifies the criteria to classify the aggregates using various parameter (shape, geometry, mechanical/physical/chemical properties) and the manufacturing processes to follow to obtain a CE mark.

This regulations is not valid just for the natural aggregates but for the artificial ones too, even if derived from construction and demolition operations (C&D).

It was written considering all the environmental needs and all the different praxis noticed all around the European Countries. In Italy for example some experimental assessment are not compulsory (wear test and the evaluation of the percentage of shell) since they are not required by the national regulation on concrete.

The UNI EN 12620 is valid for all the aggregates with density bigger than 2000 kg/m^3 after the heat-treatment in oven and for all the classes of concrete.

It could be used even with recycled aggregates with density between 1500 and 2000 kg/m^3 and in some cases even for the fine aggregates but the limitations are particularly stricter.

Summarizing the Italian scenario it’s possible to state that the national normative on the recycled aggregates in the civil engineering was modified many times in the past years following the environmental needs.

The “Decreto 8 maggio 2003, n. 203 del Ministero dell’Ambiente e della Tutela del Territorio” provides that the public institutions and the companies with prevailing public capital, must satisfy the 30% of the total annual requirements of civil construction, using recycled materials.

The “Circolare n. 5205 del 15/07/2005” imposes to the National Administration offices to cover at least the 30% of the total annual requirement with recycled aggregates.

The UNI 8520-2 sets the geometric and mechanical requirements that the recycled aggregates must have to be used to create the recycled concrete. It indicates the classes of the aggregates to be chosen following the UNI EN 12620, to obtain concretes to be used for different structures satisfying the strength and durability requirement.

To identify the properties of the natural and recycled materials to be employed to produce structural concrete the reference regulations are:

UNI EN 12620: 2008. "Aggregates for concrete";
UNI 8520-1: “Aggregati per confezione di calcestruzzi - Definizione, classificazione e caratteristiche”;
UNI 8520-2: “Aggregati per confezione di calcestruzzi – Requisiti”;
UNI EN 933-1: 2009. “ Tests for geometrical properties of aggregates - Determination of particle size distribution - Sieving method ”;
UNI EN 933-3: 2004. "Tests for geometrical properties of aggregates” - Part 3: Determination of - Flakiness index;

UNI EN 933-4: 2008. "Tests for geometrical properties of aggregates - Part 4”: Determination of particle shape - Shape index;
UNI EN 1097-2: 2008. "Tests for mechanical and physical properties of aggregates” - Part 2: Methods for the determination of resistance to fragmentation;
UNI EN 1097-6: 2008. "Tests for mechanical and physical properties of aggregates” - Part 6: Determination of particle density and water absorption “;
UNI EN 1367-1: 2007. "Tests for thermal and weathering properties of aggregates” - Part 1: Determination of resistance to freezing and thawing.

The UE M/125 established that the aggregates used in the concrete production and in particular all the inert material traded after the 1st June 2004 must be CE marked.
The “Norme tecniche per le costruzioni” – D.M. 14 gennaio 2008 – following the UNI EN 12620 and the UNI 8520-2, nowadays allow to use recycled aggregates to replace the natural ones but is explicitly demand only the employ of coarse aggregates and with very small quantity depending on the class of the concrete that it must be realised.
If the recycled aggregates are produced during demolition procedures by just concrete, the use is permitted (partial or complete) but limited just to the coarse aggregates. The replacement percentages depend by characteristic strength “Rck“ of the concrete that it must be realised.
By way of example for the resistance class ≤ C37 the admitted replacement percentage is ≤ 30 %, for the resistance class ≤ C25 the admitted replacement percentage is ≤ 60 % and in the end for the resistance class C10 up to 100%. (§ 11.2.9.2 Aggregates).

Chapter 2. Characterization of fine and coarse recycled aggregates by concrete

2.1 INTRODUCTION

Both the expense connected with disposal procedures and the scarcity of natural resources strongly suggest the using of wastes derived from construction operations to produce aggregates for use in the concrete manufacturing process.

The Italian ministerial decree of 14 January 2008 classifies recycled aggregates in three different categories: 1) aggregates that come from the demolition of buildings (debris and rubble); 2) aggregates produced by the demolition of concrete only and 3) aggregates that reuse the concrete inner part of precast reinforced concrete sites. This simple and schematic classification shows the main problems of the organization of storage sites of second class type A: the high variability of the recycled aggregates. Moreover, the crushing, usually performed with a jaw crusher, may lead to a different particle size distribution.

As is common knowledge, recycled aggregates (RA) have different properties than natural ones (NA) such as higher porosity, better permeability, lower density and strength. The differences are greater for fine recycled aggregates than for coarse ones.

An experimental survey was performed to characterize the coarse and fine recycled aggregates derived only from the construction and demolition of concrete. In a new way, this thesis did not implement the experimental campaign using customized concrete specimens created ad hoc in the laboratory and demolished, but performed the testing procedures on "real" recycled aggregates from only concrete, taken from an authorized storage site, to use them, immediately at the outlet of the crusher, for the making of structural concrete.

Due to this fact it is implicit that the status of conservation of the original concrete, its mechanical properties and age were not known.

The possibility of using recycled aggregates for produce structural concrete, as soon as they are crushed in a storage site, is an opportunity that involves technical, economic and environmental interests. The environmental benefit of using these materials is universally recognized, but their introduction into structural concrete is met with scepticism by all experts in the field.

The supply of recycled aggregates consisting of only concrete has been very difficult to find because demolition companies in Sardinia, and more precisely in the Cagliari area, are not organized to implement selective demolition of buildings and because storage sites do not divide the waste by C&D before crushing.

To select the storage sites to collect the recycled aggregates by concrete, a list of authorized sites was obtained from the website of the Region of Sardinia. After selecting and contacting them to verify their availability, inspections were conducted to check the material used and the possibility for the separation and crushing operations used at the sites.

From the first list, only the Ecoinerti (authorized storage site, II category class A, located in Iglesias) was found to be in line with the requirements to support the research activities.

Ecoinerti is at present not ready to produce recycled aggregates from only concrete, but thanks to the long experience of its staff in demolition operations, it was easy to inform point out to them of the characteristics of the recycled aggregates that we needed for the experimental campaign.

Our request at Ecoinerti consisted of recycled aggregates obtained from the crushing of only concrete blocks from demolition wastes, with a nominal diameter between 0 and 25 mm. In the recycled aggregates obtained in this way there were not to be present other types of waste.

2.2 EXPERIMENTAL SURVEY OF THE AGGREGATES

The recycled aggregates examined in the early stage of the research were labelled with the abbreviations: RA1, RA2, RA3.

They were collected during three different periods of the year: RA1 (January 2009), RA2 (March 2009), RA3 (October 2009) from Ecoinerti (Iglesias).

The choice of the materials was conducted randomly and this fact ensured the random collection of the concrete and for which the age, status of conservation and mechanical properties were not known.

Working together with the Ecoinerti staff, the concrete was identified accurately to avoid the presence of other common wastes connected with building demolition (brick, tile, etc) and then crushed using a jaw crasher to create recycled aggregates with a particle size distribution between 0 and 16 mm.

The natural aggregates, called NA1 and NA2, taken respectively from the Vibrocemento, a company producing precast reinforced concrete (located in Monastir, Cagliari), and from the Italcementi company, a producer of ready-mixed concrete (located in Quartu, Cagliari) were used for comparison.

In the very last phase of experimental operations (March 2011), according to the studies carried out in the University of East Paris "Marne La Vallee" described in Chapter 3, some other recycled aggregates were collected from Ecoinerti and labelled as RA4 with a maximum size of 25 mm.

In this chapter the results obtained in the laboratories of the University of Cagliari to describe the properties of RA1, RA2, RA3, RA4, NA1 and NA2 are reported and discussed.

For the recycled aggregates RA1, RA2, RA3 the test to determine particle size distribution, physical properties, geometry of the grains, mass and strength losses before freezing and thawing cycles, density, absorption of water and resistance to fragmentation was carried out, while the RA4 recycled aggregate were tested to measure density, absorption of water and resistance to fragmentation only.

Speaking of density, some other properties were determined: bulk density ρ_a, saturated surface dry density ρ_{ssd}.

All tests were performed according to the following standards:

UNI EN 12620: 2008. "Aggregates for concrete";
UNI 8520-1: “Aggregati per confezione di calcestruzzi - Definizione, classificazione e caratteristiche”;
UNI 8520-2: “Aggregati per confezione di calcestruzzi – Requisiti”;
UNI EN 933-1: 2009. “ Tests for geometrical properties of aggregates - Determination of particle size distribution - Sieving method ”;
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UNI EN 1097-6: 2008. "Tests for mechanical and physical properties of aggregates” - Part 6: Determination of particle density and water absorption “;
UNI EN 1367-1: 2007. "Tests for thermal and weathering properties of aggregates” - Part 1: Determination of resistance to freezing and thawing.

2.2.1 MATERIALS

Concrete is a heterogeneous material. The cohesion between the matrix and the aggregates depends on different factors: typology of the aggregates, texture of the surface (shape and roughness), quality of the mortar, inclusions and eventually the addition of mineral or chemical substances [4].

The recycled aggregates coming from the crushing of concrete have a much more irregular shape than natural ones. This fact is due to the cement matrix surrounding the original aggregates, randomly distributed with different stiffness and dimension.

During the crushing of the concrete the mortar that does not cover the aggregate is crushed more and more.

In the first experimental part of the work all the aggregates with a maximum dimension of 16 mm were characterized. They were all characterised to have a unevenly distributed attached cement mortar, and this resulted in the possibility of visualizing the surface of the original aggregates.

Afterwards, the same procedures were adopted with the remaining RA4 aggregates, with a maximum diameter of 25 mm, and an evenly distributed cement mortar along the surface of the original aggregates, than did the previous samples.

Pictures 1, 2a, 2b, 3, 4 and 5 show the natural and recycled aggregates adopted in the experimental tests.

Fig 1. – Natural Aggregates

Fig. 2a - RAC (RA1, RA2, RA3) and NA

Fig. 2b - RA4

Fig. 3 - Recycled Aggregates (left) and Natural (right)

Fig. 4 – Recycled Aggregates - Department of Structural Engineering, University of Cagliari

Fig. 5 – Natural Aggregates - Department of Structural Engineering, University of Cagliari

2.2.2 PARTICLE SIZE DISTRIBUTION OF RECYCLED AND NATURAL AGGREGATES

The particle size distribution was measured for both the recycled aggregates RA and the natural NA ones, according to UNI EN 933-1e and prEN 932-2.

The aggregates were classified by class and typology and were heat-treated at (110±5)°C for the time required to reach constant mass and then, after a pause for cooling, their mass was recorded.

Afterwards the specimens were dipped again in water for 24 hours. The day after they were then washed by means of a 63 μm sieve till the flushing water resulted perfectly clean.

After finalization of the procedures described above, the mass of the material retained by the 63 μm sieve was recorded and then the second mass of the specimen was recorded. Finally, mechanical sieving of the aggregates was performed.

This procedures allowed us to classify the aggregates in 9 different classes, one for each sieve, and thus measure their weight with an accuracy of 1% compared to the weight of the whole sample, in compliance with statutory provisions.

2.2.3 DETERMINATION OF THE SHAPE OF THE RECYCLED AND NATURAL AGGREGATES

Generally the size of aggregates is expressed by length L, equal to the maximum distance between two parallel tangent planes touching two opposite edges of the aggregates, thickness E, defined by the minimum distance of two parallel tangent planes to the surface of the aggregate and width D equal to the smallest diameter of sieve the aggregate can pass through.

2.2.3.1 FLAKINESS INDEX (FI)

A very important parameter in identifying the shape of a single grain is the ratio D/E. The UNI EN 933-3 standard was followed in performing the experiment. The test consisted of two different sieving operations: in the first one (Figure 6) a normal sieve was used to divide the sample into different particle sizes; in the second a different sieve with parallel rods was used (Figure 7). The second part was accomplished in the laboratory “Prove Materiali S.G.S” at Macchiareddu.

Fig. 6 – Normal sieve

Fig. 7 - Sieve with parallel rods

2.2.3.2 SHAPE INDEX (SI)

The coarse particles were classified with the ratio L/E by the shape coefficient that expresses cubicity (L/E ≤ 3) and non-cubicity (L/E ≥ 3). To perform this operation a sliding gauge was used.

According to UNI EN 933-4, the shape index SI was calculated using the mass of the non-cubic particles and then reported as a percentage of the total mass of the tested sample.

In Table 2.1, the results of the shape/geometry of the particle are displayed:

Test sample	size (mm)	Flakiness index FI (%)	Shape index SI (%)
[NA1]	4-20	11.99	
	4-8-16		52,3
[NA2]	4-20	10,85	
	4-8-16		47,0
[RA1]	4-20	8,73	
	4-8-16		54,8
[RA2]	4-20	11,79	
	4-8-16		43,0
[RA3]	4-20	10,6	
	4-8-16		52,0

Table 2.1 – Flakiness index and shape index of natural and recycled aggregates

2.2.4 Determination of the density and water absorption of the natural and recycled aggregates.

A method with a pycnometer, following UNI EN 1097-6, was adopted to calculate density and water absorption. This rule prescribes the parameter identification procedures for aggregates with sizes comprised between 4 and 31.5 mm and 0.063 and 4 mm.

More precisely, the test mentioned above indicates different operations for coarse and fine particles, thus in the first stage the entire sample was subdivided into 2 groups: the first was composed of set up with particles having a size between 0.063 and 4 mm, the second included 4 to 16 mm particles for the aggregates RA1, RA2 and RA3, while the reference dimension was 4 to 25 mm for the RA4 specimen.

After a washing cycle all the samples were placed inside the pycnometer and then the air was removed by rotation of the pycnometer. The whole sample was settled in a thermostatic bath for 24 hours at (22 ± 3)°C as shown in Figure 8.

Fig. 8 – Pycnometers with natural and recycled aggregates in thermostatic bath

After 24 hours the specimens were taken from the thermostatic bath and the entire mass was measured. The value of total mass includes the pycnometer, the aggregates and the water inside it.

Next, the coarse aggregates, the ones with size between 4 - 16 mm and then the others with a size between 4 - 25 mm, were put on absorbent paper and dried till the saturated surface dry condition was reached (Figure 9). The coarse aggregates were weighed before starting another heat treatment at 105 ± 5°C which allowed the sample to reach the constant mass condition.

Fig. 9 – Saturated surface dry condition of the recycled aggregates

The fine aggregates with size between 0.063 and 4 mm were placed in a 0.063 mm sieve and subjected to heat treatment with a hot air jet to help the evaporation process.
The sample was weighed again and heat-treated at 105 ± 5°C till it reached constant mass.
Following the procedures described in the standard, all the masses were weighed with an accuracy of 0.1% of the total mass of the sample used in the tests.
The results for the natural and recycled aggregates are shown in Table 2.2.

Test sample	Size (mm)	Bulk density ρ_a (Kg/m^3)	satured surface dry condition density ρ_{ssd} (Kg/m^3)	Predried density. ρ_{rd} (Kg/m^3)	WA_{24} Watre absorption (%)
[NA1]	4-16	2735	2675	2715	1,27
	0,063-4	2728	2720	2640	1,84
[NA2]	4-16	2691	2600	2580	1,40
	0,063-4	2707	2630	2610	2,00
[RA1]	4-16	2663	2509	2510	3,80
	0,063-4	2838	2626	2420	4,56
[RA2]	4-16	2383	2178	2100	5,60
	0,063-4	2528	2234	2150	9,50
[RA3]	4-16	2565	2408	2230	4,30
	0,063-4	2696	2470	2420	5,60
[RA4]	4-16	2701	2483		5,43
	0,063-4	2658	2570		4,11

Table 2.2 – Density and water absorption of natural and recycled aggregates

2.2.5 RESISTANCE TO FRAGMENTATION. THE LOS ANGELES TEST.

To calculate the resistance to fragmentation of the coarse recycled aggregates, a Los Angeles test was adopted according to UNI EN 1097-2.
The mass losses were measured for those aggregates that pass through the 14 mm sieve but that were retained by the 10 mm sieve. This particular test measures the weight losses for fragmentation of the aggregates by crushing and impacting, with the standard dimension metal balls, of standard dimensions, inserted inside the rotating cylinder.
Figure 10 shows the device used: it consists of a rotating cylinder with standard dimensions with an opening in the side wall.

Fig. 10 – Los Angeles testing machine

At the beginning the sample was winnowed using sieves of 10 mm, 12,5 mm and 14 mm, thus obtaining two different subsamples. Each subsample was washed and heat-treated at 105 ± 5°C till it reached a constant mass. The subsamples were left to cool and were mixed again to obtain a specimen of 5 ± 0.005 kg. This was then placed inside the Los Angeles testing machine with 11 steel balls for 500 rotations of the cylinder.
The whole sample of material after fragmentation was then taken out of the cylinder (Figure 11), sieved and washed again using a 1.6 mm sieve. The retained part was heat-treated at 105 ± 5°C, till it reached a constant mass; afterwards it was cooled down by air and weighed. All the results of the Los Angeles tests for natural and recycled aggregates are shown in table 2.3. It is important to highlight the fact that the higher the LA value, the lower the mechanical features of the aggregates will be.

Test sample	LA
[NA1]	18,68
[NA2]	21
[RA1]	39,5
[RA2]	35
[RA3]	39
[RA4]	25

Table 2.3 – Natural and recycled aggregates Los Angeles index

Fig 11 – Crushing of recycled aggregates after Los Angeles test

Usually the strength of the recycled aggregate is lower than that of natural ones; this fact is directly due to the lower strength of the mortar, the bond strength between cement mortar and original aggregates, and connected with the quality of the natural aggregates used in the original concrete.

Some papers have pointed out that different kinds of natural aggregates can modify the properties of the recycled aggregates. The shape and roughness of the natural aggregates have a strong connection with the quality of the concrete;

In different classes of aggregates with higher absorption, such as quartz stone or expanded clay, for example, the cohesion between the cement matrix and the aggregates can increase significantly. Cohesion increases greatly using aggregates obtained from recycled concrete; this effect is attributable to their irregular shape and roughness.

2.2.6 DETERMINATION OF FREEZING AND THAWING RESISTANCE

UNI EN 1367-1 traces the guidelines to be followed in identifying the properties of aggregates subjected to a freezing and thawing test. This test is used on aggregates with dimensions between 4 mm and 63 mm.

Three different subsamples were created and analysed for both the natural and recycled aggregates.

Each of the three subsamples was obtained using two different sieves: first the aggregates were filtered using a 16 mm sieve and then blocked by a second sieve of 8 mm . Once the samples were obtained, a washing step was performed; following this, they were heat-treated at 105 ± 5 °C till they reached the constant mass condition.

The samples were then cooled using fresh air and weighed again. After that, the subsamples were placed in distilled water for 24 hours. They then underwent 10 different thermal cycles of freezing and thawing at (20 ± 3) °C and (–17,5 ± 2,5) °C. All the tests were performed in the laboratories of the Environmental Engineering Department, University of Cagliari.

Later on, after the 10° thermal cycle, the samples were washed and weighed again to record the total mass. This led directly to the calculation of the mass losses, and the percentage of strength losses ΔSLA, after the thermal cycles and the Los Angeles test. The results are shown in Table 2.4.

Test sample	Size (mm)	Mass losses after freezing and thawing cycles F (%)	Strength losses after freezing and thawing cycles ΔS_{LA} (%)
[NA1]	8-16	0,50	2,14
[NA2]	8-16	0,46	2,21
[RA1]	8-16	0,22	4,57
[RA2]	8-16	0,23	6,10
[RA3]	8-16	0,30	7,10

Table 2.4 – Mass and strength losses after freezing and thawing cycles

2.3 RESULTS

Figure 12 shows the diagram of particle size distributions for the recycled aggregates obtained exclusively from concrete and for the natural ones.

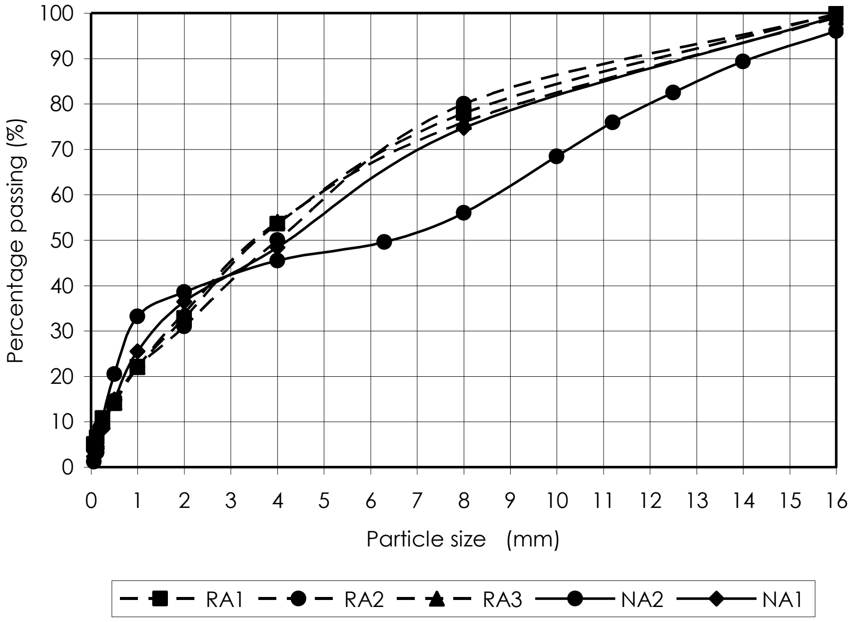

Fig. 12 – Particle size distribution of natural aggregates employed (NA1) and (NA2) and recycled aggregates (RA1, RA2 and RA3)

Figure 13 shows the diagram of particle size distributions of the recycled aggregates tested together with the ideal curves of Fuller Thompson and Bolomey (Collepardi 2009).

The diagram in Figure 12 shows that even using recycled aggregates of different kinds of concrete, the particle size distributions for particles with diameters between 0 and 16 mm are almost constant at the outlet of the crusher. Instead, the two curves of the natural aggregates are extremely different. This is due to the different specifications required. Precast reinforced concrete must be compact and with very short workability while ready-mixed concrete must ensure fluid or superfluid consistency.

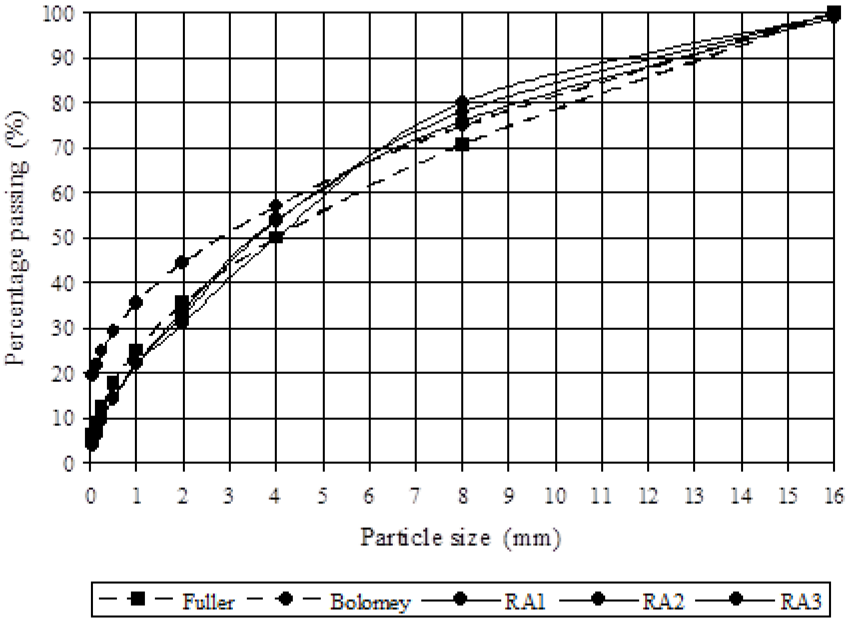

Fig.13 – Particle size distribution of recycled aggregates (RA1, RA2 and RA3) and the ideal curves proposed by Bolomey and Fuller

It can be seen from the diagram in Figure 13 that the particle size distributions at the outlet of the crusher and the ideal curves for diameters larger than 4 mm are very similar.

Figures 14a, 14b, 15a, 15b, 16a and 16b respectively show the value of water absorption WA24, bulk density ρa and saturated surface dry condition density ρssd for different diameters. The data presented in this work were obtained from the experimental campaign performed on the natural and recycled aggregates, together at other data were retrieved from the specialized literature (more than 30 papers were taken into account).

From figures 14a and 14b it can be seen that water absorption WA24% is higher for the recycled aggregates (RA1, RA2, RA3 and RA4), marked in red and black, than for the natural ones (NA1 and NA2), marked in blue. It can also be observed that permeability is higher for the fine recycled aggregates than for the coarse ones and this was confirmed both by the experimental analysis and the papers considered.
The presence of cement mortar firmly attached to the original aggregates reduces the density of the recycled aggregates and causes higher water absorption than the natural ones and this fact is not connected to the quality of the original concrete.
Normally the fine recycled aggregate particles absorb more than the coarse ones. In fact, due to the crushing of the concrete, the fine fraction may be made up of parts consisting of only cement mortar detached from the aggregates.
Table 2.2 reports the behaviour of the fine aggregates with a minimum 4.11 % value and a maximum peak of 9.5% of permeability. In general the dispersion of data is quite high and increases when the diameters are smaller than 5 mm.

The values of bulk density ρa of the recycled aggregates tested are similar to the natural ones, especially for the coarse particles; in this connection, it is possible to see the general downward trend of ρa for the tested recycled aggregates, and for the literature data retrieved from the specialised literature considered (figures 15a and 15b).

The reduction of density is indeed due to the presence of the cement mortar, endowed with higher porosity than the aggregates.

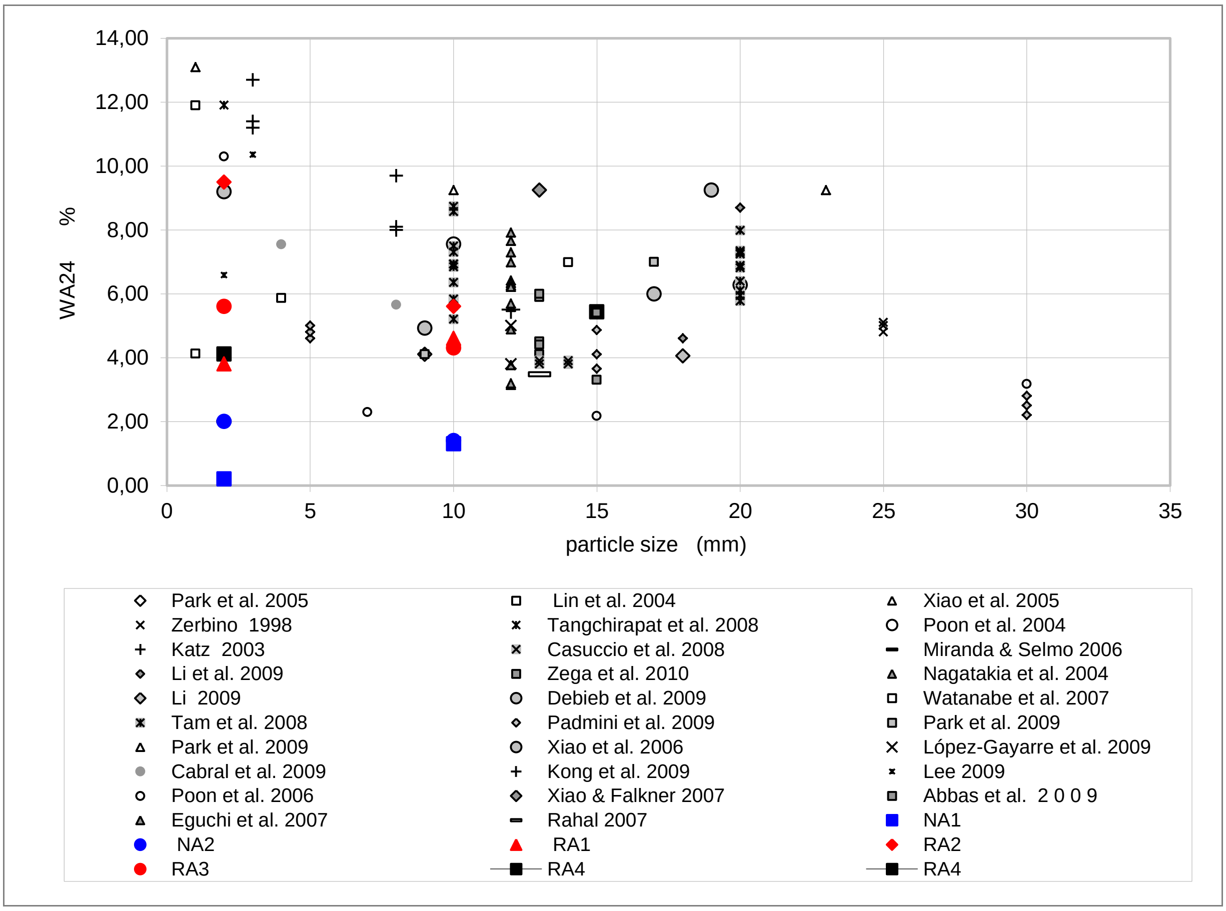

Fig. 14.a – Water absorption WA_{24}. The data were collected for different diameters by experimental analysis and from specialized literature

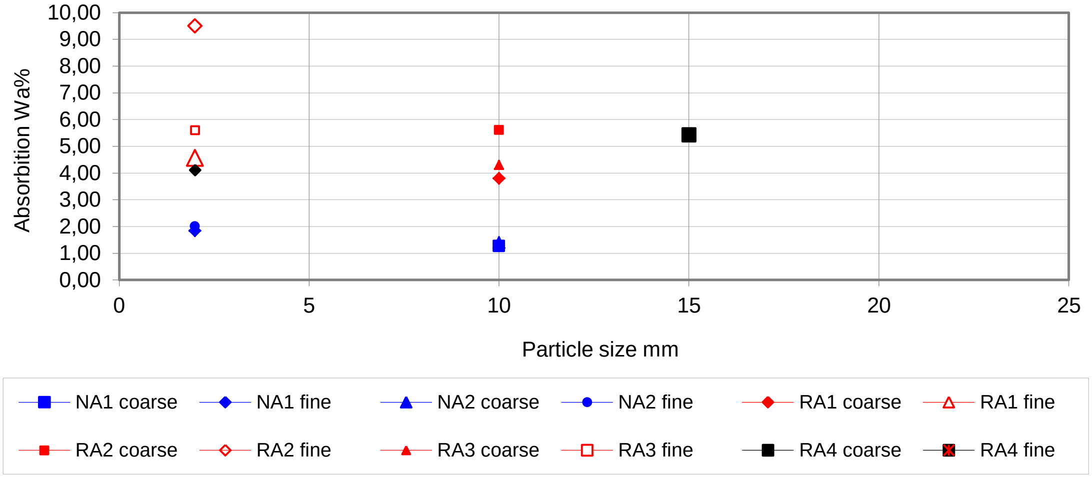

Fig. 14.b – Water absorption WA_{24} with the varying of the diameters of the aggregates

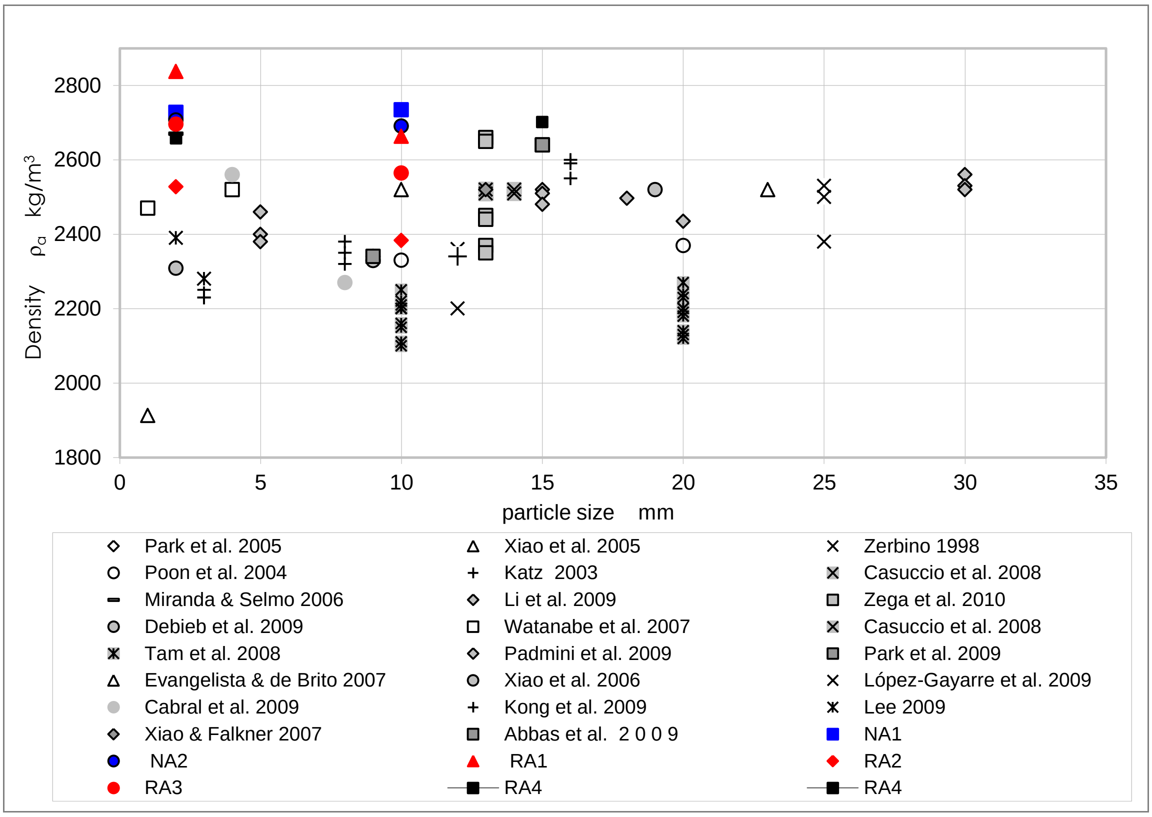

Fig. 15.a – ρ_a obtained from experimental tests and from literature for different size of aggregate

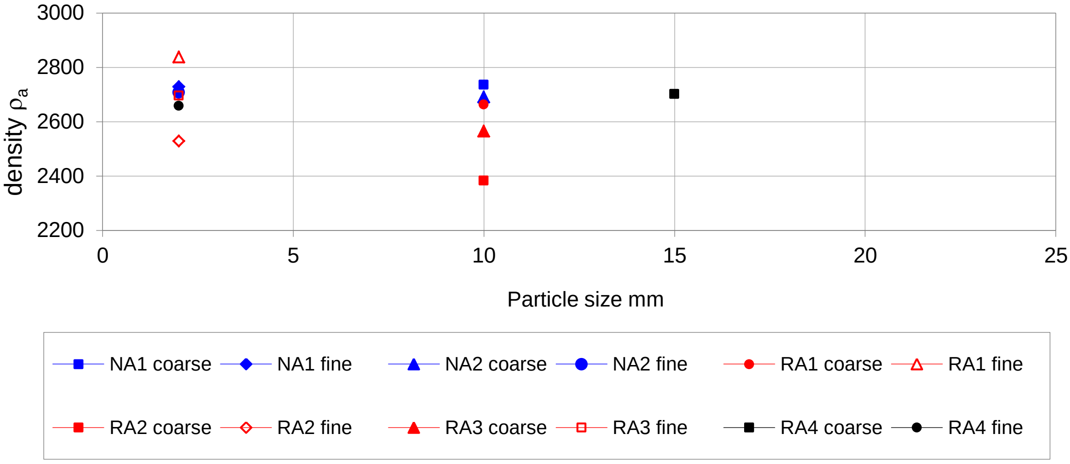

Fig.15.b – Experimental ρ_a for different size of aggregates

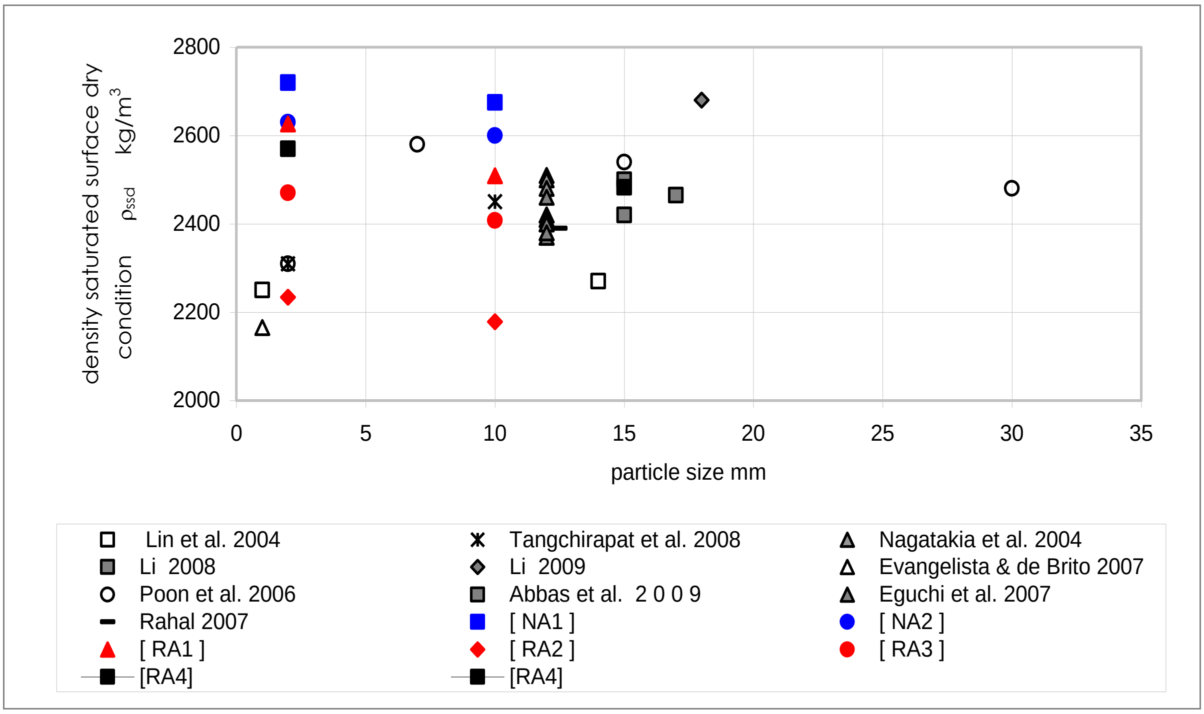

Fig. 16.a – ρ_{ssd} obtained from experimental test and from literature for different diameters of the aggregates

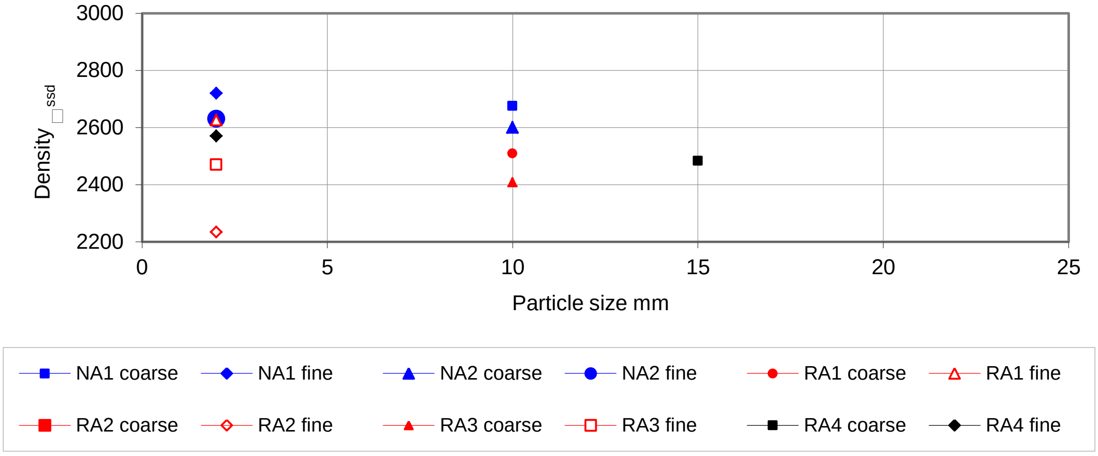

Fig. 16. b – Experimental ρ_{ssd} for different size of the aggregates.

