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Incorporation of fine concrete aggregates in mortars

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HIGHLIGHTS

- ▶ It is feasible to use very fine particles from demolition of concrete in mortars production.
- ▶ These particles are a serious environmental problem that can be turned into an opportunity.
- ▶ Most of the more important characteristics in coating mortars performance improve.
- ▶ This is a contribution to reduce the need for dumping grounds and natural re-sources dilapidation.
- ▶ It also has benefits from an economical point of view.

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ABSTRACT

This paper presents a study of performance evaluation of cement-based mortars incorporating very fine aggregates from recycled concrete. A series of standardized tests were performed during the experimental programme with the objective of improving the performance of the mortars in terms of strength, water absorption, shrinkage, and water permeability. The research results were very positive since some of the properties of most modified mortars improved, showing that it is feasible to use up to 15% of recycled concrete fines in mortar composition.

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1. Introduction

The economic development of a country is greatly influenced by its construction industry. Notwithstanding this positive effect it is also necessary to take into account the negative consequences on the environment.

Intense industrialisation, the advance of new technologies, population growth, internal emigration to urban centres and diversification of the use of goods and services, have caused waste to become a serious urban problem that is costly and complex to manage. The outcome is scarcity of dumping grounds which is made worse by the occupation and rising value of urban areas, high social costs of waste management and public sanitation and environmental contamination problems [1–5].

Therefore it is vital to intervene and find solutions other than sending construction and demolition waste to dumping grounds, since this is harmful to the environment. One of the ways is to recycle waste since there is great potential for reusing these materials, 75% of which come from natural resources [2,5]. However, one must bear in mind that even though waste generation must be reduced there are limitations due to impurities in their composition and to the quite considerable cost and technological development involved [2].

Therefore this work's main objective is to reuse the finest material from construction and demolition waste, which is crushed concrete from demolition jobs, and evaluate how its incorporation affects the performance of mortar. A filler effect – filling of the voids within the mortar structure – was expected, which would improve the mechanical and durability performance by making the mix more compact.

2. State-of-the-art

Recycling waste as mortar and concrete aggregate has various sustainability-related benefits. The understanding that recycling

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is important for sustainability has led various countries to adopt specific political guidelines to help realise its potential.

The properties of recycled aggregates are generally less useful than those of natural aggregates, which raises the issue of finding the optimal replacement ratios to most improve the quality-defining characteristics of mortars [6].

Particle size distribution and shape greatly influence the ratio of voids within the mortar, thus conditioning its performance. As the void ratio decreases so less binder and water is required to make a mortar, and then shrinkage also decreases [7].

The plasticity of mortars also depends on the smaller than 0.075 mm fines content (binder included). These fine particles improve the internal cohesion of the mix, enabling the mortar to maintain the deformation imposed by the mixing process, since smaller grains show higher surface tension forces [8].

Angelim et al. [9] and Fragata and Veiga [10] found that adding fines to cement and lime mortars, particularly limestone powder, granulite (granular metamorphic rock consisting mainly of feldspar and quartz) powder, and mica-schist and gravel powder, gives them higher workability and shortens application time compared with unmodified mortars.

According to Ishikawa [11] all fine materials, i.e. cement and lime binders, clay-related minerals in gravel and other inert materials, have a high specific surface and therefore influence the plasticity of mortar. Workability improves with higher inert fines content.

Very probably because there is a higher content of powder material in processed aggregates than in natural ones, Silva and Campiteli [12] found there is less incorporated air in mortar made with ground sand than in mortar made with natural sand.

As for concrete, the content of fine particles in the mix can significantly influence the amount of mixing water needed, thus leading to a decrease in the wear resistance, especially by abrasion [13,14].

The workability of concrete with recycled aggregates for the same w/c ratio is lower, especially when the replacement ratio exceeds 50% [15]. One of the solutions proposed in order to improve the workability is to change the humidity status of the recycled aggregates before mixing, thus reducing the mixing water absorption effect and leading to a more workable mix [16].

In the Poon et al. [17] study about the influence of recycled aggregates on the consistency and loss of fluidity of concrete, it was concluded that most of it is lost in the first hour after mixing, and more so with the recycled aggregates than the natural ones.

According to a study by Silva et al. [18] on how filler made from ground limestone influences the properties of coating mortar, this addition improves the test results, leading to an increase in compressive and flexural strength and tensile adherence, but it also has an adverse effect because of the formation of visible cracking. The presence of the filler was also found to favourably influence the water absorption and void content results.

Silva et al. [6] concluded that the incorporation of ceramic fines in mortar (5% and 10% of total aggregates volume) significantly improves their performance in terms of compressive and flexural strength. A filler effect, a lower water/cement ratio and a possible pozzolanic effect [19] of the clay brick fines were indicated as explaining these trends. These researchers also investigated the direct replacement of natural sand by ceramic fines with exactly the same grading size distribution (i.e. maximising recycling potential) with interesting results [20].

Khatib [21] observed systematic reduction of the compressive strength of concrete with the incorporation of fine recycled concrete aggregates. According to Correia et al. [22], the compressive strength of concrete can significantly change with the properties of the aggregates used to produce the original concrete.

