# Performance of mortars with incorporation of fine aggregates from construction and demolition waste recycling plants - *Aggregate recycling*

Master Thesis in Civil Engineering

**April 2019**

## Extended Abstract

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## 1. Introduction

The construction industry has been one of the largest waste producers and will remain as such for the foreseeable future. Specifically, the management and treatment of construction and demolition waste (CDW) is a worldwide problem with no definitive solution in sight. In 2016, the construction sector was responsible for over a third of all the generated waste, accounting for 36% of its total weight (Eurostat, 2018).

Regarding this issue, the European Union set a goal of recycling at least 70% of this kind of waste by 2020 through Directive No. 2008/98/CE. To achieve compliance, the Portuguese government issued Decree No. 73/2011, legislating the handling processes of CDW, from its initial dumping to its treatment and reusing (APA).

One way to value and recycle CDW is to incorporate it in new construction projects as part of the used materials. To assess the feasibility of this process, a research line has been developed around the globe, studying the use of CDW as aggregate in different types of mortar. This specific investigation intends to contribute to the reduction of natural resources used, such as river sand, and evaluates two different kinds of waste as possible replacements.

## 2. Experimental campaign

This experimental campaign studies the use of two different CDW as replacement of natural aggregates in wall coating mortars: one based on recycled concrete (RCA) and another on non-segregated waste, composed of diverse constituents such as clay brick, concrete, plastic and residual organic material (MRA). Both lots were altered to match the grading curve of the reference aggregate (river sand), and each was incorporated in mortars replacing sand at 20%, 50% and 100% (Table 1).

**Table 1 - Percentage of the various aggregates, by volume, used in the studied compositions**

| Aggregates | REF | RCA20 | RCA50 | RCA100 | MRA20 | MRA50 | MRA100 |
|---|---|---|---|---|---|---|---|
| Natural aggregate (NA) | 100% | 80% | 50% | - | 80% | 50% | - |
| Concrete recycled aggregate (RCA) | - | 20% | 50% | 100% | - | - | - |
| Mixed recycled aggregate (MRA) | - | - | - | - | 20% | 50% | 100% |

The process was divided in three stages:

- Stage I: identification and characterization of the used materials;
- Stage II: performance tests on each of the seven compositions;
- Stage III: performance and durability tests on two selected mortars.

## 2.1. Methods

All tests were carried accordingly to the specifications shown in Table 2.

**Table 2 - Tests performed and respective specifications**

| | Test | Specification | General notes |
|---|---|---|---|
| Stage I | Size distribution | EN 1015-1 (1998) | Both recycled aggregates were sieved to mimic the size distribution of the NA (< 2,38 mm) |
| | Aggregate composition | - | Removal of particles larger than 2,38 mm. Manual separation of visually distinguishable particles by material, followed by weighting the different parcels |
| | Apparent bulk density | Cahier 2669-4 (1993) | - |
| Stage II | Consistence of fresh mortar | EN 1015-3 (1999) | Mortars had to be calibrated to a slump of 160 ± 3 mm instead of the defined value |
| | Bulk density of fresh mortar | EN 1015-6 (1999) | - |
| | Bulk density of hardened mortar | EN 1015-10 (1999) | Performed at 28 and 90 days of age |
| | Dynamic modulus of elasticity | NP EN 14146 (2006) | Performed at 28 and 90 days of age |
| | Ultrasonic wave velocity | Fe Pa 43 (2010) | Two methods were used: direct and indirect. Done at 28 and 90 days of age |
| | Flexural and compressive strength of hardened mortar | EN 1015-11 (1999) | Performed at 28 and 90 days of age |
| | Water absorption by capillarity | EN 1015-18 (2002) | Performed at 28 days of age |
| | Drying | - | The specimens were left to dry after the water absorption by capillarity test. The mass variations were measured until stabilization |
| | Open porosity | NP EN 1936 (2008) | Performed at 90 days of age |
| Stage III | Dimensional stability | Cahier 2669-4 (1993) | - |
| | Susceptibility to cracking | - | Visual observation of mortar-covered brick specimens to identify eventual signs of cracking. Performed at 28 days of age and after artificial ageing |
| | Water vapour permeability | NP EN 1015-19 (2008) | Performed at 28 days of age |
| | Artificial accelerated ageing test | EN 1015-21 (2002) | Performed at 28 days of age |
| | Permeability to water under pressure | EN 1015-21 (2002) | Performed at 28 days of age and after artificial ageing |
| | Adherence strength | EN 1015-12 (2000) | Performed at 28 days of age and after artificial ageing |

