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Mechanical Performance of Concrete with Incorporation of Coarse Waste from the Marble Industry

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The waste resulting from marble extraction process is usually disposed of in landfills or dumps and its accumulation is causing serious environmental and landscaping problems. One way of reusing marble waste is to consider its incorporation in structural concrete as a non-primary aggregate. This research work attempts to alleviate the situation and provide information on the mechanical performance of concrete as a function of the replacement ratio of primary aggregates (PA) with coarse waste marble aggregates (CMA). Three concrete families, including reference concrete (RC) mixes, were studied that were made with primary aggregates of basalt (BCA), limestone (LCA) and granite (GCA) (these are the main sources of primary aggregates in the southern and central parts of Portugal), and concrete mixes with replacement ratios of 20%, 50% and 100% of PA by CMA. To evaluate their quality and mechanical performance mixes were tested for: slump (in the Abrams cone test), specific density, compressive strength, splitting tensile strength, Young's modulus of elasticity and resistance to abrasion. The results suggest a tendency for the values of all mechanical properties to decline. However, this tendency is clearly weaker than those observed for the majority of the research involving other types of non-primary recycled aggregates, which are already used in certain proportions in structural concrete, according to the limits imposed by the standards and specifications. The mechanical properties of concrete made with CMA were assessed within the scope of concurrent work also undertaken at Instituto Superior Técnico (Lisbon, Portugal), concerning the durability-related materials of the same type of concrete.

Keywords: *marble industry, coarse marble waste aggregates, concrete, incorporation ratio, mechanical performance*

1. Introduction

According to OSNET (Ornamental Stones Network), world stone production increased by 118% between 1986 and 1998 and the growth rate has remained similar since then[1]. In Portugal, one of the most successful extraction activities is the exploitation of industrial and ornamental rocks associated with current construction. Data from[2] revealed that in 2000 the amount of ornamental stone produced (including marble and granite) had reached 939 052 tonnes. This has led to a considerable amount of waste which has a detrimental impact on the environment[3,4]. Moreover, the growth of industrial production and the resulting increase in the consumption of natural resources has led to a fast depletion of available resources being registered.

The use of waste from marble quarries as aggregates can help meet the growing demand and mitigate the negative effects on the environment. Several authors have pointed out these problems and the need to find a viable destination for the waste[5-8]. According to Cetin[9] and Terzi and Karasahin[10], waste aggregates from marble quarries could be used as material for road pavement bitumen. Akbulut and Cahit[7] and Zorluer[8] suggested that marble waste can feed the huge demand for aggregates for use in paving. They single out the sector dedicated to the manufacture of products used in construction as being especially able to incorporate and reuse different types of waste, such as that from the ornamental rocks industry. However, the reuse of marble waste in the production of structural concrete is not yet widespread. To counteract this trend the European Standard EN 12620 specifies the aggregates' properties for their use in concrete, whether they are of natural origin, artificial or recycled.

2. Experimental Programme

2.1. Concrete design

Three concrete families were produced, all with 115±15 mm slump (similar workability) so that their comparison would be accurate and consistent. These concrete families included three RC mixes with PA: basalt, limestone and granite, and other mixes with incorporation ratios of 20%, 50% and 100% of CMA, according to Figure 1 and Tables 1 and 2. The reference mixes' proportion was determined using the Faury method[11].

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2.2. Experimental tests

The standards and specifications used to characterize the aggregates and the mechanical properties of fresh and hardened concrete were:

- Grading size analysis, according to NP EN 933-1;
- Particle density and water absorption, according to NP EN 1097-6;
- Loose bulk density and voids, according to NP EN 1097-3;
- Los Angeles abrasion test, according to LNEC E237;
- Shape index, according to NP EN 933-4;
- Slump (Abrams cone), according to NP EN 12350-2;
- Density, according to NP EN 12350-6;
- Compressive strength at 7, 28 and 56 days (3 specimens), according to NP EN 12390-3;
- Splitting tensile strength at 28 days (3 specimens), according to NP EN 12390-6;
- Modulus of elasticity at 28 days (2 specimens) , according to LNEC E397;
- Abrasion resistance (6 specimens), according to DIN 52108.

