TÉCNICO LISBOA

Performance of mortars with incorporation of fine aggregates from construction and demolition waste recycling plants

Filler effect and partial replacement of cement

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Master Thesis in Civil Engineering

Extended abstract

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1. Introduction

The global market of cement and construction aggregates is expected to increase due to the growing trend in the construction sector in developing countries (Freedonia, 2015; Freedonia, 2013). On the other hand, the construction and demolition waste (CDW) and its management are a major obstacle to the sustainability of the construction sector. In 2012, in the European Union (EU), over 2,5 billion tonnes of waste were generated and the construction sector is one of the largest contributors, representing 33% of this value (Eurostat). In Portugal, in the same year, approximately 928,000 tonnes of CDW were produced, of which 85% are minerals and solid waste (APA).

Despite the creation of legislation for the management of CDW (Decree No. 73/2011 of June the 17th), Portugal remains still very far from meeting the target of 70% reuse or recycling of CDW (by weight) in 2020, advocated by the European Union (EU). CDW has a high potential for recycling and reuse, since most of its components have a high resource value (European Commission). Thus, the aggregates market is an alternative for the recycling of CDW (Eurostat). Nevertheless, recycling plants have some difficulty in putting on the market these aggregates, mainly due to lack of experience in using them, difficulty in ensuring the quality of recycled materials as well as buyer's lack of confidence (European Commission - DG ENV, 2011).

Regarding this problem, a research line has been developed at Instituto Superior Técnico, in which several studies have focused on the behaviour of mortars with incorporation of fine recycled aggregates of construction waste such as ceramics, concrete, glass and sanitary ware and have provided positive prospects concerning their use. Therefore, the incorporation of CDW in rendering mortars arises as the next step. The aim of this investigation is to contribute to the study of an alternative to natural aggregates, preventing its extraction and decreasing the deposition of waste in landfills and also finding materials that can partially replace cement and thus reduce the CO_2 emissions, mitigating the environmental impacts associated to its production.

2. Experimental campaign

This experimental campaign was divided in two vectors:

- Vector I: incorporation of very fine recycled aggregates, in which the filler effect is evaluated. These particles (lower than 0,149 mm) fill the voids between aggregates and thereby the mortars become more compact;
- Vector II: partial replacement of cement by incorporation of recycled aggregates.

In vector I, all the mortars had the same volumetric ratio of 1:4 (cement: aggregates) and the incorporation of recycled aggregates was made at 0%, 10%, 15% and 20% (of the volume of the sand). Regarding vector II, the cement content was reduced from the ratio 1:4 up to 1:5 and 1:6 and the simultaneous incorporation of recycled aggregates was studied, by producing three conventional mortars and four modified mortars. Only the particles of recycled aggregates below 0.149 mm were used, hereinafter called as RCA (recycled concrete aggregates), and RMA (recycled mixed aggregates). The recycled mixed aggregates may contain several common CDW materials such as ceramics, concrete, mortar and contaminants (glass, gypsum, metals, plastic, soil or wood) and the recycled concrete aggregates are mainly composed of concrete residues.

In both vectors, the mortars' performance was evaluated by comparing to a conventional mortar (Ref_1:4). The mortars analysed in each vector were the following:

- **Vector I:** Ref_1:4; RCA_1:4_10%; RCA_1:4_15%; RCA_1:4_20%; RMA_1:4_10%; RMA_1:4_15%; RMA_1:4_20%;
- **Vector II:** Ref_1:4; Ref_1:5; RMA_1:5_15%; RCA_1:5_20%; Ref_1:6; RMA_1:6_15%; RCA_1:6_20%.

The mortars that presented the best behaviour in each recycled aggregate and in which a substantial recycling rate was achieved, went through the third experimental phase and these incorporations were selected to be tested in vector II. Therefore, all mortars were analysed in the second experimental phase and in the third phase only the following mortars were considered: Ref_1:4; RCA_1:4_20%; RMA_1:4_15%; Ref_1:5; RMA_1:5_15%; Ref_1:6; RCA_1:6_20%.

2.1. Methods and materials

The tests performed were divided into three experimental phases described in Table 3.