All mortars were made using Portland cement CEM II / B-L 32,5N, produced by the Portuguese company *Secil* and one or two of the following aggregates: concrete recycled aggregates provided by the waste treatment company *RCD - Resíduos de Construção e Demolição S.A.*, mixed recycled aggregates from *SGR - Sociedade Gestora de Resíduos, S.A.* and natural sand from the Tagus river. These materials were obtained in batches of

1 m$^3$, and sieved to remove all particles larger than 2,38 mm. The recycled lots were then sieved, separated by size and put together in different proportions to match the size distribution of the natural sand (in mass) to remove particle size as a swaying factor.

# 3. Results and analysis

The results obtained and their respective analysis and comparison are summarized in the following paragraphs.

## 3.1. Stage I

### 3.1.1. Size distribution and apparent bulk density

The grading curves of the used materials were as shown in Figure 1. After this measurement, the particles of each recycled material were separated by size and mixed in calculated proportions to match the grading of the natural sand.

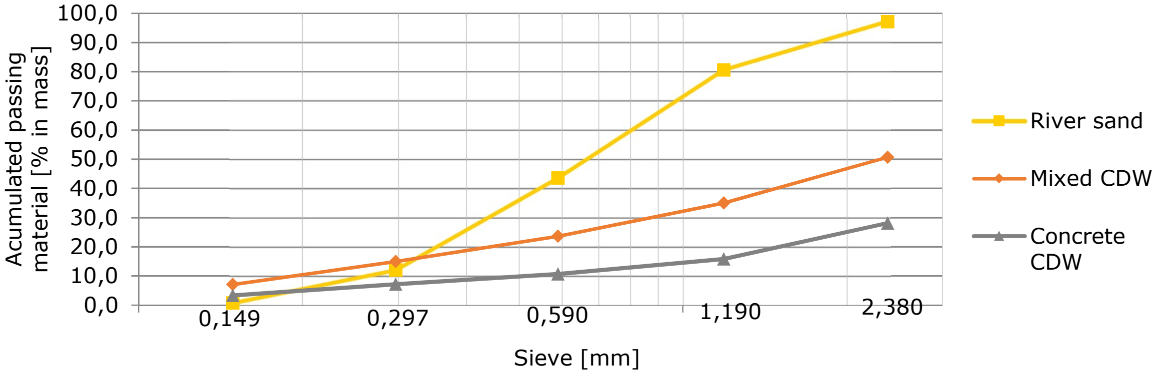

**Figure 1 - Size grading curve of the aggregates**

As a result, the apparent bulk density of the dry materials used is presented in Table 3. Both recycled aggregates have lower values than river sand, resulting in lighter mortars.

**Table 3 - Apparent bulk density of dry materials**

| Components | Apparent bulk density [kg/dm$^3$] |
|---|---|
| Cement | 1029.7 |
| River sand | 1471.4 |
| RCA | 1257.3 |
| MRA | 1161.7 |

### 3.1.2. Composition of the recycled aggregates

Samples of both recycled materials were subjected to a process in which their particles were separated accordingly to their apparent composition - the process was based on visual inspection and each fraction was then weighted to estimate the proportions of the different constituents.

While the concrete waste samples had negligible contaminants (< 1%), the mixed recycled waste was composed by several different materials, as shown in Figure 2

## 3.2. Stage II

### 3.2.1. Consistence of fresh mortar (by flow table)

The volume of water needed to produce each composition was determined by trial and error, using a flow table. To ensure sufficient workability with all mixtures, the slump used as reference was 160 ± 3 mm, as mentioned in Table 2.

