Influence of demolition waste fine particles on the properties of recycled aggregate masonry mortar

Abstract

This paper analyses the influence of the fine fraction of two types of construction and demolition waste (CDW1 and CDW2) on the properties of recycled aggregates (RA) and masonry mortars. The CDW1's main component was ceramic while the CDW2 were concrete. Three different kinds of fine RA were produced from each source of CDW; the first type was produced by only using the fraction finer than 4.76 mm, the second one by employing only the coarser fraction than 4.76 mm, and the third type was a mix of both fractions of CDW. The masonry mortars were produced employing the 100% substitution of natural aggregates. The results show that all the recycled mortars achieved a higher water retentivity capacity than that of the conventional mortars. However, the sole use of the fine fraction of the CDW was found to have a deleterious effect over the hardened mortar properties, thus making it only adequate for the rendering or bonding of interior walls at or above ground level. In contrast a combination of both the fine fraction and coarse fraction of the CDW in the production of the RA achieved all the minimum requirements for rendering and bonding masonry mortar.

Highlights

- Two sources of CDW, one with ceramic and other with concrete as main components, were employed.
- Three different RA were obtained from two different sources of CDW.
- Masonry mortars employing 100% of recycled aggregate were validated.
- Ceramic high content recycled aggregates mortars achieved the most adequate properties.
- The employment of the coarse fraction of the CDW guarantee high quality aggregates for masonry mortar.

Keywords: Masonry mortar; fine recycled aggregate; recycled aggregate mortar; construction and demolition waste; fresh mortar properties; mechanical properties.

Abbreviations

CDW - Construction and demolition waste

FRA - Fine recycled aggregate

LH - Lime hydrate

LF - Limestone filler

RA - Recycled aggregate

w/c - water/cement

1. Introduction

The use of recycled aggregates obtained from the recycling of construction and demolition waste (CDW) is a sustainable alternative to the employment of natural aggregates within the construction industry [1]. This alternative not only allows for the protection of natural resources but is also instrumental in the reduction of areas used for landfill [2]. There have been many studies with respect to the mentioned environmental benefits [3–6], although most of the studies have been focused on the use of recycled aggregates for concrete production [7–12]. Several researchers have also studied the applicability of fine recycled aggregates (FRA) for mortar production due to the high amount of FRA produced as a result of the CDW treatment process [13–20].

Most of the mortar mixes manufactured with higher percentages of recycled aggregate presented lower mechanical properties than those of conventional mortar [13,14,16,17,19,20]. However, certain authors have established that there were minor influences on the properties of mortar mixes produced with a replacement ratio of up to 20% [21,22], 25% [19] or 40% [15] of recycled aggregate in substitution of natural aggregate. According to several researches [23–26] the improvements on the mortars' properties were also achieved when fine ceramic and concrete aggregates were employed in the mortar production or the quality of the recycled aggregates were improved after their treatment [27].

The CDW, which can be recycled, is available in numerous countries as a result of human intervention or natural disasters [28]. According to the information obtained from the Cuban National Statistics and Information Office, approximately 1000 m^3 of CDW is generated per day in Havana. The largest volume of CDW being located in landfill sites, which effectively makes it unusable for recycling due to the resulting mixing of materials and consequent contamination [29]. In Cuba, uncontaminated waste is not recycled due to deficiencies in adequate technological infrastructures as well as a lack of an adequate policy with respect to the management of this type of waste [30].

The natural aggregate quarries located near the city are almost depleted as a result of their over exploitation. Consequently, natural aggregates have to be obtained from new quarries which are a long distance away from the city, with the following consequences of higher economic costs as well as having a negative environmental impact on the local landscape [30].

Masonry mortars are widely employed in the construction of buildings in Havana, in general social housing, which is the cause of the highest aggregate consumption. The mechanical properties required for rendering or bonding mortars, according to the Cuban standard [31], are relatively low (less than 10 MPa of compression strength), allowing the use of a low cement content in the mortar manufacture.

As a direct consequence of the lack of natural fine aggregates the locals in Havana have used for the maintenance and renovation of their buildings recycled material with fractions finer than 5 mm (without crushing) obtained directly from demolished or collapsed building waste. Its use is carried out without undergoing a process of selection and treatment, as a consequence of which this fine aggregate material is often of poor quality due to its contamination by detrimental material. Fig. 1 shows several images of both sources of CDW and the mortar mixes produced.

In this research work the two different sources of CDW, which are most typical in Havana, were treated for the production of fine recycled aggregates and their applicability for masonry mortar was production analyzed. Material taken from both of the CDW sources was submitted to three different crushing processes, which led on to three types of recycled aggregates being produced from each type of CDW under study. The influence of these processes on the properties of the recycled aggregates, and their applicability, in total replacement of natural aggregates, in mortar production were the main objectives of this research work. Two types of fillers were also used in the manufacturing of the mortar; hydrated lime (recommended by Cuban standard) and limestone filler (widely employed in the city due to its high availability). The physical, mechanical and durability properties of the recycled aggregate mortar mixes were analyzed and their results were compared with those of the results obtained from the analysis of a standard conventional mortar, as well as with the minimum requirements as defined by Cuban specification NC 175:2002 [31] (equivalent to ASTM C270-12 [32]) for type III masonry mortar production.

2. Materials

2.1 Cement

An ordinary Portland cement P-350, which according to Cuban standard NC 95:2001 [33], equivalent to ASTM Type I, was employed for all mortar production. It had a density of 3.12 g/cm^3, specific surface of 3089 g/cm^2 and a compressive strength of 35 MPa at 28 days.

2.2 Fillers

Two different types of fillers were employed for mortar production: lime hydrate (LH) and limestone filler (LF). According to NC 175:2002 [31] the LH which had a dry density and bulk density of 2.1 kg/dm^3 and 0.52 kg/dm^3 respectively, was considered to be an adequate filler for masonry mortar production. The LF, which had a dry density of 2.58 kg/dm^3 and bulk density of 1.14 kg/dm^3, was produced via the grinding of limestone aggregates. LF material is predominantly used within the city of Havana due to the difficulty of obtaining lime hydrate. Fig. 2 illustrates the particle size distribution of both filler materials.

2.3 Fine aggregates

2.3.1 Production and composition of the recycled fine aggregates

The recycled aggregates used in the present work were obtained from two different CDW sources (CDW1 and CDW2). Both types of CDW were representative of the two most common types of dwellings built in Havana, which date back to the middle of the past century. The CDW1 waste material was obtained from the demolition of buildings with ceramic tiled roofs and compacted earth and limestone walls. In contrast, the CDW2 waste was obtained from the demolition of buildings with roofs formed of steel beams and concrete slabs with the walls consisting of ceramic brick. The general composition of the CDW wastes was that of roof and wall elements, however, other materials were also found to be present such as mortar, tiles, etc, which proved to be less than 10% of the total weight of the whole. An important percentage of the CDW generated in the capital of Havana is produced by the demolition of this type of dwelling [30].

The representative sampling was carried out after the crushing of between 3 and 4.5 tons of each of the two types of CDW mentioned and in accordance with BS-EN 932-1:1997 regulations [34]. Both types of CDW were individually submitted to three different types of crushing processes for the production of three different kinds of recycled aggregates (-C, -F and –CF).

The process adopted for the obtaining of the first type of fine recycled aggregates (RA1/2-C) was carried out by firstly discarding all material finer than the 4.76 mm sieve from the total volume of the CDW prior to it passing through the crushing stage. Secondly, the total volume of the material greater than 4.76 mm was crushed via the employment of a jaw crusher for the production of RA1/2-C fine recycled aggregates [14,29]. For the production of the second type of fine recycled aggregates, RA1/2-F, the CDW material which proved to be finer than the 4.76 mm sieve was used without undergoing any crushing process. The third and last type of fine recycled aggregates, RA1/2-CF, were obtained via the crushing of the total volume of the CDW to that of a finer material than 4.76 mm. In all three types of processes the material finer than 4.76 mm was separated after every stage of crushing and the remaining fractions found to be coarser than that size were submitted to a new crushing process. The crushing process was completed when all the material accomplishment the desired particle size.

2.3.2 Fine aggregates properties

Raw limestone aggregate obtained from the Arimao quarry which is the highest quality commercialized aggregate in the city [14] was used for the production of the control mortar.

Fig. 3 shows the particle size distribution of all the types of aggregates used in the present study. They were determined following NC 178:2002 [35] specification (equivalent to ASTM C136/C136M-14 [36]). All the recycled aggregates were found to have a similar grading distribution, however when compared to those of the recycled aggregates, the natural aggregates were found to present a lower amount of finer aggregates than 0.297 mm, see Fig. 3. Tests proved that the recycled aggregates not only presented a higher percentage of material finer than 75μm, but that they also had lower amounts of passing material through the higher grade sieve than those of the natural aggregates.

Table 1 shows the physical properties of the natural and recycled aggregates. The density and water absorption capacity were evaluated according to Cuban standard NC 177:2002 [37] (equivalent to ASTM C29/C29M-17 [38] specification). The bulk density and the percentage of the material passing through No. 200 (< 75 μm) sieve were determined following NC 181:2002 [39] (equivalent to ASTM C29/C29M-17 [38]) and NC 182:2002 [40] (equivalent to ASTM C117-13 [41]) specifications, respectively.

The water absorption capacity of all the recycled aggregates proved to be greater than that of the natural aggregate (Table 1), a fact which has also been reported by other researchers [13,17–19,22,26,42–44]. With respect to recycled aggregates, those obtained from crushing the fine and coarse fraction of CDW1 achieved the highest and lowest absorption capacity, respectively. The water absorption capacity of the three recycled aggregates obtained from CDW2 was similar to or higher than that of RA1-C.

Table 2 shows the chemical composition of the recycled aggregates, which was determined via Panalytical, Axios PW 4400/40 XRF spectrometers. The calcium and silica content being the main differences between the CDW1 and CDW2 sources. The recycled aggregates produced from the CDW1 source proved to contain approximately 50% of silica, as a direct consequence of its high percentage of ceramic material content. The recycled aggregates produced from the CDW2 had a higher composition of calcium, as they originated from concrete elements. The magnesium and aluminum content proved to be the main difference between the composition of the coarse (-C) and fine (-F) fraction. The RA1-F aggregates proved to have a high content of magnesium due to the presence of limestone rocks, as the walls of the dwellings, which formed part of the material sourced for CDW1, had a certain amount of dolomite content in them. In contrast, the RA1-C aggregate proved to have a greater aluminum content, which was a direct result of the influence of the coarse fraction of the ceramic roof material. With respect to the

RA2-F aggregate produced from the CDW2 waste, it was determined that the high magnesium value (limestone-dolomite aggregates were used for concrete production) was a direct result of the high content of material obtained from the concrete roofing. In contrast the RA2-C aggregate, which was obtained from ceramic wall waste, proved to have higher amounts of aluminum content.

3. Mortar Manufacture and Experimental Procedure

3.1 Mortar mixture proportions

Type III Control mortar (bonding and rendering mortar for use at ground level and above) employing natural aggregate, with the volumetric mix proportion of 1:4:2 (cement: aggregate: filler) was produced following NC 175:2002 [31] specifications. This standard recommends the use of lime hydrate as filler. Unfortunately, this is difficult to obtain within Havana and as a consequence the use of limestone filler is also permitted in mortar manufacture. As a direct result of the lack of fine particles within the natural aggregates it is necessary to include filler in the mortar mixture. The mentioned added filler has the effect of reducing the volume of voids within the particle matrix, thus achieving a better performance of the mortars in the fresh and hardened state [45].

The 1:5:1 (cement: aggregate: filler) volumetric mix proportion was used for the recycled aggregate mortars production. Prior studies [14] verified that this dosage was the equivalent to the volumetric dosage (1:4:2) established by Cuban regulations for natural aggregates mortars. The higher amount of fine material contained in the recycled aggregate justified the reduction in the use of the filler volume.

The manufacturing process was carried out following NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14 [48]) specifications. The total water content added to each mortar was determined experimentally in order to obtain a consistency index of 190 ± 5 mm in all mortar mixes, and in accordance with Cuban standard NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]). The quantity of free water in the paste of each of the mortar mixes defined the effective water cement ratio (see table 3). The natural aggregates were used in dry condition while the recycled aggregates were used in wet condition. The effective water absorption capacity of the fine aggregates was determined via soaking them for 30 min (defined by DIN 4226-100 [51]). The method used in the testing was that stipulated by the Cuban regulation NC 186: 2002 [52] (equivalent to ASTM C 128-97 [53]) for the determination of the 24 h absorption capacity of natural aggregates. The effective absorption capacity of the recycled and natural aggregates was 80% and 50% respectively of their total absorption capacity.

Twelve different recycled aggregate mortar mixes were produced, as a result of the combination of the six recycled aggregates (RA1-C, RA1-F, RA1-CF, RA2-C, RA2-F and RA2-CF) with the two fillers (LH, LF). Two control mortars were also manufactured employing natural sand and two types of fillers. Table 3 shows the mix proportions of the mortars.

The mortar specimens were de-molded at 24 hours and then, in compliance with regulation NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14 [48]), cured in a humidity room until the testing stage.

3.2 Experimental procedure

3.2.1. Fresh state test

The consistency and water retentivity properties were measured. The consistency of mortar was fixed as 190 ± 5 mm for all the mortar mixes in accordance with NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]) specifications. The mortar mixes which did not achieve that requirement were rejected.

The water retentivity capacity was determined in all of the mortar mixes in accordance with NC 169:2002 [54] (equivalent to ASTM C1506-16b [55]) specifications. The fresh mortar was poured into a 100 mm diameter cylindrical mould, with a depth of 25 mm, before being subjected to a suction test employing a specific absorption filter. The water retentivity capacity was determined by the amount of water absorbed by the paper filter, being 90% the minimum value required by Cuban Specification.