	Test	Description
1st experimental phase	Size distribution	According to European Standard EN 1015-1 (1998) to the sand and recycled aggregates
	Apparent bulk density	According to Cahier 2669-4 (1993) to the sand (below 2.38 mm), cement and recycled aggregates (below 0,149 mm). Six samples per aggregate
	Physical, chemical and mineralogical composition of the recycled aggregates	Manual separation of the fraction above 2.38 mm into three categories: "mortar, concrete and cementitious particles", "ceramics" and "others". The chemical tests carried out for the *tout-venant* fraction were the following: the water soluble chlorides content, the acid soluble sulphates content, the sulphur content, the contaminants content and the humus content. The chemical composition was performed to the 0-2,38 mm fraction by FRX (X-Ray fluorescence) and the mineralogical composition was determined by DRX (X-Ray diffraction) for the fraction below 0,149 mm
2nd experimental phase	Consistence of fresh mortar (by flow table)	According to European standard EN 1015-3 (1999). Two samples per mortar
	Bulk density of fresh mortar	According to European standard EN 1015-6 (1999). Three samples per mortar
	Dry bulk density of hardened mortar	According to European standard EN 1015-10 (1999), at 28 e 90 days. Three prisms (160 x 40 x 40 mm^3) per mortar
	Dynamic modulus of elasticity	According to Portuguese standard NP EN 14146 (2006), at 28 e 90 days. Three prisms (160 x 40 x 40 mm^3) per mortar
	Ultra-sound	According to Fe Pa 43 (2010). To measure the velocity of ultra-sonic waves two methods were applied: direct and indirect. One prism (160 x 40 x 40 mm^3) per mortar, at 28 and 90 days
	Flexural and compressive strength of hardened mortar	According to European standard EN 1015-11 (1999), at 28 e 90 days. Three prisms (160 x 40 x 40 mm^3) per mortar
	Water absorption by capillarity	According to European standard EN 1015-18 (2002), at 28 days. Three semi-prisms (80 x 40 x 40 mm^3) per mortar
	Drying	After the water absorption test, the mass differences of the specimens were measured until their stabilization. Three semi-prisms (80 x 40 x 40 mm^3) per mortar
	Open porosity	According to Portuguese standard NP EN 1936 (2008). Three samples per mortar, resulting from the compressive strength test at 90 days
	Magnifying glass observation	The samples from the compressive strength test were observed, at 90 days, using a magnifying glass
3rd experimental phase	Air content of fresh mortar	According to European standard EN 1015-7 (1998). Pressure method was applied (mortars with air content lower than 20%). Two samples per mortar
	Dimensional instability	According to Cahier 2669-4 (1993). Three prisms (160 x 40 x 40 mm^3) per mortar
	Susceptibility to cracking	Observation of three ceramic bricks per mortar, subjected to different curing conditions, with a layer of mortar 2 cm thick in order to see whether cracking occurs
	Water vapour permeability	According to Portuguese standard NP EN 1015-19 (2008). Two cylinder specimens (200 x π x 2 mm^3) per mortar
	Artificial accelerated ageing test	Durability evaluation based on the artificial accelerated ageing test, performed according to European standard EN 1015-21 (2002). Specimens were subjected to eight freeze-thaw cycles and eight humidity-ice cycles
	Permeability to water under pressure	According to European standard EN 1015-21 (2002). Two ceramic bricks with a layer of mortar 2 cm thick, at 28 days and after ageing, per mortar
	Adherence strength	According to European standard EN 1015-12 (2000). Two ceramic bricks with a layer of mortar 2 cm thick and five pull-off samples per mortar, at 28 days and after ageing

The materials used in the experimental campaign were: cement, water, river sand and recycled aggregates from CDW produced by two Portuguese CDW recycling plants: *RCD – Resíduos de Construção e Demolição SA* (recycled concrete aggregates) and *SGR Ambiente* (recycled mixed aggregates). In its selection the following parameters were considered: type of recycled aggregate, degree of contamination and the particles' size. The material was not subjected to any additional proceeding, in order to preserve the properties inherent to its manufacturing process. The binder used was cement type CEM II / B-L 32,5N, from the Portuguese cement company *Secil*. The natural sand comes from the Tagus river and only particles below 2,38 mm were used.

3. Results and analysis

Hereinafter, the results of this study are presented, analysed and compared with those from another studies.

3.1 First experimental phase

3.1.1. Physical, chemical and mineralogical composition of the recycled aggregates

The results of the FRX analysis show that the major components of both recycled aggregates are: SiO_2, Al_2O_3, Fe_2O_3 and CaO, which are related to the presence of natural aggregates, ceramics and hardened mortar residues. The CaO content in the recycled concrete aggregate is almost twice that of the recycled mixed aggregate. This may explain some differences in the mortars' behaviour as noted further on in this document. It was also found that the recycled mixed aggregate had titanium, zinc and lead in higher quantities compared to the other recycled aggregate. The results of DRX analysis show that both recycled aggregates had cementitious components (e.g. calcium silicates), quartz and calcite in their composition. Gypsum, on the other hand, was found only in the RMA.

3.1.2. Size distribution and apparent bulk density

Figure 1 shows the sand and recycled aggregates size grading curves. The bulk densities of the various components (sand, cement and recycled aggregates), presented in Table 1, were determined in order to convert the volumetric ratios into weight ratios. Both recycled aggregates have lower apparent bulk densities than river sand, as expected, and cement.

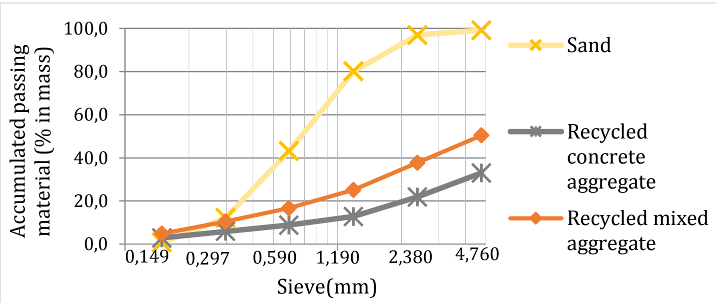

Figure 1: Size grading curve of sand and recycled aggregates

Table 1: Apparent bulk density of binder and aggregates

Component	Apparent bulk density (kg/m³)
RMA (≤0,149 mm)	809,5
RCA (≤0,149 mm)	878,1
Cement	1029,7
River sand (≤2,38 mm)	1471,4

3.2. Second and third experimental phases

3.2.1. Consistence of fresh mortar (by flow table)

According to European standard EN 1015-3 (1999), the consistency considered adequate for rendering mortars with a bulk density higher than 1200 kg/m³ is 175 ± 10 mm. Still, in this case, to ensure proper workability and improve the comparability of the mortars, it was necessary to reduce the spread range to 160 ± 3 mm. The results are presented in Table 2.