Leite [23] found that for low water/cement ratios the strength of conventional concrete is greater than that of concrete with recycled aggregates while the inverse may occur as that ratio increases. In the Khatib [21] study the replacement of natural aggregates with fine recycled brick and concrete aggregates resulted in a reduction of the dynamic modulus of elasticity.

Previous studies on the incorporation of fines in mortars suggest that the very fine recycled crushed concrete aggregates filling up voids in the mortar would improve its properties through the so called filler effect and a possible hydraulic effect (linked to unhydrated cement in the recycled aggregates). There is therefore a good chance of the modified mortars showing an improvement in mechanical strength and a reduction in capillarity, both due to improved compaction and densification. However, increased shrinkage and cracking vulnerability are possible negative effects to be expected.

3. Experimental programme

In order to establish the expected results various standard tests were performed on mortars with different replacement ratios of sand by fine recycled concrete aggregate. The original concrete was the one produced in laboratory within an on-going PhD thesis. Therefore the aggregates were uncontaminated. The average 28 day compressive strength of this concrete was 28.7 MPa and its composition is given in Table 1.

Only the aggregates with size <0.150 mm, obtained by sieving, were incorporated in the mortars.

Only the size distribution (Fig. 2) and apparent bulk density of the recycled aggregates were determined. Their behaviour and the way they reacted chemically were analysed only within the mortars. The presence of unhydrated cement was studied in a second stage of this research when part of the cement was replaced by fine recycled concrete aggregates. Those results are not presented here.

The performance of these modified mortars was compared with that of a conventional mortar, made only of cement, sand and water (hereafter called reference mortar).

The experimental programme was divided into two stages: the first was to choose, by a process of elimination) the mortar that performed best for the various properties under analysis from a set of mortars having different replacement ratios of sand by concrete fines; in the second stage only the selected mortar and the reference mortar were tested, the intention being to evaluate other relevant mortar characteristics and conclude on the feasibility of the use of fine recycled concrete aggregates.

The mortar mixes tested, all with the same volumetric ratio (1:4; cement: aggregates), are described next:

- I(0–1:4) – 0% incorporation - reference mortar.
- I(5–1:4) – 5% incorporation.
- I(10–1:4) – 10% incorporation.
- I(15–1:4) – 15% incorporation.

The particle size distribution of sand and of concrete fines is given in Fig. 1. The apparent bulk density of the various components of the mortars (sand, concrete fines and cement) is given in Table 2. To that effect three specimens of each component were tested and the average of these results was used A 379.5 g 0.5 dm^3 container was used, according to the EN 1015-6 standard.

4. First stage

This experimental stage allowed initial characterisation of the various mortar mixes under analysis and made it possible to choose the one most suitable for the purpose.

Table 1
Original concrete composition.

Concrete constituents	kg/m^3	%
Coarse gravel	681	28.39
Fine sand	554	23.09
Fine gravel	171	7.14
Coarse sand	558	23.28
Cement II 42.5R	189	7.88
Fly ash	116	4.84
Water	126	5.27
Plasticizer	3	0.13

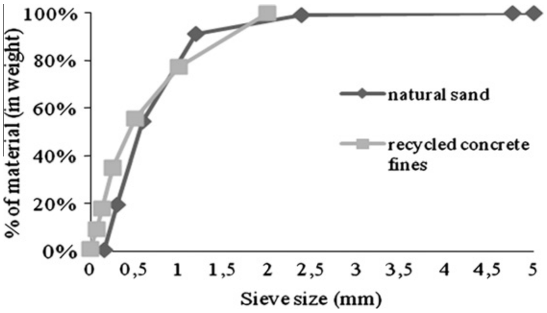

Fig. 1. Grading size distribution of natural sand and recycled concrete fines.

Table 2
Bulk density of the mortars' components.

	Apparent bulk density (kg/m^3)
Cement	1035
Sand	1433
Concrete fines <0.149 mm	842

4.1. Consistency of fresh mortar

The test was performed according to European Standard EN 1015-3 (1999) and its aim was to calibrate the water content to be added to the mix. The consistency parameter for rendering mortar is, according to the standard, 175 ± 10 mm, and this was used as the target value. The results are presented in Table 3.

As the incorporation ratio increased it was found that less water was needed to give the mix the target consistency because the voids previously filled with water were occupied by the very fine concrete particles (filler effect). A significant improvement of workability occurred during mixing as the incorporation ratio increased, indicating that the particles' size, shape and texture are relevant to this fresh-state property and justify a decrease in the water/cement ratio. The fine particles improve the internal cohesion of the mix, as reported by Selmo [8].

These results agree with those of Silva et al. [6] that also found that less water was needed as they studied the incorporation of up to 10% of ceramic fines.

Hudson [24] concluded that particles smaller than 150 μm may act as lubricants in the cement paste, as long as they are roundish, and this improves the workability and allows a reduction of the water/cement ratio.