3.2.2. Hardened state tests

Physical (density, absorption and accessible pores) and mechanical (compressive and flexural strength) properties were determined after 28 days of curing according to ASTM C270-12a [32] and NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14 [48]) specifications, respectively, employing the Automax compression equipment with 50 kN capacity.

The mortar bond tensile strength was also determined, following the NC 172:2002 [56] specifications. The test, which was carried out over a concrete block surface via the use of a Dyna Haftprufer Pull-off tester Z16 (as described in the previous work [14]), at 28 days of curing and in similar conditions to those of the other test specimens.

The capillary water absorption capacity of each mortar was also determined after 28 days of curing according to NC 171:2002 [57] (equivalent to ASTM C1403-15 [58]) specifications. All the surfaces of the specimens were sealed with an epoxy resin except for the top and bottom ends of 40 x 40 mm which were left untreated in order to ensure the one directional transport of the water as described by the regulation.

The drying shrinkage was determined according to ASTM C490/C490M-11 [59] specifications. The 25 x 25 x 285 mm mortar specimens, which had been fitted with a stainless steel stud at both ends, were de-molded after 24 hours of casting and kept in an environmental temperature of 28˚C with a humidity of 80%. The initial length readings were immediately recorded via the use of a length comparator model 62-L0035/A. The length variation was measured over a period of 90 days.

The electrical resistivity was determined via the use of a model Vasrmmk11 tester (see Fig. 4). The measurements were taken with the specimens in a saturated condition which was achieved by totally submerging the specimens in water for 24 hours after undergoing 28 days of curing.

4. Results and Discussion

4.1 Fresh state properties

4.1.1 Consistency

It was necessary to vary the water content employed for the production of the mortars in order to obtain the required consistency of 190 ± 5 mm. The variation of water content was carried out without using admixtures. Table 3 shows the consistency values obtained by all the mortar mixes produced. The recycled aggregate mortars needed more water than the control mortars in order to achieve the required workability values (190±5 mm) established by Cuban regulation NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]).

The higher absorption capacity of recycled aggregates with respect to natural aggregates has a negative effect on the consistency of the mortar produced, as the recycled aggregates absorb part of the mixing water [17,18,60,61]. Additionally, mixtures produced with angular and rough-textured particles, such as those found in recycled aggregates, tend to interlock and reduce inter-particle movement [62].

4.1.2 Water retentivity

The water retentivity results are presented in Table 3. All the mortar mixes (including those produced using recycled aggregate), except for the CM-LF mortar, achieved the minimum value of 90% required by Cuban specifications. The lower percentage of fine material in the LF filler compared to that of the LH filler (Fig. 2) and the water retaining ability of LH, influenced strongly on this property [63,64]. The recycled aggregate mortars achieved similar or higher water retentivity capacity to that of the control mortar, despite the employment of a lower volume of filler. The finer particle combined with the greater roughness of RA produce a larger specific surface which has the effect of causing a higher amount of water on the surface pores. The result being the creation of a cohesive force, which is prompted by the electrostatic attraction between the positive hydrogen atom and the highly electronegative oxygen atom within a neighboring water molecule (i.e. hydrogen bond) [65]. Neno et al [18] also mentioned that as opposed to sand very fine concrete recycled particles (RCA) must have been retained. The very fine particles of RCA were described as eventually leading on to a filler effect which improved the fresh state. An increase of RCA content within the mortar mixes had the effect of producing a higher water retentivity value.

4.2 Hardened state properties

4.2.1 Physical properties

Table 4 shows the physical properties achieved by all the mortar mixes. The density and absorption capacity of the recycled aggregate mortars was lower and higher, respectively than that of the control mortars. As a result of the mentioned properties of the recycled aggregate [14,18,20,26,65], the mortars manufactured with RA1-F and RA2-F recycled aggregates presented a lower density than the mortars produced employing recycled aggregates obtained via the crushing of the coarser fraction of CDW (RA1-C/-CF and RA2-C/-CF). The mortar produced employing the RAF-1 aggregate achieved the lowest density and highest absorption capacity. The mortar mixes produced employing RA1-F achieved up to 100% higher absorption capacity than those of the conventional mortars.

A comparative study [19,66] showed that the mortars produced employing recycled aggregates achieved a considerably higher porosity and water absorption capacity value than those of the control mortar. In general, the mortar mixes produced employing LH filler achieved a slightly higher absorption capacity to those of the mortar mixes produced employing the LF filler. The RM1-F-LH and RM1–F-LF mortars achieved values which were twice as great as those of the control mortars.

The mortar produced employing RA2-C with LH filler (RM2-C-LH) proved to achieve a higher absorption capacity than the mortar produced employing RA2-F and RA2-CF. The reason for this being its need for a higher water/cement ratio in order to achieve the minimum workability required by Cuban standard.

4.2.2 Mechanical properties

Figures 5, 6 and 7 show the mechanical property (compressive strength, flexural strength and bond tensile strength, respectively) values of each mortar as well as their corresponding standard deviation.

Compressive strength

The type III masonry mortar (which is adequate for using at ground level and above, as rendering or bonding material) must have a minimum compressive strength value of 5.2 MPa at 28 days in order to comply with the Cuban standard NC 175:2002 [31]. As shown in Fig. 5, all the mortars achieved the minimum required strength value with the exception of the RM1-F-LF mortar.

The recycled mortars achieved a lower compressive strength than those of the conventional mortars, a fact also noted by other researchers[17,67–69]. The mortar mixes produced employing recycled aggregates obtained from the crushing of the coarse type CDW1 (RA1-C) proved to achieve higher strength levels than those produced using the coarse type CDW2 recycled aggregates (RA2-C). The mortars produced employing the RA1-C aggregates achieved a lower than 10% reduction of compressive strength with respect to that of conventional mortar.

The recycled mortars produced employing the aggregates obtained from the fine fraction of the CDW (RA1-F, RA2-F) proved to achieve the lowest strength values. These mortars achieved a reduction in strength value of up to 40% in the mortars produced with RA1-F and up to 35% in the mortars produced with RA2-F. It must be noted that although the four mortars, RM1-F-LH, RM2-F-LH, RM1-F-LF and RM2-F-LF, were produced using a lower w/c ratio to that of the other recycled mortars (in order to obtain adequate workability). A determining factor on the compressive strength of the four mentioned mortars was the poor quality of the recycled aggregates employed in their production. It is known that with respect to conventional mortars the low w/c ratio produces higher strength values. However, this water/cement ratio parameter cannot be considered as an appropriate means of predicting recycled aggregate mortar's strength. This fact has also been noted in other works [65,70].

In all cases, the mortar mixes manufactured with LF filler achieved lower compressive strength values than those produced employing LH filler, this was due to its low binder property and coarser fraction. It is known [24] that the improvement of the mechanical strength of the mortars is related to the incorporation of fines within the mortar mixes.

Nevertheless, it must be noted that all the mortar mixes manufactured with recycled aggregates obtained by crushing the coarse fraction of the CDW achieved the minimum required values of compressive strength established by Cuban specifications. This denotes the possibility of the total replacement of natural aggregates by those of recycled aggregates with respect to type III mortar production. Certain research [16,18,26,63] also described the possibility of the total substitution of natural aggregate by recycled aggregates for masonry mortar production.

Flexural strength

Flexural strength is not considered a restricted property according to Cuban specification requirements. A comparative study proved that most of the recycled mortars achieved lower flexural strength when compared to natural aggregate mortars, a fact noted by other researchers [16,42,67,69,71]. Nevertheless, all the mortars produced employing LH achieved a higher strength value than their corresponding LF mortars. The control and RM1-C-LH mortars produced employing hydrated lime filler achieved the same strength values. The mortars produced employing RA1-F/-CF and RA2-F/-CF achieved lower strength values than those of the mortar mixes produced by employing recycled aggregates obtained solely from the coarse fraction (nominated -C) of CDW (see Fig. 6). The mortars produced employing RA1-F/-CF and RA2-F/-CF with LH as the filler achieved a reduction of up to 33% and up to 45% respectively, with respect to CM-LH.

The mortar produced employing the previous aggregates and LF as a filler achieved a reduction of up to 48% and 55% respectively, with respect to the CM-LF mortar.

Similarly, with regard to compressive strength values, no relation between the total w/c ratio and the flexural strength of mortars was found. This fact has also been reported in previous works [16,60].

According to Vegas et al. [19], Jimenez et al. [20], and Ledesma et al. [15,68], mortars produced employing recycled aggregates of up to 25%, 30% and 40%, respectively, in substitution of natural aggregates obtained similar strength values to those of the control mortars. According to Lopez Gayarre [26] the flexural strength of the recycled aggregate mortar increased with the percentage of recycled ceramic aggregates employed in its manufacture. Neno et al. [18], also related this as happening when employing 100% of recycled concrete aggregates and verified that this was undoubtedly caused by the reduction that the amount of effective water experienced when the percentage of recycled aggregate for natural aggregate substitution was increased.

Bond tensile strength

According to Cuban regulation NC 175:2002 [31], 0.3 MPa is the minimum bond strength value required for type III masonry mortars. That value could be reduced to 0.2 MPa when the masonry mortars are employed as rendering or bonding for interior walls.

Fig. 7 shows the bond strength results obtained by all the mortars as well as the two restrictive values. All the recycled mortars were found to have obtained a lower bond tensile strength than that of the mortars produced employing natural aggregates. The recycled mortars manufactured with aggregates obtained from the CDW-1 source (mainly of ceramic composition), were found to achieve higher bond strength values than the mortars produced with aggregates from the CDW-2 source (heterogeneous source containing mortar, low quality concrete composition and ceramic material). Moreover, the use of recycled aggregates obtained via the crushing of the coarse material within the CDW (RA1-C) achieved the highest property values. According to certain researchers [14,16], recycled aggregate mortars achieve a lower bond strength capacity than that of control mortars. In contrast, several researchers [42,67,69,72] have determined that mortars produced employing 100% of recycled aggregate replacement ratio could achieve a higher bond strength value~~s~~ than that of the control mortar.

The use of LF filler in substitution of LH filler caused a reduction of the bond strength, although the highest reduction took place in the mortar produced with natural aggregates. The binder effect of the LH resulted in the increase of the mortars' adhesive capacity [71]. The mortars produced employing RA1-F and RA2-F recycled aggregates achieved the lowest bond results. The reduction of bond strength of mortars produced employing LH and LF using RA-F reached levels of up to 45% and 35%, respectively, with respect to the conventional mortars produced with the corresponding filler.

All mortars achieved the 0.2 MPa value established by Cuban standard for rendering mortars which are as suitable for employment on interior walls. However, the RM2-F-LH, RM1-F-LF and RM2-F-LF mortars, produced employing recycled aggregates RA-F, which were obtained from the fine CDW fraction, did not reach the minimum strength of 0.3 MPa needed for type III masonry mortar.

4.2.3 Durability properties

Capillary absorption

Fig. 8 and Fig. 9 indicate the capillary absorption values of the different mortars tested. According to the obtained results, the final capillary absorption value was greatly influenced by the water absorption capacity of the recycled aggregates (see Table 1), a fact which has also been verified by other researchers [18–20,69]. According to Lopez Gayarre et al. [26], the recycled mortar produced with 100% of ceramic recycled aggregates achieved lower capillary absorption capacity than those of the conventional mortar due to the decrease in the amount of effective water. This decrease being a direct result of an increase in the percentage of the ceramic recycled aggregates employed in the production of the mortar.

In this case, all mortars showed similar behavior at 7 hours of testing. However, at 72 hours of testing the difference of the high absorption capacity of the recycled aggregates in comparison to those of the natural aggregates was notable. Nevertheless, after 168 hours of testing, the mortars produced employing the recycled aggregates with the highest water absorption capacity, RM1-F and RM2-F achieved the highest capillary absorption values. The RM1-C-LH and RM1-CF-LH recycled mortars were the mortars which of all the other recycled mortars obtained the lowest capillary absorption capacity values.

However, these achieved values were higher than those of the conventional mortar CM-LH, which obtained the lowest value.

Fig.8 and Fig. 9 denote the capillary absorption of the mortars produced employing limestone filler (LF), which proved to have a higher capillary absorption capacity in the early stages of testing than those of the mortars produced with hydrated lime (LH). The reason for this difference in capillary absorption was due to the low transfer sorptivity and high water retaining characteristics of hydrated lime [64]. Nevertheless, after 168 hours of testing it was determined that the capillary absorption of the mortars depended on the type of aggregates employed in the mortar production and not on the type of filler used. At 168 hours of testing, the capillary absorption values of all the mortars were analyzed. The analysis was carried out by dividing the mortars into in three groups: Group 1 describes the mortars produced employing the RA1-F recycled aggregate, the RM1-F-LH and RM1-F-LF mortars, which achieved the highest values; Group 2 describes the behavior of all the other recycled aggregate mortars, which all proved to have achieved similar capillary absorption; Finally, Group 3 describes the control mortars, CM-LF and CM-LH, which achieved the lowest capillary absorption values of all the mortars tested.

The capillary absorption values of the mortars from group 1, 2 and 3 were 6, 5 and 4 g/cm^2 at 168 h, respectively. The test results imply that the final value of the capillary absorption (at 168 h) depended directly on the water absorption of the recycled aggregate which was employed in the mortar manufacture [60,63]. There was no significant difference noted on the capillary absorption values when LH or LF filler was employed for mortar production.