From the diagram in figures 16a and 16b, it is clear that the saturated surface dry condition density ρ_{ssd} is quite variable for the natural and recycled aggregates for both the experimental and the literature data. The average value is 2500 kg/m^3.

The single aggregate is in the condition of saturated surface dry when all the pores are filled with water. That is a very important state of the material because it is precisely the status of the aggregates when they are placed in the fresh concrete; in this state the particles cannot absorb or lose water, thus resulting in the impossibility of modifying the water/concrete ratio.

All these important facts converge to point out the importance of control of the amount of water during the fresh concrete packaging operation.

In recycled aggregates the reaching of the saturated surface dry condition presents great difficulties and often represents an unknown factor due to the presence of cement mortar (adhering to the recycled aggregates) having a different structure and major porosity compared to natural aggregates. Furthermore, its amount is extremely variable, depending on the way in which it is crushed.

All this may explain the obvious dispersion of the results obtained.

The diagram in figures 18, 19 and 20 shows the resistance to fragmentation LA and the flakiness index FI of the tested recycled aggregates together with the LA and FI values extrapolated from the literature, in comparison with the average value for the natural aggregates.

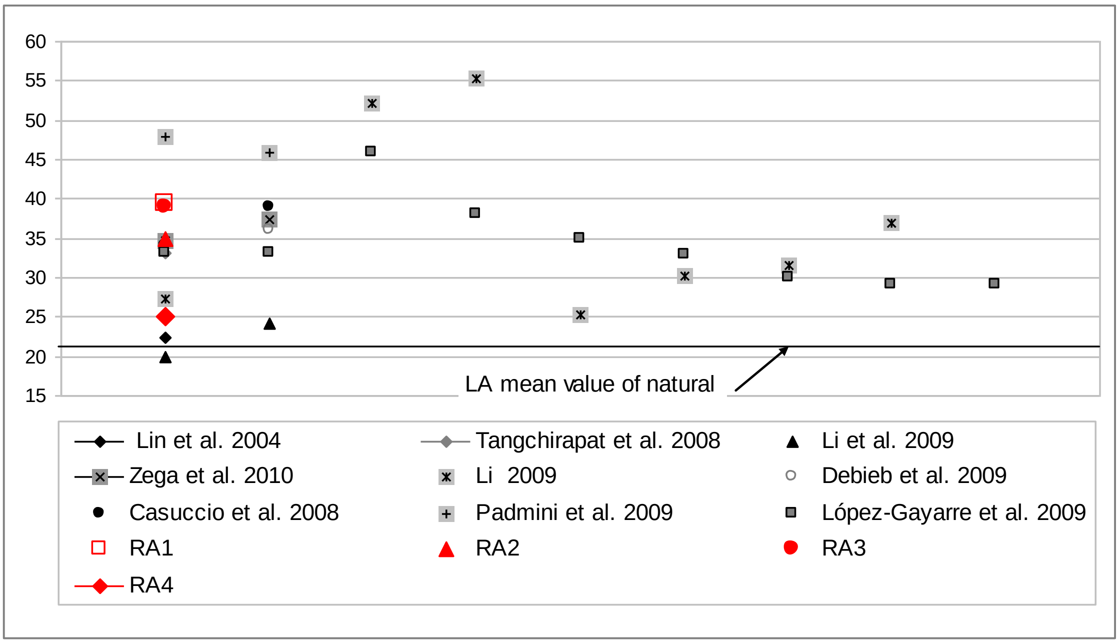

Fig. 18 - Resistance to fragmentation LA.

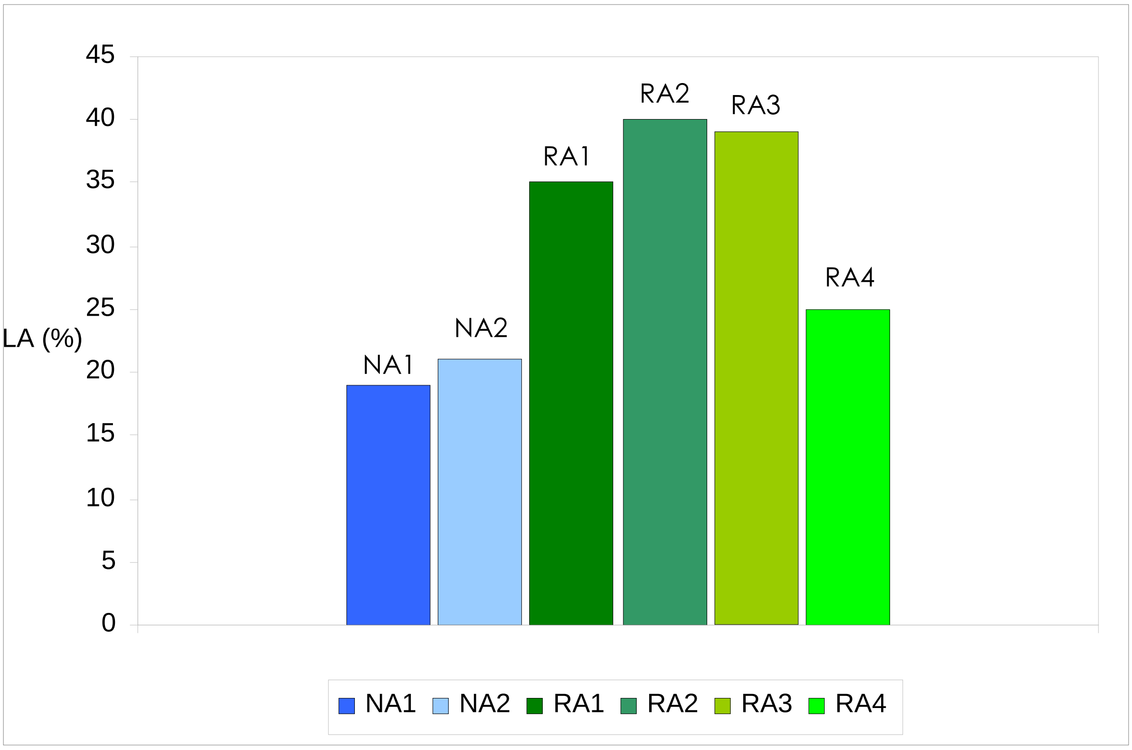

Fig. 19 – Post-fragmentation mass losses

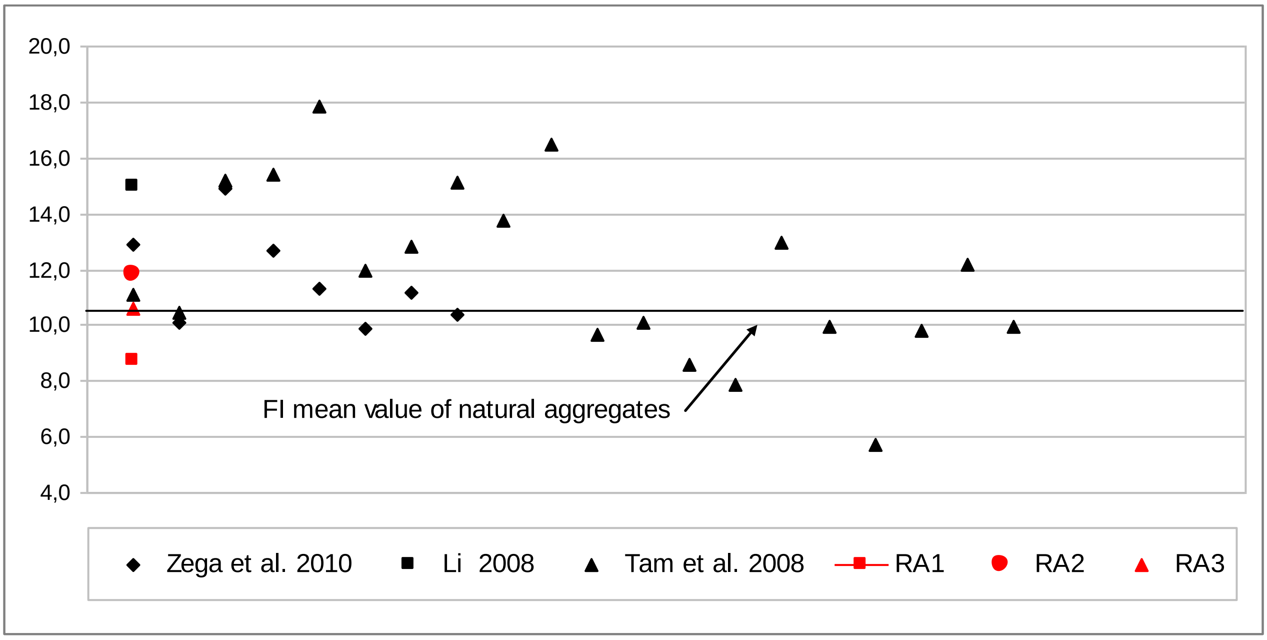

Fig. 20 – Flakiness index FI %

Usually the recycled aggregates have a higher LA value than the average value of the natural ones, as shown in Figures 18 and 19. The LA value for the recycled aggregates RA1, RA2 and RA3 are almost constant (LA = 37) even though they were obtained by crushing different kinds of concrete. The LA value of the RA4 was much lower, close to the average value estimated for the natural aggregates.

This fact is probably due to different causes; there surely is a strong dependency on the strength, shape and texture of the original aggregate, the quantity of mortar attached on it and the strength of adhesion between the aggregate and the cement mortar.

During our experimental Los Angeles test on the recycled aggregates, the adherent cement mortar was largely destroyed, as clearly indicated in Figure 11.

After the Los Angeles tests a large amount of the aggregates had no cement mortar on their surfaces due to the fact that mortar is less resistant to fragmentation procedures than the aggregates.

This phenomena caused an higher LA value during the test; the LA value is calculated by subtracting the part retained by the 1.6 mm sieve from the original mass.

The values of the recycled aggregate flakiness index that emerged from the experimental analysis and the literature data indicate an important dispersion, but the average value of the natural aggregates is similar to the estimates made for the recycled aggregates (Figure 20).

The results obtained from the freezing and thawing test of the recycled aggregates show that the strength loss is greater for the recycled aggregates while the mass loss is slightly lower, as shown in Table 2.4.

Chapter 3 Analysis and methods of simulation of behaviour at the cement matrix – aggregate interface

University of Paris East "Marne la Vallee," Tutor Prof. Julien Yvonnet

3.1 INTRODUCTION

This chapter shows the work done during the period of PhD study abroad, precisely in France at the University of East Paris "Marne la Vallee." The study involved the analysis of the behaviour of the interface between the cement matrix and the natural and recycled aggregates in concrete, in order to highlight the main differences in the phenomenon of adhesion between the cement mortar and two types of aggregate and then to understand the different behaviour of recycled and ordinary concrete.

The first part of the work was characterized by the study of the state of the art of physical and mechanical properties of the transition zone (ITZ), in natural and recycled aggregates in order to investigate their influence on the mechanical characteristics of concrete made with them.

The second part of the work involved research and study on simulation methods, with particular interest focused on the representation methods of natural, recycled aggregates and interface areas (ITZ). The objective was to create a finite element model that simulated the behaviour of recycled concrete. This is very promising future line of research.

3.2 INTERFACE ZONE (ITZ)

Concrete is a heterogeneous material in which a porous cement matrix surrounds a complex of stones (aggregates) with different strength and size, and distributed randomly. Between matrix and aggregates there are transition zones ITZ with properties different from those of the cement matrix. The transition zones govern the fracture process of the material and they are the areas of greatest weakness in the concrete, especially due to their high porosity.

The behavior of the transition zone justifies the differences in the break mechanisms of concrete. The adhesion between matrix and aggregate depends on the matrix characteristics, type of aggregate and its surface texture, the presence of mineral additions and chemical additives, incorporated air, etc. After a stress, if the aggregates have a smooth surface, the cracks propagate mainly along the surface of the aggregates. If the aggregates have a rough surface, the cracks can develop through the matrix and, in some cases, through the aggregate. The crushed aggregate surfaces have, in general, greater adhesion to the cement matrix than those of natural aggregates [53-56].

In ordinary concrete, the volume of ITZ is approximately 20 to 50% of the total volume of the concrete, and depends on the fineness of the cement, ratio A / C and the surface texture of the aggregate. Many studies have investigated the ITZ dimension, showing that the thickness ranges typically between 10μm and 100 μm . In Figures 1 and 2 it is possible to see the transition zones and their size.

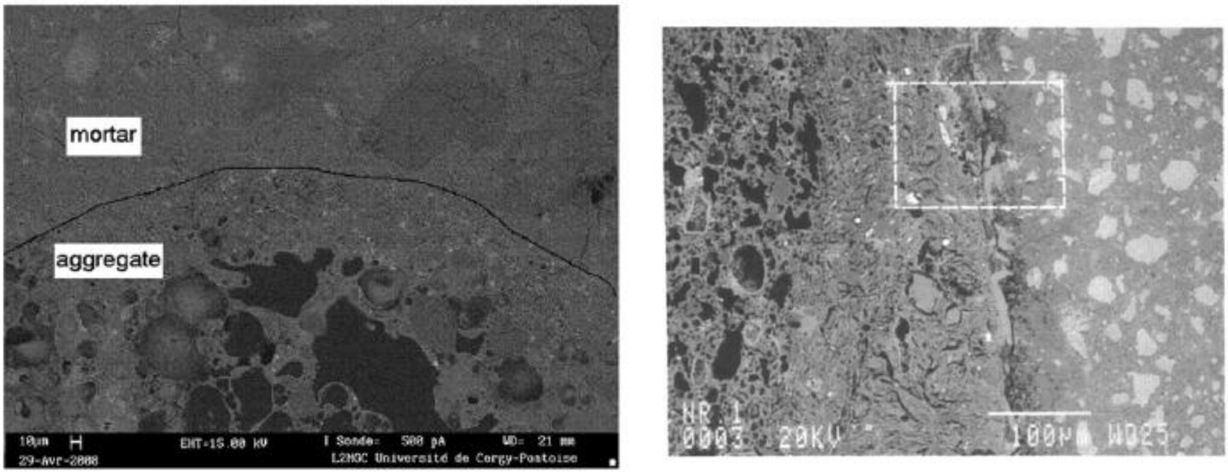

Fig. 1 - ITZ zone

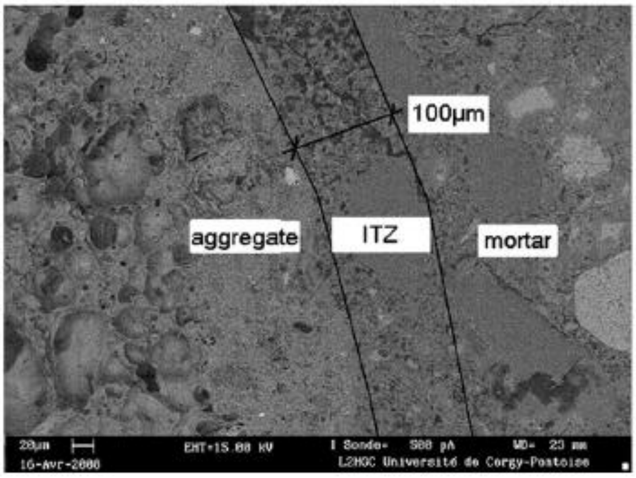

Fig. 2 - ITZ Dimension

3.2.1 POROSITY OF INTERFACE AREAS

During the hydration of fresh concrete, the distribution of anhydrous cement particles is more widespread near the aggregate surface, so the fresh concrete porosity and the A / C ratio increases near the aggregates and the reactions are influenced by their chemical properties.

There is a close connection between the properties of the ITZ, the porosity and the process of hydration. In fact, the process of hydration near the aggregates is different from the rest of the concrete. We can say that the excess of porosity in these areas is at the same time cause and consequence of the existence of interface areas.

This phenomenon is called the "wall effect", due to scanty distribution of the cement grains near the aggregates [57].

The main modifications of porosity near the aggregates occur at a distance of 15µm / 20µm, but in older concrete the variation of porosity decreases. By introducing silica fumes into the mix, the variations of porosity are inexistent, because the tiny grains of silica fumes in the ITZ condense the cement as shown in Figure 3.

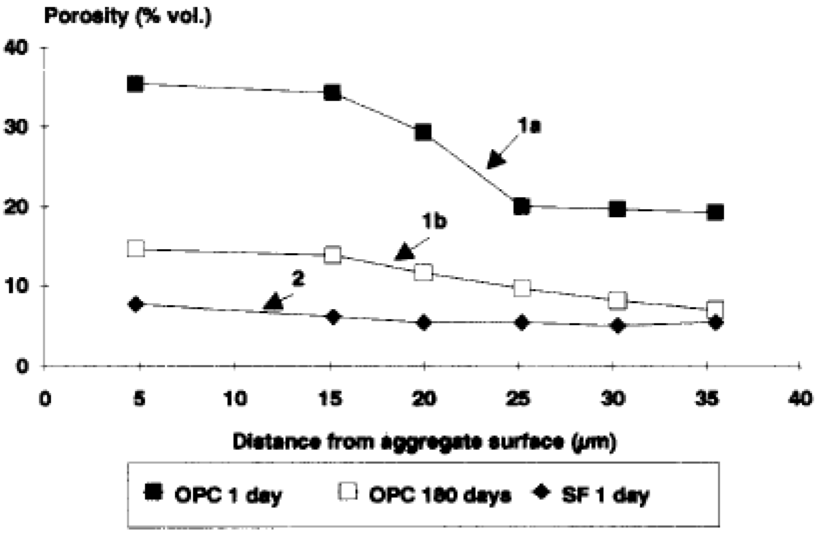

Fig. 3 - ITZ porosity variations

In general the ITZ have:

- Increased porosity: 2 or 3 times higher than the rest of the structure;
- Increased A / C ratio;
- Pores larger than the rest of the structure;
- Variations of porosity at a distance from the aggregate of less than 15 µm / 20 µm.

These features can be a cause of mechanical weakness of ITZ compared to the rest of the concrete, but also play an important role the characteristics of the cement, the chemical and physical properties of aggregates and the nature and union of the cement paste.

3.2.2 PHYSICAL PROPERTIES OF AGGREGATES AND ITZ

There is a direct bond between the texture of aggregates and the union with the ITZ, as demonstrated in numerous studies. Furthermore the literature shows that the cement matrix-aggregate bond depends on three mechanisms:

- Concrete hydration around the aggregates;
- Epitaxial growth (deposition of thin layers of material) of the hydration products on the surface of the aggregates;
- The chemical and physical bond between the cement paste and aggregate.

Furthermore, it is shown that the possible failure modes of concrete are mainly four [56]:

- Fracture of the ITZ;
- Cracks that cross the ITZ and continue in the cement paste;
- Cracks that cross the ITZ and continue in the aggregates;
- Fracture of ITZ but with loose fragments of concrete and aggregates.

In general, the bond strength of the cement matrix-aggregate increases when the surface area available for bonding increases, that is, with the increasing of aggregate roughness, but this is not connected to the strength of the concrete, in fact, the aggregate must be mechanically strong to support the strength of this bond.

The size of the aggregates also influences the bond with the cement matrix; in [57] for example, the length of micro-cracks decreases with an increase in the aggregate size, while their average width increases with the diameter of the aggregates.

3.2.3 RECYCLED AGGREGATES AND ITZ

The study of the behaviour of the cement matrix-recycled aggregate interface is quite interesting; in fact, the particular surface of the recycled aggregates increase the adherence in the transition zone of new cement matrix, but this additional adhesion does not correspond to higher mechanical strength of recycled concrete made with them, compared to ordinary concrete

This phenomenon can be caused by micro-cracking; in fact, in recycled concrete micro crack propagation takes place with equal frequency in the cement mortar and in cement mortar-aggregate interfaces. In concretes with a low A/C ratio the mechanical strength and the cement mortar-aggregate adhesion with the new cement matrix exceeds the resistance of the old mortar with the original aggregate. This can cause the formation of cracks through the recycled aggregates [22].

Furthermore, in recycled concrete there are two interface areas, the first between the original aggregate and the old cement mortar, the second between the old cement mortar and the new cement mortar.

In Figures 3a and 3b respectively, it is possible to see the single area of the interface between the cement mortar and the natural aggregates and the double area of the interface between new cement mortar and recycled aggregate.

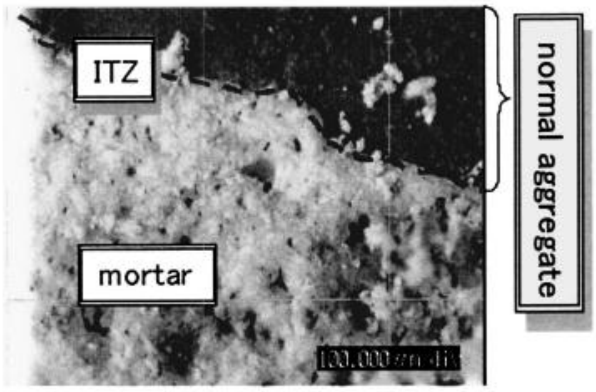

Fig. 3a - ITZ zone natural aggregate

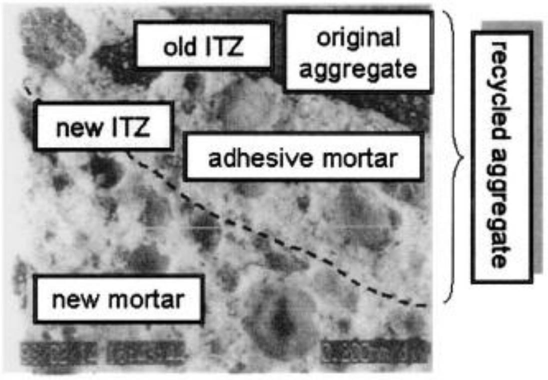

Fig. 3b - ITZ zone recycled aggregate

To analyse the influence of the transition zones in the break mechanisms and the relative force of adherence to the recycled aggregates, concretes were produced using recycled aggregates having a maximum diameter of 25 mm.

Such aggregates were taken from the Ecoinerti storage site and their characterisation is given in Chapter 2. The recycled concrete made with these aggregates was subjected to compression and traction tests and the results are reported in Chapter 4.

3.3 SIMULATION METHODS

3.3.1 FINITE ELEMENT METHOD

Assume a general three-dimensional body that occupies a domain $\Omega \in R^3$ which is defined by a set of points x. A body force *b* is prescribed inside the domain. Furthermore, surface tractions *t* and boundary displacements *u* are applied on the domain boundary surfaces *Γ*. The motion of this body with respect to the applied loading is expressed by the unknown displacement field *u*. Assuming small displacements and a linear relationship between stresses *σ* and strains *ε* the governing differential equations can be written as:

$$\sigma_{ij} = C^{e}_{ijkl}\,\varepsilon_{kl} \qquad \forall x \in \Omega \qquad \textit{Constitutive equation}$$

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\vartheta u_i}{\vartheta u_j} + \frac{\vartheta u_j}{\vartheta x_i}\right) \qquad \forall x \in \Omega \qquad \textit{Kinetic equation}$$

$$\frac{\vartheta \sigma_{ij}}{\vartheta x_j} = \bar{b}_i \qquad \forall x \in \Omega \qquad \textit{Static equation}$$

$$u_i = \grave{u}_i \qquad \forall x \in \Gamma_u \qquad \textit{Essential boundary condition}$$

$$\sigma_{ij}\eta_j = t_i \qquad \forall x \in \Gamma_t \qquad \textit{Natural boundary condition}$$

where *n* is a vector normal to the boundary surface. Considering an isotropic material, the linear elastic material tensor C^{e} is given by:

$$C^{e}_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$$

where *δ* denotes the Kronecker delta which is defined as

$$\delta_{ij} = \begin{cases} 1 & if \;\; i = j \\ 0 & if \; i \neq j \end{cases}$$

and where

$$\lambda = \frac{Ev}{(1+v)(1-2v)} \qquad\qquad \mu = \frac{E}{2(1+v)}$$

In all the equations the tensor notation is used for the stresses and strains:

$$\delta_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \qquad\qquad \varepsilon_{ij} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix}$$

Using vector notation, the constitutive equations can be written as:

$$\sigma_i = C^{e}_{ij}\,\varepsilon_j$$

with

$$C^e = \frac{E}{(1+v)(1-2v)} \begin{bmatrix} 1-v & v & v & 0 & 0 & 0 \\ v & 1-v & v & 0 & 0 & 0 \\ v & v & 1-v & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2v}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2v}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2v}{2} \end{bmatrix}$$

There are very not many problems for which these equations give a closed form solution. For most engineering problems, the problem must be solved in an approximate way by using a numerical method. Today, the finite element method (FEM) is a technique widely applied for the simulation of elements with arbitrary geometry and given boundary conditions.

Using the finite element method, the entire body is subdivided into finite elements which are connected at a discrete number of nodes on the element boundaries. Each element is defined by a certain number of nodes

3.3.2 REPRESENTATION SCALE

Concrete is a highly heterogeneous material. Its simulation or its numerical representation can be made at different scales:

- **macroscopic scale** - the concrete, heterogeneous material, is represented as a homogeneous material. The ease is the advantage of this method. To perform the discretization, the macroscopic scale method uses a coarse mesh, but this cause a little correspondence between simulated and real behaviour

- **mesoscopic scale** - individual components of the heterogeneous structure within the concrete, are represent separately, such as for example the shape and the spatial distribution of aggregates.
  As a result, the properties of each specific material can be assigned for each component. With mesoscopic scale simulations the physical effects, such as the propagation of cracks or the rupture of the aggregate - cement matrix interface, are considered separately, therefore to represent the concrete behaviour can be used a simple formulation for each part of the material.
  The mesoscopic scale require the discretization of the internal concrete structure. Compared to the macroscopic scale simulations, the numerical effort increases significantly. For this reason it is generally limited for specimens with a simple structure.

- **multiscale approach** - different scales are used.

The mesoscopic scale will be used to realized a volume of ordinary concrete for analyse the behaviour of interface zones when it is subjected at stress actions.

The model obtained for the ordinary concrete will be adapted for the recycled concrete, changing in a convenient way, the parameters such as shape and texture of the aggregates, properties, size and type of the interface areas and the constitutive laws.

3.3.3 MESOSCOPIC SCALE REPRESENTATION OF CONCRETE

3.3.3.1 AGGREGATES

Aggregates occupy 60-80% of the concrete volume and they influence its properties.

The crucial point in the mesoscopic scale simulations is an appropriate description of the material, and of its internal structure, with an appropriate numerical model.

In mesoscopic scale the concrete structure is characterized from the spatial distribution of its components and from the size of aggregates. In literature, can be find two different approaches to mesoscopic scale representation.

In the first approach, the authors use experiments of X-ray tomography, or digital images of concrete sections [56-58], to determine the real structure of specimen of concrete.

In the second approach, the authors use numerical simulations to generate artificial specimens of virtual concrete.

In these models, the aggregates are generally represented by simple geometric shapes such as circles, spheres, ellipsoids, or polygons, [61-63].

A popular method called "take-and-place" is used for the aggregates simulation. This method consists in two phases, the take-process, followed by the place-process.

During the take-process, the aggregates and their distribution are created The size distribution of aggregates can be approximated by the Fuller curve, or it can be explicitly known.

The final structure of the concrete volume is generated during the place-process. The aggregates are randomly placed in the volume one particle at a time, avoiding their overlap. The place-process starts with the greater particles and then it is repeated for the smaller particles until all the particles are included in the virtual specimen.

3.3.3.2 AGGREGATES SIMULATION AND THEIR DISTRIBUTION (TAKE PROCESS)

A simple way to represent the surface of the aggregates could be to use an ellipse, using the following formula:

$$\left(\frac{x}{r_1}\right)^2 + \left(\frac{y}{r_2}\right)^2 + \left(\frac{z}{r_3}\right)^2 = 1$$

This permit to write two rays as a function of the third rays with the following equations:

$$r_1 = \left(1 + x_2 * \frac{\eta_{13} - 1}{\eta_{13} + 1}\right) * x_2$$

$$r_2 = \left(1 - x_3 * \frac{\eta_{13} - 1}{\eta_{13} + 1}\right) * x_2$$

Where X2 and X3 represent a random distribution of numbers between 0 and 1. The parameter η13 is the maximum value of the relationship between r1 and r3, and it is used to control the shape of the aggregates.

The relationship between r1 and r3 is equal to 1 for spherical aggregates, while higher values are used for get the representations of elliptical aggregates [61].

A very interesting aggregates simulation was made by Wang, Kwan and Chan in the work entitled "Mesoscopic study of concrete I: generation of random aggregate structure and finite element mesh" [63]; in this study in mesoscopic scale was generated a random structure of aggregates with shape, size and distribution as much as possible similar at the real model.

In this study the aggregates shape is described in polar coordinates and the polar radius is expressed by a harmonic function.

$$r = r(\theta) = A_0 + \sum_{j=1}^{m} Ajcos(j\theta + \alpha j)$$

A_0 = average radius
Aj = width of the frequency Fourier
αj = the corresponding phase angles
with αj between 0 to 2π

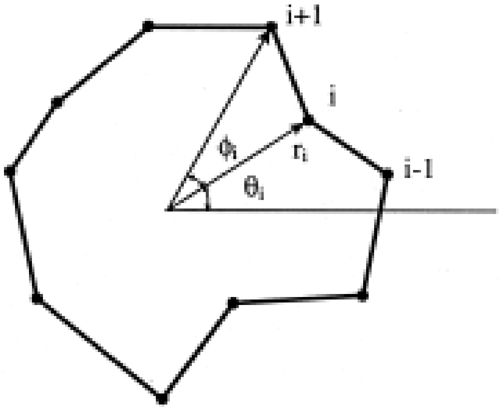

Fig. 4 - Aggregate contour representation

The polygon shape is complete if you define the sides and two sets of variables: the polar angle θi and the polar radius ri for the n vertex.
This information can be used to create an all shape polygon.
In the first case (A) θi and ri for each vertex are variable between 0 and 2π. So θi and ri can be created through the random numbers ηi uniformly distributed between 0 and 1, multiplying these random numbers for 2π:

$$\theta_i = \eta_j * 2\pi$$

$$r_i = A_0 + (2 * \eta_i - 1) * A_1$$

with r_i between (A_0-A_1) and $(A_0 + A_1)$ and where A_0 is a average radius

In the second case (B)

$$\phi_i = 2\frac{\pi}{n} + (2 * \eta_i - 1) * \delta * 2\frac{\pi}{n}$$

where ϕ_i between $2\frac{\pi}{n}$ and 1

With the hypothesis A particles with irregular edges are generated, with the hypothesis B particles with a cubic shape are generated.

