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Durability performance of structural concrete containing fine aggregates from waste generated by marble quarrying industry

F. Gameiro, J. de Brito*, D. Correia da Silva

Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

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ABSTRACT

The aim of this research is to assess the durability performance of concrete containing various percentages of fine aggregates produced from the waste generated by the marble quarrying industry (0%, 20%, 50% and 100% of the total volume of fine aggregates). The workability and bulk density of fresh concrete were measured and the water absorption by capillary action and immersion, together with the carbonation, chloride penetration and drying shrinkage of hardened concrete, were determined.

It was concluded that the durability properties of concrete containing fine aggregates of granite, basalt and river sand tend to improve, remain constant and decrease, respectively, with the incorporation of fine aggregates from marble quarrying waste. However, these changes do not compromise the use of these secondary aggregates in structural concrete.

1. Introduction

1.1. Preliminary remarks

Humans have always consumed natural resources to meet their needs. However, their importance in terms of environmental sustainability has only recently been appreciated. It is reckoned that 80% of all the rock extracted in the Estremoz, Borba and Vila Viçosa districts in Portugal, is treated as waste. It has therefore become necessary to create sustainable destinations for this material to mitigate or eliminate this trend and to improve its economic value. However, to assess the usability of this waste in the building industry we must ensure that all quality parameters are satisfied, as well as accurately defining the performance of the concrete produced with such waste fine aggregates.

This paper examines the durability related properties of concrete made with these aggregates and supplements the results of Silva et al. [42] that focused on the mechanical performance of the same mixes. It follows on from a previous programme of work on coarse marble aggregates from the same locality [3,27].

1.2. Research significance

This research addresses the sustainable exploitation of marble by ensuring the proper utilisation of the waste and by-products generated by quarrying, the environmental recovery of the areas affected and the prevention of adverse environmental impacts. Part of the innovation of this research lies in the formulation of the mixes by a direct replacement of the fine aggregates (in volume), keeping their size grading and the concrete workability class constant. Any entropic influence of the aggregates' size distribution, water/cement ratio (w/c) and other composition related aspects on the experimental results was thus avoided.

2. State of the art

For a better understanding of the properties and performance of the mixes to be produced, the related research done so far was reviewed. Although some studies in this area have been published there remain several gaps in the information, especially in terms of the durability-related properties.

Coutinho and Gonçalves [11] report that workability is related to the physical properties of concrete such as segregation and exudation, cohesion, viscosity, bulk density and the friction angle of the mix. Aïtcin [1] and Ramachandran et al. [40] consider that these physical properties result from the physical and chemical nature of the materials present in concrete. They single out the reactivity of the cement and additives, the amount of aggregates in the mix, the coarse/fine aggregate ratio, the size grading curve and the shape of the aggregates as the chemical and physical aspects to take into account for workability.

According to Hebhoub et al. [20], the bulk density of concrete does not significantly vary with the proportion of aggregate replaced because the bulk density of all the aggregates was similar. Their study notes that the bulk density of concrete is a function of the density of its components, the proportions of each material

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* Corresponding author. Tel.: +351 218419709; fax: +351 218497650.
E-mail address: jb@civil.ist.utl.pt (J. de Brito).

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used in the mix, the initial and final water content and the concrete's hydration level.

Verbeck [47] states that the amount and characteristics of the pores of the cement paste and aggregates influence the most important properties of hardened concrete. Given the influence that the aggregates' pore size has on this property, Basheer et al. [4] observed that increasing the coarse aggregate ratio increases the permeability of concrete.

Concerning the porous structure and permeability of concrete, Coutinho and Gonçalves [11] say that the concrete's water absorption varies with its w/c ratio, the fineness and content of the cement, age, curing conditions, compactness, workability and water absorption of the aggregate. Permeability mechanisms are absorption and diffusion and they can be measured by capillary action and immersion test methods.

The permeability of concrete is a transport mechanism associated with two degradation mechanisms, i.e. carbonation and chloride penetration. According to Neville [31], the presence of CO_2 in the porous structure of reinforced concrete leads to a large pH reduction, compromising the steel's protection against the corrosive effect of water and oxygen. When it comes to concrete's resistance to chloride penetration, Ferreira [15] states that this phenomenon consists of a molecular reaction of the chloride ions, leading to the destruction of the passive rebar layer.

An important aspect of the durability of concrete is shrinkage control. According to Coutinho and Gonçalves [11], this phenomenon depends on the mix's water content, the amount of cement used and its properties, the aggregates' rock type and size distribution and the concrete's curing conditions. Troxell et al. [45] found that shrinkage increased in their test samples over 30 years, concluding that after the second year this mechanism was due to carbonation. Their study also found a strong influence of the aggregates' rock type on concrete shrinkage, due to their shape and texture which consequently affects the compactness of the mixes.

