Mechanical properties of structural concrete containing fine aggregates from waste generated by the marble quarrying industry

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Abstract: The aim of this research is to assess the mechanical performance of concrete containing different percentages of fine aggregates produced from the waste generated by the marble quarrying industry (0%, 20%, 50% and 100% of the total volume of aggregates). More specifically, the workability and bulk density of fresh concrete were measured and the compressive strength, splitting tensile strength, modulus of elasticity and abrasion resistance of hardened concrete were determined.

In general, concrete containing secondary fine aggregates proved to have worse mechanical properties than conventional concrete, made with primary siliceous sand, basalt and granite fine aggregates. This poorer performance was more noticeable when the replacement percentage was higher. However, the reduction in mechanical performance is acceptable and does not compromise the use of these secondary aggregates in structural concrete.

Subject headings: Secondary fine marble aggregates; structural concrete; mechanical performance.

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INTRODUCTION

Preliminary remarks

The uncontrolled exploitation of natural resources by humans has been harshly criticized in recent decades. Every year millions of tonnes of marble waste pile up in Estremoz, Borba and Vila Viçosa region (the most important Portuguese marble quarrying area), a by-product of the local quarrying industry. This enormous waste represents 80% to 90% of the total volume of rock extracted (Figure 1). It has therefore become necessary to create sustainable destinations for this waste material, to mitigate or put a stop to this trend. Using waste generated by the marble quarrying industry to produce fine aggregates for the production of structural concrete has therefore been studied as a useful alternative, from the perspective of both environmental protection and the sustainability of natural resources. However, in order to publicize and implement this alternative within the construction sector it is necessary to ensure quality and safety, in addition to providing a clear understanding of the performance of concrete containing fine aggregates from waste generated by the marble quarrying industry.

Research significance

This research addresses the important environmental problem of how to dispose of the waste generated by the Portuguese marble quarrying industry and analyses the feasibility of a possible solution, which is to use fine aggregates from that waste in concrete production, with respect to mechanical performance. Part of the innovation lies in eliminating the entropy caused in the analysis of results by the grading curve of the aggregate, the effective water-cement ratio (w/c) or any composition-related factors except those directly resulting from changing from fine primary aggregates to fine secondary aggregates, while keeping the workability constant.

STATE-OF-THE-ART

Although a relatively extensive bibliography is now available on the subject, it is the lack of experience in Portugal plus the facts that some areas have not been sufficiently clarified and that inconsistencies exist in others, which has motivated this study.

Concerning aggregates' properties, de Brito (2005) emphasizes that it is only possible to compare conventional concrete and recycled aggregates concrete in terms of their performance and durability if the size grading of both the fine and coarse aggregates is the same in the two types of concrete. In fact, Leite (2001) claims that size distribution of the aggregates is one of the most important properties as it influences several concrete characteristics, such as workability, mechanical strength and water absorption.

The effect of aggregate type on the mechanical properties of concretes with different strengths was reported by Özturan and Çeçen (1997). They concluded that normal strength concrete made with basalt and sandstone had similar compressive strength while limestone concrete achieved a somewhat higher strength. Higher tensile strength was obtained with crushed basalt and limestone than with sandstone aggregate when used in high strength concrete.

Larrard and Belloc (1997) reported that the strength of concrete is determined by the characteristics of the mortar, coarse aggregate, and interface. For the same quality mortar, different types of coarse aggregate of different shapes, textures, mineralogy and strengths may result in different concrete strengths. However, one of the basic concepts is the limitations of the water/cement ratio (w/c) to produce high-strength and high-performance concrete in which the aggregate plays a more important role.

Kiliç et al (2008) note that the factors influencing the strength of concrete are: the amount and type of cement, w/c ratio, aggregate type and grading, workability of fresh concrete, mineral admixtures, curing conditions and time.

Zhou et al (1995) studied the effect of coarse aggregate on the compressive strength of high-performance concrete. They reported that weaker aggregates reduced the strength of concrete.