Drying shrinkage

The mortars produced employing recycled aggregates suffered a higher shrinkage than the mortars manufactured employing natural aggregates (see Fig. 10 and Fig. 11). This was due to their greater water absorption capacity. This difference in levels of shrinkage has also been described by several researchers [16,18,68,73].

Silva et al. [61], found that mortars employing 20%, 50% and 100% of ceramic recycled aggregates achieved similar shrinkage values amongst themselves, but those values were higher than those obtained by the control mortar. According to Vegas et al. [19], Cabrera-Covarrubias et al. [74], Jimenez et al [20], and Lopez Gayarre et al. [26] the mortar produced employing up to 25%, 30%, 40%, and 50% respectively, of ceramic aggregates achieved acceptable shrinkage values when compared to the same values obtained by conventional mortars.

Although the mortars produced using LH filler proved to have higher shrinkage values than those of the mortars manufactured with limestone filler (LF), they were found to achieve the minimum required workability using less water content than the mortars incorporating LF. A comparative study between the LH filler and the LF filler showed that the higher quantity of material finer than 75 µm in the LH filler and its water retaining capacity proved to have a great influence on the increase of the shrinkage value. This fact has also been described by other researchers [70,75].

All the recycled mortars produced using LF filler achieved similar shrinkage values in spite of the different composition and properties of the recycled aggregates employed. According to Miranda and Selmo [75], the use of different percentages of recycled aggregates was influential on the mortars' shrinkage but not on their composition.

Electrical resistivity

Fig. 12 indicates the electrical resistivity values of all the studied mortars. All the mortars achieved a low resistivity value as a result of their high absorption capacity and low mechanical properties. However, all the recycled mortars, with the exception of those mortars produced employing RA1-F and RA2-F aggregates, achieved a higher resistivity level than those of the control mortars.

In all probability, the presence of ceramic material in the recycled aggregates explains the higher value achievement of the recycled mortars when compared to the same values obtained from the control mortars. Similar results to those exposed have been reported in a previous study [14]. The coarse fraction of the CDW contained a higher percentage of ceramic material than the fine fraction. CDW-1 proved to have the highest amount of this ceramic material, and it was this ceramic content which caused the highest electrical resistivity levels in these mortars due to its inherent electrical insulating properties. Consequently, the property of electrical resistivity is not an adequate form of assessing the quality of mixed recycled aggregates mortars, as the values reported are more affected by the content of siliceous material than by the saturated porous ramification.

5. Conclusions

The following conclusions and recommendations for the use of RA and filler in masonry mortar can be drawn from the results of this study:

Recycled aggregates:

- For the adequate quality of the RA1 recycled aggregates production, a coarse fraction (>4.76 mm) of the CDW1 is required. Taking into consideration in this study that the main component of the CDW1 was ceramic, with soil and limestone as the finest materials and minor components and with the complete absence of concrete.
- When the main component of the CDW is concrete combined with a low amount of impurities, the recycled aggregate produced employing only the fine fraction of CDW (<4.76mm) achieved similar properties to those produced crushing the coarse fraction of CDW.

Fresh state of recycled aggregate mortars:

- Although the recycled aggregate mortars needed more water than those of the control mortars to achieve the required workability, it was found that the recycled aggregate mortars obtained a higher water retentivity capacity than that of the conventional mortars. The water retentivity capacity was noted to be higher when employing lime hydrate (LH) rather than limestone filler (LF).

Hardened state of recycled aggregate mortars:

- The use of recycled aggregates produced from the fine fraction of CDW1, which was mainly composed of earth and limestone, increased the mortars' absorption capacity of up to 100% with respect to that of conventional mortar. Consequently, it was necessary to employ the ceramic material presented in the coarse fraction of CDW for recycled aggregate production.
- Whereas the mortars produced employing recycled aggregate obtained from the CDW1, which had ceramic as its main component, achieved similar mechanical properties to conventional mortar, it was discovered that the use of the recycled aggregates obtained from CDW2 (concrete with main component) achieved lower properties than those of conventional one.

- The employment of LH filler as opposed to LF can result in 50% higher strength mortars than those of mortars made with LF employing the same type of recycled aggregates.
- Although recycled aggregate mortars achieved a higher shrinkage value than that of conventional mortars, the employment of LF filler in recycled aggregate mortars reduced the shrinkage achieved by mortars produced with LH by up to 25%.

The recycled aggregates produced from the CDW composed of ceramic materials achieved the best properties and were found to be able to produce recycled mortars with adequate properties. However, in order to comply with the minimum quality requirements established for recycled aggregate mortars, it is necessary to employ the coarse fraction of the CDW in recycled aggregate production. Test results of the RA-F (recycled aggregates produced using only the fine fraction of CDW) determined that it was only adequate for the rendering or bonding of interior walls at or above ground level.

Although the mortars produced employing hydrated lime achieved higher mechanical properties than those of the mortars produced using limestone filler, it was established that both, the physical properties and the shrinkage values, of the mortars produced employing the limestone filler were more adequate. A finer grading distribution of the limestone filler (only 40% of the available LF is finer than 75 µm) could be responsible for improving both the retentivity and the mechanical properties of the mortars assuring a general improvement of properties of masonry recycled mortars.

Acknowledgements

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Influence of demolition waste fine particles on the properties of recycled aggregate masonry mortar

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ANSWER TO REVIEWERS

All the comments given by reviewers have been carried out.

REVIEWER #4:

Some arguments and improvements have been fixed. Others persist and are not properly solved. Again they are indicated and more arguments detail them. The reviewer has requested these improvements since the first review (February / 2017, 7 months), the only arguments that the authors provide are: The authors consider that they are not necessary and the authors have performed the tests that are technically used to apply this material. I remind the authors that to publish in this "Scientific Journal" necessarily means to carry out a scientific work with demonstrations, laboratory tests and specific tests that guarantee and explain the exposed behaviors. Without this, the work is a simple laboratory report.

The authors consider that this paper is interesting, it describes many tests and analyzed scientifically the results values. The obtained results have been discussed with respect to the chemical, physical and mechanical properties achieved by the raw recycled materials as well as comparing the obtained results to those achieved by other authors.

COMMENTS TO BE SOVED:
- **14** (important, please provide experimental or documentary evidence of the comments, not assumptions).

This comment had been done in the previous reviews: "*Without the statistical validation of the data, or in the absence of the EXACT quantification of the parameters involved in the experiment, unable to validate the scientific contribution (it is a particular case of study and the variables interfering have not been established or determined). There are substances potentially polluting or affecting the behavior of mortars that "could" be included in the "random" samples studied (gypsum, paint, organic, wood, asphalt, metals, etc., etc.); for which, it is necessary (and obliged) to include tests that show its absence or presence (and its quantification in quantity). Without this information (statistical or of tests) ALL the research does not have a valid sustenance.")*

Answer 14:

The dispersion of the obtained values (of mechanical properties) are given in the figures. The authors do not consider that more detailed statistical data are necessary due to:

- The presence of paint is irrelevant in all cases, it is not even measurable in terms of percent of weight. In addition, the gypsum was not employed as construction material in demolished building. Furthermore, as Table 2 shows, the sulfate amount is negligible. The chemical composition of all the types of recycled aggregates are described in table 2 in the section 2.3 “Fine aggregates”.

- The samples of CDW were collected on the demolition site, making the collection under good control. Consequently, none of the other polluting substance could be included. In addition, the CDW has been added manually to crushing process, in consequence avoiding the inclusion of this polluted substances. Furthermore, Table 2 shows that the sulfate amount is negligible.

- **21** (is obliged to do so, please provide experimental or documentary evidence of the comments, not assumptions. Perform laboratory tests).
This comment had been made in the previous reviews: “*What procedure, technique, standards, equipment, instruments, etc., etc., were used to obtain the data of the Table 5? Is necessary that is contribution information of the existence of more compounds with possible involvement in the behavior of the mortars: chlorides, sulfates, gypsum, metals, organic, etc., etc. It is requested to use precision techniques such as XRD or FT-NIR.”*

Answer 21:
Table 5 now is named Table 2.

The composition of aggregates were determined via Panalytical, Axios PW 4400/40 XRF spectrometers. In this case, the chemical composition was required to determine, however the crystallography which could be determined via XRD would not give any additional information, since their chemical composition and components are known. As it was mentioned above, the samplings were collected manually from the demolition site and the external contaminations were not present in the material. Moreover, the addition of the material to the crusher was also made manually.

- **25** (please indicate the sequence and mixing times, initial and final water).
This comment had been made in the previous reviews: “*It is necessary to indicate the process of mixture used, since the recycled aggregates have a high absorption; If it was not considered, will provoke that the free water for hydration is not adequate one, and therefore the behavior of mortars in hardened phase is affected.”*

Answer 25:
The manufacturing process of mortars is indicated in the section 3.1 and was carried out following the corresponding ASTM and Cuban standards. The total water used in the mortar production was the added water required in order to get adequate workability in each mortar.
As it is exposed in the section 3.1, even with the high water absorption of the recycled aggregates, the effective w/c ratio of those mortars was very high (see table 3). This has a negative influence over the hardened state properties, but in masonry mortars

admixtures are rarely used. As a consequence, in order to achieve the required workability, a high w/c proportion is necessary.

- **27** (please perform ALL TESTING and TESTS, including NON-STANDARDS). This comment had been made in the previous reviews: *"It is necessary to indicate the brand, model and place of manufacture of all the equipment used in the tests."*

Answer 27:
All test and equipment used are indicated in the text since the first revision.

- **28** (important. Please include the requested tests, it is not a laboratory report for validity "an application", it is a "scientific research". It is necessary to carry out the tests that have been requested.).
This comment had been made in the previous reviews: *"Why was not obtained the density in fresh, the air content and some another test of fluency of the mixtures? It is requested to include them."*.
Answer 28:
The authors think that the asked tests are not relevant for the study. The fresh state tests of consistency and water retentivity were determined, which were required by standards and values defined by references. The physical properties of density and absorption capacity were determined in hardened state of masonry mortars. Most of the tests described by the reviewer are not included in the papers used as references.

- **37** (is obliged to do so, please perform the experimental tests and laboratory tests requested).

This comment had been made in the previous reviews: *"It is necessary that the authors rewrite this section, improving their wording and arguing the cause that makes evident the differences between mortars; For which it is necessary to carry out specific tests that allow a correct explanation. The authors are asked to characterize the matrix of the mortars, identification of the ITZ and study of the porous network (SEM tests and mercury porosimetry)"*.

Answer 37:
The obtained results have been discussed according to the previous works done by several author. Since the samples had a very high water/cement ratio and in consequence a high amount of accessible porous and absorption capacity, the physical properties determined in this paper (table 4) give enough details and properties to make an appropriate comparison.

- **<u>40</u>** (as the reviewer-number 1 also comments, writing needs to be improved. Again, the authors try to publish in a scientific Journal, NOT validating an application of a material. To publish in this Scientific Journal it is necessary to carry out an investigation that explains the behavior of this material. Please carry out the requested tests).
This comment had been made in the previous reviews: *"Authors are requested to be accurate in their comments: ...in all probability due to its low binder...*
It is necessary to include a study of the matrix of the mortars that allows to explain the described behaviors; Otherwise, this work does not solve or explain the results indicated.
"

<u>Answer 40:</u>
The authors think that the writing is concise. All the tests (physical, mechanical and durability properties) required by the standards for masonry mortars were carried out and the obtained results by recycled aggregate mortars were compared to those of conventional mortar as well as the required values defied by standards and scientific references, which gave us the most valuable parameter.

- **<u>43</u>** (is obliged to do so, please do the tests requested, without these you can not prove what you say).

This comment had been made in the previous reviews:

"Durability properties
Capillary absorption
It is necessary to include studies of the porous network of mortars (porosimetry with mercury), which allow to EXPLAIN the values included in this research. The authors have limited themselves to performing just one description of the values."

<u>Answer 43:</u>
The % of accessible porous, the effective w/c ratio and the absorption capacity of recycled aggregates were measured and known. The authors consider that for the objective of the paper, the MIP test cannot give more valuable properties than the values already described, due to the high w/c ratio and high porosity of masonry mortars. Moreover, there is very hard to find a single paper where MIP measurements are used, including the papers which have been recommend by the reviewer to be consider in this paper.
The determined properties influence considerably at the capillary absorption capacity. So, the authors think that the capillary absorption graphs and the sorptivity coefficient value describe adequately the different behaviors of those masonry mortars.

- **<u>45</u>** (important, please carry out the tests with the detail that was requested).

This comment had been made in the previous reviews: *"It is necessary that the work distinguish total shrinkage, drying shrinkage and basic shrinkage.*
It is necessary to indicate the standard that was used and the instruments (marks, models, precision, etc.)"

Answer 45:
The drying shrinkage was determined according to ASTM C490/C490M-11 [59] specifications. (see section 3.2.2. Hardened state tests). As the high amount of water has been used for mortars production, the drying shrinkage is the most important shrinkage to be considered.

- **47** (please perform the tests, so the arguments given are based on facts and not on assumptions; comments that the authors make)

This comment had been sent in the previous reviews: *"Given the type of aggregates used and the possibility of containing materials that affect the durability of mortars, it is necessary to include leaching tests and accelerated expansion studies."*

Answer 47:
As the recycled aggregates have not been contaminated, it is explain above (see Comment/answer14), the hazard leached components was expected to be lower than the limit specify by standards, considering an inert material. There were not metals either gypsum present at the CDW.

- **49** (please indicate in the text to publish the indicated reasons).

This comment had been sent in the previous reviews:" *Reference Authors are requested to:*
1) Reflect on the reason why these two works "owned by the same authors" have not been cited.
2) Explain what new or new contribution has the current proposal of work that is not included in these references "omitted".

The authors think that is not appropriate to indicate in the text the difference between this work and other(s) previous work(s) carried out by the authors.