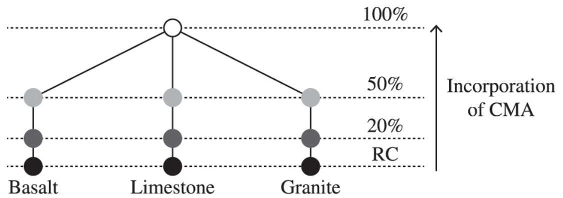

Figure 1. Concrete mixes families.

3. Results and Discussion

3.1. Properties of the aggregates

Concrete performance is highly dependent on the characteristics of the aggregates. Their shape, particle size, and chemical composition influence the concrete mechanical and durability properties.

Table 3 summarizes the results obtained for the properties of the aggregates, which have been analysed in more detail by André et al.[12], in parallel research work using the same materials and concrete mixes but focused on the durability-related properties.

3.2. Properties of fresh concrete

3.2.1. Slump

The results are within the range 115±15 mm, corresponding to an S3 consistency class (100 to 150 mm). The w/c ratio was the same for all mixes, at 0.55.

Table 1. RC composition (per m^3).

Sieve (mm)	BRC*	LRC*	GRC*	MRC*
	Mass (kg/m^3)			
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
Coarse sand (1-4)	650.7	650.7	650.7	619.1
Fine sand (<1)	183.5	183.5	183.5	174.6
CEM II A-L 42.5 R (kg/m^3)	350			
Water	189			
w/c	0.55			

*BRC - Basalt reference concrete; LRC - Limestone reference concrete; GRC - Granite reference concrete; MRC - Marble reference concrete.

Table 2. Composition of CMA mixes (per m^3).

% of marble incorporation	20%						50%					
Sieves (mm)	BA*	MA*	LA*	MA	GA*	MA	BA	MA	LA	MA	GA	MA
16-22.4	293.1	66.3	259.9	66.3	270.0	66.3	183.2	165.8	162.4	165.8	168.7	165.8
11.2-16	289.9	65.6	257.0	65.6	267.0	65.6	181.2	163.9	160.7	163.9	166.9	163.9
8-11.2	112.5	25.4	99.7	25.4	103.6	25.4	70.3	63.9	62.33	63.9	64.7	63.6
5.6-8	111.2	25.2	98.6	25.2	102.4	25.2	69.5	62.9	61.66	62.9	64.0	62.9
4-5.6	97.9	22.1	86.8	22.1	90.2	22.1	61.2	55.4	54.2	55.44	56.3	55.4
Coarse sand (1-4)	619.1	-	619.1	-	619.1	-	619.1	-	619.1	-	619.1	-
Fine sand (<1)	174.6	-	174.6	-	174.6	-	174.6	-	174.6	-	174.6	-
CEM II A-L 42.5 R (kg/m^3)	350											
Water	189											
w/c	0.55											

*BA - Basalt aggregates; LA - Limestone aggregates; GA - Granite aggregates; MA - Marble aggregates.

Table 3. Aggregates' properties (average and standard deviation).

	Fine sand		Coarse sand		BCA		LCA		GCA		CMA	
		σ		σ		σ		σ		σ		σ
Particle dry density (kg/m³)	2576	-	2621	-	2953	22.2	2641	9.6	2705	48.3	2687	22.5
Particle saturated surface-dried density (kg/m³)	2584	-	2625	-	2976	20.5	267	3.2	2734	33.9	2705	17.5
Loose bulk density (kg/m³)	1500	-	1543	-	1475	48.5	1430	7.4	1350	30.3	1352	33.8
Voids content (%)	41.8	-	41.1	-	50.0	1.4	45.9	0.2	50.1	2.0	49.7	1.0
Water absorption (%)	0.091	-	0.048	-	0.782	0.2	1.149	0.1	1.077	0.6	0.662	0.2
Los Angeles coefficient (%)	-	-	-	-	11.8	2.8	32.3	1.7	24.7	3.9	38.8	0.4
Shape index (%)	-	-	-	-	23.4	5.3	16.2	3.0	37.7	11.8	30.1	1.4

Figure 2 shows that the granite family had the lowest slump values. This may be related to the aggregates' higher shape index, which shows a large proportion of non-cubic particles. That irregular, elongated shape makes it difficult for the particles to slide past each other. Because CMA have a lower shape index than GCA, it is expected that their introduction in the GCA mix will help to increase the workability. This behaviour was different for the basalt and limestone families (Figure 2).