On the other hand, Angelim et al. [9] found that it was necessary to increase the mixing water quantity to obtain the target workability when they used fines incorporation ratios between 20% and 40%.

Therefore, the literature identifies a trend of improved workability with the incorporation of fines but sensitive to their nature and content.

Table 3
Mixing water needed to achieve the target workability and corresponding results of the consistency test.

Mortar	Water/cement ratio	Water needed per dm^3 of mortar (ml)	Consistence (mm)
I(0–1:4)	1.41	220	170.8
I(5–1:4)	1.24	199	177.0
I(10–1:4)	1.18	191	176.5
I(15–1:4)	1.12	183	172.0

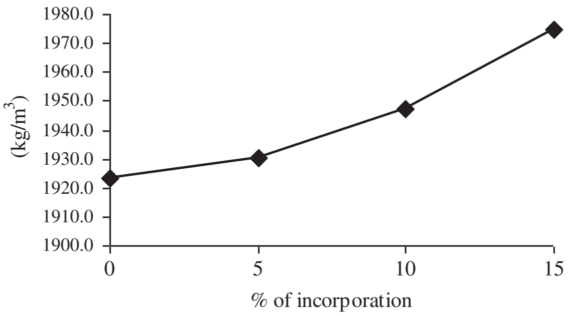

Fig. 2. Bulk density of fresh mortar for the incorporation ratios studied (average of three specimens: I(0–1:4) = 1923.4 kg/m^3; I(5–1:4) = 1930.2 kg/m^3; I(10–1:4) = 1947.2 kg/m^3; I(15–1:4) = 1975.0 kg/m^3).

4.2. Bulk density of fresh mortar

This test was performed according to European Standard EN 1015-6 (1998). Results are presented in Fig. 2.

Even though the concrete fines had a lower bulk density than sand, the fresh mortar bulk density increased when the former were incorporated. This is because of the reduction of the mortar's water content linked to the filler effect.

4.3. Dry bulk density of hardened mortar

The test was performed in accordance with European Standard EN 1015-10 (1999). Three specimens of each type of mortar were cured for 28 days and tested immediately afterwards. Results are presented in Fig. 3.

Just as for fresh mortar, an increase in bulk density was detected in hardened mortar as the concrete fines were incorporated. The reason is that the part of the voids in the mortar not occupied by sand is filed by the concrete fines, which are smaller. Thus, as the replacement ratio increases there are fewer voids initially occupied by water and the mortar becomes more compact. In tune with these results Ishikawa [11] found that a higher content of particles that pass through a 0.150 mm sieve helps to decrease the air content, pack the mix particles better, and thus to increase the bulk density.

Just as for fresh mortar the filler effect prevailed over the effect of lower bulk density of the concrete fines compared with sand, for the incorporation ratio range tested.

4.4. Flexural and compressive strength of hardened mortar

This test was performed according to European Standard EN 1015-11 (1999). Three specimens of each type of mortar were

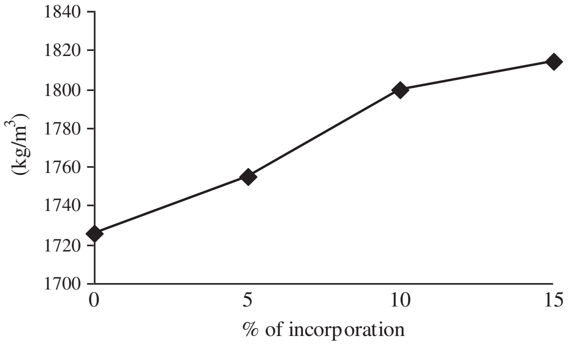

Fig. 3. Dry bulk density of hardened mortar for the incorporation ratios studied (average of three specimens: I(0–1:4) = 1725.8 kg/m^3; I(5–1:4) = 1754.6 kg/m^3; I(10–1:4) = 1799.6 kg/m^3; I(15–1:4) = 1814.5 kg/m^3).

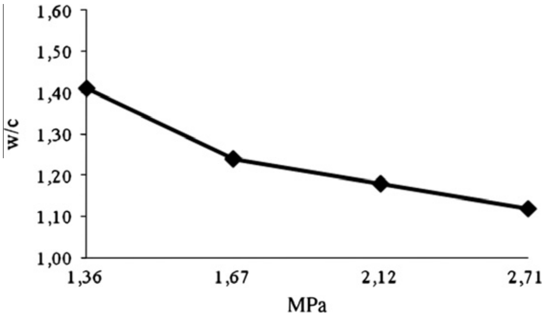

Fig. 4. 28-Day flexural strength of hardened mortar for the incorporation ratios studied vs. w/c (average of three specimens: I(0–1:4) = 1.36 MPa; I(5–1:4) = 1.67 MPa; I(10–1:4) = 2.12 MPa; I(15–1:4) = 2.71 MPa).

cured for 28 days and tested immediately afterwards. The results are presented in Figs. 4 and 5, as a function of the w/c ratio.

