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ORIGINAL ARTICLE

Reduction of the cement content in mortars made with fine concrete aggregates

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Abstract This study's main objective is to show the viability of reducing the cement content of mortars by incorporating fine crushed concrete aggregates whilst simultaneously maintaining a good performance in terms of functional requisites. The advantages of this, if the results are positive, are both environmental and economic: less energy is consumed in cement manufacture and the mortars' direct costs are lower. To evaluate the hypothetical binding characteristics of concrete fines incorporated in mortars, and thus allow a cement consumption reduction, various standard tests were performed to quantify their most important properties (e.g. mechanical strength, water-related performance, cracking susceptibility, shrinkage) and compare them with those of a reference mortar containing no recycled fines and not reducing the cement content.

Keywords Mortars · Fine concrete aggregates · Cement · Energy

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1 Introduction

In a traditional render/plaster mortar, made of water, sand and cement, by far the most expensive and energy-consuming component is the cement. Its functions are to promote the cohesion of aggregates in the mix's fresh-state, its initial adhesion to the render's substrate and setting of the paste, to confer mechanical strength and reduce the permeability of the coating to the passage of water [1].

Various researchers have studied ways of reducing the cement content of mortars and, consequently, their overall cost and energy consumption, without compromising their performance and intended function.

The aim of this work is to check the viability of reducing the cement content of mortars without significant loss of performance, by the incorporation of fine crushed concrete residues. In order to achieve this objective the effect on the mortars' performance of both reducing the cement content and at the same time incorporating given ratios of fine crushed concrete aggregates was analysed, through the determination and comparison of the main characteristics of the mortars: reference mortars without waste and mortars with different contents of waste.

It is accepted that the concrete aggregates may contain some non-hydrated cement that gives them binding properties. The filler effect is also expected to compensate characteristics that could be jeopardized by the decrease of cement.

If the results are positive the main advantages will be to cut the production cost and the energy consumption of mortars and also to create a use for the waste from construction and demolition works that would otherwise be dumped.

This study is in the continuation of a previous one, conducted with the aim of finding the optimal replacement ratio of sand by fine concrete aggregates in order to maintain or even improve the main characteristics of mortars by taking advantage of the filler effect of the finer particles [2]. That optimal replacement ratio was the one used for the mortars in this study.

2 Literature review

Research on the use of the fine fraction of construction and demolition waste in mortars (unlike concrete) is still rather restricted, beyond the scope of refereed international journals.

It has been found that replacing up to 10 % of cement by fines does not greatly affect the compressive strength of conventional concrete [3] and that the actual replacement of fine natural aggregates by fine crushed concrete aggregates may not have a negative impact on concrete's compressive strength either, due to a combined hydraulicity and filler effect [4]. The use of superplasticizers may even improve this property in concrete containing fine recycled aggregates, compared with conventional mixes [5].

Oliveira et al. [6] concluded in a study on the potential of a kaolin calcined at 700 °C to replace Portland cement in mortars that compressive strength gains considerably, up to a 30 % substitution ratio.

Silva et al. [7] concluded in their study on recycled ceramic fines that the results from tests on mortars with a reduced cement content (from a volumetric ratio cement: aggregate of 1:4–1:5 and 1:6) were acceptable. The same authors also demonstrated the potential of the filler effect of ceramic fines [8] and the viability of replacing natural sand with fine ceramic waste, but maintaining the aggregate's size distribution [9].

Mortars produced with recycled material showed an average saving of 30 % in cement consumption compared with conventional mortars [10]. Geyer et al. [11] demonstrated that the use of highly pollutant sludge ash from an urban sewer may be a safe and economic alternative in partial substitution (up to 20 %) of Portland cement.

Araújo [12] observed a significant reduction in the incorporated air content as the dry fine aggregate/cement and water/cement ratios increased in mortars with incorporation of gravel. This reduction was caused mostly by the increase of the gravel and water consumption, regardless of the void volume of the fine aggregate.

Corinaldesi et al. [13] used demolition rubble to make mortars and concluded that when combined with polypropylene or stainless steel fibres this led to a good performance of the mixes in which part of the cement was replaced by fine recycled aggregates, particularly in terms of flexural tensile strength.

Kim and Choi [14] used waste concrete powder as a by-product manufacturing high quality aggregate. The compressive strength of mortar decreased by up to 73 % as replacement level increased and sorptivity coefficients increased by 70 %. According to the test results, it is desirable to keep the replacement ratio below 15 %.

Alaejo et al. [15] used recycled sand to produce mortars and concrete. The results obtained on mortars indicate that the use of up to 20 % recycled sand caused a drop in the compressive and flexural strength.

Chen et al. [16] used 11 kinds of different recycled fine aggregate replacement rate (ranging from 0 to 100 %) to study the mechanical behaviour of mortars. Because the water absorption rate of the mortar with high porosity is higher, and there are mass micro-cracks in recycled fine aggregate interior due to damage accumulation, the apparent density decreases, the water absorption rate increases and the water absorption of recycled fine aggregate increases. So the fluidity of recycled fine aggregate mortars is fine, but the water retention is bad, and the compressive strength is lower than the natural fine aggregate mortar about 50 %.