1) The previous papers of the authors have been referenced in order to avoid some details that had been already published in previous papers and they were necessary to describe. One of the reference [23] has been removed, since the authors considered that it was very difficult to find it by the reader.
2) The objective of this paper was to analyze the influence of the fine particles (<4.76mm) within the construction and demolition waste obtained from dwellings in

Havana on the properties of the recycled aggregates obtained from that source. The RA was to be used together with two types of fillers (limestone or hydrated lime) for the production of type III masonry mortars and their respective qualities were to be analyzed. From both types of the CDW used, three types of recycled aggregates were to be produced (-F, CF, and –C). The six types of recycled aggregates were to be mixed with two types of fillers for the production of masonry mortars. In the previous paper "*MARTINEZ, Iván; ETXEBERRIA, Miren; PAVON, Elier y DIAZ, Nelson. Analysis of the properties of masonry mortars made with recycled fine aggregates for use as a new building material in Cuba. Revista de la Construcción [online]. 2016, vol.15, n.1, pp.9-21. ISSN 0718-915X*", only one type of recycled aggregate was produced of each type of CDW. In addition, for recycled mortar production also only one type of filler was employed. The main objective of the previous paper was to determine, according to the grading distribution of recycled aggregates, the optimum mix proportion for recycled masonry mortar production, in order to be used as a bond and rendering mortar. For that purpose, different cement/aggregate/filler proportions were employed for mortar production. While in the previous work only one type of recycled aggregate was produced from each type of CDW and one type of filler was used for mortar production, in this research work 3 types of recycled aggregates were produced from each CDW and two types of fillers were employed. In addition, although in this work the optimum mix proportion defined in the previous work has been used, that it is not the case with the recycled aggregates production, their characteristics and the type of filler employed were different to the prior work and the influence of those parameters on the properties of masonry mortars are important and were assessed in this new work.

NOTES:

The reviewer maintains the following comment, HAS NOT BEEN SOLVED PROPERLY:

Figure 2 and 3, curves outside the graph.

The authors had corrected this error in the previous review.

The given answered was: "Figure 2 and Figure 3 have been modified. The previous error was just due to the type of graphic employed for drawing. "

Images should be enhanced in editing and provide information with labels.

All the figures fulfill the IJCE specifications.

The reviewer maintains the following comment, HAS NOT BEEN SOLVED PROPERLY (the reviewer disagrees in the comment; you can use different colors, textures and graphics). Having the graphics together simplifies the work and allows other researchers to have a joint view of the study.

Do you consider that the union in a single graph of Figures 5, 6 and 7 would be better to reach a joint compression of the behavior of the mortar?

The authors think that it is better not to join the three figures. The values of each property are very difference in magnitude between them, and there are 14 columns in each graph. In addition, the limited value described by Cuban specifications are also included in each figure.

The reviewer maintains this request, that the document is a public document does not grant automatically or necessarily the scientific value and rigor. It needs to be reviewed by experts in this field before granting complete credibility.

Inadequate reference for a scientific article:

[30] Ingrid Muñoz, "Estudio económico y ambiental del cambio de la gestión de residuos de construcción y demolición en la ciudad de La Habana", Master thesis directed by Miren Etxeberria & Alvar Garola Universidad Politécnica de Cataluña, 2012. https://upcommons.upc.edu/handle/2099.1/14827

The authors consider that the reference is adequate as it shows the real data of La Habana, it is a extend work and it is validated by professor of CUJAE.

REVIEWER # 1

-1. The highlights are still not very different from the abstract.

Answer 1:
The highlights have been rewritten.

-2. There is no mention of loss of prestress. Justify.

Answer 2:
The loss of mechanical properties of recycled aggregate mortars with respect to conventional control is due to the low quality of recycled aggregates.

It is explained in section “4.2.2 Mechanical properties”.

For example at :

Line 361 “A determining factor on the compressive strength of the four mentioned mortars was the poor quality of the recycled aggregates employed in their production.”

-3. The authors should justify how the masonry blocks of so low strength could take care of prestressing. The failure patterns of yw -2, yw-3, yw-4 and yw-5 show that failure occurred in concrete/masonry and not in the bond/grout possibly due to their low compressive strength. Further, at transfer, the check for stresses may be presented.

Answer 3:

The masonry mortars produced in this research work were validated according to the Cuban specifications. In order to comply with the Cuban standard NC 175:2002 [31].The type III masonry mortar (which is adequate for using at ground level and above, as rendering or bonding material) must have a minimum compressive strength value of 5.2 MPa at 28 days. As shown in Fig. 5, all the mortars achieved the minimum required strength value with the exception of the RM1-F-LF mortar. (see section 4.4.2. Compressive strength, Line 343).

Line 404: According to Bond tensile strength

According to Cuban regulation NC 175:2002 [31], 0.3 MPa is the minimum bond strength value required for type III masonry mortars. That value could be reduced to 0.2 MPa when the masonry mortars are employed as rendering or bonding for interior walls.

Line 430:" the RM2-F-LH, RM1-F-LF and RM2-F-LF mortars, produced employing recycled aggregates RA-F, which were obtained from the fine CDW fraction, did not reach the minimum strength of 0.3 MPa needed for type III masonry mortar."

The lowest strength mortars can only be used for drying state (as rendering or bonding for interior walls), thus it is guaranteed their durability condition.

4. Authors have not qualitatively justified how the technique is economical and competent compared to other techniques.

Answer 4:
The environmental and economic study was carried out in a previous work referenced in the text:
[30] I. Muñoz Fernández, Estudio económico y ambiental del cambio de la gestión de residuos de construcción y demolición en la ciudad de La Habana, Master Thesis directed by Miren Etxeberria & Alvar Garola, Universidad Politécnica de Cataluña (UPC), 2012, http://upcommons.upc.edu/handle/2099.1/14827.
It is a very extensive work, in consequence a reference of that work has been added to the paper. This work focused in the technical capability of the material.

5. Although the paper has been corrected in terms of English language, it still does not meet the standards of a journal like INCE. Very poor use of capital letters, spellinmistakes, poor usage of articles are not expected at this level.

Answer 5:
A native English speaker has checked the article one more time.

6. More papers need to be referred after 2013.

Answer 6:
This aspect has been corrected in the previous reviews. There are more than 30 papers refered which were published after 2013.

7. Units for some parameters in tables are still missing.

Answer 7:
The authors checked all tables one more time, and all the units have been added.

8. Notation for all the symbols (in alphabetical order) is required in addition to them being defined as and when they are first used in the paper.

Answer 8:
All symbols have been indicated in the section Abbreviations.

9. Methodology described is not very clear. A flow chart describing the code would help the readers. Refer the above paper for understanding how to present a flowchart.

Answer 9:
The authors think that the methodology in very clear. Several papers focused on the same issue of this work have a similar structure, without the necessity of the inclusion of any flow chart.

10. Conclusions still need revision. They are very general and qualitative in nature and appear to be mere observations. They are too long and are just repetition of the result analysis.

Answer 10:
Conclusions have been rewritten again, many modifications were included.

11. In the absence of having a clear picture of "what part of your manuscript, the comments/clarifications have been implemented" it is difficult to ensure if all the suggestions have been addressed.

Answer 11:
All the modification performed in the text have been indicated in red color (see the file “blinded manuscript_R3_with corrections”). The location of the changes are also described by the line number in the answers of reviewer’s comments.

LIST OF TABLES

Table 1. Physical properties of the natural and recycled aggregates studied.

Properties	NA	RA1-C	RA1-F	RA1-CF	RA2-C	RA2-F	RA2-CF
Dry density (kg/dm^3)	2.6	2.13	1.96	2.08	2.09	2.02	2.06
Water absorption (%)	1.3	4.71	9.14	5.52	7.45	7.77	7.15
Bulk density (kg/dm^3)	1.48	1.25	1.05	1.19	1.16	1.19	1.22
Fineness modulus	2.93	2.78	2.78	2.89	2.92	3.02	3.08
Material finner than 75µm (%)	1	13	11	13	12	7	11

Table 2.Chemical composition of the recycled aggregates.

Elements (wt %)	Fe_2O_3	MnO	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O
RA1-C	4.93	0.08	0.38	26.09	0.83	0.08	47.43	13.29	3.82	2.21
RA1-F	4.94	0.07	0.13	24.08	0.22	0.23	47.83	3.26	14.65	0.30
RA1-CF	5.64	0.09	0.28	27.16	0.55	0.08	41.47	8.92	11.88	1.41
RA2-C	4.06	0.07	0.23	47.01	0.68	0.15	31.31	7.86	5.81	1.10
RA2-F	3.90	0.07	0.15	60.14	0.27	0.25	18.25	3.65	9.22	0.24
RA2-CF	3.92	0.07	0.22	47.96	0.50	0.13	27.00	5.74	7.86	0.79

Table 3. Mix proportion of masonry mortars.

Nomenclature	Volumetric proportion*	Aggregate	Filler	Total w/c ratio	Effective w/c ratio	Consistency (mm)	Water retentivity (%)
CM-LH	1:4:2	NA	LH	1.31	1.28	195	91.3
RM1-C-LH	1:5:1	RA1-C	LH	1.9	1.77	189	92.2
RM1-F-LH	1:5:1	RA1-F	LH	1.61	1.41	189	90.9
RM1-CF-LH	1:5:1	RA1-CF	LH	1.65	1.49	187	90.1
RM2-C-LH	1:5:1	RA2-C	LH	1.98	1.79	190	90.8
RM2-F-LH	1:5:1	RA2-F	LH	1.75	1.55	189	92.9
RM2-CF-LH	1:5:1	RA2-CF	LH	1.82	1.63	187	92.4
CM-LF	1:4:2	NA	LF	1.41	1.38	191	89.3
RM1-C-LF	1:5:1	RA1-C	LF	1.9	1.78	189	90.6

RM1-F-LF	1:5:1	RA1-F	LF	1.68	1.49	194	90.3
RM1-CF-LF	1:5:1	RA1-CF	LF	1.66	1.52	185	90
RM2-C-LF	1:5:1	RA2-C	LF	1.98	1.81	191	90.4
RM2-F-LF	1:5:1	RA2-F	LF	1.8	1.6	190	90.8
RM2-CF-LF	1:5:1	RA2-CF	LF	1.86	1.68	186	90.7

*Volumetric and gravimetric proportions (cement: aggregate: filler)

Table 4. Physical properties of the hardened mortars.

Mortars	Density (kg/m^3)	Water absorption (%)	Porosity (%)
CM-LH	2086	13.8	25.3
RM1-C-LH	1864	23.3	35.2
RM1-F-LH	1779	28.9	39.8
RM1-CF-LH	1872	24.2	36.5
RM2-C-LH	1840	25.4	37.3
RM2-F-LH	1824	22.3	33.6
RM2-CF-LH	1861	19.3	30.2
CM-LF	2125	13.3	24.9
RM1-C-LF	1913	20.3	32.3
RM1-F-LF	1809	26.7	38.1
RM1-CF-LF	1896	22.1	34.3
RM2-C-LF	1888	22.7	34.9
RM2-F-LF	1880	20.7	32.2
RM2-CF-LF	1901	20.1	31.5

LIST OF FIGURES

Fig. 1. Source of CDW 1 and 2 (figures A and B, respectively), and recycled mortars placed over concrete blocks (figure C).

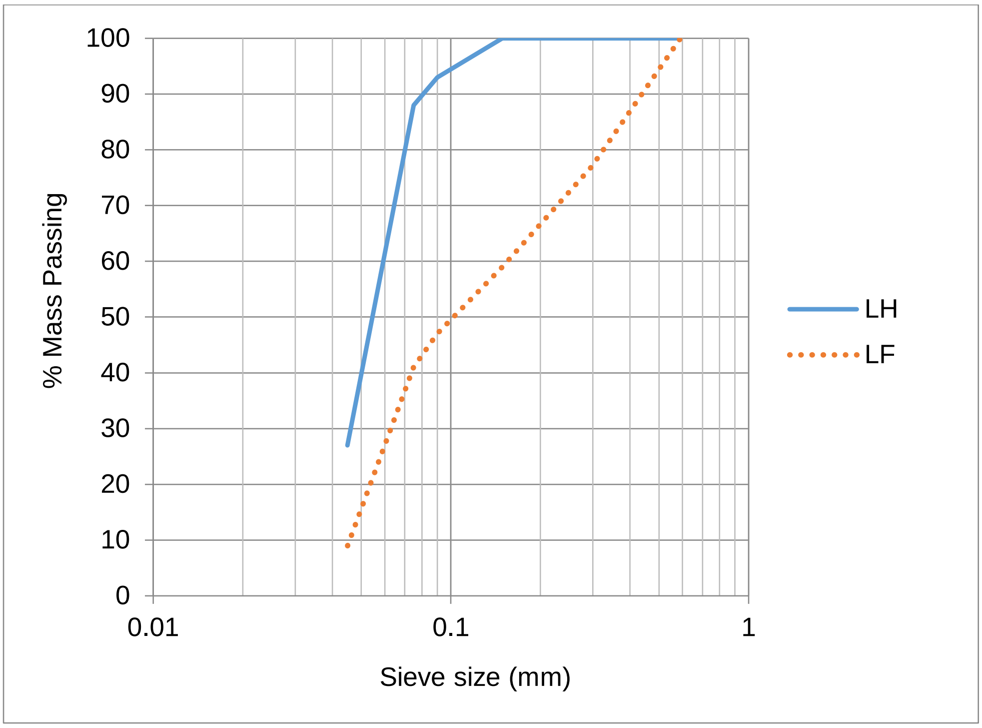

Fig. 2. Particle size distribution of the fillers used.