The graphs show a significant, almost linear, improvement of the mortars' mechanical strength, both flexural and compressive, as the concrete fines incorporation ratio increases. According to Angelim et al. [9] these results may be justified by the presence of fines in the mix (filler effect), the lower water/cement ratio than in the reference mortar and possibly a hydraulic effect of the concrete fines. All these reasons are also applicable in the present case. As a matter of fact Figs. 4 and 5 show that the strength increase, both compressive and flexural, can be correlated with the water reduction and it is possible that the concrete cement could still undergo some hydration after it is introduced in the mortars as part of the aggregates and could therefore contribute to the strength increase. Additionally, the existence of fly ash in the concrete used for recycled aggregates justifies that some slow reactions can still occur with the cement used for the mortar.

The improvement of the mechanical strength of the modified mortars is in agreement with the results of other authors who have studied the incorporation of fines in mortar. The comparison in terms of flexural strength (Fig. 6) shows that Silva et al. [6] obtained higher values than ours with the incorporation of ceramic fines and that, from a given ratio on (10%), the results from our study were better than those obtained by Angelim et al. [9]. Whilst our work and that of Silva et al. [6] show a monotonic improvement trend with the incorporation of fines, Angelim et al. [9] found an opposite trend, except partially for limestone filler. Silva et al. [18] also found an increase in flexural strength when ground sand (6%) was incorporated, but this was less significant than with ceramic and concrete fines.

As for compressive strength, when comparing the results of our study with those of Angelim et al. [9], Silva et al. [6] and Silva et al. [18] (Fig. 7), all mixes with ≈5% fines incorporation ratio showed an increase relative to the reference mortar; but for higher percentages this trend only holds for the incorporation of ceramic and concrete fines. Mortars with 15% granulite and mica-schist fines showed lower strength than the mix without fines.

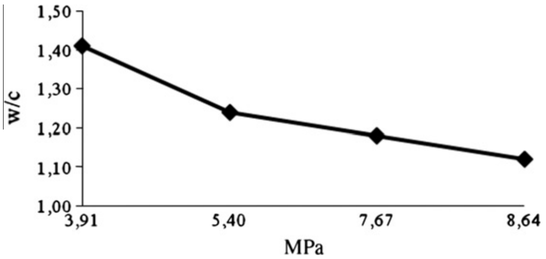

Fig. 5. 28-Day compressive strength of hardened mortar for the incorporation ratios studied vs. w/c (average of three specimens: I(0–1:4) = 3.91 MPa; I(5–1:4) = 5.40 MPa; I(10–1:4) = 7.67 MPa; I(15–1:4) = 8.64 MPa).

Finally, only when ceramic fines were incorporated in the mortar was mechanical performance better than for the mortars with concrete fines from our study.

4.5. Water absorption due to capillary action of hardened mortar

This test was performed according to European Standard EN 1015-18 (2002). Three specimens (semi-prisms) of each type of mortar were cured for 28 days and laterally waterproofed and tested immediately afterwards. The results are presented in Fig. 8.

Higher strength in mortar generally corresponds to a higher compacity and therefore a lower absorption coefficient. When part of the sand is replaced with fine particles these will fill some of the voids, leaving mostly very small pores of hardened mortar that hinder water circulation and therefore capillary water flow is smaller. The reduction of porosity results in lower total water absorption by capillarity, while the smaller pore size leads to a decrease of the absorption rate (lower coefficient of capillarity) [25].

It is thus concluded that this mortar property improves significantly as the concrete fines incorporation ratio increases up to at least 15% (maximum amount tested in this work). The additional justifications given in 4.4 for the strength increase with the recycled aggregates are also possible reasons for the decrease of capillary absorption. In fact, the water reduction in the mortars with recycled aggregates, together with retarded hydration and fly ash reaction of the concrete used for the aggregates, could also contribute to improve the water absorption performance.

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).

At the end of the water absorption test, the drying test begins, in the same conditioned environment. It consists on monitoring the water loss during the period needed to achieve an asymptotic value close to the dry weight (weight before the absorption test). Measurements of the weight are made at 30, 60, 90, 270, 450, 1440 min and, after that, every 24 h.

The specimens' performance during drying is presented in Fig. 9.

The drying graph shows that incorporating concrete fines up to 15% of total aggregates volume does not greatly influence drying, which is quite similar to that found for 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 predetermined period. None of the mortars under test showed any signs of cracking after 9 months (Fig. 10). The mortar was applied to very small area, however, and application procedures in the laboratory are different from those on site, and therefore this test merely indicates that nothing serious is expected to happen in this respect.