3 Experimental work

To achieve the aim of the work and assess the viability of reducing the cement content and simultaneously incorporate fine concrete residues, the characteristics considered as the most relevant for mortars, namely for masonry mortars (both setting and rendering mortars), were determined. The characteristics selected were used to evaluate the mortars performance, especially in terms of mechanical behaviour, water behaviour and susceptibility to cracking.

The mortar mixes of this work were selected based on the results from previous work [2], where the characteristics of mortars in which part of the sand was replaced by various ratios of fine crushed concrete aggregates were determined in order to find the replacement ratio that optimized the mortar's properties.

With the chosen replacement ratio of sand by fine crushed concrete aggregates, a reference mix and two other mixes with reduced cement content were tested to analyse the eventual binding characteristics of the recycled fines.

Therefore the experimental programme was divided into two stages: the first was an elimination contest in which two mixes with volumetric ratios cement-aggregates 1:5 and 1:6, both with 15 % concrete fines (size <0.150 mm), were tested and their results were compared with those of a reference mortar with a volumetric ratio 1:4 and no recycled fines and of another one with the same cement-aggregate ratio and 15 % recycled aggregates; in the second stage, of the 1:5 and 1:6 volumetric ratio mixes the one that performed best in the first set of tests was selected and a second set of tests was conducted on the mix selected and on another with the same cement: aggregate ratio and no recycled fines, to determine other important characteristics of the mortars.

Therefore the mortar mixes tested in this series of experiments were:

- II(0-1:4)—0 % incorporation—volumetric ratio 1:4 (cement: siliceous sand)—reference mortar;
- II(15-1:4)—15 % incorporation—volumetric ratio 1:4 (cement: siliceous sand and fine concrete aggregates);
- II(0-1:5)—0 % incorporation—volumetric ratio 1:5 (cement: siliceous sand);
- II(15-1:5)—15 % incorporation—volumetric ratio 1:5 (cement: siliceous sand and fine concrete aggregates);
- II(15-1:6)—15 % incorporation—volumetric ratio 1:6 (cement: siliceous sand and fine concrete aggregates).

The size distributions of the sand and the concrete fines are presented in Figs. 1 and 2. The bulk densities of the various components of the mixes (sand, concrete fines and cement) are provided in Table 1.

4 1st stage

The various mortar mixes were characterized so that the one most suitable for the purpose could be chosen.

4.1 Consistency of fresh mortar

The test was performed according to European Standard EN 1015-3 (1999) [29] and its aim was to calibrate the water content to be added to the mix. The consistency parameter considered adequate for rendering mortars with a bulk density higher than 1,200 kg/m^3 is, according to the standard, 175 $\pm$ 10 mm, and this was used as the target value. The results are presented in Table 2.

The results show that the mixes containing less cement, either with or without recycled fines in their composition, need more water to reach the same slump; this is because there is an increase of the specific surface of the aggregates, which require more water to wet them.

From the mixes with the same cement: aggregate ratio the ones requiring less water were those with 15 % incorporation of concrete fines instead of the

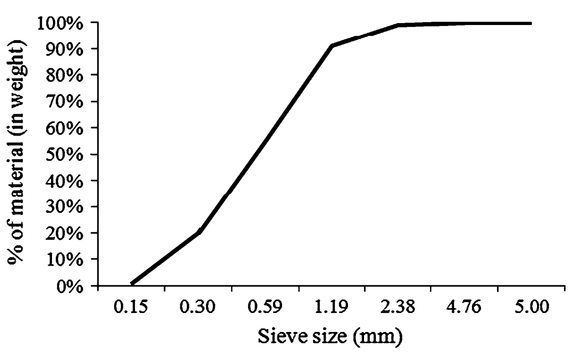

Fig. 1 Grading size distribution of natural sand

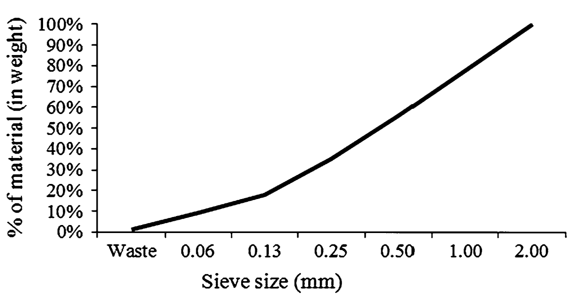

Fig. 2 Grading size distribution of recycled concrete fines

Table 1 Bulk density of the mortars' components

	Bulk density (kg/m^3)
Cement	1,035
Sand	1,433
Concrete fines <0.149 mm	842

Table 2 Water/cement ratio and results of the consistency test

Mortar	Water/cement ratio	Water needed per dm^3 of mortar (ml)	Consistency (mm)
II(0-1:4)	1.41	220	170.8
II(0-1:5)	2.14	234	170.5
II(15-1:4)	1.12	183	172.0
II(15-1:5)	1.43	192	177.5
II(15-1:6)	1.76	201	176.0

same volume of sand. This is because the increase in the workability of mortars containing recycled aggregates allows a reduction of kneading water. This effect depends on the balance between increase in the workability and water absorption of the recycled fines, and in this specific case it was favourable to the first parameter and allowed a reduction in kneading water. The same happened in other works [7–9, 17].

