High quality of mortar with marble waste aggregate

Argamassa de alto desempenho com agregado proveniente do rejeito de mármore

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Abstract

The use of industrial waste has raised great interest regarding its potential of contributing both to the reduction of costs and to sustainable development. In this context, there has been an increasingly high number of studies addressing the use of alternative materials in the construction industry, especially when considering the difficulty in obtaining building materials near urban centers, which results in an increase in the final price due to transportation costs. This research has characterized and evaluated the use of crushed marble waste to replace natural sand in the production of mortar. Many admixtures of mortar were subject to research regarding their physical and mechanical properties. It has been concluded that mortars produced with sand made of crushed marble waste have improved mechanical properties when compared to traditional mortar.

Keywords: Mortar. Marble waste. Sand. Properties. Sustainability.

Resumo

O reaproveitamento de rejeitos industriais desperta grande interesse, pois proporciona a redução dos custos do seu descarte e contribui para o desenvolvimento sustentável. Neste contexto, é notório o crescente número de pesquisas que viabilizam novos empregos para os rejeitos possibilitando o surgimento de materiais alternativos aplicáveis à Indústria da Construção Civil, especialmente quando se considera a dificuldade em obter materiais de construção perto dos centros urbanos, o que resulta em um incremento do preço final devido aos custos de transporte. Este trabalho caracterizou e avaliou a potencialidade do emprego do rejeito de mármore triturado em substituição à areia natural para a produção de argamassas. Diversas misturas foram avaliadas em suas propriedades físicas e mecânicas. Conlcuiu-se que as argamassas fabricadas com a areia proveniente do rejeito de mármore triturado possuem proriedades superiores às tradicionais.

Palavras-chaves: *Argamassa. Rejeito de mármore. Areia. Propriedades. Sustentabilidade.*

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Introduction

The Construction Industry first began to recognize the impact of its activities in the 1990s, due to its strong influence in society and in the economy. This sector, being associated with issues of global sustainable development has, since then, strongly contributed to the establishment of environmental, economic and social sustainable principles (COX *et al.*, 2015).

The consumption of mortar, that reaches approximately 100 million tons a year worldwide, associated with the consumption of its manufacturing materials (cement and aggregate (sand), for example), transportation costs and the environmental damage caused by the use of river sand in mortar. The composition highlight the importance of reusing waste products and materials in order to meet the sustainable development requirements of the 21st century (BARBOSA; SANTOS, 2013; SANTOS, 2011).

Researchers have indicated that the incorporation of waste products in the production of materials can contribute to the reduction of: energy consumption and transport distances, depending on where the waste and its consumer market are located (ISAIA, 2011). Many authors corroborate that the insertion of waste as aggregate can lead to interesting characteristics in terms of strength of the concrete and/or mortar and contribute to sustainable development (KILBERT, 1995; ACCHAR; VIEIRA; HOTIZA, 2006; BINICI *et al.*, 2008; TAM *et al.*, 2009; CORINALDESI; MORICOMI; NAIK, 2011).

The volume of ornamental rocks marketed in Brazil in 2014 was of 2,547,185.49 tons, and 50% of this volume has become production waste, such as rock powder, rock fragments and abrasive slurry. This waste and its improper disposal cause: contamination of water, soil and air; visual pollution; and loss of native vegetation, among others (SANTOS, 2011; ASSOCIAÇÃO…, 2015).

Therefore, waste obtained from marble processing has a potential use in the construction industry and there are several studies that have demonstrated the possibility of using this waste as aggregate for the production of concrete and mortar (BARBOSA; COURA; MENDES, 2008; PEREIRA *et al.*, 2009; VEGAS *et al.*, 2009; CABRERA; TRAVERSA; ORTEGA, 2011; PÉREZ-BENEDICTO *et al.*, 2012; BARBOSA; SANTOS, 2013; ALIABDO; ELMOATY; AUDA, 2014).

This study assessed the use of crushed marble waste – artificial sand (WA) – aiming to replace natural sand in the production of mortar. The experimental program considering different admixtures of mortars containing Portland cement, with or without hydrated lime, assessed these admixtures for their mechanical properties, such as: compressive strength; tensile strength; elasticity modulus; pull-off test; capillary and immersion absorption and shrinkage.

The experimental program is being very extensive and it began in the 2nd PII/ UFJF (2011) (Innovation Incentive Program/ Federal University of Juiz de Fora[1]). This paper presents some of the most relevant results. Finally, the analysis of research indicated that the use of marble aggregate resulted in mortar of good performance.

Materials and methods

Materials

The cement used for this experiment was CP II-E-32. Its characterization is shown in Table 1, and the hydrated lime used was CH I Hydrated lime. Its characterization can be seen in Table 2.