Hameed and Sekar [18] investigated the durability-related properties of concrete that incorporated fine recycled marble aggregates and dust from several quarries. They found improvements in the concrete's physical and mechanical characteristics because the particles' bond was more efficient, which resulted in better molecular cohesion. In terms of durability, they found that resistance to sulphate attack improved. A similar conclusion was reached by Binici et al. [5]. They also reported that the incorporation of natural and artificial pozzolan increases concrete's chemical resistance. Binici et al. [6] studied the incorporation of coarse marble aggregates in concrete. In their study, an improvement of chemical resistance to sulphate was noticed and this was due to a better bond between the aggregates and the cement paste, resulting in a more condensed and consistent bonding matrix.

3. Experimental programme

3.1. Materials used

The primary aggregates used were limestone gravel, basalt sand, granite sand and siliceous river sand. The secondary aggregates were sand made from waste generated by the Solubema marble quarrying industry. CEM II 42.5 R cement from the SECIL cement works in Outão, Setúbal, Portugal was used as binder. Tap water was used.

3.2. Characterisation of the aggregates

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

- Sieve analysis – NP EN 933-1 [33] and NP EN 933-2 [34].
- Bulk density and water absorption – NP EN 1097-6 [37].
- Apparent bulk density – NP EN 1097-3 [36].
- Shape index – NP EN 933-4 [35] (coarse aggregates only).
- Los Angeles abrasion test – LNEC E237 [21] (coarse aggregates only).

3.3. Concrete mixes composition

Based on Standard NP EN 206-1 [32], ten concrete mixes were produced that had average compression strength, of cube samples of approximately 44 MPa (C 30/37) and workability defined by the slump test in the range 125 ± 15 mm were tested.

The concrete formulations were calculated using Faury's [14] reference curves and are presented in Table 1.

Taking into account that the slump range is 125 ± 15 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" has particles below 6 mm, gravel 1 particles are below 12 mm and gravel 2 particles are below 16 mm.

Having optimised and established the reference grading curve, constant for all mixes, the aggregates were replaced in the specified percentages for each grading size within the sieve's size range. The concrete was thus produced in accordance with the reference grading curve and with balanced proportions of aggregates.

However, the fine aggregates' differences in terms of texture and geometry had to be considered, as well as the consequent change of compactness in the mixes produced. Therefore, taking into account the loss of workability caused by the more elongated and angular marble sand, corrections were made to the w/c ratio to maintain the workability, measured indirectly by the slump (Table 2).

Ten mixes were produced (Table 2): three reference mixes (BRB, with basalt sand only; BRC, with river sand only; BRG, with granite sand only); two mixes per family with 20% and 50% replacement ratios of the fine primary aggregates by fine secondary (marble) aggregates (B$/M#, where $ can be B, C or G and # can be 20 or 50); one mix with marble sand only (BRM).

3.4. Testing of fresh concrete

The following tests were carried out on fresh concrete:

- Slump test (Abrams cone) – NP EN 12350-2 [38].
- Bulk density – NP EN 12350-6 [39].

3.5. Testing of hardened concrete

The following tests were carried out on hardened concrete:

- Water absorption by capillary action at 3, 6, 24 and 72 h – LNEC E-393 [23].
- Water absorption by immersion at 28 days – LNEC E-394 [24].
- Carbonation at 7, 28, 56 and 91 days after curing – LNEC E-391 [22].
- Chloride penetration at 28 and 91 days after curing – LNEC E-463 [26].
- Drying shrinkage at 91 days – LNEC E-398 [25].

The water absorption by capillary action test defined by standard LNEC E-393 advocates the use of 250 × 100 × 100 mm samples. Four samples were used for each concrete type and the measurements were taken at 3, 6, 24 and 72 h, after 28 days wet curing.

For the water absorption by immersion test (standard LNEC E-394 [24]), four 100 × 100 × 100 mm cubic samples were

Table 1
Composition of the reference concrete mixes.

		Particle size		Basalt sand	River sand	Granite sand
				kg/m^3		
Aggregates	Fine	<0.063	0.063	90.72	57.64	72.29
		0.063	0.125	113.78	72.29	90.67
		0.125	0.25	158.37	100.62	126.2
		0.25	0.5	78.42	49.82	62.49
		0.5	1	107.63	68.38	85.77
		1	2	127.62	81.08	101.69
		2	4	118.39	75.22	94.34
		>4		76.88	48.84	61.26
	Course	“Rice grain”		235.21	213.83	384.89
		Gravel 1		149.68	256.59	85.53
		Gravel 2		577.33	748.39	598.71
Binder	Cement CEM II 42.5 R			440.68	440.68	440.68
	Water			242.43	216.57	237.97

Table 2
Water–cement ratio in 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

produced for each concrete type. These samples were submitted to a 28-day wet curing period after casting.