4.2 Bulk density of fresh mortar

This test was performed according to European Standard EN 1015-6 (1998) [30]. The results are presented in Fig. 3.

The results show a trend for the mortar's fresh-state bulk density to increase when 15 % of concrete fines are incorporated in the mix, keeping the cement: aggregate ratio constant at 1:4. This is very probably due to a filler effect. In fact, the concrete fines, being finer than sand smaller grains, fill small voids between the sand grains, reducing water need and increasing compacity, and these factors lead to an increase in bulk density. A decrease of the fresh-state bulk density is observed for the 1:5 ratio mix with no concrete fines relative to the reference mix (1:4, no concrete fines), but then it remains almost the same when 15 % concrete fines are incorporated with same 1:5 ratio. This effect can be explained by the increase in water, which is less dense than cement, needed to reach the same consistency, and this increased the mortar's porosity and created more voids between the aggregates, thus prevailing over the filler effect. If the cement: aggregate ratio is further reduced to 1:6 in the mix with 15 % concrete fines the bulk density sticks to the previous descending trend, which in this case may be related to the bulk density of the concrete fines being lower than that of the cement.

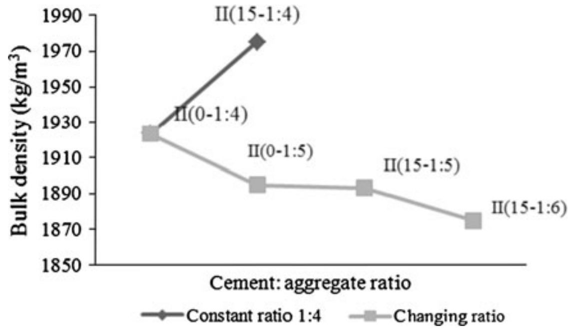

Fig. 3 Bulk density of fresh mortar for the incorporation ratios studied (average of three specimens: II(0-1:4) = 1923.4 kg/m^3, II(15-1:4) = 1975.0 kg/m^3, II(0-1:5) = 1894.8 kg/m^3, II(15-1:5) = 1893.2 kg/m^3, II(15-1:6) = 1875.0 kg/m^3)

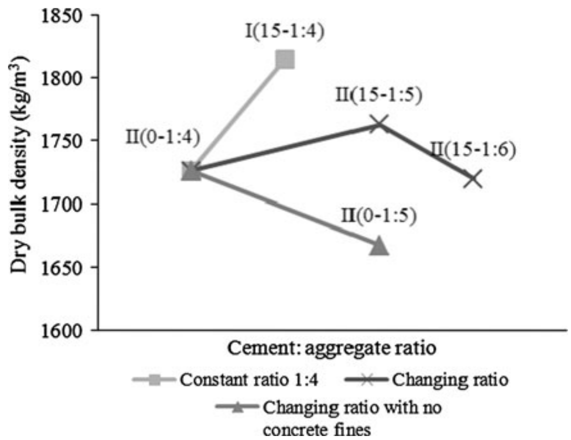

Fig. 4 Dry bulk density of hardened mortar for the incorporation ratios studied (average of three specimens: II(0-1:4) = 1725.8 kg/m^3, II(15-1:4) = 1814.5 kg/m^3, II(0-1:5) = 1667.8 kg/m^3, II(15-1:5) = 1763.0 kg/m^3, II(15-1:6) = 1719.8 kg/m^3)

4.3 Dry bulk density of hardened mortar

The test was performed in accordance with European Standard EN 1015-10 (1999) [32]. Three specimens of each type of mortar were cured for 28 days and were tested immediately afterwards. The results are presented in Fig. 4.

The results indicate similar behaviour to that of fresh mortar, apart from the cement-aggregate ratio 1:5 mix with 15 % concrete fines which displays a significant increase compared with 1:5 and no recycled fines, and even with 1:4 without fines, showing the importance of the filler effect of the recycled fines. The improvement of the dry bulk density of the mix with the same 1:5 ratio but 15 % concrete fines leads to the conclusion that the fines filled the existing empty spaces and made the mortar more compact, which did not occur in the fresh state. This mix also needed less water in its composition, which led to less porosity. The mix with a 1:5 cement-aggregate ratio and 15 % concrete fines also displays a reduction in the dry bulk density, coming very close to that of the reference mortar [II(0-1:4)], which may be due to the bulk density of the concrete fines being lower than that of cement. The reduction of the cement-aggregate ratio from 1:5 to 1:6 without a relevant increase of fines reduces the compacity and may also explain the fall in the dry bulk density.

