The role of powder content of the recycled aggregates of CDW in the behaviour of rendering mortars

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Abstract

In recent years, the number of studies on the incorporation of recycled aggregate (RA) into mortars has grown considerably. However, mixed recycled aggregate (MRA) is investigated on a much smaller scale due mainly to its high-water absorption capacity and higher powder content (<.150 mm). As a result, large volumes of this RA is stored in recycling plants, offering no alternatives that allow it to be used in construction, further aggravating the problems involved in the generation and destination of construction and demolition waste (CDW). This study evaluated the effects of this aggregate used with and without powder content on physical properties (fresh bulk density, incorporated air content, water retention, capillary absorption and porosity), mechanical properties (compressive strength, flexural strength, modulus of dynamic elasticity and adhesion to substrate) and the susceptibility of cracking of mortars. The natural aggregate (NA) was replaced by MRA at 25%, 50%, 75% and 100%. The mortars were mixed using a 1:1:6 volume ratio (cement: lime hydrated: aggregate). The results showed that the physical-mechanical behaviour of the mortars improved, as the content of MRA with higher powder content increased. On the other hand, higher percentages of NA replaced by MRA contributed to the excessive emergence of micro-cracks in the renderings. Finally, we have verified that the use of MRA of CDW for the production of rendering mortar is feasible, especially when there are aggregates with adequate granulometric composition and, preferably, free of powder.

Keywords: Construction and demolition waste; mixed recycled aggregate; mortar; filler effect.

1. Introduction

The large and complex production chain of the construction industry is responsible for consuming more raw materials (around 3000 Mt/year) than any other economic activity, which proves to be unsustainable for the development of the planet. [1]. It is also estimated that the construction sector is responsible for the consumption of about 40% of all natural resources available on the planet [2] and that 1/3 of these resources are converted into cement-based products [3].

Aggregates, for example, taking into account their weight or volume, are the main constituents of cementitious materials, representing a worldwide consumption of 40 billion tons/year [4]. In Brazil, aggregate consumption is around 741 Mt, equivalent to a *per capita* consumption of 3.7 tons [5]. In particular, natural sand reached a consumption of around 392 Mt in 2014 [6], out of which more than 90% is extracted from river beds [7], constituting a strong environmental impact that can cause, in addition to other damage to the environment, modification of the biological balance [8,9] and soil microbiota [10].

With this in view, recycling and reusing construction and demolition waste (CDW) in engineering works is highlighted due to its potential for use as aggregate, which contributes to reducing the consumption of natural resources and solving problems related to the generation of such wastes. In the European Union, CDW generation exceeds 850 Mt/year [11], out of which up to 90% of landfill waste can be recycled and reused [4].

In Brazil, in 2016, about 45.1 million tons of CDW were collected, which represents a reduction of 0.08% compared to the previous year [12]. However, this national scenario requires special attention since it is believed that the total volume of CDW produced in the country is greater. For example, other studies [13,14] mention that the CDW production in the country is over 70 Mt/year, representing an additional 50% of the urban solid waste mass.

Although there are laws on recycling in Brazil, currently only 6.14% of this volume of CDW is recycled [4] and most of it is destined for landfills or illegally disposed of in vacant lots and along riverbanks and roadsides. As a consequence, the environment suffers from several environmental impacts, such as silting rivers and lakes, obstructing urban drainage systems, causing flooding, urban landscape degradation, so-called visual pollution, proliferation of vectors that are harmful to human health, as well as numerous social problems, since its removal implies high costs for municipalities [15,16].

Accordingly, there is a need to produce eco-friendly materials. The incorporation of recycled aggregate (RA) from the crushing of the CDW in cementitious materials is an alternative compatible with this concept, since it is possible to minimize the environmental impact generated by both the extraction of natural resources and the inadequate disposal of these wastes [17].

For these reasons, in recent years there has been a growing interest in the use of RA in building materials. However, the number of studies evaluating the use of RA obtained from recycling plants of CDW (namely, Mixed Recycled Aggregate – MRA) in mortar and concrete is still limited. Most previous research evaluates the use of a single type of RA from CDW [18], neglecting the potential of MRA.. The reasons are clear: (i) it has high heterogeneity; (ii) it has high water absorption capacity; (iii) it contains a greater amount of contaminants [19] and powder content [20,21] and therefore directly affects concrete [22–26] and mortar [27–30] properties. Thus, a large amount of this type of waste/MRA is stored in the plants, with no alternatives for its recovery, contributing even more to the environmental problem.

Normally, for RA of CDW, the powder fraction is considered to be a material below the 0.15 mm sieve due to the higher amount of undesirable materials (adhered mortar, clay minerals, etc.) and the higher water absorption capacity [23,29,31–34]. In mortars, for example, the excess of powder content in RA can negatively affect its properties, mainly in terms of the occurrence of cracking [20,30,35–37].

In recent years, many researchers have been studying the improvements to the physical properties of RA by treatments that can remove or improve the quality of the mortar adhered to RA particles [38–40]. However, studies that exhaustively analyze the effects of the content of powder present in MRA on coating mortar properties are limited.

One of the most efficient alternatives in the attempt to improve the quality of this RA without introducing great negative effects on the material or the environment is the elimination of powder content through washing and sifting [8,36,41]. The simple beneficiation of MRA can improve the properties of the mortars, potentializing use on a large scale by the construction industry. This would contribute to the preservation of the environment by withdrawing large volumes of waste that are inappropriately disposed in nature and, at the same time, would reduce the use of natural resources as it provides substitutes for natural aggregate (NA).

It is further noted that the studies that evaluate the use of MRA cement-lime mortar based are scarce, although previous studies have shown the beneficial effects of the use of lime to compaction, physical and mechanical properties of mortars [42–44]. From the environmental point of view, lime is an eco-efficient material, including its capacity of low energy consumption during the production process, reduction of carbon dioxide emissions, as well as the consumption of carbon dioxide during carbonation [45]. In addition, the free lime ($Ca(OH)_2$) present in the starting material provides a great potential for the initiation of an autogenous self-healing mechanism when necessary [46,47].

Thus, this study evaluates three types of MRA obtained from recycling plants, taking into account the different characteristics of the CDW and the effects of removal of the powder content of this RA on the physical and mechanical properties of rendering mortars. For this purpose, simple powder removal processes were used to improve mortar behaviour and to contribute to the acceptance of these materials in the construction industry, as well as to favour the circular economy.

2. Materials and methods

2.1. Binders

In this study Brazilian Pozzolanic Portland cement (PC) (similar to ASTM C 595 Portland Pozzolanic) was used, with a density of 3.15 g/cm³, a bulk density of 1.04 kg/dm³, a specific surface BET of 3.28 m²/g, 27.7 µm and compressive strength of 30 MPa at 28 days. Cement similar to that used in this research was recommended by other authors [44,48,49] for the production of mortars with RA. As a complimentary binder, we made use of hydrated lime (HL) of type CH-I (similar to ASTM C207-6) with a density of 2.30 g/cm³, bulk density of 0.42 kg/dm³, specific surface BET of 6.74 m²/g and an average diameter of the particles of 2.77 µm. The use of hydrated lime is justified by its beneficial effect on the properties of mortars and the reduction of cement consumption, as previously mentioned.

2.2. Aggregates

Two different aggregates were used in this study: river siliceous sand as the NA and recycled sand produced in a CDW recycling plant located in São José do Mipibú (RN, Brazil) as MRA. The MRA was collected from piles stored in the recycling plant after being sieved in the laboratory to remove particles larger than 4.75 mm.

The mortar and concrete (74.43%) aggregates with a small or no amount of mortar adhered (17.64%) and ceramic materials (9.32%) were the main constituents of the MRA, determined from the manual separation of grains retained in the 2.36 mm sieve. Other minor components were also present, such as gypsum particles (0.55%) and other materials (0.05%, Styrofoam, wood, paper, etc.).