A possible procedure of generation could be the next [64]:

1. Calculate the volume of aggregates belonging at the class of larger diameter
2. Generate a random number uniformly distributed between 0 and 9, to define the size of an aggregate.
3. Calculate the aggregate volume generated and subtract it from the total aggregates volume within the class.
4. Repeat steps 2 and 3 until the aggregate volume is not sufficient for the generation another particle.
5. Repeat all steps for the smaller next class, and then again gradually for the other class, up to the last particle of the smallest class.

3.3.3.3 PLACE PROCESS

The place-process reproduces the geometric configuration of the generic concrete volume, to represent the basic features of real material. The aggregates spatial distribution must be as possible homogeneous and isotropic.
The configuration of concrete volume must be randomly generated and it can have arbitrary shape.
When a particle is inserted into the concrete volume its position is defined by an x-coordinate
Two conditions must be satisfied to place a particle in a free position within the concrete volume: no overlap with the other particles, and each particle must be completely covered with a minimum thickness of cement mortar. This implies a minimum distance between the edge of each particle and the sample boundary and between two adjacent particles. Of course the cement mortar thickness between two particles varies with the aggregates content; it is smaller when the overall content is higher.
In the following representation [64] the minimum thickness of cement mortar is represented with an arbitrary γ parameter. Its value is in function of the total volume, and of the generic particle diameter.

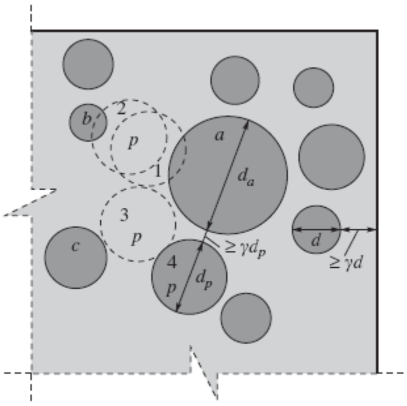

Fig. 5 - Placing-Process

At the beginning of the placement process an initial γ value must be chosen. If there are difficulties with the particles placing process, the γ value must be reduced and the process must be repeated entirely until all particles will be placed in the concrete sample.
In figure 6 there is an example of 3D concrete structure. The structure was randomly generated with different particle size.

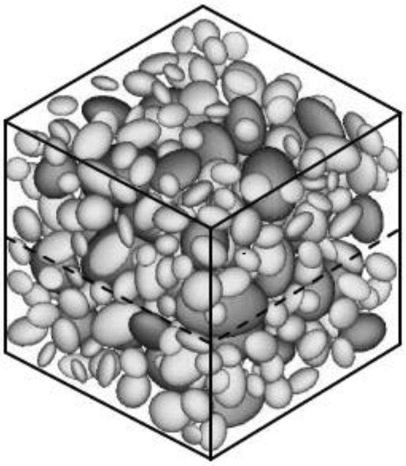

Fig. 6 - 3D representation of concrete volume

3.3.3.4 ITZ SIMULATION

ITZ physical characteristics are known from the analysis performed on them; usually the ITZ elastic modulus is equal to 50% of the cement paste elastic modulus.

Literature shows different finite element models for the modelling of ITZ areas, they can be classified as follows:

- Finite element standards with a small thickness;
- Elements with a plane of weakness in interface direction;
- Linkage elements in which are considered the connections between the opposites nodes;
- Interface elements in which the nodes displacement in front of the other nodes are the primary variables of deformation.

In general 2D line interface elements, or 3D surface interface elements, are used to connect two solid elements, as shown in figure 7. The major difference compared to solid elements are the kinematic equations and the constitutive law. In both the representations the nodes number depends by personal choice [65, 66].

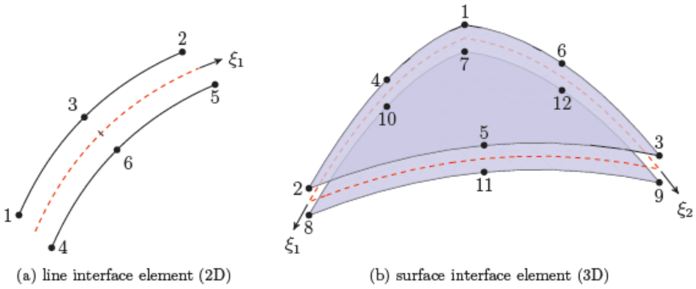

Fig. 7 - ITZ Simulation: 2D (dx) and 3D (sx)

Figure 8 shows an example of mesoscopic scale discretization of concrete specimens. For aggregates a standard geometry has been used and for ITZ zone, a zero thickness and triangular elements at 3 and 4 nodes were used.
A linear elastic behaviour was considered [68].

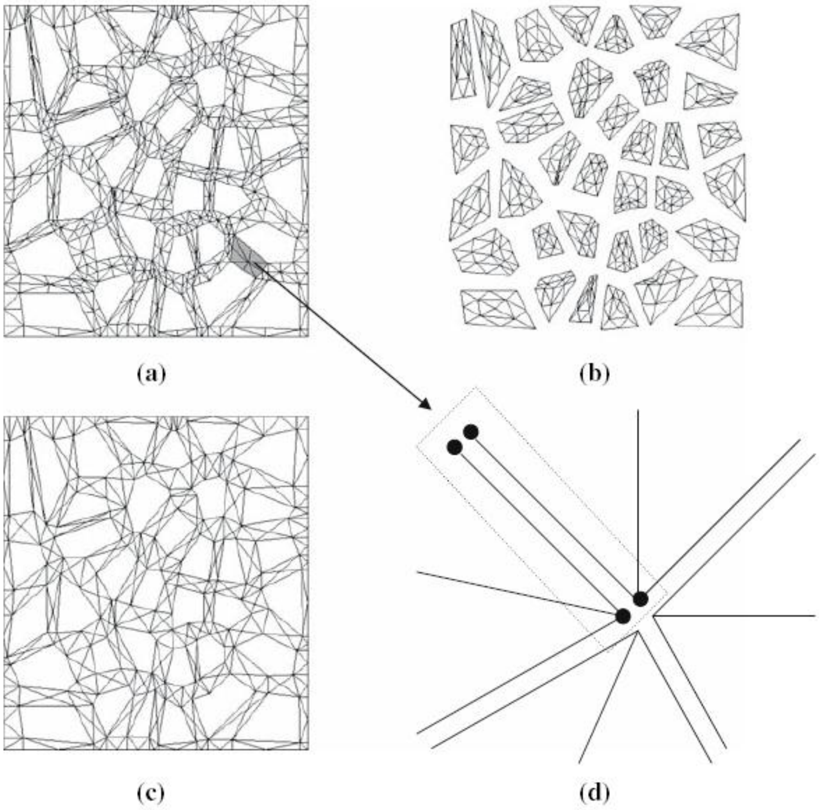

Fig. 8 - Mesoscopic scale discretization

Recycled concrete is a material with heterogeneous behaviour having a not easily predictable performance. It is influenced by many parameters (nature of the original aggregates, quality and quantity of the adhering mortar, bond between old and new mortar, mix design and packaging conditions) which determine different break mechanisms in the transition zone, and from which depend the mechanical performances of the material.
An important development and future impulse for this research may be represented by the modelling at the finite elements, which is useful in understanding the complicated physical and mechanical phenomena that take place in the recycled concrete.

Chapter 4 Properties of fresh and hardened structural concrete made with coarse and fine recycled aggregates

4.1 INTRODUCTION

The concrete industry impacts strongly on nature and consumption of energy resources.
The excessive exploitation of borrow pits and the extreme use of natural sand causes a gradual and inevitable depletion of these resources.
During the last few years the increasing environmental awareness has inspired numerous papers and studies focused on concrete made with recycled aggregates.
After a detailed analysis of the studies presented in the specialized literature it is possible to state that the concrete made with coarse recycled aggregates, that completely or partially replacing natural ones, has mechanical properties similar to those of normal concrete made with natural aggregates, and this represents a very interesting future opportunity to start the production of high-resistance concrete using the same environmentally sustainable technique.
The use of fine recycled aggregates for the same purpose has not yet been studied frequently since it is a common conviction that the high water absorption connected with this solution may create a deficit in the final mechanical properties of the concrete.
All of these research and study activities have produced a large number of laws and regulations that are valid for the present, but these provisions limit the use of coarse recycled aggregates and forbid the use of fine recycled aggregates in the production of structural concrete.
This chapter describes the mechanical properties of concrete made with different replacement percentages of fine and coarse and only coarse recycled aggregates. The recycled aggregates were taken from an authorized storage site, the Ecoinerti company (Iglesias in Sardinia).
All the mixes of recycled concrete were produced so as to ensure workability at 5 minutes from mixture of the fluid or semifluid type. This workability is suitable for immediate production in concrete plants, transport in cement mixers and simple implementation. The need to ensure this workability caused slight differences in the amount of water and additive used in the mix.
An ordinary control concrete for the comparison tests was employed.
All the concretes were made by Italcementi located in Quartucciu, close to the Cagliari area.
The main results obtained from the research concern the workability of the fresh concrete, its compression and tensile strength, elastic modulus and the non-destructive ultrasonic tests of the hardened concrete.

4.2 EXPERIMENTAL CAMPAIGN

4.2.1 PROPORTIONS AND COMPOSITIONS OF THE CONCRETE MIXTURES

The cement adopted in this work is a 42.5 II A/L, a water-based additives superplasticiser Axim Driver 2E and Creative L Axim with acrylic polymers was used. The additive Axim Driver 2E was used in the first 8 mixes (produced in April 2010). For the remaining 3 mixes (produced in April 2011), the additive Creative L Axim was used since it was available at that time in the Italcementi concrete plant. It is to be noted that the former has an additive power roughly twice that of the latter so the amount of Creative L Axim was increased accordingly. Both the additives ensure the maintenance of workability and high performance of the concrete.

After that the recycled aggregates were moved from Ecoinerti (located in Iglesias) to Italcementi (located in Quartucciu - Cagliari). The mixtures to realize the recycled concrete were prepared with the use of coarse and fine recycled (mixtures from 1 RC to 8 RC with RA1, RA2, RA3 mixed together and mixtures from 9 RC to 11 RC with only RA4) and natural aggregates (NA2) in 11 different combinations.

Four mixtures (from 1 RC to 4 RC) were made using fine and coarse recycled aggregates, the others were made with only coarse recycled aggregates. Moreover a reference concrete mixture was made with natural aggregates (0NC made with NA2).

In the annex 1 it is possible to see all the specifications and the particle size distributions of the mixtures that were used.

It was decided not to include silica fumes and fly ash so that the analysis considers exclusively the effects of the replacement between natural and recycled aggregates. Table 4.1 shows the specifications of the 12 concrete mixtures.

						Fine aggregate Kg/mc		Coarse aggregate Kg/mc		Fine recycled	Coarse recycled
N°	Dmax recycled aggregates	a/c	Addit. Kg/mc	cement	Water Lt	Nat.	Ric.	Nat.	Ric.	% sostit.	% sostit.
0 NC		0,54	2,10	42.5	190	914	0	892	0	0	0
1 RC	16 mm	0,54	2,80	42.5	190	0	883	0	851	100	100
2 RC	16 mm	0,54	2,10	42.5	190	183	707	178	682	80	80
3 RC	16 mm	0,54	2,10	42.5	190	458	442	446	426	50	50
4 RC	16 mm	0,54	2,10	42.5	190	733	179	713	170	20	20
5 RC	16 mm	0,54	2,10	42.5	190	914	0	0	852	0	100
6 RC	16 mm	0,54	2,10	42.5	190	914	0	178	682	0	80
7 RC	16 mm	0,54	2,10	42.5	190	914	0	446	426	0	50
8 RC	16 mm	0,54	2,10	42.5	190	914	0	713	170	0	20
9 RC	25 mm (RA4)	0,57	2,80	42.5	200	915	0	0	852	0	100
10 RC	25 mm (RA4)	0,57	3,50	42.5	200	915	0	438	419	0	50
11 RC	25 mm (RA4)	0,57	4,20	42.5	200	915	0	612	253	0	30

Table 4.1 – Concrete composition (kg/m^3)

The natural and recycled aggregates should be put into the mix in saturated surface dry conditions; in this state the aggregates neither release nor absorb water. In normal practice in a concrete plant this condition is reached immediately after mixing.

Due to their high absorption, the recycled aggregates should first be pre-saturated (immersed in water and then drained) and then added to the concrete mixer. This theoretically recommended practice is often found to be unreliable.

In fact, during pre-saturation the recycled aggregates may hold an excess of water which would inevitably be released into the concrete mix with a consequent increase in the W/C ratio. The excess of water makes the transition zones more porous and thus weaker, thus compromising the final strength of the concrete.

In this experimental campaign the recycled aggregates were introduced into the mixtures following the same criteria applied in the concrete plant (Italcementi) for natural aggregates, which is to say using the aggregates with no prior presaturation, since in practice this operation is totally impossible. In general, aggregates are divided by grain size and stocked in the open air. For the mixing of concrete they are taken from their mounds and transported on belts to the concrete mixer.

Prior to their placing in the mixer their humidity and absorption are measured according to the regulations in force. The saturated surface dry condition is present when humidity is equals absorption.

In almost all cases the recycled aggregates used in the mixes had an absorption higher than humidity and were thus in unsaturated conditions (see the technical tables of the mixes present in annex 1). On the basis of these data, a program written for the study of ordinary concrete mixes calculated the amount of water necessary for the mix and saturation of the aggregates. In some cases the presence of recycled aggregates, with their different times and absorption capacities compared to natural aggregates, evidently determined the need to adjust the mixing water with the addition of small amounts of water so as to ensure the necessary workability and compactability for transport and implementation.

4.2.2 PREPARATION OF SPECIMENS

For each single mixture with coarse and fine recycled aggregates (1RC, 2RC, 3RC, 4RC) and for the ones made with coarse recycled aggregates only (5RC, 6RC, 7RC, 8RC), 6 cubical specimens were made (150x150x150 mm) to perform tensile and cubic compression tests (3 specimens for each experimental test), 3 cylindrical specimens (diameter 7 mm and height 20 mm) were made and tested to identify the elastic modulus and cylindrical compression strength. All the specimens underwent a non-destructive evaluation using ultrasonic waves. For each mixture made with coarse recycled aggregates only (9RC, 10RC, 11RC), 6 cubical specimens were made (150x150x150 mm). Compression and tensile tests, were performed on them, 3 specimens for both the analyses (this part of experimentation was made in according to the studies done at the University of Paris described in Chapter 3). In total 90 specimens of recycled concrete were made.

All the specimens were formed with stripping from the concrete casting after 24 hours and aged in water (20°C) for 28 days. Table 4.2 shows the laws and the specifications followed during the experimental campaign.

Test	Normative
Compressive strength	UNI EN 12390-3:2003
Tensile strength	UNI EN 12390-6:2002
Elastic modulus	UNI 6556:1976

Table 4.2 - Specifications followed for experimental analysis

Before packaging of specimens, for all the fresh concretes the lowering at the slump cone (Abrams) after 5 and 30 minutes was measured.

4.3 RESULTS OF ANALYSES

Table 4.3 shows the average values of lowering at the slump cone (Abrams), time t = 5 and t = 30 minutes, the values of the cubical (Rc) and cylindrical (fc) compression strength, the values of the tensile strength (fct) and the values of the elastic modulus (Ec), for each mixture.

N°	Slump 5 ‘ mm	Slump 30 ‘ mm	R_{cm} MPa	f_{cm} MPa	f_{ctm} MPa	E_{cm} MPa
0 NC	210	160	45,36	47,87	5,47	26869
1 RC	220	220	41,60	34,00	3,77	21176
2 RC	200	150	37,07	35,04	4,23	21775
3 RC	220	160	36,97	37,05	4,53	22994
4 RC	210	190	40,33	41,42	4,50	25613
5 RC	210	170	38,75	37,88	4,13	23787
6 RC	200	100	42,51	40,44	4,43	25265
7 RC	205	120	43,43	45,32	4,33	26626
8 RC	205	150	43,86	45,78	4,43	26150
9 RC	210	210	53,47	-	3,48	-
10 RC	230	150	43,93	-	2,96	-
11 RC	230	160	42,83	-	3,08	-

Table 4.3 – Experimental results

4.3.1 CONCRETE WORKABILITY

Workability is the capacity of fresh concrete to move and compact itself. These are both fundamental features because they are very important in facilitating transportation, removal of air pockets, ensure the maximum possible density and perfect connection with the reinforcement.

To produce commercial recycled concrete so as to ensure facility in production, transport and implementation, all the mixes were made with suitable workability with a fluid or superfluid consistency class (Table 4.4).

Class of consistency	Slump (mm)	Use
S1 – humid soil	10-40	Concrete pavements
S2 - plastic	50-90	Circular structures
S3 - semifluid	100-150	Structures without reinforcement
S4 - fluid	160-210	Structures with a little reinforcement
S5 - superfluid	>210	Structures with a lot of reinforcement, with small section and complex geometry

Table 4.4 – Class of consistency

Figures 1-12 show the slump after 5 and 30 minutes of most of the mixtures. In Figures 13 and 14 the slump of the reference fresh concrete after 5 and 30 minutes is shown.

Fig. 1 - Slump 80% coarse and fine recycled aggregates + 20% coarse and fine natural aggregates, 5’- 2RC

Fig. 2 - Slump 80% coarse and fine recycled aggregates + 20% coarse and fine natural aggregates, 30’- 2RC

Fig. 3 - Slump 50% coarse and fine recycled aggregate + 50% coarse and fine natural aggregates, 5’- 3RC

Fig. 4 - Slump 50% coarse and fine recycled aggregate + 50% coarse and fine natural aggregates, 30’- 3RC

Fig. 5 - Slump 20% coarse and fine recycled aggregates + 80% coarse and fine natural aggregates, 5’- 4RC

Fig. 6 - Slump 20% coarse and fine recycled aggregates + 80% coarse and fine natural aggregates, 30’- 4RC

Fig. 7 - Slump 100% coarse and fine recycled aggregates, 5’- 1RC

Fig. 8 - Slump 100% coarse and fine recycled aggregates, 30’- 1RC

Fig. 9 - Slump 100% coarse recycled aggregates, fine totally natural , 5’- 5RC

Fig. 10 - Slump 100% coarse recycled aggregates, fine totally natural , 30’- 5RC

Fig. 11 - Slump 100% coarse recycled aggregates, fine totally natural , 5’ – 9RC

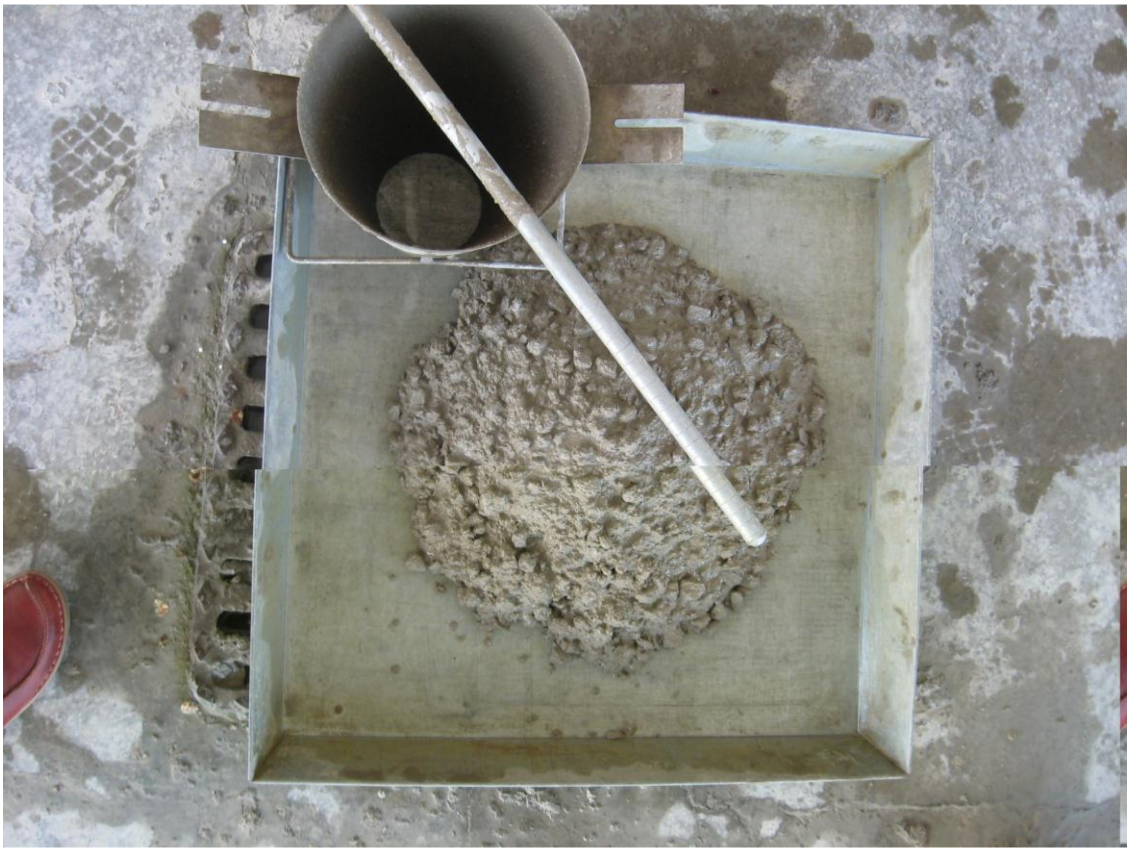

Fig. 12 - Slump 100% coarse recycled aggregates, fine totally natural, 30’- 9RC

Fig. 13 - Slump conventional concrete, 5 ‘

Fig. 14 - Slump conventional concrete, 30 ‘

Even when the recycled concrete was made with different replacement percentages of coarse and fine or only coarse recycled aggregates in place of natural ones, the workability after 5 minutes from the packaging is the same as that of the ordinary concrete, as shown in Figure 15.

This fact is fundamental for use of the product, for its economic feasibility and for its transportation, avoiding damage to the machinery and at the concrete plants.

The workability after 30 minutes for all concretes made with only coarse recycled aggregates decreased for replacement percentage between 50 and 80% as shown in Figure 16.

The concretes made with coarse and fine recycled aggregates showed very good values for the workability and compaction of all the mixtures, up to from the one made with 80% of replacement percentage but the mixture with 100% of coarse and fine recycled aggregates was quite fragmented after both 5 and 30 minutes, as shown in Figures 7 and 8.

Generally speaking, the concrete made with coarse and fine recycled aggregates maintained a workability of fluid or superfluid type (S4/S5).

This is a very good result because most concrete construction work require a workability between S3 (semifluid) and S5 (superfluid).

In Figure 17 the plot shows the index of loss workability IL, defined by the ratio between the slump at 5 and 30 minutes. Normal concrete usually results around IL = 0.76.

As can be seen, the concrete made with coarse and fine recycled aggregates has values similar or greater than those of ordinary concrete; the concrete made with only coarse recycled aggregates with replacement percentages of 50 and 80% have a reduction in the IL index between 0,6 and 0,5.

Figure 18 shows the values of slumps after 5 minutes for the fresh concretes made with different replacement percentages of only coarse recycled aggregates with dmax 16 mm and dmax 25 mm.

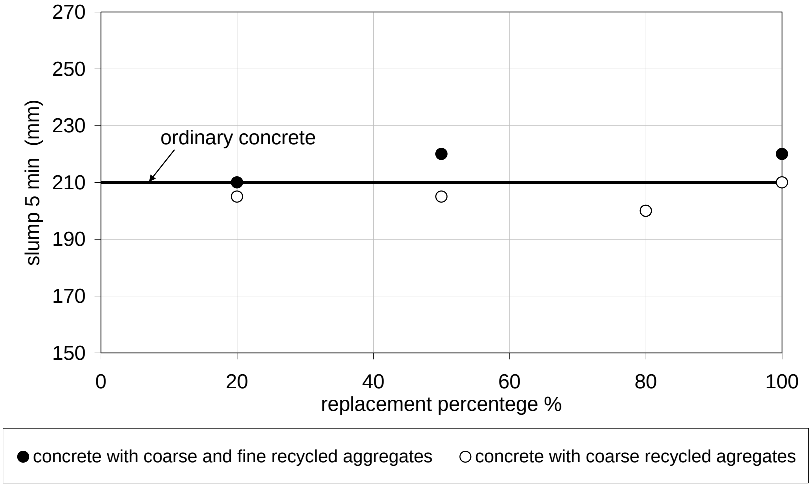

Fig. 15 - Slump at 5 min for fresh concrete dmax 16 mm

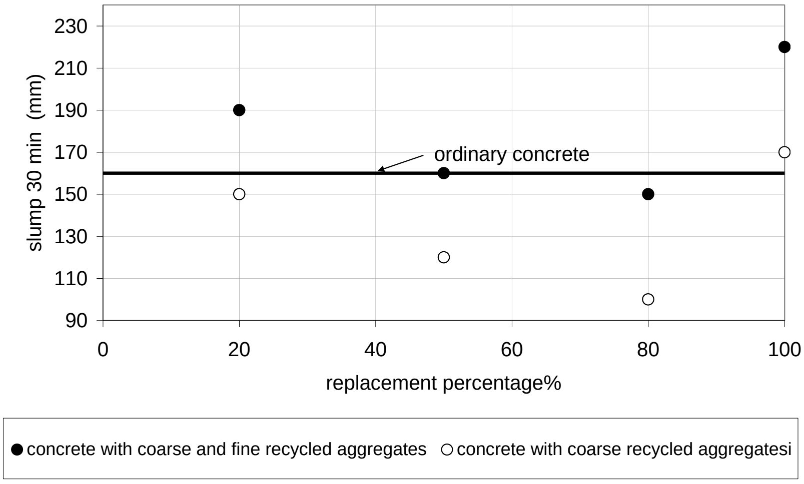

Fig. 16 - Slump at 30 min for fresh concrete dmax 16 mm

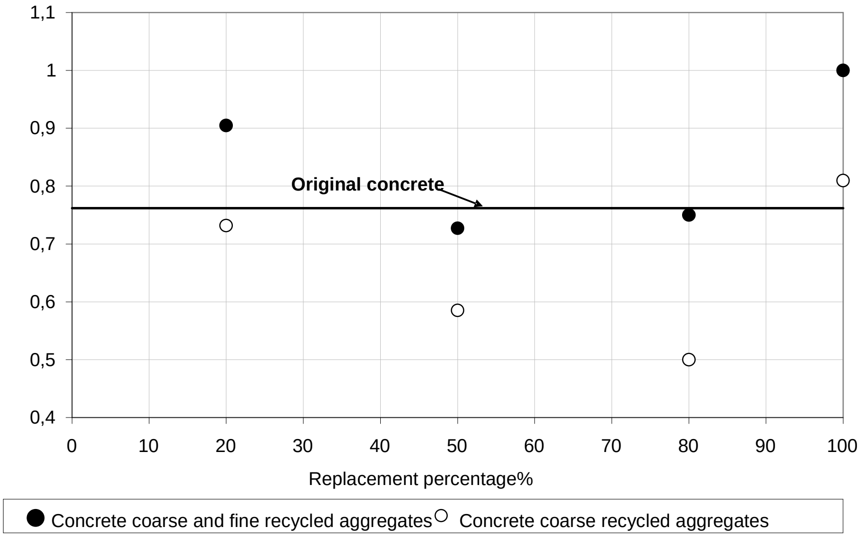

Fig. 17 - Loss of workability IL of mixtures made with recycled concrete dmax 16mm and ordinary concrete

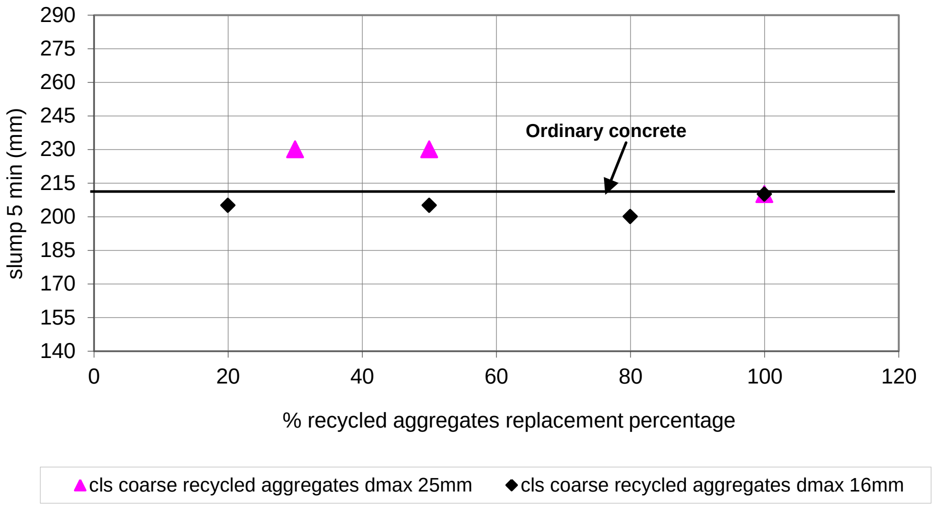

Fig. 18 - Comparison between slump at 5 min for all mixtures made with only coarse recycled aggregates

In general, these results show differences in workability at 30 minutes between mixes with only coarse recycled aggregates and those with coarse and fine recycled aggregates for all replacement percentages. The introduction of the fine recycled fraction, characterised by very high absorption power, made it possible to obtain recycled concretes with high workability and compactability even at 30 minutes, very similar to those of conventional concretes.

This phenomenon may be attributed to the times and dynamics of absorption of the fine recycled aggregates, also due to the presence of grains composed of mortar only.

4.3.2 COMPRESSIVE STRENGTH

4.3.2.1 CONCRETE MADE WITH COARSE AND FINE AND ONLY COARSE RECYCLED AGGREGATES (1-8 RC)

The mechanical behaviour of concrete is influenced by many factors; the key role of aggregates is clear because by itself it occupies more than two thirds of the total volume of concrete.

The compressive strength was evaluated using cubical and cylindrical specimens aged for 28 days at normal thermohygrometric conditions.

In Figures 19 and 20 the compression strength for the cubical and cylindrical specimens are reported for different replacement percentages of recycled aggregates.

Both the cubical (Figure 19) and the cylindrical (Figure 20) strength of the concrete made with coarse and fine recycled aggregates was lower compared to the reference concrete and the concrete made only with coarse recycled aggregates. The gap increased for higher replacement percentages of recycled aggregate in place of natural ones. The reductions in strength was then 16% for cubical strength and 26% for cylindrical strength.

The cubical and cylindrical strength of the concrete made with only coarse recycled aggregates was slightly lower than that of normal concrete; if the replacement percentage was less than 50% the largest reduction detected was 5%.

Using only coarse recycled aggregates with 100% of substitution the cubic strength decreased by 8% compared to the normal concrete. These reductions were limited and coherent with the ones detected in some other scientific papers.

It is important to note that the maximum loss in the cubic strength of the concrete made with a replacement percentage of 100% was 15%, as shown in Figure 21, but the Los Angeles test showed large differences in the measured strength values between the recycled and the natural aggregates with a peak of 88%.

Thus it is possible to state that probably the compression cubical strength of the recycled concrete was only partially affected to the strength of the recycled aggregates.

On the other hand, the cylindrical strength was more sensitive to the recycled aggregates used: It was observed that when only coarse aggregates are used, the reduction in strength reaches 20% (Figure 21).

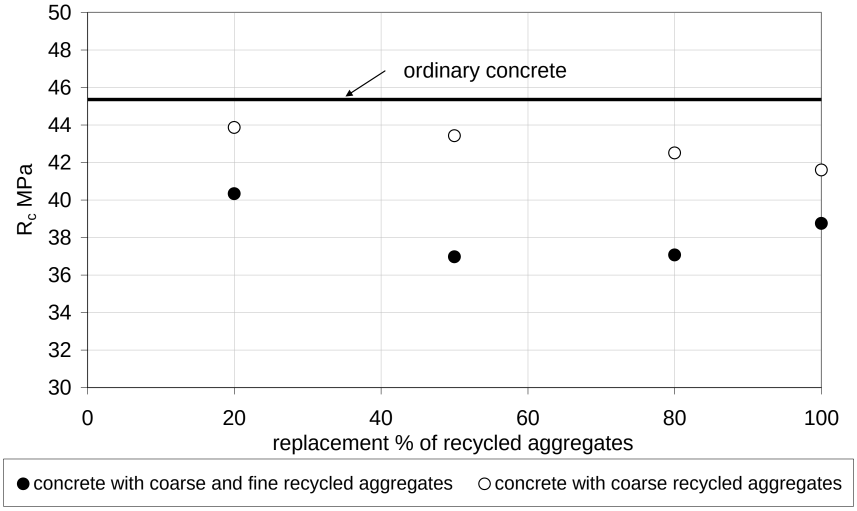

Fig. 19 - Cubic compressive strength with the varying of the recycled aggregates replacement percentage

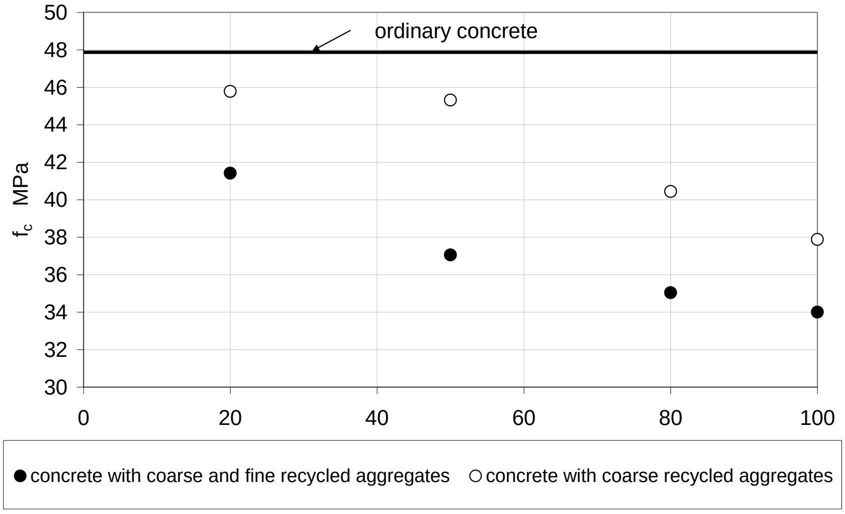

Fig. 20 - Cylindrical compressive strength with the varying of the recycled aggregates replacement percentage

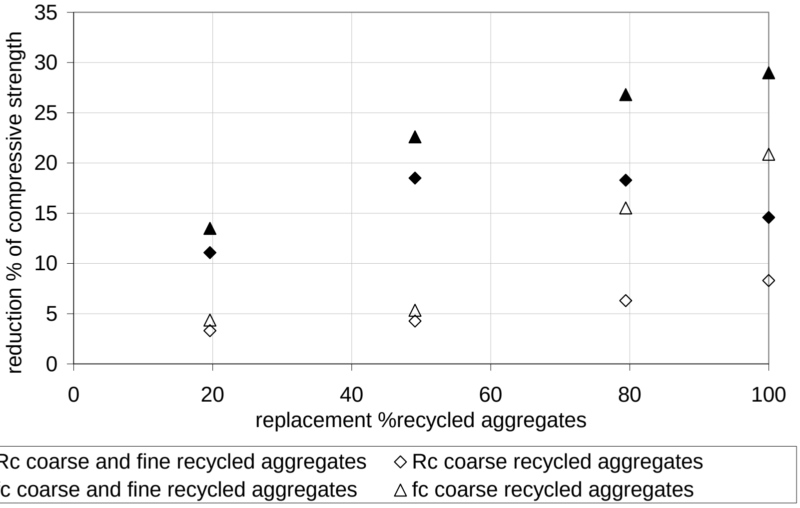

Fig. 21 - Reductions in cubic and cylindrical compressive strength for recycled concretes compared with ordinary ones

The introduction of fine fraction caused a reduction of both cubic and cylindrical strengths, for all replacement percentage. Nevertheless the resistances obtained are valid for structural concrete.
The ratio between the cubical and cylindrical compressive strength was close to the one suggested by the EC2 for the concrete of class C30/37 (fck / Rck = 0,81). This is reported in Figure 22 and is independent of the replacement percentage.