Giaccio and Zerbino (1996) stated that because concrete is a composite material its properties depend on those of its components and the interactions between them. They emphasize that the boundaries between the various components are the weakest link in concrete and have an important role in the rupture process.

Costa et al. (1991) carried out research at the Portuguese National Laboratory of Civil Engineering (LNEC) with the purpose of evaluating the mechanical properties of marble waste for its use as aggregate. They concluded that this waste has good mechanical properties and can be used as aggregate in concrete.

According to de Brito (2005), the density of fresh concrete reflects the particle density of each component, especially the aggregates, because they comprise the greater part of the concrete's volume. Therefore, higher densities of each component result in mixes with higher densities.

The initial moisture of the recycled aggregates is also expected to influence the mixing water absorption, and therefore the concrete's workability. Poon et al. (2004) studied several concrete compositions, incorporation rates (0%, 20%, 50% and 100%) and aggregates' moisture content. The results of the workability variation over time, for different replacement rates with coarse aggregates and in three moisture conditions (oven-dry, air-dry and saturated surface dry), showed that the initial slump for the mix with oven-dry particles is always highest. Moreover, recycled aggregates concrete with oven-dry aggregate has higher slump than conventional concrete because of the extra water added to the mix to compensate for absorption by the aggregates. After the initial period, these mixes have a significant loss of workability compared with the others. This behaviour is more obvious as the incorporation rate increases.

Corinaldesi et al. (2010) showed that 10% replacement of sand by marble powder yields maximum compressive strength with about the same workability; mixes were evaluated based on cement or sand replacement by marble powder.

Binici et al. (2007) studied some mechanical properties of concrete containing marble and limestone powder; mixes were modified to 5%, 10% and 15% marble and limestone powder instead of fine sand aggregates and their compressive strength was compared. Binici et al. (2008) went on to look at the durability and fresh properties of concrete made with granite and marble as recycled aggregates. There is a much better bond between the additions, cement and aggregates in the specimens containing marble and granite. Furthermore, it may be said that marble and granite replacement provided a good dense matrix. The increased durability of concrete can be attributed to the quartz content and chemical composition of granite. This study showed that marble and granite waste aggregates can be used to improve the mechanical properties, workability and chemical resistance of conventional concrete mixes.

Topçu et al. (2009) and Corinaldesi et al. (2010) stated that the use of marble powder as mineral addition for mortars and concretes, especially for self-compacting when a superplasticizing admixture is used, provided maximum compressive strength for the same workability level, comparable to that of the reference mix.

Ergun (2011) carried out a study on the mechanical properties of concrete specimens containing diatomite and waste marble powder (WMP) as a partial replacement of cement. Test results indicated that the concrete specimens containing 10% diatomite, 5% WPM and 5% WPM +10% diatomite replacement by weight for cement had the best compressive and flexural strength, and replacing cement with diatomite and WMP separately and together, using a superplasticizing admixture, would improve the mechanical properties of conventional concrete mixes.

Belachia and Hebhoub (2011) tried to prove the technical feasibility of using the waste marble aggregates in hydraulic concrete. The results showed that marble scrap can be used as a replacement material. Aruntas et al. (2010) studied the usability of waste marble powder as an additive in blended cement. The results showed that cements containing waste marble powder can be used as an addition in cement manufacture.

Hebhoub et al. (2011) carried out a study to demonstrate the possibility of using marble waste instead of natural aggregates in concrete production. The results showed that the mechanical properties of concrete specimens produced using the marble waste were found to conform to the concrete production standards and the replacement of natural aggregates by waste marble aggregates, up to 75% of any formulation, is beneficial for concrete strength.

According to Dhir et al. (1991), abrasion resistance depends on multiple factors, such as w/c ratio, curing, workability, maximum aggregate size and components. According to Evangelista and de Brito (2007), it seems to be generally agreed that concrete performance in terms of this property improves as the incorporation rate of recycled aggregates increases, for both coarse and fine fractions.