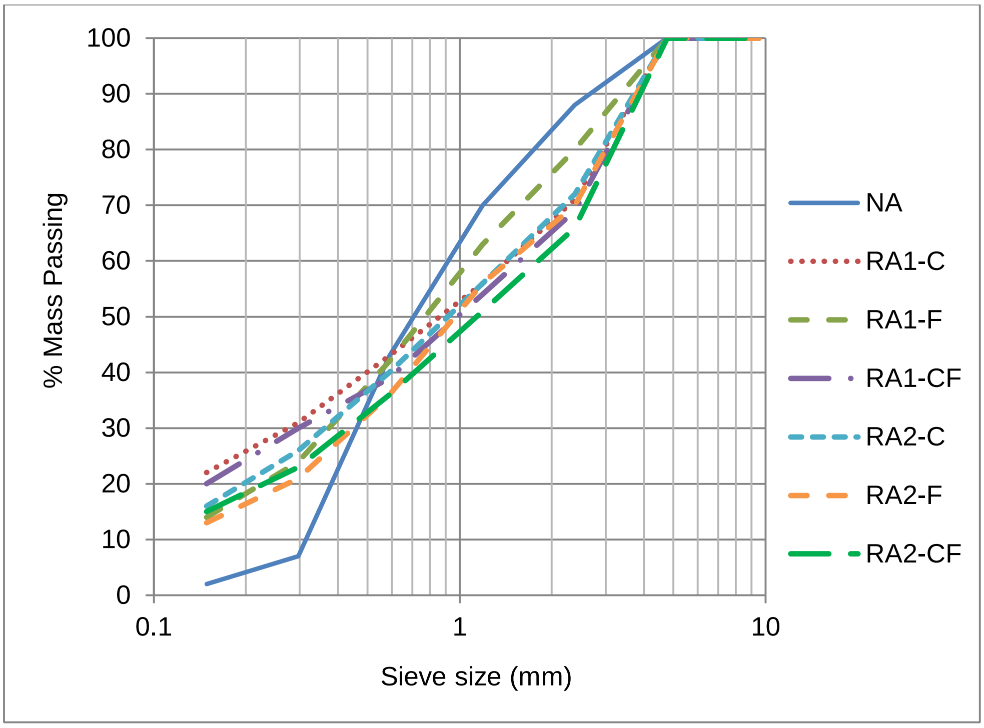

Fig. 3. Particle size distribution of the aggregates studied.

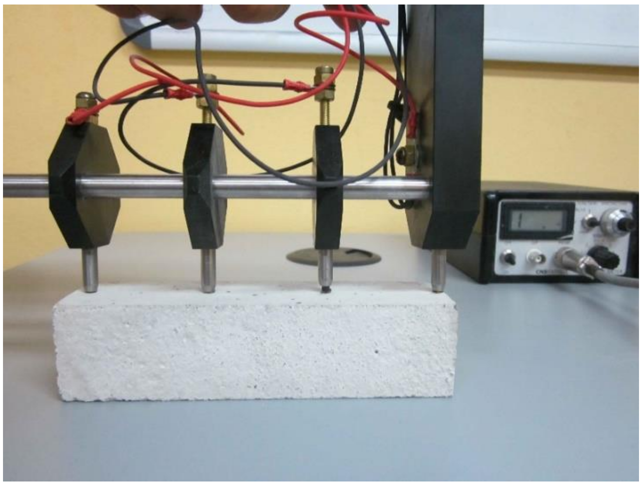

Fig. 4. Electrical Resistivity test.

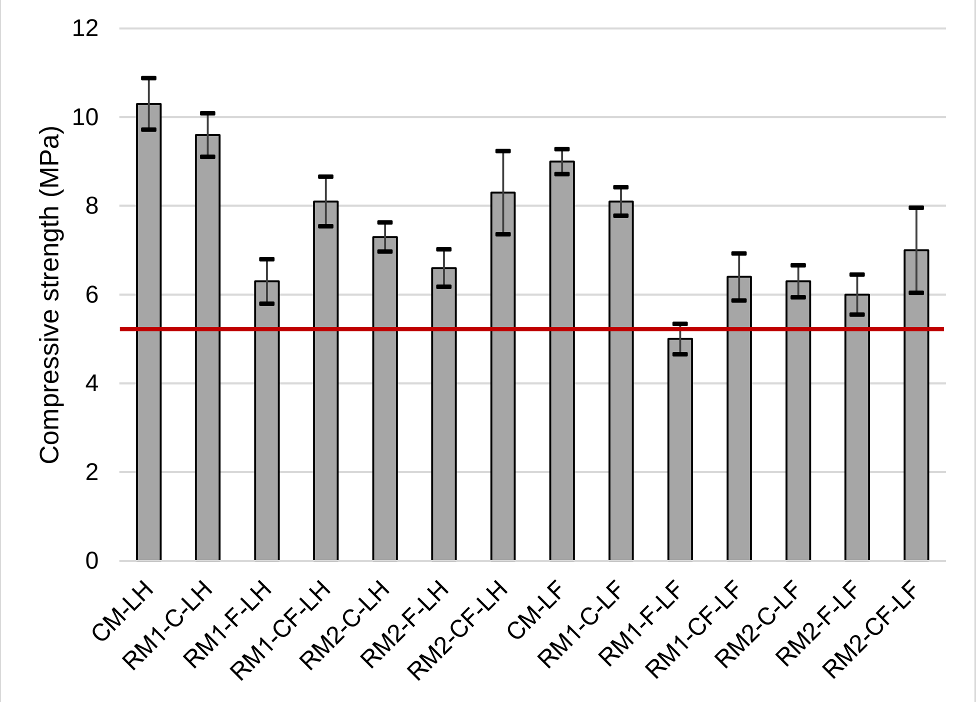

Fig. 5. Compressive strength (the standard deviation is presented at the top of each column) of the mortars studied. The horizontal line marks the minimum value (5.2 MPa) required by Cuban standard.

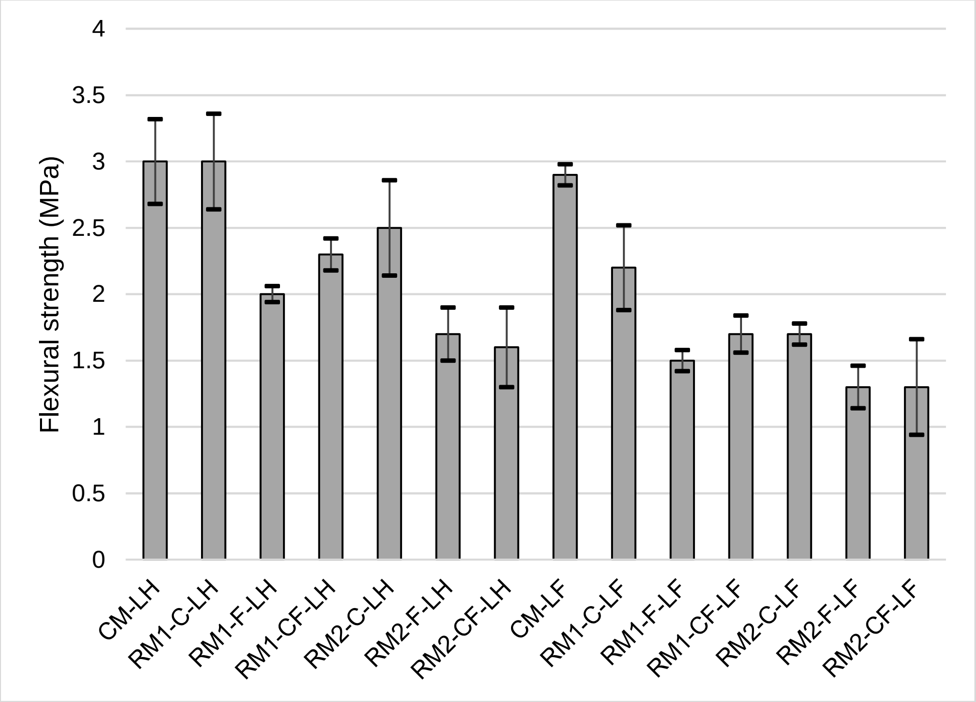

Fig. 6. Flexural strength (the standard deviation is presented at the top of each column) of the mortars studied.

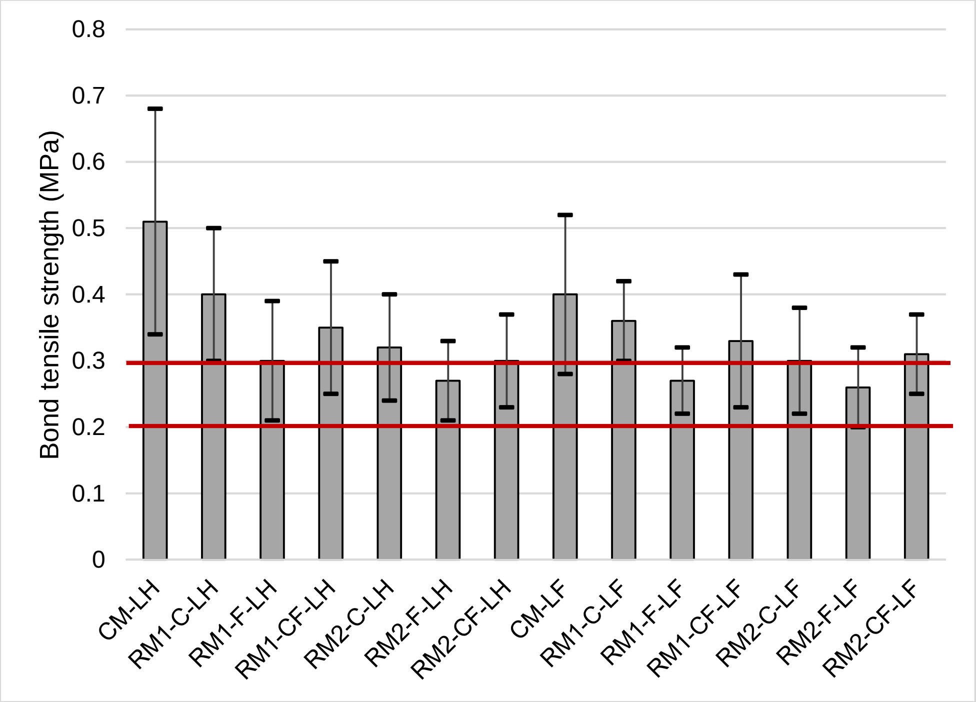

Fig. 7. Bond tensile strength (the standard deviation is presented at the top of each column) of the mortars studied. The horizaontal lines mark the values (0.2 MPa and 0.3 MPa) required by Cuban standard to define the mortar application.

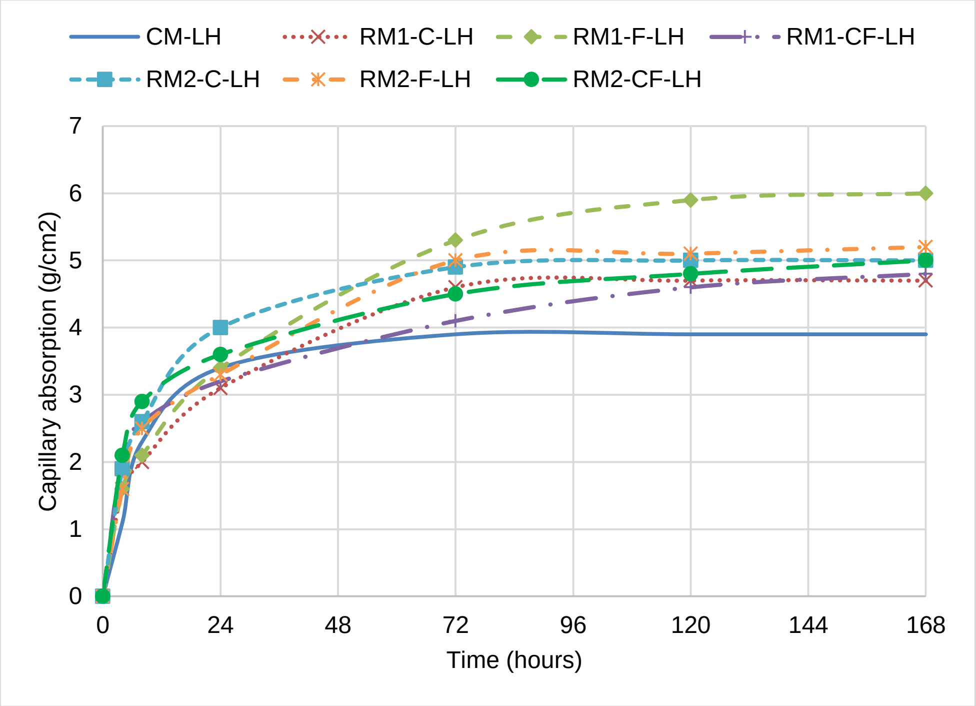

Fig. 8. Capillary absorption as a function of time of hydrated lime mortars at 28 days of curing.