Table 3 shows the characterization of the sand: crushed marble waste aggregate (WA – waste aggregate) and natural sand (NA – natural aggregate). Tables 4 and 5 indicate that the waste aggregate does not have enough minerals (such as opal, cristobalite, silica and others) to cause alkali-aggregate reaction (see Figures 1, 2 and 3). The characteristics of the rock were determined through petrographic analysis (X-ray diffraction) in order to evaluate the physical and mechanical behavior of materials, which were diagnosed through specific technological tests or observed during the processing (especially cutting and polishing). The petrographic analysis was carried out according to the standard NBR 7389 of 2009 (ABNT, 2009a).

Methods: items of investigation

As far as rheology is concerned, fresh mortar is defined by variables with heavy impact on workability, including water demand, shape and texture of the surface of the aggregate particles. The critical parameter related to workability is the fact that natural aggregate absorbs more water than waste marble aggregate. Therefore, the correct amount of water required for mixes needs to be corrected according to different mix proportions and materials (BINICI *et al.*, 2008).

[1]Disponible: <http://www.ufjf.br/critt>.

In order to obtain mortars that enable a wide range of applications (flooring, walls, ceilings, coatings), admixtures based on different proportions of materials were tested for two different levels of workability with flow table fixed in 180 mm (± 10 mm) and 210 mm (± 10 mm). Workability was defined according to the expectations of Brazilian construction sites of maintaining a cohesive mixture without segregation. Workability and water/cement ratio were obtained using a flow table, created by measuring mortar flow. The procedure was carried out according to the Brazilian standard (ABNT, 2005a).

Table 1 - **Characteristics of Portland cement (type CP II-E-32)**

Chemical Composition (%)		Physical properties		Compressive strength (MPa)	
SiO_2	24.05	Setting time (initial) (min.)	190	days	f_c
Al_2O_3	7.15	Setting time (end) (min.)	240	1	8.6
Fe_2O_3	2.47	(%) Fineness modulus #325	17.1	3	24.8
CaO	57.50			7	32.3
MgO	3.36	Volumetric expansion(mm)	0.0	28	40.9
K_2O	0.60				
CO_2	3.41	Density (g/cm^3)	4.18		
SO_3	1.84				

Table 2 - **Characteristics of hydrated lime (CHI)**

Chemical Properties	(CO_2)	≤ 5%
	CaO + MgO Hydrated	≤ 10%
Physical Properties	Fineness modulus #0.075 (%)	≤ 10%
	Water retention	≤ 75%
	Volumetric expansion	absent
	Plasticity	≥ 110

Table 3 - **Physical characteristics of the waste sand (WA) and natural sand (NA)**

Sand	Waste aggregate (WA)	Natural aggregate (NA)
Maximum Diameter	4.80 mm	2.40 mm
Fineness Modulus	2.58	2.54
Specific Density	2.91 kg/dm^3	2.62 kg/dm^3
Powdered Material Content	5.00 %	0.06 %
Organic Impurity	<300 p.p.m.	<300 p.p.m.
Water Absorption	1.27 %	3.16 %

Table 4 - **Chemical analysis of the WA (waste sand)**

Main component	%
Ca	18.1
Mg	19.2
CaO	25.4
MgO	7.8
Others	29.5

Note: *classification: Magnesium.

Table 5 - **Petrographic analysis of the WA**

Mineral	Chemical formula	%
Carbonate	($CaCO_3$) ou ($CaMg(CO_3)_2$)	95%
Olivine – Fosterite	(Mg_2SiO_4)	3%
Chlorite – Mg	($Mg_{12}[(Si,Al)_8O_{20}](OH)_{16}$)	*
Serpentine	$Mg_3[Si_2O_5](OH)_4$	*
Amphibole - Tremolite	[$Ca_2Mg_5Si_8O_{22}(OH_2)$]	*

Note: *the sum of the three minerals is 2%.

Figure 1 **- Chlorite - Mg with tabular format - resolution of 0.55 mm**

Figure 2 **- Tremolite crystal - resolution of 2.3 mm**

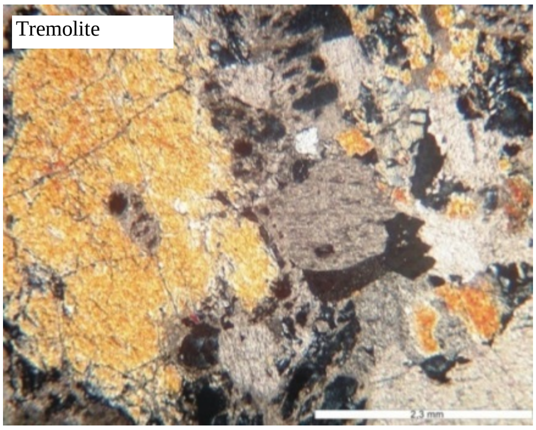
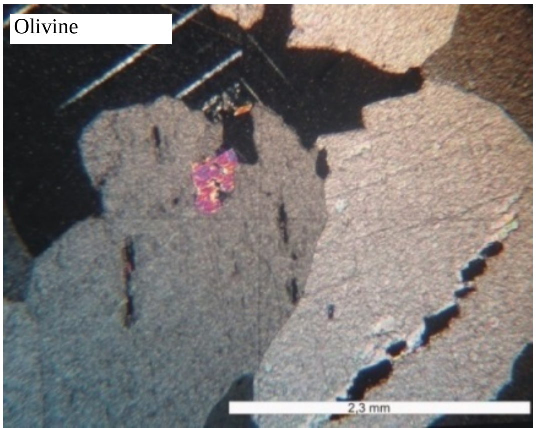