To evaluate the effects of MRA powder content on mortars properties, aiming to enhance its use in civil construction, this study investigated the use of MRA in three different ways:

- MRA: Mixed Recycled Aggregate in the way it is produced by the recycling plant, that is, with particles smaller than 4.75 mm;
- MRA-B: Mixed Recycled Aggregate Benefited, that is, based on MRA, but with its particle size limited from 2.36 to 0.15 mm;
- MRA-BW: Mixed Recycled Aggregate Benefited and Washed, that is, a variation of MRA-B, considering, however, the removal of the thin material (<0.15 mm) by washing under running water and a sieve of 0.15 mm.

Table 1 presents the physical characteristics of the aggregates studied. MRA showed lower apparent specific gravity and less bulk density, higher modulus of fineness, higher friability coefficient, and a higher water absorption when compared to NA. These results are similar to those obtained by other authors [48,50,51], and, according to the limits established by the Brazilian (NBR 15116: 2004) and European (UNE-EN 13139: 2002) standards. However, the removal of the powder through the sieving and washing of MRA increased the specific mass and decreased the water absorption due to the removal of particles with greater surface area (<150µm and <75µm, respectively).

In Fig. 1, an analysis of particle size distribution of the analyzed aggregates is presented, determined according to the Brazilian standard NBR NM 248:2003 (similar to UNE-EN 933-1:2006). The incorporation of the three MRA types resulted in an improvement in the particle size distribution of the mixtures, justifying the results of the uniformity coefficient (Table 1). Similar results were obtained in previous studies [43,49], where it was verified that the RA studied in these investigations had a more continuous particle size distribution than the NA.

Table 2 lists the main physical characteristics of NA and MRA powder (<0.15mm), determined by laser grain size and BET surface area. The pozzolanic activity of the MRA fines was also evaluated according to Brazilian standards NBR 5751:2015 and NBR 5752:2014. MRA powder has particles with smaller mean diameter and larger specific area compared to NA powder. The MRA powder showed no pozzolanic activity indexes with cement and lime. The performance index obtained with cement was 76.81%, being lower than that required by NBR 12653: 2015, which is at least 90%. However, it is above the value required by the American Standard ASTM C618-12:2018, which is 75%, showing that these particles have some reactivity with the cement due probably to the alumina (Al_2O_3) and silica (SiO_2) content and the hydrated cement's calcium hydroxide ($Ca(OH)_2$) [52,53].

The shape and surface texture of the aggregate powders were evaluated by scanning electron microscopy (SEM). The micrographs of Fig. 2 (a) and (c) show that the powders of both aggregates are irregularly shaped. However, the MRA powder has more defined edges and vertices, which is attributed to the crushing process.

The surface texture and particle size variation are the major differentials of these materials. The MRA powder has a great diversity of size and forms of dispersed particles, besides presenting a rough and rough textured porous surface (Fig. 2 (d)), corroborating the micrographs presented in other studies [19,54]. The rough texture of the MRA powder, as well as the larger surface area, explain the higher absorption of this RA.

2.3. Production of mortars

The following criteria were established for the manufacture of mortars:

- Based on a preliminary analysis, we defined a ratio by volume of 1:1:6 (cement: lime hydrated: wet aggregate). This proportion is commonly used in civil construction in Brazil.
- NA was replaced by volume by MRA, MRA-B and MRA-BW at 0%, 25%, 50%, 75% and 100% levels. Then, the resulting ratio (cement: lime hydrated: NA: RA) was converted to weight with the aggregates in dry condition.
- The consistency index of the mortars was kept constant in such a way that all the mixtures reached a flow value of 260 mm, according to the criteria established by the Brazilian standard NBR 13276:2016 (similar to ASTM C1329/C1329M:2016). Thus, the ideal amount of water for mixing the mortars was experimentally adjusted to strictly guarantee the specified workability.
- The mortars were mixed in a standard mechanical mixer according to the procedure described by Brazilian Standard NBR 16545:2016.

The percentage of substitution and the type of RA used was suffixed to some of the series. For example, a mixing ratio with 0% to 100% MRA is a series. Thus, the material compositions of the three series to produce 1m^3 of mortar are shown in Table 3.

The incorporation of the three types of MRA resulted in a linear increase in the amount of water needed for the mortars to reach a consistency of 260 mm (Table 3). This was due to higher water absorption of MRA compared to NA (Table 1). Similar behaviour was observed in previous studies [28,30,33,37,48,51,55,56]. However, the removal of MRA powder favored a decrease in the w/c ratio of

MRA-B and MRA-BW mortars compared to mortars produced with MRA. The consumption of cement and lime decreased slightly with an increase in the amount of MRA, considering the same volume (1 m^3). The reason for this decrease is the difference between the specific masses of NA and MRA.

2.4. Tests on mortar mixes

During the first 48 hours, the surface of the specimens was protected with a glass plate to avoid evaporation of the kneading water. After this period, demoulding was carried out, keeping the specimens exposed to air and at room temperature of 25±5 ºC until the ages established for each test. Details regarding the specimen size and numbers with the applicable standards and curing time for these tests are listed in Table 4.

The dynamic modulus of the mortars was calculated based on the results of the dry density tests of the hardened mortar (NBR 13280:2005 equivalent to EN 1015-10:1999) and ultrasonic pulse (NBR 8802:2013 equivalent to ASTM C 597-2:2009), according to Brazilian standardization (NBR 15630:2009 similar to EN 14146:2004). Cracking control of the renderings was done in terms of quantity and length of visible cracks, by square meter of covered wall for each mortar. The procedures were the same as those used by Miranda and Selmo [20].

3. Results and discussion

3.1. Properties of fresh mortar

3.1.1. Bulk density

The incorporation of the three types of MRA investigated resulted in mortars with lower fresh mass density (Fig. 3) due to the lower density of these aggregates in relation to NA. Lighter mortars become easier to apply and for the same volume, the amount of mass to be transported is lower, thus increasing productivity. On the other hand, light mortars are usually porous, which limits their use outdoors because of the ease of access of aggressive agents [48]. The fresh bulk density was clearly affected by the removal of the powder content from the MRA. As the powder content was reduced, the mass density decreased due to reducing the compactness of the mixture and increasing the amount of voids.Fig. 3 shows that no linear trend of decrease as the NA was replaced by the MRA, as observed in previous studies [13,48,55,57,58]. From the 50% substitution of the MRA, the mass density of the mortars increased slightly. This is due to the higher uniformity coefficient of the MRA and the filling effect of voids by the fine particles of this RA, resulting in fresh mortars that are more compact and therefore denser. The higher number of particles for the same volume of mortar [55], as well as the filling of voids filled with water by the smaller particles (<0.15mm) of the MRA [58] increased the density of the fresh mortar.

In general, there is a decrease in the mass density of mortars produced with up to 75% of MRA-B and MRA-BW. However, the bulk density increases when 100% of these aggregates are used due to better sieve behavior.

3.1.2. Occluded air content

The Fig. 4 shows in general, the incorporation of the three types of MRA reduced the amount of occluded air content in mortars. The NA was replaced by the MRA, the occluded air content of the mortars decreases linearly ($R^2 = 0.901$) (Fig. 4), confirming the results obtained in other studies [48,57]. A linear tendency ($R^2 = 0.915$) reduction was also observed for mortars with percentages of NA replacement by MRA-B equal to or greater than 25%. However, no linear tendency was found for mortars produced with MRA-BW.

Removal of the powder content did not clearly follow a trend for this property. The mortars produced with MRA-B did not present a similar behaviour to mortars with MRA. This demonstrates that in addition to the powder content, the particle size distribution of RA is important to describe mortar behaviour, as shown in Fig 5.