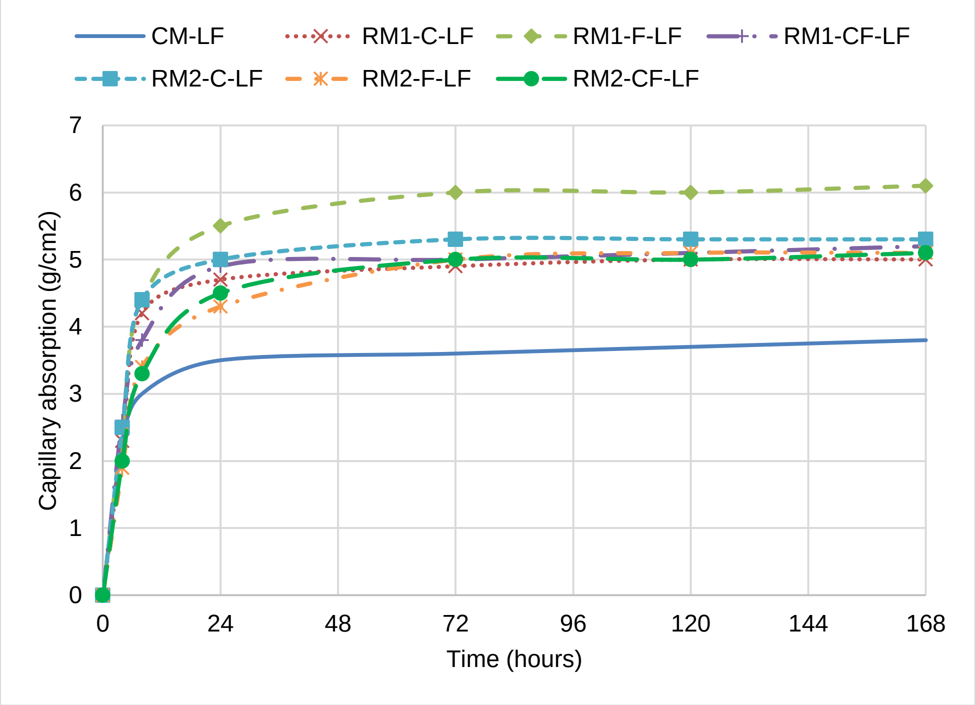

Fig. 9. Capillary absorption as a function of time of lime filler mortars at 28 days of curing.

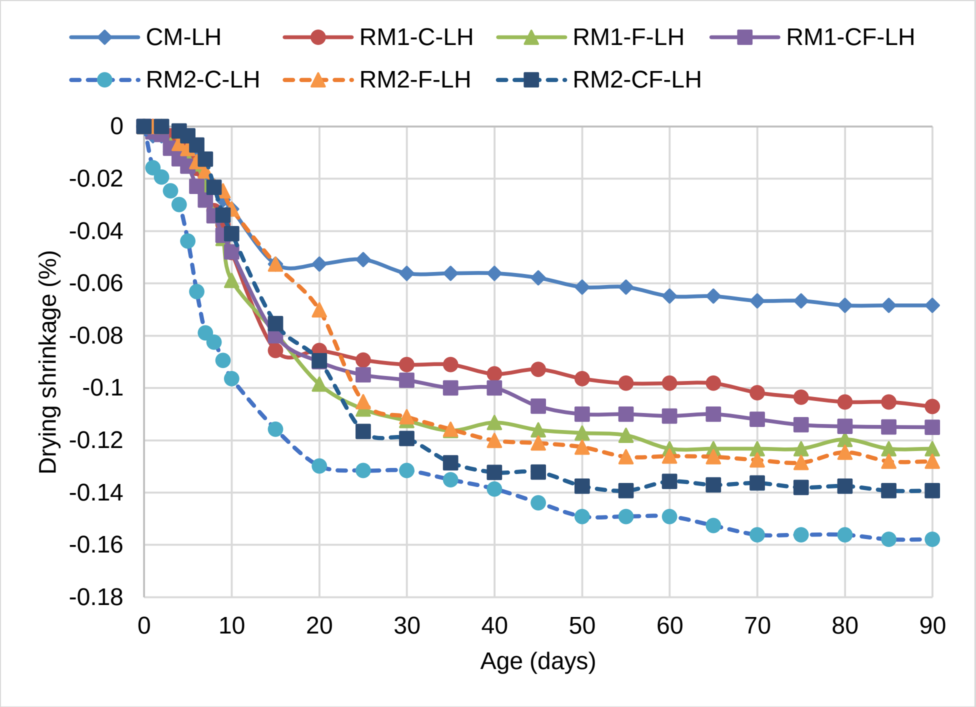

Fig. 10. Drying shrinkage of mortars produced with lime hydrate.

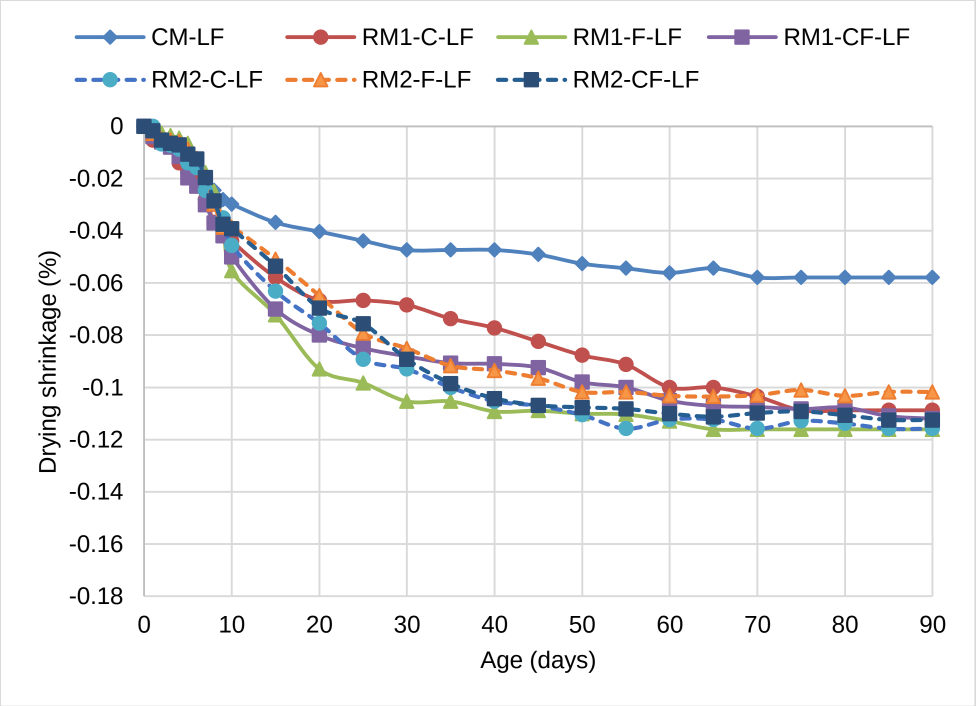

Fig. 11. Drying shrinkage of mortars produced with lime filler.

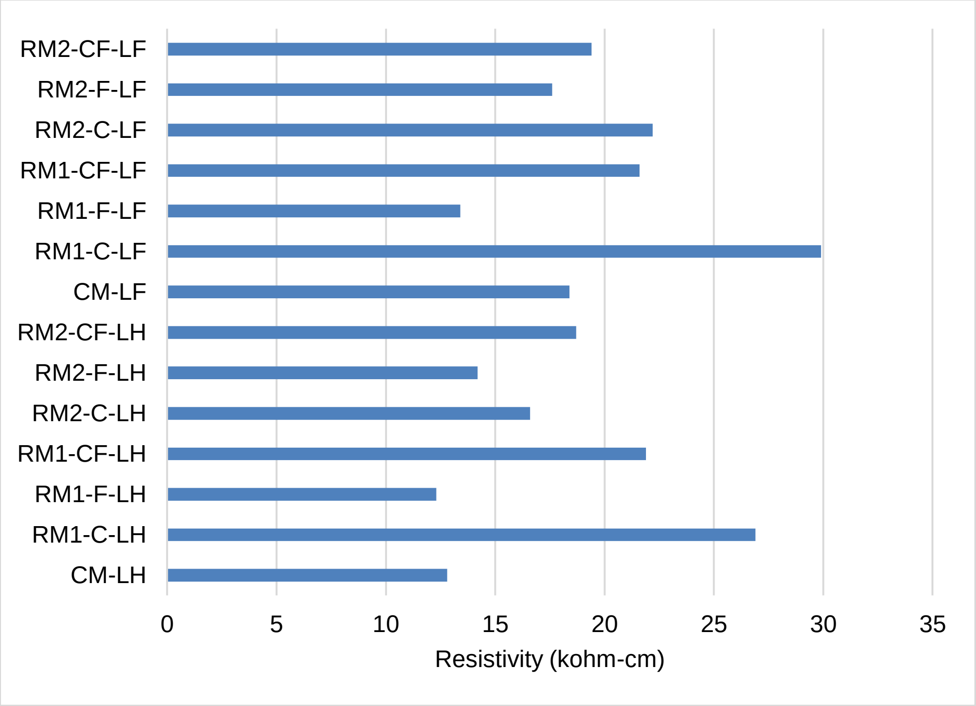

Fig.12. Electrical resistivity of mortars at 28 days.

Influence of demolition waste fine particles on the properties of recycled aggregate masonry mortar

Abstract

This paper analyses the influence of the fine fraction of two types of construction and demolition waste (CDW1 and CDW2) on the properties of recycled aggregates (RA) and masonry mortars. The CDW1's main component was ceramic while the CDW2 were concrete. Three different kinds of fine RA were produced from each source of CDW; the first type was produced by only using the fraction finer than 4.76 mm, the second one by employing only the coarser fraction than 4.76 mm, and the third type was a mix of both fractions of CDW. The masonry mortars were produced employing the 100% substitution of natural aggregates. The results show that all the recycled mortars achieved a higher water retentivity capacity than that of the conventional mortars. However, the sole use of the fine fraction of the CDW was found to have a deleterious effect over the hardened mortar properties, thus making it only adequate for the rendering or bonding of interior walls at or above ground level. In contrast a combination of both the fine fraction and coarse fraction of the CDW in the production of the RA achieved all the minimum requirements for rendering and bonding masonry mortar.

Highlights

- Two sources of CDW, one with ceramic and other with concrete as main components, were employed.
- Three different RA were obtained from two different sources of CDW.
- Masonry mortars employing 100% of recycled aggregate were validated.
- Ceramic high content recycled aggregates mortars achieved the most adequate properties.
- The employment of the coarse fraction of the CDW guarantee high quality aggregates for masonry mortar.

Keywords: Masonry mortar; fine recycled aggregate; recycled aggregate mortar; construction and demolition waste; fresh mortar properties; mechanical properties.

Abbreviations

CDW - Construction and demolition waste
FRA - Fine recycled aggregate
LH - Lime hydrate
LF - Limestone filler
RA - Recycled aggregate
w/c - water/cement

1. Introduction

The use of recycled aggregates obtained from the recycling of construction and demolition waste (CDW) is a sustainable alternative to the employment of natural aggregates within the construction industry [1]. This alternative not only allows for the protection of natural resources but is also instrumental in the reduction of areas used for landfill [2]. There have been many studies with respect to the mentioned environmental benefits [3–6], although most of the studies have been focused on the use of recycled aggregates for concrete production [7–12]. Several researchers have also studied the applicability of fine recycled aggregates (FRA) for mortar production due to the high amount of FRA produced as a result of the CDW treatment process [13–20].

Most of the mortar mixes manufactured with higher percentages of recycled aggregate presented lower mechanical properties than those of conventional mortar [13,14,16,17,19,20]. However, certain authors have established that there were minor influences on the properties of mortar mixes produced with a replacement ratio of up to 20% [21,22], 25% [19] or 40% [15] of recycled aggregate in substitution of natural aggregate. According to several researches [23–26] the improvements on the mortars' properties were also achieved when fine ceramic and concrete aggregates were employed in the mortar production or the quality of the recycled aggregates were improved after their treatment [27].

The CDW, which can be recycled, is available in numerous countries as a result of human intervention or natural disasters [28]. According to the information obtained from the Cuban National Statistics and Information Office, approximately 1000 m^3 of CDW is generated per day in Havana. The largest volume of CDW being located in landfill sites, which effectively makes it unusable for recycling due to the resulting mixing of materials and consequent contamination [29]. In Cuba, uncontaminated waste is not recycled due to deficiencies in adequate technological infrastructures as well as a lack of an adequate policy with respect to the management of this type of waste [30].

The natural aggregate quarries located near the city are almost depleted as a result of their over exploitation. Consequently, natural aggregates have to be obtained from new quarries which are a long distance away from the city, with the following consequences of higher economic costs as well as having a negative environmental impact on the local landscape [30].

Masonry mortars are widely employed in the construction of buildings in Havana, in general social housing, which is the cause of the highest aggregate consumption. The mechanical properties required for rendering or bonding mortars, according to the Cuban standard [31], are relatively low (less than 10 MPa of compression strength), allowing the use of a low cement content in the mortar manufacture.

As a direct consequence of the lack of natural fine aggregates the locals in Havana have used for the maintenance and renovation of their buildings recycled material with fractions finer than 5 mm (without crushing) obtained directly from demolished or collapsed building waste. Its use is carried out without undergoing a process of selection and treatment, as a consequence of which this fine aggregate material is often of poor quality due to its contamination by detrimental material. Fig. 1 shows several images of both sources of CDW and the mortar mixes produced.

In this research work the two different sources of CDW, which are most typical in Havana, were treated for the production of fine recycled aggregates and their applicability for masonry mortar was production analyzed. ~~The recycled aggregates were used in total replacement of natural aggregates~~. Material taken from both of the CDW sources was submitted to three different crushing processes, which led on to three types of recycled aggregates being produced from each type of CDW under study~~. A total of six types of recycled aggregates were employed in this work~~. The influence of these processes on the properties of the recycled aggregates, and their applicability, in total replacement of natural aggregates, in mortar production were the main objectives of this research work. Two types of fillers were also used in the manufacturing of the mortar; hydrated lime (recommended by Cuban standard) and limestone filler (widely employed in the city due to its high availability). The physical, mechanical and durability properties of the recycled aggregate mortar mixes were analyzed and their results were compared with those of the results obtained from the analysis of a standard conventional mortar, as well as with the minimum requirements as defined by Cuban specification NC 175:2002 [31] (equivalent to ASTM C270-12 [32]) for type III masonry mortar production.