Figure 3 **- Olivine enclosed in carbonate - resolution of 2.3 mm**



The influence of the addition of hydrated lime (binder) was evaluated and, for that purpose, the admixture proportions of cement, hydrated lime and sand (natural or artificial) and the water/cement ratio were as shown in Tables 6 and 7. Additionally, the water content and, consequently, the water/cement ratio varied according to the different mortars, maintaining the fluidity of the fresh mortar. The hydrated lime increases the water/cement ratio, however it improves plasticity in the fresh mortar and deformability of the mortars in general (SABBATINMI; BAÍA, 2002; CINCOTTO *et al.*, 2009).

The water used for making the specimens subject to test was drinking water and the specimens were cast in stainless steel modulus and wet cured at 20ºC until test time. Several specimens were made, i. e., four for each age, for each test, for each mortar admixture. The results shown represent the average value.

The specimens subject to test were cured and the tests were conducted according to the Brazilian standards described in Table 7 and the compression and tensile strength tests were performed at the age of 3, 7 and 28 days; tests were conducted with the use of mortar prisms (4 x 4 x 16 cm) and the other tests, on cylinders (5 x 10 cm, diameter x height).

Table 6 – **Admixture of mortar (in weight) adopted in the experimental program**

Admixture of mortar (cement: hydrated lime: sand)	**Water/cement ratio**			
	Natural Aggregate (NA)		**Waste Aggregate (WA)**	
	180 mm	**210 mm**	**180 mm**	**210 mm**
1: 0.0: 2	0.59	0.61	0.48	0.57
1: 0.5: 1.5	0.70	0.84	0.72	0.80
1: 1: 1	1.02	1.22	1.04	1.21
1: 0.0: 3	0.80	0.80	0.58	0.72
1: 0.5: 2.5	0.88	1.00	0.81	0.94
1: 1: 2	1.15	1.38	1.11	1.33
1: 0.0: 4	1.00	1.14	0.69	0.80
1: 0.5: 3.5	1.02	1.13	0.90	1.04
1: 1: 3	1.00	1.48	1.18	1.36
1: 0.0: 5	1.2	1.40	0.90	1.00
1: 0.5: 4.5	1.23	1.33	0.98	1.17
1: 1: 4	1.20	1.64	1.22	1.51
1: 0.0: 6	1.4	1.70	0.95	1.10
1: 0.5: 5.5	1.49	1.45	1.11	1.27
1: 1: 5	1.50	1.60	1.30	1.61
1: 0.0: 7			1.12	1.32
1: 0.5: 6.5			1.20	1.37
1: 1: 6			1.40	1.72
1: 0.0: 8			1.15	1.54
1: 0.5: 7.5			1.23	1.47
1: 1: 7			1.43	1.83
1: 0.0: 9			1.41	1.81
1: 0.5: 8.5			1.41	1.62
1: 1: 8			1.51	1.94
1: 0.0: 10			1.53	1.95
1: 0.5: 9.5			1.50	1.77
1: 1: 9			1.50	2.10

Table 7 – **Summary of tests performed and number of specimens tested (ST)**

Test	**Age (days)**	**Nº ST**
Compressive strength (ABNT, 2005b) Tensile Strength (Brazilian test) (ABNT, 2010a)	3, 7 and 28	4
Capillary Absorption of Water (ABNT, 1995) Immersion Absorption of Water (ABNT, 2009b) Elasticity Modulus (ABNT, 2008) Pull-Off Test (ABNT, 2010b) Shrinkage (ABNT, 1997)	28	4

The experimental program verified and analyzed the properties of all the admixtures of mortar with both WA and NA (see Table 6). The mix proportions with segregation in the fresh mortar have been excluded, i.e., the mortars with natural aggregate and proportion over than 1:7 (cement: aggregate). The influence of the addition of hydrated lime was not verified in proportions with segregation because it increased water consumption which is not good for sustainable development.