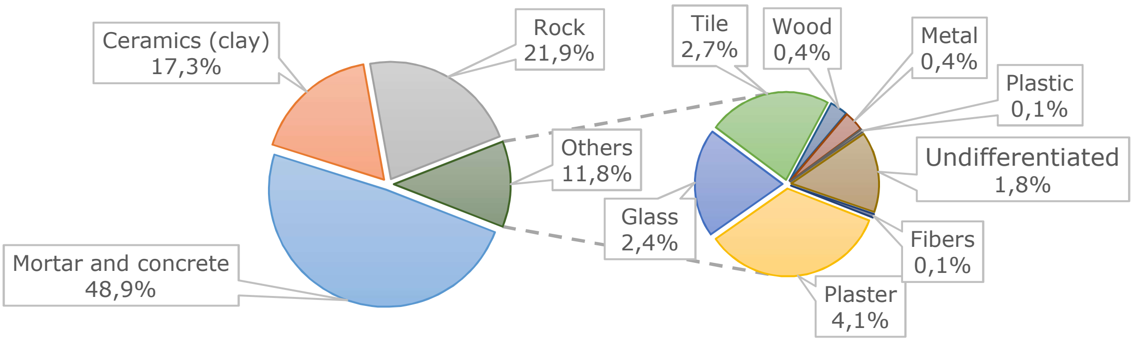

**Figure 2 - Approximate distribution of the various identified materials - MRA**

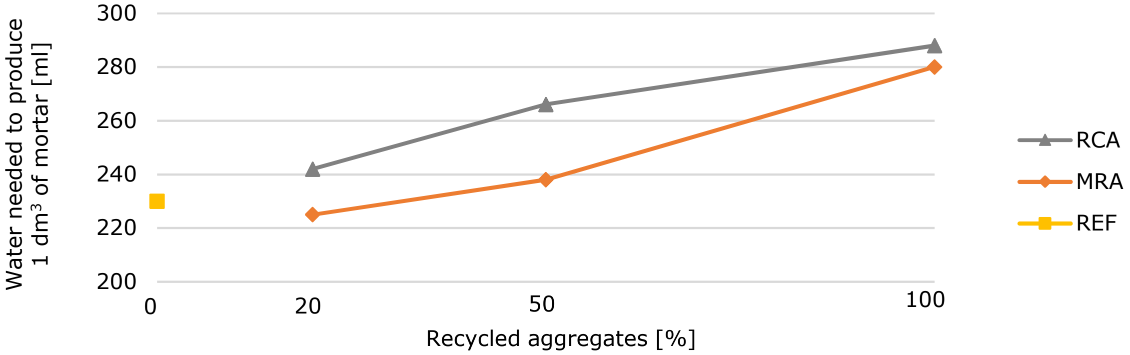

**Figure 3 - Water requirements of the produced mortars**

As seen in Figure 3, the amoun of water used in each mortar highly depends on the aggregates used. RCA mortars tend to require higher amounts of water, possibly due to the presence of non-hydrated cement. Similarly, MRA mortars are also more water-demanding than the reference composition, which can be justified not only by the same phenomenon, but also by the presence of more porous materials, like clay and plaster.

### 3.2.2. Bulk density of fresh and hardened mortar

With the replacement of river sand with lighter aggregates, both fresh and hardened bulk densities decrease, a propensity that heightens in the dry state due to the evaporation of the added kneading water.

### 3.2.3. Dynamic modulus of elasticity and ultrasonic wave velocity

The results of both tests follow similar trends, as shown in Figure 4 and Figure 5. The reference mortar obtained the highest values, followed by both 20% mixes. As for 50% and 100% incorporations of recycled aggregates, the RCA mortars showed higher values than their counterparts. This correlation is due to the fact that both properties depend directly on the density of the test specimen and its constituents.