Fig. 5 shows that there is a relation between the uniformity coefficient of the three MRA and the air content occluded of the mortars. With the increase in the aggregate granular skeleton continuity, there is a linear decrease in the content of occluded air of mortars with MRA and MRA-B ($R^2 = 0.944$ and 0.981, respectively).

The mortars produced with MRA obtained better performance due to the higher powder content present in this aggregate. In the study of Corinaldesi [42], the higher amount of fine particles reduces the number of macropores due to the filling effect and consequently the volume of air incorporated decreases. In addition, the higher amount of RA friable particles explain the lesser amount of incorporated air from the mortars due to voids being filled by the broken particles during the mixing process [48]. As a result, the occluded air content in mortars produced with MRA decreases.

3.1.3. Water retentivity

Fig. 6 shows the results obtained in the water retention test of the mortars studied. For this property, the water retention capacity of the mortars decreased as the powder content of the MRA was removed. However, in general, the incorporation of the three investigated RA resulted in mortars with greater water retention capacity (83.5 to 95%) compared to the reference mortar (93.3%). These results can be explained by the higher roughness of the MRA, allowing a greater amount of water to be retained in the surface pores due to the creation of cohesive forces between the water molecules [30].

Besides that, these results are consistent with previous studies [34,46,61] and confirm the premise that the content fine particles of RA are beneficial to water retention of mortars produced with RA. In addition, water retention increases linearly as NA is replaced by the three types of MRA, for percentages greater than 25% MRA-B/MRA-BW and 50% MRA.

3.2. Properties of hardened mortar

3.2.1. Compression strengths and flexural strengths

The compressive and flexural strengths were measured in two curing times and the results are shown in Fig. 7 and 8, respectively. It can be observed that the compressive and flexural strengths of mortars do not follow a linear trend of decrease with the incorporation of the three types of MRA, as observed by Ledesma et al. [48].

In general, the incorporation of the three MRA studied, for substitution rates of up to 50%, resulted in a decrease in compressive strength of mortars at both ages, which was expected due to the higher water absorption of these aggregates, which was also expected due to the gradual increase in the water content of the mixtures to maintain the same consistency.

In the long-term, the compressive strengths increase considerably and do not follow a linear trend as the RA is incorporated, except for mortars produced with the MRA (Fig. 7-b). Overall, these results are consistent with previous studies [28,44,55,58,59]. Comparing the results obtained with the compressive strength classes proposed in NP EN 998-1: 2013, it is noted that all mortars produced with the three types of RA belong to the classes CS III and CS IV, making them suitable for most applications.

In general, the removal of the powder content of the MRA contributed to obtaining mortars with lower compressive strengths in the two curing periods analyzed. Regarding the flexural strength, the removal of powder content did not cause significant changes. The higher powder content of the MRA provides a micro-fill effect of the voids in the mixtures, which without the addition of powder would be filled with water. This results in mortars that are more compact and therefore more resistant.

From the analysis of the XRD patterns of hardened mortars (Fig. 9), it was identified that the increase in compressive strength observed for mortar with 75 and 100% of MRA is also associated with pore fill due to carbonation and creation of nucleation points.

The MRA powder promotes the formation of nucleation points that, together with the carbonation and rehydration of the cementitious materials present in the particles of this RA, favour the decrease in the crystals of Portlandite [$(Ca(OH)_2$] and, consequently, ($CaCO_3$) as the MRA is incorporated, accounting for the resistance gain of these mortars. In mortars the carbonation is advantageous due to the formation of $CaCO_3$, which results in the filling of the surface pores and, therefore, increase of the performance in mechanical properties and indicators of material durability, as has also been observed in other studies [51,60,61]. In addition, mortars produced with MRA presented greater potential for CO_2 capture, thus contributing to the sustainable development of the construction sector.

The mortars with the three types of MRA presented flexural strength similar to that of the reference mortar, at both ages of curing (Fig. 8). In general, removal of MRA powder did not have significant effects on the flexural strength of mortars. In this case, the irregular format of the MRA had a determining effect on obtaining the results. Although no linear tendency of increase or decrease was observed, in general the incorporation of RA improved the flexural strength of mortars. At 91 days, mortars with higher RA percentages showed a significant gain of flexural strength (Fig. 8-b), despite not following the tendency of the results obtained at 28 days of curing. These results can be explained by the better physical adhesion between the matrix and the RA as a function of the greater angular porosity of these aggregates. In mortars the flexural strength is important because it is a property that is related to the cracking and adhesion of rendering mortars [30].

3.3.2. Dynamic modulus of elasticity

Fig. 10 shows that the incorporation of the three types of MRA results in mortars with smaller modulus of elasticity due to the lower stiffness of these aggregates. The removal of the MRA powder had different effects on the three mortars studied. For mortars produced with MRA and MRA-BW the dynamic modulus of elasticity increased as RA content increased.

The reason for this increase is due to the better granulometric behaviour of MRA-BW and the higher powder content of MRA. In the case of mortars with MRA, the results confirm the premise that the powder of this RA occupies the voids in the mixture, resulting in more compact and therefore more resistant and rigid mortars (greater modulus of elasticity). However, greater stiffness averages greater internal stress, less deformation and greater risk of rupture [62], which may be detrimental to the performance of rendering mortars in terms of micro cracking [58].

The opposite effect occurred for mortars produced with MRA-B. These mixtures were more sensitive to powder removal compared to other mortars (MRA and MRA-BW) due to their poor compaction system.

3.3.3. Capillary water absorption

For this property, the removal of the powder content of MRA had a significant effect. That is, as the powder content was removed, the water absorption by capillarity of the mortars increased (Fig. 10). However, in general, mortars produced with the three types of MRA showed lower water absorption by capillarity.. Mortars with higher powder content were less permeable to water, according to the capillary coefficients. Although these results appear to be contradictory due to the high-water absorption of the MRA studied, they can be attributed to the filling of the micropores existing in the mortars and the greater amount of fine particles (<150 µm) present in the MRA and MRA-B. For the MRA series another effect may be superimposed, as the filling of the surface pores due to calcite formation, as observed in the XRD patterns (Fig. 9).

Other factors may have contributed to this performance, such as: (i) the angular and lamellar shape of RAs, which makes it difficult to pass water; (ii) the better hydration of the cement due to the release of water absorbed by RA [63]; and (iii) the presence of cement with a high degree of hydration that possibly has lower porosity than the matrix itself [44].

3.3.4. Water absorption and porosity

The mortars produced with the three types of MRA studied absorb a greater amount of water and, therefore, are more porous (Fig. 12). In general, these results are in accordance with those obtained in previous studies [44,51,64,65] and confirm that the high porosity of RA produces mortars with higher porosity in the hardened state. This is not an appreciable feature, especially in outdoor environments, since water is an agent that has the capacity to degrade cementitious materials. However, the high open porosity of mortars produced with RA contributes to the better diffusion of CO_2 present in the atmosphere, which over time is beneficial to mortar properties and to the environment.

The results also show that as the powder content of the MRA is removed, the absorption capacity and porosity of the mortars increases (Figure 12-a and 12-b). Although it appears to be contradictory, especially for the MRA series that has higher w/ c ratios, the higher amount of fine particles in the system contributes to obtaining more compact mortars in the fresh state and, therefore, less porosity in the hardened state.

3.4.5. Adhesive strength

Regardless of the type of MRA used, its incorporation resulted in mortars with lower potential of adhesion to the substrate (Fig. 13). However, the results obtained are above the minimum value (0.20 MPa for indoor environment and ceiling) established by the Brazilian regulation (NBR 13749: 2013). In general, these results are compatible with other studies [28,43,48]. It should be noted that mortars studied by these authors had different percentages of NA substitution by different RAs and lower w/c ratios than those used in this study, which accounts for, despite the similarity of results, the higher adhesion strengths obtained.