2. Materials

2.1 Cement

An ordinary Portland cement P-350, which according to Cuban standard NC 95:2001 [33], equivalent to ASTM Type I, was employed for all mortar production. It had a density of 3.12 g/cm^3, specific surface of 3089 g/cm^2 and a compressive strength of 35 MPa at 28 days.

2.2 Fillers

Two different types of fillers were employed for mortar production: lime hydrate (LH) and limestone filler (LF). According to NC 175:2002 [31] the LH which had a dry density and bulk density of 2.1 kg/dm^3 and 0.52 kg/dm^3 respectively, was considered to be an adequate filler for masonry mortar production. The LF, which had a dry density of 2.58 kg/dm^3 and bulk density of 1.14 kg/dm^3, was produced via the grinding of limestone aggregates. LF material is predominantly used within the city of Havana due to the difficulty of obtaining lime hydrate. Fig. 2 illustrates the particle size distribution of both filler materials.

2.3 Fine aggregates

2.3.1 Production and composition of the recycled fine aggregates

The recycled aggregates used in the present work were obtained from two different CDW sources (CDW1 and CDW2). Both types of CDW were representative of the two most common types of dwellings built in Havana, which date back to the middle of the past century. The CDW1 waste material was obtained from the demolition of buildings with ceramic tiled roofs and compacted earth and limestone walls. In contrast, the CDW2 waste was obtained from the demolition of buildings with roofs formed of steel beams and concrete slabs with the walls consisting of ceramic brick. The general composition of the CDW wastes was that of roof and wall elements, however, other materials were also found to be present such as mortar, tiles, etc, which proved to be less than 10% of the total weight of the whole. An important percentage of the CDW generated in the capital of Havana is produced by the demolition of this type of dwelling [30].

The representative sampling was carried out after the crushing of between 3 and 4.5 tons of each of the two types of CDW mentioned and in accordance with BS-EN 932-1:1997 regulations [34]. Both types of CDW were individually submitted to three different types of crushing processes for the production of three different kinds of recycled aggregates (-C, -F and –CF).

The process adopted for the obtaining of the first type of fine recycled aggregates (RA1/2-C) was carried out by firstly discarding all material finer than the 4.76 mm sieve from the total volume of the CDW prior to it passing through the crushing stage. Secondly, the total volume of the material greater than 4.76 mm was crushed via the employment of a jaw crusher for the production of RA1/2-C fine recycled aggregates [14,29]. For the production of the second type of fine recycled aggregates, RA1/2-F, the CDW material which proved to be finer than the 4.76 mm sieve was used without undergoing any crushing process. The third and last type of fine recycled aggregates, RA1/2-CF, were obtained via the crushing of the total volume of the CDW to that of a finer material than 4.76 mm. In all three types of processes the material finer than 4.76 mm was separated after every stage of crushing and the remaining fractions found to be coarser than that size were submitted to a new crushing process. The crushing process was completed when all the material accomplishment the desired particle size.

2.3.2 Fine aggregates properties

Raw limestone aggregate obtained from the Arimao quarry which is the highest quality commercialized aggregate in the city [14] was used for the production of the control mortar.

Fig. 3 shows the particle size distribution of all the types of aggregates used in the present study. They were determined following NC 178:2002 [35] specification (equivalent to ASTM C136/C136M-14 [36]). ~~The range established by Cuban standard NC 657:2008 [37] (equivalent to ASTM C 144 [38]) for aggregates for masonry mortar is also illustrated in the graph.~~ All the recycled aggregates were found to have a similar grading distribution, however when compared to those of the recycled aggregates, the natural aggregates were found to present a lower amount of finer aggregates than 0.297 mm, see Fig. 3. Tests proved that the recycled aggregates not only presented a higher percentage of material finer than 75µm, but that they also had lower amounts of passing material through the higher grade sieve than those of the natural aggregates.

Table 1 shows the physical properties of the natural and recycled aggregates. The density and water absorption capacity were evaluated according to Cuban standard NC 177:2002 [37] (equivalent to ASTM C29/C29M-17 [38] specification). The bulk density and the percentage of the material passing through No. 200 (< 75 µm) sieve were determined following NC 181:2002 [39] (equivalent to ASTM C29/C29M-17 [38]) and NC 182:2002 [40] (equivalent to ASTM C117-13 [41]) specifications, respectively.

The water absorption capacity of all the recycled aggregates proved to be greater than that of the natural aggregate (Table 1), a fact which has also been reported by other researchers [13,17–19,22,26,42–44]. With respect to recycled aggregates, those obtained from crushing the fine and coarse fraction of CDW1 achieved the highest and lowest absorption capacity, respectively. The water absorption capacity of the three recycled aggregates obtained from CDW2 was similar to or higher than that of RA1-C.

Table 2 shows the chemical composition of the recycled aggregates, which was determined via Panalytical, Axios PW 4400/40 XRF spectrometers. The calcium and silica content being the main differences between the CDW1 and CDW2 sources. The recycled aggregates produced from the CDW1 source proved to contain approximately 50% of silica, as a direct consequence of its high percentage of ceramic material content. The recycled aggregates produced from the CDW2 had a higher composition of calcium, as they originated from concrete elements. The magnesium and aluminum content proved to be the main difference between the composition of the coarse (-C) and fine (-F) fraction. The RA1-F aggregates proved to have a high content of magnesium due to the presence of limestone rocks, as the walls of the dwellings, which formed part of the material sourced for CDW1, had a certain amount of dolomite content in them. In contrast, the RA1-C aggregate proved to have a greater aluminum content, which was a direct result of the influence of the coarse fraction of the ceramic roof material. With respect to the RA2-F aggregate produced from the CDW2 waste, it was determined that the high magnesium value (limestone-dolomite aggregates were used for concrete production) was a direct result of the high content of material obtained from the concrete roofing. In contrast the RA2-C aggregate, which was obtained from ceramic wall waste, proved to have higher amounts of aluminum content.

3. Mortar Manufacture and Experimental Procedure

3.1 Mortar mixture proportions

Type III Control mortar (bonding and rendering mortar for use at ground level and above) employing natural aggregate, with the volumetric mix proportion of 1:4:2 (cement: aggregate: filler) was produced following NC 175:2002 [31] specifications. This standard recommends the use of lime hydrate as filler. Unfortunately, this is difficult to obtain within Havana and as a consequence the use of limestone filler is also permitted in mortar manufacture. As a direct result of the lack of fine particles within the natural aggregates it is necessary to include filler in the mortar mixture. The mentioned added filler has the effect of reducing the volume of voids within the particle matrix, thus achieving a better performance of the mortars in the fresh and hardened state [45].

The 1:5:1 (cement: aggregate: filler) volumetric mix proportion was used for the recycled aggregate mortars production. Prior studies [14] verified that this dosage was the equivalent to the volumetric dosage (1:4:2) established by Cuban regulations for natural aggregates mortars. The higher amount of fine material contained in the recycled aggregate justified the reduction in the use of the filler volume.

The manufacturing process was carried out following NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14 [48]) specifications. The total water content added to each mortar was determined experimentally in order to obtain a consistency index of 190 ± 5 mm in all mortar mixes, and in accordance with Cuban standard NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]). The quantity of free water in the paste of each of the mortar mixes defined the effective water cement ratio (see table 3). The natural aggregates were used in dry condition while the recycled aggregates were used in wet condition. The effective water absorption capacity of the fine aggregates was determined via soaking them for 30 min (defined by DIN 4226-100 [51]). The method used in the testing was that stipulated by the Cuban regulation NC 186: 2002 [52] (equivalent to ASTM C 128-97 [53]) for the determination of the 24 h absorption capacity of natural aggregates. The effective absorption capacity of the recycled and natural aggregates was 80% and 50% respectively of their total absorption capacity.

Twelve different recycled aggregate mortar mixes were produced, as a result of the combination of the six recycled aggregates (RA1-C, RA1-F, RA1-CF, RA2-C, RA2-F and RA2-CF) with the two fillers (LH, LF). Two control mortars were also manufactured employing natural sand and two types of fillers. Table 3 shows the mix proportions of the mortars.

The mortar specimens were de-molded at 24 hours and then, in compliance with regulation NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14 [48]), cured in a humidity room until the testing stage.

3.2 Experimental procedure

3.2.1. Fresh state test

The consistency and water retentivity properties were measured. The consistency of mortar was fixed as 190 ± 5 mm for all the mortar mixes in accordance with NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]) specifications. The mortar mixes which did not achieve that requirement were rejected.

The water retentivity capacity was determined in all of the mortar mixes in accordance with NC 169:2002 [54] (equivalent to ASTM C1506-16b [55]) specifications. The fresh mortar was poured into a 100 mm diameter cylindrical mould, with a depth of 25 mm, before being subjected to a suction test employing a specific absorption filter. The water retentivity capacity was determined by the amount of water absorbed by the paper filter, being 90% the minimum value required by Cuban Specification.

3.2.2. Hardened state tests

Physical (density, absorption and accessible pores) and mechanical (compressive and flexural strength) properties were determined after 28 days of curing according to ASTM C270-12a [32] and NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14 [48]) specifications, respectively, employing the Automax compression equipment with 50 kN capacity.

The mortar bond tensile strength was also determined, following the NC 172:2002 [56] specifications. The test, which was carried out over a concrete block surface via the use of a Dyna Haftprufer Pull-off tester Z16 (as described in the previous work [14]), at 28 days of curing and in similar conditions to those of the other test specimens.

The capillary water absorption capacity of each mortar was also determined after 28 days of curing according to NC 171:2002 [57] (equivalent to ASTM C1403-15 [58]) specifications. All the surfaces of the specimens were sealed with an epoxy resin except for the top and bottom ends of 40 x 40 mm which were left untreated in order to ensure the one directional transport of the water as described by the regulation.

The drying shrinkage was determined according to ASTM C490/C490M-11 [59] specifications. The 25 x 25 x 285 mm mortar specimens, which had been fitted with a stainless steel stud at both ends, were de-molded after 24 hours of casting and kept in an environmental temperature of 28˚C with a humidity of 80%. The initial length readings were immediately recorded via the use of a length comparator model 62-L0035/A. The length variation was measured over a period of 90 days.

The electrical resistivity was determined via the use of a model Vasrmmk11 tester (see Fig. 4). The measurements were taken with the specimens in a saturated condition which was achieved by totally submerging the specimens in water for 24 hours after undergoing 28 days of curing.

4. Results and Discussion

4.1 Fresh state properties

4.1.1 Consistency

It was necessary to vary the water content employed for the production of the mortars in order to obtain the required consistency of 190 ± 5 mm. The variation of water content was carried out without using admixtures. Table 3 shows the consistency values obtained by all the mortar mixes produced. The recycled aggregate mortars needed more water than the control mortars in order to achieve the required workability values (190±5 mm) established by Cuban regulation NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]).

The higher absorption capacity of recycled aggregates with respect to natural aggregates has a negative effect on the consistency of the mortar produced, as the recycled aggregates absorb part of the mixing water [17,18,60,61]. Additionally, mixtures produced with angular and rough-textured particles, such as those found in recycled aggregates, tend to interlock and reduce inter-particle movement [62]. ~~For the exposed reasons a higher water content is necessary in the production of recycled mortar mixes, a fact noted in this work.~~

4.1.2 Water retentivity

The water retentivity results are presented in Table 3. All the mortar mixes (including those produced using recycled aggregate), except for the CM-LF mortar, achieved the minimum value of 90% required by Cuban specifications. The lower percentage of fine material in the LF filler compared to that of the LH filler (Fig. 2) and the water retaining ability of LH, influenced strongly on this property [63,64]. The recycled aggregate mortars achieved similar or higher water retentivity capacity to that of the control mortar, despite the employment of a lower volume of filler. The finer particle combined with the greater roughness of RA produce a larger specific surface which has the effect of causing a higher amount of water on the surface pores. The result being the creation of a cohesive force, which is prompted by the electrostatic attraction between the positive hydrogen atom and the highly electronegative oxygen atom within a neighboring water molecule (i.e. hydrogen bond) [65]. Neno et al [18] also mentioned that as opposed to sand very fine concrete recycled particles (RCA) must have been retained. The very fine particles of RCA were described as eventually leading on to a filler effect which improved the fresh state. An increase of RCA content within the mortar mixes had the effect of producing a higher water retentivity value.

4.2 Hardened state properties

4.2.1 Physical properties

Table 4 shows the physical properties achieved by all the mortar mixes. The density and absorption capacity of the recycled aggregate mortars was lower and higher, respectively than that of the control mortars. As a result of the mentioned properties of the recycled aggregate [14,18,20,26,65], the mortars manufactured with RA1-F and RA2-F recycled aggregates presented a lower density than the mortars produced employing recycled aggregates obtained via the crushing of the coarser fraction of CDW (RA1-C/-CF and RA2-C/-CF). The mortar produced employing the RAF-1 aggregate achieved the lowest density and highest absorption capacity. The mortar mixes produced employing RA1-F achieved up to 100% higher absorption capacity than those of the conventional mortars. A comparative study [19,66] showed that the mortars produced employing recycled aggregates achieved a considerably higher porosity and water absorption capacity value than those of the control mortar. In general, the mortar mixes produced employing LH filler achieved a slightly higher absorption capacity to those of the mortar mixes produced employing the LF filler. The RM1-F-LH and RM1–F-LF mortars achieved values which were twice as great as those of the control mortars.