Results and discussion

Figure 4 shows the results obtained in the compressive strength test in average values. It is possible to observe that mortars made with WA present values that are 60% higher than those of mortars made with NA for an early age (7 days). The aggregate's (marble waste) low water absorption values, the low porosity and the good granulometric distribution favor the rheology of the mortars (BARBOSA; COURA; MENDES, 2008; CARASEK *et al*., 2016). The benefits of the hydrated lime are seen in the plasticity and cohesion of the admixture in its fresh state, mainly for poor mortars. This can be verified by the similar trend of results of compressive strength tests in the poorest mortar admixtures.

It has been found that the compressive strength of mortar made with WA after 28 days is higher than 40 MPa for a mix proportion of 1:2 (cement: aggregate) and a workability of 180 mm, which shows a higher strength of the mortars (see Figure 4), which is favored by the aggregate properties such as particle size, surface texture, low absorption and good granulometric distribution, leading to improvements in the quality of the composite (CORINALDESI; MORICOMI; NAIK, 2011; CABREIRA; TRAVERSA; ORTEGA, 2011, PAN; WENG, 2012).

In the preliminary analysis, the artificial aggregate can be defined as "good material" for mortars since it has a high proportion of recycled materials that will be used in mortars. This is an extremely important aspect regarding environmental responsibility. Therefore, in a second step it was decided to analyze some other properties of mortars with waste aggregate only, since the employment of this material is the main object of study in this paper. The following tests were carried out: tensile strength, capillary absorption, immersion absorption, elasticity modulus, pull-off and shrinkage (see Table 7). The mix proportions used were 1:0:3.0; 1:1: 2.0; 1:0:7.0, 1:1:6.0; 1:0:10.0 and 1:1:9.0 (cement: hydrated lime: aggregate (sand)). After the compressive strength test, it was decided to carry out the remaining tests with the admixtures that presented minimum, medium and maximum values in the compressive strength test, even including the analysis of the effect of including hydrated lime in their composition. These admixtures were those with the following proportions: 1:0:3.0; 1:0:7.0, 1:0:10.0.

Figures 5 and 6 present the results of the tensile strength tests (Brazilian Test). It was found that mortars without hydrated lime have higher results regarding tensile strength, thus demonstrating that the use of this binder had no contribution to improving results related to this property, as expected due to the cohesion effect of fresh mortar. Tensile strength has the same behavior as compressive strength.

Figure 7 presents the results of the relationship between compressive strength and elasticity modulus. The static elasticity modulus has higher values in mortars without hydrated lime, showing its relationship with mechanical strength, due to a greater compactness and, consequently, high strength (MALHOTRA; SIVASUNDARAM, 2004; VEGAS *et al.*, 2009; CARASEK, 2012; BARBOSA *et al*., 2015). The decrease in the elasticity modulus with the inclusion of hydrated lime improves mortar resilience and, consequently, increases their durability. This correlation (compressive strength x elasticity modulus) also represents the interconnection between these properties through the bond between the elements of the cement matrix, responsible for the mortar's mechanical properties.