4.8. Selection of mortars for the second stage

After the first stage tests were completed one of the three modified mortar mixes was chosen for the second stage: the one with 15% incorporation because it provided the best results in all the properties analysed. It is feasible that results could be even better

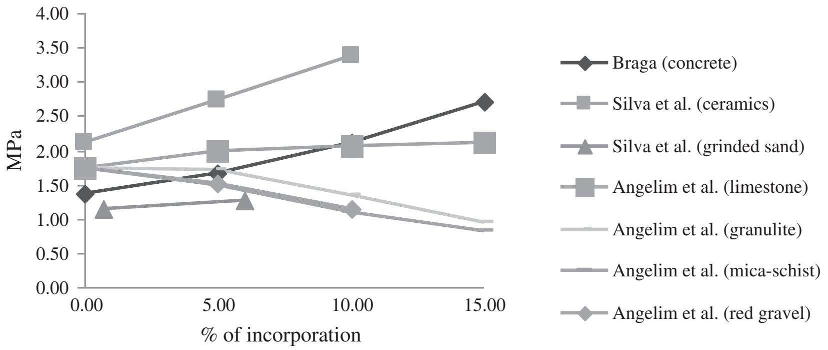

Fig. 6. Comparison of the interpolated results obtained for 28 day flexural strength of hardened mortar with those of Silva et al. [6,18], and Angelim et al. [9].

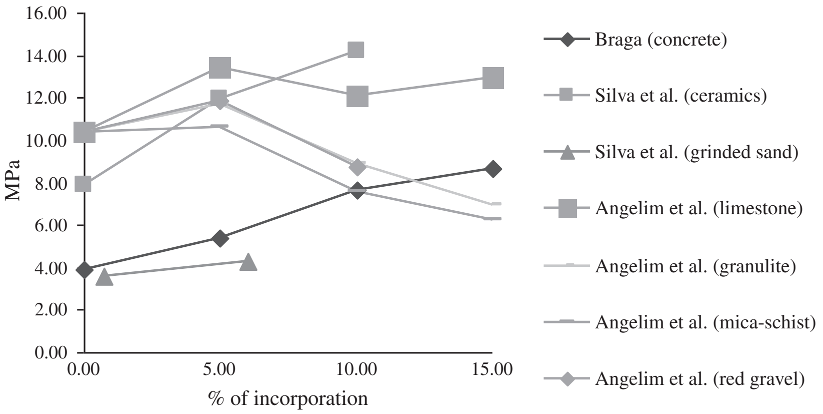

Fig. 7. Comparison of the interpolated results obtained for 28 day compressive strength of hardened mortar with those of Silva et al. [6], Silva et al. [18] and Angelim et al. [9].

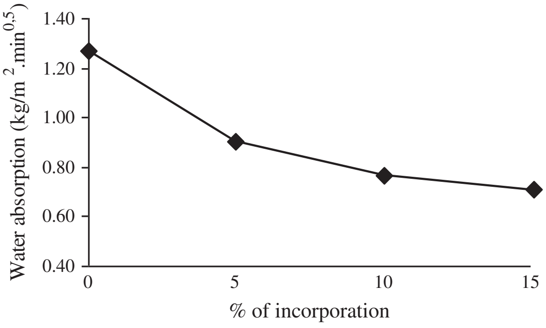

Fig. 8. Water absorption due to capillary action of hardened mortar for the incorporation ratios studied (average of three specimens: I(0–1:4) = 1.270 kg/(m^2 min$^{0.5}$); I(5–1:4) = 0.905 kg/(m^2 min$^{0.5}$); I(10–1:4) = 0.764 kg/(m^2 min$^{0.5}$); I(15–1:4) = 0.708 kg/(m^2 min$^{0.5}$)).

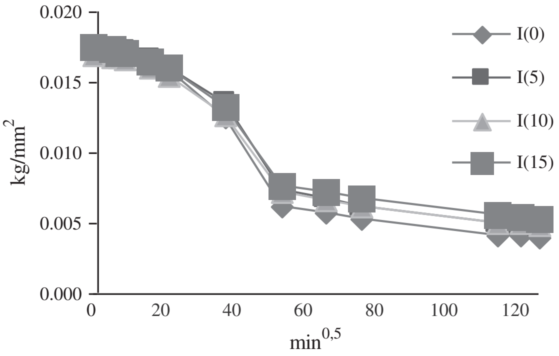

Fig. 9. Mortars' drying progress for the incorporation ratios studied.

if a higher ratio than 15% were tested, which would be positive in terms of maximising recycling.

However since that was not proved by actual tests, a conservative figure of 15% was adopted, an option that was proved correct in light of the results from the second stage.

5. Second stage

The only mortar mixes tested in this stage were the reference mortar and the mix selected in the first stage (I(15–1:4)). The purpose was to study other important characteristics of mortar performance and characterise the benefits and drawbacks of incorporating concrete fines.

5.1. Water retentivity of fresh mortar

This test was performed according to European Standard EN 1015-8 (1999). Three specimens of fresh mortar, of each mix, were used. The results are presented in Table 4.

The table shows that the modified mortar has higher water retentivity than the reference mortar. This difference is explained by the addition of fines since they hinder the exit of water from the mortar mass. But this is contrary to the findings of Ishikawa [11], cited by Silva et al. [18], which concluded that increasing the fines content did not contribute to water retentivity. Silva et al. [6], however, obtained results concurring with those from our study. They found a 13% increase in the mortar's capacity to retain water after adding 10% of ceramic fines.