Hebhoub et al.[5] state that some of the factors that influence workability of this type of concrete are the size grading and shape of fine aggregates, the coarse/fine aggregates ratio and the materials' characteristics. However, the authors point out that the critical parameter is water absorption of the aggregates. In fact, the use of recycled aggregates to produce concrete normally requires special attention on this property, because the incorporation of different types and contents of aggregates (PA and marble) makes it difficult to control whether the aggregates are in a saturated dry surface state or not. For this study, the water compensation method was used[13], which, according to Gomes et al.[14], is the most adequate procedure to avoid the excess/insufficiency of free water in the mix. Because marble aggregates have the lowest water absorption value, it is expected that their incorporation in the mix will contribute to an increase in the slump results, which is consistent with the results shown in Figure 2.

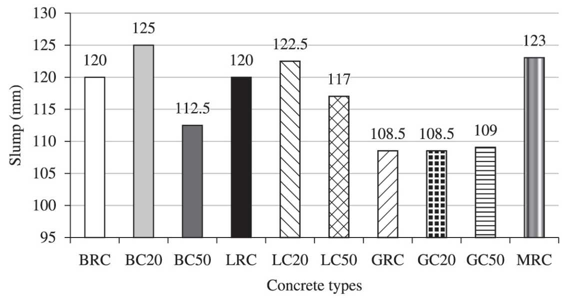

Figure 2. Slump.

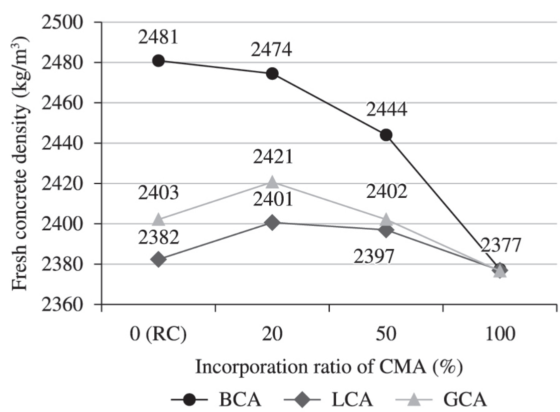

Figure 3. Concrete density.

3.2.2. Density

The concrete fresh density results are related to its compacity and, consequently, to its porosity in the hardened state.

Because basalt has a higher density than marble aggregates, increasing the incorporation ratio of marble aggregates will contribute to a loss of concrete density, whilst for granite and limestone that decrease is only relevant when the incorporation ratio is 100%, as seen in Figure 3. Compared with RC, the increase for the incorporation ratio of 20% for limestone and granite, and for 50% for limestone, may be due to a positive arrangement of the particles, when there are different aggregates, with different shape indexes in the same mix. This spatial arrangement may be responsible for increased compacity and, subsequently, higher density.

3.3. Properties of hardened concrete

3.3.1. Compressive strength

Table 4 shows the results for compressive strength. The highest strength loss was 10.3% for the granite family at 28 days with 100% incorporation ratio and 11.4% for the same family with 50% incorporation ratio; for the other mixes the loss was always less than 10%.

Comparing our results with those reported by Binici et al.[6], in general the results are quite similar, except for the limestone reference concrete which showed a considerably lower result. According to Binici et al.[6], it is favourable, from a mechanical point of view, to replace limestone with marble. This may be because the limestone used in that research was weaker rather than being related to the marble properties themselves, as suggested by the results in Figure 4. There is a clear trend showing that the mixes' performance worsens when the replacement ratio of limestone, granite or basalt with marble aggregates increases.