Figure 4 - **Compressive strength (f_c) versus admixture proportion**

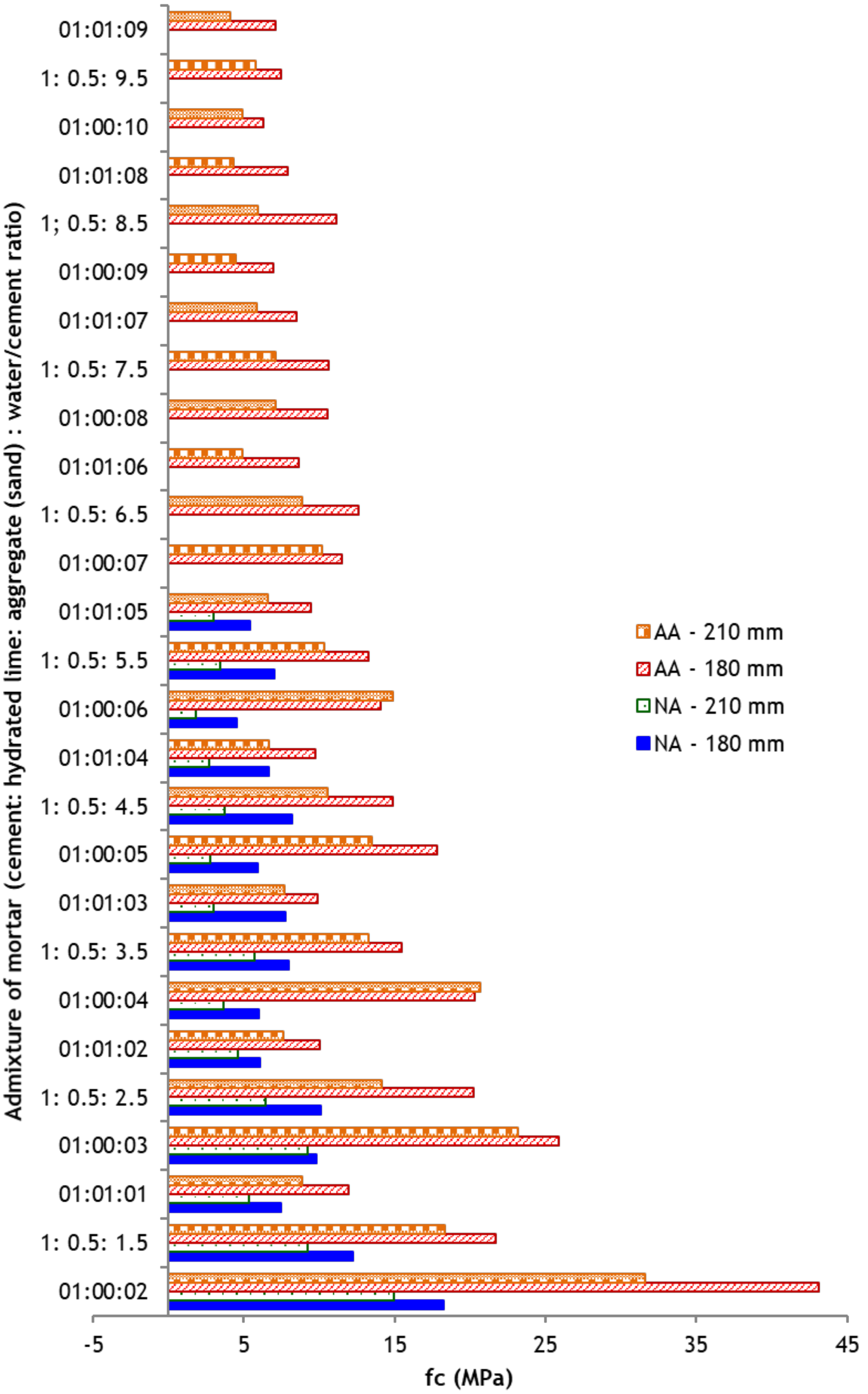


Figure 5 - **Tensile strength ($f_{ct,sp}$) versus age - WA (waste aggregate) - workability = 180 mm**

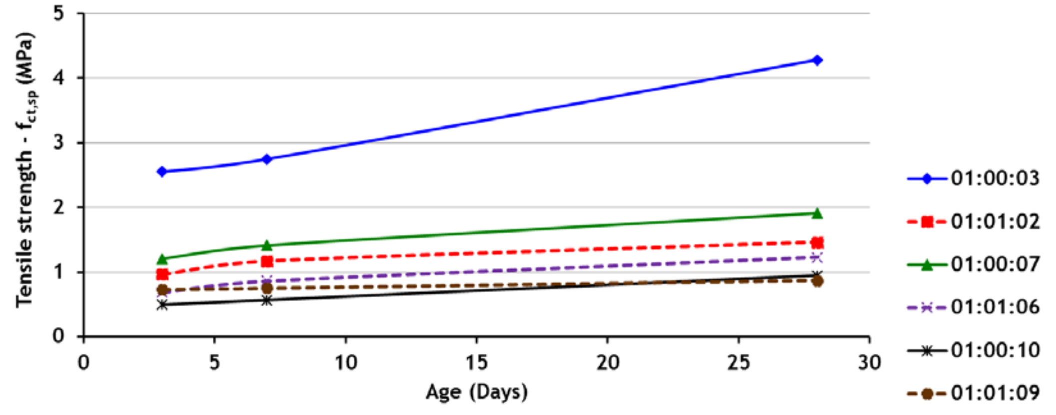


Figure 6 - **Tensile strength ($f_{ct,sp}$) versus age - WA (waste aggregate) - workability = 210 mm**