The carbonation test was performed in accordance with standard LNEC E-391 [22], on cylindrical samples 105 mm in diameter and 40 mm tall. They were submitted to 14-day wet curing followed by 14-day dry curing and afterwards placed in a carbonation chamber and tested after a further 7, 28, 56 and 91 days.

The chloride penetration test followed the stipulations of standard LNEC E-463 [26], and was performed on cylindrical samples 105 mm in diameter and 50 mm tall. Three samples were used for each concrete type and tested 28 and 91 days after a 14-day period of wet curing followed by 14-day dry curing.

According to standard LNEC E-398 [25], prismatic samples with a 150 mm square base and 600 mm tall were tested for drying shrinkage. Two samples per concrete type were tested. The tests were performed in a dry chamber 24 h after the production of each concrete type.

4. Results and discussion

4.1. Properties of the aggregates

Table 3 shows that the aggregates have different physical properties. Basalt sand had the highest bulk density and granite sand the lowest.

Apart from granite sand, the aggregates’ specific mass followed the trend observed for bulk density. River sand had the lowest specific mass.

After immersion for 24 h, it was noticed that the voids volume and water absorption followed the same trend. Aggregates with higher water absorption have a higher void volume. Of the aggregates analysed marble sand had the lowest water absorption (0.14%) and voids volume (33.5%).

The Los Angeles abrasion and shape index tests revealed that these properties increase and decrease, respectively, with the aggregates’ size. Nevertheless, the results obtained in the Los Angeles test show that the aggregates’ resistance is acceptable for their use in structural concrete. The shape index results showed a similar geometry for the various coarse aggregates.

4.2. Fresh concrete properties

4.2.1. Workability

Table 4 shows that the slump values are within the target range of 125 ± 15 mm. Despite the angular and elongated geometry of the secondary aggregates having a negative influence on the mixes’ workability, it was found that changing slightly the w/c ratio was an effective way of achieving the target workability. The w/c ratio was nearly constant in the basalt and granite sand concrete specimens and increased in the river sand concrete specimens.

A loss of workability with the incorporation of marble sand was also reported by Binici et al. [5] and Hebhoub et al. [20]. These authors identified the water content, the correct proportion of fine and coarse aggregates and their characteristics as the factors that matter for workability improvement. Shelke et al. [41] registered a decrease in concrete workability when silica fume and marble waste were added. To offset this effect the authors used a superplasticizer.

4.2.2. Bulk density

Table 5 shows the bulk density test of fresh concrete. The trends due to the incorporation of marble sand are shown in Fig. 1 The maximum change in the bulk density was 1.3% from the BRC to the BRM mix and so it was concluded that the incorporation of these secondary aggregates tends to reduce the bulk density of concrete.

Fig. 1 shows that the bulk density of fresh concrete follows the trend observed for the aggregates’ bulk density. This was also reported by de Brito [12], who found that the bulk density is influenced by the bulk density of the aggregates and by the mix compactness.

4.3. Hardened concrete properties

4.3.1. Water absorption by capillary action

The results of the water absorption and water height by capillary action at 72 h are shown in Table 6 and Figs. 2 and 3 With respect to water absorption, Fig. 2 shows that the incorporation of fine marble waste aggregates initially induces a general reduction of capillary action. In fact, the reduction of water absorption by capillary action is more pronounced in the 20% replacement ratio

Table 3
Results of aggregate tests.

	Bulk density (kg/m^3)	Water absorption (%)	Apparent bulk density (kg/m^3)	Voids (%)	Los Angeles abrasion test (%)	Shape index (%)
Gravel 2	2606	1.5	1363	47.7	26.52	15.3
Gravel 1	2620	1.3	1356	48.3	25.45	16.8
“Rice grain”	2489	2.84	1354	45.6	22.45	18.4
Coarse river sand	2600	0.75	1542	40.7	–	–
Fine river sand	2523	0.75	1526	39.5	–	–
Basalt sand	2820	1.05	1838	34.8	–	–
Granite sand	2467	0.59	1560	36.8	–	–
Marble sand	2684	0.14	1784	33.5	–	–

Table 4
Slump.