Some researchers[15-17] support the idea that there is a linear relationship between compressive strength and the incorporation ratio of RA. However, marble aggregates cannot be fully regarded as 'recycled aggregates', as they are derived from the ornamental rock industry's waste. There are so few studies on CMA concrete, not to mention the non-conclusive studies by Binici et al.[6] and Hebhoub et al.[5], that the relationship between compressive strength and the incorporation ratio of CMA in concrete is not yet known. In a first attempt to fill that gap, a linear relationship hypothesis was considered and discussed in this study. Linear regression formulas and their corresponding correlation coefficients can be found in Figures 5 to 7, for mixes with limestone, granite and basalt as PA, at 7, 28 and 56 days.

The existence of a linear relationship is not clear. The closest result to a linear relationship is that for the granite family at 7 days. Only in this case can the compressive strength variation be fully explained by the incorporation ratio, in approximately 92% (the value of R^2). At 28 and 56 days, the correlation coefficient is 80% and 64%, respectively. The results for the limestone and basalt families are lower on average and, in some cases, not significant. In the light of these results it seems plausible that the incorporation of CMA in concrete does not directly affect this property. However, higher correlation values could be achieved in a more detailed analysis, excluding some particular points, and this is the case of basalt for a 20% incorporation ratio at 7 days (R^2 would change from 29% to 100%) and of limestone for 0% incorporation ratio at 56 days (R^2 would change from 29% to 96%). However, it must be pointed out that almost all the results are inside a relatively narrow range.

On the whole, regardless of the type of relationship, a slight decrease can be observed in the compressive strength with the incorporation of CMA for every ratio (20%, 50% and 100%) and at every age (7, 28 and 56 days), which is supported by the negative or close to zero value of the linear regression slope.

A significant loss of compressive strength was registered for every concrete and age for an incorporation ratio of 20%, in relation to RC, except for limestone at 28 and 56 days. Unexpectedly, there was a slight improvement for 50% incorporation ratio for some mixes.

The decrease observed for the 20% incorporation ratio may be partly explained by the effective w/c ratio. Although the gross w/c ratio was kept constant, that does not mean

Table 4. Compressive strength.

	$f_{cm,7}$ (MPa)	σ (MPa)	Δ (%)	$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)	$f_{cm,56}$ (MPa)	σ (MPa)	Δ (%)
BRC	34	1.10	0.0	46	0.62	0.0	51	0.64	0.0
BC20	33	0.20	–5.2	44	0.91	–4.2	49	1.52	–5.0
BC50	34	0.98	–2.3	44	0.57	–3.9	49	0.76	–4.4
MRC	33	1.07	–4.7	42	1.28	–9.0	47	0.98	–7.2
LRC	34	0.89	0.0	43	1.89	0.0	45	0.19	0.0
LC20	34	0.35	–2.1	43	1.48	–0.5	50	0.56	9.3
LC50	34	0.53	–1.1	44	1.10	1.8	49	0.36	8.3
MRC	33	1.07	–4.6	42	1.28	–3.7	47	0.98	4.6
GRC	35	0.61	0.0	47	0.34	0.0	50	0.59	0.0
GC20	34	0.16	–2.9	44	1.24	–6.2	47	1.58	–5.4
GC50	34	0.17	–3.4	41	3.81	–11.4	47	1.64	–6.6
MRC	33	1.07	–6.2	42	1.28	–10.3	47	0.98	–4.9

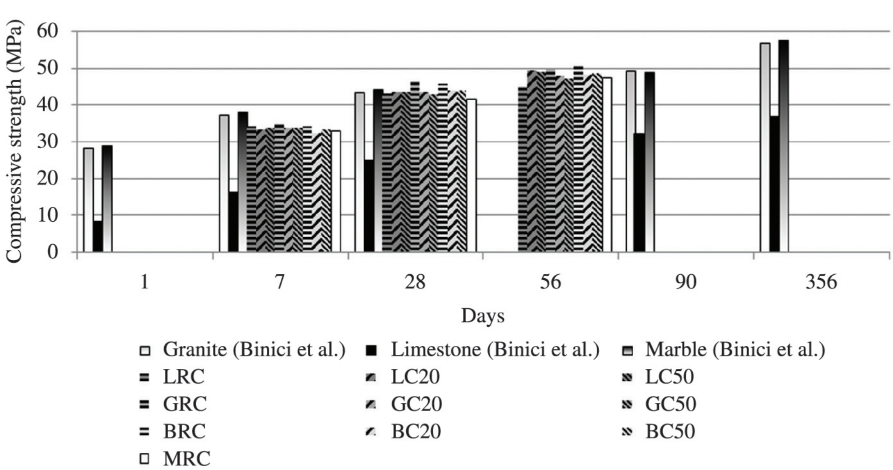

Figure 4. Compressive strength results: Binici et al.[6] vs. present study.

