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Durability performance of concrete incorporating coarse aggregates from marble industry waste

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A B S T R A C T

The quarrying of marble, a well-known ornamental stone, has a substantial positive impact on Portugal's economy, but it also generates large environmental impacts. The amount of waste produced during quarrying can be as much as 80% of all stone/soil extracted. That waste is then dumped near the quarry, where it accumulates indiscriminately because a viable alternative for its disposal has not yet been found. In this context, solutions must be found that can transform this waste into a by-product and restore some of its economic value.

The main goal of this study was to evaluate the influence of the replacement of primary aggregates (PA) with marble aggregates. No additions or admixtures were used, as those could change the fresh or hardened properties of the resulting concrete and disguise the influence of the replacement under study. This evaluation required the production of three concrete families. The conventional primary aggregates (PA; basalt, granite and limestone) were replaced in the three families by coarse marble aggregates (CMA) at ratios of 20%, 50% and 100% of the total volume of aggregates. These mixes were tested in the concrete's fresh state for workability and density and in its hardened state for compressive strength, water absorption by capillarity and immersion, carbonation and chloride penetration. The results indicate that there are no significant differences between a concrete produced using CMA and one made with PA in terms of durability, making the use of this waste as concrete aggregate perfectly feasible.

The mechanical properties of the concrete made with CMA were assessed in the scope of concurrent work also performed at the Instituto Superior Técnico (Lisbon, Portugal).

1. Introduction

The stone industry is of major importance to the Portuguese economy and to that of the world. However, by its very nature, this industry frequently has significant environmental impacts. Advances in the exploitation of quarries have led to the extraction of blocks containing more impurities and of worse quality, which lowers the productivity of ornamental stone. The waste produced during the extraction process can amount to as much as 80% of the total volume of stone extracted (Hebhoub et al., 2011). Bulkier waste is disposed of at sites located far from the excavation front, contributing to the degradation of the environment and the natural landscape by occupying the land indiscriminately.

The construction industry can use marble waste for purposes other than as ornamental stone. Marble dust (also called sludge, an agglomeration of water and very fine particles produced by cutting the stone) is the most widely studied alternative, primarily because it is quite versatile. According to Saboya et al. (2007), marble dust can enhance the properties of ceramic bricks. Aruntas et al. (2010) studied the effects of adding marble dust to cement, whereas Ergün (2011) evaluated the effect of replacing cement with diatomite and marble dust on the mechanical properties of concrete. Marble dust can also be used as filler for road construction and asphalt mixes (Karasahin and Terz1, 2005). Binici et al. (2007) showed that using up to 15% marble dust as an additive may result in more durable concrete. It is also possible to improve all of the properties of a self-consolidating concrete by adding 200 kg/m^3 of marble dust, as shown by Topçu et al. (2009). Finally, Corinaldesi et al. (2010) reported that when 10% of sand is replaced with marble dust and

Abbreviations: PA, Primary aggregates; CMA, Coarse marble aggregates; RC, Reference concrete; BRC, Basalt reference concrete; GRC, Granite reference concrete; LRC, Limestone reference concrete; MRC, Marble reference concrete; BCA, Basalt coarse aggregates; GCA, Granite coarse aggregates; LCA, Limestone coarse aggregates.

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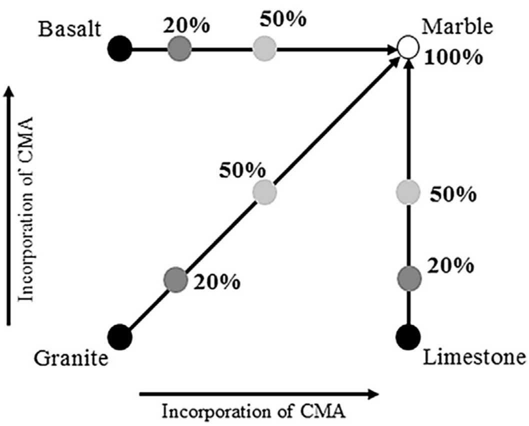

Fig. 1. Experimental concrete mixes.

superplasticizers are used, the compressive strength of mortar is maximized but the level of workability is unchanged.