		Slump (mm)
Reference basalt concrete	BRB	113
Basalt concrete with 20% aggregate replacement	BB/M20	143
Basalt concrete with 50% aggregate replacement	BB/M50	143
Concrete with 100% aggregate replacement	BRM	135
Reference river sand concrete	BRC	133
River sand concrete with 20% aggregate replacement	BC/M20	127
River sand concrete with 50% aggregate replacement	BC/M50	132
Reference granite concrete	BRG	127
Granite concrete with 20% aggregate replacement	BG/M20	116
Granite concrete with 50% aggregate replacement	BG/M50	130

because of the improved bond between aggregates and cement paste, which is linked to the more angular and elongated geometry of the fine marble waste aggregates. For higher replacement ratios, the average pore size of the concrete tends to increase, negatively affecting the water absorption and (partially) offsetting the previous effect.

Binici et al. [5], Hameed and Sekar [18], Corinaldesi et al. [9] and André et al. [3] observed that concrete incorporating marble waste aggregates achieves better water absorption by capillary action, especially between the 15% and 30% replacement ratios. Hanžič and Ilić [19] and Topçu et al. [44] found that the porosity and capillarity coefficient decreases for small replacement ratios, increasing for higher ratios.

Fig. 3 shows a drop in the capillary height for concrete with basalt fine aggregates, in accordance with the decrease in water absorption shown in Fig. 2. Although lower water absorption was also noticed in the granite sand concrete specimens, the capillary height value remained nearly constant, with an increase of 5.1% relative to the reference concrete. Regarding concrete with river sand, Fig. 3 shows an 18.8% increase in capillary height (for a 100% replacement ratio) despite the fact that capillary absorption changes only slightly, as seen in Fig. 2. However, comparing Figs. 2 and 3 show that the decrease in the total change in water absorption in the other concrete specimens has less impact on the capillary height. If there is no significant capillary absorption variation the height increases, as in the concrete mixes with river sand.

The changes observed in the capillary height are due to the fact that marble sand has a smoother surface than basalt, granite and river sand. This aspect is reflected in the aggregates' spatial distribution, i.e. the rougher the particles the worse the mix packing and the higher the cement paste content. Therefore, since capillary action is affected by the shape of the capillary pores in the cement paste, the results of the capillary height shown in Fig. 3 are understandable.

Another phenomenon detected was that the capillary action was more intense in the first 24 h of the test, contributing an

Table 5
Bulk density of fresh concrete mixes.

		Bulk density (kg/m^3)
Reference basalt concrete	BRB	2412.5
Basalt concrete with 20% aggregate replacement	BB/M20	2389.5
Basalt concrete with 50% aggregate replacement	BB/M50	2385.2
Concrete with 100% aggregate replacement	BRM	2387.6
Reference river sand concrete	BRC	2356.4
River sand concrete with 20% aggregate replacement	BC/M20	2381.7
River sand concrete with 50% aggregate replacement	BC/M50	2384.2
Reference granite concrete	BRG	2361.6
Granite concrete with 20% aggregate replacement	BG/M20	2360.4
Granite concrete with 50% aggregate replacement	BG/M50	2381.1

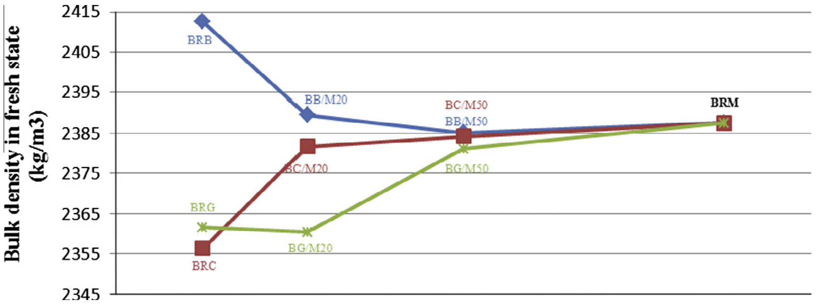

Fig. 1. Bulk density of fresh concrete mixes.

Table 6
Water absorption by capillary action after 28 days curing.