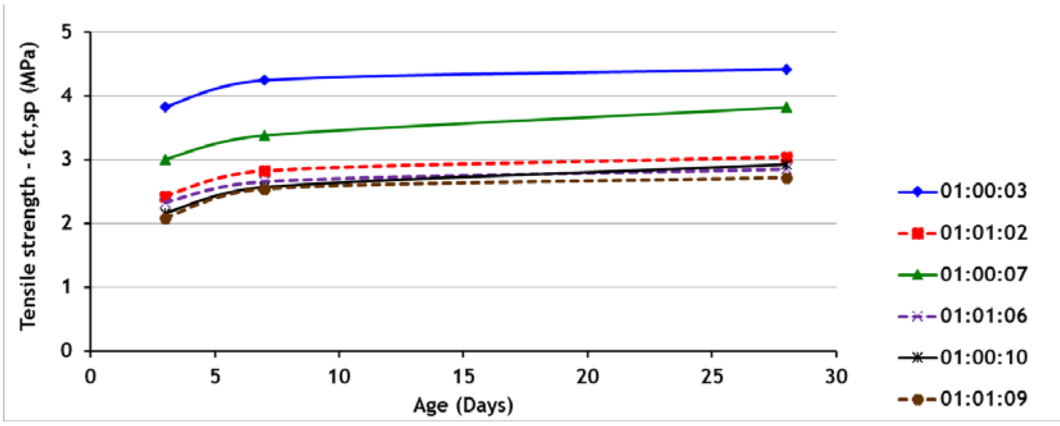


Figure 7 - **Elasticity modulus (E_{ci}) versus compressive strength**

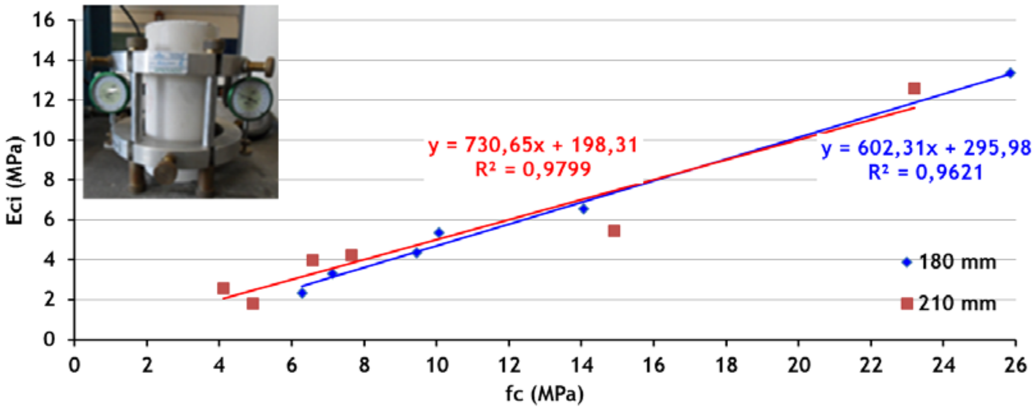


Figure 8 shows the results and correlations between compressive strength (f_c) and pull-off test (tensile strength (R_A)). By analyzing Figure 8, it is possible to see that pull-off tensile strength (R_A) is proportional to compressive strength. R_A is an important property because rigid mortars have poor deformability performance and, consequently, tend to have their durability reduced (CARASEK, 2012; HADDAD, 2015; HADDAD *et al*., 2016). R_A ranges from approximately 11% to 13% of the compressive strength.

Figures 9, 10 and 11 show the results. It can be seen that the increase in the proportion of aggregate and/or hydrated lime leads to an increase in capillary absorption and this depends on the proportion of cement in the admixture, that is, on the permeability of the cement matrix. The increase in the porosity due to the lower amount of cement results in a more permeable matrix which allows the access of aggressive agents and/or water and, consequently, compromises mortar durability. However, it is very common to paint mortars, therefore these results do not associate the lack of durability with water exposure (KHATIB, 2005).

The porosity and permeability of the mortars are correlated with the consistence of the mortar due to changes imposed by the volume of the mortar paste resulting from the voids between aggregate grains (CARASEK *et al.*, 2016). In this case, good quality is ensured due to the artificial aggregate.