4.4 Flexural and compressive strength of hardened mortar

These tests were performed according to European Standard EN 1015-11 (1999) [33]. Three specimens of each type of mortar were cured for 28 days and were tested immediately afterwards. The results are presented in Figs. 5 and 6.

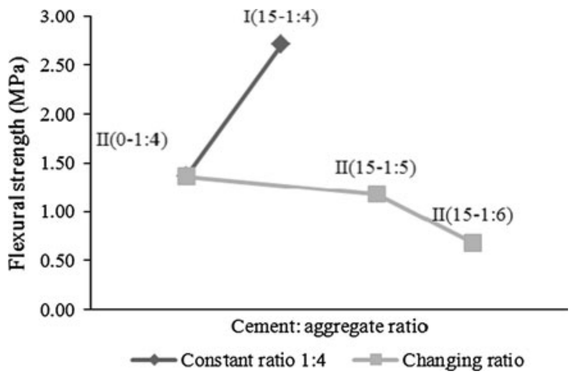

Fig. 5 Twenty-eight-day flexural strength of hardened mortar for the incorporation ratios studied (average of three specimens: II(0-1:4) = 1.36 MPa, II(15-1:4) = 2.71 MPa, II(15-1:5) = 1.18 MPa, II(15-1:6) = 0.68 MPa)

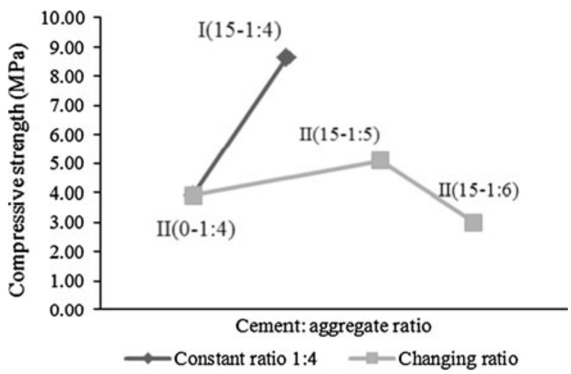

Fig. 6 Twenty-eight-day compressive strength of hardened mortar for the incorporation ratios studied (average of three specimens: II(0-1:4) = 3.91 MPa, II(15-1:4) = 8.64 MPa, II(15-1:5) = 5.09 MPa, II(15-1:6) = 3.00 MPa)

The results of the flexural strength test show that as the cement content decreases, values go down, as expected with conventional aggregates. The mix with a 1:5 cement-aggregate ratio and 15 % concrete fines displays a 13 % decrease in flexural strength compared with the reference mortar with higher cement content and no recycled aggregates. This relatively small difference is probably due partly to the presence of some non-hydrated cement in the concrete fines used in the mix, which increases its strength, and also to some filler effect. The fall in the flexural strength of the mix with a 1:6 cement-aggregate ratio and 15 % concrete fines relative to that of the reference mortar is around 50 %, significantly higher than that of the mix with 1:5 cement-aggregate ratio.

The results of the compressive strength test shows a 30 % increase for the mix with 1:5 cement-aggregate ratio and 15 % concrete fines, compared with the reference mortar. This phenomenon is similar to that found in the Silva et al. [7] study for the mix with 1:5 ratio and 10 % ceramic fines. It can be explained by an increase in the mortar's compacity with the incorporation of concrete fines that proved to offset the reduction in the cement content.

The trends of compressive strength follow very closely the trends of bulk density, showing that the filler effect, and the related increase in compacity, is a major responsible for the increase in mechanical strength. In what concerns the flexural strength, there is a difference in trends for the mortar 1:5 with 15 % of concrete recycled fines (there is a reduction by comparison with 1:4 without recycled fines), by comparison with compressive strength and bulk density. This difference can be explained by some micro-cracking due to the increased shrinkage motivated by fines, as seen in Sect. 5.2.

A comparison with the Silva et al. [7] results (Figs. 7 and 8) shows that they obtained higher values for mechanical characteristics than those reported here. However, the relative changes with the incorporation of recycled fines and the reduction of cement are similar. The curves obtained in both studies are actually almost parallel.

4.5 Water absorption due to capillary action of hardened mortar

This test was performed according to European Standard EN 1015-18 (2002) [35]. Three specimens (semi-prisms) of each type of mortar were cured for 28 days and were laterally waterproofed and tested immediately afterwards. The results are presented in Fig. 9.

The results show that for the same incorporation ratio of concrete fines (15 %), when the cement-aggregate ratio is reduced from 1:4 to 1:5 and then to 1:6 the water absorption increases, as expected. This is due to the reduction of the cement content in the mixes and the increase of the water/cement ratio, which cause an increase in capillary pores and in water flux through them. Notwithstanding the reduction in the cement content the mix with the highest water absorption is the reference mortar (1:4), with no recycled fines, which means that the incorporation of concrete fines for the percentage and the cement-aggregate ratios tested confers a better performance for this property.