Table 2: Consistency, bulk density of fresh mortar and dry bulk density of hardened mortar at 90 days (vector I and II)

Mortar	Water content per dm³ of mortar (ml)	Consistency average	Water / binder ratio	Bulk density of fresh mortar (kg/m³)	Dry bulk density of hardened mortar (kg/m³)
Ref_1:4	230	159,5	1,12	1952 ± 4,3	1854 ± 14,0
RMA_1:4_10%	200	159,0	0,97	1862 ± 10,5	1822 ± 9,9
RMA_1:4_15%	198	160,0	0,96	1858 ± 8,9	1832 ± 3,2
RMA_1:4_20%	205	162,0	1,00	1908 ± 3,0	1834 ± 16,1
RCA_1:4_10%	208	161,5	1,01	1973 ± 1,2	1860 ± 10,5
RCA_1:4_15%	204	158,5	0,99	1980 ± 2,1	1892 ± 1,9
RCA_1:4_20%	198	158,0	0,96	1982 ± 7,2	1916 ± 11,9
Ref_1:5%	244	162,0	1,42	1927 ± 8,4	1789 ± 9,0
RMA_1:5_15%	200	163,0	1,17	1884 ± 13,1	1837 ± 7,9
RCA_1:5_20%	207	162,5	1,20	1968 ± 2,9	1796 ± 4,3
Ref_1:6%	250	159,0	1,70	1915 ± 2,2	1749 ± 14,2
RMA_1:6_15%	210	159,5	1,43	1845 ± 17,2	1750 ± 2,1
RCA_1:6_20%	210	163,0	1,43	1907 ± 16,4	1804 ± 6,2

Up to ratios of 15% of recycled aggregates, the water content to maintain the consistency decreases with the percentage of very fines added, regardless of the nature of the waste. All the mortars have the same volumetric ratio of

1:4. Consequently, there is a reduction of water/binder ratio. This is due to a filler effect. The voids between the sand aggregates, previously filled with water, are replaced with voids occupied by very fine recycled aggregate particles. This trend remains up to incorporations of 20% of RCA. However, the mortar RMA_1:4_20% requires more water to reach the same workability. This is because there is an increase of the specific surface of the aggregates, caused by the increase of fine content, which requires more water to wet the aggregates. However, all the modified mortars show an improvement of workability and lower water/cement ratios than the reference mortar. This means that these mortars probably have better mechanical strengths and a better behaviour when in contact with water.

In vector II, the balance between the reduction of cement content and a filler effect, caused by the incorporation of recycled aggregates, led to a decrease in the water amount needed to lubricate the aggregates and fill the voids. The modified mortars poorer in cement (RMA_1:5_15% and RCA_1:6_20%) need less water to maintain an adequate consistency relative to the reference mortar. Nevertheless, this decrease was not enough to reduce the water/cement ratio.

3.2.2. Bulk density of fresh mortar and dry bulk density of hardened mortar

The results of the bulk density of fresh mortar and the dry bulk density are presented in Table 2. In vector I, although RCA had a lower apparent bulk density than sand, there is an increase in the mortars' bulk density with the incorporation of RCA, due to a filler effect. On the other hand, the bulk density decreases with the incorporation of RMA. This is due to the lower apparent bulk density of RMA compared to sand, which more than offsets the filler effect and leads to a decrease in the mortars' bulk density. The results in the hardened state mortar follow, at both ages, the same trend found in the fresh state. Still, the results in this case were lower those of the fresh state due to three factors: loss of importance of the air content in the hardened state, water evaporation and chemical reactions (cement hydration).

In vector II, the bulk density of both recycled aggregates is lower than that of cement and sand. Also, the cement reduction led to a higher water/binder ratio and thus to an increase of the mortar's porosity. These two factors contribute to the decrease of bulk density of fresh mortars, prevailing over the filler effect. The only exception is the modified mortar RCA_1:5_20%. This mortar presented a bulk density similar to the reference mortar. In accordance to the results obtained in the fresh state, all the modified mortars had dry bulk densities lower or similar to those of the conventional mortar, at 28 and 90 days.

3.2.3. Flexural and compressive strength of hardened mortar

The results of the flexural and compressive strength test are presented in Figures 2 to 5. In vector I, regardless of the testing age, both flexural and compressive strength increased with the incorporation of recycled aggregates. Although the incorporation of RCA allows higher flexural and compressive strengths, all modified mortars had a better performance compared to the reference mortar. These results may be explained by two factors: a filler effect (higher compactness of the modified mortars) and the presence of partially hydrated cement in the recycled aggregates, which may provide higher mechanical strengths. Both strengths increased with the incorporation of RCA. It was also found that the incorporation of RMA up to 10% also increased the mechanical strengths and it decreased from then on. This is because this incorporation led to an increase of porosity.