EXPERIMENTAL PROGRAMME

Materials used

Primary aggregates are limestone gravel, basalt sand, granite sand and siliceous river sand. The secondary aggregates are sand made from waste generated by the Solubema marble quarry, a by-product of this industry. CEM II 42.5 R cement from the SECIL cement works in Outão, Setúbal was used as binder. Tap water was used.

Characterization of the aggregates

Some tests were performed to characterize the aggregates, enable the correct design of concrete mixes and understand possible differences in/effects on the results:

- Sieve analysis - NP EN 933-1 (2000) and NP EN 933-2 (1999);
- Bulk density and water absorption - NP EN 1097-6 (2003);
- Apparent bulk density - NP EN 1097-3 (2003);
- Shape index - NP EN 933-4 (2002) (coarse aggregates only);
- Los Angeles abrasion test - LNEC E237 (coarse aggregates only).

Reference concrete

Considering Portuguese standard NP EN 206-1 (2005), the purpose was to produce a concrete of average compressive strength, tested on cubic samples of approximately 44 MPa (C 30/37 according to Eurocode 2) and with workability defined by the slump range 125 ± 10 mm. Table 1 presents the proportions of the materials used. No admixtures or additions were used.

Composition of concrete mixes

Faury’s concrete design method (1958) was used to determine the mixes' composition, assuming a target slump of 125 ± 10 mm.

The replacement ratios were set at 0%, 20%, 50% and 100% of the total aggregate volume. Fine aggregates are particles below 4 mm, "rice grain" is particles below 6 mm, gravel 1 is particles below 12 mm below and gravel 2 is particles below 16 mm.

As both the fine and coarse mixes were subdivided into various particle size fractions, one must explain exactly how the replacement was carried out. The underlying concept was to minimize any discontinuity in the grading curve of the aggregates, which also affected the intervals for the sieves that were used. This meant, for example, that to replace a particular percentage of fine aggregate, all the particle size fractions that were less than 4 mm were affected to the extent that each contributed towards defining the standard curve. In simple terms, each primary particle was replaced by a secondary particle of the same size to the extent of the replacement ratio established for each mix.

Finally, the w/c ratio was calibrated so as to maintain the level of workability, which was expected to be affected by an increase in the amount of secondary aggregates incorporated (Table 2).

Testing of fresh concrete

The following tests were carried out on fresh concrete:

- Slump test (Abrams cone) - NP EN 12350-2 (2002);
- Bulk density - NP EN 12350-6 (2002).

Testing of hardened concrete

The following tests were carried out on hardened concrete:

- Compressive strength at 7, 28 and 56 days - NP EN 12390-3 (2003);
- Splitting tensile strength at 28 days - NP EN 12390-6 (2003);
- Modulus of elasticity at 28 days - LNEC E397;
- Abrasion resistance at 91 days - DIN 52108 (2002).

The compressive strength test method is specified in NP EN 12390-3, using a total of eleven 15 x 15 x 15 cm^3 wet-cured specimens, three for tests at 7 days, five for tests at 28 days and three for tests at 56 days.

The method described by standard NP EN 12390-6 was used to determine the splitting tensile strength. Tests were performed on wet-cured specimens: three cylinders 30 cm tall and 15 cm diameter per concrete mix analysed.

The modulus of elasticity method is specified in the standard LNEC E397, using two cylinders 30 cm tall and 15 cm diameter per concrete mix analysed.

The determination of the wear resistance by abrasion followed the test method specified in the German standard DIN 52108, using four 8 x 8 x 5 cm^3 specimens.

RESULTS AND DISCUSSION

Aggregates' properties

Table 3 shows the results of the tests on the aggregates.

Table 3 shows that the fine aggregate with the highest bulk density is basalt sand. Granite sand and fine river sand have lower bulk density than basalt and marble sand.

Regarding water absorption after 24 h immersion, Table 3 shows that secondary fine marble aggregates had the lowest value (0.14%), a conclusion that was also reached by Costa et al. (1991) and Cardani and Meda (1999). There is a significant difference between the water absorption of marble sand and basalt sand.