These results are similar to those of Silva et al. [7], who also observed a decrease in the water absorption of the mixes with lower cement-aggregate ratios and incorporation of recycled fines compared with the reference mortar, and also found an increase in this property from the ratio 1:5 mix to the ratio 1:6 mix.

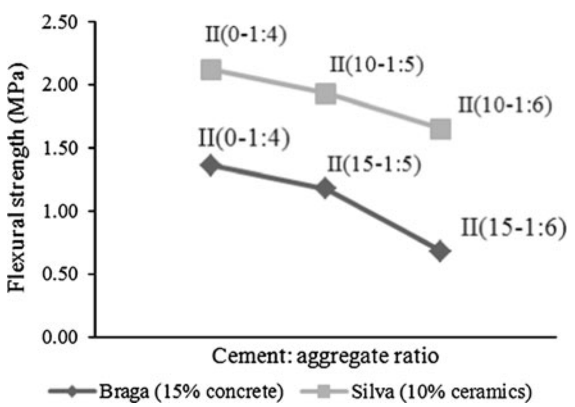

Fig. 7 Comparison of our 28-day hardened mortar flexural strength results obtained with those of Silva et al. [6]

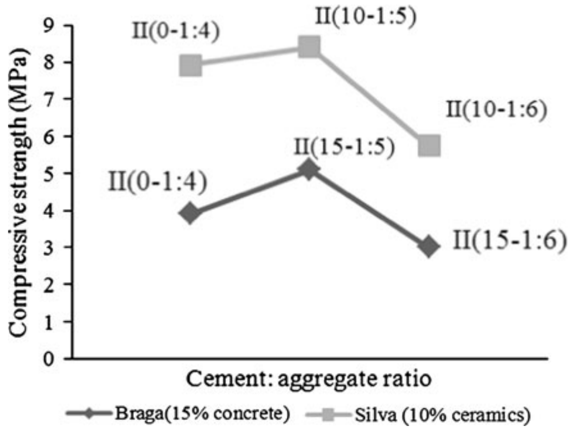

Fig. 8 Comparison of our 28-day hardened mortar compressive strength results with those of Silva et al. [6]

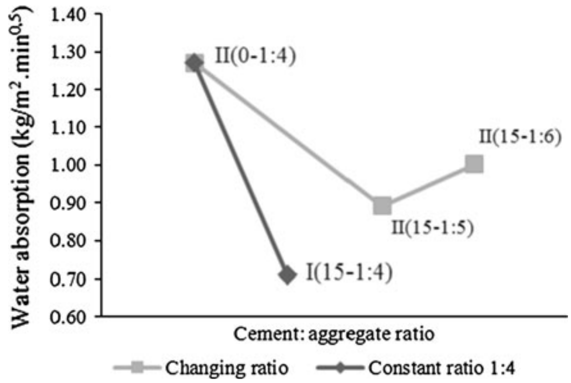

Fig. 9 Water absorption due to capillary action of hardened mortar for the incorporation ratios studied (average of three specimens: II(0-1:4) = 1.270 kg/(m^2 min^{0,5}), II(15-1:4) =0.708 kg/(m^2 min^{0,5}), II(15-1:5) = 0.891 kg/(m^2 min^{0,5}), II(15-1:6) = 1.001 kg/(m^2 min^{0,5}))

4.6 Drying

The semi-prisms used to evaluate water absorption due to capillary action were also used in this test, in which the mass differences were measured during drying in a conditioned laboratory environment (20 ± 2 °C and 65 ± 5 % RH). The specimens' performance during drying is presented in Fig. 10.

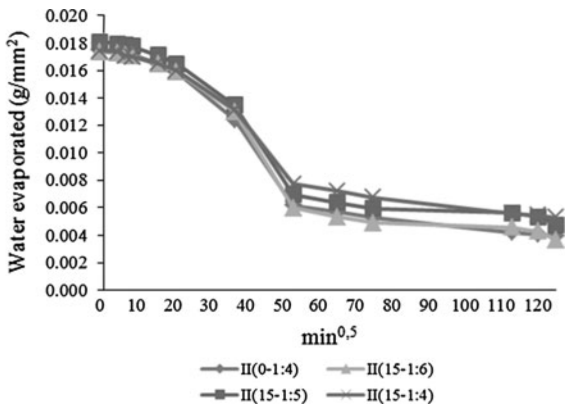

Fig. 10 Mortars' drying progress for the incorporation ratios studied

The drying graph shows that reducing the cement content by incorporating concrete fines does not have a significant influence on the mortars' drying behaviour, which remains similar to that of the reference mortar.

4.7 Susceptibility to cracking

This test consisted of applying a 2 cm mortar layer to a ceramic brick that is observed to see whether cracking occurs within a pre-determined period. None of the mortars under test showed any signs of cracking after 9 months. The mortar was applied to very small area, however, and application procedures in the laboratory differed from those on site. The results of this test therefore merely indicate that nothing serious is expected to happen on site in this respect.