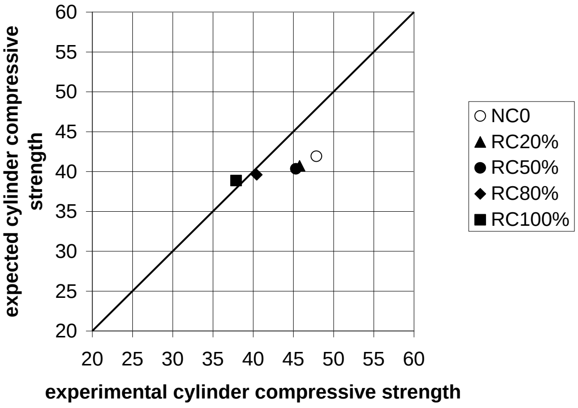

Fig. 22 - Relationship between cubic and cylindrical compressive strength for the recycled concrete and that proposed by EC2

Pictures from 23 to 27 show the compressive failure of some cylindrical specimens made with different percentages of recycled aggregates.

In some cases, contrary to what happens usually, the cylinder compressive strength was greater than the cubical. This fact could be due to the cylindrical specimens that were not of standard size and that were obtained by probing operations. The use of non-conventional cylindrical specimens it was necessary for the characteristics of the machine wherein the mechanical tests were performed. In addition, the compressive strength test was performed after the cycles of loading and unloading for the elastic modulus evaluation.

Fig. 23 - Compressive test on specimen made with 100% of coarse and fine recycled concrete

Fig. 24 - Compressive test on specimen made with 80% of coarse and fine recycled aggregates + 20% naturals

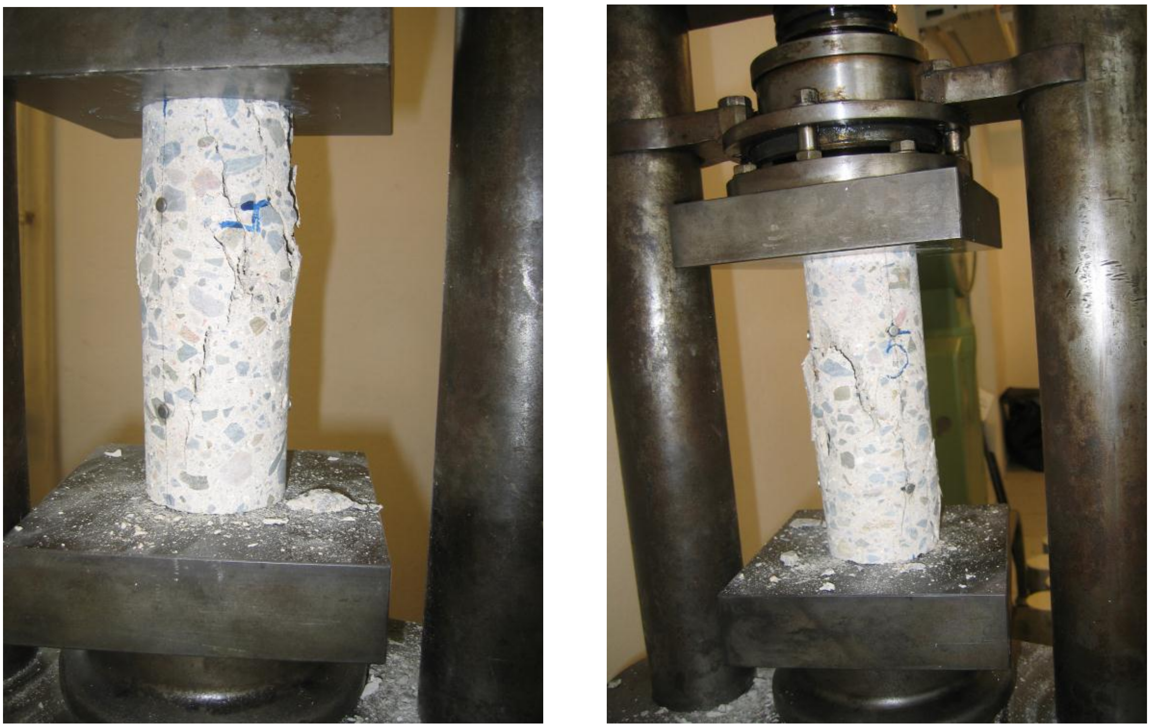

Fig. 25 - Compressive test on specimen made with 50% of coarse and fine recycled aggregates + 50% naturals

Fig. 26 - Compressive test on specimen made with 100% of coarse recycled concrete

Fig. 27 - Compressive test on specimen of normal concrete

4.3.2.2 CONCRETE MADE WITH COARSE RECYCLED AGGREGATES (9RC, 10RC, 11RC)

Compressive strength was evaluated on cubical specimens aged for 28 days at normal thermohygrometric conditions.

The plot in figure 28.a shows all the cubical strength values for specimens with different replacement percentages of coarse recycled aggregates with a maximum diameter of 25 mm, labelled 9RC, 10 RC and 11RC, against the cubical strength values for the reference normal concrete, indicated with the abbreviation 0NC.

It is easy to see that the recycled concretes show cubical strengths comparable with those of the specimens made with the reference concrete. The gap is more or less 4% .

As concerns the concretes made with only coarse recycled aggregates, the values of the Rc/Rc0 ratio between compression strength of recycled concrete and that of ordinary control concrete with variation in the replacement percentage are shown in Figure 28.b. As can be seen, the values of the Rc/Rc0 ratio obtained for the concrete produced with recycled aggregates with a maximum diameter of 25 mm (9RC, 10RC, 11RC), are very similar to those for the concrete made with aggregates having a maximum diameter of 16 mm (5RC, 6RC, 7RC, 8RC).

The Los Angeles test of the recycled aggregates with dmax = 25 mm gave LA equal to 25. This is an important fact because LA = 25 is a value quite similar to the one obtained for the natural aggregates, and it is very far from the LA average value measured for the recycled aggregates with dmax 16 mm equal to 37.

These experimental results clearly indicate that the cubical compressive strength of the recycled concrete is only partially affected by the mechanical features of the recycled aggregates used.

These results are important because they show a constant trend of recycled concrete compressive strength for all replacement percentages, even if vary the physical and mechanical properties of recycled aggregates used.

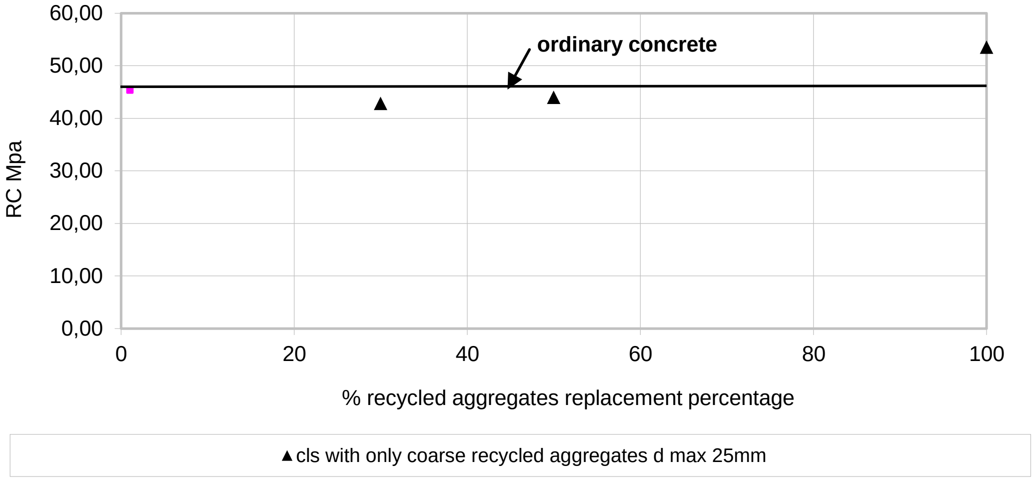

Fig. 28 a - Compressive strength with the varying of the recycled aggregates replacement percentage

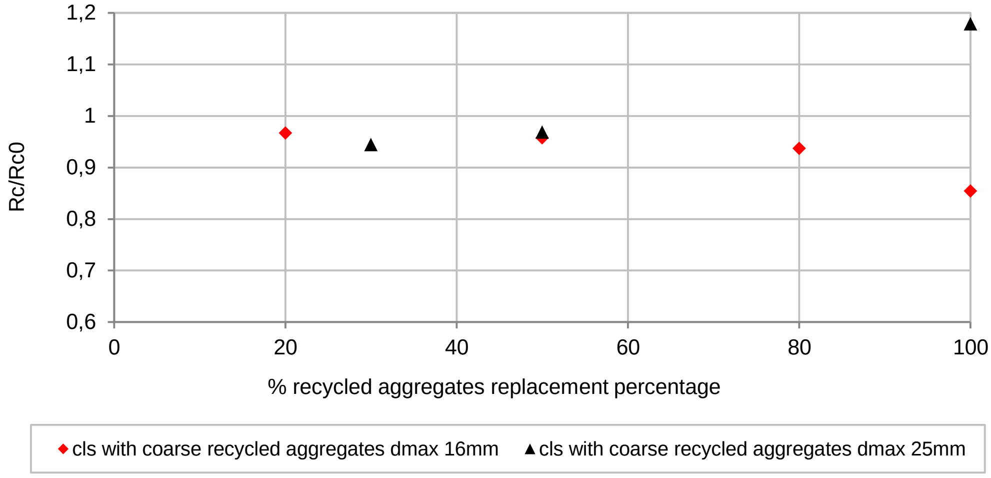

Fig. 28 b - Ratio Rc/Rc0 for all recycled concretes made with only coarse recycled aggregates with variation of the replacement percentage

4.3.2.3 CONCRETE MADE WITH 30 % OF COARSE RECYCLED AGGREGATES

Figure 29.a and 29.b show the data extrapolated from 30 different scientific papers on the determination of the cubical compressive strength of concrete made with coarse recycled aggregates with a maximum replacement percentage of 30%, together with the experimental data obtained in this work in compressive strength tests of recycled concrete with the same replacement percentage of substitution equal to 30% , using only coarse aggregates (red markers, labelled 8RC and 11RC), compared with ordinary reference concretes.

The differences are slight very small and often not very appreciable (Figure 29.a). The percentage of reduction of these values taken into account are between 2% and 6% (Figure 29.b). As a consequence of the tests on our specimens and the results of the comparative analysis with the data extrapolated from international literature, it is possible to state that when the replacement percentage of coarse recycled aggregates is lower than (or equal to) 30%, the mechanical strength of the final concrete is very similar to the ordinary ones.

For the results obtained in this study, the limitation presented in the DM 14.01.2008, which provides for the use of only coarse recycled aggregates up to 30% in replacement of natural aggregates for structural concrete of class C30/37, appears to be excessively precautionary, thus limiting the potential for the recycling of concrete and increasing the scepticism about this practice of packaging.

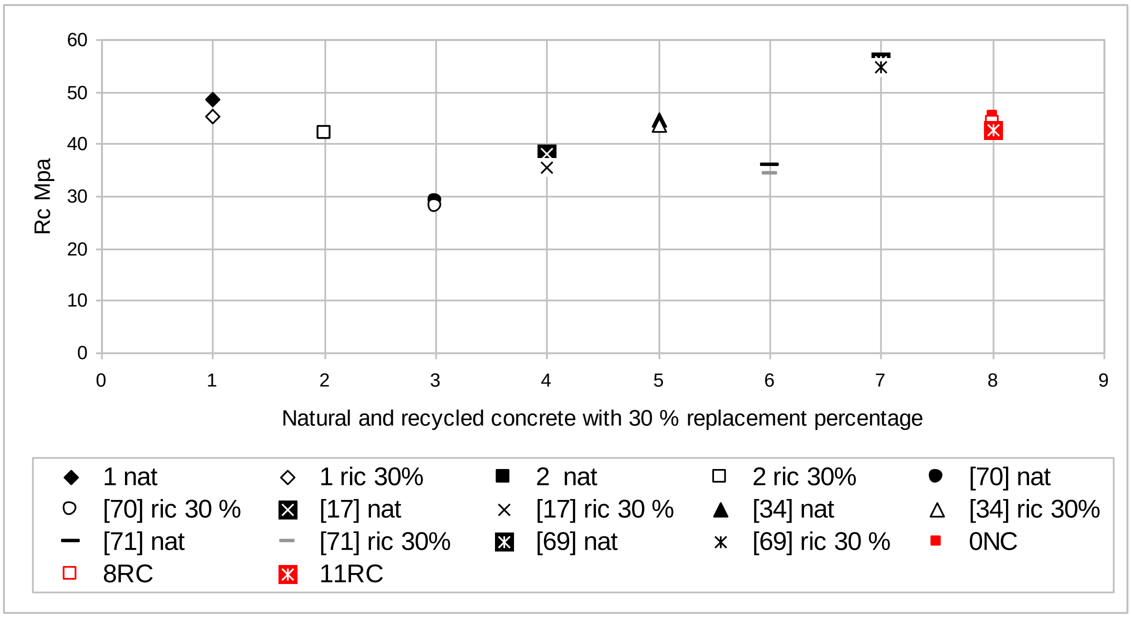

Fig. 29 a - Compressive strength of recycled and natural concrete made with 30% of recycled aggregate

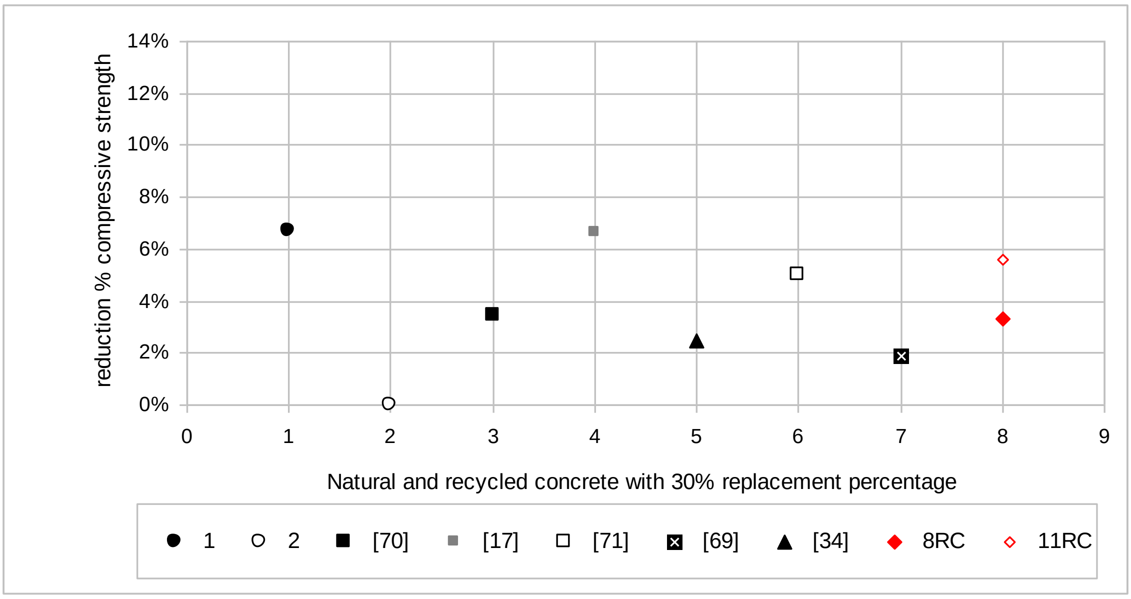

Fig. 29 b - Comparison between reduction percentage of compressive strength of concrete made with 30% of recycled aggregate and the natural concrete

4.3.3 TENSILE STRENGTH

4.3.3.1 CONCRETE MADE WITH COARSE AND FINE AND ONLY COARSE RECYCLED AGGREGATES (1-8 RC)

Tensile strength values were evaluated with an indirect test on cubic specimens, 3 for each mixture, aged for 28 days at standard thermohygrometric conditions.

From figures 30 and 31 it is possible to see that tensile strength is not influenced by the presence of fine recycled aggregates: indeed, the average values of the concretes made with coarse and fine recycled aggregates are comparable to the ones obtained for the concrete made with only coarse recycled aggregates.

Moreover, a comparison between the recycled and normal concrete showed that tensile strength decreased when the replacement percentage of the recycled aggregates increased.

The decrease in tensile strength reached 31% with a 100% replacement percentage of coarse and fine recycled aggregates and reached 25% with a 100% replacement percentage of only coarse recycled aggregates.

With replacement percentages up to 80%, in any case beyond the limits established by the Italian code, the average reduction of tensile strength between the reference and recycled concrete was equal to 20% (Figures 30 and 31).

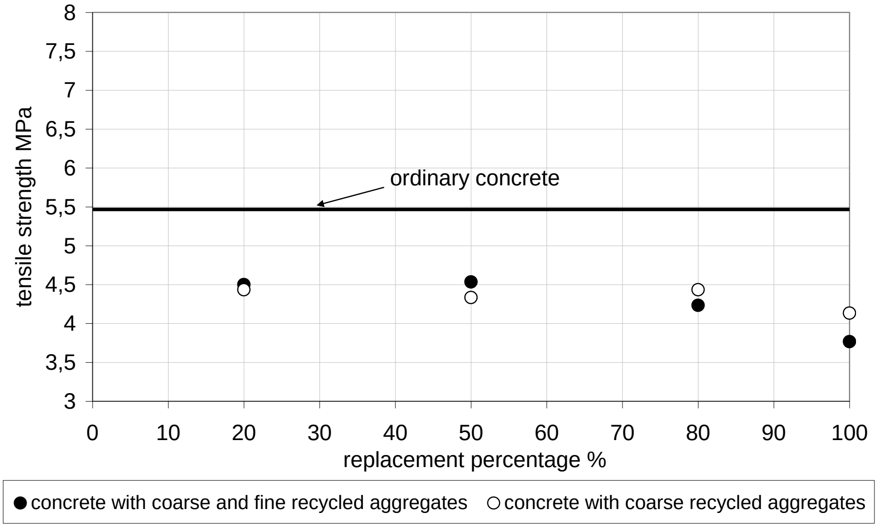

Fig. 30 - Tensile strength with the varying of the recycled aggregates replacement percentage

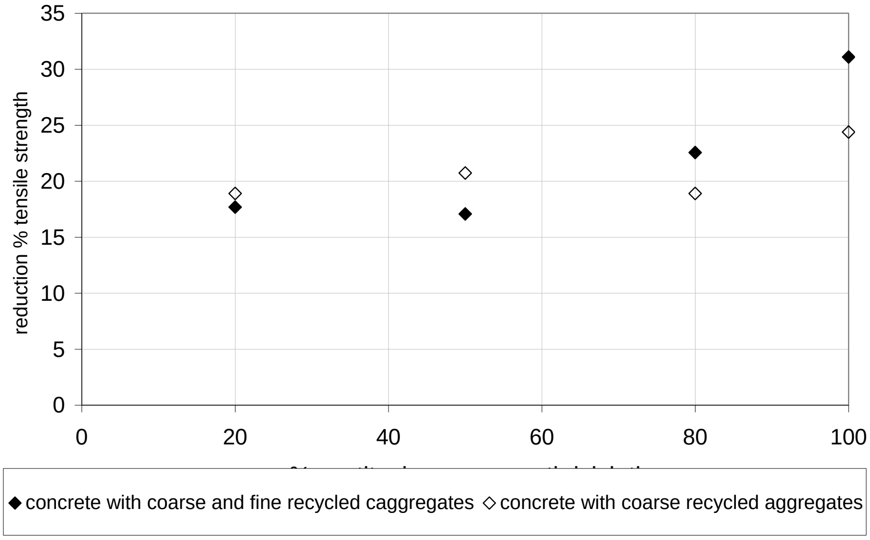

Fig. 31 - Reductions in the recycled concrete tensile strength in comparison with the ordinary concrete

4.3.3.2 CONCRETE MADE WITH COARSE RECYCLED AGGREGATES (9RC, 10RC, 11RC)

Tensile strength was evaluated with an indirect tensile strength test on cubical specimens, 3 for each mixture, 28 days aged at standard thermohygrometric conditions.

From Figure 32.a it is easy to see that the tensile strength of the recycled concretes 9RC, 10 RC and 11 RC is inferior to the values of tensile strength achieved for reference normal concrete. An average decrease of 40% compared to the reference normal concrete were obtained.

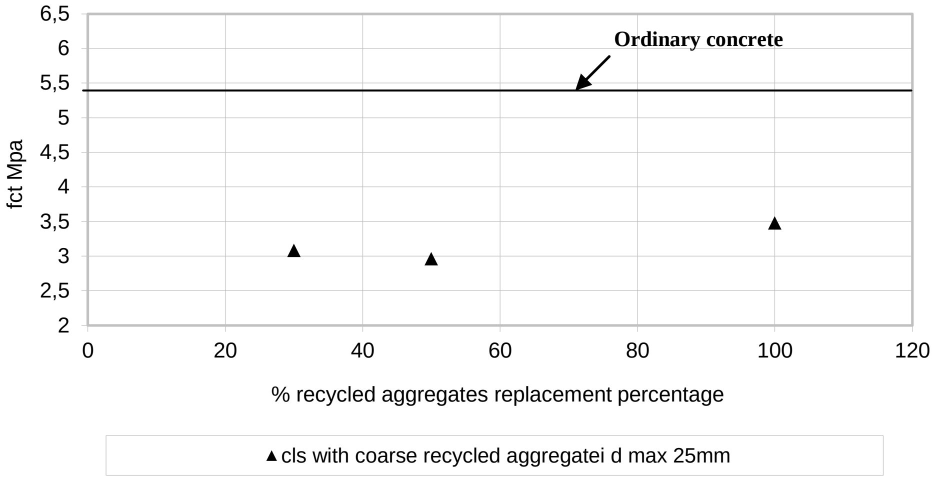

Fig. 32 a - Tensile strength with the varying of the recycled aggregates replacement percentage

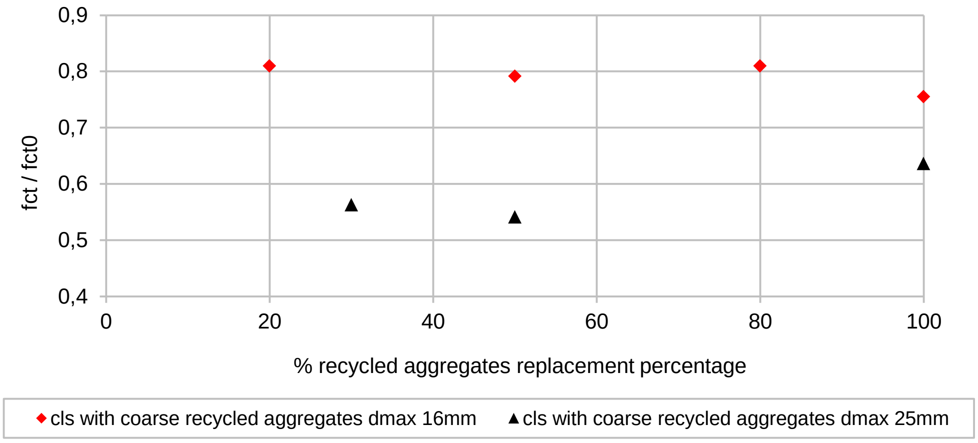

Fig. 32 b - Ratio fc/fc0 for all recycled concretes made with only coarse recycled aggregates with the varying of the replacement percentage

The comparison between values of fct/fct0 ratio for all concretes made with only coarse recycled aggregate shows a constant trend of tensile strength for all replacement percentages, but in this case it seems to affect the maximum diameter of aggregate, in fact the average ratio is equal to 0.8 when the dmax used is 16 mm, and 0.6 when the dmax used is equal to 25 mm, (figure 32. b).

4.3.3.3 POST FRACTURE ANALYSES

After tensile fracture, all the specimens made with only coarse recycled aggregates underwent a visual examination performed to highlight the different internal fracture modes.

In the Figures from 33 to 37 it is possible to see the fracture modes of cubic specimens; different colours were used to flag the various fracture modes encountered.

The green lines indicate the fracture due to detachment of the mortar from the aggregate. The blue lines mark the failure of the aggregates and the red lines signal the “mixed” mode of failure, that is, the joint fracture of mortar and aggregate.

As can be observed from the pictures, the “green” failure mode, failure caused by detachment between mortar and aggregate, decreased when the amount of recycled aggregates instead of the natural ones increased. In fact, when the replacement percentage was about 30% this failure mode was predominant, but when the percentage reached up to 100% this failure mode was no longer detectable. The number of the other two failure modes (red and blue lines) were found to be constant with the variation of the percentage of substitution.

It appears that the concrete made with the lowest replacement percentage of recycled aggregates, when the characteristics of the natural aggregates and the respective interfacial zone were predominant, the rupture occurred mainly by detachment between mortar and aggregates.

But in general, for replacement percentages of recycled aggregates below 100%, it is impossible to understand if the aggregates visible owing to detachment of the adhering mortar are the natural ones introduced into the mix or the recycled ones from which the old mortar has become detached.

While from the comparison between the break of the specimens made with 100% coarse recycled aggregates we can see that in general the yield plane presents the clear fracture of most of the recycled aggregates and not their detachment from the cement matrix. This occurs both with test pieces made with recycled aggregates with a maximum diameter of 25 mm and with those with a maximum diameter of 16 mm.

This is probably caused by the double transition zone present in the recycled aggregates and by the greater adherence between the old and new mortar produced by the irregular shape and rougher texture of the recycled aggregates compared to natural aggregates (Chapter 3).

In fact, the original stone elements of the recycled aggregates should have a resistance capable of supporting both the greater adherence and the influence of the double transition zone (ITZ). However, for all diameters used the results obtained demonstrate that the latter probably do not possess such resistance and this, together with the major porosity of the ITZ, may be at the base of the reduction in strength that normally characterises recycled concretes.

Fig. 33 - Specimen after tensile test, 100% of coarse recycled aggregates

Fig. 34 - Specimen after tensile test, 100% of coarse recycled aggregates

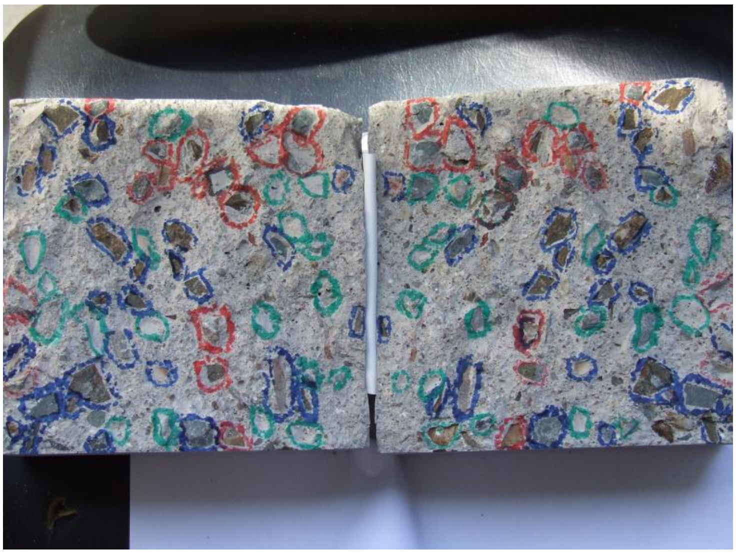

Fig. 35 - Specimen after tensile test, 50% of coarse recycled aggregates

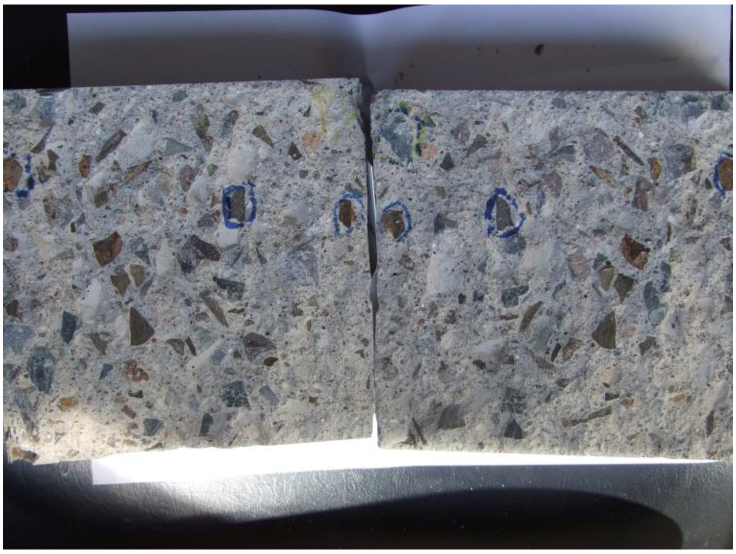

Fig. 36 - Specimen after tensile test, 30% of coarse recycled aggregates

Fig. 37 - Specimen after-tensile test, 30% of coarse recycled aggregates

4.3.4 ELASTIC MODULUS

The elastic modulus of concrete is closely connected to mechanical properties, the shape and the size of the aggregates used.

In this work several measures of the elastic modulus were performed on cylindrical specimens, 3 for each mixture, aged 28 days at standard thermohygrometric conditions.

Figures from 38 to 43 show some of the specimens tested. Each cylinder was equipped with 6 different length gauges placed as prescribed by the Italian code.

During the experiments the readings of length gauge displacements was performed using a digital reader characterized by centesimal precision.

In the same Figures (38-43) it is possible to see the superficial differences and the different concentrations of the aggregates for all the kinds of concrete used during the experimental campaign. (different replacement percentages of fine and coarse and only coarse recycled aggregates, and ordinary concrete).

Fig. 38 - Cylinder specimens made with 100% of coarse and fine recycled aggregates

Fig. 39 - Cylinder specimens made with 50% of coarse and fine recycled aggregates + 50% naturals

Fig. 40 - Cylinder specimens made with 20% of coarse and fine recycled aggregates + 80% naturals

Fig. 41 - Cylinder specimens made with 100% of coarse recycled aggregates

Fig. 42 - Cylinder specimens made with 50% of coarse recycled aggregates + 50% naturals

Fig. 43 - Cylinder specimens made with ordinary concrete

The plot in Figure 44 clearly shows that the elastic modulus of the concrete made with only coarse recycled aggregates is comparable to the ordinary concrete for replacement percentages up to 50%, while the elastic modulus slightly decreases when the percentage of substitution tends towards 100%.

A different Ec value was found for the concrete made with coarse and fine recycled aggregates which have a smaller elastic modulus than the ordinary concrete and the concrete made with only coarse recycled aggregates.

The reductions of the elastic modulus of the recycled concrete with different replacement percentages compared to the ordinary concrete are shown in Figure 45. The maximum reduction found is about 20% for the concrete made with coarse and fine recycled aggregates while a negligible reduction was measured (10% maximum) when only the coarse recycled aggregates were used.

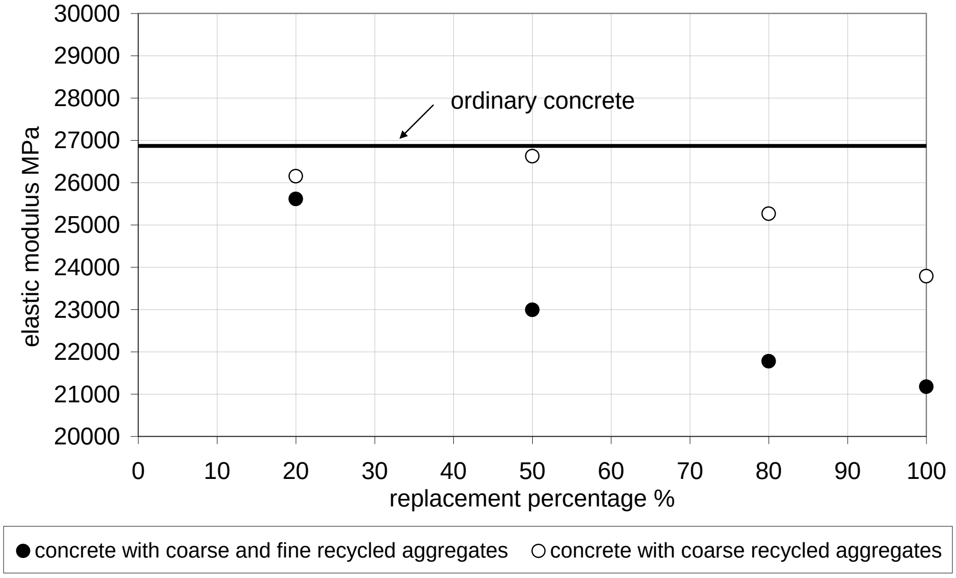

Fig. 44 - Elastic modulus with the varying of the recycled aggregates replacement percentage

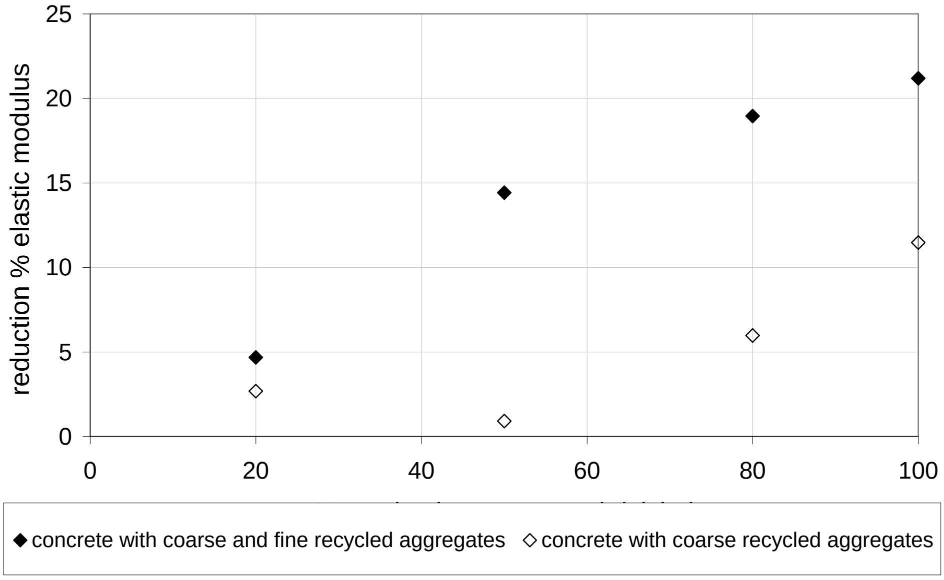

Fig. 45 - Ec reduction for concrete made with recycled aggregates in comparison with the Ec of ordinary concrete

Concerning the correlation between the elastic modulus and the average cylindrical compressive strength, the equation proposed by the EC2 for ordinary concrete was found to be valid for all the recycled concretes tested. $E_{cm} = 0{,}70 \cdot 22000 \cdot \left(\frac{f_{cm}}{10}\right)^{0{,}3}$

In fact, the elastic modulus evaluated experimentally was found to be very close to the one predicted by the relation (figure 46).