		Water absorption by capillary action at 72 h (g/mm^2)	Water height by capillary action at 72 h (mm)
Reference basalt concrete	BRB	4.14E−03	46.9
Basalt concrete with 20% aggregate replacement	BB/M20	2.96E−03	38.5
Basalt concrete with 50% aggregate replacement	BB/M50	3.34E−03	38.4
Concrete with 100% aggregate replacement	BRM	3.20E−03	41.3
Reference river sand concrete	BRC	3.01E−03	34.7
River sand concrete with 20% aggregate replacement	BC/M20	2.47E−03	43.6
River sand concrete with 50% aggregate replacement	BC/M50	3.04E−03	40.3
Reference granite concrete	BRG	3.93E−03	39.3
Granite concrete with 20% aggregate replacement	BG/M20	2.56E−03	38.5
Granite concrete with 50% aggregate replacement	BG/M50	2.81E−03	38.7

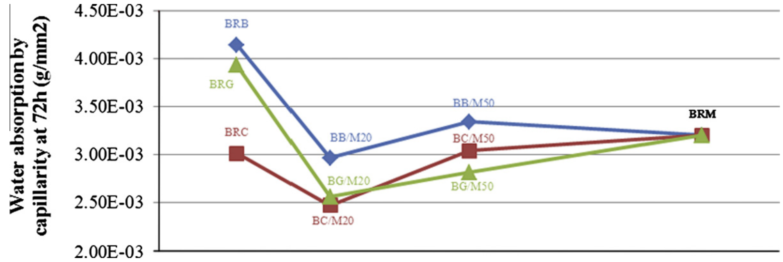

Fig. 2. Water absorption by capillary action at 72 h after 28 days curing.

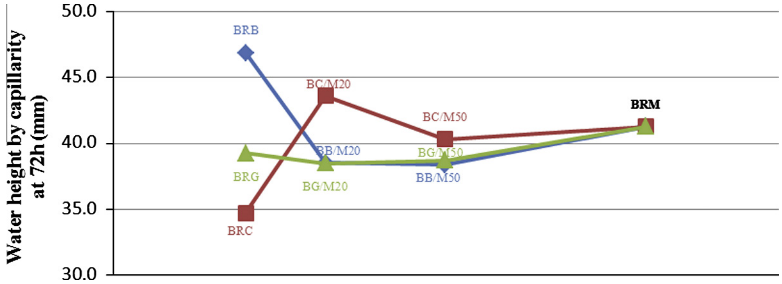

Fig. 3. Water height by capillary action at 72 h after 28 days curing.

average of 70.6% of the water absorption and 73.7% water height achieved at 72 h. After the first few hours the water absorption by capillary action tends to gradually decrease as the concrete's porous network's inner pressure reaches a balance.

4.3.2. Water absorption by immersion

Table 7 and Fig. 4 show that the incorporation of marble sand is beneficial by reducing the water absorption of basalt and granite sand concrete by 3.1% and 17.8%, respectively. However, an increase of 11.2% in water absorption is observed in the river sand concrete with 100% replacement ratio. Nevertheless, decreases in water absorption for 20% and 50% replacement ratios were observed. These differences are due to the properties of marble. Metha and Monteiro [28] concluded that concrete with better mechanical/durability aggregates' characteristics absorbs more water.

The air content in the mix is significant for water absorption by immersion which means that, for replacement ratios of over 50% with marble sand, the compactness of the mix is compromised by the aggregates' roughness. This results in worse aggregate packing and higher air retention. Consequently, the retained air generates an open porous network which offsets the marble sand's lower water absorption and produces concrete with higher water absorption by immersion. However, only slight differences in water absorption by immersion were observed, due to the identical production and curing conditions of the concrete mixes.

4.3.3. Carbonation

Based on Table 8, Fig. 5 (lower right corner) shows the carbonation front for all the mixes at 91 days. Carbonation resistance increases with the incorporation of secondary marble aggregates in the granite aggregates' specimens. The river sand concrete specimens, however, shows a loss of carbonation resistance within the incorporation of marble fine aggregates. The basalt aggregates' specimens exhibited little variation in terms of carbonation resistance.

The results obtained in shorter periods were also important. Fig. 5 represents the carbonation depth measured at 7, 28 and 58 days. Similar trends to that at 91 days were found which indicates consistency of the results.

In accordance with the experimental results obtained by André et al. [3], who studied concrete with incorporation of coarse marble

Table 7
Water absorption by immersion at 28 days.

		Water absorption by immersion (%)
Reference basalt concrete	BRB	16.4
Basalt concrete with 20% aggregate replacement	BB/M20	17.1
Basalt concrete with 50% aggregate replacement	BB/M50	15.7
Concrete with 100% aggregate replacement	BRM	15.9
Reference river sand concrete	BRC	14.3
River sand concrete with 20% aggregate replacement	BC/M20	13.5
River sand concrete with 50% aggregate replacement	BC/M50	13.9
Reference granite concrete	BRG	19.4
Granite concrete with 20% aggregate replacement	BG/M20	17.1
Granite concrete with 50% aggregate replacement	BG/M50	16.7