Removal of the powder had basically two distinct effects on this property. The first effect was that, in general, at the average in which the powder was removed the adhesion potential of the mortars was reduced. It initially assumes that the fine particles tend to fill the existing pores of the substrate, taking the place of the hydrated cement products that would form at the substrate-mortar interface. This results in a lesser locking of the mortar, which reduces its extent of adhesion. However, the second effect showed that for 100% replacement of NA by MRA and MRA-B, which is compatible with previous studies. [30,42,65]. In these cases, a greater presence of powders in the composition of RA improves the rheological behavior of the mortars, resulting in a better penetration in the substrate surface and, therefore, ensuring a better physical interlocking between the mortar, and the substrate is improved.

The opposite effect was observed for the MRA-BW series. In general, these mortars, despite the linear reduction of the adhesion potential with the increase in the replacement ratio, obtained the best results (especially for the percentages of 50 and 75%), probably due to the higher consumption of lime and, consequently, the suitable water retention capacity of these compositions.

In general, the mortar rupture occurred more frequently at the mortar/substrate interface and indicates that the adhesion strength of the rendering is equal to the value obtained in the test (Table 5), according to the Brazilian standard NBR 13528:2010. In relation to the moisture content of the coatings, it was observed that the mortars produced with MRA presented a linear increase of humidity with an increase in the percentage of substitution. For Ledesma et al. [48], these observations are not discussed by other authors, and they are important because there is a greater susceptibility to the appearance of pathological manifestations due to moisture or freeze-thaw problems if these mortars are used in outdoor environments.

3.4.6. Susceptibility to cracking

There is a general consensus that when incorporating RA in mortars the retraction tensions of mortars increase [21,30,43,48,49] due mainly to the higher powder content of RA [21,62,66,67]. If these stresses exceed the tensile strength of the mortar, the mortars can crack, which allows the entrance of water and other external agents into the masonry wall, contributing to the appearance of pathological manifestations, such as fungal and mold proliferation and even, in extreme cases, the detachment of the rendering mortars [30].

Fig. 14 shows that during the curing period studied the incorporation of the three types of MRA causes a linear increase in the cracking rate of the mortars. However, removal of the MRA powder content contributed to reducing the amount of cracks per square metre of coated wall. Miranda and Selmo [20] showed that the use of fine fractions (<75 μm) of MRA in mortars, although not affecting the mechanical properties, contributes to a greater cracking. These authors also indicate that the content of these fines should be limited to 25%. In another study, Braga et al. [62] observed that the incorporation of fines (<150 μm), obtained from concrete residues, increases the retraction of mortars by 44% when compared to the reference mortar.

The highest index of cracking obtained by MRA is due to the use of aggregates with a greater amount of ultrafine particles (<150 μm). These materials have a high specific surface area and thus increase the water demand for the blends to reach the desired consistency. This results in greater w/b ratios and therefore greater retraction in the hardened mortar due to the loss of water by evaporation. In addition, as discussed, MRA powder increased the mechanical strength and the modulus of elasticity of mortars, which confirms the premise that more resistant and rigid mortars are more susceptible to cracking.

On the other hand, removal of the MRA powder decreased the number of cracks. When powder is removed from these RA, the water absorption and particle arrangement decreased. Thus, mortars with lower water loss by evaporation (retraction) and with greater capacity to absorb the small deformations resulting from the imbalance between the internal capillary voltages and the environment are obtained.

These results confirm that the use of RA with high amount of powder is not indicated for the production of rendering mortars. Although the Brazilian standards do not establish limits for the amount of cracks in rendering mortars, it is generally agreed that the larger the number of cracks, the less durability of renderings. Thus, it is believed that at substitution levels of up to 50%, it is possible to produce mortars without excessive cracking. However, it is necessary for the MRA to be free of powder and any contaminants that may affect the hydration of the cement. Another possibility would be the use of superplasticizers to reduce the water demand in the mixtures. However, this alternative would add costs to the production of mortars, which is not the intention of this research.

4. Conclusions

The use of mixed recycled aggregate (MRA) obtained from the crushing of construction and demolition wastes (CDW) as a substitute for the natural aggregate (NA) for the production of rendering mortars was investigated in this paper. Three MRAs were used: (i) MRA as produced by the recycling plant (<4.75 mm); (ii) MRA-B – mixed recycled aggregate benefited: MRA with particle size limited between 2.36 and 0.15 mm; and (iii) MRA-BW – mixed recycled aggregate benefited and washed: MRA-B washed for removal of remaining powder (<150 µm). In addition, other important aspects of this research can be highlighted: a) use of hydrated lime as a complementary binder aiming to improve mortar properties and decrease cement consumption; and b) use of procedures similar to those used in the construction industry. Thus, the following conclusions can be drawn from this research:

- The incorporation of the three types of MRA investigated resulted in the production of mortars with lower bulk density in the fresh state. Removal of the powder caused a decrease in bulk density and increase of the occluded air content due to the decrease of the granular compactness of the blends. Water retention did not change significantly with the incorporation of MRA. However, the use of MRA with higher powder content contributes to obtaining mortars with greater capacity of retention of water in the fresh state.
- In general, the incorporation of the three types of MRA increased the mechanical strength of mortars. The use of RA with higher powder content provides a micro fill of the voids, which makes the mortars more resistant. In addition, as the NA is replaced by the MRA, the surface pores are filled due to the products of the carbonation reaction and the creation of nucleation points.
- The mortars produced with the three types of MRA are less permeable and more porous when compared to mortars with NA. The higher powder content contributed to produce mortars with lower pore connectivity. However, due to the higher absorption of MRA, mortars with these RAs had greater open porosity.

- Regardless of the type of MRA used, the mortars presented lower potential of adhesion to the substrate compared to the reference mortar. The mortars produced with MRA in washed condition presented the best results.
- The incorporation of the three types of RA investigated resulted in the production of mortars with greater amount of cracks per m² of coated wall. Mortars produced with RA that had higher powder content (mortars with MRA) were less resistant to cracking. Removal of the powder by sieving and, especially, washing of the MRA was efficient to reduce significantly the number of cracks.

Although specific studies are required in order to reduce the appearance of cracks, it is recognized that it is technically feasible to use MRA for the production of rendering mortars, especially when RA is free of powder content. In external environments, there is a need to investigate further into what is specifically required regarding the durability of coatings against the action of aggressive agents. Nevertheless, this study indicates that the residue, until then considered as an environmental problem, does not prevent the production of rendering mortars. The results obtained in this research show that a simple physical treatment process (removal of MRA powder content) can contribute to the acceptance of these materials in the construction industry and, consequently, increase the recycling rates of CDW in order to mitigate the environmental impacts and achieve sustainable built environments..

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Table 1

Physical properties of the analyzed aggregates.

Characteristic	**Brazilian standard**	**NA**	**MRA**	**MRA-B**	**MRA-BW**
Maximum size (mm)	NBR 248[1]:2003	0.6	4.75	2.36	2.36
Fineness modulus	NBR 248[2]:2003	1.36	2.12	2.35	2.75
Powder content <75 µm (%)	NBR NM 46[3]:2003	2.0	7.0	2.65	-
Powder content <150 µm (%)	-	14.0	10.3	1.20	0.5
Bulk density (kg/dm^3)	NBR NM 45[4]:2006	1.50	1.38	1.30	1.30
Apparent specific gravity (kg/dm^3)	NBR NM 52[5]:2009	2.64	2.52	2.53	2.56
Water absorption (%)	NBR NM 30[6]:2006	1.34	6.09	5.37	4.43
Friability coefficient (%)	NBR 7218[7]:2010	0.24	1.82	2.17	2.10
Uniformity coefficient (Cu)	-	2.60	3.60	2.90	3.83

[1]Equivalent to EN 933-1 (2012) and ASTM C136 (2014); [2]Equivalent to EN 13.139 (2002); [3]Equivalent to ASTM C117 (2017); [4,5,6]Equivalent to NP EN 1097-6 (2003); [7]Equivalent to ASTM C142 (2017).