Despite the successful use of marble dust, there is little information on the potential use of larger marble waste as a coarse aggregate, especially with respect to its effect on concrete durability. However, Akbulut and Gurer (2007) explored this potential and concluded that CMA can be used in binder layers of asphalt pavements bearing low to medium traffic volume. Moreover, Gencel et al. (2012) determined that concrete pavement blocks made with CMA are of adequate quality. Concerning the use of CMA in concrete, Hebhoub et al. (2011) studied the effect of the replacement of conventional aggregates with several ratios of fine, coarse and fine and coarse marble waste on concrete. The results obtained revealed that for incorporation ratios up to 75%, the use of CMA is beneficial for concrete strength. Furthermore, Binici et al. (2008) showed that CMA significantly increases resistance to chloride penetration, and Pereira et al. (2009) found that the durability of class C30/37 concrete is not affected by the aggregate's mineralogy. Overall, marble aggregates can be used to enhance the mechanical properties and chemical resistance of concrete mixes.

2. Experimental program

2.1. Concrete mix design

The 10 concrete mixes used are depicted in Fig. 1: three reference concrete (RC) mixes with 100% basalt (BRC), granite (GRC) or limestone (LRC) coarse aggregates; six concrete mixes obtained by replacing each of the primary aggregates (PA) used in the reference concretes with marble coarse aggregates (CMA) at ratios of 20% or 50% of the total volume; and finally, a concrete with 100% CMA (MRC). To create a set of concrete families that were usable for a significant number of current structural applications, it was guaranteed that the concrete produced met the requirements specified in NP EN 206-1 (2005) for a given class of environmental exposure. Therefore, the concrete produced complied with the characteristics described in Tables 1 and 2.

All of the mixes had a slump range of 115 ± 10 mm, which is lower than the standard set. The three reference concretes were designed using Faury reference curves.

2.2. Testing

The characterization tests of the aggregates and the fresh and hardened concrete were conducted according to the following standards and specifications:

Table 1
Compositions of reference mixes (per m^3).

	Sieve (mm)	BRC	LRC	GRC	MRC
		Mass (kg/m^3)	Mass (kg/m^3)	Mass (kg/m^3)	Mass (kg/m^3)
Coarse aggregates	16–22.4	366.4	324.9	337.5	331.5
	11.2–16	362.4	321.3	333.8	327.9
	8–11.2	140.6	124.6	129.5	127.2
	5.6–8	139.0	123.3	128.0	125.8
	4–5.6	122.4	108.5	112.7	110.7
Fine aggregates	Coarse sand	650.7	650.7	650.7	619.1
	Fine sand	183.5	183.5	183.5	174.6
CEM II A-L 42.5 R (kg/m^3)		350.0			
Water (kg/m^3)		189.0			
w/c		0.55			

- NP EN 933-1 (2000), Grading size analysis;
- NP EN 933-4 (2002), Shape index;
- NP EN 1097-3 (2002), Loose bulk density and voids;
- NP EN 1097-6 (2003), Particle density and water absorption;
- LNEC E 237 (1971), "Los Angeles" abrasion test;
- NP EN 12350-2 (2009), Slump test with Abrams cone;
- NP EN 12350-6 (2009), Density;
- NP EN 12350-3 (2009), Compressive strength, 4 specimens/test;
- LNEC E 391 (1993), Carbonation resistance, 3 specimens/test (7, 28, 56 days);
- LNEC E 393 (1993), Absorption by capillarity, 4 specimens/test;
- LNEC E 394 (1993), Absorption by immersion, 4 specimens/test;
- LNEC E 463 (2004), Chloride penetration resistance, 3 specimens/test (7, 28, 56 days).

3. Experimental results and discussion

3.1. Aggregate properties

Table 3 summarizes the experimental results of the tests performed to characterize the aggregates.

3.1.1. Particle density and bulk density

Particle density depends on the source rock, and it obviously varies according to the mineralogical composition of each material. Basalt has the highest particle density because of its rich content of iron-magnesium minerals, such as pyroxenes and olivine, according to Rutley (1916). Although its origin is similar to that of basalt, granite is composed of feldspar minerals that have a lower percentage of heavy elements than of iron-magnesium minerals. Therefore, the particle density of granite is lower than that of basalt. The limestone formation process produces rocks with the worst characteristics in terms of particle density. Limestone results when a deposition of inorganic sediments is combined with some organic material and solidified by compression, creating less dense and more porous rocks. It is thus expected that limestone will have the lowest particle density. Marble's particle density values are within the range obtained by the authors who have studied this material (Hebhoub et al. (2011), Pereira et al. (2009) and Binici et al. (2008)) and are similar to those of the PA.

Basalt has the highest bulk density, followed by limestone, marble and granite, contrary to the results obtained for particle density. Taking the void content of limestone, given in Table 3, this result was expected, meaning that limestone aggregates have a better spatial arrangement of particles than the others.