In vector II, even though a slight fall occurs on the mechanical strengths of the modified mortar (RCA_1:6_20%), the reduction of cement content up to 1:6 with simultaneous incorporation of 20% of RCA does not considerably affect its performance. Furthermore, an increase of 17% and 34% was also found in the compressive and flexural strengths, respectively, of the modified mortar RCA_1:5_20% relative to the conventional mortar. However, the incorporation of 15% RMA in mortars with less cement content led to a decrease of the mechanical strengths. In this case, the reduction of cement content more than offsets the combined action of three factors: a filler effect, some pozzolanic effect of the brick powder and the presence of non-hydrated cement in the recycled aggregate used.

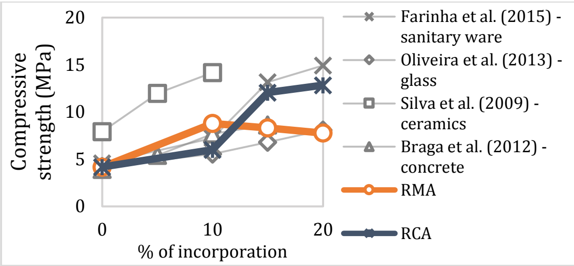

Figure 2: Comparison of the compressive strength of the mortars tested in vector I, at 28 days, with those from other studies

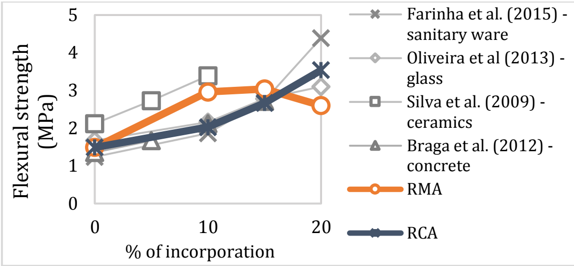

Figure 3: Comparison of the flexural strength of the mortars tested in vector I, at 28 days, with those from other studies

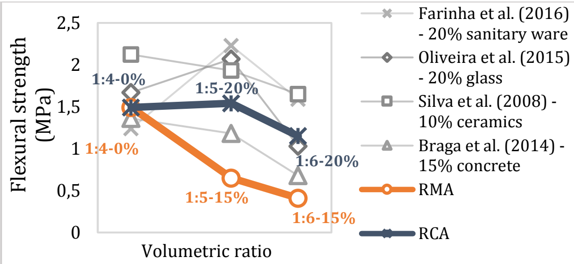

Figure 4: Comparison of the flexural strength of the mortars tested in vector II, at 28 days, with those from other studies

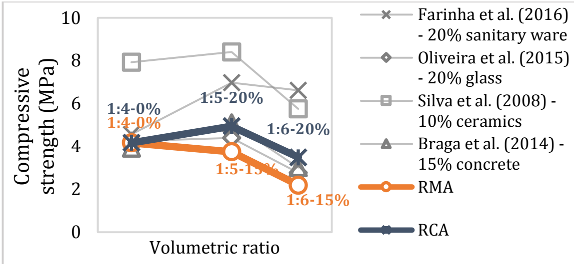

Figure 5: Comparison of the compressive strength of the mortars tested in vector II, at 28 days, with those from other studies

3.2.4. Dynamic modulus of elasticity

The results of the dynamic modulus of elasticity test are presented in Figures 6 and 7.

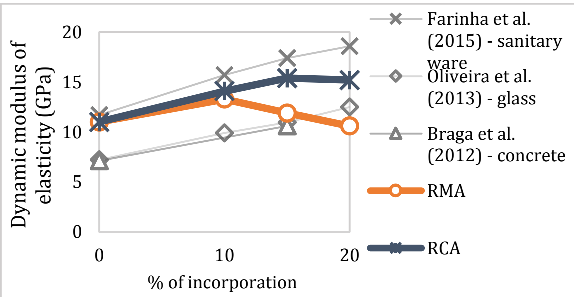

Figure 6: Comparison of the dynamic modulus of elasticity of the mortars tested in vector I, at 28 days, with those from other studies

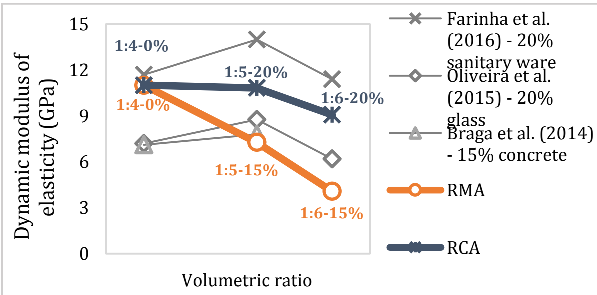

Figure 7: Comparison of the dynamic modulus of elasticity of the mortars tested in vector II, at 28 days, with those from other studies

In both vectors, the trend of the dynamic modulus of elasticity is the same as that obtained in the flexural and compressive strengths. Concerning vector I, the dynamic modulus of elasticity increased, in general, with the incorporation of RCA and RMA, due to the same reasons given before: a filler effect and the presence of non-hydrated cement residues, which produces more compact mortars. The modified mortar RMA_1:4_20% is the only mortar with a modulus of elasticity lower than that of the conventional mortar, due to the increase of porosity. In vector II, all mortars had a modulus of elasticity lower or similar to that of the conventional mortar, at both ages, which is considered a positive trend. Therefore, these mortars had a higher or similar capability to absorb deformations without cracking. However, the incorporation of RMA led to the highest decrease in this parameter.