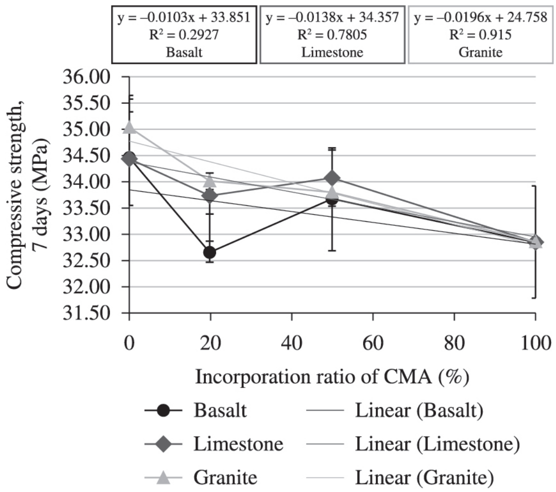

Figure 5. Compressive strength at 7 days.

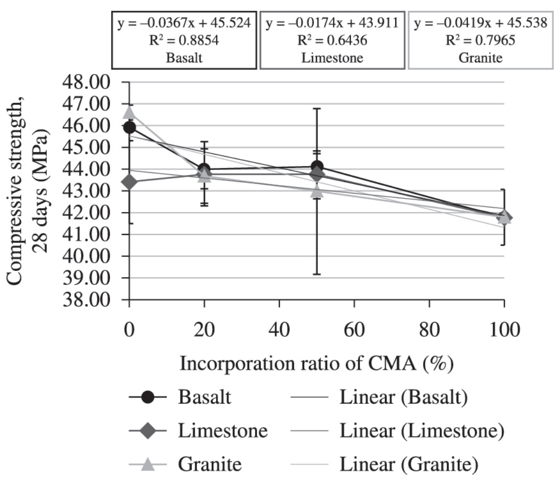

Figure 6. Compressive strength at 28 days.

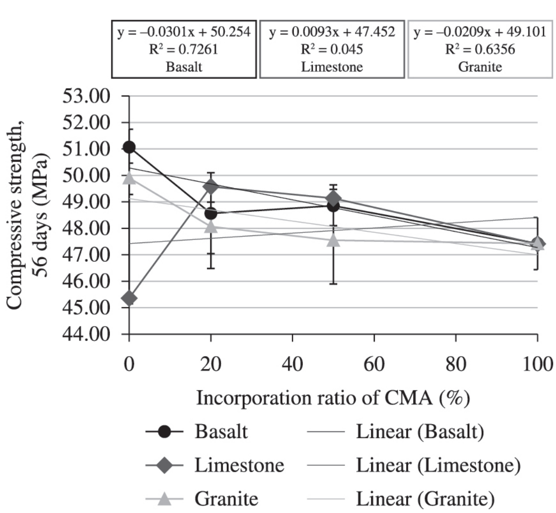

Figure 7. Compressive strength at 56 days.

that the effective w/c ratio was also the same for every mix because the water available for binder hydration can be absorbed in different quantities depending on the type of aggregate. That can also explain why limestone and basalt, for an incorporation ratio of 20%, registered the highest slump values, an indirect measure of the effective w/c ratio, and the lowest compressive strength. A larger amount of water than is strictly necessary for cement hydration can promote workability but may jeopardize the aggregate-binder bond and/or lead to higher porosity, which is translated into lower compressive strength.