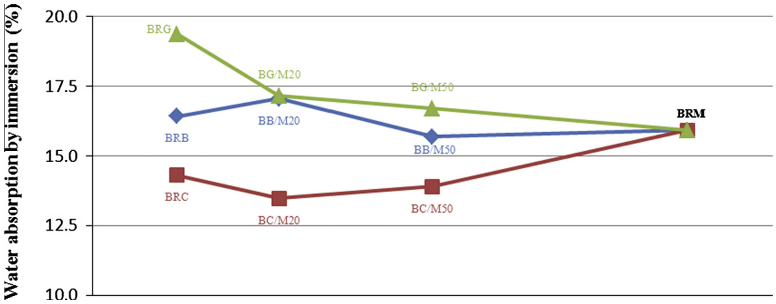

Fig. 4. Water absorption by immersion at 28 days.

Table 8
Carbonation depth.

	Carbonation depth (mm)			
	7 Days	28 Days	56 Days	91 Days
Reference basalt concrete	2.15	4.6	7.91	10.25
Basalt concrete with 20% aggregate replacement	2.37	5.13	8.02	10.73
Basalt concrete with 50% aggregate replacement	1.97	5.41	7.68	10.94
Concrete with 100% aggregate replacement	2.28	5.53	9.09	11.02
Reference river sand concrete	2.13	4.08	5.9	7.52
River sand concrete with 20% aggregate replacement	2.57	4.35	6.59	8.08
River sand concrete with 50% aggregate replacement	2.55	5.61	6.71	10.19
Reference granite concrete	3.96	8.44	12.02	15.21
Granite concrete with 20% aggregate replacement	3.61	7.17	9.87	12.78
Granite concrete with 50% aggregate replacement	3.52	6.91	9.33	12.08

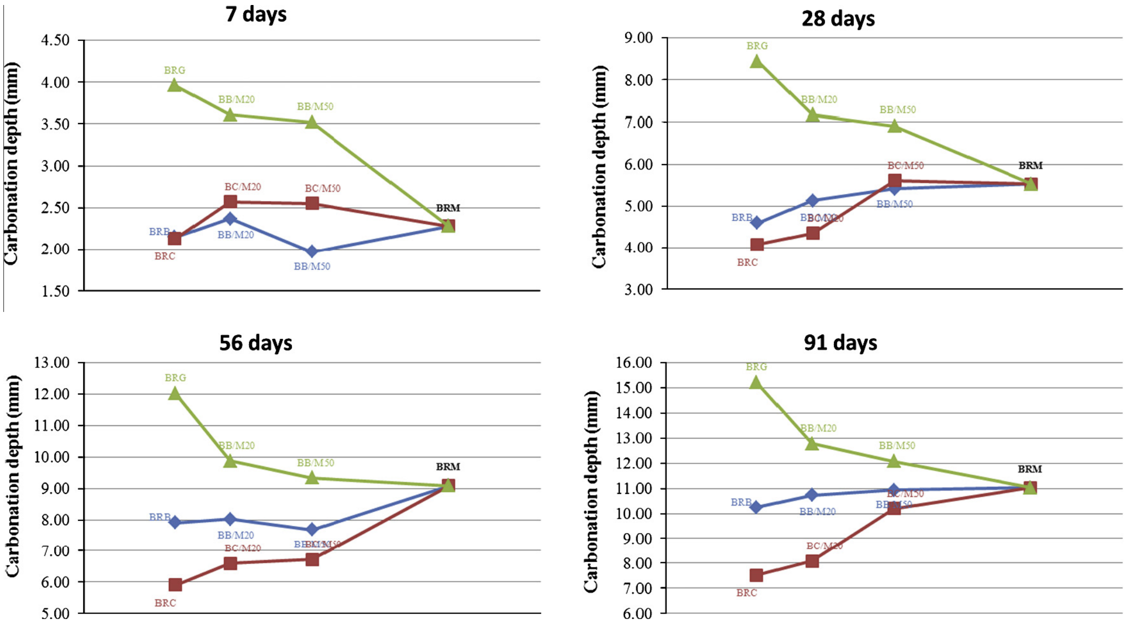

Fig. 5. Carbonation depths in concrete mixes at various ages.

Table 9
Chloride migration.