3.1.2. Water absorption

CMA has the lowest water absorption of all aggregates tested, followed by the basalt (BCA) and granite (GCA) aggregates due to

Table 2
Mixes with CMA (per m^3).

			BC				LC				GC			
% of marble incorporation			20%		50%		20%		50%		20%		50%	
Sieves (mm)			PA[a]	MA[a]	PA	MA	LA	MA	LA	MA	GA	MA	GA	MA
Aggregates	Coarse	16–22.4	293.1	66.3	183.2	165.8	259.9	66.3	162.4	165.8	270.0	66.3	168.7	165.8
		11.2–16	289.9	65.6	181.2	163.9	257.0	65.6	160.7	163.9	267.0	65.6	166.9	163.9
		8–11.2	112.5	25.4	70.3	63.9	99.7	25.4	62.33	63.9	103.6	25.4	64.7	63.6
		5.6–8	111.2	25.2	69.5	62.9	98.6	25.2	61.66	62.9	102.4	25.2	64.0	62.9
		4–5.6	97.9	22.1	61.2	55.4	86.8	22.1	54.2	55.44	90.2	22.1	56.3	55.4
	Fine	Coarse sand	619.1	–	619.1	–	619.1	–	619.1	–	619.1	–	619.1	–
		Fine sand	174.6	–	174.6	–	174.6	–	174.6	–	174.6	–	174.6	–
CEM II A-L 42.5 R (kg/m^3)			350.0											
Water (kg/m^3)			189.0											
w/c			0.55											

[a] PA – Primary aggregates; MA – Marble aggregates.

Table 3
Aggregate properties (average value and standard deviation).

	Particle dry density (kg/m^3)		Particle saturated surface-dried density (kg/m^3)		Loose bulk density (kg/m^3)		Void content (%)		Water absorption (%)		Los Angeles coefficient (%)		Shape index (%)	
	$\bar{x}$	σ	$\bar{x}$	Σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	Σ	$\bar{x}$	σ
Fine sand	2576	–	2584	–	1500	–	41.8	–	0.091	–	–	–	–	–
Coarse sand	2621	–	2625	–	1543	–	41.1	–	0.048	–	–	–	–	–
BCA	2953	22.2	2976	20.5	1475	48.5	50.0	1.4	0.782	0.2	11.8	2.8	23.4	5.3
LCA	2641	9.6	2671	13.2	1430	7.4	45.9	0.2	1.149	0.1	32.3	1.77	16.2	3.0
GCA	2705	48.3	2734	33.9	1350	30.3	50.1	2.0	1.077	0.6	24.7	3.9	37.7	11.8
CMA	2687	22.5	2705	17.5	1352	33.8	49.7	1.0	0.662	0.2	38.8	0.4	30.1	1.4

the dense matrix of their source rocks, and finally the limestone (LCA) aggregates. Most of the results are below the means reported by the authors cited, as shown in Table 4. Because these figures are relatively low, this property was considered unnecessary for the determination of the effective *w/c* ratio.

3.1.3. Los Angeles coefficient

The Los Angeles coefficient of the CMA is high, 38.8%, but still lower than 50%, which is the maximum recommended for incorporation in structural concrete. BCA is the least susceptible to wear with a coefficient of 11.8%, followed by GCA with 24.7%, indicating that the mineralogical composition is relevant to this property. As such, it is expected that the mass loss of LCA (32.3%) will be considerably higher than that of BCA and GCA as well as that of the CMA because of LCA's richer content of fragile minerals that are sensitive to mechanical actions. These results are summarized in Table 3.

3.1.4. Shape index

CMA's shape index demonstrates that most of its particles are both elongated and angular. These two characteristics may lead to a concrete with a poorer performance in terms of its mechanical and durability properties.

Table 3 shows that, except for LCA, the aggregates' shape indexes are higher than 20%. This may cause workability issues for fresh concrete because angular particles lead to a larger internal friction angle and to a worse spatial arrangement. Additionally, the hardened concrete may be more porous and consequently less durable. The 20% figure is the maximum recommended limit for recycled aggregates incorporated in concrete with a class strength of C20/25 or higher, according to the *Technical guideline for recycled aggregate concrete in Hungary*.

It is important to note that the crushing process may influence an aggregate's shape. Crushing may lead to rounder shapes, which will help improve the mechanical and durability performance of the concrete.

Further discussion of the aggregates' properties is available in another paper by the authors Martins et al. (2013).

Table 4
Water absorption (comparison with previous studies).