3.2.5. Water absorption by capillarity of hardened mortar

The results of the water absorption by capillarity test are presented in Figures 8 and 9. Concerning vector I, all the modified mortars improved their performance comparing to the reference mortar, since the incorporation of recycled aggregates allows reducing the coefficients of water absorption by capillarity. This is due to a filler effect, which provided smaller capillary pores and thus a reduced water flux within the mortar. The highest incorporation of RCA produces the lowest coefficient of capillarity, about 46% lower than that of the conventional mortar. On the other hand, up to 10% RMA incorporation, there was a maximum decrease in property of about 41%. However, the modified mortar RMA_1:4_20% also exhibited a lower water absorption by about 17%.

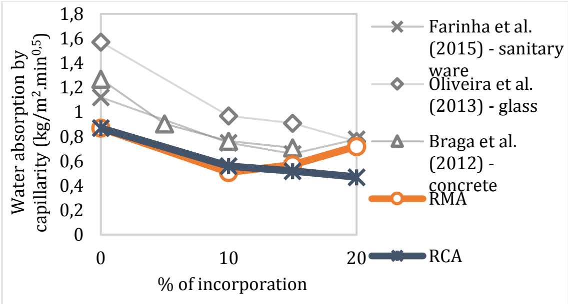

Figure 8: Comparison of water absorption by capillarity of the mortars tested in vector I with those from other studies

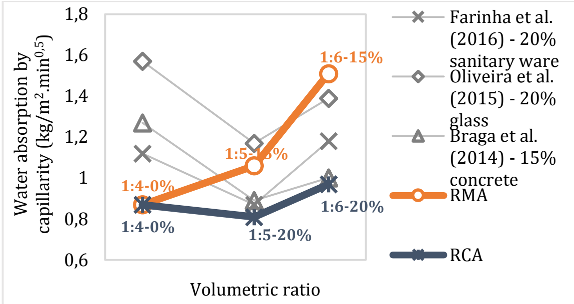

Figure 9: Comparison of water absorption by capillarity of the mortars tested in vector II with those from other studies

In vector II, the reduction of cement increases, in general, the water absorption of mortars and the incorporation of recycled aggregates decreases it. The modified mortar RCA_1:5_20% had a decrease in the water absorption about 7%, which means that the incorporation of RCA more than offsets the reduction of cement. Thus this mortar presented better behaviour to water than the conventional mortar. In the other modified mortars, the opposite happened. However, the mortar with less cement content and 20% RCA incorporation had a slightly increase in the capillarity coefficient (about 11,5%), compared with mortars with incorporation of RMA. Despite the substantial increase in the water absorption rate compared to the conventional mortar, mortars RMA_1:5_15% and RMA_1:6_15% only showed a small increase in the total water absorbed.

3.2.6. Drying

Mortar's drying is most pronounced in the first few weeks. In vector I, it was found that despite the incorporation of recycled aggregates leading to an increase in the drying time, the decrease in evaporation rate did not significantly change the drying curves of these modified mortars, which are similar to that noted for the conventional mortar. This decrease in the evaporation rate is due to a filler effect. The modified mortars had smaller capillary pores and thus, it is more difficult for water to exit the mortar. In vector II, reducing the cement content by incorporating recycled aggregates does not significantly influence the mortars' drying behaviour. The modified mortars behave similarly to the conventional mortar because the reduction of cement content balanced the filler effect.

3.2.7. Open porosity

The results of the open porosity test are presented in Figures 10 and 11. Mortars behave differently depending on the type of recycled aggregate under analysis. It was found that the incorporation of RCA decreased the open porosity, while the incorporation of RMA caused an opposite trend. The open porosity of the modified mortar RCA_1:4_20% was lower than that of the conventional mortar by about 10,5%. The incorporation of RMA up to 10% also decreased the open porosity, which increased from then on. However, these changes were not significant and thus, the modified mortars with RMA had a similar open porosity to that of the conventional mortar.

In vector II, the trend of the results of this test is the same noted for the water absorption by capillarity. The incorporation of recycled aggregates and simultaneous reduction of cement content from 1:4 to 1:5 and 1:6 led to an increase in the mortars' porosity. The only exception was mortar RCA_1:5_20%, in which the increase in compactness, due to a filler effect and the presence of non-hydrated cement, more than offsets the reduction of the cement content. Therefore, this mortar had a lower open porosity (about 5%) compared to the conventional mortar.