Figure 8 - **Pull-off tensile strength (R_A) versus compressive strength**

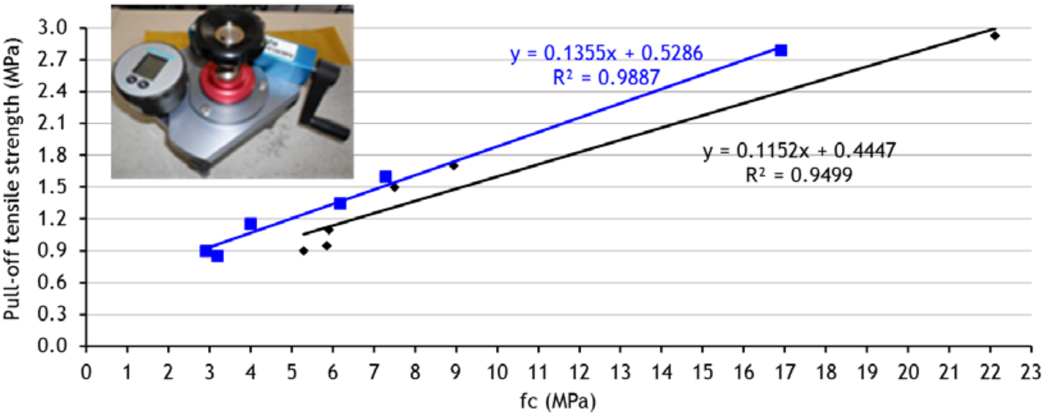


Figure 9 - **Capillary absorption versus age - 180 mm**

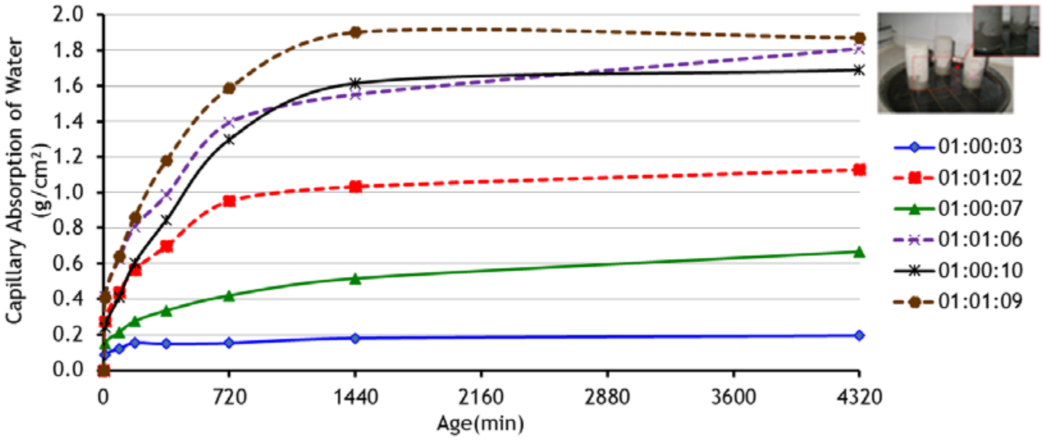


Figure 10 - **Capillary absorption versus age - 210 mm**

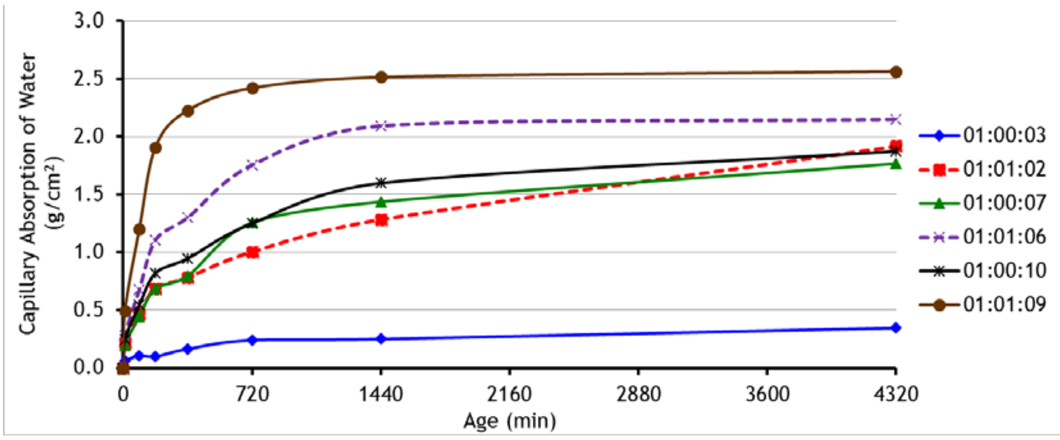
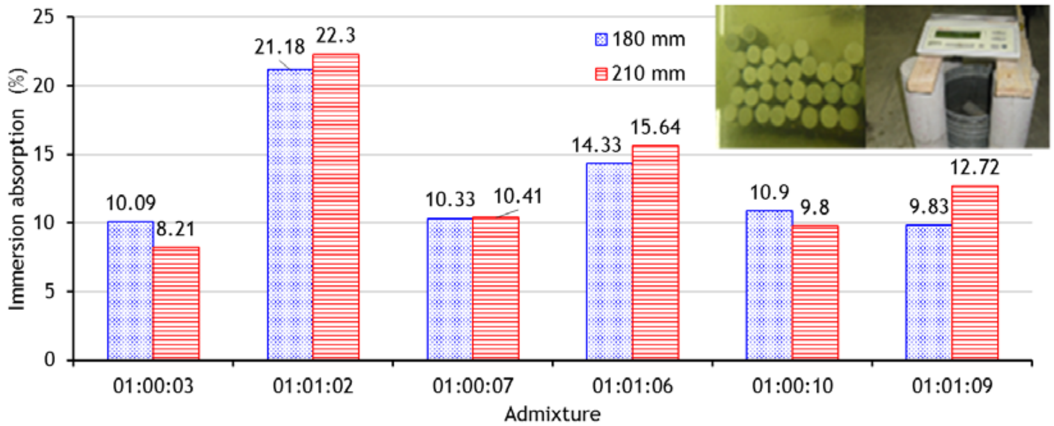


Figure 11 - **Immersion absorption**



Shrinkage may result in damages to mortar quality and durability. Figures 12 and 13 present the evolution of the shrinkage of the mortars analyzed. It is clear that the increase in water increases shrinkage, which results in a longer time needed for the stabilization of the mortars. Furthermore, it can also be seen that shrinkage is lower in mortars without lime in their composition due to the differences in the hardening process, i.e., between cement and hydrated lime.