Authors	Water absorption (%)			
	Basalt	Limestone	Granite	Marble
Binici et al. (2008)	–	2.30	1.50	1.40
Pereira et al. (2009)	1.50	2.80	0.30	0.05
Hebhoub et al. (2011)	–	–	–	0.39
Mean value	1.50	2.55	0.90	0.92
André et al.	0.78	1.15	1.08	0.66

3.2. Fresh concrete properties

3.2.1. Slump

Fig. 2 shows the results of the Abrams cone test for all of the mixes. Note that to ensure the reliability of the comparison between the various properties of the concrete mixes produced, it was established that all of the mixes should have similar workability. Therefore, all results are within the range of 115 ± 10 mm.

Fig. 2 also proves that the workability exhibits no clear trend as PA is replaced by CMA, contrary to what was found by Binici et al. (2008) and Hebhoub et al. (2011) in their studies. The workability of mixes made with GCA is not significantly affected by its replacement with CMA, possibly due to the high shape index of GCA. For mixes made with BCA and GCA, there is an increase in workability

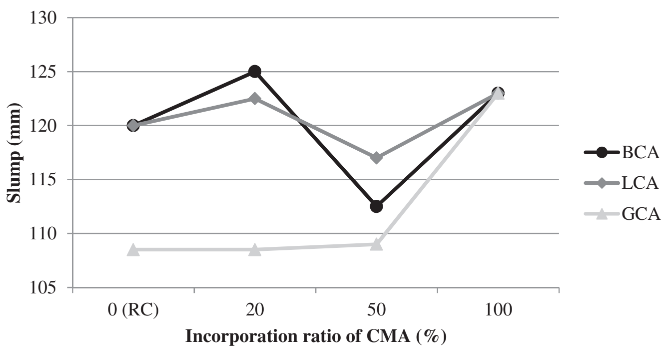

Fig. 2. Slump.

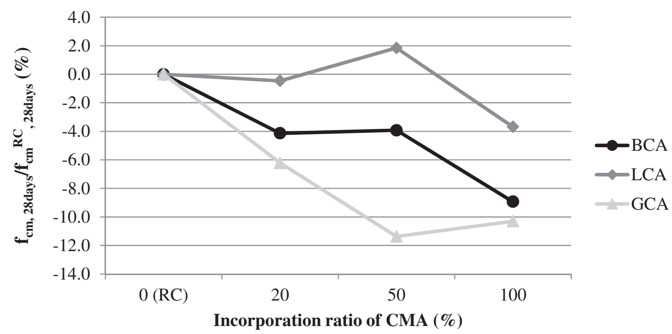

Fig. 4. Compressive strength relative to that of the reference concrete mixes.

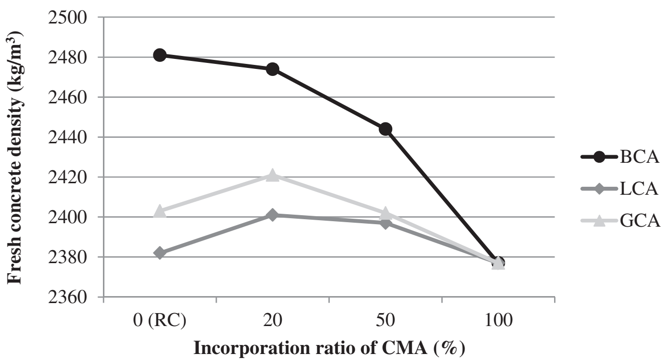

Fig. 3. Fresh concrete density.

for the 20% incorporation ratio, most likely because of the CMA's plain surface and low absorption. However, the results show a loss of workability for the 50% replacement ratio, most likely because the shape index has more influence than the flow increase observed for the 20% replacement ratio.

3.2.2. Density

Fig. 3 presents the density results for the mixes. The results show that the density of the concrete made with BCA decreases with higher incorporation ratios of CMA, but it is still higher than those of the LCA and GCA mixes. This result was expected because the aggregates have similar densities, the concretes were produced with the same workability, and no extra water was needed. The slight increase observed in the 20% replacement ratio mix in the GCA and LCA families may be due to an improved spatial arrangement of the particles provided by the compacted mixes, as observed in the slump test results.