3.3.2. Splitting tensile strength

The results in Table 5 and Figure 8 show the influence of the incorporation ratio on the splitting tensile strength at 28 days. The curves have a slightly decreasing trend for this property as the incorporation of CMA increases. These results are in agreement with those obtained in other mechanical properties such as the compressive strength, modulus of elasticity and the abrasion resistance. However, this decreasing trend is not as pronounced as for compressive strength at 28 days. The greatest decrease of about 10.4% occurred for an incorporation ratio of 20% for basalt, as opposed to limestone for a 50% incorporation ratio, which registered a gain of 6.9%. The incorporation ratio of 20% was found to be the worst, with the lowest results for every mix. As with the compressive strength, this may be related to the concrete's workability, effective w/c ratio and excess water, which can lead to higher porosity. Nonetheless, Binici et al.[6] observed an improvement in this property with an incorporation ratio of 100% of CMA. Hebhoub et al.[5], too, who studied the replacement of LCA by CMA, concluded that all mixes exhibited a good performance with increasing incorporation ratio, except for 100%. However the results in this series of experiments suggest a different conclusion, as shown in Figure 9. Because the variation is more moderate, it is suggested that replacing LCA with CMA does not significantly affect the splitting tensile strength.

As reported by Coutinho[18], a plausible explanation for the variations found in Figure 9 is the fact that concrete splitting tensile strength is substantially influenced by the aggregates' tensile strength, as well as by their surface roughness and shape. This means that, although similar materials were used in these studies, it is not possible to control all the differences and variables related to the aggregates that generate the differences found in the results.

3.3.3. Elasticity modulus

The results of the elasticity modulus test are given in Table 6. Figure 10 shows a clear decrease of the elasticity modulus with higher incorporation ratios for the limestone and basalt mixes but not for granite mixes, which do not seem to show any trend with the increase of the incorporation ratio. As expected, the relative decrease in the elasticity modulus in comparison with the corresponding RC follows similar trends to those of compressive strength and splitting tensile strength. The greatest losses were obtained for an incorporation ratio of 100%, with limestone reaching 27.7%, followed by basalt with 26.5%, as shown in Figure 10.

Table 5. Splitting tensile strength.

Incorporation ratio (%)	Basalt			Limestone			Granite		
	$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)	$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)	$f_{cm,28}$ (MPa)	σ (MPa)	Δ (%)
0	3.11	0.15	0.0	3.06	0.69	0.0	3.31	0.26	0.0
20	2.78	0.31	–10.4	2.91	0.14	–5.0	3.06	0.21	–7.5
50	3.30	0.15	6.1	3.27	0.18	6.7	3.18	0.10	–3.9
100	3.07	0.07	–1.0	3.07	0.07	0.4	3.07	0.07	–7.0

Table 6. Elasticity modulus at 28 days.

Incorporation ratio (%)	Basalt			Limestone			Granite		
	$E_{cm,28}$ (GPa)	σ (GPa)	Δ (%)	$E_{cm,28}$ (GPa)	σ (GPa)	Δ (%)	$E_{cm,28}$ (GPa)	σ (GPa)	Δ (%)
0	37.88	0.68	0.0	38.51	1.06	0.0	29.55	1.05	0.0
20	35.81	0.46	–5.5	34.73	1.19	–9.8	29.47	1.29	–0.3
50	33.13	1.02	–12.5	32.76	0.74	–14.9	30.46	0.67	3.1
100	38.51	1.53	–26.5	27.83	1.53	–27.7	27.83	1.53	–5.8

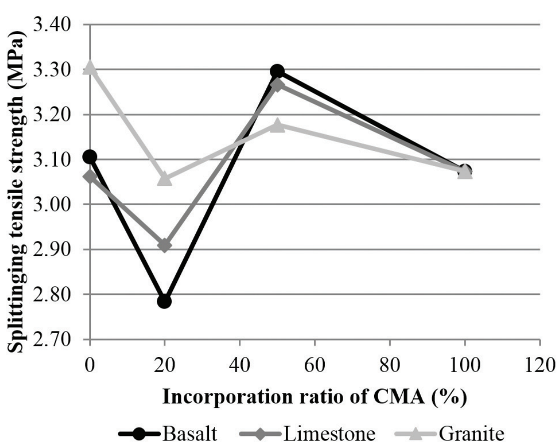

Figure 8. Splitting tensile strength at 28 days.