4.8 Selection of mortars for the second stage

Mix II(15-1:5) was chosen for the second stage of testing because it had the best results for the properties tested in the 1st stage. It had higher compressive strength than the reference mortar and it and the closest result to it in the flexural strength test, proving to be more resistant than mix II(15-1:6). In the capillary water absorption test the two mixes with cement content reduction had a lower coefficient than the reference mortar, but mix II(15-1:5) got the lowest/best result.

Other important properties of mix II(15-1:5) were studied in the second stage of testing to better characterize it and collect more precise information on its behaviour.

5 2nd stage

Tests were performed on the reference mortar, mix II(0-1:5) and the mix selected from the first stage, II(15-1:5)

5.1 Water retentivity of fresh mortar

Water retentivity also influences the performance of a render/plaster mortar. As a matter of fact as soon as they are applied and throughout the application area these mortars are subjected to the suction of the substrate, which may lead to their rapid desiccation and prevent complete cement hydration. Good water retentivity thus helps to optimize the use of cement as a binder [18, 19].

This test was performed according to European Standard EN 1015-8 (1999) [31]. Three specimens of fresh mortar, of each mix, were used. The results are presented in Table 3.

It is shown that the mixes with different cement-aggregate ratios and no incorporation of concrete fines have practically the same water retentivity, proving that the cement content reduction had no influence. The mixes with concrete fines incorporation (15 %) and ratios 1:4 and 1:5, on the contrary, both showed an increase relative to the two previous mixes (the greatest increase was for the 1:4 ratio).

The increase in water retentivity of the mix with a 1:5 cement-aggregate ratio and 15 % concrete fines compared with the mix with same cement content but without recycled aggregates strengthens the impression that the incorporation of recycled fines has a substantial influence on the increase of water retentivity because it hinders its circulation within the mortar matrix.

It is concluded that even though there is a slight decrease in water retentivity when the cement content goes down because of the incorporation of concrete fines, the resulting value is still higher than that of the

Table 3 Results of the water retentivity test

Mortar	Water retentivity (%)
II(0-1:4)	63.8
II(15-1:4)	79.6
II(0-1:5)	63.9
II(15-1:5)	72.0

reference mortar and therefore the positive effect of incorporating recycled aggregates is not totally reversed.

Silva et al. [7] found an increase in water retentivity due to a reduction in cement content (Table 4). This phenomenon is explained by the excellent water retention capacity of ceramic fillers [20].

5.2 Dimensional instability (shrinkage)

This test was performed according to CSTB Cahier 2669-4 (1993) [28]. Three specimens (prisms) of each type of mortar were tested immediately after demoulding. The results are presented in Fig. 11.

They show that the mixes with no concrete fines with cement-aggregate ratios 1:4 and 1:5 have similar performances, with a 9 % reduction in shrinkage from the first (higher cement content) to the second.

The mixes with 15 % concrete fines exhibited very similar behaviour but registered an increase in shrinkage relative to the two previous mixes. This was to be expected since the incorporation of fines enhances mortar's shrinkage. This is an effect well known in practice that can be explained by some the following mechanisms: the specific surface is higher for finer particles, and this causes an increase of the surface tension due to the adsorbed water film, enhancing the volume reduction (shrinkage) [18, 21, 22]; in addition, the fine aggregates have a lower capacity of restraining shrinkage compared with rougher aggregate [18]. In this particular the increase of shrinkage may also be enhanced by some non-hydrated cement of the concrete waste.

The shrinkage for the mix with the lowest cement content, II(15-1:5), at 90 days was around 4 % lower than the mix with the highest cement content, II(15-1:4), which is not significant. However this difference is small compared with the one observed for the reference mortar. This indicates that the lower cement content did not cancel out the effect of the incorporation of concrete fines, leading to an increase in shrinkage of almost 40 %.

Table 4 Results of the adhesive strength test

Mortar	Adhesive strength (MPa)	Predominant rupture type
II(0-1:4)	0.33	B
II(15-1:4)	0.45	A
II(0-1:5)	0.16	B
II(15-1:5)	0.35	AB

A—Adhesive rupture (at coating-substrate interface), *B*—cohesive rupture (within the coating)

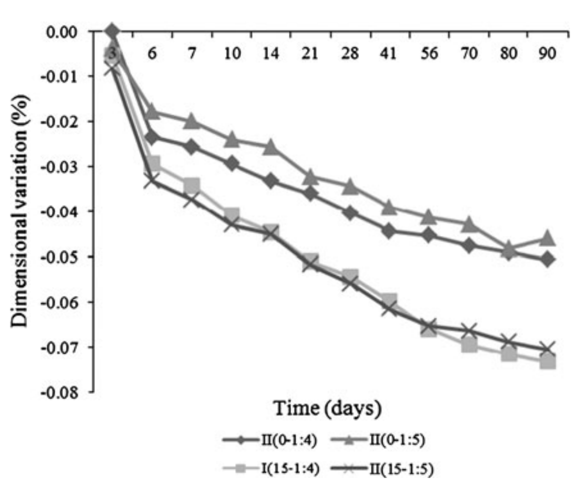

Fig. 11 Time relative to size variation

5.3 Adhesive strength of hardened mortar

This test was performed according to European Standard EN 1015-12 (2000) [34]. Three specimens of each type of mortar were applied to the surface of a brick and cured for 28 days. They were tested immediately afterwards. The results are presented in Table 4.