3.3. Hardened concrete properties

3.3.1. Compressive strength

Although concrete durability cannot be directly characterized by compressive strength, that parameter is still frequently used to assess concrete's quality and thus indirectly reveals its durability. As such, the results obtained by Martins et al. (2013) in their concurrent research work were analyzed, and the mean compressive strength at 28 days is presented in Table 5. Although Fig. 4 indicates a general downward trend of the mean compressive strength at 28 days with increasing incorporation ratio, this decrease may be considered almost insignificant with variations up to 10.3% (for the granite concrete mix). Hebhoub et al. (2011) obtained identical results for the difference between the reference concrete and the one produced with 100% marble aggregates. However, the concrete strength improved for the 25%, 50% and 70% incorporation ratios. Binici et al. (2008) concluded that the use of marble and granite improves the flexural and splitting tensile strengths of concrete.

Table 6
Water absorption by immersion (average, standard deviation and difference from the reference mix).

	$\bar{x}$ (%)	σ (%)	Δ (%)		$\bar{x}$ (%)	σ (%)	Δ (%)		$\bar{x}$ (%)	σ (%)	Δ (%)
BRC	13.6	0.3	0	LRC	14.1	0.3	0	GRC	13.8	0.44	0
BC20	14.4	5.8	5.8	LC20	13.8	0.5	−2.3	GC20	13.6	0.2	−1.6
BC50	14.4	5.8	5.8	LC50	13.3	0.3	−5.4	GC50	14.0	0.2	1.9
MRC	14.0	3.0	3.0	MRC	14.0	0.4	−0.8	MRC	14.0	0.4	1.5

3.3.2. Water absorption by immersion

The results from the water absorption by immersion test are presented in Table 6. This property characterizes the open porosity of the cement matrix at 28 days. Open porosity is due to either excess water in the mix that is neither consumed in the cement hydration reactions nor absorbed by the aggregates or to air that is still trapped after the vibration process.

From Fig. 5, it can be concluded that although there is an upward linear trend ($R^2 = 0.93$), the introduction of CMA does not significantly influence water absorption. All mixes exhibited very similar absorption values with variations of between −5.4% and 5.8%. This can be explained both by the weak absorption of the aggregates in the mix and by the (expected) similarity of the concretes' microstructure. These results are in agreement with those obtained by Pereira et al. (2009).

Table 5
Compressive strength at 28 days (average, standard deviation and difference from the reference mix).

	$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)		$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)		$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)
BRC	45.9	0.62	0	LRC	43.4	1.89	0	GRC	46.6	0.34	0
BC20	44.0	0.91	−4.1	LC20	43.2	1.48	−4.1	GC20	43.7	1.24	−4.1
BC50	44.1	0.57	−3.9	LC50	44.2	1.10	−3.9	GC50	41.3	3.81	−3.9
MRC	41.8	1.28	−8.9	MRC	41.8	1.28	−8.9	MRC	41.8	1.28	−8.9

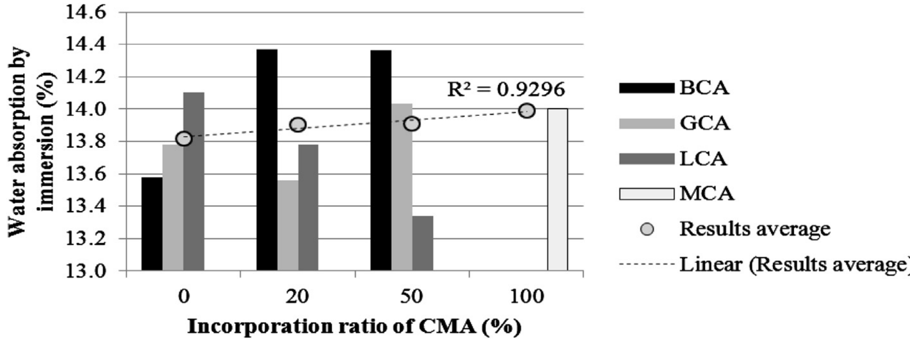

Fig. 5. Water absorption by immersion.

Table 7
Water absorption by capillarity (average, standard deviation and difference from the reference mix).

	Water absorption by capillarity coefficient at 72 h			Water height by capillarity at 72 h		
	$\bar{x}$ (g/mm^2 x 10^{-4})	σ (g/mm^2 x 10^{-4})	Δ (%)	x (mm)	σ (mm)	Δ (%)
BRC	7.2	0.9	0.0	17.4	11.1	0.0
BC20	10.0	0.8	38.9	15.8	13.4	−9.2
BC50	12.1	0.6	68.1	20.5	14.7	17.8
MRC	8.0	0.6	11.1	15.4	9.8	−11.5
LRC	14.2	0.1	0.0	21.3	7.0	0.0
LC20	11.7	0.3	−17.6	12.6	9.2	−40.8
LC50	13.3	0.8	−6.3	19.3	13.2	−9.4
MRC	8.0	0.6	−43.7	15.4	9.8	−27.7
GRC	13.6	0.7	0.0	31.2	16.4	0.0
GC20	9.4	0.1	−30.9	16.3	11.7	−47.8
GC50	11.6	0.7	−14.7	16.0	13.8	−48.7
MRC	8.0	0.6	−41.2	15.4	9.8	−50.6