	Chloride migration coefficient at 28 days ($\times 10^{-12}$ m^2/s)	Chloride migration coefficient at 91 days ($\times 10^{-12}$ m^2/s)
Reference basalt concrete	15.4	15.67
Basalt concrete with 20% aggregate replacement	17.62	16.71
Basalt concrete with 50% aggregate replacement	16.02	13.73
Concrete with 100% aggregate replacement	13.99	13.36
Reference river sand concrete	13.82	11.05
River sand concrete with 20% aggregate replacement	13.37	10.98
River sand concrete with 50% aggregate replacement	14.63	13.46
Reference granite concrete	19.92	17.93
Granite concrete with 20% aggregate replacement	16.64	14.97
Granite concrete with 50% aggregate replacement	14.66	13.61

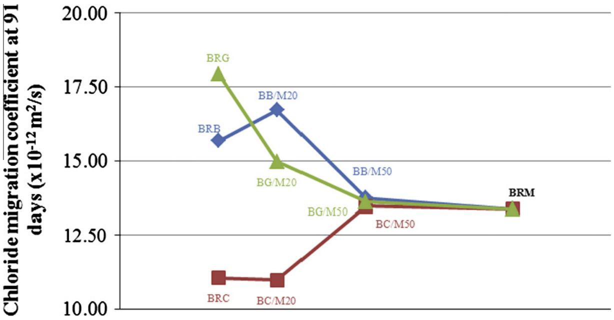

Fig. 6. Chloride migration coefficient at 91 days.

aggregates from the same source, it was found that the concrete's carbonation depth depends on its porosity. This aspect is indirectly controlled in the water absorption by immersion test. Another aspect that agrees with this study is the influence of the aggregates size on the durability of concrete exposed to carbonation. Since the physical and geometrical characteristics of the aggregates strongly affect the packing of the mix and its porous structure; fine aggregates have a greater influence on this phenomenon than coarse aggregates. Basheer et al. [4] note that carbonation resistance depends on gas permeability, which was not measured in this experimental programme.

4.3.4. Chloride penetration

According to Table 9 and Fig. 6 the chloride migration coefficient follows the same trend as the carbonation depth and water absorption by immersion. The results are highly conditioned by porosity of the concrete. Thus, a slight increase in the migration coefficient is observed at 28 days for small replacements of basalt sand by marble sand, followed by a 25.9% fall for the 100% replacement ratio. A more pronounced drop in the migration coefficient (29.8%) is observed for the granite concrete specimens. However, it was noticed that for the river sand concrete specimens the migration coefficient tends to increase. At 91 days the trends found at 28 days are the same. Only small variations in the concrete chloride migration coefficient were registered. Similar findings were reported by Gesoğlu and Güneyisi [16] and Bravo and de Brito [7].

Comparison with André et al.'s [3] results shows that the replacement of fine primary aggregates by fine secondary marble aggregates instead of coarse aggregates has less influence on concrete's resistance to chloride penetration. This is due to the low

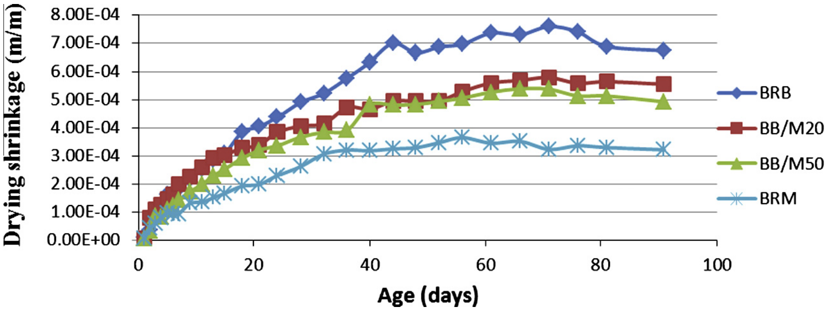

Fig. 7. Drying shrinkage of concrete mixes with basalt fine aggregates.

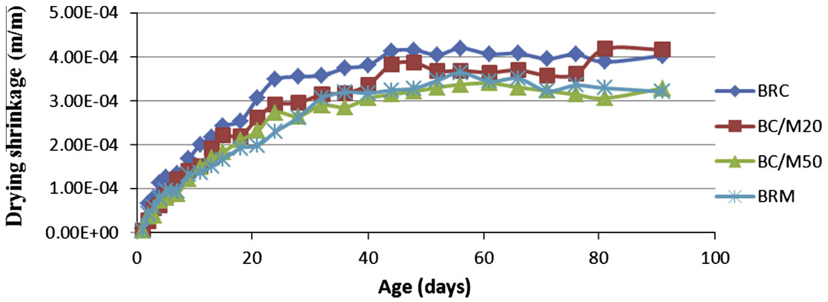

Fig. 8. Drying shrinkage of concrete mixes with river sand fine aggregates.