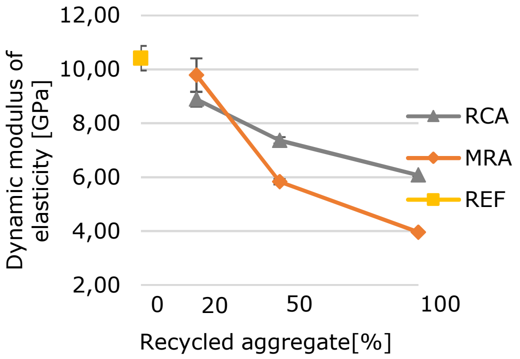

**Figure 4 - Dynamic modulus of elasticity**

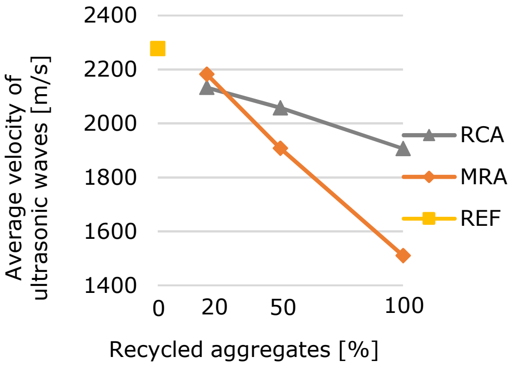

**Figure 5 - Ultrasonic behaviour**

All mortars with recycled aggregates showed modulus of elasticity considered acceptable according to Veiga (2005) - bellow 10 GPa. The reference values, while above the desirable 10 GPa, are in line with those obtained by other authors e.g. Farinha *et al.* (2015) and Silva *et al.* (2015).

### 3.2.4. Flexural and compressive strength of hardened mortar

As shown in Figure 6 and Figure 7, the exclusive use of recycled aggregates leads to significant drops in both strengths. In particular, the mechanical strengths of the MRA100 mixture are over 40% lower than those of the reference mortar.

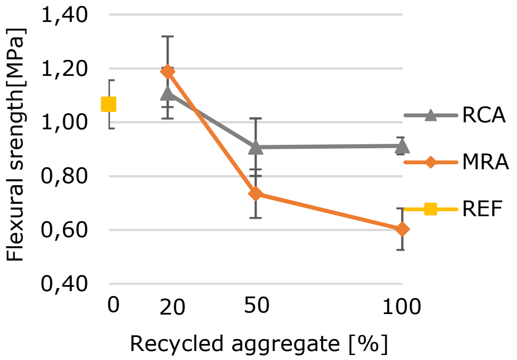

**Figure 6 - Flexural strength - 90 days**

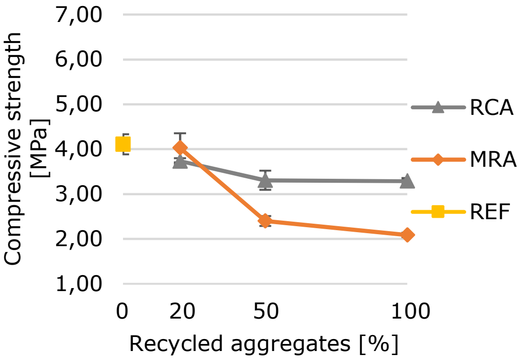

**Figure 7 - Compressive strength - 90 days**

Regardless, using only 20% of the same recycled aggregate results in reasonable values, with flexural strength being even higher than the one of reference. This may be due to the existence of fibrous materials such plastics and wood, which help counteract the influence of the additional kneading water and weaker materials (Al-Tulaian *et al.*, 2016 and Ledesma *et al.*, 2015).

### 3.2.5. Water absorption by capillarity

As seen in Figure 8, all mortars made with recycled concrete aggregates initially showed similar behaviour, with RCA50 only showing a slightly greater velocity of absorption. However, after roughly 300 minutes ($17.3^2$), it becomes clear that the total amount of water absorbed by the specimens increases with the amount of recycled aggregates used. This trend may be justified by the greater porosity inherent to the recycled aggregates.