The Los Angeles abrasion test shows that all the aggregates complied with the limits set for use in structural concrete. Results varied from 22.45% to 26.52%. The shape index results showed a similar geometry for the various coarse aggregates.

Fresh concrete properties

Workability - Table 4 shows the slump test result and the water cement ratio for each concrete produced.

Table 4 shows that although the secondary aggregates negatively but slightly affect the workability of the concrete in which they are incorporated, changing the w/c ratio effectively addresses the problem. In fact, slump figures within the target interval were obtained, regardless of the replacement percentage. It was also noticed that the w/c ratio had to be increased as the percentage of aggregate replacement increased.

Marble sand is the fine aggregate with the lowest water absorption according to our study. Therefore, it was expected that workability would improve with the incorporation of marble sand, which it did not. In their study, Hebhoub et al. (2011) obtained the same result. They conclude that some of the factors that may affect the workability of concrete are the grading and shape of fine aggregates, the proportion of fine to coarse aggregates and the characteristics of the materials. Corinaldesi et al (2010) state that marble sand has a high specific surface area and its addition to concrete should enhance cohesiveness, which decreases the workability. Pereira et al. (2007) found that it was necessary to add water to concrete produced with saturated marble aggregates to obtain the same workability as that of conventional concrete. They stated that the reason for the extra water was to counter the highly cohesive, but low workability, mixture, which resulted from the high values of the shape index and smooth surface of the marble particles.

The target slump loss was 125 ± 10 mm, so some corrections would still have to be made to the w/c in some of the mixes to ensure that they all had the correct slump value. In the basalt sand concrete family (BB), a very small amount of water would have to be added to the BRB mix and the water would have to be reduced for the BB/M20 and BB/M50 mixes. This might in fact change some of the test results and explain some of the trends detected further on. The other two families (river sand and granite concrete families (BC and BG)) could be analysed in the same way.

Bulk density - Table 5 shows the bulk density test on fresh concrete. Figure 2 shows the fresh-state bulk density of each mix relative to the corresponding reference concrete, as a function of the aggregate replacement ratio.

It shows that incorporating fine aggregates from marble quarrying waste into concrete has a small influence on the bulk density in the fresh state. This is due to the similar values of the fine, primary and secondary, aggregates’ bulk density.

Hardened concrete properties

Compressive strength - Tables 6, 7 and 8 show the compressive strength test results for the BB, BC and BG mixes, respectively. So as to understand the influence of the aggregate replacement ratio on the compressive strength of concrete at 28 days, the test results are shown in Figure 3.

The BB showed a compressive strength decrease with the incorporation of secondary marble fine aggregates at 7 and 28 days. This is due to the increase of the w/c ratio with the incorporation ratio. Since the purpose is to produce a concrete of average compressive strength of approximately 44 MPa (C 30/37), tested using cubic samples, rupture is expected to occur mostly through the cement matrix. Adding extra water to the mix for higher incorporation ratios will increase the porosity of the matrix, thereby weakening it. Martins et al. (2013) stated in his study that excess water in the mix (more than is strictly necessary for the hydration reactions) can result in increased workability, but leads to greater porosity and a consequent loss of compressive strength. Poon et al. (2004) observed that the saturation of recycled aggregates may lead to a slight reduction in concrete strength because the mechanical bond between the cement paste and recycled aggregates is weaker when surface moisture is higher. Therefore, a higher proportion of recycled aggregates for the same effective w/c ratio, together with the addition of extra water needed to saturate the recycled aggregates, leads to lower compressive strength results, as found by Tavakoli and Soroushian (1996). At 56 days the compression test results do not conform exactly to this reasoning, which may be caused by an unidentified laboratory error.