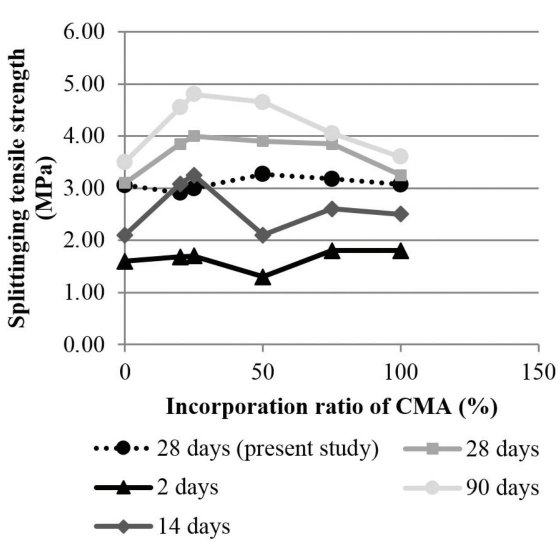

Figure 9. Splitting tensile strength result: Hebhoub et al.[5] vs. present study.

So far no relevant data has been found to support the results obtained, which is encouraging. Because this property is extremely important in the material's characterization and provides valuable information on its performance, further investigation is required.

3.3.4. Abrasion resistance

A reduction in abrasion resistance (higher abrasion loss) as the incorporation ratio increases is clear in Table 7 for all concrete families. This trend is more evident in the granite mix that exhibited the highest percent decrease in comparison to the reference concrete (Figure 11). The highest value, 50.7%, was obtained with the incorporation ratio of 100% for the granite family. For every mix, the substitution ratio of 20% seems to be proportionately more detrimental, similar to what happened with the other mechanical tests, which may be linked to the slump, effective w/c ratio and porosity. Overall, it is reasonable to suggest that wear sensitivity is more significant as the incorporation ratio increases.

It is well known that the results of the Los Angeles test are generally linked to those of the abrasion test. As shown in Table 7, the Los Angeles test results for CMA are higher than those for the primary aggregates. This supports the idea that the introduction of CMA leads to increasing wear loss by abrasion.

Moreover, the significant porous structure of marble leads to a lower aggregate bulk density than is found in the other materials, and results in an increasing loss of resistance.

According to Binici et al.[6], the abrasion results were satisfactory, revealing a lower wear loss with the incorporation of CMA, and this is in line with their previous mechanical results for CMA mixes. However, these results are contrary to ours, as illustrated in Figure 12. The reasons for these discrepancies, already discussed in relation to the previous properties, are still valid. Nevertheless, despite the general trend of the mechanical properties to decrease when CMA are incorporated, this effect is weaker than that registered for the majority of recycled aggregates that are

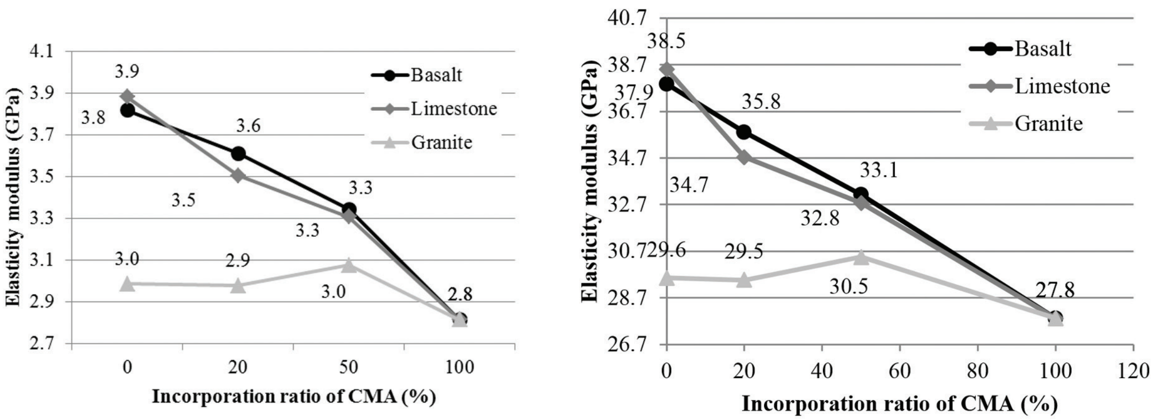

Figure 10. Elasticity modulus at 28 days.