Table 2

Main results of the characterization of the fines of the aggregates.

Fines	**D_{10} (μm)**	**D_{50} (μm)**	**D_{90} (μm)**	**D_m (μm)**	**SA (m^2/g)**	**Pozzolanic activity**
NA	60.47	117.12	220.16	130.64	1.23	-
MRA	6.24	55.73	149.68	69.31	3.55	None, less than required

D_{10}, D_{50} and D_{90} = indicate the percentage of 10%, 50% and 90%, respectively, of passing particulates; D_m = mean diameter; SA = surface area by BET.

Table 3

Mixture proportions required to produce 1 m^3 of mortar.

Mixtures design	Proportions (kg/m^3)							
	NA/RA (%)	PC	HL	NA	MRA	MRA-B	MRA-BW	w/c
MRA0	100/0	231.7	93.6	1507.5	-	-	-	1.36
MRA25	75/25	227.3	91.8	1109.3	380.2	-	-	1.39
MRA50	50/50	219.5	88.7	714.2	734.3	-	-	1.50
MRA75	75/25	215.4	87.0	350.4	1080.9	-	-	1.54
MRA100	100/0	209.2	84.5	-	1399.8	-	-	1.63
MRA-B25	75/25	230.8	93.2	1126.5	-	363.7	-	1.37
MRA-B50	50/50	226.9	91.6	738.3	-	715.1	-	1.44
MRA-B75	75/25	223.1	90.1	362.9	-	1054.5	-	1.50
MRA-B100	100/0	218.7	88.3	-	-	1378.1	-	1.59
MRA-BW25	75/25	228.9	92.4	1117.0	-	-	360.7	1.41
MRA-BW50	50/50	225.7	91.2	734.3	-	-	711.3	1.47
MRA-BW75	75/25	224.6	90.7	365.3	-	-	1061.4	1.50
MRA-BW100	100/0	219.1	88.5	-	-	-	1380.9	1.61

PC – Portland Cement; HL – Hydrated Lime.

Table 4

Tests performed on mortars and their respective methods and standards.

Properties	**Brazilian Standard**	**Specimens and size**	**Curing time (days)**
Properties of fresh mortar			
Bulk density	NBR 13278[1]:2005	4	-
Occluded air content	NBR 13278[2]:2005	4	-
Water retentivity	NBR 13277[3]:2005	4	-
Properties of hardened mortar			
Dynamic modulus of elasticity	NBR 15630[4]:2009	4 Prismatic (40x40x160 mm)	28
Flexural strength	NBR 13279[5]:2005	4 Prismatic (40x40x160 mm)	28, 90
Compressive strength	NBR 13279[6]:2005	8 Prismatic (40x40x80 mm)	28, 90
Water absorption by immersion	NBR 9778[7]:2009	4 Prismatic (40x40x160 mm)	28
Capillary water absorption	NBR 15259[8]:2005	4 Prismatic (40x40x160 mm)	28
Bond strength	NBR 13528[9]:2010	6 Circular (50x10mm)	56
Susceptibility to Cracking	Not standardized[10]	1 panel (70x50 cm, e= 2cm)	150

[1,2] Equivalent to EN 1015-6 (1998) and EN 1015-7 (1998), respectively; [3]Equivalent to EN 1015-8 (1998); [4]Equivalent to ASTM C597 (2009) and EN 14146 (2004); [5,6]Equivalent to EN 1015-11 (1999) and ASTM C1314 (2016); [7]Equivalent to EN 1936 (2007) and ASTM C642 (2013); [8]Equivalent to EN 1015-18 (2002); [9]Equivalent to EN 1015-12 (2000) and ASTM C952 (2012); [9]Specific procedure by [20].

Table 5

Adhesive strength of hardened mortar.

Mixtures design	**Adhesive strength** Average (MPa)	SD (MPa)	**Type of rupture** Adhesive (%)	Cohesive (%)	**Humidity** (%)
MRA					
MRA0	0.43	0.09	50	50	2.61
MRA50	0.25	0.11	52	48	1.76
MRA75	0.24	0.10	56	44	3.27
MRA100	0.29	0.02	2	98	3.47
MRA-B					
MRA-B0	0.43	0.09	50	50	2.61
MRA-B50	0.26	0.04	17	83	1.99
MRA-B75	0.27	0.07	77	23	2.09
MRA-B100	0.28	0.04	43	57	2.13
MRA-BW					
MRA-BW0	0.43	0.09	50	50	2.61
MRA-BW50	0.33	0.03	90	10	1,81
MRA-BW75	0.29	0.08	29	71	2,04
MRA-BW100	0.28	0.05	48	52	2,15

SD = standard deviation; Adhesive rupture (in the interface coating –substrate); Cohesive rupture (within the coating); Cohesive rupture (within the substrate).

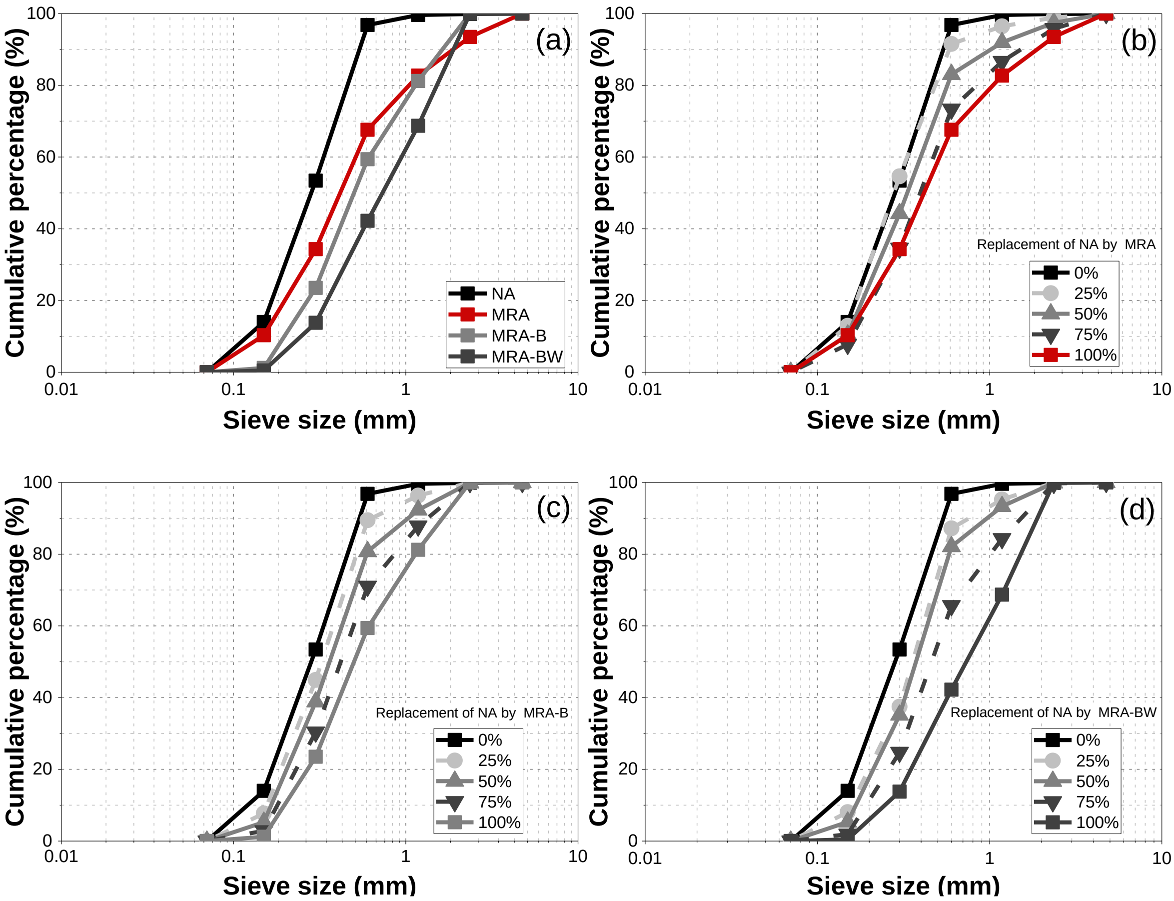

Fig. 1. Particle size distribution of the natural and recycled aggregates.