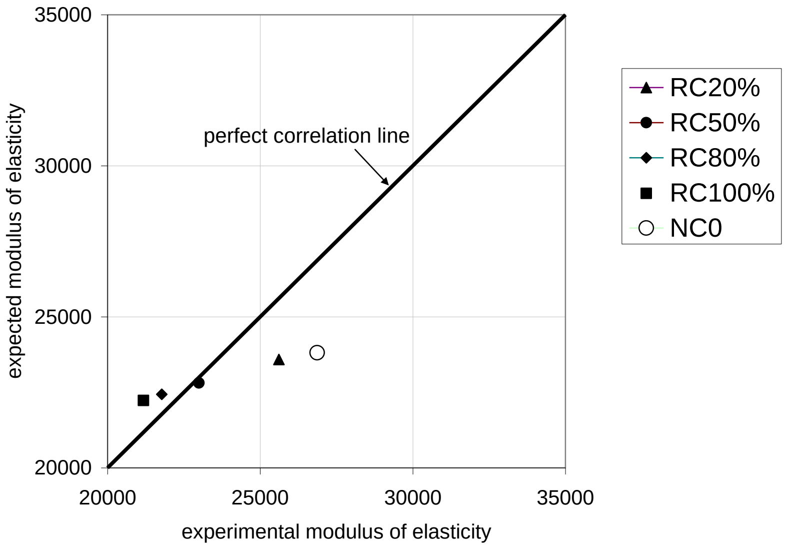

Fig. 46 - Relationship between elastic modulus and cylinder compressive strength of concrete proposed by EC2

4.3.5 ULTRASONIC TEST

Non-destructive test is based on the propagation of elastic longitudinal compressive waves between two points with different frequencies inside the material: the sonic method employs a frequency up to 20 kHz and the ultrasonic method a frequency above 20 kHz.

The key factor is that the propagation of the waves is closely connected to the properties and features of the material tested. The changes in the propagation of the waves are generated by modifications in the mechanical properties of the material [51]. For concrete, with the use of longitudinal ultrasonic waves it is possible to obtain very important information such as:

- Concrete uniformity;
- Changes in the mechanical properties of the concrete;
- Dynamic elastic modulus;
- Dynamic Poisson ratio;
- Individuation of defects and flaws;
- Percentage of voids;
- Good estimation of the strength of the concrete;
- Thickness of the damaged concrete;
- Superficial crack evaluation; [52].

The common application of this technique is based on the measure of the acoustic speed through the specimens. The standard [EN 12504-4 2004] suggests working with the "Techniques of Direct Transmission Techniques (DTT)". The tests require two devices: 1 transducer and 1 receiver placed on the opposite side. By means of these two devices it is possible to measure the transit time T, which represents the time required to go through the specimen. The distance between the transducer and the receiver, named length L. The speed of the wave is then computed using the ratio L/T. Figure 47 schematically shows three of the possible configurations: direct, semi-direct and indirect.

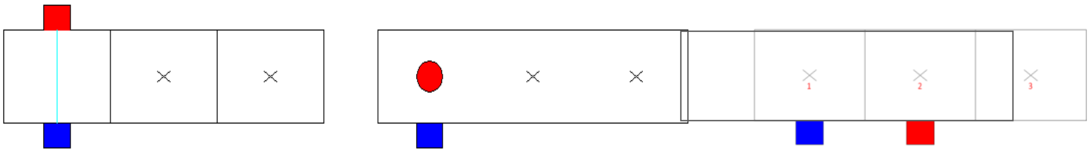

Fig. 47 - From left to right: position of the transducer for direct, semi-direct, indirect technique

In this work the direct transmission technique was performed to assess 48 cubical and 24 cylindrical specimens made with different kinds of concretes made with different replacement percentages of aggregates: natural , coarse and fine and coarse only.

All the data were measured along the chosen paths and points (one for each side of the cubical specimens, and six different point on each lateral surface plus two on the bases of the cylindrical specimens). All the results are reported in the annex 2.

The setup used during the experimental tests was been assembled in the Department of Civil Engineering, University of Cagliari and the components were:

- A wave generator, Vellemann Instruments, to cause the signal;
- A digital oscilloscope, Vellemann Instruments, to see the signal and for its analysis;
- A couple of piezoelectric transducers (with a frequency of 54 kHz) for the transmission and reception of the signal;
- A PC, with dedicated software for the acquisition and use of the signal.

Figure 48 shows the experimental setup:

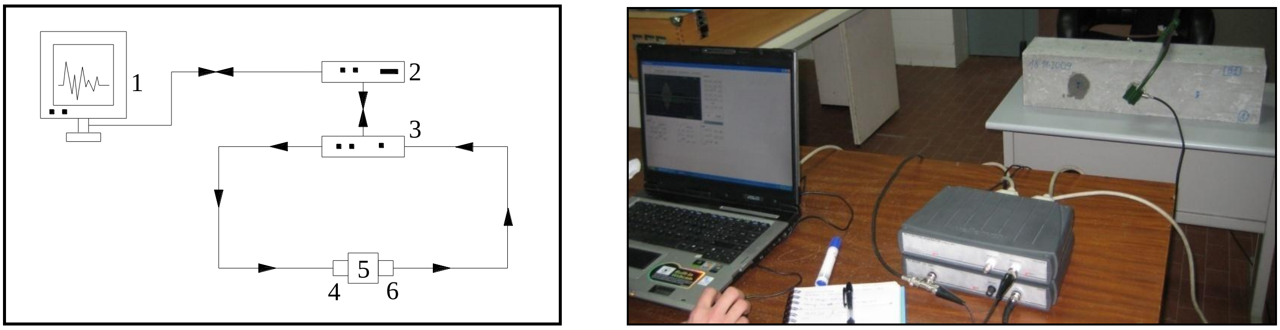

Fig. 48 - Experimental Set-up Scheme. 1) PC. 2) Signal Generator. 3) Oscilloscope. 4) Transducers. 5) Specimen

Figures 49, 50 and 51 show the average transit speed for different recycled aggregates replacement percentages for cubical and cylindrical specimens.

It is clearly shown that the average transit speed signal was quite similar for all the specimens tested, thus for the transit speed, it would appear that the recycled concrete has a behaviour quite similar to ordinary concrete.

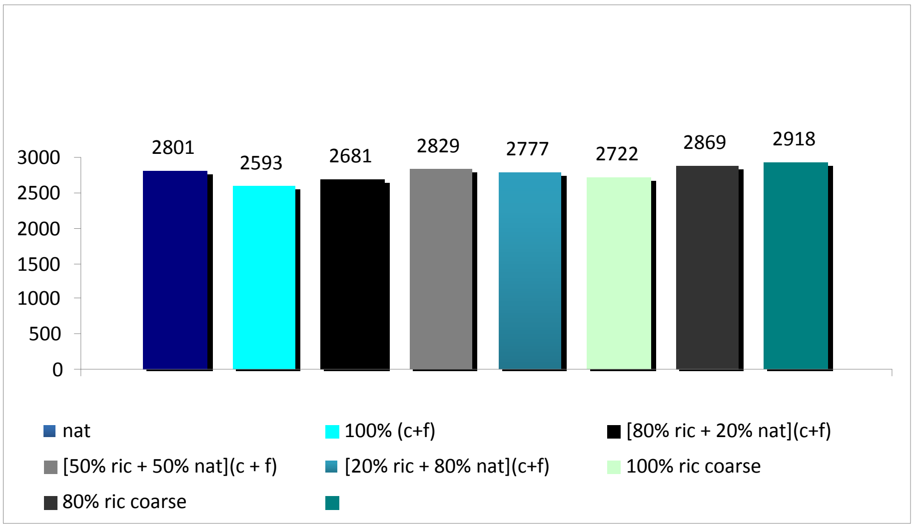

Fig. 49 - Cubic specimens; Average transit speed with the varying of the recycled aggregates replacement percentage

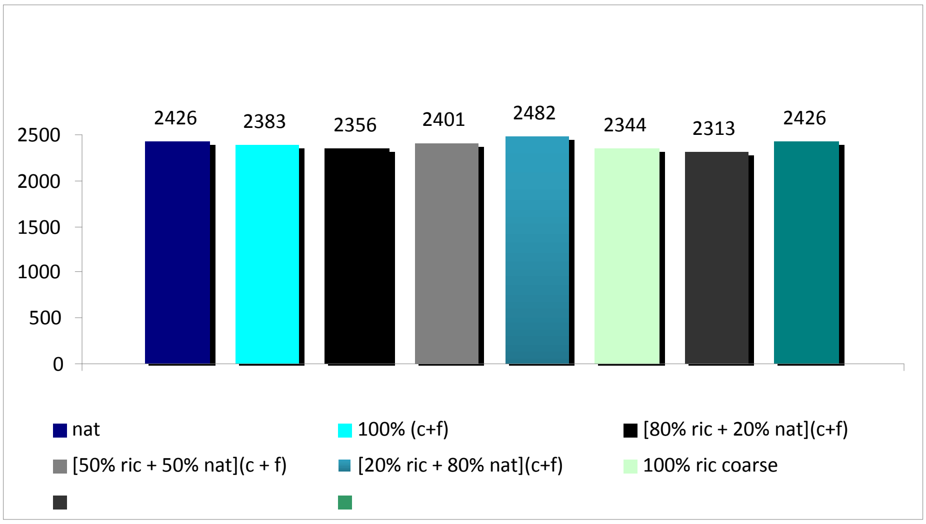

Fig. 50 - Cylindrical specimens; Lateral surface. Average transit speed with the varying of the recycled aggregates replacement percentage

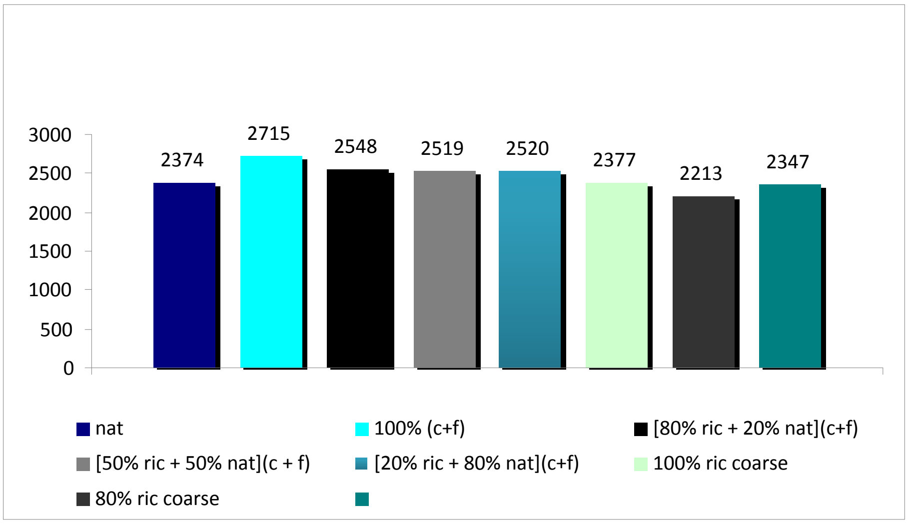

Fig. 51 - Cylindrical specimens; Bases surfaces. Average transit speed with the varying of the recycled aggregates replacement percentage

Chapter 5 Conclusions

5.1 RECYCLED AGGREGATES

The experiment carried out on recycled aggregates showed that:

- The shape, size and texture of recycled aggregates, as well as crushing with a jaw crusher, influence the amount of cement mortar adhering to the original aggregate. This means that it is generally quite variable so that it is impossible to estimate in advance.

The recycled aggregates we tested, with maximum diameter of 16 mm, had a unevenly distributed attached cement mortar adhering to the original aggregate; in fact, the original aggregate was often perfectly visible and with entire zones clean and free from old cement mortar, while the recycled aggregate with a maximum diameter of 25 mm had an evenly distributed attached cement mortar adhering to the original aggregate than did the other ones.

In both cases, the fine fraction possessed a considerable amount of free cement mortar. In fact, due to the crushing of concrete a high percentage of fine material may be composed of cement mortar alone, completely detached from the original aggregate.

- The particle size distribution immediately after crushing, for diameters between 0 and 16 mm, is almost constant, even though recycled aggregates are come from different concretes with completely unknown origins. In addition, the particle size distribution of recycled aggregates immediately after crushing, for diameters greater than 4 mm, is in line with the ideal curves for natural aggregates. Instead, the particle size distribution is highly variable for diameters smaller than 4 mm.

It can be said that the quality and type of concrete used to produce recycled aggregates do not affect particle size distribution.

- In general, water absorption Wa24 is higher for recycled aggregates than for natural ones. The increase is caused by the presence of cement mortar adhering to original aggregates and appears to be independent of the quality of the original concrete.

In general, fine recycled aggregates absorb more water than coarse recycled aggregates. This is probably because a considerable part of the fine fraction is composed of only cement mortar, characterized by an absorption significantly higher than the aggregates.

This fact leads to significant difficulties in their characterization procedure and for using them to package the recycled concrete.

- Due to the presence of cement mortar, with a porosity greater than natural aggregates, there is a decrease in recycled aggregate density compared to natural ones.

The bulk density ρa of the recycled aggregates we tested is similar to that of natural aggregates, with a downward trend, especially for the coarse aggregates, as well as the values retrieved from the specialised literature considered.

The saturated surface dry density ρssd is variable for natural and recycled aggregates, for the ones we tested and for the others extrapolated from the literature.

In recycled aggregates the reaching of the saturated surface dry condition presents great difficulties and often represents an unknown factor due to the presence of cement mortar (adhering to the recycled aggregates) having a different structure and major porosity compared to natural aggregates. Furthermore, its amount is extremely variable, depending on the way in which it is crushed. All this may explain the obvious dispersion of the results obtained.

- Recycled aggregates have higher values of LA compared to natural ones. For the aggregates examined, with a maximum diameter of 16 mm, this increase is considerable; in fact, they have an LA average value equal to 37. The LA average value of natural aggregates is equal to 21. On the other hand, there is a slight increase in the LA value for recycled aggregates with a maximum diameter of 25 mm, for which we obtained an LA value equal to 25.
This fact is probably due to different reasons; there is surely a strong dependency on strength, shape and texture of the original aggregates, the quantity of mortar on them and the strength of the connection between aggregate and cement mortar.
The Los Angeles Test is based on evaluation of the crushed part subtracted from the original mass.
It is known that the crushing resistance of cement mortar is significantly lower than that of aggregate; in fact, during the fragmentation test, the cement mortar surrounding the granules was almost completely destroyed. At the end of the LA test the original aggregates were almost completely free of the cement mortar.

- The flattening index is variable for both natural and recycled aggregates.

- In general, recycled aggregates show a loss of resistance greater than natural ones, when subjected to freezing and thawing cycles.

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The results obtained from characterization of fine and coarse recycled aggregates, drawn randomly from a storage site, show a variability in line with what usually occurs in the characterization of natural aggregates, especially for coarse aggregates.
The CE marking of recycled aggregates from concrete only, now completely absent in Sardinia, appears to be a feasible goal. However, a complete reorganization of demolition companies with selective demolition and separation of C&D waste is essential, together with a reorganization of authorized storage sites.

5.2 RECYCLED CONCRETE

The experimental investigation conducted on recycled concretes made with fine and coarse recycled aggregates and only coarse recycled aggregates, showed that:

- Workability after 5 and 30 minutes of fresh recycled concrete, made with fine and coarse recycled aggregates, is similar to that of ordinary concrete. With a replacement percentage in substitution of naturals between 30% and 80%, it maintained a workability of the fluid or superfluid S4/S5 type.
It can be said that these mixtures, for their workability and compactability, are transportable and usable in practice, while the mixtures with 100% of fine and coarse recycled aggregate are highly disaggregated and not very operable in general.
The workability of recycled concrete made with different replacement percentages of only coarse recycled aggregates, after 5 minutes from the packaging is very similar both to the one measured for recycled concrete made with fine and coarse recycled aggregates and to ordinary concrete.
The workability after 5 minutes of the recycled concrete made with only coarse recycled aggregates is usually of the fluid or superfluid type, while the workability after 30 minutes undergoes a strong reduction for replacement percentages exceeding 50%. The use of mixtures made with only coarse recycled aggregate for replacement percentages above 50% is possible only by means of an

optimization of the water content of the mixtures and of the type and amount of additive that has been used.

It is evident that the introduction of the fine recycled fraction, characterised by very high absorbent power, made it possible to obtain recycled concrete with high workability and compactability even at 30 minutes, very similar to those of conventional concrete.

This phenomenon may be attributed to the times and dynamics of absorption of the fine recycled aggregates, also due to the presence of grains composed of mortar only.

▪ It is evident that in general, recycled concrete has cubic and cylindrical strengths lower than normal concrete. This reduction increases when the replacement percentage of recycled aggregate in place of natural increases.

Cylindrical and cubic compressive strength of concrete made with only coarse recycled aggregates, for all replacement percentages, is generally higher than that of concrete made with coarse and fine recycled aggregates.

The cubic and cylindrical strengths of recycled concrete made with only coarse recycled aggregate are slightly lower than that of ordinary concrete. For replacement percentages below 50%, the reduction is about 5%. For replacement percentages equal to 100%, cubic resistance shows a reduction of about 8%.

The cubic and cylindrical strengths of concrete made with coarse and fine recycled aggregates has a mean decrease of 16% and 26% respectively compared to ordinary concrete.

These reductions are quite limited, even when the replacement percentage of recycled aggregate in place of the natural is very high. Compared to cube strength, cylindrical strength is more sensitive to the presence of recycled aggregate.

As concerns the concretes made with only coarse recycled aggregates, the values of the Rc/Rc0 ratio between compression strength of recycled concrete and that of ordinary control concrete with variation in the replacement percentage shown very similar values for the different aggregate used.

The reduction of resistance of the recycled aggregates observed with the Los Angeles test, very high for aggregates with a maximum diameter of 16 mm, is not directly proportional to the reduction of compressive strength of recycled concrete.

It can be said that the compressive strength, of recycled concrete, especially cubic compressive strength, is only partially influenced by the strength quality of recycled aggregates.

The correlations proposed by EC2 for ordinary concrete in estimating cylindrical strength in function of cubic strength adapt very well for recycled concrete for all replacement percentages.

In general the results show a constant trend of the recycled concrete compressive strength, to vary of physical and mechanical properties of recycled aggregates used.

▪ The tensile strength of recycled concrete is generally lower than that of ordinary concrete.

Concrete made with 100% of coarse and fine recycled aggregates, with maximum diameter of 16 mm, showed a maximum decrease of 31% and a maximum decrease of 25% when there was 100% of only coarse recycled aggregates. In both cases, when a replacement percentage up to 80% was considered, the average strength reduction was about 20%, if compared with ordinary concrete.

Experimentation showed differences between concrete compressive strength made with only coarse recycled aggregates and that made with coarse and fine recycled aggregates. These are not appreciable in the evaluation of tensile strengths.

It seems that tensile strength is not influenced by the presence of fine recycled aggregates: indeed, the average values of the concretes made with coarse and fine recycled aggregates are comparable to the ones obtained for the concrete made with only coarse recycled aggregates.

The tensile strength of concrete made with only coarse recycled aggregate with maximum diameter of 25 mm was significantly lower than that of ordinary concrete.

The comparison between the values of fct/fct0 ratio for all concretes made with only coarse recycled aggregate shows a constant trend of tensile strength for all replacement percentages

Tensile strength appears to be influenced by the dimension of aggregates, by the characteristics and strength of interface areas, but not in a very incisive way by the mechanical properties of aggregates.
In fact, the tensile strength of recycled aggregate with a maximum diameter of 25 mm, (even though it has a higher resistance evaluated by LA tests), is much lower than the one characterised by a maximum diameter of 16 mm.

The comparison between the break of the specimens made with 100% coarse recycled aggregates shows that in general the failure plane presents the clear fracture of most of the recycled aggregates and not their detachment from the cement matrix. This occurs both with test pieces made with recycled aggregates with a maximum diameter of 25 mm and with those with a maximum diameter of 16 mm.
This is probably caused by the double transition zone present in the recycled aggregates and by the greater adherence between the old and new cement mortar produced by the irregular shape and rougher texture of the recycled aggregates compared to natural aggregates.
In fact, the original stone elements of the recycled aggregates should have a resistance capable of supporting both the greater adherence and the influence of the double transition zone (ITZ). However, for all diameters used the results obtained demonstrate that the latter probably do not possess such resistance and this, together with the major porosity of the ITZ, may be at the base of the reduction in strength that normally characterises recycled concretes.

- The elastic modulus of concrete made with only coarse recycled aggregate was very similar to that of ordinary concrete for replacement percentages up to 50%, and underwent a negligible reduction of 10% for 100% replacement percentages of coarse recycled aggregates.

The concrete made with fine and coarse recycled aggregates had an elastic modulus lower than that of normal concrete and also that of recycled concrete made with only coarse recycled aggregate. A maximum reduction of 20% for concrete made with 100% of fine and coarse recycled aggregates was observed.

- Ultrasonic tests showed that the average transit speed of the signal was quite similar for all the specimens tested, thus for the transit speed, it would appear that the recycled concrete has a behaviour quite similar to ordinary concrete.

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Experimental results show a generally good behaviour of fresh and hardened recycled concrete. In concrete made with only coarse recycled aggregates, for very high replacement percentages of 50% and 80%, the differences with the strength properties of ordinary concrete are minimal, and sometimes irrelevant. In concrete made with fine and coarse recycled aggregates a reduction in strength was found, but was contained for replacement percentages up to 50%.
In this experiment the values found for the mechanical strength of all recycled concrete are related to structural concrete. The recycled concrete made with only coarse recycled aggregates maintained class C35/45 of ordinary concrete, even for a replacement percentage of 80%.
Concretes made with fine and coarse recycled aggregates went from class C35/45 for ordinary concrete, to one class C32/40, for replacement percentages of 80%.
Evidently, substitution of recycled aggregates in place of natural ones, up to 30%, does not cause significant changes in the mechanical properties of recycled concretes compared to ordinary ones.
Fine recycled aggregates present more problems compared to coarse recycled aggregates, especially as regards water absorption and particle size distribution. Their use in practice is possible if the dosage of water, cement and additives to be included in the mix is studied in advance.

The study of the mix in producing concrete, and in particular for recycled concretes, plays a role of fundamental importance.

The excellent results obtained in this experimental work, in terms of workability and strength are probably for the most part to be attributed to the choices made in this stage, mostly as concerns the choice of the additive and the amount of compensating water added to the mixtures.

The present study has shown that the limitation present in the DM 14.01.2008, which provides for the use of only coarse recycled aggregates up to 30% in replacement of natural aggregates for structural concrete of class C30/37, appears excessively precautionary.

In conclusion, it can be said that the use of coarse and fine recycled aggregates produced by crushing of only C&D concrete in authorized storage sites, is a real possibility for normal packaging of structural concrete, if the reorganization of demolition methods and the restructuring of storage sites is implemented.

An important result of the experiments performed concerns the possibility of producing structural concrete using real coarse and fine recycled aggregates coming exclusively from the waste crushed concrete, immediately as it comes out of the crusher, without the need to optimise the grain size curve. However, an optimal mix design must be arrived at, especially as concerns the W/C ratio and the quality and quantity of additive used.

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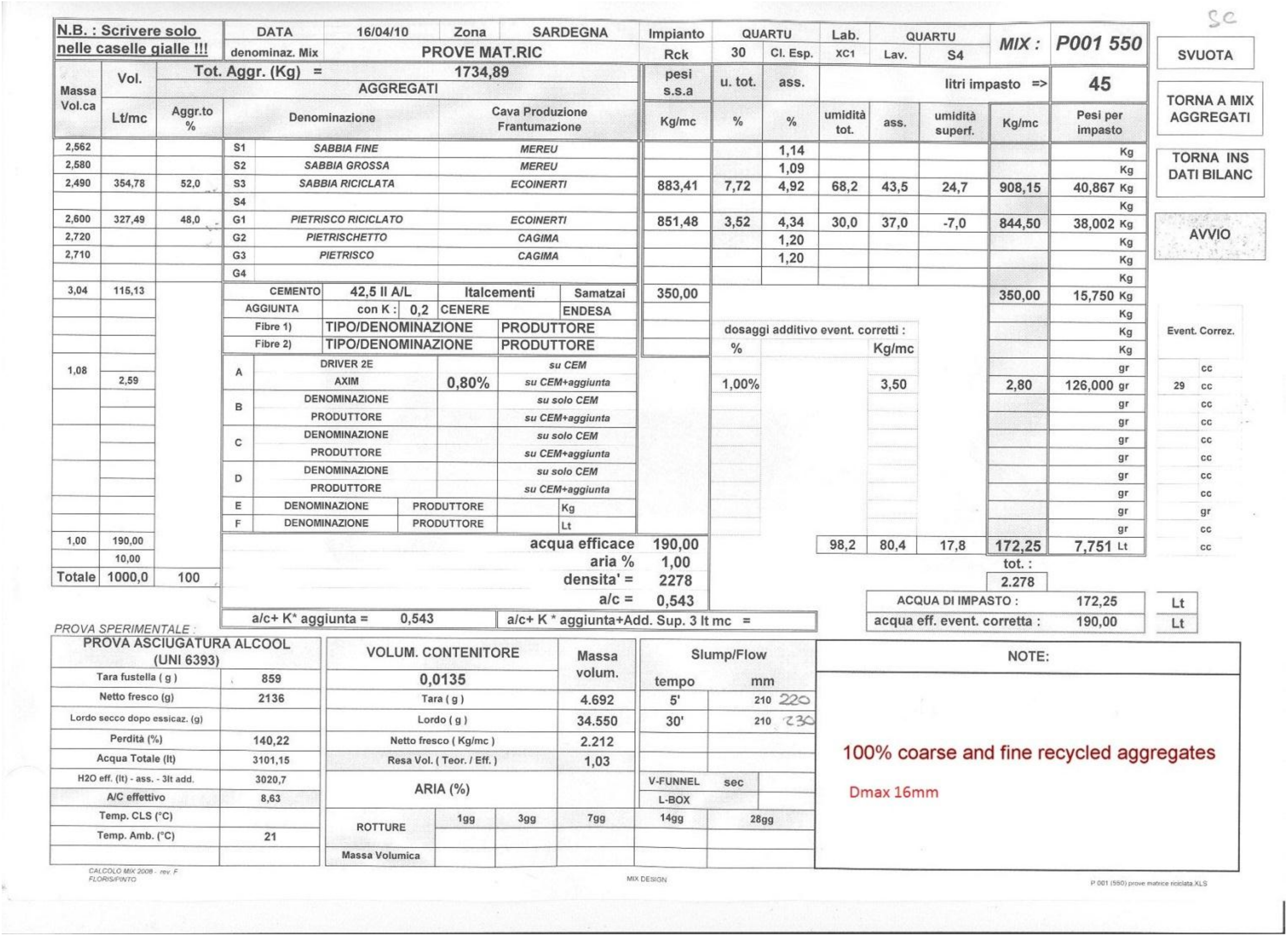
Annex 1: Mixture and particle size distributions of natural and recycled concrete



sc

N.B. : Scrivere solo nelle caselle gialle !!!	DATA	16/04/10	Zona	SARDEGNA	Impianto	QUARTU		Lab.	QUARTU		*MIX :*	*P001 550*
	denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp.	XC1	Lav.	S4		

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1734,89

AGGREGATI

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	Event. Correz.
2,562			S1	*SABBIA FINE*	*MEREU*			1,14					Kg	
2,580			S2	*SABBIA GROSSA*	*MEREU*			1,09					Kg	
2,490	354,78	52,0	S3	*SABBIA RICICLATA*	*ECOINERTI*	883,41	7,72	4,92	68,2	43,5	24,7	908,15	40,867 Kg	
			S4										Kg	
2,600	327,49	48,0	G1	*PIETRISCO RICICLATO*	*ECOINERTI*	851,48	3,52	4,34	30,0	37,0	-7,0	844,50	38,002 Kg	
2,720			G2	*PIETRISCHETTO*	*CAGIMA*			1,20					Kg	
2,710			G3	*PIETRISCO*	*CAGIMA*			1,20					Kg	
			G4										Kg	
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg	
			AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg	
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE		dosaggi additivo event. corretti :						Kg	Event. Correz.
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE		%		Kg/mc				Kg	
1,08			A	DRIVER 2E	*su CEM*								gr	cc
	2,59			AXIM	0,80% *su CEM+aggiunta*		1,00%		3,50			2,80	126,000 gr	29 cc
			B	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			C	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			D	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			E	DENOMINAZIONE	PRODUTTORE Kg								gr	gr
			F	DENOMINAZIONE	PRODUTTORE Lt								gr	cc
1,00	190,00				acqua efficace	190,00			98,2	80,4	17,8	172,25	7,751 Lt	cc
	10,00				aria %	1,00						tot. :		
Totale	1000,0	100			densita' =	2278						2.278		
					a/c =	0,543								

a/c+ K* aggiunta =	0,543	a/c+ K * aggiunta+Add. Sup. 3 lt mc =	

ACQUA DI IMPASTO :	172,25	Lt
acqua eff. event. corretta :	190,00	Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	859
Netto fresco (g)	2136
Lordo secco dopo essicaz. (g)	
Perdità (%)	140,22
Acqua Totale (lt)	3101,15
H2O eff. (lt) - ass. - 3lt add.	3020,7
A/C effettivo	8,63
Temp. CLS (°C)	
Temp. Amb. (°C)	21

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.692
Lordo (g)	34.550
Netto fresco (Kg/mc)	2.212
Resa Vol. (Teor. / Eff.)	1,03
ARIA (%)	

Slump/Flow		
tempo	mm	
5'	210	220
30'	210	230
V-FUNNEL	sec	
L-BOX		

	1gg	3gg	7gg	14gg	28gg
ROTTURE					
Massa Volumica					

NOTE:

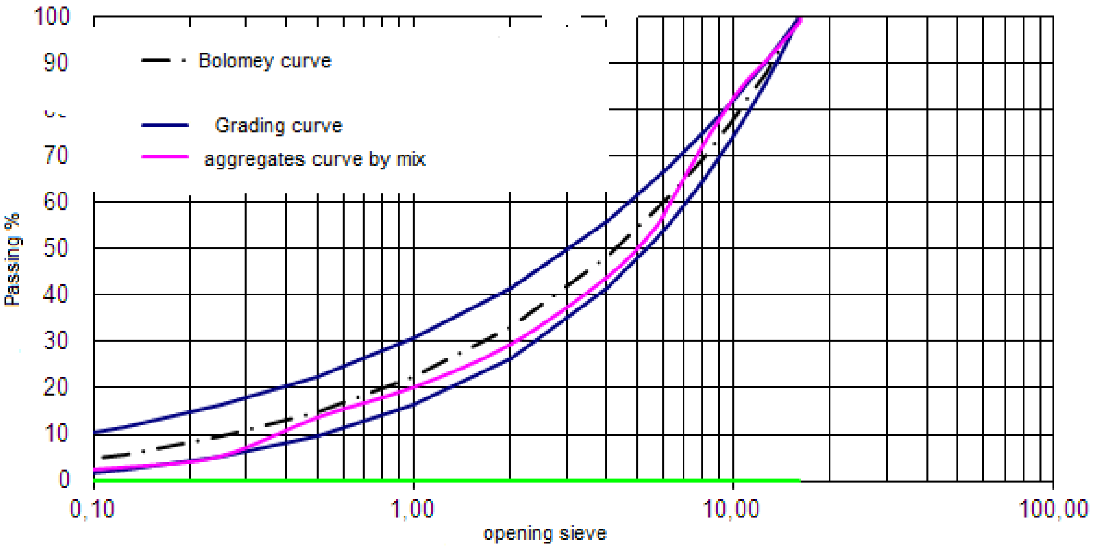
100% coarse and fine recycled aggregates

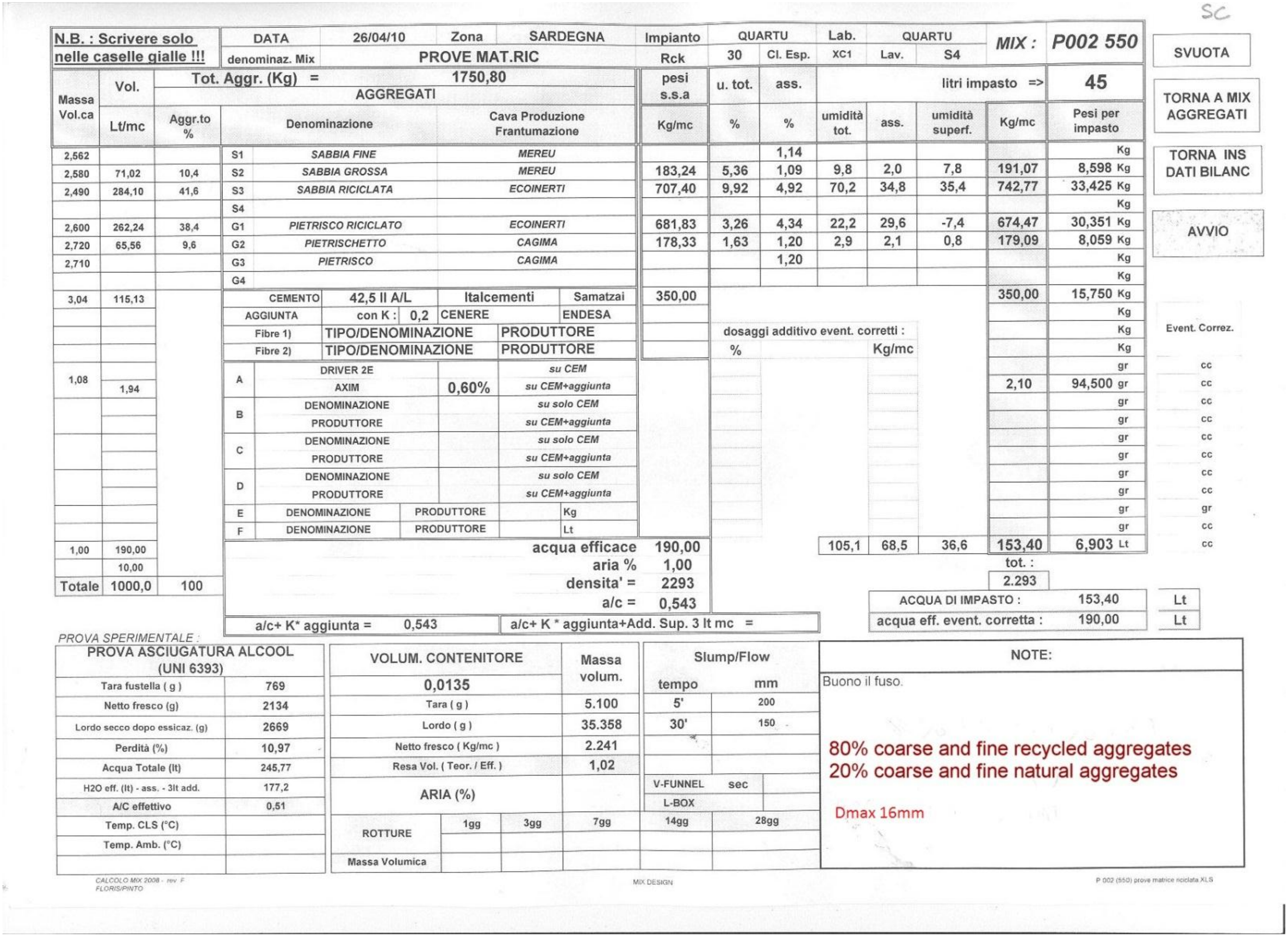
Dmax 16mm

CALCOLO MIX 2008 - rev. F
FLORIS/PINTO

MIX DESIGN

P 001 (550) prove matrice riciclata.XLS





SC

N.B. : Scrivere solo nelle caselle gialle !!!	DATA	26/04/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	MIX :	P002 550
	denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp.	XC1	Lav.	S4

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1750,80

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %	AGGREGATI	Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	Event. Correz.
2,562			S1	SABBIA FINE	MEREU			1,14					Kg	
2,580	71,02	10,4	S2	SABBIA GROSSA	MEREU	183,24	5,36	1,09	9,8	2,0	7,8	191,07	8,598 Kg	
2,490	284,10	41,6	S3	SABBIA RICICLATA	ECOINERTI	707,40	9,92	4,92	70,2	34,8	35,4	742,77	33,425 Kg	
			S4										Kg	
2,600	262,24	38,4	G1	PIETRISCO RICICLATO	ECOINERTI	681,83	3,26	4,34	22,2	29,6	-7,4	674,47	30,351 Kg	
2,720	65,56	9,6	G2	PIETRISCHETTO	CAGIMA	178,33	1,63	1,20	2,9	2,1	0,8	179,09	8,059 Kg	
2,710			G3	PIETRISCO	CAGIMA			1,20					Kg	
			G4										Kg	
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg	
			AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg	
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg	
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg	

dosaggi additivo event. corretti :

%		Kg/mc

Massa Vol.ca	Vol. Lt/mc		Denominazione			Kg/mc	Pesi per impasto	Event. Correz.
1,08		A	DRIVER 2E		su CEM		gr	cc
	1,94		AXIM	0,60%	su CEM+aggiunta	2,10	94,500 gr	cc
		B	DENOMINAZIONE		su solo CEM		gr	cc
			PRODUTTORE		su CEM+aggiunta		gr	cc
		C	DENOMINAZIONE		su solo CEM		gr	cc
			PRODUTTORE		su CEM+aggiunta		gr	cc
		D	DENOMINAZIONE		su solo CEM		gr	cc
			PRODUTTORE		su CEM+aggiunta		gr	cc
		E	DENOMINAZIONE	PRODUTTORE	Kg		gr	gr
		F	DENOMINAZIONE	PRODUTTORE	Lt		gr	cc

Massa Vol.ca	Vol. Lt/mc	Aggr.to %			umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	Event. Correz.
1,00	190,00		acqua efficace	190,00	105,1	68,5	36,6	153,40	6,903 Lt	cc
	10,00		aria %	1,00				tot. : 2.293		
Totale	1000,0	100	densita' =	2293						
			a/c =	0,543						

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO :	153,40	Lt
acqua eff. event. corretta :	190,00	Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	769
Netto fresco (g)	2134
Lordo secco dopo essicaz. (g)	2669
Perdità (%)	10,97
Acqua Totale (lt)	245,77
H2O eff. (lt) - ass. - 3lt add.	177,2
A/C effettivo	0,51
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	5.100
Lordo (g)	35.358
Netto fresco (Kg/mc)	2.241
Resa Vol. (Teor. / Eff.)	1,02
ARIA (%)	

Slump/Flow	
tempo	mm
5'	200
30'	150
V-FUNNEL sec	
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

Buono il fuso.