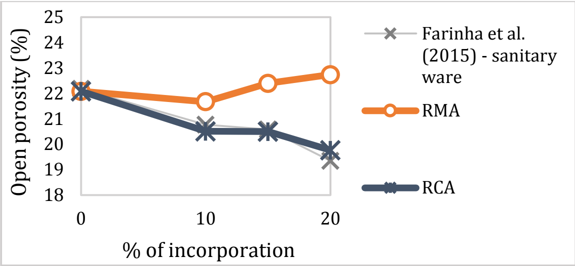

Figure 10: Comparison of the air content of the mortars tested in vector I with those from other study

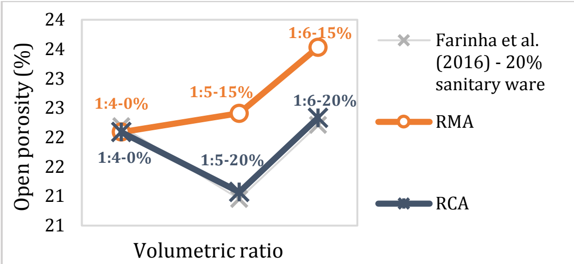

Figure 11: Comparison of the air content of the mortars tested in vector II with those from other study

3.2.8. Magnifying glass observation

In order to assess whether internal microcracking occurred in the mortars of this study, the resulting samples from the compressive strength test were observed, at 90 days, under an electronic magnifying glass. Internal microcracking was found in all the mortars of vector I. In general, the microcracking pattern and widths increased with the recycled aggregate incorporation ratio. Mortar RCA_1:4_20% had the greatest microcracking pattern. These results explain the decrease in some properties (mechanical strengths and dynamic modulus of elasticity) at 90 days. In vector II, only in the modified mortars RMA_1:5_15% and RMA_1:6_15% some microcracks were observed, with the higher magnification (700%). However, this does not mean that the remaining mortars do not have any internal microcracking, since there is a decrease in their properties between 28 and 90 days. Even so, the detected microcracks have widths below those observed in all the mortars of vector I.

3.2.9. Air content

The results of the air content test are presented in Figures 12 and 13. In vector I, both modified mortars display a significant increase of the air content relative to the reference mortar, especially the mortar with 15% of RMA. The modified mortars RMA_1:4_15% and RCA_1:4_20% had an air content 95% and 54% higher than that of the reference mortar, respectively. This may also explain the decrease in bulk density of mortars produced with RMA. In vector II, all the conventional mortars with different cement contents (Ref_1:4, Ref_1:5 and Ref_1:6) had similar air content. Therefore, the reduction of cement did not affect this parameter, and as noted in vector I, the incorporation of RCA and RMA led to a considerable increase of the air content. The modified mortar RMA_1:5_15% had the higher increase (about 107%).

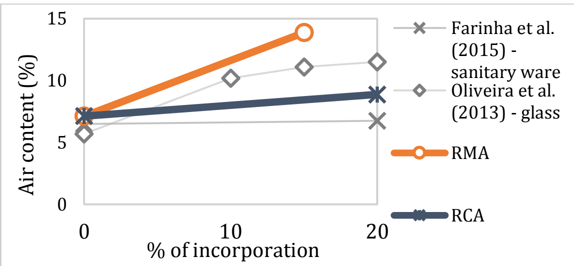

Figure 12: Comparison of the air content of the mortars tested in vector I with those from other studies

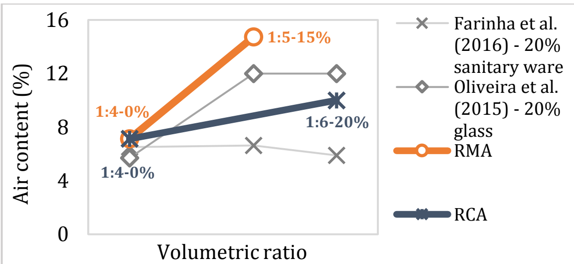

Figure 13: Comparison of the air content of the mortars tested in vector II with those from other studies

3.2.10. Water vapour permeability of the hardened mortar

The results of the water vapour permeability test are presented in Figures 14 and 15. In vector I, there is a decrease by about 11% of the water vapour permeability in the mortar with 20% RCA, due to a filler effect, whereas the mortar with 15% RCA has a similar water vapour permeability to the reference mortar.

Concerning vector II, as expected, the reduction of cement content increases the water vapour permeability. However, the incorporation of 15% of RMA and 20% of RCA, for the same volumetric ratio, led to a decrease in this property compared to the conventional mortars (Ref_1:5 and Ref_1:6). Despite that, both modified mortars presented a higher water vapour permeability than the reference mortar (Ref_1:4), which means that the reduction of cement more than offsets the filler effect. Thus, the modified mortars RMA_1:5_15% and RCA_1:6_20% are more permeable to vapour than the reference mortar by about 28 and 25%, respectively, which is considered positive.