Conclusions

This research has confirmed that a marble waste aggregate is adequate for construction materials and allows the production of mortars with enhanced strength and better efficiency (with reduction of the factor water/cement and cement consumption). In other words, the study confirmed that mortars produced with waste marble have shown higher strength than the ones produced with natural aggregate (river sand). The hydrated lime (binder) usually improved the cohesion of fresh mortar.

The main conclusions drawn about the use of marble waste as an aggregate and/or the use of hydrated lime for the production of mixed mortars were:

(a) mortars with marble waste have high mechanical properties (it is up to four times higher than those that use natural sand) because the aggregate (sand) has lower porosity;

(b) the addition of hydrated lime results in a trend of equal results regarding the compressive strength tests, which is suitable for poor mortars;

(c) the elasticity modulus of the mortars is higher due to the lower volume of voids and represents the interconnection between these properties through the bond between the elements of the paste matrix; and

(d) the hydrated lime and the amount of aggregate increase the volume of voids, increasing the porosity of mortars and compromising their durability.

The recycling process of waste should follow an adequate methodology so that the products developed may present performances compatible with the technical standards and may not cause environmental risks. In the case of waste, the object of this research, it is clear that the results are compatible with, and even superior to, the technical standards, reinforcing the great benefits that can be acquired by this new product in the production of mortars. Besides, it also stands out the greatest advantage of using waste to produce a new product that will support concepts such as: social responsibility (*use of the waste*), environmental responsibility (*reduction of waste disposal area and reduction of natural sand use*), economic responsibility (*reject value*) and technical responsibility (*viability check*). All these aspects foster the expansion of sustainable development in the construction industry.

Figure 12 - **Shrinkage for the workability - 180 mm**

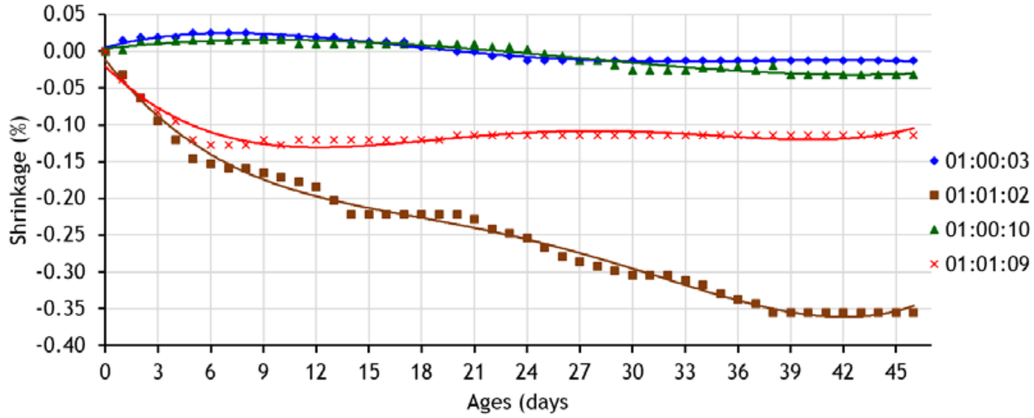
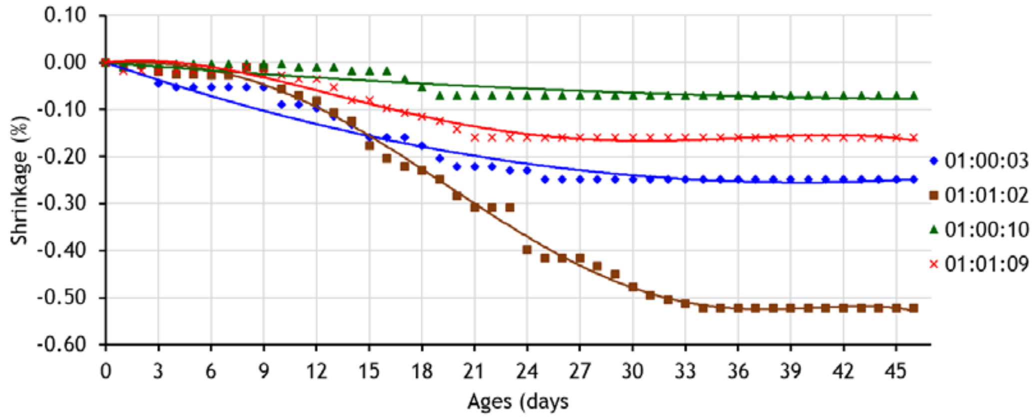


Figure 13 - **Shrinkage for the workability - 210 mm**



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