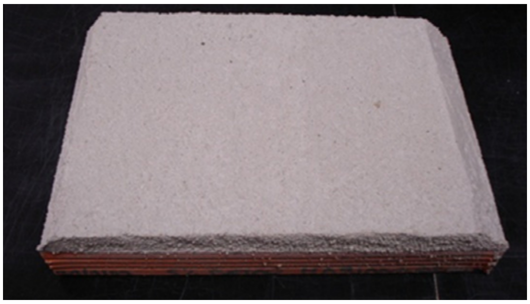

Fig. 10. Result of the test of susceptibility to cracking.

The capacity of mortar to retain water is important because it prevents eventual problems such as excessive water absorption by the substrate onto which the mortar is applied, and rapid water loss from the mortar with consequent poor cement hydration. The first problem may lead to expansion of the substrate and greater probability of shrinkage when drying; the second leads to loss of adhesive strength in the substrate/mortar interface because the mortar layer is insufficiently hydrated [26].

Therefore it was concluded that this increase in water retentivity, as long as it does not worsen other mortar properties such as water vapour permeability, is likely to improve the main characteristics of mortars in most circumstances, making them less sensitive to porosity and the substrate's moistness.

5.2. Dimensional instability (shrinkage)

This test was performed according to draft European Standard prEN 1015-13 (1993). Three specimens (prisms) of each type of mortar were tested immediately after demolding. The results are presented in Fig. 11.

The results show that there is a significant increase in the shrinkage of the modified mortar (around 44%) compared with the reference mortar.

According to the literature, increased shrinkage is to be expected from the incorporation of recycled aggregates. Nevertheless it is important to check whether this leads to a significant build-up of cracks, which was evaluated with a test for cracking susceptibility.

Having found that shrinkage increased in concrete with recycled aggregates by between 40% and 80% compared with concrete with natural aggregates, Hansen [27] explains this with the high content of hardened mortar bonded to the recycled aggregates surface.

According to Neville [20] increased plastic shrinkage is linked to three factors: low exudation rates, high autogenous shrinkage and high capillary pressure due to the fineness of the cementitious materials.

Comparing the results of our study with those of Silva et al. [6], Silva et al. [18] and Angelim et al. [9] (Fig. 12), they all also found an increase in shrinkage when fines were incorporated compared with the reference mortars. Only the 5% mica-schist incorporation mortar registered a decrease in shrinkage, which seems to result from an experimental error. The mortar with red gravel fines showed a very significant increase in shrinkage that may have negative consequences.

Table 4
Results of the water retentivity test.

Mortar	Water retentivity (%)
I(0–1:4)	63.81
I(15–1:4)	79.59

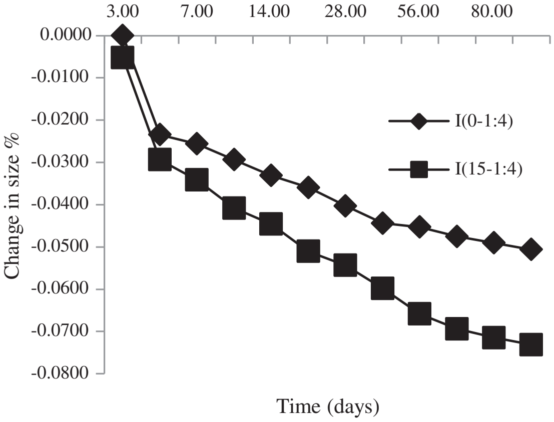

Fig. 11. Time relative to size variation.

5.3. Adhesive strength of hardened mortar

This test was performed according to European Standard EN 1015-12 (2000). 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 5.

There was a significant improvement in the mortar's adherence capacity with the incorporation of 15% concrete fines. The rupture of the reference mortar cores was mostly cohesive and it occurred within the coating layer. In the case of the modified mortar rupture was adhesive (between the coating and the substrate), which is due to the mortar's higher tensile strength.

Silva et al. [6] obtained results very close to ours for a mortar made with 10% ceramic fines, with a significant improvement relative to their reference mortar.

Silva et al. [18] also obtained an increment of adherence capacity by adding 6% of ground sand fines.

On the other hand Paes et al. [29] found a slightly declining adhesive strength trend as the fines content increased. But the incorporation ratios studied are higher than those in our study which may suggest that after a certain replacement percentage the adhesive strength tends to decrease. Also Scartezini [30] and Amorim et al. [31] concluded in separate studies that mortar with higher fines content tends to have lower substrate absorption and less adhesive strength.

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). Three prismatic specimens of each type of mortar were cured for 28 days and were tested immediately afterwards. The results are presented in Table 6.

The dynamic modulus of elasticity expresses the hardened mortar's stiffness due to cement hydration, the arrangement of the aggregate particles, given their shape and their rugosity, and the content of powdery material. Water consumption and cement content are determining parameters in compressive, flexural and adhesive strength, which directly influence the modulus of elasticity.

Table 6 shows an increase in the mortars' modulus of elasticity as concrete fines are incorporated.