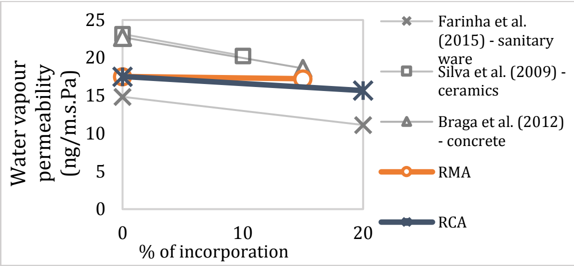

Figure 14: Comparison of the water vapour permeability of the mortars tested in vector I with those from other studies

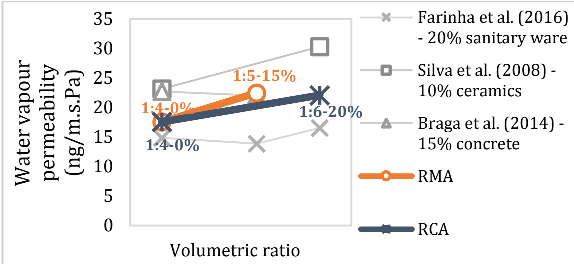

Figure 15: Comparison of the water vapour permeability of the mortars tested in vector II with those from other studies

3.2.11. Dimensional instability (shrinkage)

The results of the dimensional instability test are presented in Figures 16 and 17.

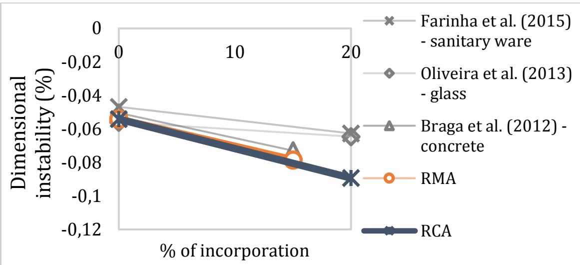

Figure 16: Comparison of the dimensional instability of the mortars tested in vector I with those from other studies

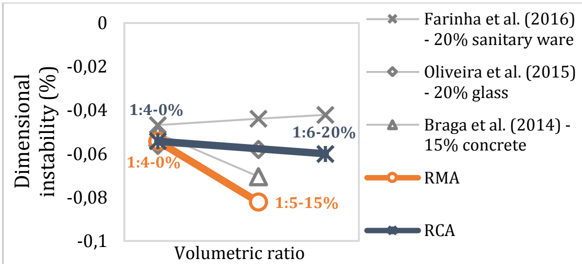

Figure 17: Comparison of the water vapour permeability of the mortars tested in vector II with those from other studies

In both vectors, it was found that the largest dimensional variation occurs at early ages. Moreover, there is a significant increase in the shrinkage of the modified mortars compared to the conventional mortar, with the incorporation of recycled aggregates, as expected. In vector I, at 90 days, the incorporation of 20% of RCA and 15% of RMA increased the shrinkage up to 65% and 45%, respectively, increasing the probability of cracking. This may be explained by the increase of the capillary pores stress as well as by the increase on the modified mortars' cementitious content, caused by the high content of CaO related with the presence of hardened mortar in the recycled aggregates. In vector II, it was found that the reduction of cement content decreased the shrinkage and the incorporation of recycled aggregates increased it. Mortar RCA_1:6_20% had a shrinkage slightly higher (about 11%) than the conventional mortar. Therefore, the reduction of cement content offsets the negative effect of the incorporation of RCA. On the other hand, the reduction of the volumetric ratio of cement from 1:4 to 1:5 was not enough and the shrinkage of the modified mortar RMA_1:5_15% was higher (about 52%) than that of the conventional mortar.

3.2.12. Susceptibility to cracking

After three months of observation, only the specimen of mortar RCA_1:4_20%, submitted to B type curing condition (the most unfavourable curing conditions), showed signs of cracking visible to the naked eye. The high modulus of elasticity as well as the considerable increase in shrinkage compared to those of the reference mortar, caused by the incorporation of 20% of RCA, may explain the increase these mortar's potential to cracking. None of the other mortars of vectors I and II showed any signs of cracking, regardless of the curing conditions.

3.2.13. Evaluation of durability by the artificial accelerated ageing test

The artificial accelerated ageing test consists of subjecting the mortars to climatic cycles. The specimens were evaluated before and after ageing in terms of their permeability to water under pressure and adherence strength. The results are presented hereinafter. After the artificial accelerated ageing, none of the specimens showed any signs of cracking. However, some leaching of the upper coating layer was observed.

a) Permeability to water under pressure

The results of the permeability to water under pressure test are presented in Figures 18 and 19.

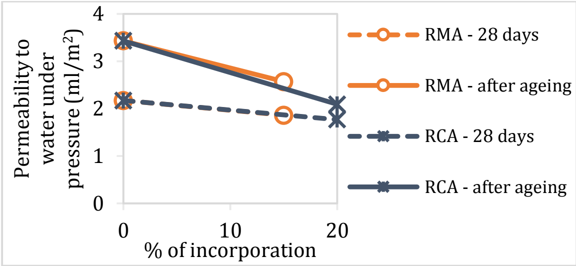

Figure 18: Permeability to water under pressure of the mortars tested in vector I.

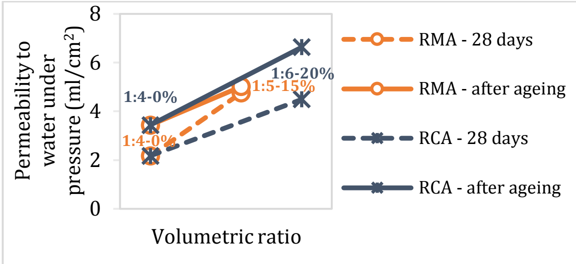

Figure 19: Permeability to water under pressure of the mortars tested in vector II.