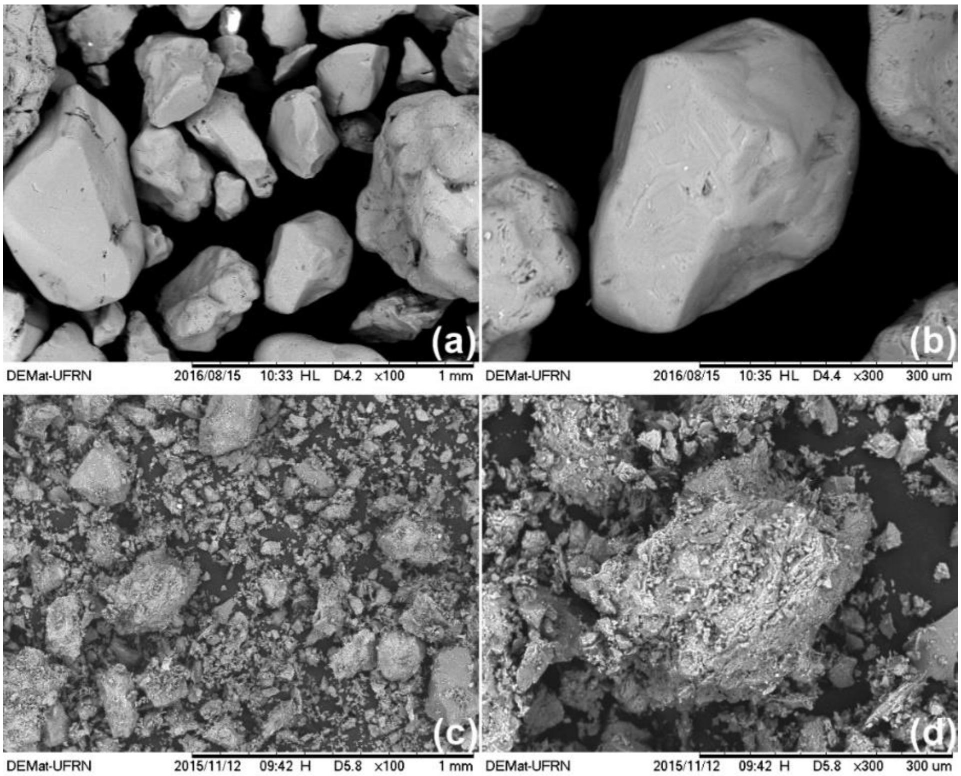

Fig. 2. Shape and surface texture: (a) and (b) of the fine of NA; (c) and (d) of the fine of MRA.

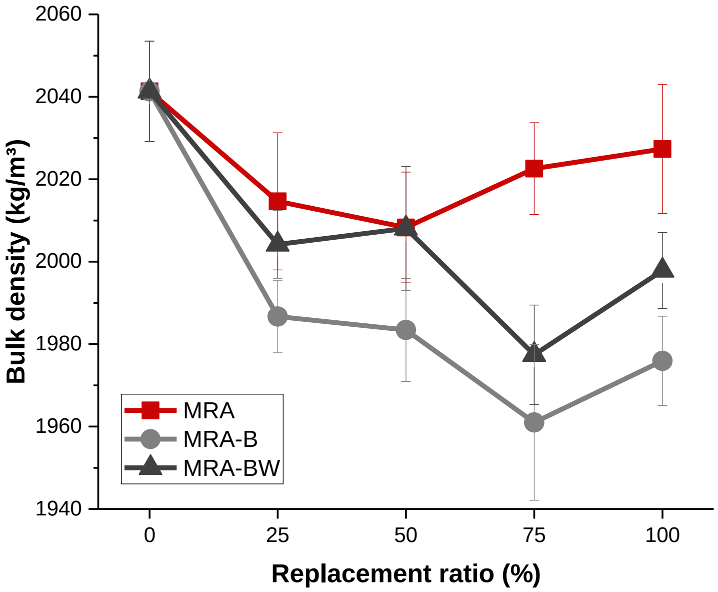

Fig. 3. Bulk density of fresh mortar vs. replacement ratio of the NA by MRA, MRA-B and MRA-BW.

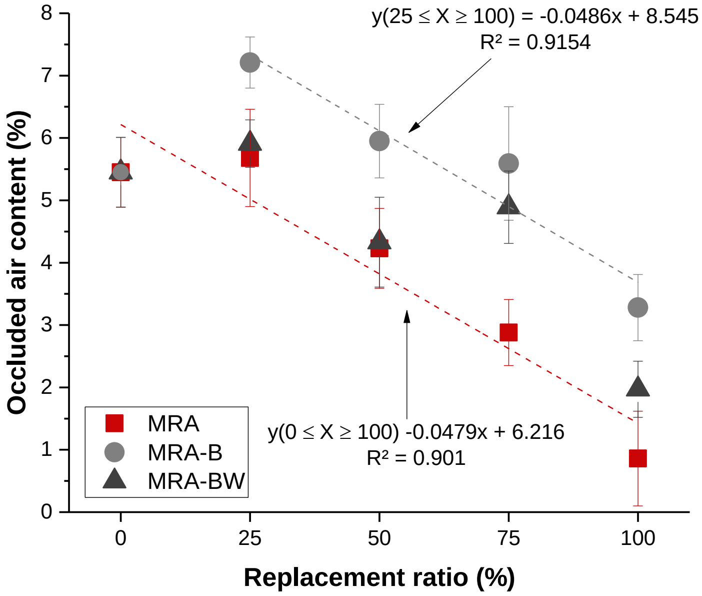

Fig. 4. Occluded air content vs. replacement ratio of the NA by MRA, MRA-B and MRA-BW.

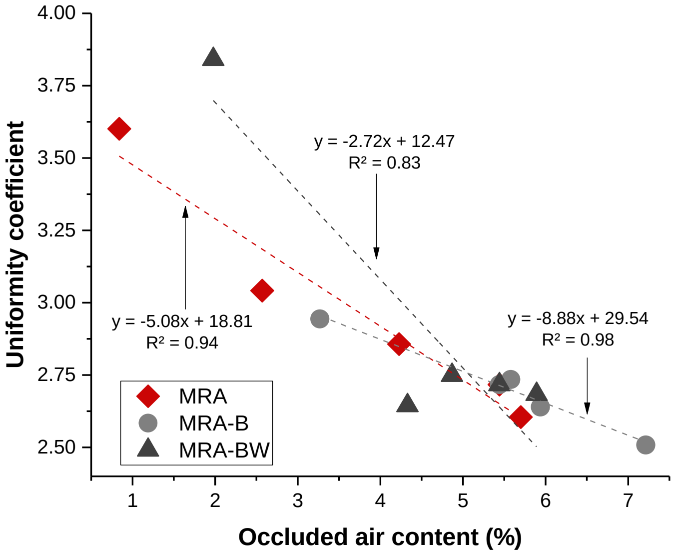

Fig. 5. Relation between the uniformity coefficient of the aggregates and the occluded air content in the mortars.