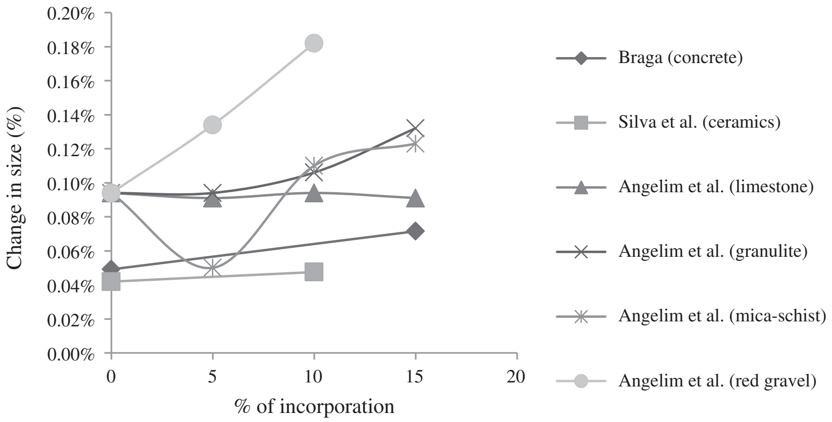

Fig. 12. Comparison of the interpolated results obtained for 80 day shrinkage of hardened mortar with those of Silva et al. [6] and Angelim et al. [9].

Table 5
Results of the adhesive strength test.

Mortar	Adhesive strength (MPa)	Predominant rupture type
I(0–1:4)	0.33	B
I(15–1:4)	0.45	A

A – adhesive rupture (in the interface coating-substrate); B – cohesive rupture (within the coating).

Silva et al. [18] obtained a higher modulus of elasticity for mortars made with ground sand than for those made with natural sand. They say the main reasons are a higher powdery material content which leads to better packing of the particles, and consequently greater mass density. Furthermore, the water demand in mortars with ground sand was lower and that may also have helped to increase their modulus of elasticity, given that mechanical characteristics decline as the water/cement ratio grows.

The reasons proposed by Silva et al. [18] for the modulus of elasticity improvement apply equally to our study. In modified mortar I(15–1:4) there was a lower water content and higher compacity and stiffness.

Silva et al. [6] noted a slight decrease in mortars with 10% ceramic fines compared with the reference mortar. These results disagree with those from our study and those of Silva et al. [18]. Silva et al. [6] believe that the closeness of the results in this test is due to the similarity of the mortar mixes tested, since only 10% by volume of the aggregates was replaced.

In conclusion, an increase of almost 50% was found in the modulus of elasticity of the mortar with 15% concrete fines relative to the reference mortar, which may have a negative effect under certain circumstances because higher stiffness represents higher internal stresses, less deformation and greater risk of rupture. But it was expected that the improvement of some of the mortars' properties with the incorporation of concrete fines would also lead to a slight decline in some of the others.

5.5. Water vapour permeability of hardened mortar

This test was performed in accordance with European Standard EN 1015-19 (1998). Three specimens of each type of mortar, consisting of a mortar disc 20 mm thick, were cured for 60 days and tested immediately afterwards. The results are presented in Table 7.

Table 6
Results of the determination of the modulus of elasticity.

Mortar	Modulus of elasticity (GPa)
I(0–1:4)	7.11
I(15–1:4)	10.62

The table shows that the modified mortar has around 18% lower water vapour permeability than the reference mortar. Water vapour permeability helps to dry the wall and stops the condensation of water on its surface. However, the decrease can be considered small in this case, i.e. the mortar still performs adequately.

The results of our study agree with those of Silva et al. [6] who also found a ≈20% reduction in water vapour permeability in mortars with 10% ceramic fines, and those of Angelim et al. [9] who concluded that fines incorporation decreases water permeability in general.

5.6. Susceptibility to cracking (restrained shrinkage)

This test was developed at the Portuguese National Laboratory of Civil Engineering (LNEC) by Veiga [32,33]. It is described in LNEC's test form FE Pa 37, and is based on two criteria:

- CSAF – first crack coefficient, given by the ratio between the tension rupture force (R_t) and the maximum force during the restrained shrinkage test ($F_{r\ max}$);
- CREF – 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 8.

Results obtained in the two criteria are presented in Table 9.

It can be seen that the reference mortar I(0–1:4) may be considered to have low susceptibility to cracking, albeit near the limit, while the modified mortar, classified as having medium susceptibility to cracking, shows a reduction in both coefficients, thus indicating a decline, albeit moderate, in this property. These results agree with those from the dimensional instability test, where an increase in shrinkage was found for the modified mortar.

The fact that the reference mortar has higher water content and is more porous should have led to a decrease in its tensile strength,

Table 7
Results of the water vapour permeability test.

Mortar	Water vapour permeability	
	Permeability (ng/(ms Pa))	Diffusion coefficient
I(0–1:4)	22.7	8
I(15–1:4)	18.62	10

Table 8
Classification of coating mortars in terms of susceptibility to cracking [32,33].

Susceptibility to cracking class		
1 (Low)[a]	CSAF $\geqslant$ 1	CREF $\geqslant$ 1
2 (Medium)[a]	CSAF $\geqslant$ 1	0.6 $\leqslant$ CREF < 1
3 (High)[b]	CSAF < 1	CREF < 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.