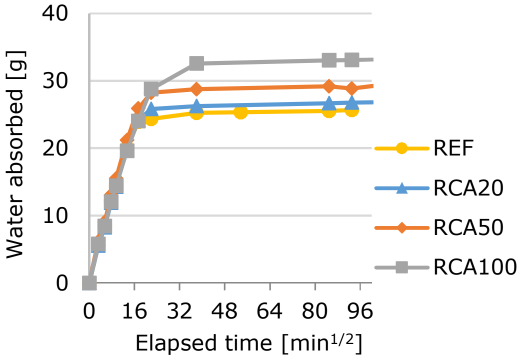

**Figure 8 - Absorbed water over time - RCA**

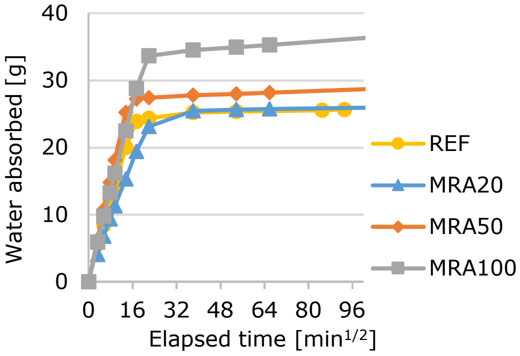

**Figure 9 - Absorbed water over time - MRA**

Figure 9 shows that the use of 20% of mixed recycled aggregates results in less absorbent mortars. Even though at the end of the test both MRA20 and REF had absorbed similar amounts of water, the coefficient of capillarity of the reference mortar - which reflects the initial behaviour of the specimens - is higher. This, however, is not true for MRA50 and MRA100 as they not only have higher capillarity coefficients, but also absorb greater quantities of water overall.

### 3.2.6. Drying

All mortars showed similar drying rates, except for RCA50 which took longer to release the accumulated water, as it was the one with faster absorption.

### 3.2.7. Open porosity

The results of the open porosity tests are summarized in Figure 10. Both sets of mortars show similar trends, with their average values rising with the increase of recycled aggregates used. These results are in line with those from the water absorption by capillarity tests, as mortars that showed higher rates of absorption now show higher values of open porosity. This correlation may be partially assigned to the amount of water needed for the production of each mortar, in every case higher than that of the reference mix. However, mortars made using concrete recycled aggregates, despite needing more water, here show lower values than their MRA counterparts.

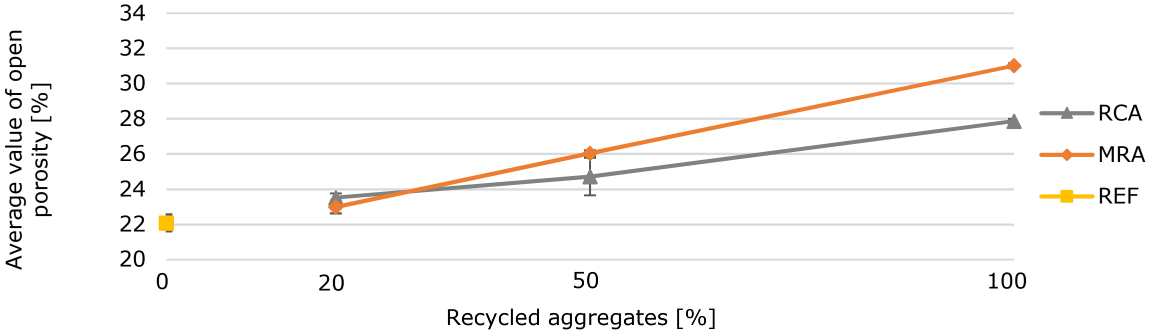

**Figure 10 - Average values of open porosity**

From these results it is possible to infer that the kneading water is not the only aspect affecting this property, with the geometry of the particles and the hydration process of the cement present in the aggregates being possible factors.

## 3.3. Stage III

Considering the results from stage II, MRA20 showed the best performance of the recycled mixes, surpassing the reference values in some tests. As for the RCA mixes, RCA100 stands out for its flexural and compressive strengths, which may make it a sustainable option in low humidity environments. With that in mind, those were the two mortars selected for stage III.

### 3.3.1. Dimensional stability (shrinkage)

As Figure 11 shows, the RCA100 specimens shrank close to 0,024%, which is twice the 0,012% value of the reference composition. Mortars made with mixed recycled aggregates once again showed values similar to the reference mortar, stabilizing at 0,010%.

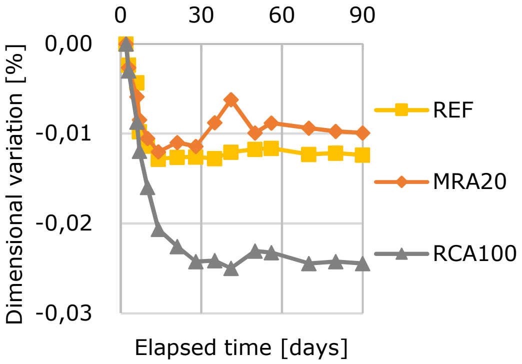

**Figure 11 - Dimensional variation**

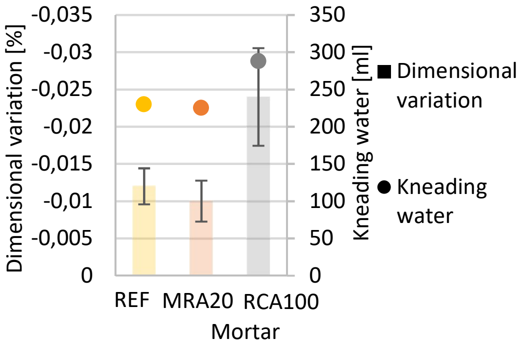

**Figure 12 - Dimensional variation and kneading water**

As seen in Figure 12, there is a correlation between the amount of kneading water used and the shrinkage observed after 90 days. This is because more kneading water leads to higher evaporation losses, which results in higher shrinkage.