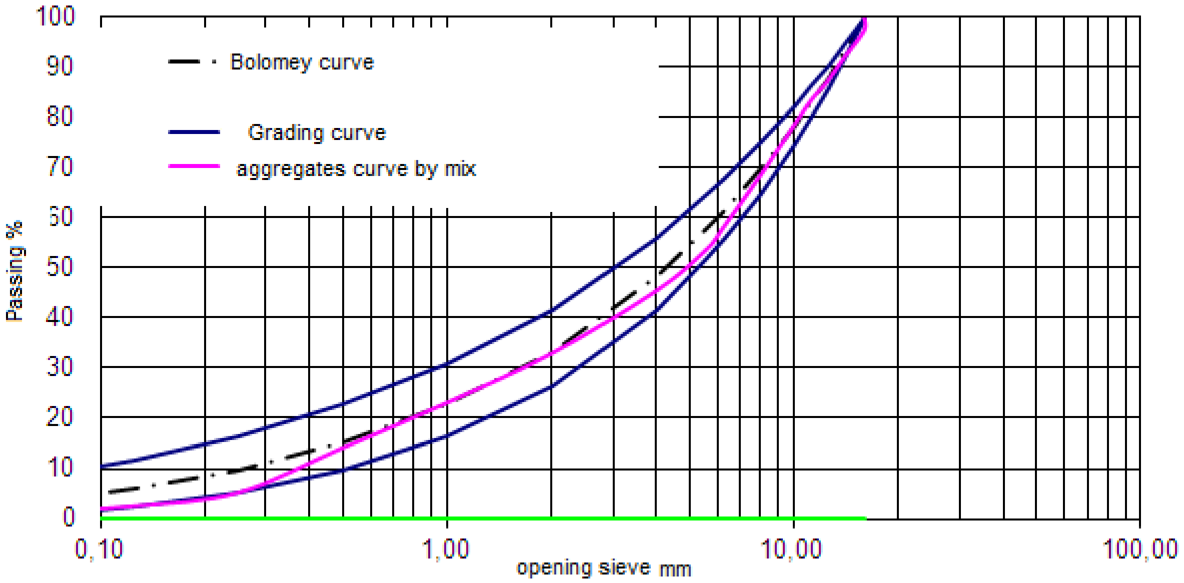
80% coarse and fine recycled aggregates
20% coarse and fine natural aggregates

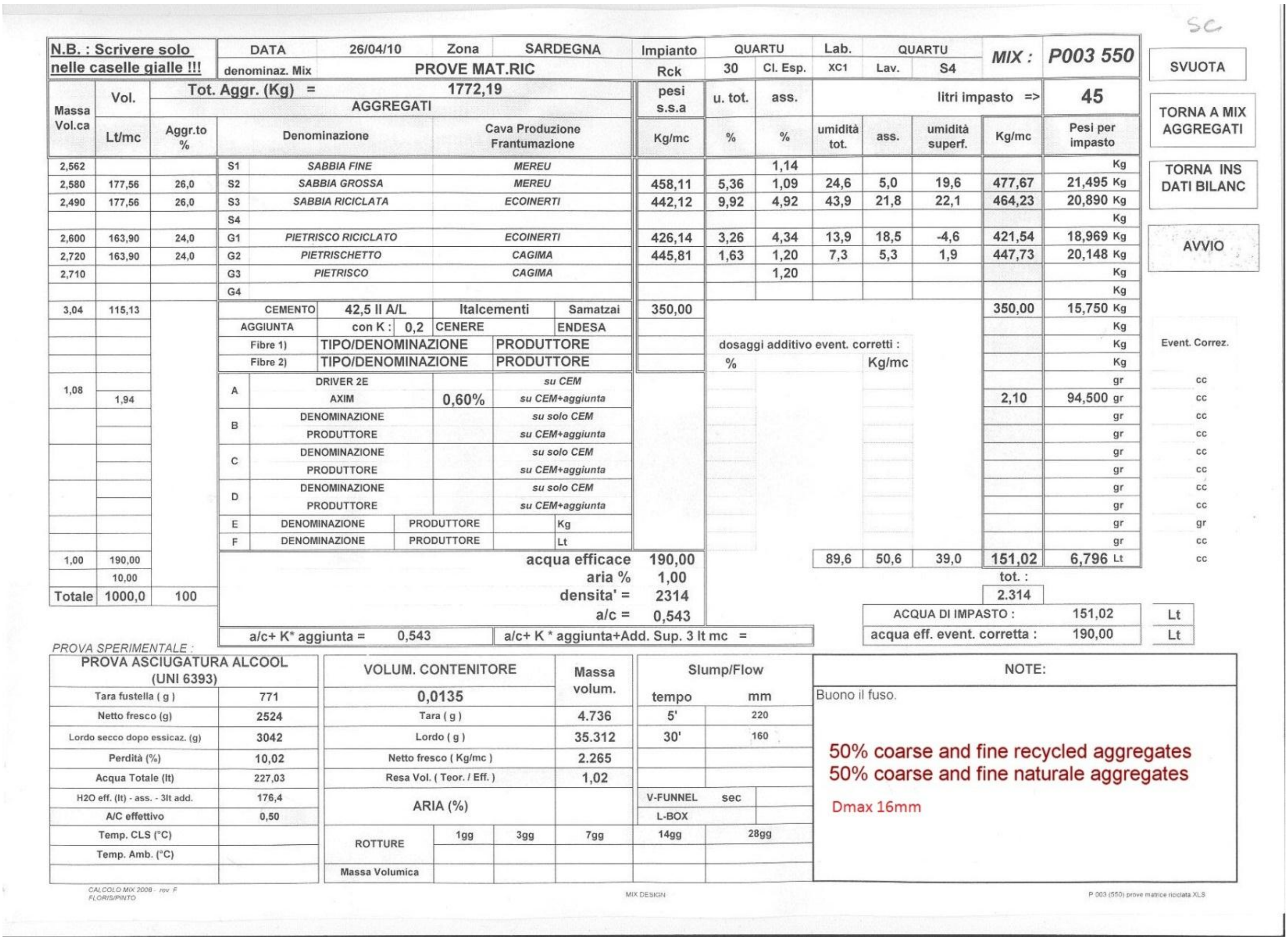
Dmax 16mm

CALCOLO MIX 2008 - rev. F
FLORIS/PINTO

MIX DESIGN

P 002 (550) prove matrice riciclata.XLS





SC

N.B. : Scrivere solo nelle caselle gialle !!!

DATA	26/04/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU
denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp. XC1	Lav. S4

MIX : ***P003 550***

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1772,19

AGGREGATI

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	
2,562			S1	*SABBIA FINE*	*MEREU*			1,14					Kg	
2,580	177,56	26,0	S2	*SABBIA GROSSA*	*MEREU*	458,11	5,36	1,09	24,6	5,0	19,6	477,67	21,495 Kg	
2,490	177,56	26,0	S3	*SABBIA RICICLATA*	*ECOINERTI*	442,12	9,92	4,92	43,9	21,8	22,1	464,23	20,890 Kg	
			S4										Kg	
2,600	163,90	24,0	G1	*PIETRISCO RICICLATO*	*ECOINERTI*	426,14	3,26	4,34	13,9	18,5	-4,6	421,54	18,969 Kg	
2,720	163,90	24,0	G2	*PIETRISCHETTO*	*CAGIMA*	445,81	1,63	1,20	7,3	5,3	1,9	447,73	20,148 Kg	
2,710			G3	*PIETRISCO*	*CAGIMA*			1,20					Kg	
			G4										Kg	
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg	
			AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg	
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE		dosaggi additivo event. corretti :						Kg	Event. Correz.
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE		%			Kg/mc			Kg	
1,08			A	DRIVER 2E	*su CEM*								gr	cc
	1,94			AXIM	0,60% *su CEM+aggiunta*							2,10	94,500 gr	cc
			B	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			C	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			D	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			E	DENOMINAZIONE	PRODUTTORE Kg								gr	gr
			F	DENOMINAZIONE	PRODUTTORE Lt								gr	cc
1,00	190,00				acqua efficace	190,00			89,6	50,6	39,0	151,02	6,796 Lt	cc
	10,00				aria %	1,00						tot. :		
Totale	1000,0	100			densita' =	2314						2.314		
					a/c =	0,543								

a/c+ K* aggiunta = 0,543 | a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO : 151,02 Lt

acqua eff. event. corretta : 190,00 Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	771
Netto fresco (g)	2524
Lordo secco dopo essicaz. (g)	3042
Perdità (%)	10,02
Acqua Totale (lt)	227,03
H2O eff. (lt) - ass. - 3lt add.	176,4
A/C effettivo	0,50
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.736
Lordo (g)	35.312
Netto fresco (Kg/mc)	2.265
Resa Vol. (Teor. / Eff.)	1,02
ARIA (%)	

Slump/Flow	
tempo	mm
5'	220
30'	160
V-FUNNEL	sec
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

Buono il fuso.

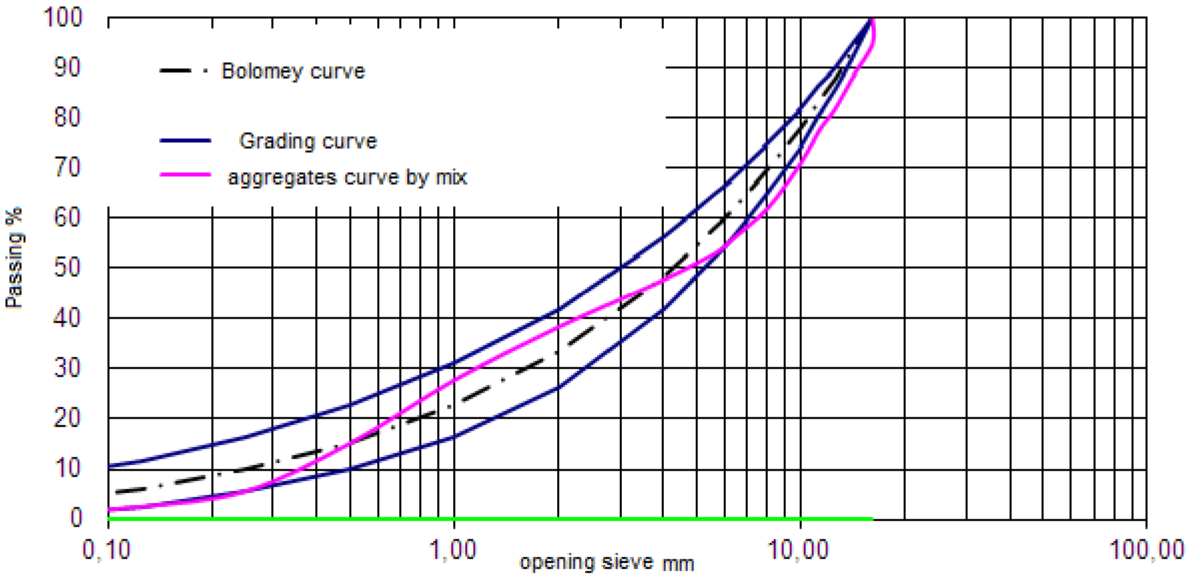
50% coarse and fine recycled aggregates
50% coarse and fine naturale aggregates

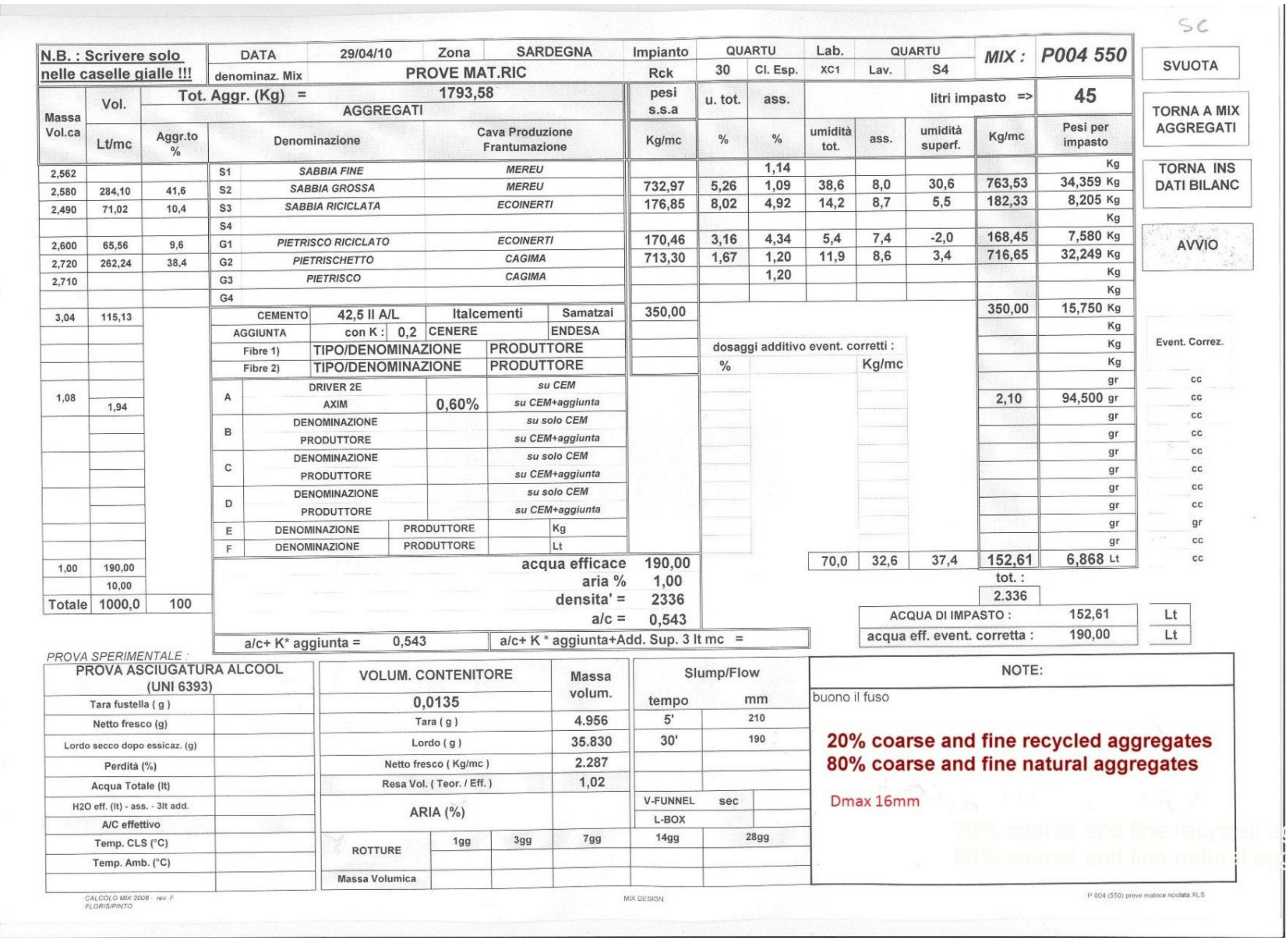
Dmax 16mm

CALCOLO MIX 2008 - rev F
FLORIS/PINTO

MIX DESIGN

P 003 (550) prove matrice riciclata XLS





SC

N.B. : Scrivere solo nelle caselle gialle !!!	DATA	29/04/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	MIX :	P004 550
	denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp. XC1	Lav. S4		

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1793,58

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		AGGREGATI Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto
2,562			S1	SABBIA FINE	MEREU			1,14					Kg
2,580	284,10	41,6	S2	SABBIA GROSSA	MEREU	732,97	5,26	1,09	38,6	8,0	30,6	763,53	34,359 Kg
2,490	71,02	10,4	S3	SABBIA RICICLATA	ECOINERTI	176,85	8,02	4,92	14,2	8,7	5,5	182,33	8,205 Kg
			S4										Kg
2,600	65,56	9,6	G1	PIETRISCO RICICLATO	ECOINERTI	170,46	3,16	4,34	5,4	7,4	-2,0	168,45	7,580 Kg
2,720	262,24	38,4	G2	PIETRISCHETTO	CAGIMA	713,30	1,67	1,20	11,9	8,6	3,4	716,65	32,249 Kg
2,710			G3	PIETRISCO	CAGIMA			1,20					Kg
			G4										Kg

3,04	115,13	CEMENTO	42,5 II A/L	Italcementi	Samatzai	350,00	350,00 / 15,750 Kg
		AGGIUNTA	con K : 0,2	CENERE	ENDESA		Kg
		Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE			Kg
		Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE			Kg

1,08		A	DRIVER 2E		su CEM	gr
	1,94		AXIM	0,60%	su CEM+aggiunta	2,10 / 94,500 gr
		B	DENOMINAZIONE		su solo CEM	gr
			PRODUTTORE		su CEM+aggiunta	gr
		C	DENOMINAZIONE		su solo CEM	gr
			PRODUTTORE		su CEM+aggiunta	gr
		D	DENOMINAZIONE		su solo CEM	gr
			PRODUTTORE		su CEM+aggiunta	gr
		E	DENOMINAZIONE	PRODUTTORE	Kg	gr
		F	DENOMINAZIONE	PRODUTTORE	Lt	gr
1,00	190,00					70,0 / 32,6 / 37,4 / 152,61 / 6,868 Lt
	10,00					
Totale	1000,0	100				

dosaggi additivo event. corretti :

%	Kg/mc

Event. Correz.

cc
cc
cc
cc
cc
cc
cc
cc
gr
cc
cc

acqua efficace 190,00
aria % 1,00
densita' = 2336
a/c = 0,543

tot. : 2.336

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO :	152,61	Lt
acqua eff. event. corretta :	190,00	Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	
Netto fresco (g)	
Lordo secco dopo essicaz. (g)	
Perdità (%)	
Acqua Totale (lt)	
H2O eff. (lt) - ass. - 3lt add.	
A/C effettivo	
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.956
Lordo (g)	35.830
Netto fresco (Kg/mc)	2.287
Resa Vol. (Teor. / Eff.)	1,02
ARIA (%)	

Slump/Flow	
tempo	mm
5'	210
30'	190
V-FUNNEL sec	
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

buono il fuso

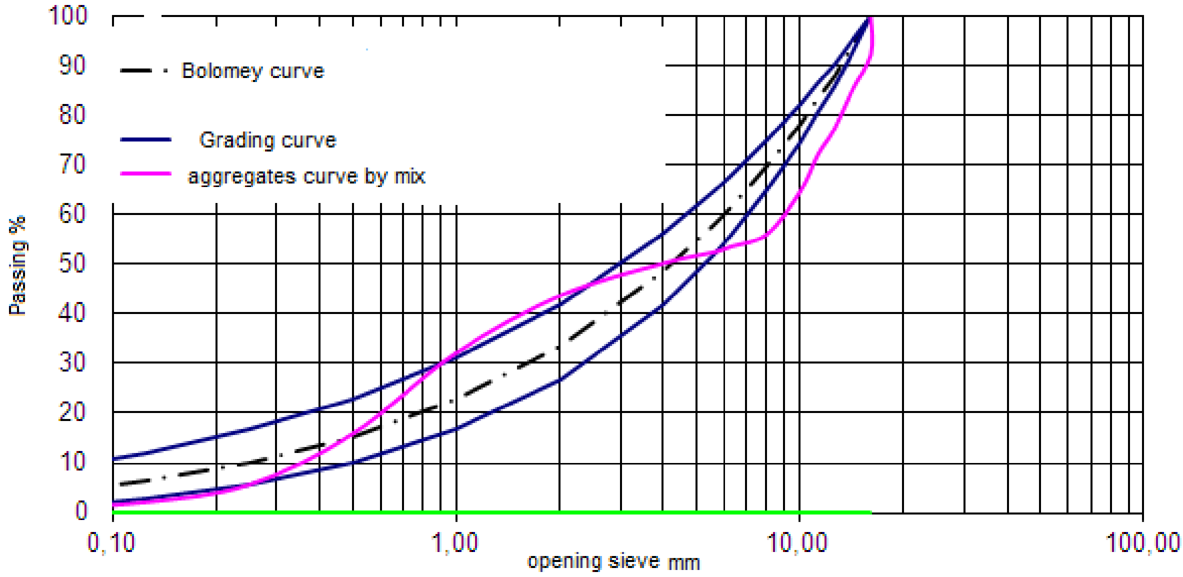
20% coarse and fine recycled aggregates
80% coarse and fine natural aggregates

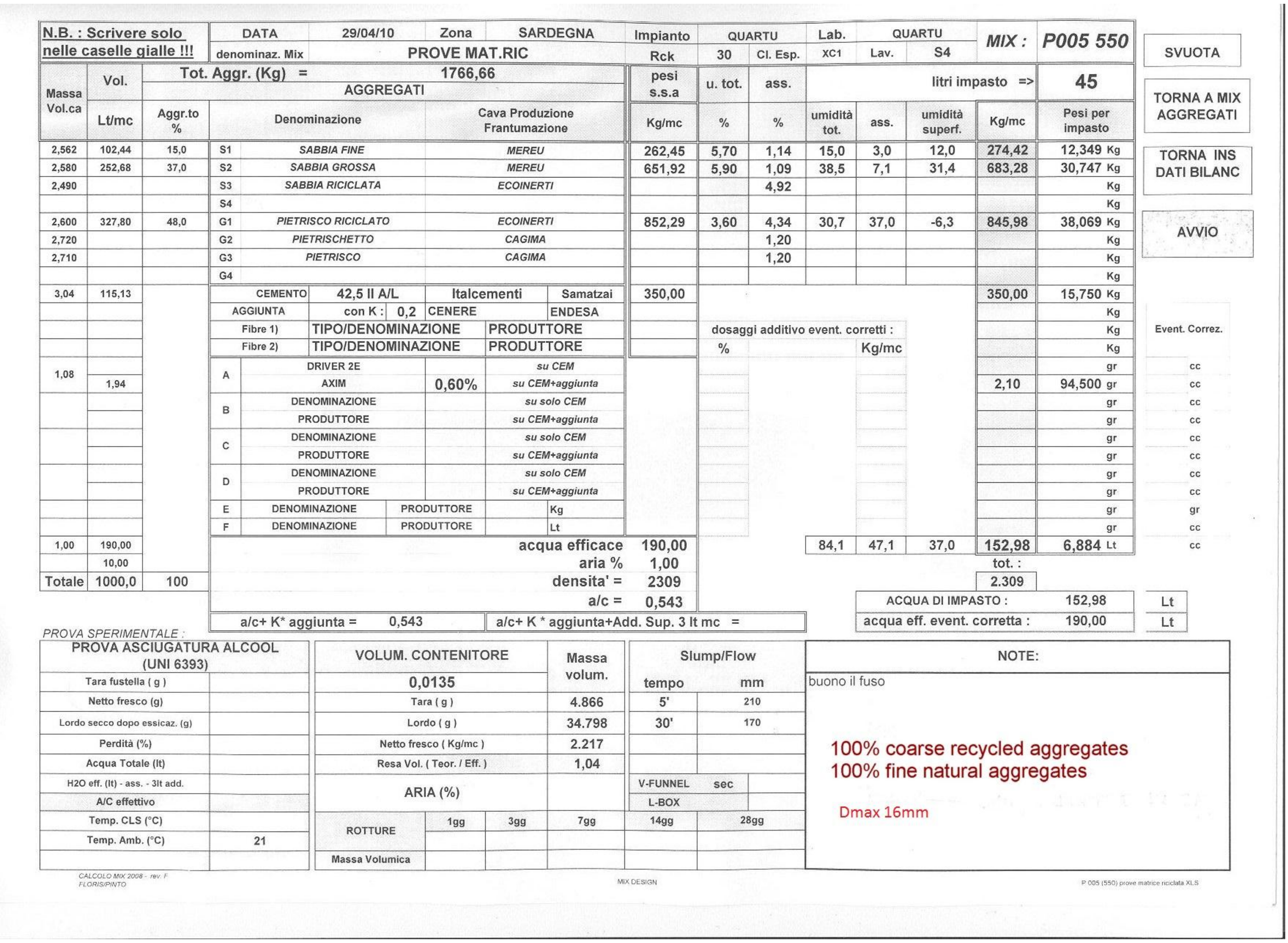
Dmax 16mm

CALCOLO MIX 2008 - rev. F
FLORIS/PINTO

MIX DESIGN

P 004 (550) prove matrice riciclata.XLS





N.B. : Scrivere solo nelle caselle gialle !!!	DATA	29/04/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	*MIX :* *P005 550*
	denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp. XC1	Lav. S4	

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1766,66

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		AGGREGATI Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	
2,562	102,44	15,0	S1	*SABBIA FINE*	*MEREU*	262,45	5,70	1,14	15,0	3,0	12,0	274,42	12,349 Kg	
2,580	252,68	37,0	S2	*SABBIA GROSSA*	*MEREU*	651,92	5,90	1,09	38,5	7,1	31,4	683,28	30,747 Kg	
2,490			S3	*SABBIA RICICLATA*	*ECOINERTI*			4,92					Kg	
			S4										Kg	
2,600	327,80	48,0	G1	*PIETRISCO RICICLATO*	*ECOINERTI*	852,29	3,60	4,34	30,7	37,0	-6,3	845,98	38,069 Kg	
2,720			G2	*PIETRISCHETTO*	*CAGIMA*			1,20					Kg	
2,710			G3	*PIETRISCO*	*CAGIMA*			1,20					Kg	
			G4										Kg	
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg	
			AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg	
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE		dosaggi additivo event. corretti :						Kg	Event. Correz.
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE		%		Kg/mc				Kg	
1,08			A	DRIVER 2E	*su CEM*								gr	cc
	1,94			AXIM	0,60% *su CEM+aggiunta*							2,10	94,500 gr	cc
			B	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			C	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			D	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			E	DENOMINAZIONE PRODUTTORE	Kg								gr	gr
			F	DENOMINAZIONE PRODUTTORE	Lt								gr	cc
1,00	190,00				acqua efficace	190,00			84,1	47,1	37,0	152,98	6,884 Lt	cc
	10,00				aria %	1,00						tot. :		
Totale	1000,0	100			densita' =	2309						2.309		
					a/c =	0,543								

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO :	152,98	Lt
acqua eff. event. corretta :	190,00	Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	
Netto fresco (g)	
Lordo secco dopo essicaz. (g)	
Perdità (%)	
Acqua Totale (lt)	
H2O eff. (lt) - ass. - 3lt add.	
A/C effettivo	
Temp. CLS (°C)	
Temp. Amb. (°C)	21

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.866
Lordo (g)	34.798
Netto fresco (Kg/mc)	2.217
Resa Vol. (Teor. / Eff.)	1,04
ARIA (%)	

Slump/Flow tempo	mm
5'	210
30'	170
V-FUNNEL	sec
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

buono il fuso

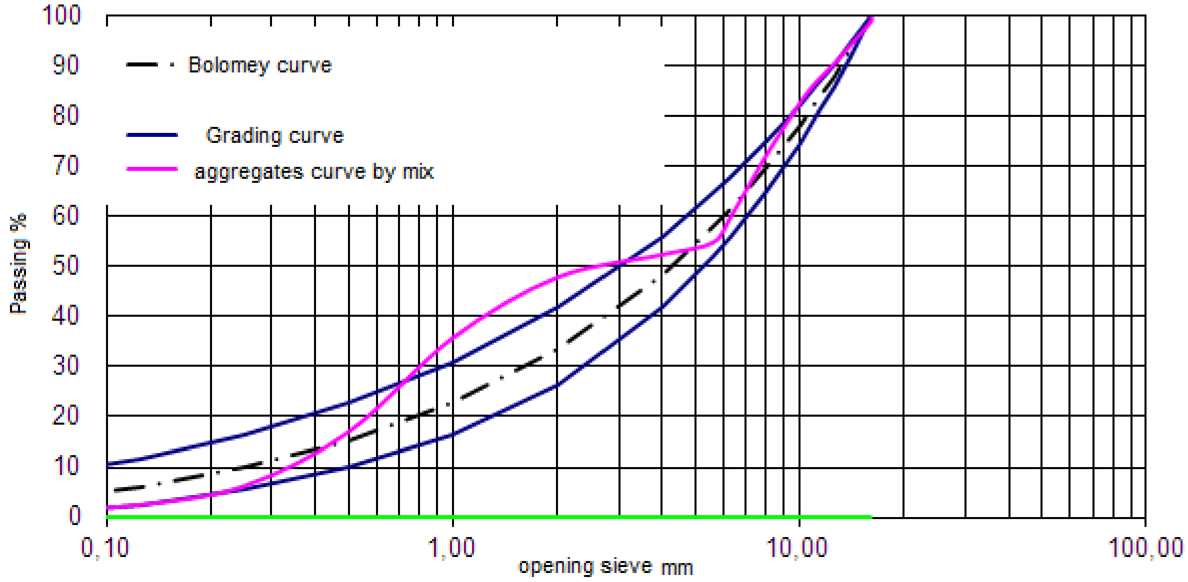
100% coarse recycled aggregates
100% fine natural aggregates

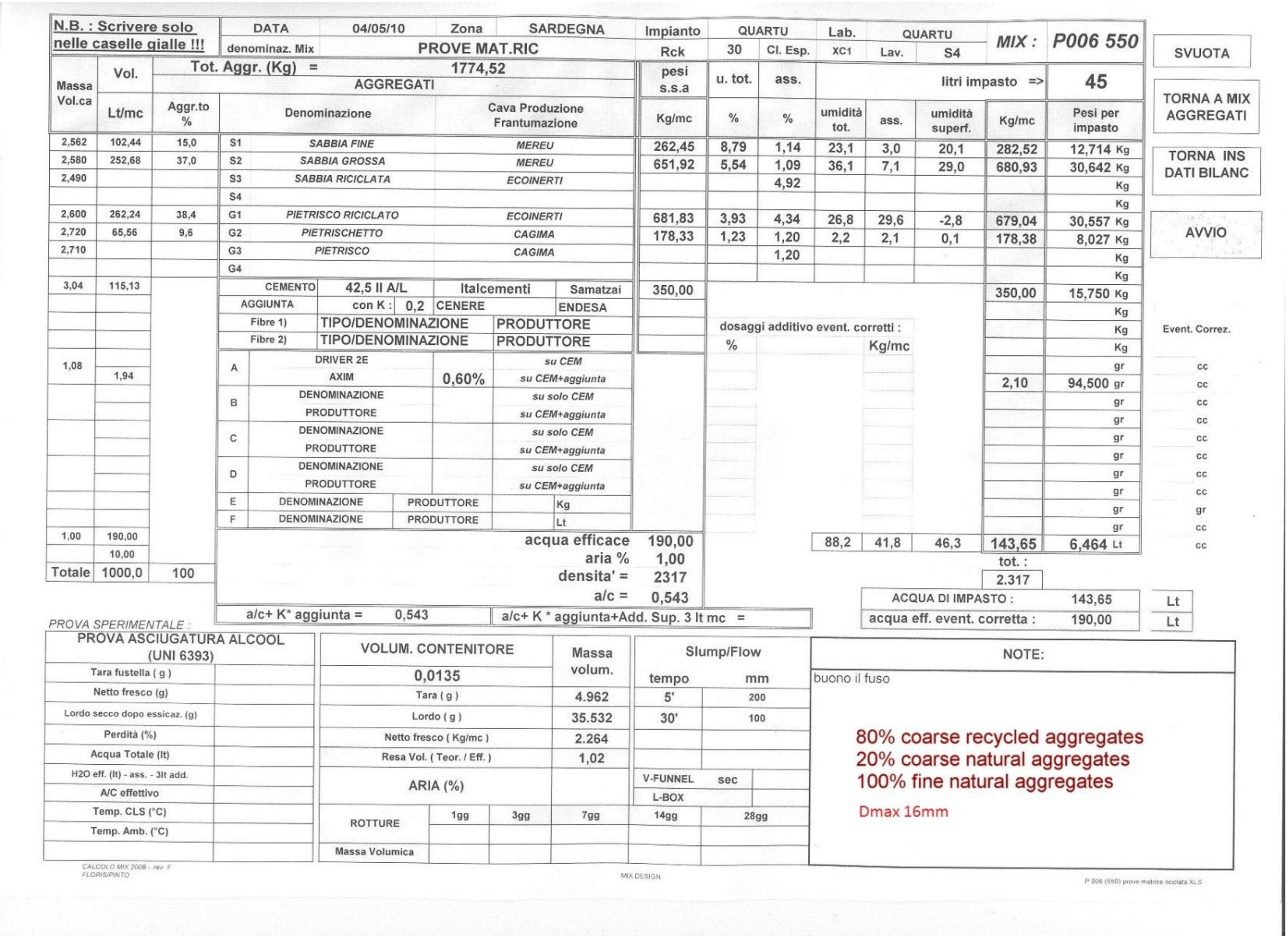
Dmax 16mm

CALCOLO MIX 2008 - rev. F
FLORIS/PINTO

MIX DESIGN

P 005 (550) prove matrice riciclata XLS





N.B. : Scrivere solo nelle caselle gialle !!!	DATA	04/05/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	MIX : P006 550
	denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp. XC1	Lav. S4	