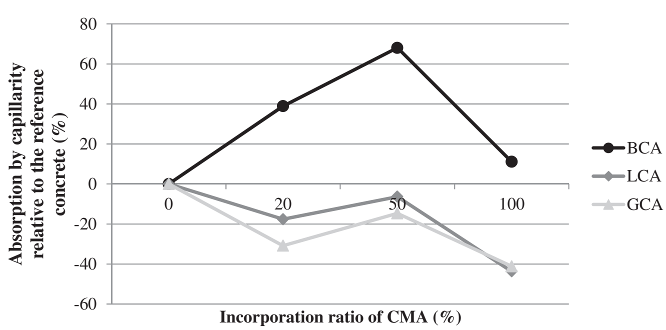

Fig. 6. Absorption by capillarity compared with the reference concrete (%).

3.3.3. Water absorption by capillarity

The results for water absorption by capillarity at 72 h are shown in Table 7, and the comparison with the reference concretes is shown in Fig. 6. They reveal that this property slightly decreases with the addition of CMA for the mixes made with LCA and GCA, with variations of 17.4% and 31% for absorption by capillarity and 40.6% and 48.7% for capillary height, respectively. However, in the case of BCA concrete, such water absorption increases by up to 67.7% (for the 50% replacement ratio) as a result of the poorer adherence between the CMA and the cement paste compared to the BCA, thereby increasing the interface zone pores in which absorption is more severe. According to Pereira et al. (2009), the LCA mix registered the highest capillarity coefficient, followed by the GCA mix. For all mixes, the absorption is more intense in the first hours when the specimen is in contact with water, as shown in Fig. 7.

Ferreira (2000) and Bravo and de Brito (2012) concluded that the capillary height at 72 h varies exponentially with absorption by immersion at 28 days. Fig. 8 demonstrates that, for this experimental campaign, this parameter is insensitive to increased water absorption by immersion. Therefore, there is no statistically significant relationship between them, which contradicts the previous studies.

3.3.4. Carbonation resistance

Table 8 and Fig. 9 show the carbonation depth for all of the concrete mixes.

As expected, carbonation depth is quite similar for the various mixes at any given age. The analysis of water absorption, which is influenced by the same factors, led to a similar conclusion. The variations are quite small; the most significant, 25.1%, occurred for GC50 at 7 days in comparison to its reference concrete. However, at 91 days, the variation was only 11.1%. It is also noted that the carbonation depth increased suddenly in the first days and exhibited a slower rate of increase at 56 and 91 days. Overall, it is inferred that

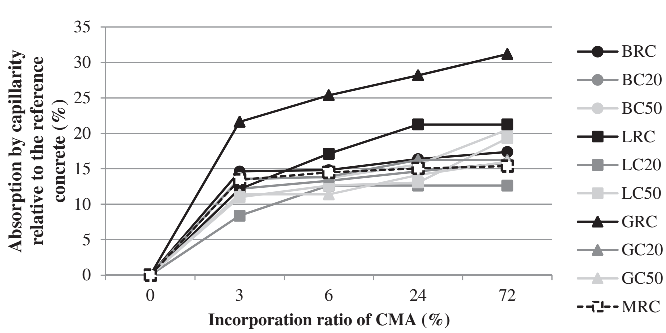

Fig. 7. Water height by capillary action for every mix *versus* Time.

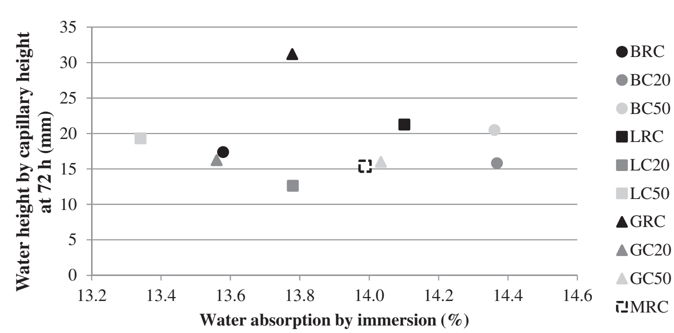

Fig. 8. Water height by capillary action *versus* water absorption by immersion at 72 h.