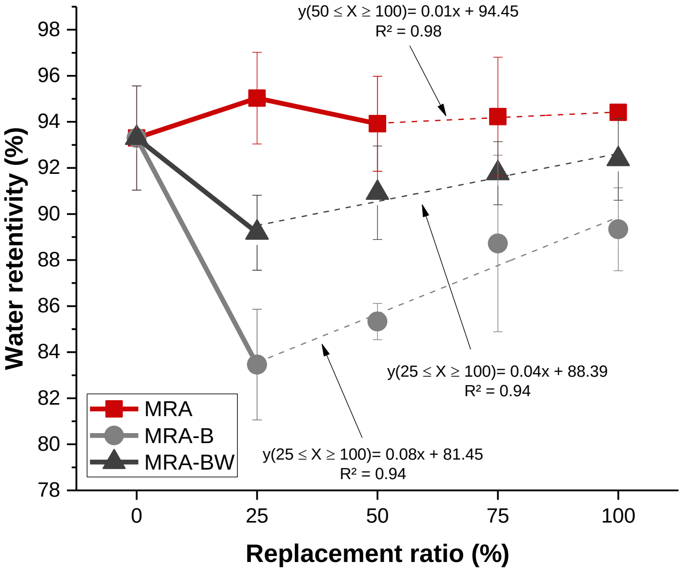

Fig. 6. Water retentivity of fresh mortar vs. replacement ratio of the NA by MRA, MRA-B and MRA-BW

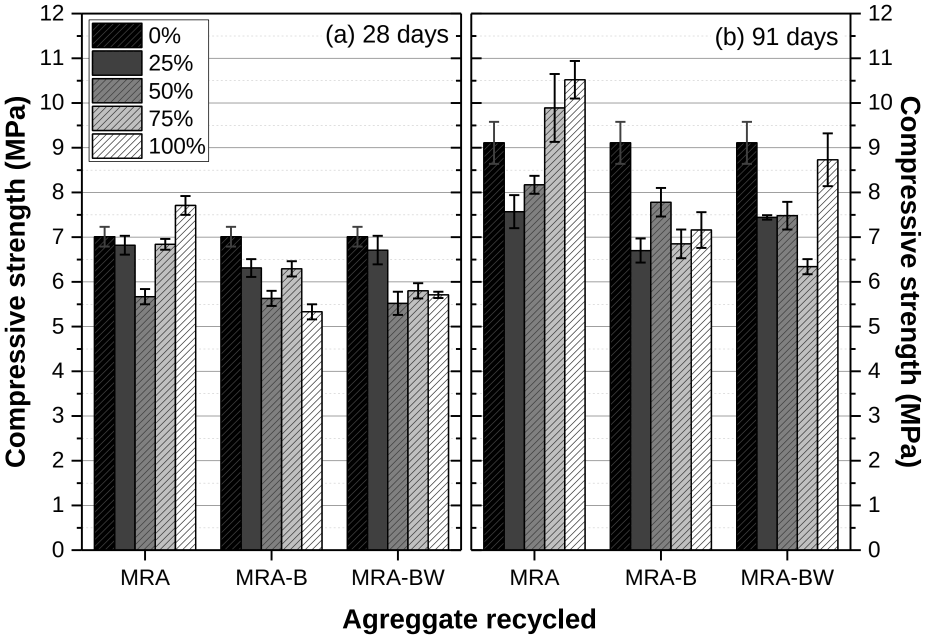

Fig. 7. Compressive strength of the mortars at (a) 28 days and (b) 91 days of curing.

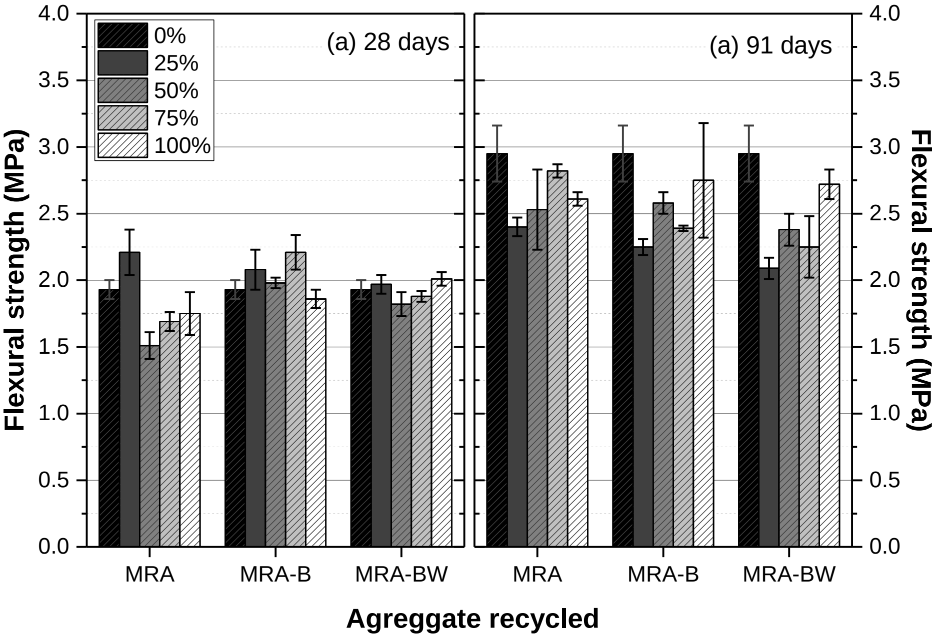

Fig. 8. Flexural strength of the mortars at (a) 28 days and (b) 91 days of curing.

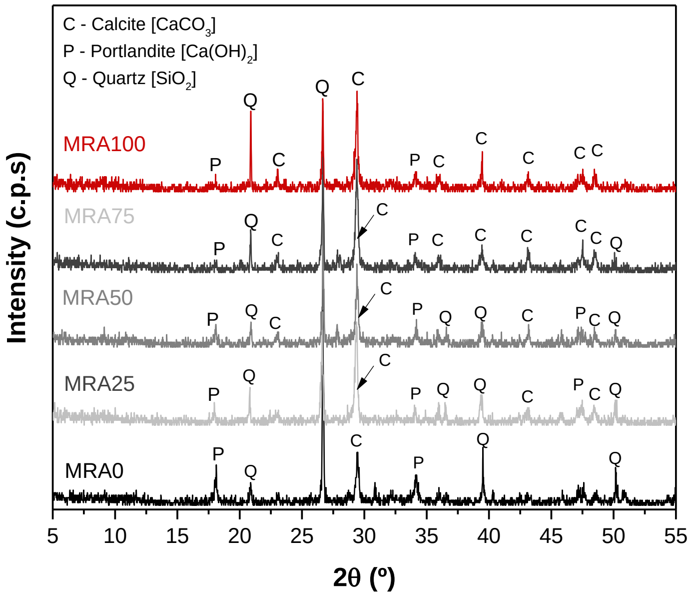

Fig. 9. XRD of the mortar with MRA at 28 days of curing.