The BC and BG showed a compressive strength decrease with the incorporation of secondary marble fine aggregates at 7, 28 and 56 days. The BC results are higher than those of the other two families. River sand showed low water absorption, close to the marble sand value. This means that, to achieve the same workability level, concrete incorporating river sand will have a lower w/c ratio than concrete incorporating basalt and granite sand, as seen in Table 4. The reduction of water in this concrete family (BC) thus resulted in higher compressive strength than found for the other two concrete families. Özturan and Çeçen (1997) reached similar conclusions in their study. They concluded that normal strength concrete made with basalt and sandstone had similar compressive strength while concrete made with river sand achieved a perceptibly higher strength. The reason for the reduction in compressive strength with the secondary marble sand aggregates incorporation ratio is the same as that for the basalt sand family at 7 and 28 days. Similar conclusions were presented by Belachia and Hebhoub (2011), Hebhoub et al. (2011) and Martins et al. (2013).

The poor compressive strength of the 100% replacement rate concrete (BRM) compared with other mixes with similar workability and w/c ratio can be explained by the smooth surface of the marble particles. This results in a poor adhesion and bonding strength to the cement matrix. This was concluded by Larrard and Belloc (1997).

Splitting tensile strength - According to Coutinho (1988), concrete tensile strength decreases with the w/c ratio. This parameter is also influenced by the characteristics of the aggregates, such as their nature and shape, especially the coarse ones. Evangelista and de Brito (2007) argue that it is expected that a higher incorporation ratio decreases the splitting tensile strength.

Table 9 and Figure 4 show the splitting tensile strength test results for the BB, BC and BG families, respectively.

As with the trend shown for compressive strength, the results in this case also reveal a reduction in performance as the percentage of incorporated secondary aggregates increases, for the BC and BG families. The reasons for this strength decrease are the same as those for the compression strength loss. However, the BB family exhibited a contrary trend in compressive strength, i.e. the splitting tensile strength increased with the incorporation ratio. This is due to the fact that, in the test process, the load is distributed over a cross section of the sample. Thus, the lamellar geometry of the basalt particles causes weaker zones to form on the cross section, leading to a premature tensile rupture. This susceptibility may have been amplified by the less effective intermolecular bonding between the cement matrix and the basalt particles (Van der Waals forces). Tasong et al. (1999) report that the chemical reaction between basalt and cement paste resulted in a reduction of bond strength. They concluded that the tensile bond strength between basalt and the cement paste was lower than that of limestone and quartzite. These observations confirm the findings of Odler and Zurz (1987), who reported that the cleavage strength of the basalt-cement paste composite was lower than that of limestone. Hebhoub et al. (2011) found that higher carbonate content improves the aggregate-cement paste bond. The higher carbonate content is a characteristic of marble aggregates. Tasong et al. (1999) consider that the main reason for the low cement paste-basalt bond strength is the chemical breakdown of feldspars due to their interaction with the hydrating cement to produce clay materials, which swell on absorbing water. Alternatively, the chemical breakdown of feldspars and other mineral grains on the basalt surface in contact with the cement paste may reduce the surface roughness and weaken the mechanical interlocking effect between the rock surface and the hydration products, resulting in a weaker bond.

Modulus of elasticity - Table 10 and Figure 5 show the modulus of elasticity test results for the BB, BC and BG families, respectively.

Table 10 shows that the modulus of elasticity was the property that showed least variation. The BB and BG families demonstrate a nearly constant behaviour. The BC family exhibits the greatest decrease in modulus of elasticity.

The reasons for the high values of the BC family are the same as those for compressive strength. The low water absorption levels shown by the river sand resulted in a lower w/c ratio than that of concrete incorporating basalt and granite sand. As concluded, a lower w/c ratio results in increased compressive strength. Experience shows that the modulus of elasticity has a strict relation with the compression strength. Therefore, these conclusions can be applied to the results of the BC's modulus of elasticity.

Abrasion resistance - Table 11 and Figure 6 show the average abrasion wear test results for the BB, BC and BG families, respectively.