### 3.3.2. Water vapour permeability

The ability of a mortar to be permeated by water vapour largely depends on its internal structure. The existence of communication channels between pores, expressed by the open porosity value, is what facilitates the travel of water vapour through the hardened mortar of the test specimens. The values of both properties are shown in **Erro! A origem da referência não foi encontrada.**, supporting this correlation.

### 3.3.3. Adherence strength

All the tested mortars showed a mixed failure mechanism, consisting partially in separation between the hardened mortar and the brick, and partially internal failure of the coating.

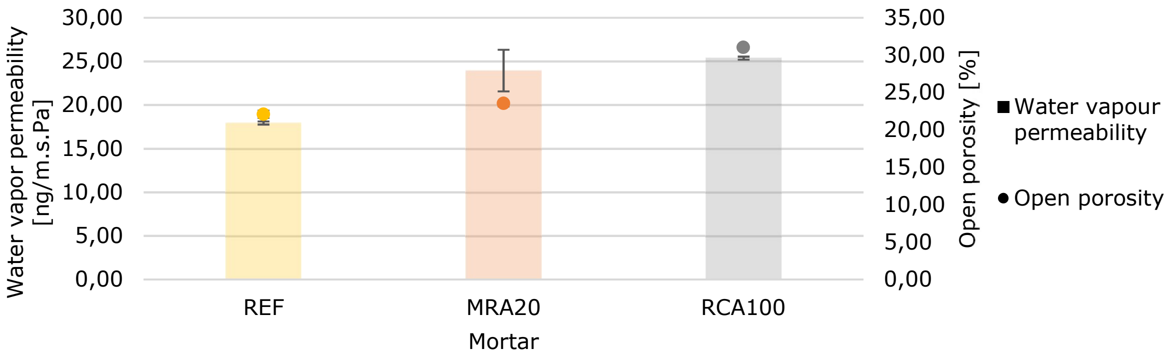

**Figure 13 - Water vapour permeability and open porosity**

**Table 4 - Average adherence strength**

| Mortar | Average adherence strength [MPa] | Standard deviation [MPa] |
|---|---|---|
| **REF** | 0.54 | 0.11 |
| **MRA20** | 0.48 | 0.04 |
| **RCA100** | 0.90 | 0.07 |

However, the values presented in Table 4 for each mortar are largely inferior to their flexural strength of 1.49 MPa (-64%), 1.55 MPa (-69%) and 1.57 MPa (-43%) respectively. This validates that the measurements of this test reflect in fact the adherence strength between mortar and brick as opposed to the flexural strength of the mortar.

### 3.3.4. Artificial ageing

This procedure consisted of multiple cycles of simulated rain, frost and high temperatures in order to rapidly emulate the ageing process of the test specimens. The results allow inference about the durability of the subjected mortars.

#### a) Permeability to water under pressure

Similarly to water vapour permeability, water absorption by capillarity and open porosity, this type of permeability is related to the internal structure of the mortar. The amount and size of pores and whether they communicate among themselves are the factors that determine the behaviour of the test specimens in the presence of water.

Figure 14 shows that all mortars absorbed a higher volume of water after the artificial ageing. This is due to the damage the process causes as water cyclically permeates, freezes and returns to the liquid state. The repeated expansion of the freezing water creates small internal ruptures that result in higher permeation. This effect is in part offset by the non-hydrated cement present in the recycled aggregates, which explains why these mortars suffered lower increases than REF.

#### a) Susceptibility to cracking

None of the tested mortars showed visible cracking signs after the artificial ageing process, meaning that this property is not significantly affected by the use of these recycled aggregates.