Table 7. Abrasion wear loss.

Incorporation ratio (%)	Basalt			Limestone			Granite		
	Dl (mm)	σ (mm)	Δ (%)	Dl (mm)	σ (mm)	Δ (%)	Dl (mm)	σ (mm)	Δ (%)
0	2.89	0.17	0.0	2.79	0.14	0.0	2.43	0.20	0.0
20	3.16	0.28	9.3	3.07	0.27	10.0	2.81	0.27	15.7
50	3.41	0.29	18.1	3.20	0.22	14.8	3.08	0.08	26.5
100	3.66	0.59	26.8	3.66	0.59	31.3	3.66	0.59	50.7

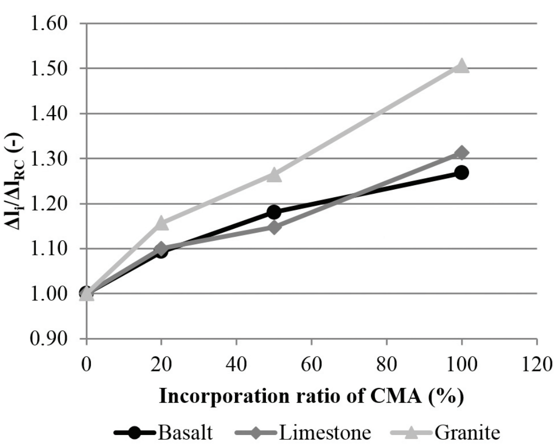

Figure 11. Abrasion wear loss relative to the RC.

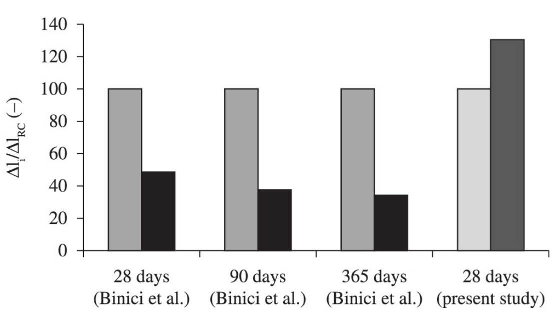

Figure 12. Abrasion wear loss relative to the RC: Binici et al.[6] vs. present study.

being incorporated in concrete mixes[19-24]. Therefore, the results obtained do not in any way inhibit the use of CMA in structural concrete, if suitable and convenient incorporation ratios are used, depending on the purpose intended for the concrete.

4. Conclusions

This work reports the mechanical performance of concrete formulations incorporating CMA in three concrete families (primary aggregates: limestone, granite and basalt). The research enabled the following conclusions to be drawn:

- Compressive strength is moderately affected by the incorporation of CMA: the highest loss relative to the RC was observed for granite mixes (10.3% with 100% incorporation ratio at 28 days and 11.4% with 50% incorporation ratio at 56 days);
- Splitting tensile strength is negligibly or slightly influenced by the incorporation of CMA;
- The decrease in elasticity modulus follows the trend observed for compressive strength. The decrease is more pronounced in the limestone and basalt families (38 GPa to 28 GPa) and substantially lower in the granite family (30 GPa to 28 GPa);
- The loss of abrasion resistance is consistent with the other mechanical properties. The increase in the incorporation ratio leads to lower wear resistance, whose worst results were observed in the granite family (50.7% wear loss);
- The abrasion results are associated with the Los Angeles wear test: marble showed the highest wear loss, corresponding to an expected increase in the abrasion loss as the incorporation ratio increases;

- The incorporation ratio of 20% was found to have the most proportionately detrimental results, for every mechanical property mentioned. This may be related to the concrete workability, effective w/c ratio and excess water, which can lead to higher porosity and so weaken the concrete performance.

The lack of studies on the mechanical properties of marble as recycled aggregates has hindered further conclusions and comparisons, particularly with respect to the elasticity modulus. Despite the general trend for the performance of this type of concrete to deteriorate, the use of recycled marble in structural and non-structural concrete is still feasible if the proportions used are in accordance with the relevant standards and specifications. The high potential of these aggregates should be taken into consideration and be further explored in future research.

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