Table 9
Characteristics of the mortars subjected to the restrained shrinkage test.

Mortar	$F_{r\,max}$ (N)	R_t (N)	G (N mm)	CSAF	CREF (mm)	Classification
I(0–1:4)	56.0	266.0	54.9	4.75	1.0	Low
I(15–1:4)	76.3	213.3	64.0	2.80	0.8	Medium

which did not occur. According to Veiga et al. [32,33] the test environment (23 °C and 50% RH), which was very dry, may hinder complete hydration of the cement, and in those circumstances the mortar with more water available favours cement hydration, which increases tensile strength and thus offsets its higher porosity. The fact that part of the sand was replaced by smaller aggregates (the concrete fines) also tends to increase susceptibility to cracking. According to Sousa Coutinho [34], when the aggregate size increases, shrinkage develops more slowly because there is a greater possibility of dissipating stresses. For finer aggregates, on the contrary, the maximum stress is constant for longer, which promotes rupture.

6. Conclusions

After a thorough analysis of the results of the first stage of the experimental programme it was concluded that all the modified mortar mixes showed very satisfactory performances, with improvements in most of the properties of the reference mortar that were studied. The mortar with the highest (15%) concrete fines incorporation ratio stood out as the one with the best results.

In the flexural strength test, mortars I(5–1:4), I(10–1:4) and I(15–1:4) obtained increments of 23%, 56% and 99%, respectively, relative to the reference mortar. In the compressive strength test, the corresponding results were 38%, 96% and 121%, respectively. The capillary water absorption coefficient decreased (by 29%, 40% and 44% in the same mortar order as above) as the incorporation ratio increased, which were very satisfactory values.

In the second experimental stage other mortar characteristics were studied in depth for the modified mortar I(15–1:4) selected in the first stage. In the substrate adhesive strength and water retentivity tests the modified mortar behaved better than the reference mortar, with relative increases of 36% and 25%, respectively. In the water vapour permeability, modulus of elasticity and dimensional instability tests mortar I(15–1:4) behaved worse than the reference mortar, showing a relative decrease of 18%, an increase of 49% and an increase of 49%, respectively. In the test for susceptibility to cracking by restrained shrinkage there was a slight increase, changing the evaluation class from low to medium.

In conclusion, taking into account the requirements of a coating mortar and the environment it is subjected to after application, the incorporation of concrete fines may offer some advantages in terms of performance, which will be a bonus to the environmental benefit of reusing a type of waste that is produced in great quantities. From the results obtained in the first stage it is reasonable to assume that the performance improvements would have been even greater if a slightly lower concrete fines incorporation ratio had been used in the second stage.

Standards used in the experimental work

- EN 1015-1, European Standard, “Methods of test for mortar masonry – Part 1: Determination of particle size distribution (by sieve analysis)”, European Committee for Standardization (CEN), October 1998.
- EN 1015-3, European Standard, “Methods of test for mortar for masonry – Part 3: Determination of consistence of fresh mortar (by flow table)”, European Committee for Standardization (CEN), February 1999.
- EN 1015-6, European Standard, “Methods of test for mortar for masonry – Part 6: Determination of bulk density of fresh mortar”, European Committee for Standardization (CEN), October 1998.
- prEN 1015-8, draft European Standard, “Methods of test for mortar for masonry – Part 8: Determination of water retentivity of fresh mortar”, European Committee for Standardization (CEN), October 1998.
- EN 1015-10, European Standard, “Methods of test for mortar for masonry – Part 10: Determination of dry bulk density of hardened mortar”, European Committee for Standardization (CEN), August 1999.
- EN 1015-11, European Standard, “Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar”, English European Committee for Standardization (CEN), August 1999.
- EN 1015-12, European Standard, “Methods of test for mortar for masonry – Part 12: Determination of adhesive strength of hardened rendering and plastering mortars on substrates”, European Committee for Standardization (CEN), February 2000.
- prEN 1015-13, draft European Standard, “Methods of test for mortar for masonry – Part 13: Determination of dimensional stability of hardened mortars”, European Committee for Standardization (CEN), February 1993.
- EN 1015-18, European Standard, “Methods of test for mortar for masonry - Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar”, European Committee for Standardization (CEN), December 2002.
- EN 1015-19, European Standard, “Methods of test for mortar for masonry - Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars”, European Committee for Standardization (CEN), September 1998.
- FE Pa 37, Test form – Test of susceptibility to cracking - Coatings of mineral binders for walls (in Portuguese), Portuguese National Laboratory of Civil Engineering (LNEC), Lisbon, March 1998.
- NF B 10-511, Norme Française Homologué, “Mesure du module d’élasticité dynamique”, Association Française de Normalisation (AFNOR), Avril 1975.
- CAHIER 2669-4, Certification CSTB des enduits monocouches d’imperméabilisation, “Modalités d’essais”, Centre Scientifique et Technique du Bâtiment, Juillet/Août 1993.

7. Uncited reference

[28].

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