Tot. Aggr. (Kg) = 1774,52

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		AGGREGATI Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto
2,562	102,44	15,0	S1	*SABBIA FINE*	*MEREU*	262,45	8,79	1,14	23,1	3,0	20,1	282,52	12,714 Kg
2,580	252,68	37,0	S2	*SABBIA GROSSA*	*MEREU*	651,92	5,54	1,09	36,1	7,1	29,0	680,93	30,642 Kg
2,490			S3	*SABBIA RICICLATA*	*ECOINERTI*			4,92					Kg
			S4										Kg
2,600	262,24	38,4	G1	*PIETRISCO RICICLATO*	*ECOINERTI*	681,83	3,93	4,34	26,8	29,6	-2,8	679,04	30,557 Kg
2,720	65,56	9,6	G2	*PIETRISCHETTO*	*CAGIMA*	178,33	1,23	1,20	2,2	2,1	0,1	178,38	8,027 Kg
2,710			G3	*PIETRISCO*	*CAGIMA*			1,20					Kg
			G4										Kg
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg
			AGGIUNTA	con K : 0,2 CENERE	ENDESA								Kg
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg

dosaggi additivo event. corretti : % Kg/mc

Massa Vol.ca	Vol. Lt/mc		Denominazione	%		Kg/mc	Pesi per impasto	Event. Correz.
1,08		A	DRIVER 2E		*su CEM*		gr	cc
	1,94		AXIM	0,60%	*su CEM+aggiunta*	2,10	94,500 gr	cc
		B	DENOMINAZIONE		*su solo CEM*		gr	cc
			PRODUTTORE		*su CEM+aggiunta*		gr	cc
		C	DENOMINAZIONE		*su solo CEM*		gr	cc
			PRODUTTORE		*su CEM+aggiunta*		gr	cc
		D	DENOMINAZIONE		*su solo CEM*		gr	cc
			PRODUTTORE		*su CEM+aggiunta*		gr	cc
		E	DENOMINAZIONE	PRODUTTORE	Kg		gr	gr
		F	DENOMINAZIONE	PRODUTTORE	Lt		gr	cc
1,00	190,00		acqua efficace	190,00	88,2 / 41,8 / 46,3	143,65	6,464 Lt	cc
	10,00		aria %	1,00				
Totale	1000,0	100	densita' =	2317		tot. : 2.317		
			a/c =	0,543				

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO : 143,65 Lt

acqua eff. event. corretta : 190,00 Lt

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	
Netto fresco (g)	
Lordo secco dopo essicaz. (g)	
Perdità (%)	
Acqua Totale (lt)	
H2O eff. (lt) - ass. - 3lt add.	
A/C effettivo	
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.962
Lordo (g)	35.532
Netto fresco (Kg/mc)	2.264
Resa Vol. (Teor. / Eff.)	1,02
ARIA (%)	

Slump/Flow	
tempo	mm
5'	200
30'	100
V-FUNNEL	sec
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

buono il fuso

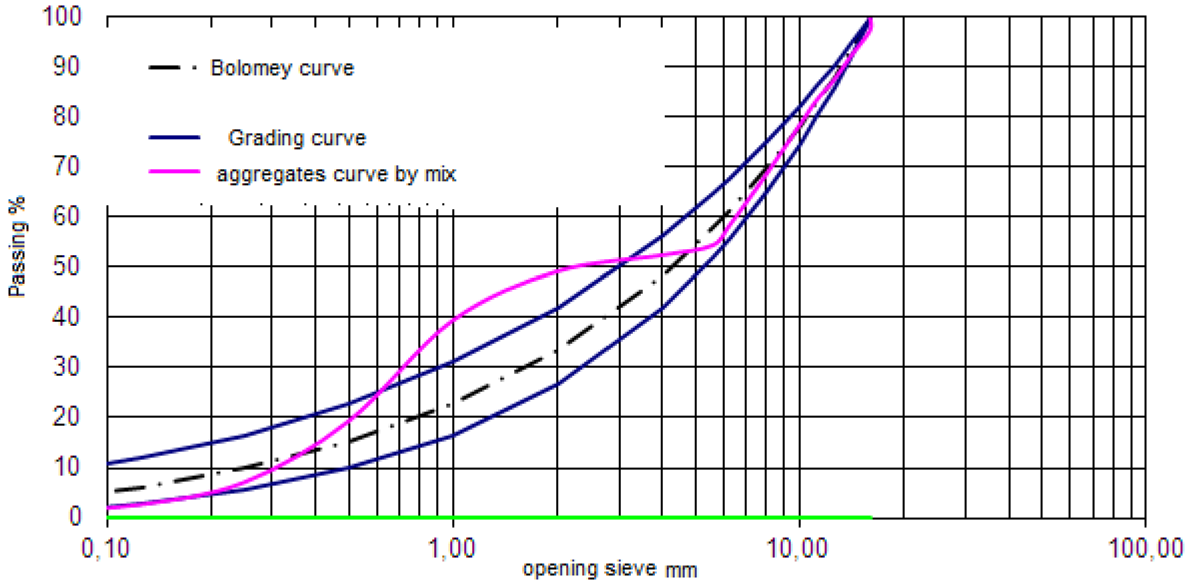
80% coarse recycled aggregates
20% coarse natural aggregates
100% fine natural aggregates

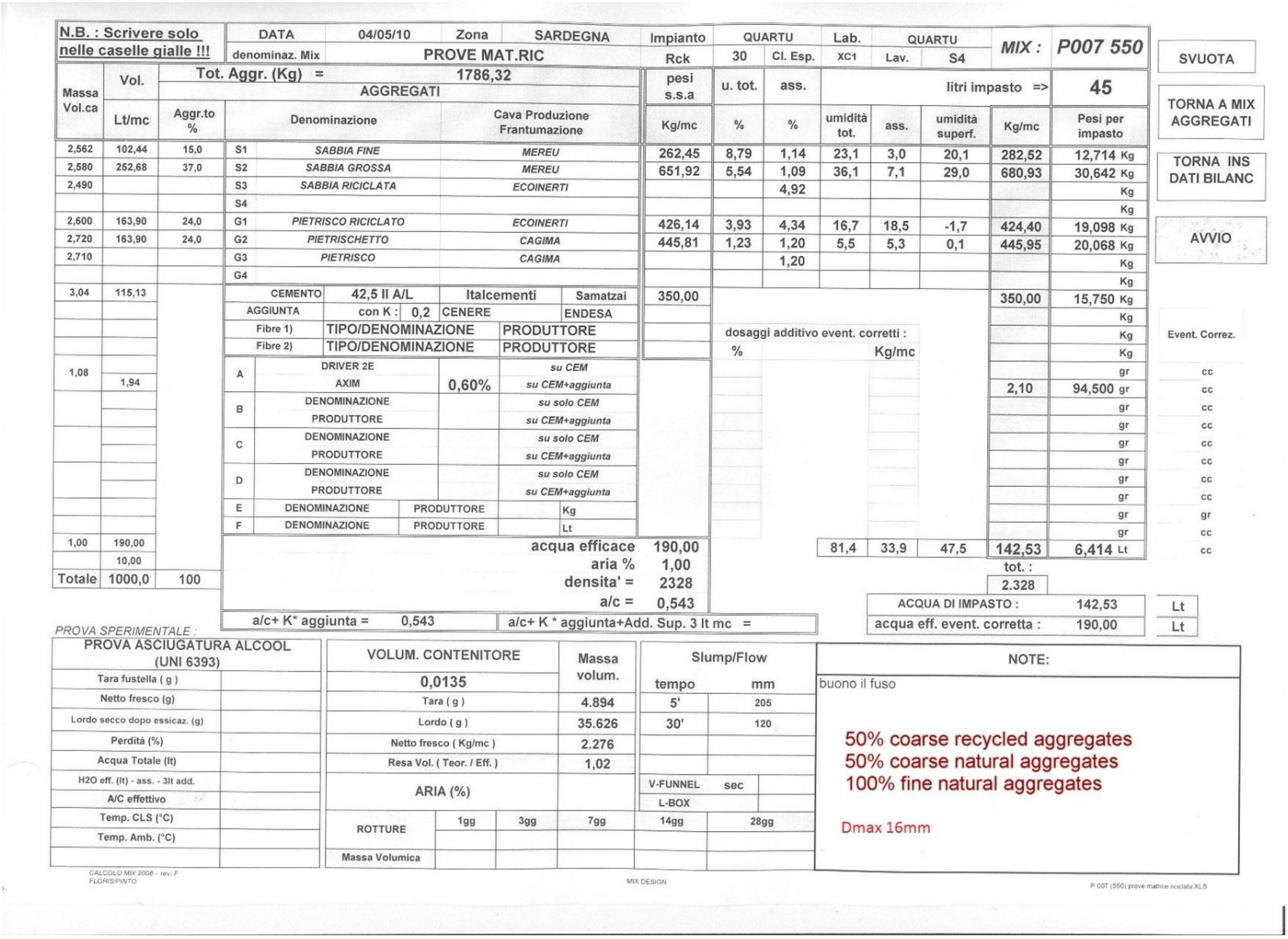
Dmax 16mm

CALCOLO MIX 2008 - rev. F FLORIS/PINTO

MIX DESIGN

P 006 (550) prove matrice riciclata XLS





N.B. : Scrivere solo nelle caselle gialle !!!	DATA	04/05/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	MIX :	P007 550
	denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp.	XC1	Lav.	S4

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1786,32

AGGREGATI

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	Event. Correz.
2,562	102,44	15,0	S1	*SABBIA FINE*	*MEREU*	262,45	8,79	1,14	23,1	3,0	20,1	282,52	12,714 Kg	
2,580	252,68	37,0	S2	*SABBIA GROSSA*	*MEREU*	651,92	5,54	1,09	36,1	7,1	29,0	680,93	30,642 Kg	
2,490			S3	*SABBIA RICICLATA*	*ECOINERTI*			4,92					Kg	
			S4										Kg	
2,600	163,90	24,0	G1	*PIETRISCO RICICLATO*	*ECOINERTI*	426,14	3,93	4,34	16,7	18,5	-1,7	424,40	19,098 Kg	
2,720	163,90	24,0	G2	*PIETRISCHETTO*	*CAGIMA*	445,81	1,23	1,20	5,5	5,3	0,1	445,95	20,068 Kg	
2,710			G3	*PIETRISCO*	*CAGIMA*			1,20					Kg	
			G4										Kg	
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg	
			AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg	
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg	
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg	
1,08			A	DRIVER 2E	*su CEM*								gr	cc
	1,94			AXIM	0,60% *su CEM+aggiunta*							2,10	94,500 gr	cc
			B	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			C	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			D	DENOMINAZIONE	*su solo CEM*								gr	cc
				PRODUTTORE	*su CEM+aggiunta*								gr	cc
			E	DENOMINAZIONE	PRODUTTORE Kg								gr	gr
			F	DENOMINAZIONE	PRODUTTORE Lt								gr	cc
1,00	190,00				acqua efficace	190,00			81,4	33,9	47,5	142,53	6,414 Lt	cc
	10,00				aria %	1,00						tot. :		
Totale	1000,0	100			densita' =	2328						2.328		
					a/c =	0,543								

dosaggi additivo event. corretti :

% Kg/mc

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO :	142,53	Lt
acqua eff. event. corretta :	190,00	Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	
Netto fresco (g)	
Lordo secco dopo essicaz. (g)	
Perdità (%)	
Acqua Totale (lt)	
H2O eff. (lt) - ass. - 3lt add.	
A/C effettivo	
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.894
Lordo (g)	35.626
Netto fresco (Kg/mc)	2.276
Resa Vol. (Teor. / Eff.)	1,02
ARIA (%)	

Slump/Flow	
tempo	mm
5'	205
30'	120
V-FUNNEL sec	
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

buono il fuso

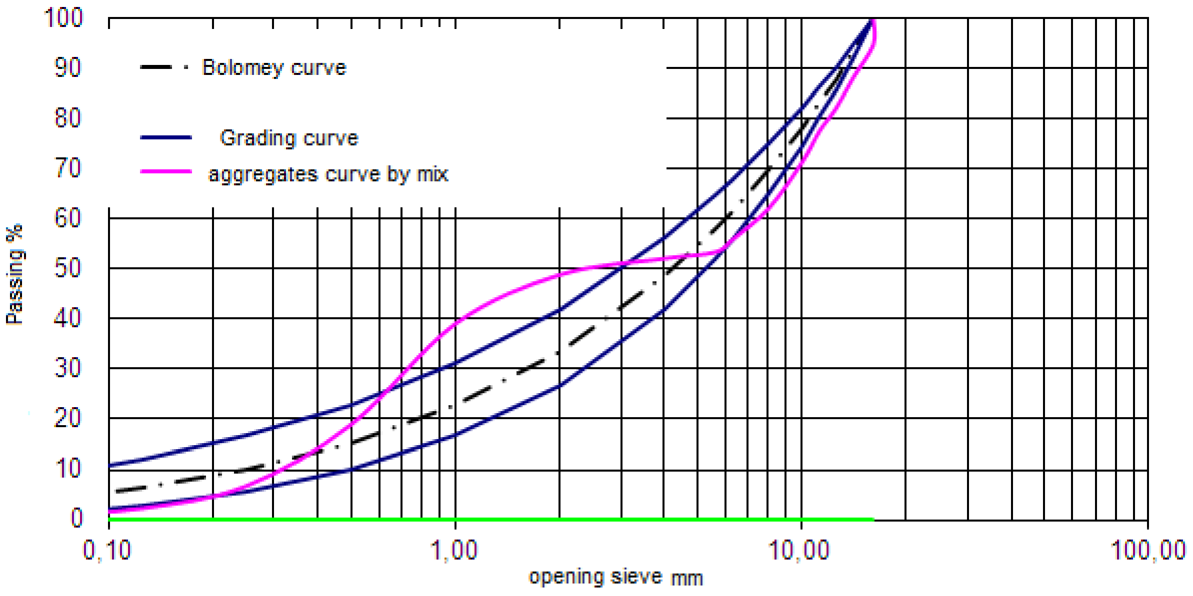
50% coarse recycled aggregates
50% coarse natural aggregates
100% fine natural aggregates

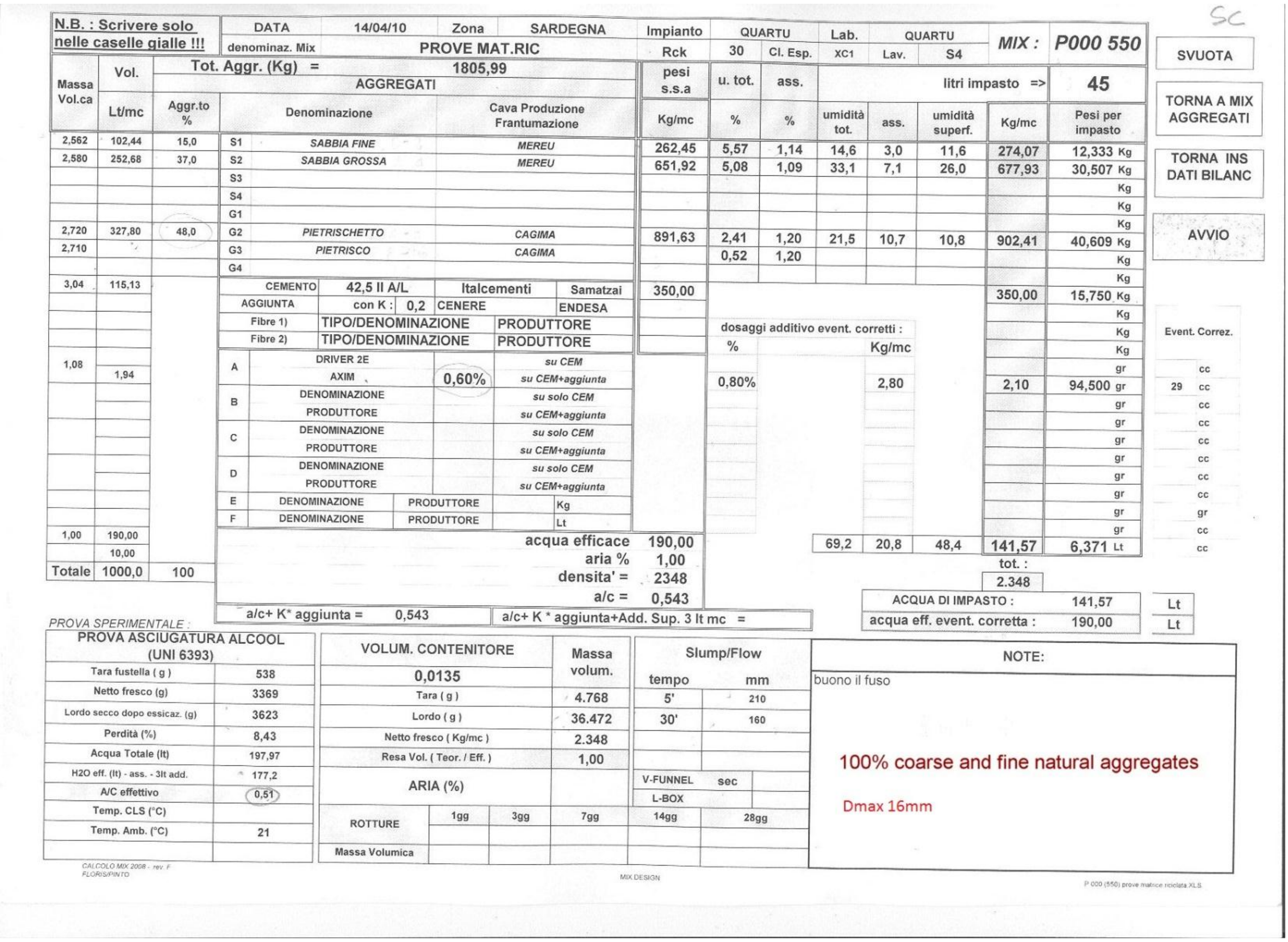
Dmax 16mm

CALCOLO MIX 2008 - rev. F FLORIS/PINTO

MIX DESIGN

P 007 (550) prove matrice riciclata.XLS





SC

N.B. : Scrivere solo nelle caselle gialle !!!

DATA	14/04/10	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	MIX :	P000 550
denominaz. Mix	PROVE MAT.RIC			Rck	30	Cl. Esp.	XC1	Lav.	S4

SVUOTA

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

Tot. Aggr. (Kg) = 1805,99

AGGREGATI

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto
2,562	102,44	15,0	S1	SABBIA FINE	MEREU	262,45	5,57	1,14	14,6	3,0	11,6	274,07	12,333 Kg
2,580	252,68	37,0	S2	SABBIA GROSSA	MEREU	651,92	5,08	1,09	33,1	7,1	26,0	677,93	30,507 Kg
			S3										Kg
			S4										Kg
			G1										Kg
2,720	327,80	48,0	G2	PIETRISCHETTO	CAGIMA	891,63	2,41	1,20	21,5	10,7	10,8	902,41	40,609 Kg
2,710			G3	PIETRISCO	CAGIMA		0,52	1,20					Kg
			G4										Kg
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg
			AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg

dosaggi additivo event. corretti :

Massa Vol.ca	Vol. Lt/mc		Denominazione			%	Kg/mc	Kg/mc	Pesi per impasto	Event. Correz.
1,08		A	DRIVER 2E		su CEM				gr	cc
	1,94		AXIM	0,60%	su CEM+aggiunta	0,80%	2,80	2,10	94,500 gr	29 cc
		B	DENOMINAZIONE		su solo CEM				gr	cc
			PRODUTTORE		su CEM+aggiunta				gr	cc
		C	DENOMINAZIONE		su solo CEM				gr	cc
			PRODUTTORE		su CEM+aggiunta				gr	cc
		D	DENOMINAZIONE		su solo CEM				gr	cc
			PRODUTTORE		su CEM+aggiunta				gr	gr
		E	DENOMINAZIONE	PRODUTTORE	Kg				gr	cc
		F	DENOMINAZIONE	PRODUTTORE	Lt					

Massa Vol.ca	Vol. Lt/mc	Aggr.to %								
1,00	190,00		acqua efficace	190,00	69,2	20,8	48,4	141,57	6,371 Lt	cc
	10,00		aria %	1,00				tot. :		
Totale	1000,0	100	densita' =	2348				2.348		
			a/c =	0,543						

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO :	141,57	Lt
acqua eff. event. corretta :	190,00	Lt

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	538
Netto fresco (g)	3369
Lordo secco dopo essicaz. (g)	3623
Perdità (%)	8,43
Acqua Totale (lt)	197,97
H2O eff. (lt) - ass. - 3lt add.	177,2
A/C effettivo	0,51
Temp. CLS (°C)	
Temp. Amb. (°C)	21

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4.768
Lordo (g)	36.472
Netto fresco (Kg/mc)	2.348
Resa Vol. (Teor. / Eff.)	1,00
ARIA (%)	

Slump/Flow	
tempo	mm
5'	210
30'	160
V-FUNNEL	sec
L-BOX	

ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

buono il fuso

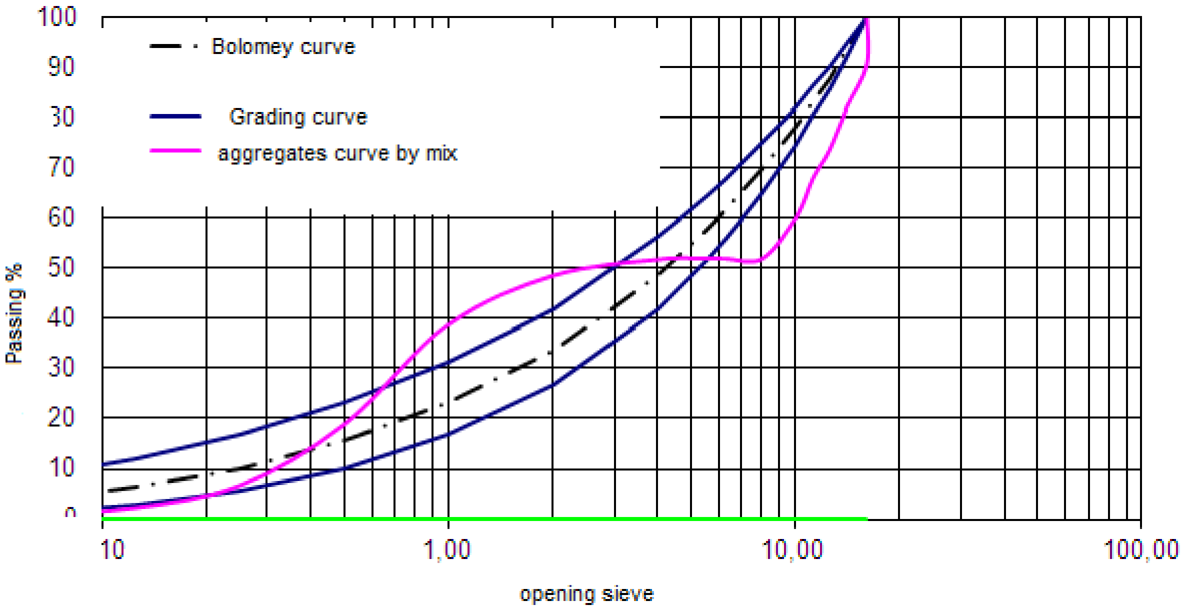
100% coarse and fine natural aggregates

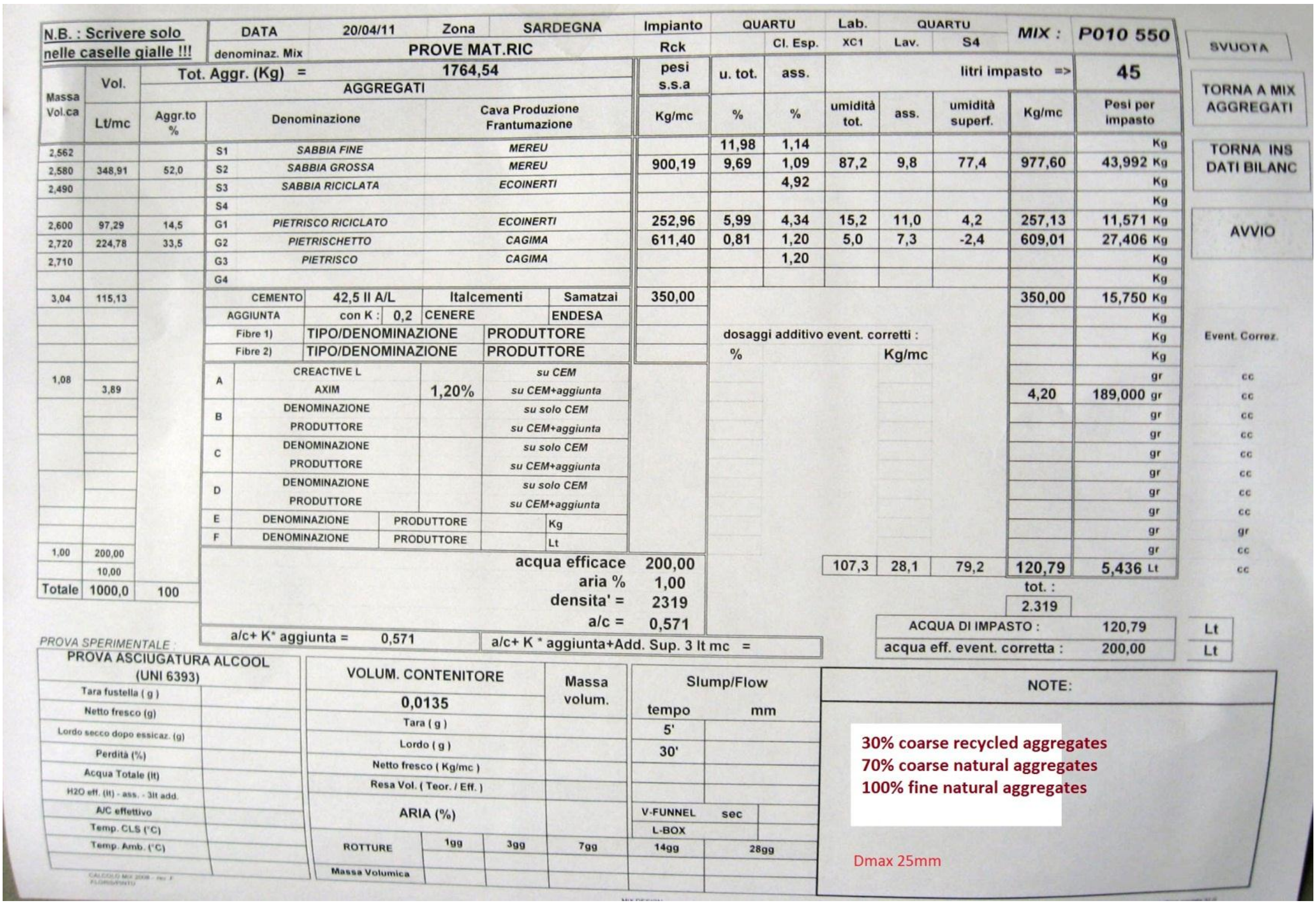
Dmax 16mm

CALCOLO MIX 2008 - rev. F FLORIS/PINTO

MIX DESIGN

P 000 (550) prove matrice riciclata.XLS





N.B. : Scrivere solo nelle caselle gialle !!!

DATA	20/04/11	Zona	SARDEGNA	Impianto	QUARTU	Lab.	QUARTU	MIX :	P010 550
denominaz. Mix	PROVE MAT.RIC			Rck		Cl. Esp.	XC1	Lav.	S4

Tot. Aggr. (Kg) = 1764,54

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %		AGGREGATI Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto
2,562			S1	SABBIA FINE	MEREU		11,98	1,14					Kg
2,580	348,91	52,0	S2	SABBIA GROSSA	MEREU	900,19	9,69	1,09	87,2	9,8	77,4	977,60	43,992 Kg
2,490			S3	SABBIA RICICLATA	ECOINERTI			4,92					Kg
			S4										Kg
2,600	97,29	14,5	G1	PIETRISCO RICICLATO	ECOINERTI	252,96	5,99	4,34	15,2	11,0	4,2	257,13	11,571 Kg
2,720	224,78	33,5	G2	PIETRISCHETTO	CAGIMA	611,40	0,81	1,20	5,0	7,3	-2,4	609,01	27,406 Kg
2,710			G3	PIETRISCO	CAGIMA			1,20					Kg
			G4										Kg
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg
			AGGIUNTA	con K : 0,2 CENERE	ENDESA								Kg
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg

dosaggi additivo event. corretti :

% Kg/mc

1,08		A	CREACTIVE L		su CEM		gr
	3,89		AXIM	1,20%	su CEM+aggiunta	4,20	189,000 gr
		B	DENOMINAZIONE		su solo CEM		gr
			PRODUTTORE		su CEM+aggiunta		gr
		C	DENOMINAZIONE		su solo CEM		gr
			PRODUTTORE		su CEM+aggiunta		gr
		D	DENOMINAZIONE		su solo CEM		gr
			PRODUTTORE		su CEM+aggiunta		gr
		E	DENOMINAZIONE	PRODUTTORE	Kg		gr
		F	DENOMINAZIONE	PRODUTTORE	Lt		gr
1,00	200,00						
	10,00						
Totale	1000,0	100					

acqua efficace 200,00
aria % 1,00
densita' = 2319
a/c = 0,571

107,3	28,1	79,2	120,79	5,436 Lt

tot. :
2.319

a/c+ K* aggiunta = 0,571
a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO : 120,79 Lt
acqua eff. event. corretta : 200,00 Lt

SVUOTA
TORNA A MIX AGGREGATI
TORNA INS DATI BILANC
AVVIO
Event. Correz.
cc
cc
cc
cc
cc
cc
cc
cc
gr
cc
cc

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	
Netto fresco (g)	
Lordo secco dopo essicaz. (g)	
Perdità (%)	
Acqua Totale (lt)	
H2O eff. (lt) - ass. - 3lt add.	
A/C effettivo	
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	
Lordo (g)	
Netto fresco (Kg/mc)	
Resa Vol. (Teor. / Eff.)	
ARIA (%)	

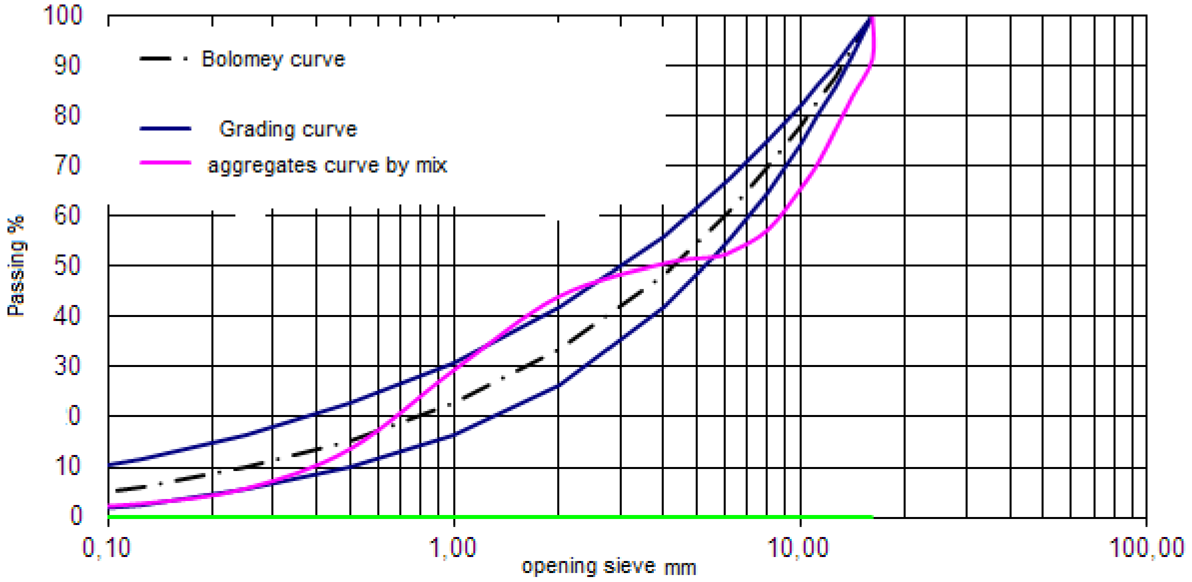
Slump/Flow tempo	mm
5'	
30'	
V-FUNNEL sec	
L-BOX	