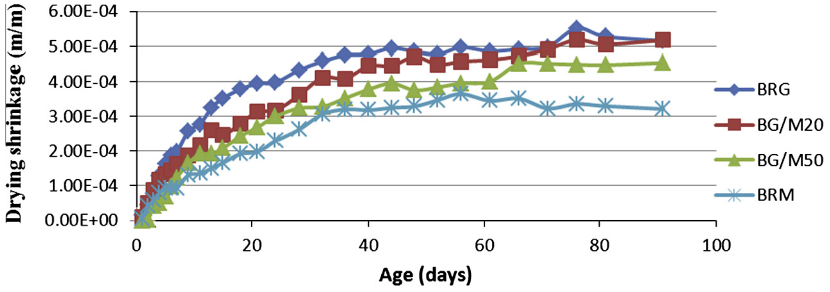

Fig. 9. Drying shrinkage of concrete mixes with granite fine aggregates.

percentage of alumina Al_2O_3, in the marble aggregates. The presence of this oxide favours the formation of tricalcium aluminate, C_3A, which fixes the chloride ions and forms insoluble compounds. Therefore, with the reduction of free ions in concrete less chloride penetration occurs and so lower diffusion coefficients are obtained. This conclusion was also reached by Missau [29], Nayak et al. [30] and Uysal et al. [46]. But because the fine aggregates represent a smaller volume in the concrete mix their influence on chloride migration is less relevant. Therefore, in this case the chloride migration is mostly conditioned by the porous structure created in the curing process rather than by the alumina content, as in the replacement of coarse aggregates.

4.3.5. Drying shrinkage

Figs. 7–9 show the results of the drying shrinkage test of the mixes produced. The drying shrinkage is lower when fine primary aggregates are replaced by fine secondary marble aggregates. Taking into account the marble particles' geometric characteristics, this is essentially because the mixes produced had better compactness and less cement paste in the interstices between the particles, which improved the concrete's porous structure. Owing to this greater difficulty in releasing water by evaporation, that water remains in contact with the cement particles for longer, and improves their hydration. Lower stresses caused by sudden evaporation are thus generated within the pores.

Analysis of the results shows that the concrete specimens where aggregate replacement had the most influence were basalt and granite. Moreover, the physical similarity of the river sand concrete specimens' aggregates with marble means that the variation in that specimens was less pronounced. These experimental results are in accordance with the conclusions of Troxell et al. [45] in terms of the types of primary aggregates, i.e. shrinkage is higher in the basalt concrete specimens, it is intermediate in the concrete with granite sand, and the lowest in the mixes with river sand.

5. Conclusions

The aim of this study was to evaluate the durability performance of structural concrete containing fine marble waste aggregates from marble quarrying. After the experiments, the following conclusions were drawn:

1. The workability of fresh concrete tends to decrease as the replacement ratio increases (0%, 20%, 50% and 100%), except for the river sand specimens.
2. Concrete density is directly proportional to the density of the aggregates and packing ability; density variations proved to be almost imperceptible with a maximum of 1.3%.
3. In terms of water absorption by capillary action, the incorporation of marble aggregates proved to be positive, especially at a replacement ratio of 20%.
4. Regarding water absorption by immersion, it can be concluded that incorporating marble improved the permeability of the granite and basalt concrete specimens, which is beneficial for durability.
5. Concerning carbonation resistance, granite sand mixes improved with the incorporation of marble sand whereas river sand concrete mixes did not; basalt sand concrete mixes had imperceptible changes in terms of carbonation resistance; the changes in this property were mainly caused by variations in concrete permeability.
6. There is a solid relationship between the chloride penetration results and the rates of water absorption by immersion; the chloride migration coefficient decreased in the granite and basalt concrete mixes as the fine marble waste aggregates replacement ratio increased, but it did not do so in the river sand concrete mixes.
7. The effect of marble sand on all mixes' drying shrinkage proved to be beneficial because compactness improved and internal stresses decreased; drying shrinkage was more pronounced in the first 20 days.

In light of the analysis, the general conclusion of this study is that the incorporation of fine marble waste aggregates was beneficial to some durability-related characteristics. Furthermore, it was found when the use of marble fines adversely affected properties this did not compromise the intended durability properties of sound structural concrete. Nevertheless, further evaluation of this solution are recommended with tighter ranges of replacement ratios, especially between the range 50–100% of replacement of primary fine aggregates by secondary marble fine aggregates in order to assess the general behaviour of these concrete and to guarantee the good performance within its usage. Therefore, under normal circumstances, these aggregates can be used in concrete production, from a durability performance point of view, and they compare very favourably with the majority of recycled aggregates that are currently being incorporated in concrete [10,17,13,2,7,43,8].

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