In vector I, it was found that the incorporation of 15% of RMA and 20% of RCA decreased the permeability to water under pressure, both at 28 days and after ageing, due to a filler effect. The conventional mortar is the most affected by the climate cycles. Despite the increase in this parameter in all the mortars after ageing, probably due to the microcracking, the differences between the modified mortars and the conventional mortar were higher. On the other hand, mortars from vector II had an increase of the permeability before and after ageing. The reduction of binder, prevailing over the filler effect, led to an increase of porosity. Therefore, these modified mortars were more permeable than the conventional mortar.

b) Adherence strength

The results of the adherence strength test are presented in Figures 20 and 21. In vector I, the incorporation of RCA and RMA, before and after ageing, increased the adherence strength and this can be explained by the increased suction of water mixed with very fine recycled aggregates by the substrate, improving the bond between the substrate and the mortar. In vector II, a similar trend was noticed. The only exception was mortar RMA_1:5_15% before ageing. Once again, the incorporation of recycled aggregates counteracted the reduction of binder. Therefore, after ageing, both modified mortars had higher adherence strength compared to the conventional mortar, despite the slightly decrease in mortar RCA_1:6_20% after the climate cycles probably due to the microcracking.

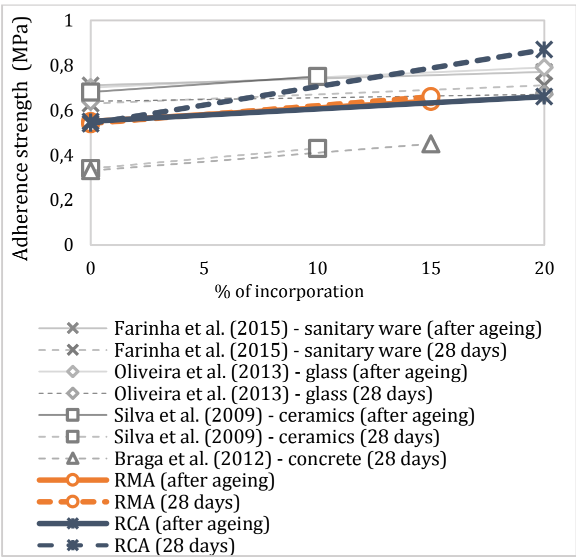

Figure 20: Comparison of the adherence strength of the mortars tested in vector I with those from other studies

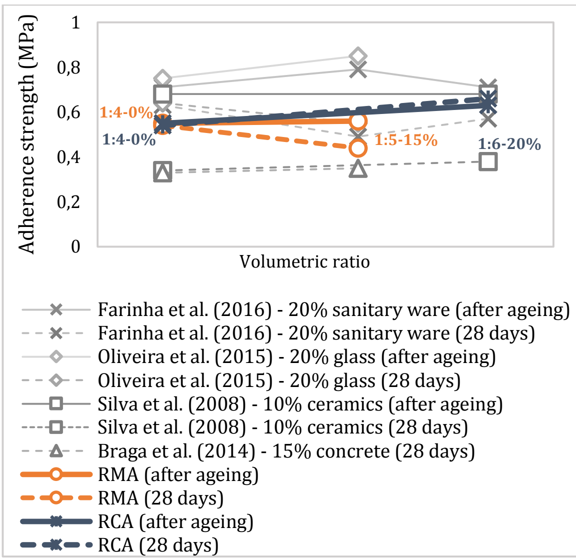

Figure 21: Comparison of the adherence strength of the mortars tested in vector II with those from other studies

4. Conclusions

The processing technologies in CDW recycling platforms improve the quality of recycled aggregates by eliminating contaminant materials. Thus, it would be expected that the incorporation of different recycled aggregate would influence mortars' performance depending on the type of waste used. In fact, it was found that the incorporation of RCA and RMA presented different trends. In vector I, mortars with incorporations of RCA showed higher improvements compared to those of the incorporation of RMA, particularly in mechanical strength, water absorption by capillarity, water permeability under pressure and adherence strength, due to these mortars' higher compactness. However, the incorporation of 20% of RCA led to significantly increase the modulus of elasticity and mortar's shrinkage, which may had caused mortar's cracking. Therefore, it would be necessary to further analyse the susceptibility to cracking of this mortar. In general, mortars of vector I had a high modulus of elasticity and thus are suitable only for some substrates (with also high modulus of elasticity). However, the use of 15% of RMA in mortars with a volumetric ratio of 1:4 is feasible. This mortar presented only some issues regarding the air content and shrinkage, even though this aggregate had a higher amount of contaminant material.

In vector II, it was possible to reduce the cement content from 1:4 up to 1:6 with the simultaneous incorporation of 20% RCA. These mortars benefited from the binder reduction and also from a filler effect and the presence of non-hydrated cement residues, which allowed a satisfactory behaviour of this mortar. The mechanical strength losses are not significant, considering the requirements of a coating mortar. There were only some issues related to the water permeability under pressure. Therefore, it was concluded that the incorporation of 20% of RCA in mortars poorer in cement may offer some advantages in terms of performance and allow recycling this CDW. On the other hand, the use of RMA in mortars poorer in cement led to a more substantial loss in the performance of these mortars.

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