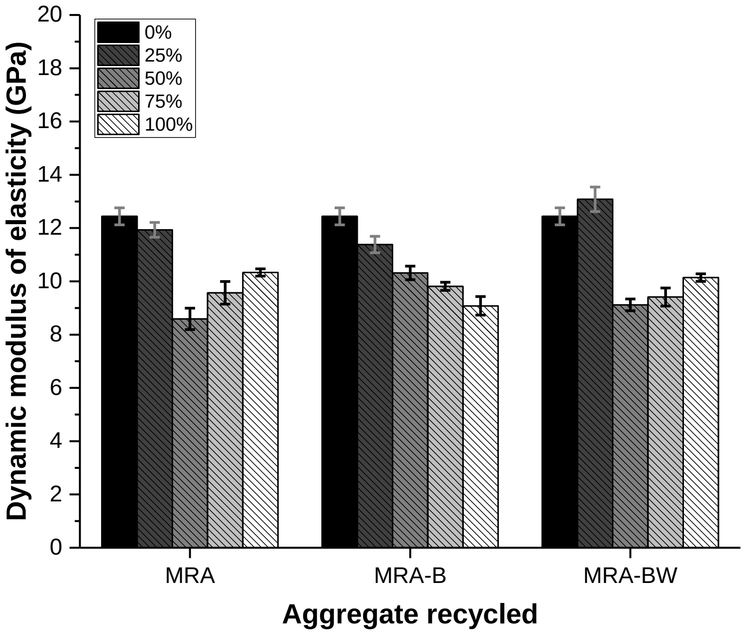

Fig. 10. Dynamic modulus of elasticity of hardened mortar vs. replacement ratio of NA by MRA, MRA-B and MRA-BW.

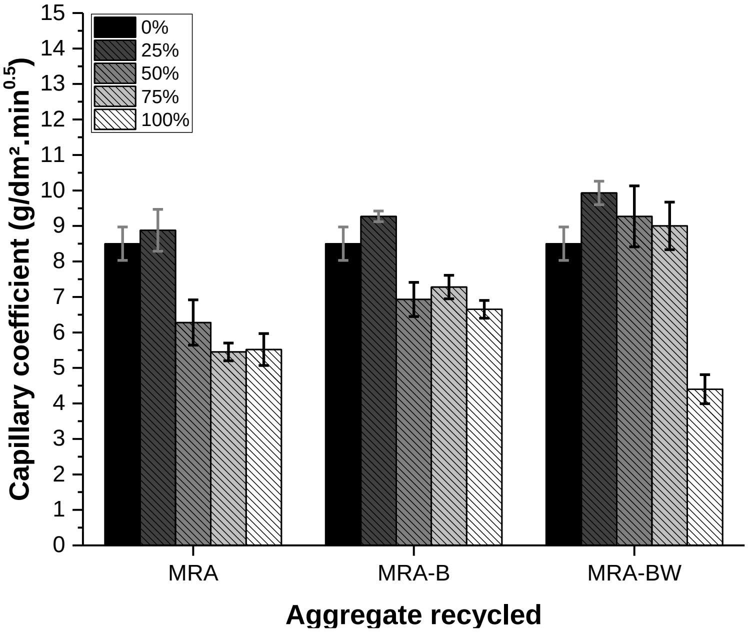

Fig. 11. Capillary water absorption of hardened mortar vs. replacement ratio of the NA by MRA, MRA-B and MRA-BW.

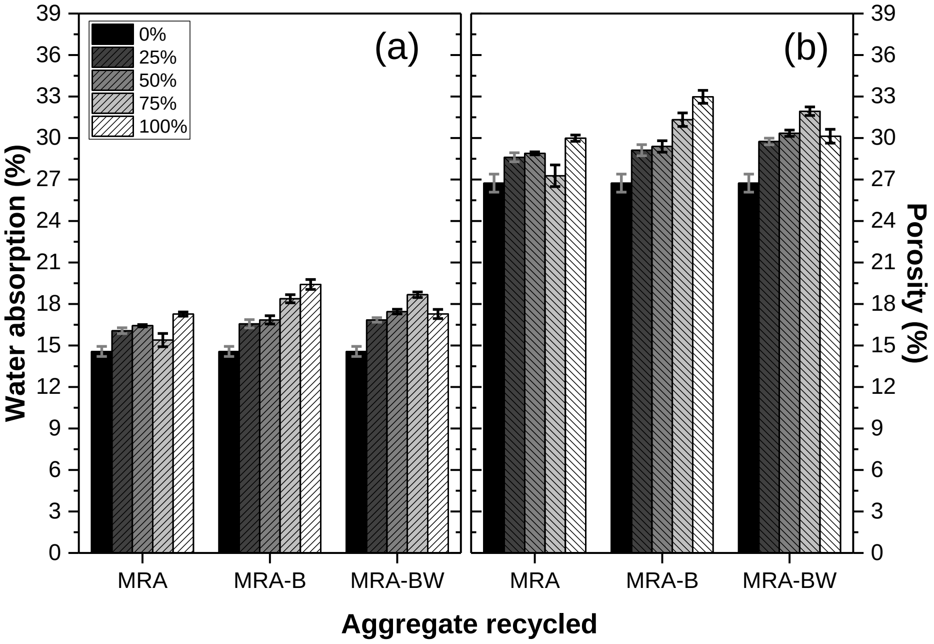

Fig. 12. (a) Water absorption and (b) porosity of hardened mortar.

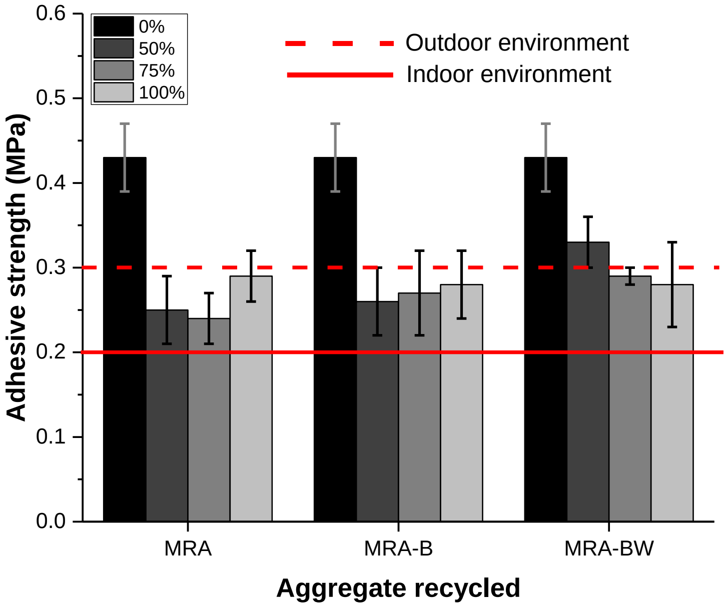

Fig. 13. Adhesive strength of hardened mortar vs. replacement ratio of the NA by MRA, MRA-B and MRA-BW.

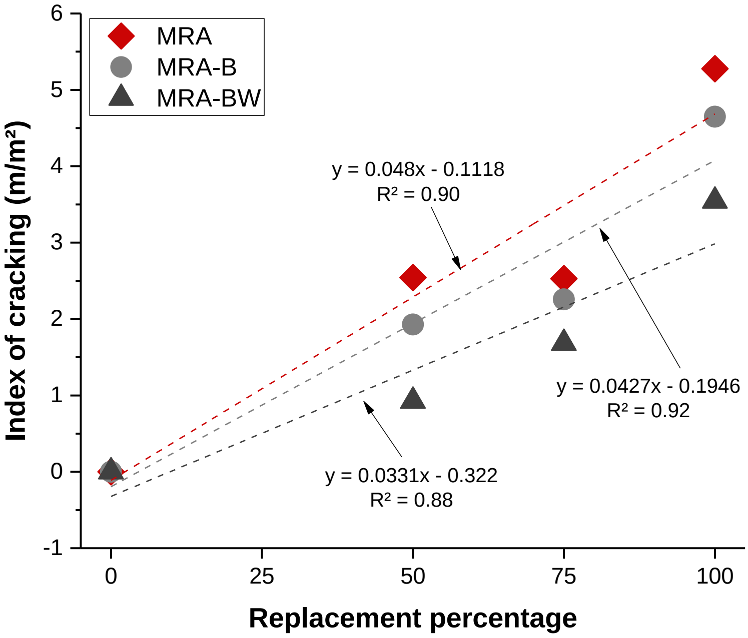

Fig. 14. Index of cracking of the hardened mortars.