Table 11 shows that the abrasion resistance decreases with the incorporation ratio. This decrease is mainly due to the higher w/c ratio. However, a secondary cause may have amplified this trend. Martins et al. (2013) performed the Los Angeles wear test on coarse basalt, granite, limestone and marble aggregates from the same locations as the ones used in this study. The results showed that marble is the aggregate most sensitive to wear. Therefore, due to the marble aggregates' limitations in terms of wear relative to basalt, river sand and granite, its incorporation may have led to a decrease in abrasion resistance. This conclusion was also reached by Martins et al. (2013) when comparing concrete mixes with various replacement ratios of primary basalt, granite and limestone coarse aggregates by secondary marble coarse aggregates.

CONCLUSIONS

The mechanical performance of structural concrete containing fine aggregates from waste generated by marble quarrying, i.e. a by-product of this industry, has been analysed. After completing the work, the following conclusions can be drawn:

1. - The incorporation of secondary marble fine aggregates negatively influenced the workability of concrete; this is mostly because the geometry of the marble particles and smooth texture of its surface resulted in a highly cohesive mix.
2. Compressive strength is affected by the incorporation of secondary aggregates, and as the replacement ratio increases the compressive strength of all the concrete families studied decreases. This decrease was found to be caused by the increase in the w/c ratio due to the incorporation of marble fine aggregates.

3. The splitting tensile strength exhibited trends (losses as the incorporation ratio increased) that were similar to those of compressive strength for the BG (granite) and BC (siliceous river sand) families; the BB (basalt) family showed a contrary trend (gains), mostly due to the geometry of basalt particles and their weak intermolecular bond with the cement.
4. The modulus of elasticity results showed no significant variation with the replacement ratio for the BB and BG families; the BC family suffered a significant decrease, mostly due to its low w/c ratio.
5. All the concrete families showed a decrease of abrasion resistance with the replacement ratio, the reasons being a higher w/c ratio and the poorer wear resistance of the secondary fine aggregates, compared with the primary ones.

In general, the incorporation of fine aggregates from waste generated by marble quarrying in concrete yielded good results. They showed a slight decrease in the mechanical properties of concrete, especially for high replacement ratios. The incorporation of fine aggregates using marble quarrying waste in concrete does not compromise the mechanical properties and these aggregates can be used to produce structural concrete.

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Tables and Figures

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Table 1 - Composition of the reference concrete mixes

Size grading			Basalt sand	River sand	Granite sand
Fine aggregates	< 0.063	0.063	3.68	2.4	3.02
	0.063	0.125	4.62	3.01	3.79
	0.125	0.25	6.43	4.19	5.27
	0.25	0.5	3.18	2.07	2.61
	0.5	1	4.37	2.85	3.58
	1	2	5.18	3.37	4.25
	2	4	4.8	3.13	3.94
	> 4		3.12	2.03	2.56
Coarse aggregates	"Rice grain"		9.55	8.9	16.08
	Gravel 1		6.07	10.68	3.57
	Gravel 2		23.43	31.15	25.01
Cement			17.88	18.34	18.41
Water			7.69	7.89	7.92
			100	100	100

Table 2 - Main characteristics of the composition of the concrete mixes

		W/C
Reference basalt concrete	BRB	0.55
Basalt concrete with 20% aggregate replacement	BB/M20	0.55
Basalt concrete with 50% aggregate replacement	BB/M50	0.56
Concrete with 100% aggregate replacement	BRM	0.54
Reference river sand concrete	BRC	0.49
River sand concrete with 20% aggregate replacement	BC/M20	0.5
River sand concrete with 50% aggregate replacement	BC/M50	0.5
Reference granite concrete	BRG	0.54
Granite concrete with 20% aggregate replacement	BG/M20	0.55
Granite concrete with 50% aggregate replacement	BG/M50	0.56

Table 3 - Aggregate test results

	Gravel		"Rice grain"	Sand				
	2	1		Coarse river	Fine river	Basalt	Granite	Marble
Bulk density (kg/m^3)	2606	2620	2489	2600	2523	2820	2467	2684
Water absorption (%)	1.50	1.30	2.84	0.75	0.20	1.05	0.59	0.14
Apparent bulk density (kg/m^3)	1363	1356	1354	1542	1526	1838	1560	1784
Los Angeles abrasion test (%)	26.52	25.45	22.45	-	-	-	-	-
Shape index (%)	15.3	16.8	18.4	-	-	-	-	-