Table 8
Carbonation depth (average, standard deviation and difference from the reference mix).

Concrete	Carbonation depth (mm)											
	7 days	σ (mm)	Δ (%)	28 days	σ (mm)	Δ (%)	56 days	σ (mm)	Δ (%)	91 days	σ (mm)	Δ (%)
BRC	3.47	0.26	0.0	8.49	0.36	0.0	10.68	0.81	0.0	13.54	0.59	0.0
BC20	3.56	0.21	2.4	7.74	1.10	−8.9	11.79	0.54	10.4	13.36	0.52	−1.3
BC50	3.81	0.70	9.6	8.28	0.27	−2.5	10.06	0.57	−5.8	11.12	0.71	−17.9
LRC	3.99	0.70	0.0	7.83	1.14	0.0	10.32	1.53	0.0	13.06	0.86	0.0
LC20	3.65	0.44	−8.6	7.36	0.91	−6.0	10.81	0.80	4.8	13.24	1.29	1.4
LC50	3.76	0.21	−5.7	7.38	0.66	−5.8	11.45	0.49	11.0	14.47	0.40	10.7
GRC	3.75	0.15	0.0	8.29	0.75	0.0	10.51	0.81	0.0	12.61	0.64	0.0
GC20	3.96	0.31	5.6	8.03	0.57	−3.1	10.22	1.15	−2.8	14.04	0.75	11.3
GC50	4.70	0.77	25.1	9.08	0.36	9.5	12.15	0.50	15.6	14.01	0.37	11.1
MRC	3.69	0.60	−1.6	8.51	0.57	2.7	10.83	0.93	3.0	13.53	1.33	7.3

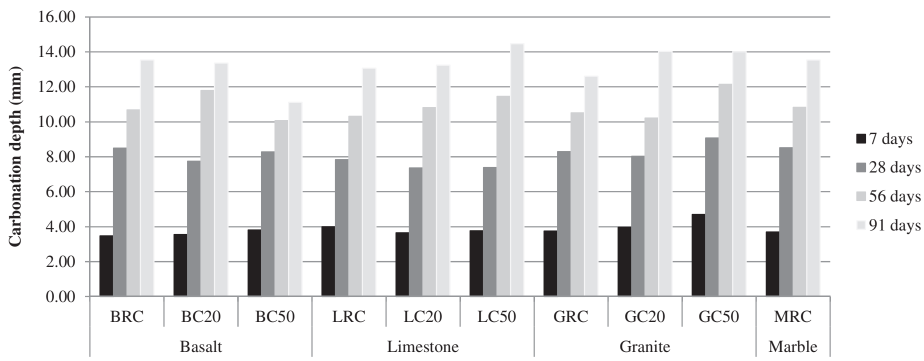

Fig. 9. Carbonation depth.

the incorporation of CMA contributes to the concrete matrix's carbonation-related characteristics exactly as the other PAs do.

De Brito and Alves (2010), de Brito and Robles (2010) and Amorim et al. (2012) also evaluated the relationship between carbonation resistance and the weighted bulk density of the recycled aggregates. Their results and those of our study are summarized in Fig. 10. Contrary to the other campaigns, the carbonation depth in this study decreases as the bulk density increases. This can be explained by the CMA's considerable influence on the basalt family, for which small carbonation depth decreases were recorded with the introduction of CMA.

3.3.5. *Chloride penetration resistance*

The results for chloride penetration at 28 and 91 days are presented in Table 9 and in Fig. 11 (where it is noticeable that some results are missing because of experimental problems that could not be solved). They show that the chloride migration coefficient increases with the replacement ratio of PA with CMA. This increase may be due to the low percentage of alumina (Al_2O_3), approximately 0.64%, present in the CMA. Alumina favors the formation of tricalcium aluminate (C_3A), which fixes the chloride ions. With a low alumina content, the free chloride percentage within the concrete matrix increases and therefore promotes chloride migration and worsens the concrete's performance (Uysal et al., 2012). However, Binici et al. (2008) obtained contrary results. Concrete produced with CMA exhibited a clearly superior chloride penetration resistance compared to concrete with LCA. The CMA chemical analysis performed in their work showed that the CMA alumina content was 21.9%, whereas the LCA alumina content was 2.1%. Apart from the contradictory results, the others corroborate the previous hypothesis that the alumina content undoubtedly influences the chloride penetration depth.