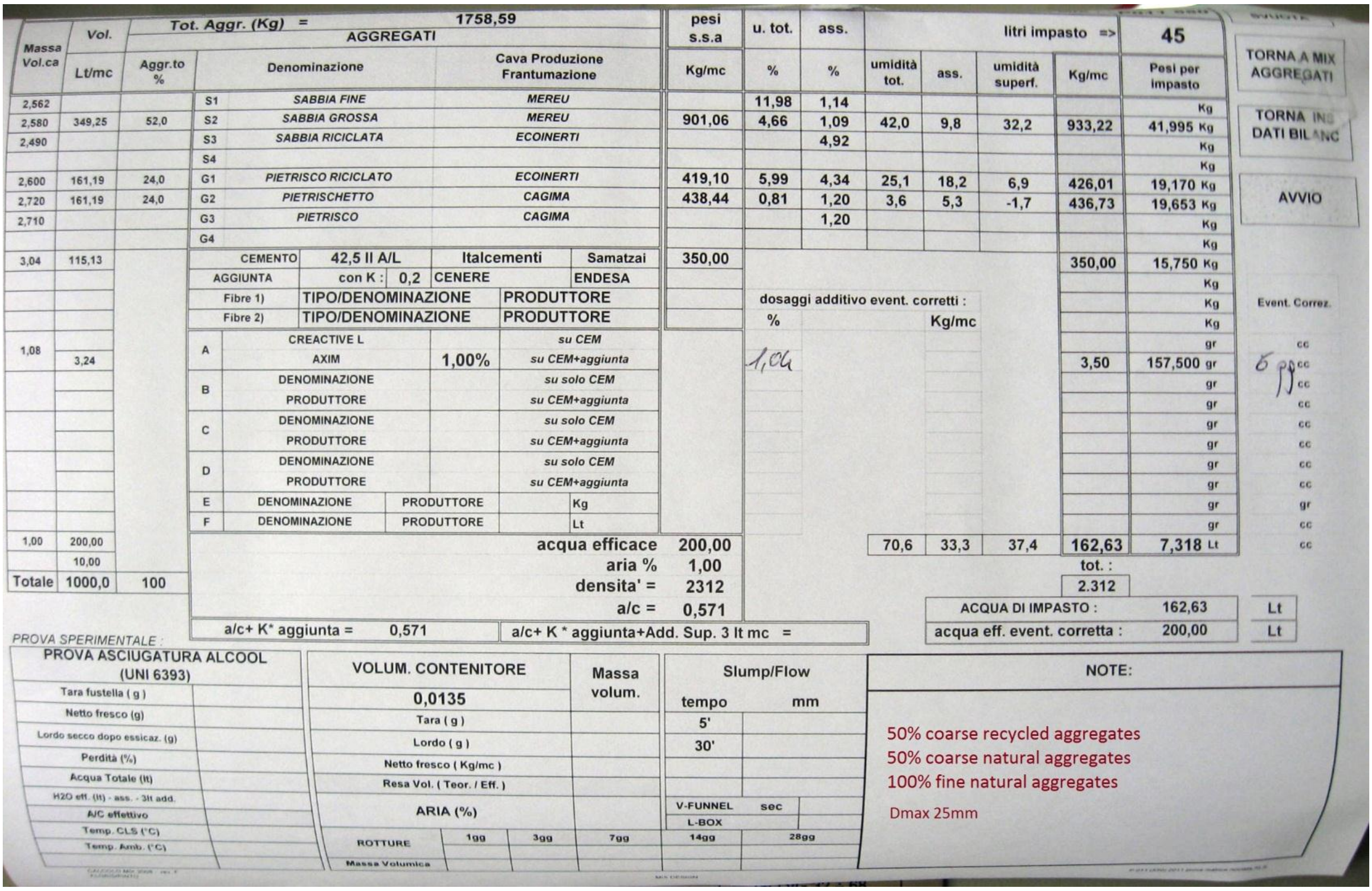
ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

30% coarse recycled aggregates
70% coarse natural aggregates
100% fine natural aggregates

Dmax 25mm





Tot. Aggr. (Kg) = 1758,59

litri impasto => 45

Massa Vol.ca	Vol. Lt/mc	Aggr.to %	AGGREGATI	Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	Event. Correz.
2,562			S1	SABBIA FINE	MEREU		11,98	1,14					Kg	
2,580	349,25	52,0	S2	SABBIA GROSSA	MEREU	901,06	4,66	1,09	42,0	9,8	32,2	933,22	41,995 Kg	
2,490			S3	SABBIA RICICLATA	ECOINERTI			4,92					Kg	
			S4										Kg	
2,600	161,19	24,0	G1	PIETRISCO RICICLATO	ECOINERTI	419,10	5,99	4,34	25,1	18,2	6,9	426,01	19,170 Kg	
2,720	161,19	24,0	G2	PIETRISCHETTO	CAGIMA	438,44	0,81	1,20	3,6	5,3	-1,7	436,73	19,653 Kg	
2,710			G3	PIETRISCO	CAGIMA			1,20					Kg	
			G4										Kg	
3,04	115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg	
			AGGIUNTA	con K : 0,2 CENERE	ENDESA								Kg	
			Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg	
			Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg	
1,08			A	CREACTIVE L	su CEM								gr	cc
	3,24			AXIM	1,00% su CEM+aggiunta							3,50	157,500 gr	6 [illegible] cc
			B	DENOMINAZIONE	su solo CEM								gr	cc
				PRODUTTORE	su CEM+aggiunta								gr	cc
			C	DENOMINAZIONE	su solo CEM								gr	cc
				PRODUTTORE	su CEM+aggiunta								gr	cc
			D	DENOMINAZIONE	su solo CEM								gr	cc
				PRODUTTORE	su CEM+aggiunta								gr	cc
			E	DENOMINAZIONE	PRODUTTORE Kg								gr	gr
			F	DENOMINAZIONE	PRODUTTORE Lt								gr	cc
1,00	200,00			acqua efficace		200,00			70,6	33,3	37,4	162,63	7,318 Lt	cc
	10,00			aria %		1,00						tot. :		
Totale	1000,0	100		densita' =		2312						2.312		
				a/c =		0,571								

dosaggi additivo event. corretti :

% 1,04 Kg/mc

a/c+ K* aggiunta = 0,571

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO :	162,63	Lt
acqua eff. event. corretta :	200,00	Lt

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

PROVA SPERIMENTALE :

PROVA ASCIUGATURA ALCOOL (UNI 6393)	
Tara fustella (g)	
Netto fresco (g)	
Lordo secco dopo essicaz. (g)	
Perdità (%)	
Acqua Totale (lt)	
H2O eff. (lt) - ass. - 3lt add.	
A/C effettivo	
Temp. CLS (°C)	
Temp. Amb. (°C)	

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	
Lordo (g)	
Netto fresco (Kg/mc)	
Resa Vol. (Teor. / Eff.)	
ARIA (%)	

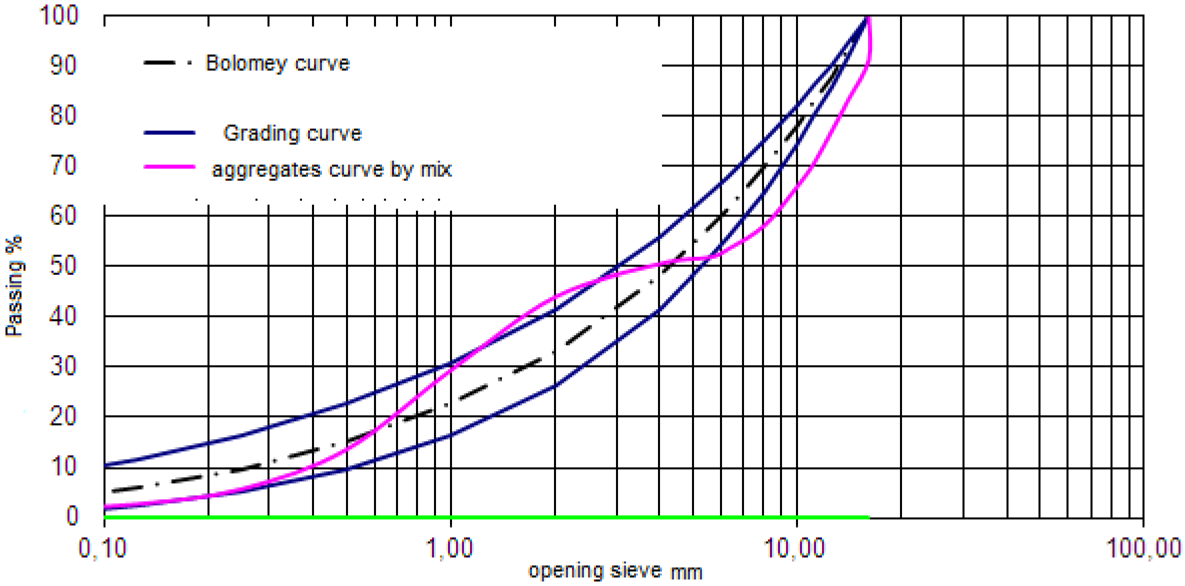
Slump/Flow	
tempo	mm
5'	
30'	
V-FUNNEL sec	
L-BOX	

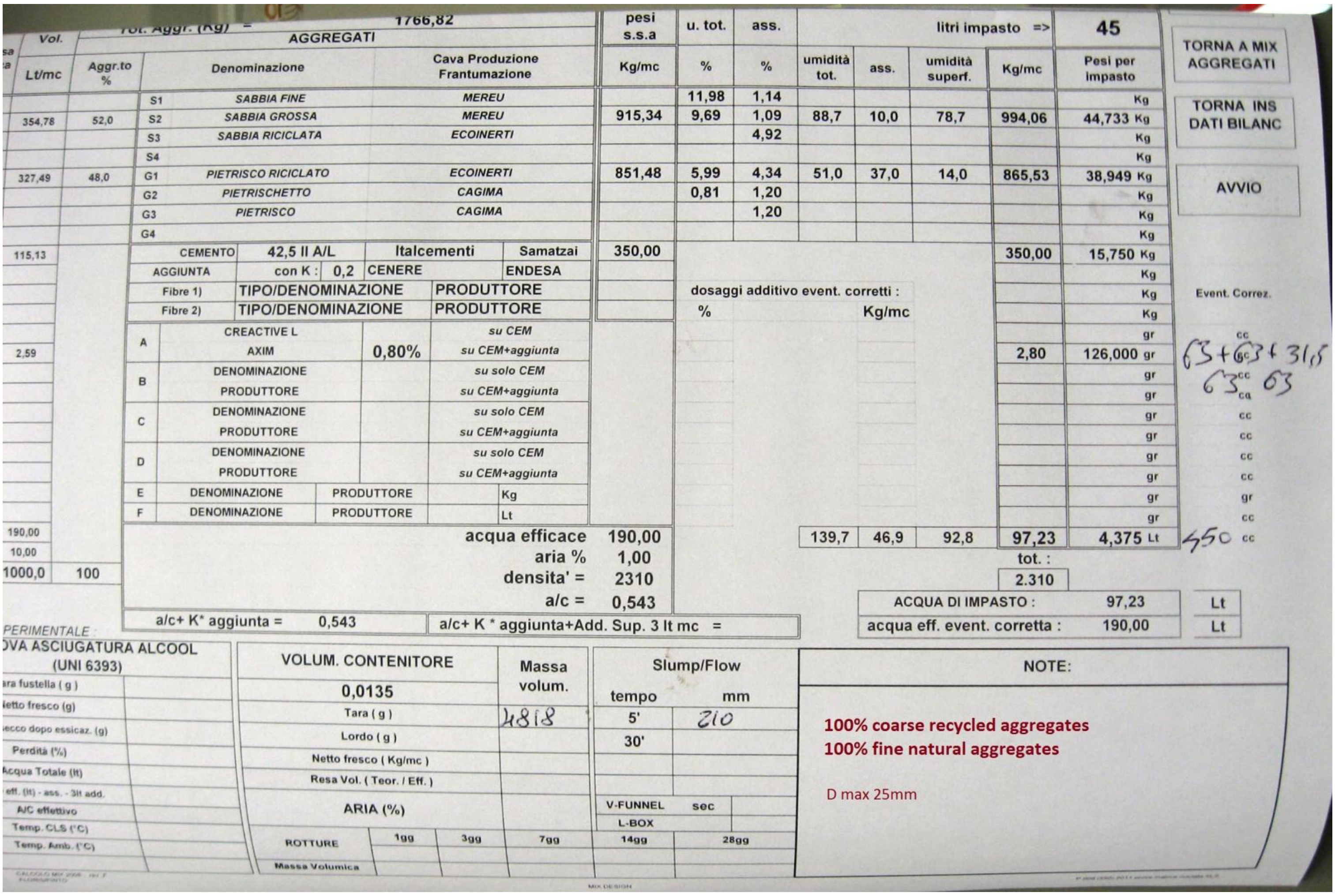
ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

NOTE:

50% coarse recycled aggregates
50% coarse natural aggregates
100% fine natural aggregates

Dmax 25mm





Tot. Aggr. (Kg) = 1766,82 litri impasto => 45

Vol. Lt/mc	Aggr.to %		AGGREGATI Denominazione	Cava Produzione Frantumazione	pesi s.s.a Kg/mc	u. tot. %	ass. %	umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto
		S1	*SABBIA FINE*	*MEREU*		11,98	1,14					Kg
354,78	52,0	S2	*SABBIA GROSSA*	*MEREU*	915,34	9,69	1,09	88,7	10,0	78,7	994,06	44,733 Kg
		S3	*SABBIA RICICLATA*	*ECOINERTI*			4,92					Kg
		S4										Kg
327,49	48,0	G1	*PIETRISCO RICICLATO*	*ECOINERTI*	851,48	5,99	4,34	51,0	37,0	14,0	865,53	38,949 Kg
		G2	*PIETRISCHETTO*	*CAGIMA*		0,81	1,20					Kg
		G3	*PIETRISCO*	*CAGIMA*			1,20					Kg
		G4										Kg
115,13		CEMENTO	42,5 II A/L	Italcementi Samatzai	350,00						350,00	15,750 Kg
		AGGIUNTA	con K : 0,2	CENERE ENDESA								Kg
		Fibre 1)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg
		Fibre 2)	TIPO/DENOMINAZIONE	PRODUTTORE								Kg

TORNA A MIX AGGREGATI

TORNA INS DATI BILANC

AVVIO

dosaggi additivo event. corretti :

% Kg/mc

Event. Correz.

Lt/mc						Kg/mc	Pesi per impasto	
	A	CREACTIVE L		*su CEM*			gr	cc
2,59		AXIM	0,80%	*su CEM+aggiunta*		2,80	126,000 gr	63+63+31,5 cc 63 cc 63 ca
	B	DENOMINAZIONE		*su solo CEM*			gr	cc
		PRODUTTORE		*su CEM+aggiunta*			gr	cc
	C	DENOMINAZIONE		*su solo CEM*			gr	cc
		PRODUTTORE		*su CEM+aggiunta*			gr	cc
	D	DENOMINAZIONE		*su solo CEM*			gr	cc
		PRODUTTORE		*su CEM+aggiunta*			gr	cc
	E	DENOMINAZIONE	PRODUTTORE		Kg		gr	gr
	F	DENOMINAZIONE	PRODUTTORE		Lt		gr	cc

				umidità tot.	ass.	umidità superf.	Kg/mc	Pesi per impasto	
190,00		acqua efficace	190,00	139,7	46,9	92,8	97,23	4,375 Lt	450 cc
10,00		aria %	1,00				tot. :		
1000,0	100	densita' =	2310				2.310		
		a/c =	0,543						

a/c+ K* aggiunta = 0,543

a/c+ K * aggiunta+Add. Sup. 3 lt mc =

ACQUA DI IMPASTO : 97,23 Lt

acqua eff. event. corretta : 190,00 Lt

PERIMENTALE :

OVA ASCIUGATURA ALCOOL (UNI 6393)

ara fustella (g)

etto fresco (g)

ecco dopo essicaz. (g)

Perdità (%)

Acqua Totale (lt)

eff. (lt) - ass. - 3lt add.

A/C effettivo

Temp. CLS (°C)

Temp. Amb. (°C)

VOLUM. CONTENITORE	Massa volum.
0,0135	
Tara (g)	4818
Lordo (g)	
Netto fresco (Kg/mc)	
Resa Vol. (Teor. / Eff.)	
ARIA (%)	

Slump/Flow	
tempo	mm
5'	210
30'	
V-FUNNEL sec	
L-BOX	

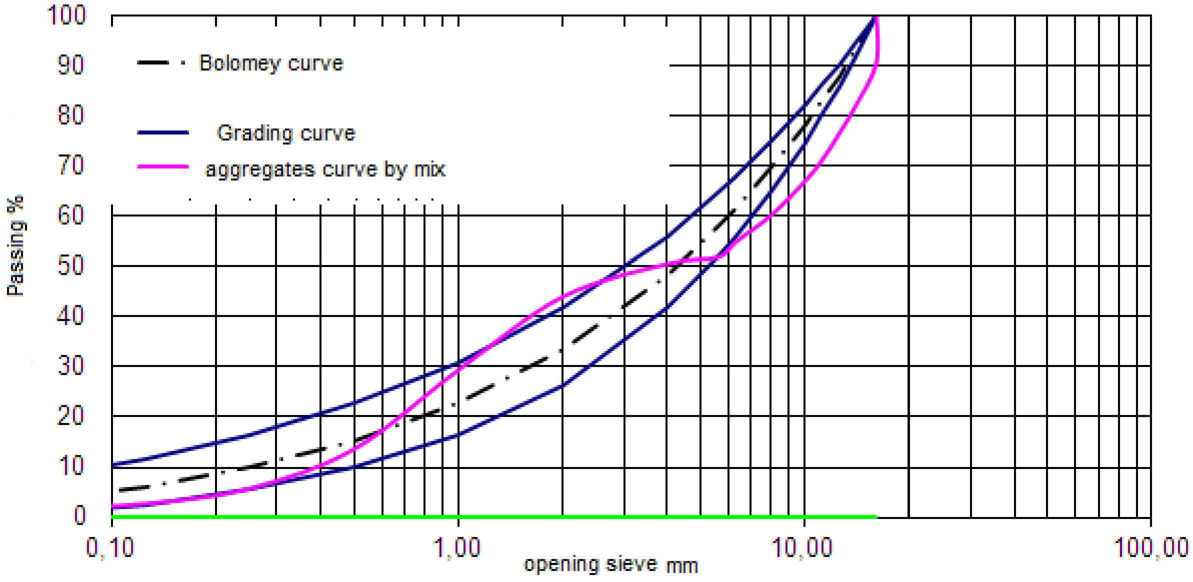
ROTTURE	1gg	3gg	7gg	14gg	28gg
Massa Volumica					

MIX DESIGN

NOTE:

100% coarse recycled aggregates
100% fine natural aggregates

D max 25mm



Annex 2: Data of ultrasonic tests

Natural concrete													
Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	57,20	0,0000572	0,15	2622	101,56	0,10	Vm =	2784	m/s	Am =	0,16	V
	2	50,80	0,0000508	0,15	2953	193,75	0,19	D.st =	134,96		D.st =	0,04	
	3	54,00	0,000054	0,15	2778	170,31	0,17	D.st =	4,85	%	D.st =	74,79	%
2	1	58,00	0,000058	0,15	2586	42,66	0,04	Vm =	2665	m/s	Am =	0,12	V
	2	58,40	0,0000584	0,15	2568	145,31	0,15	D.st =	124,45		D.st =	0,06	
	3	52,80	0,0000528	0,15	2841	171,88	0,17	D.st =	4,67	%	D.st =	53,55	%
3	1	51,20	0,0000512	0,15	2930	74,33	0,07	Vm =	2750	m/s	Am =	0,12	V
	2	55,20	0,0000552	0,15	2717	140,63	0,14	D.st =	134,93		D.st =	0,03	
	3	57,60	0,0000576	0,15	2604	142,19	0,14	D.st =	4,91	%	D.st =	73,43	%
4	1	54,40	0,0000544	0,15	2757	41,25	0,04	Vm =	2860	m/s	Am =	0,16	V
	2	49,60	0,0000496	0,15	3024	300,00	0,30	D.st =	117,30		D.st =	0,11	
	3	53,60	0,0000536	0,15	2799	146,88	0,15	D.st =	4,10	%	D.st =	34,71	%
5	1	52,40	0,0000524	0,15	2863	175,00	0,18	Vm =	2870	m/s	Am =	0,16	V
	2	52,40	0,0000524	0,15	2863	115,63	0,12	D.st =	10,38		D.st =	0,03	
	3	52,00	0,000052	0,15	2885	187,50	0,19	D.st =	0,36	%	D.st =	80,33	%
6	1	53,20	0,0000532	0,15	2820	47,81	0,05	Vm =	2878	m/s	Am =	0,11	V
	2	52,40	0,0000524	0,15	2863	125,00	0,13	D.st =	55,50		D.st =	0,05	
	3	50,80	0,0000508	0,15	2953	156,25	0,16	D.st =	1,93	%	D.st =	58,45	%

Recycled concrete 100% (coarse + fine)													
Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	62,00	0,000062	0,15	2419	100,00	0,10	Vm =	2507	m/s	Am =	0,11	V
	2	58,00	0,000058	0,15	2586	112,50	0,11	D.st =	68,44		D.st =	0,01	
	3	59,60	0,0000596	0,15	2517	118,75	0,12	D.st =	2,73	%	D.st =	92,94	%
2	1	60,40	0,0000604	0,15	2483	60,94	0,06	Vm =	2473	m/s	Am =	0,11	V
	2	60,00	0,00006	0,15	2500	118,75	0,12	D.st =	27,55		D.st =	0,03	
	3	61,60	0,0000616	0,15	2435	142,19	0,14	D.st =	1,11	%	D.st =	68,18	%
3	1	63,60	0,0000636	0,15	2358	118,75	0,12	Vm =	2533	m/s	Am =	0,09	V
	2	54,40	0,0000544	0,15	2757	91,41	0,09	D.st =	166,58		D.st =	0,02	
	3	60,40	0,0000604	0,15	2483	66,09	0,07	D.st =	6,58	%	D.st =	76,65	%
4	1	53,20	0,0000532	0,15	2820	298,44	0,30	Vm =	2772	m/s	Am =	0,22	V
	2	55,20	0,0000552	0,15	2717	300,00	0,30	D.st =	41,94		D.st =	0,11	
	3	54,00	0,000054	0,15	2778	64,69	0,06	D.st =	1,51	%	D.st =	49,98	%
5	1	51,60	0,0000516	0,15	2907	32,34	0,03	Vm =	2689	m/s	Am =	0,12	V
	2	54,40	0,0000544	0,15	2757	200,00	0,20	D.st =	210,95		D.st =	0,07	
	3	62,40	0,0000624	0,15	2404	131,25	0,13	D.st =	7,84	%	D.st =	43,22	%
6	1	60,80	0,0000608	0,15	2467	60,94	0,06	Vm =	2585	m/s	Am =	0,17	V
	2	53,20	0,0000532	0,15	2820	293,75	0,29	D.st =	166,14		D.st =	0,10	
	3	60,80	0,0000608	0,15	2467	159,38	0,16	D.st =	6,43	%	D.st =	44,31	%

Recycled concrete[80% Rec + 20% nat] (coarse+ fine)

Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	57,60	0,0000576	0,15	2604	44,53	0,04	Vm =	2524	m/s	Am =	0,07	V
	2	59,20	0,0000592	0,15	2534	104,69	0,10	D.st =	69,36		D.st =	0,02	
	3	61,60	0,0000616	0,15	2435	66,09	0,07	D.st =	2,75	%	D.st =	65,32	%
2	1	53,20	0,0000532	0,15	2820	41,72	0,04	Vm =	2842	m/s	Am =	0,08	V
	2	51,20	0,0000512	0,15	2930	76,88	0,08	D.st =	64,08		D.st =	0,03	
	3	54,00	0,000054	0,15	2778	115,63	0,12	D.st =	2,25	%	D.st =	61,34	%
3	1	51,60	0,0000516	0,15	2907	52,50	0,05	Vm =	2864	m/s	Am =	0,05	V
	2	51,60	0,0000516	0,15	2907	52,50	0,05	D.st =	60,90		D.st =	0,00	
	3	54,00	0,000054	0,15	2778	45,00	0,05	D.st =	2,13	%	D.st =	92,93	%
4	1	51,20	0,0000512	0,15	2930	30,00	0,03	Vm =	2771	m/s	Am =	0,06	V
	2	49,60	0,0000496	0,15	3024	47,34	0,05	D.st =	294,08		D.st =	0,03	
	3	63,60	0,0000636	0,15	2358	96,88	0,10	D.st =	10,61	%	D.st =	51,20	%
5	1	56,00	0,000056	0,15	2679	140,63	0,14	Vm =	2520	m/s	Am =	0,10	V
	2	54,80	0,0000548	0,15	2737	109,38	0,11	D.st =	267,44		D.st =	0,04	
	3	70,00	0,00007	0,15	2143	45,00	0,05	D.st =	10,61	%	D.st =	59,51	%
6	1	53,60	0,0000536	0,15	2799	60,47	0,06	Vm =	2568	m/s	Am =	0,04	V
	2	59,60	0,0000596	0,15	2517	40,78	0,04	D.st =	171,24		D.st =	0,01	
	3	62,80	0,0000628	0,15	2389	31,88	0,03	D.st =	6,67	%	D.st =	73,08	%

Recycled concrete[50% Rec + 50% nat] (coarse+ fine)

Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	51,20	0,0000512	0,15	2929,69	30,47	0,03	Vm =	2938	m/s	Am =	0,05	V
	2	50,00	0,00005	0,15	3000	75,47	0,08	D.st =	47,48		D.st =	0,02	
	3	52,00	0,000052	0,15	2884,62	51,56	0,05	D.st =	1,62	%	D.st =	64,98	%
2	1	53,60	0,0000536	0,15	2798,51	137,50	0,14	Vm =	2871	m/s	Am =	0,07	V
	2	52,00	0,000052	0,15	2884,62	33,75	0,03	D.st =	54,42		D.st =	0,05	
	3	51,20	0,0000512	0,15	2929,69	36,09	0,04	D.st =	1,90	%	D.st =	30,02	%
3	1	50,40	0,0000504	0,15	2976,19	74,53	0,07	Vm =	2908	m/s	Am =	0,05	V
	2	52,80	0,0000528	0,15	2840,91	33,28	0,03	D.st =	55,23		D.st =	0,02	
	3	51,60	0,0000516	0,15	2906,98	44,06	0,04	D.st =	1,90	%	D.st =	65,49	%
4	1	52,00	0,000052	0,15	2884,62	53,44	0,05	Vm =	2849	m/s	Am =	0,08	V
	2	52,00	0,000052	0,15	2884,62	134,38	0,13	D.st =	50,36		D.st =	0,04	
	3	54,00	0,000054	0,15	2777,78	61,88	0,06	D.st =	1,77	%	D.st =	56,35	%
5	1	52,40	0,0000524	0,15	2862,6	129,69	0,13	Vm =	2768	m/s	Am =	0,07	V
	2	51,60	0,0000516	0,15	2906,98	71,72	0,07	D.st =	166,45		D.st =	0,04	
	3	59,20	0,0000592	0,15	2533,78	22,50	0,02	D.st =	6,01	%	D.st =	41,30	%
6	1	58,40	0,0000584	0,15	2568,49	35,63	0,04	Vm =	2642	m/s	Am =	0,04	V
	2	51,60	0,0000516	0,15	2906,98	59,53	0,06	D.st =	193,31		D.st =	0,01	
	3	61,20	0,0000612	0,15	2450,98	25,78	0,03	D.st =	7,32	%	D.st =	64,85	%

Recycled concrete[20% Rec + 80% nat] (coarse+ fine)

Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	58,80	0,0000588	0,15	2551,02	115,63	0,12	Vm =	2766	m/s	Am =	0,12	V
	2	52,80	0,0000528	0,15	2840,91	192,19	0,19	D.st =	154,60		D.st =	0,06	
	3	51,60	0,0000516	0,15	2906,98	52,03	0,05	D.st =	5,59	%	D.st =	52,23	%
2	1	59,60	0,0000596	0,15	2516,78	93,75	0,09	Vm =	2747	m/s	Am =	0,09	V
	2	52,40	0,0000524	0,15	2862,6	114,06	0,11	D.st =	163,02		D.st =	0,03	
	3	52,40	0,0000524	0,15	2862,6	51,09	0,05	D.st =	5,93	%	D.st =	69,59	%
3	1	59,20	0,0000592	0,15	2533,78	34,22	0,03	Vm =	2618	m/s	Am =	0,06	V
	2	53,20	0,0000532	0,15	2819,55	114,06	0,11	D.st =	143,34		D.st =	0,04	
	3	60,00	0,00006	0,15	2500	29,06	0,03	D.st =	5,48	%	D.st =	34,18	%
4	1	51,20	0,0000512	0,15	2929,69	42,66	0,04	Vm =	2757	m/s	Am =	0,07	V
	2	52,80	0,0000528	0,15	2840,91	118,75	0,12	D.st =	185,21		D.st =	0,03	
	3	60,00	0,00006	0,15	2500	56,72	0,06	D.st =	6,72	%	D.st =	54,54	%
5	1	52,40	0,0000524	0,15	2862,6	89,06	0,09	Vm =	2900	m/s	Am =	0,05	V
	2	50,40	0,0000504	0,15	2976,19	34,22	0,03	D.st =	53,55		D.st =	0,03	
	3	52,40	0,0000524	0,15	2862,6	35,16	0,04	D.st =	1,85	%	D.st =	51,46	%
6	1	51,60	0,0000516	0,15	2906,98	276,56	0,28	Vm =	2871	m/s	Am =	0,14	V
	2	54,00	0,000054	0,15	2777,78	96,88	0,10	D.st =	66,90		D.st =	0,10	
	3	51,20	0,0000512	0,15	2929,69	35,16	0,04	D.st =	2,33	%	D.st =	24,82	%

recycled concrete 100% coarse recycled

Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	52,80	0,0000528	0,15	2840,91	65,63	0,07	Vm =	2755	m/s	Am =	0,05	V
	2	51,60	0,0000516	0,15	2906,98	38,91	0,04	D.st =	170,52		D.st =	0,01	
	3	59,60	0,0000596	0,15	2516,78	37,97	0,04	D.st =	6,19	%	D.st =	73,01	%
2	1	51,20	0,0000512	0,15	2929,69	25,78	0,03	Vm =	2540	m/s	Am =	0,03	V
	2	54,00	0,000054	0,15	2777,78	42,66	0,04	D.st =	447,66		D.st =	0,01	
	3	78,40	0,0000784	0,15	1913,27	20,63	0,02	D.st =	17,62	%	D.st =	68,31	%
3	1	52,40	0,0000524	0,15	2862,6	52,50	0,05	Vm =	2615	m/s	Am =	0,04	V
	2	59,60	0,0000596	0,15	2516,78	35,16	0,04	D.st =	175,90		D.st =	0,01	
	3	60,80	0,0000608	0,15	2467,11	27,19	0,03	D.st =	6,73	%	D.st =	72,40	%
4	1	59,60	0,0000596	0,15	2516,78	29,53	0,03	Vm =	2612	m/s	Am =	0,03	V
	2	53,20	0,0000532	0,15	2819,55	51,56	0,05	D.st =	146,84		D.st =	0,01	
	3	60,00	0,00006	0,15	2500	18,28	0,02	D.st =	5,62	%	D.st =	58,27	%
5	1	50,80	0,0000508	0,15	2952,76	55,78	0,06	Vm =	2916	m/s	Am =	0,04	V
	2	53,20	0,0000532	0,15	2819,55	33,28	0,03	D.st =	68,98		D.st =	0,01	
	3	50,40	0,0000504	0,15	2976,19	27,66	0,03	D.st =	2,37	%	D.st =	68,77	%
6	1	53,60	0,0000536	0,15	2798,51	35,63	0,04	Vm =	2894	m/s	Am =	0,03	V
	2	51,20	0,0000512	0,15	2929,69	32,81	0,03	D.st =	67,93		D.st =	0,00	
	3	50,80	0,0000508	0,15	2952,76	30,94	0,03	D.st =	2,35	%	D.st =	94,18	%

recycled concrete 80% coarse recycled

Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	52,00	0,000052	0,15	2884,62	114,06	0,11	Vm =	2886	m/s	Am =	0,08	V
	2	53,60	0,0000536	0,15	2798,51	78,13	0,08	D.st =	72,55		D.st =	0,02	
	3	50,40	0,0000504	0,15	2976,19	58,13	0,06	D.st =	2,51	%	D.st =	72,27	%
2	1	50,80	0,0000508	0,15	2952,76	27,19	0,03	Vm =	2953	m/s	Am =	0,03	V
	2	50,80	0,0000508	0,15	2952,76	51,56	0,05	D.st =	0,00		D.st =	0,01	
	3	50,80	0,0000508	0,15	2952,76	23,91	0,02	D.st =	0,00	%	D.st =	63,96	%
3	1	50,40	0,0000504	0,15	2976,19	57,19	0,06	Vm =	2829	m/s	Am =	0,04	V
	2	57,60	0,0000576	0,15	2604,17	21,56	0,02	D.st =	161,55		D.st =	0,01	
	3	51,60	0,0000516	0,15	2906,98	43,13	0,04	D.st =	5,71	%	D.st =	63,93	%
4	1	50,40	0,0000504	0,15	2976,19	45,47	0,05	Vm =	2821	m/s	Am =	0,04	V
	2	50,80	0,0000508	0,15	2952,76	66,56	0,07	D.st =	203,25		D.st =	0,02	
	3	59,20	0,0000592	0,15	2533,78	19,69	0,02	D.st =	7,21	%	D.st =	56,35	%
5	1	51,60	0,0000516	0,15	2906,98	49,22	0,05	Vm =	2901	m/s	Am =	0,05	V
	2	50,40	0,0000504	0,15	2976,19	63,75	0,06	D.st =	64,09		D.st =	0,01	
	3	53,20	0,0000532	0,15	2819,55	31,88	0,03	D.st =	2,21	%	D.st =	73,02	%
6	1	50,80	0,0000508	0,15	2952,76	54,84	0,05	Vm =	2821	m/s	Am =	0,05	V
	2	50,40	0,0000504	0,15	2976,19	73,59	0,07	D.st =	203,25		D.st =	0,02	
	3	59,20	0,0000592	0,15	2533,78	28,13	0,03	D.st =	7,21	%	D.st =	64,26	%

recycled concrete 50% coarse recycled

Sample	Side	t [µs]	t [s]	L [m]	V [m/s]	A [mV]	A [V]						
1	1	51,20	0,0000512	0,15	2929,69	39,38	0,04	Vm =	2871	m/s	Am =	0,10	V
	2	53,60	0,0000536	0,15	2798,51	200,00	0,20	D.st =	54,42		D.st =	0,07	
	3	52,00	0,000052	0,15	2884,62	52,97	0,05	D.st =	1,90	%	D.st =	25,37	%
2	1	50,80	0,0000508	0,15	2952,76	50,63	0,05	Vm =	2930	m/s	Am =	0,08	V
	2	50,80	0,0000508	0,15	2952,76	106,25	0,11	D.st =	32,12		D.st =	0,02	
	3	52,00	0,000052	0,15	2884,62	69,38	0,07	D.st =	1,10	%	D.st =	69,36	%
3	1	52,00	0,000052	0,15	2884,62	140,63	0,14	Vm =	2915	m/s	Am =	0,09	V
	2	50,80	0,0000508	0,15	2952,76	59,06	0,06	D.st =	28,36		D.st =	0,04	
	3	51,60	0,0000516	0,15	2906,98	68,41	0,07	D.st =	0,97	%	D.st =	59,21	%
4	1	52,40	0,0000524	0,15	2862,6	100,00	0,10	Vm =	2931	m/s	Am =	0,07	V
	2	49,60	0,0000496	0,15	3024,19	65,63	0,07	D.st =	68,17		D.st =	0,02	
	3	51,60	0,0000516	0,15	2906,98	50,16	0,05	D.st =	2,33	%	D.st =	71,04	%
5	1	52,00	0,000052	0,15	2884,62	84,38	0,08	Vm =	2970	m/s	Am =	0,07	V
	2	50,80	0,0000508	0,15	2952,76	92,81	0,09	D.st =	78,22		D.st =	0,02	
	3	48,80	0,0000488	0,15	3073,77	38,91	0,04	D.st =	2,63	%	D.st =	67,14	%
6	1	51,20	0,0000512	0,15	2929,69	63,28	0,06	Vm =	2892	m/s	Am =	0,05	V
	2	52,40	0,0000524	0,15	2862,6	57,19	0,06	D.st =	27,92		D.st =	0,01	
	3	52,00	0,000052	0,15	2884,62	38,44	0,04	D.st =	0,97	%	D.st =	80,04	%