There is a decrease in adhesive strength of the mortars without concrete fines when the cement-aggregate ratio decreases from 1:4 to 1:5. This is in agreement with the study of Carasek and Djanikian [23] who concluded that as the cement content increases the adhesive strength also increases. The mix with a 1:5 ratio and 15 % concrete fines has a higher adhesive strength (by around 6 %) than the reference mortar (ratio 1:4) but around 22 % lower than the mix with the same concrete fines content and a 1:4 ratio.

It is thus concluded that the effect of reducing the cement content did not cancel out that of incorporating concrete fines.

Silva et al. [7] reached conclusions similar to those of our study. They found that a mix with a 1:6 cement-aggregate ratio, with 10 % ceramic fines, had an almost 11 % higher adhesive strength than the reference mortar.

5.4 Modulus of elasticity of hardened mortar

This test was based on the method of the resonance frequency according to French Standard NF B10-511F (1975) [38]. Three prismatic specimens of each type of mortar were cured for 28 days and were tested immediately afterwards. The results are presented in Table 5.

The results show that the reduction of a mortar's cement content has an opposite effect to that of incorporating concrete fines—it leads to a decrease of its modulus of elasticity: the mix with the lowest value was the II(0-1:5), with no recycled fines and the lowest cement content. A lower modulus of elasticity can be favourable since it better potentiates the accommodation of the initial deformations of the structure and reduces the stresses and the consequent tendency to cracking [11, 12, 18, 19]. However, a low modulus of elasticity does not by itself preclude cracking. In their study Miranda and Selmo [1] obtained high and low values of the modulus of elasticity in various mixes and none of them showed cracking. Other parameters must be analysed as well, such as the level of stress developed by the degree of restriction of the render, the tensile strength of the mortar [11, 18, 19] and the size and distribution of the pores.

The increase of the modulus of elasticity observed in the II(15-1:5) mortar relative to the reference mortar II(0-1:4) is around 10 %, which can be considered a small difference that does not greatly alter the behaviour of the mortar with respect to this property. In conclusion, the reduction of the cement content in the mortars with concrete fines incorporation does not have negative consequences and even leads to a better value (7.8 GPa) than for the mix with the same concrete fines content but greater cement content, II(15-1:4) (10.62 GPa).

5.5 Water vapour permeability of hardened mortar

This test was performed in accordance with European Standard EN 1015-19 (1998) [36], by the wet method.

Table 5 Results of the modulus of elasticity test

Mortar	Modulus of elasticity (GPa)
II(0-1:4)	7.11
II(15-1:4)	10.62
II(0-1:5)	3.80
II(15-1:5)	7.80

The water vapour was made to diffuse through a 20 mm thick mortar layer applied on a recipient, by the pressure difference created between the 98 % HR in the recipient and the 50 % HR outside it, in a climatic chamber. Three specimens of each type of mortar, consisting of a mortar disk 20 mm thick, were cured for 60 days and tested immediately afterwards. The results are presented in Table 6.

The results show that there is a significant increase in water vapour permeability for a lower cement content of the reference mortar with no recycled fines. This agrees with Veiga [19], i.e. high water vapour permeability is achieved by reducing the cement content. The addition of 15 % of concrete fines to the mix with a 1:5 cement-aggregate ratio caused the permeability value to fall slightly (around 3 %) relative to that of the reference mortar.

Low water vapour permeability is an unfavourable factor because it hinders the drying of the walls. But it can be argued that the decrease in this property compared with the reference mortar and the mix with reduction of the cement content and simultaneous incorporation of concrete fines is so low that is meaningless, again indicating an adequate performance of the modified mortar.

5.6 Susceptibility to cracking (restrained shrinkage)

This test was developed at the Portuguese National Laboratory of Civil Engineering (LNEC) by Veiga [18, 24–26]. It is described in LNEC's test form FE Pa 37 [37], and is based on two criteria:

- *S*—first-crack coefficient, given by the ratio between the tensile rupture force (R_t) and the maximum force during the restrained shrinkage test ($F_{r\ max}$);

Table 6 Results of the water vapour permeability test

	Permeability [ng/(m.s.Pa)]	Thickness or air diffusion layer equivalent to 20 mm of mortar (m)
II(0-1:4)	22.70	0.16
II(15-1:4)	18.62	0.20
II(0-1:5)	27.69	0.13
II(15-1:5)	21.97	0.17

- R—resistance to cracking evolution coefficient, given by the ratio between the rupture energy in the tensile test and the maximum force during the restrained shrinkage test.