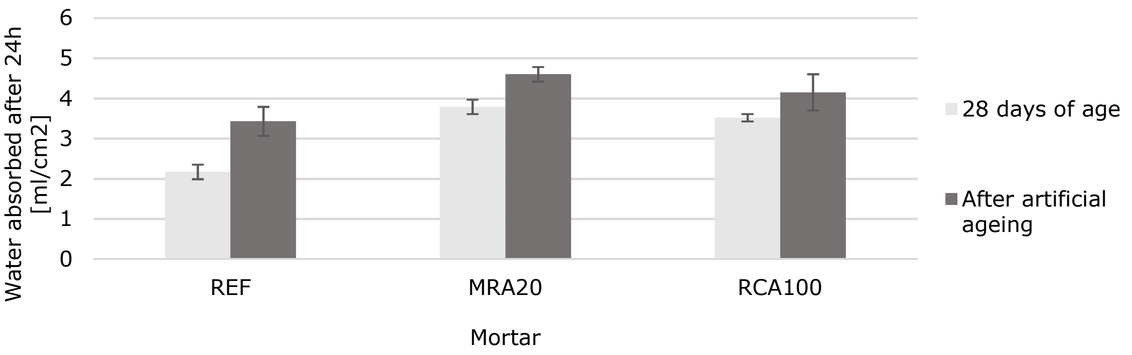

**Figure 14 - Absorbed water before and after artificial ageing**

## 4. Conclusions

It is evident that the nature of the aggregates used in wall coating mortars highly influences their performance and behaviour. Test specimens with identical quantities of different recycled aggregates showed different strengths and weaknesses. Table 5 summarizes how each mortar relates to reference in each test.

**Table 5 - Qualitative performance of the modified mortars relative to the reference one**

| Tests | RCA20 | RCA50 | RCA100 | MRA20 | MRA50 | MRA100 |
|---|---|---|---|---|---|---|
| Kneading water | ⤴ | ⤴ | ⤴ | ↪ | ↪ | ⤴ |
| Apparent bulk density – fresh | ↪ | ↪ | ⤵ | ⤵ | ⤵ | ⤵ |
| Apparent bulk density – hardened | ↪ | ⤵ | ⤵ | ↪ | ⤵ | ⤵ |
| Dynamic modulus of elasticity | ⤵ | ⤵ | ⤵ | ⤵ | ⤵ | ⤵ |
| Ultrasonic behaviour | ⤵ | ⤵ | ⤵ | ↪ | ⤵ | ⤵ |
| Compressive strength | ⤵ | ⤵ | ⤵ | ↪ | ⤵ | ⤵ |
| Flexural strength | ↪ | ⤵ | ⤵ | ⤴ | ⤵ | ⤵ |
| Water absorption by capillarity | ↪ | ↪ | ↪ | ⤵ | ⤴ | ⤴ |
| Open porosity | ⤴ | ⤴ | ⤴ | ↪ | ⤴ | ⤴ |
| Dimensional variation | - | - | ⤴ | ⤵ | - | - |
| Susceptibility to cracking | - | - | ↪ | ↪ | - | - |
| Water vapour permeability | - | - | ⤴ | ⤴ | - | - |
| Permeability to water under pressure | - | - | ⤴ | ⤴ | - | - |
| Permeability to water under pressure- after ageing | - | - | ⤴ | ⤴ | - | - |
| Adherence strength | - | - | ⤴ | ⤵ | - | - |

**Legend:** ⤴ - higher than reference; ⤵ - lower than reference; ↪ – less than 5% difference.

As previously mentioned, due to the nature of the recycled aggregates used, mortars incorporating them showed some global trends relative to the reference mix, such as lower bulk densities and lower dynamic modulus of elasticity. These differences are considered advantageous and mean that it is possible to produce lighter materials with lesser propensity to cracking. However, as these mortars tend to have lower mechanical strength and higher water absorption levels, they could only be used in less demanding environments with low exposure to humidity and some protection from physical harm.

In conclusion, the obtained results show that, in addition to the environmental benefits inherent to the use of recycled materials, it is possible to obtain functional improvements in mortars. Of the six formulations, MRA20 stands out, composed of 80% of natural aggregate and 20% of mixed recycled aggregate, which performed better than the reference mortar in most evaluated parameters, while still being a more sustainable material.

## 5. References

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