Table 4 - Slump test results

	w/c	h (cm)
BRB	0.55	11.3
BB/M20	0.55	14.3
BB/M50	0.56	14.3
BRM	0.54	13.5
BRC	0.49	13.3
BC/M20	0.50	12.7
BC/M50	0.50	13.2
BRG	0.54	12.7
BG/M20	0.55	11.6
BG/M50	0.56	13.0

Table 5 - Bulk density of fresh concrete

	Bulk density (kg/m^3)
BRB	2412.5
BB/M20	2389.5
BB/M50	2385.2
BRM	2387.6
BRC	2356.4
BC/M20	2381.7
BC/M50	2384.2
BRG	2361.6
BG/M20	2360.4
BG/M50	2381.1

Table 6 - Compressive strength of the basalt sand concrete family

	$f_{cm,7}$ (MPa)	Δ (%)	$f_{cm,28}$ (MPa)	Δ (%)	$f_{cm,56}$ (MPa)	Δ (%)
BRB	38.1	-	50.4	-	54.2	-
BB/M20	35.8	-6.1	49.2	-2.5	58.4	7.8
BB/M50	35.6	-6.8	46.7	-7.4	54.6	0.9
BRM	36.8	-3.5	45.3	-10.2	51.4	-5.1

Table 7 - Compressive strength of the river sand concrete family

	$f_{cm,7}$ (MPa)	Δ (%)	$f_{cm,28}$ (MPa)	Δ (%)	$f_{cm,56}$ (MPa)	Δ (%)
BRC	45.6	-	56.9	-	62.0	-
BC/M20	42.7	-6.3	56.0	-1.5	60.8	-2.0
BC/M50	40.1	-12.0	51.2	-10.1	54.3	-12.3
BRM	36.8	-19.3	45.3	-20.4	51.4	-17.1

Table 8 - Compressive strength of the granite sand concrete family

	$f_{cm,7}$ (MPa	Δ (%)	$f_{cm,28}$ (MPa)	Δ (%)	$f_{cm,56}$ (MPa)	Δ (%)
BRG	39.6	-	49.2	-	51.3	-
BG/M20	38.6	4.1	47.6	-3.2	49.7	-3.0
BG/M50	38.3	5.0	46.2	-6.0	50.7	-1.2
BRM	36.8	7.7	45.3	-7.9	51.4	0.1

Table 9 - Splitting tensile strength test results

	Replacement ratio (%)							
	0		20		50		100	
	$f_{ctm,sp,28}$ (MPa)	Δ (%)	$f_{ctm,sp,28}$ (MPa)	Δ (%)	$f_{ctm,sp,28}$ (MPa)	Δ (%)	$f_{ctm,28}$ (MPa)	Δ (%)
BB	3.5	-	3.5	1.5	4.0	15.7	3.6	3.6
BC	4.4		3.9	-11.4	3.5	-19.4	3.6	-17.5
BG	3.9		3.9	-0.3	3.5	-9.7	3.6	-7.9

Table 10 - Modulus of elasticity test results

	Replacement ratio (%)							
	0		20		50		100	
	$E_{cm,28}$ (GPa)	Δ (%)	$E_{cm,28}$ (GPa)	Δ (%)	$E_{cm,28}$ (GPa)	Δ (%)	$E_{cm,28}$ (GPa)	Δ (%)
BB	32.0	-	32.6	1.9	33.3	4.1	33.1	3.5
BC	38.8		38.0	-2.1	34.2	-11.8	33.1	-14.6
BG	32.5		32.1	-1.0	32.8	1.2	33.1	2.1

Table 11 - Abrasion resistance test results

	Replacement ratio (%)							
	0		20		50		100	
	ΔL (mm)	Δ (%)	ΔL (mm)	Δ (%)	ΔL (mm)	Δ (%)	ΔL (mm)	Δ (%)
BB	5.1	-	5.6	10.1	5.7	11.1	6.7	31.9
BC	4.5		4.7	2.5	4.6	1.9	6.7	47.8
BG	5.9		6.5	9.8	5.9	0.2	6.7	13.7