The mortars are classified in terms of their susceptibility to cracking, as shown in Table 7.

The results obtained in the two criteria are presented in Table 8. They show that, notwithstanding the reduction of the cement content, the cracking susceptibility of mix II(15-1:5) is classified as medium, just like mixes II(0-1:4) and II(15-1:4). When compared with the mix with same concrete fines content but greater cement-aggregate ratio II(15-1:4), however, there was less tendency for micro-cracking to appear, even though the tendency was still higher than for the reference mortar. According to Joisel [27] the greater the cement content the higher the cracking susceptibility: relaxation decreases and shrinkage increases, giving rise to greater stresses that are not offset by the improved strength.

The tensile strength of mix II(15-1:5) is lower than that of the other mixes and this is reflected in the lower value of the first-crack safety coefficient (S). But while the rupture energy (G) increases there is a greater increase of the restrained stress, and the rupture energy even decreases in the mix with lower binder content; that is why the resistance to the cracking evolution coefficient (R) showed a decreasing trend.

Table 7 Classification of rendering mortars in terms of susceptibility to cracking [18, 24]

Susceptibility to cracking class		
1 (Low)[a]	$S \geq 1$	$R \geq 1$
2 (Medium)[a]	$S \geq 1$	$0.6 \leq R < 1$
3 (High)[b]	$S < 1$	$R < 0.6$

[a] Must comply with both criteria to belong to class

[b] Only needs to comply with one of the criteria to belong to class

It is concluded that the level of incorporation of concrete fines studied and the reduction of the cement content led to the mortar being slightly more susceptible to cracking, which is considered moderate and not very different from that of the reference mortar.

6 Conclusions

The results from this study on mortars with incorporation of crushed concrete fines and simultaneous reduction of the cement content led to surprisingly good results, given the initial expectations.

With respect to the mortars' mechanical performance and compared with the reference mortar (cement-aggregate ratio 1:4 and no concrete fines) it was found that the mix with the cement content ratio of 1:5 and containing 15 % concrete fines had increments of 30 % in compressive strength and 6 % in adhesive strength. The mix with 1:6 cement content ratio and 15 % concrete fines, on the contrary, showed a decline in compressive strength, revealing that the incorporation of concrete fines in this mix was not enough to compensate for the effect of reducing the cement content. Reducing the cement content negatively affected the flexural strength of the mixes containing 15 % concrete fines by 14 and 50 % for the ratios 1:5 and 1:6 respectively. The 50 % fall may raise doubts about the mechanical performance of the corresponding mix but a 14 % reduction for the 1:5 ratio is not very significant and should not jeopardize the fulfilment of the mortar's mechanical requirements.

Positive results were obtained in both the water absorption by capillarity test and the water retentivity test when the mixes' cement content was reduced. For the mix with 1:5 ratio and 15 % concrete fines there was a 30 % decrease in the capillary absorption coefficient and a 13 % increase in water retentivity. For the mix with 1:6 ratio and the same concrete fines content the result of the water absorption by capillarity

Table 8 Characteristics of the mortars subjected to restrained shrinkage test

Mortar	$F_{r\ max}$ (N)	R_t (N)	G (N mm)	S	R (mm)	Classification
II(0-1:4)	56.0	266.0	54.9	4.75	0.98	Medium
II(15-1:4)	76.3	213.3	60.3	2.80	0.79	Medium
II(15-1:5)	54.8	125.8	48.2	2.30	0.88	Medium

$S = R_t/F_m$, $R = G/F_m$

test was also positive, revealing a decrease of around 21 % in the capillary absorption coefficient.

The results of the water vapour permeability, shrinkage and modulus of elasticity tests were not quite as good as those for the reference mortar. However, the difference between the mix with a cement-aggregate ratio of 1:5 and 15 % concrete fines and the reference mortar was only 3 % in the water vapour permeability test (which is considered almost nil in experimental terms, given all the factors that may affect the results), 10 % in the modulus of elasticity test and a significant 39 % in the shrinkage test. Furthermore, and even though the incorporation of concrete fines and reduction of cement content affected these properties negatively, the values were better than those for mixes with the same concrete fines content and no cement content reduction.

Susceptibility to cracking was very slightly affected but kept the same classification (medium) as the reference mortar in terms of tendency to crack.

In conclusion, the viability of reducing the cement content and simultaneously incorporating fine concrete waste in masonry mortars without significant reduction of performance was confirmed, based on a large set of properties: mechanical characteristics, water protection capability, applicability (workability and water retention), and cracking susceptibility. Some of these properties, very important to the effective use of mortars in masonry, especially for renders and plasters, were seldom determined and evaluated as a whole, based on the literature.

Given all these results, which are considered quite acceptable for render/plaster mortars, plus the fact that some of the properties have been considerably improved, it seems perfectly reasonable and quite safe (in terms of efficiency and durability) to use this type of mortars in practice, namely to reduce the cement-aggregate ratio to up to 1:5 and incorporate up to 15 % of fine recycled concrete aggregates.

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