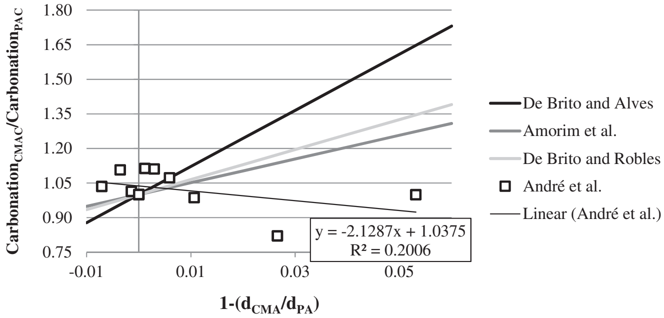

Fig. 10. Concrete carbonation coefficient *versus* weighted bulk density of the aggregates.

Table 9
Chloride migration coefficient (average, standard deviation and difference from the reference mix).

Concrete	Chloride migration coefficient ($\times10^{-12}$ m^2/s)					
	28 days	σ ($\times10^{-12}$ m^2/s)	Δ (%)	91 days	σ ($\times10^{-12}$ m^2/s)	Δ (%)
MRC	–	2.18	–	17.91	2.00	–
BRC	13.51	2.76	0.0	–	1.57	–
BC20	–	0.83	–	–	1.61	–
BC50	15.24	2.34	12.8	–	1.94	–
LRC	17.92	2.54	0.0	14.34	2.45	0.0
LC20	21.49	0.85	19.9	14.86	1.67	3.6
LC50	–	2.69	–	16.27	1.09	13.5
GRC	–	1.29	–	15.21	2.07	0.0
GC20	18.73	1.37	0.0	17.3	1.39	14.3
GC50	20.51	1.72	9.5	19.86	1.42	30.5

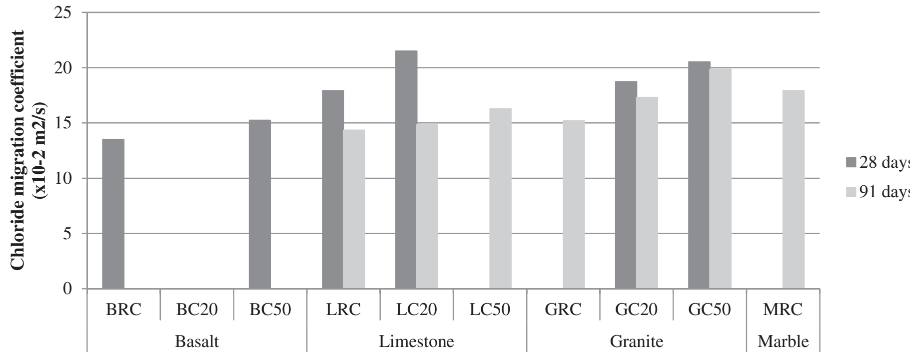

Fig. 11. Chloride migration coefficient at 28 and 91 days.

4. Conclusions

The experimental results allow the following conclusions to be drawn:

- Workability is neither significantly affected (for a constant *w*/*c* ratio) nor does it exhibit a defined trend when CMA is incorporated. Despite this, there is still an increase in workability for the 20% incorporation ratio and a decrease for the 50% ratio for mixes made with BCA and LCA. The workability of mixes made with GCA is unchanged;
- Concrete density reflects the density of each of its components and their packing. Concrete density therefore decreases with the addition of CMA for mixes made with BCA and is approximately constant for concretes made with LCA and GCA;
- Overall, there is a slight loss of compressive strength at 28 days with an increase in the replacement ratio of PA with CMA;
- As for water absorption by immersion, the behavior of concrete made with CMA is similar to that of the reference concretes. This may be due to the low absorption of the aggregates used and the microstructural similarity between the mixes;
- The incorporation of CMA in the mixes made with LCA and GCA results in lower water absorption by capillary action. The opposite trend is observed in the mixes made with BCA. This can be explained by the worse adhesion of the CMA and consequent increase of the interface zone pores, which is where this phenomenon is more severe.
- Concrete made with CMA has a similar carbonation depth to that of the reference concretes, thus supporting the microstructural similarity hypothesis between all the families;
- The incorporation of CMA in the mixes resulted in a significant increase of the chloride migration coefficient. The low alumina percentage of these aggregates may be the primary cause, as this compound promotes the formation of tricalcium aluminate, which favors the fixation of the chloride ions.
- In terms of durability, it was shown that CMA produces concrete with similar characteristics to those made with BCA, LCA and GCA, which are typically used in the construction industry. Therefore, the incorporation of CMA in concrete is perfectly feasible. However, great care must be taken in chloride-contaminated environments, where CMA with low alumina content exhibited its worst performance.

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