Figure 1 - Marble waste pile

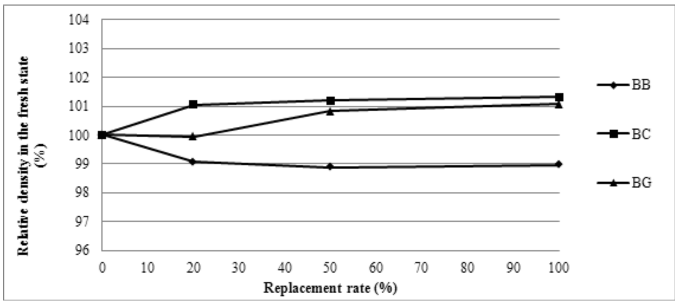

Figure 2 - Bulk density of fresh concrete

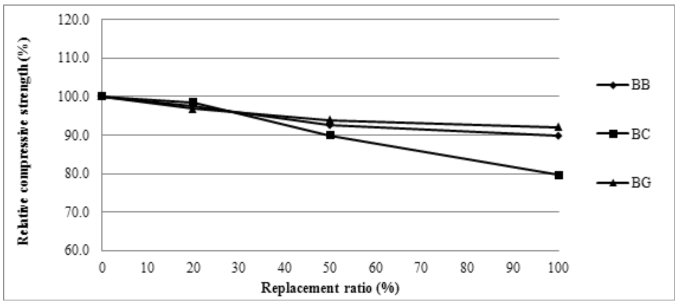

Figure 3 - Compressive strength test (28 days)

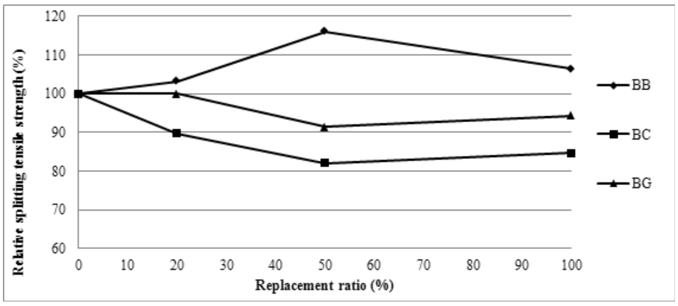

Figure 4 - Splitting tensile strength test (28 days)

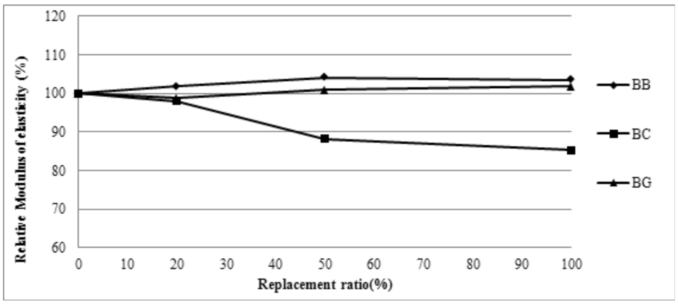

Figure 5 - Modulus of elasticity test (28 days)

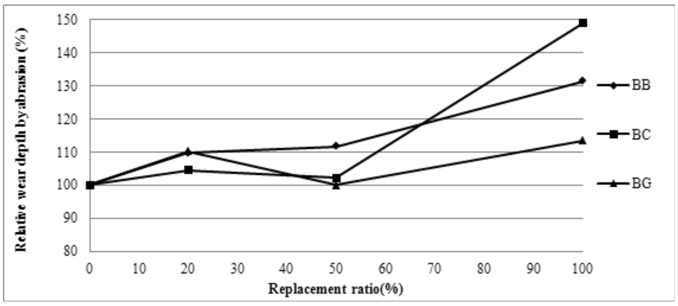

Figure 6 - Abrasion resistance test (91 days)