The mortar produced employing RA2-C with LH filler (RM2-C-LH) proved to achieve a higher absorption capacity than the mortar produced employing RA2-F and RA2-CF. The reason for this being its need for a higher water/cement ratio in order to achieve the minimum workability required by Cuban standard.

4.2.2 Mechanical properties

Figures 5, 6 and 7 show the mechanical property (compressive strength, flexural strength and bond tensile strength, respectively) values of each mortar as well as their corresponding standard deviation.

Compressive strength

The type III masonry mortar (which is adequate for using at ground level and above, as rendering or bonding material) must have a minimum compressive strength value of 5.2 MPa at 28 days in order to comply with the Cuban standard NC 175:2002 [31]. As shown in Fig. 5, all the mortars achieved the minimum required strength value with the exception of the RM1-F-LF mortar.

The recycled mortars achieved a lower compressive strength than those of the conventional mortars, a fact also noted by other researchers[17,67–69]. The mortar mixes produced employing recycled aggregates obtained from the crushing of the coarse type CDW1 (RA1-C) proved to achieve higher strength levels than those produced using the coarse type CDW2 recycled aggregates (RA2-C). The mortars produced employing the RA1-C aggregates achieved a lower than 10% reduction of compressive strength with respect to that of conventional mortar.

The recycled mortars produced employing the aggregates obtained from the fine fraction of the CDW (RA1-F, RA2-F) proved to achieve the lowest strength values. These mortars achieved a reduction in strength value of up to 40% in the mortars produced with RA1-F and up to 35% in the mortars produced with RA2-F. It must be noted that although the four mortars, RM1-F-LH, RM2-F-LH, RM1-F-LF and RM2-F-LF, were produced using a lower w/c ratio to that of the other recycled mortars (in order to obtain adequate workability). A determining factor on the compressive strength of the four mentioned mortars was the poor quality of the recycled aggregates employed in their production. It is known that with respect to conventional mortars the low w/c ratio produces higher strength values. However, this water/cement ratio parameter cannot be considered as an appropriate means of predicting recycled aggregate mortar’s strength. This fact has also been noted in other works [65,70].

In all cases, the mortar mixes manufactured with LF filler achieved lower compressive strength values than those produced employing LH filler, this was due to its low binder property and coarser fraction. It is known [24] that the improvement of the mechanical strength of the mortars is related to the incorporation of fines within the mortar mixes.

Nevertheless, it must be noted that all the mortar mixes manufactured with recycled aggregates obtained by crushing the coarse fraction of the CDW achieved the minimum required values of compressive strength established by Cuban specifications. This denotes the possibility of the total replacement of natural aggregates by those of recycled aggregates with respect to type III mortar production. Certain research [16,18,26,63] also described the possibility of the total substitution of natural aggregate by recycled aggregates for masonry mortar production.

Flexural strength

Flexural strength is not considered a restricted property according to Cuban specification requirements. A comparative study proved that most of the recycled mortars achieved lower flexural strength when compared to natural aggregate mortars, a fact noted by other researchers [16,42,67,69,71]. Nevertheless, all the mortars produced employing LH achieved a higher strength value than their corresponding LF mortars. The control and RM1-C-LH mortars produced employing hydrated lime filler achieved the same strength values. The mortars produced employing RA1-F/-CF and RA2-F/-CF achieved lower strength values than those of the mortar mixes produced by employing recycled aggregates obtained solely from the coarse fraction (nominated -C) of CDW (see Fig. 6). The mortars produced employing RA1-F/-CF and RA2-F/-CF with LH as the filler achieved a reduction of up to 33% and up to 45% respectively, with respect to CM-LH. The mortar produced employing the previous aggregates and LF as a filler achieved a reduction of up to 48% and 55% respectively, with respect to the CM-LF mortar.

Similarly, with regard to compressive strength values, no relation between the total w/c ratio and the flexural strength of mortars was found. This fact has also been reported in previous works [16,60].

According to Vegas et al. [19], Jimenez et al. [20], and Ledesma et al. [15,68], mortars produced employing recycled aggregates of up to 25%, 30% and 40%, respectively, in substitution of natural aggregates obtained similar strength values to those of the control mortars. According to Lopez Gayarre [26] the flexural strength of the recycled aggregate mortar increased with the percentage of recycled ceramic aggregates employed in its manufacture. Neno et al. [18], also related this as happening when employing 100% of recycled concrete aggregates and verified that this was undoubtedly caused by the reduction that the amount of effective water experienced when the percentage of recycled aggregate for natural aggregate substitution was increased.

Bond tensile strength

According to Cuban regulation NC 175:2002 [31], 0.3 MPa is the minimum bond strength value required for type III masonry mortars. That value could be reduced to 0.2 MPa when the masonry mortars are employed as rendering or bonding for interior walls.

Fig. 7 shows the bond strength results obtained by all the mortars as well as the two restrictive values. All the recycled mortars were found to have obtained a lower bond tensile strength than that of the mortars produced employing natural aggregates. The recycled mortars manufactured with aggregates obtained from the CDW-1 source (mainly of ceramic composition), were found to achieve higher bond strength values than the mortars produced with aggregates from the CDW-2 source (heterogeneous source containing mortar, low quality concrete composition and ceramic material). Moreover, the use of recycled aggregates obtained via the crushing of the coarse material within the CDW (RA1-C) achieved the highest property values. According to certain researchers [14,16], recycled aggregate mortars achieve a lower bond strength capacity than that of control mortars. In contrast, several researchers [42,67,69,72] have determined that mortars produced employing 100% of recycled aggregate replacement ratio could achieve a higher bond strength value~~s~~ than that of the control mortar.

The use of LF filler in substitution of LH filler caused a reduction of the bond strength, although the highest reduction took place in the mortar produced with natural aggregates. The binder effect of the LH resulted in the increase of the mortars' adhesive capacity [71]. The mortars produced employing RA1-F and RA2-F recycled aggregates achieved the lowest bond results. The reduction of bond strength of mortars produced employing LH and LF using RA-F reached levels of up to 45% and 35%, respectively, with respect to the conventional mortars produced with the corresponding filler.

All mortars achieved the 0.2 MPa value established by Cuban standard for rendering mortars which are as suitable for employment on interior walls. However, the RM2-F-LH, RM1-F-LF and RM2-F-LF mortars, produced employing recycled aggregates RA-F, which were obtained from the fine CDW fraction, did not reach the minimum strength of 0.3 MPa needed for type III masonry mortar.

4.2.3 Durability properties

Capillary absorption

Fig. 8 and Fig. 9 indicate the capillary absorption values of the different mortars tested. According to the obtained results, the final capillary absorption value was greatly influenced by the water absorption capacity of the recycled aggregates (see Table 1), a fact which has also been verified by other researchers [18–20,69]. According to Lopez Gayarre et al. [26], the recycled mortar produced with 100% of ceramic recycled aggregates achieved lower capillary absorption capacity than those of the conventional mortar due to the decrease in the amount of effective water. This decrease being a direct result of an increase in the percentage of the ceramic recycled aggregates employed in the production of the mortar.

In this case, all mortars showed similar behavior at 7 hours of testing. However, at 72 hours of testing the difference of the high absorption capacity of the recycled aggregates in comparison to those of the natural aggregates was notable. Nevertheless, after 168 hours of testing, the mortars produced employing the recycled aggregates with the highest water absorption capacity, RM1-F and RM2-F achieved the highest capillary absorption values. The RM1-C-LH and RM1-CF-LH recycled mortars were the mortars which of all the other recycled mortars obtained the lowest capillary absorption capacity values. However, these achieved values were higher than those of the conventional mortar CM-LH, which obtained the lowest value.

Fig.8 and Fig. 9 denote the capillary absorption of the mortars produced employing limestone filler (LF), which proved to have a higher capillary absorption capacity in the early stages of testing than those of the mortars produced with hydrated lime (LH). The reason for this difference in capillary absorption was due to the low transfer sorptivity and high water retaining characteristics of hydrated lime [64]. Nevertheless, after 168 hours of testing it was determined that the capillary absorption of the mortars depended on the type of aggregates employed in the mortar production and not on the type of filler used. At 168 hours of testing, the capillary absorption values of all the mortars were analyzed. The analysis was carried out by dividing the mortars into in three groups: Group 1 describes the mortars produced employing the RA1-F recycled aggregate, the RM1-F-LH and RM1-F-LF mortars, which achieved the highest values; Group 2 describes the behavior of all the other recycled aggregate mortars, which all proved to have achieved similar capillary absorption; Finally, Group 3 describes the control mortars, CM-LF and CM-LH, which achieved the lowest capillary absorption values of all the mortars tested.

The capillary absorption values of the mortars from group 1, 2 and 3 were 6, 5 and 4 g/cm^2 at 168 h, respectively. The test results imply that the final value of the capillary absorption (at 168 h) depended directly on the water absorption of the recycled aggregate which was employed in the mortar manufacture [60,63]. There was no significant difference noted on the capillary absorption values when LH or LF filler was employed for mortar production.

Drying shrinkage

The mortars produced employing recycled aggregates suffered a higher shrinkage than the mortars manufactured employing natural aggregates (see Fig. 10 and Fig. 11). This was due to their greater water absorption capacity. This difference in levels of shrinkage has also been described by several researchers [16,18,68,73].

Silva et al. [61], found that mortars employing 20%, 50% and 100% of ceramic recycled aggregates achieved similar shrinkage values amongst themselves, but those values were higher than those obtained by the control mortar. According to Vegas et al. [19], Cabrera-Covarrubias et al. [74], Jimenez et al [20], and Lopez Gayarre et al. [26] the mortar produced employing up to 25%, 30%, 40%, and 50% respectively, of ceramic aggregates achieved acceptable shrinkage values when compared to the same values obtained by conventional mortars.

Although the mortars produced using LH filler proved to have higher shrinkage values than those of the mortars manufactured with limestone filler (LF), they were found to achieve the minimum required workability using less water content than the mortars incorporating LF. A comparative study between the LH filler and the LF filler showed that the higher quantity of material finer than 75 µm in the LH filler and its water retaining capacity proved to have a great influence on the increase of the shrinkage value. This fact has also been described by other researchers [70,75].

All the recycled mortars produced using LF filler achieved similar shrinkage values in spite of the different composition and properties of the recycled aggregates employed. According to Miranda and Selmo [75], the use of different percentages of recycled aggregates was influential on the mortars’ shrinkage but not on their composition.

Electrical resistivity

Fig. 12 indicates the electrical resistivity values of all the studied mortars. All the mortars achieved a low resistivity value as a result of their high absorption capacity and low mechanical properties. However, all the recycled mortars, with the exception of those mortars produced employing RA1-F and RA2-F aggregates, achieved a higher resistivity level than those of the control mortars.

In all probability, the presence of ceramic material in the recycled aggregates explains the higher value achievement of the recycled mortars when compared to the same values obtained from the control mortars. Similar results to those exposed have been reported in a previous study [14]. The coarse fraction of the CDW contained a higher percentage of ceramic material than the fine fraction. CDW-1 proved to have the highest amount of this ceramic material, and it was this ceramic content which caused the highest electrical resistivity levels in these mortars due to its inherent electrical insulating properties. Consequently, the property of electrical resistivity is not an adequate form of assessing the quality of mixed recycled aggregates mortars, as the values reported are more affected by the content of siliceous material than by the saturated porous ramification.

5. Conclusions

The following conclusions and recommendations for the use of RA and filler in masonry mortar can be drawn from the results of this study:

Recycled aggregates:

- For the adequate quality of the RA1 recycled aggregates production, a coarse fraction (>4.76 mm) of the CDW1 is required. Taking into consideration in this study that the main component of the CDW1 was ceramic, with soil and limestone as the finest materials and minor components and with the complete absence of concrete.
- When the main component of the CDW is concrete combined with a low amount of impurities, the recycled aggregate produced employing only the fine fraction of CDW (<4.76mm) achieved similar properties to those produced crushing the coarse fraction of CDW.

Fresh state of recycled aggregate mortars:

- Although the recycled aggregate mortars needed more water than those of the control mortars to achieve the required workability, it was found that the recycled aggregate mortars obtained a higher water retentivity capacity than that of the conventional mortars. The water retentivity capacity was noted to be higher when employing lime hydrate (LH) rather than limestone filler (LF).

Hardened state of recycled aggregate mortars:

- The use of recycled aggregates produced from the fine fraction of CDW1, which was mainly composed of earth and limestone, increased the mortars’ absorption capacity of up to 100% with respect to that of conventional mortar. Consequently, it was necessary to employ the ceramic material presented in the coarse fraction of CDW for recycled aggregate production.

- Whereas the mortars produced employing recycled aggregate obtained from the CDW1, which had ceramic as its main component, achieved similar mechanical properties to conventional mortar, it was discovered that the use of the recycled aggregates obtained from CDW2 (concrete with main component) achieved lower properties than those of conventional one.
- The employment of LH filler as opposed to LF can result in 50% higher strength mortars than those of mortars made with LF employing the same type of recycled aggregates.
- Although recycled aggregate mortars achieved a higher shrinkage value than that of conventional mortars, the employment of LF filler in recycled aggregate mortars reduced the shrinkage achieved by mortars produced with LH by up to 25%.

The recycled aggregates produced from the CDW composed of ceramic materials achieved the best properties and were found to be able to produce recycled mortars with adequate properties. However, in order to comply with the minimum quality requirements established for recycled aggregate mortars, it is necessary to employ the coarse fraction of the CDW in recycled aggregate production. Test results of the RA-F (recycled aggregates produced using only the fine fraction of CDW) determined that it was only adequate for the rendering or bonding of interior walls at or above ground level.

Although the mortars produced employing hydrated lime achieved higher mechanical properties than those of the mortars produced using limestone filler, it was established that both, the physical properties and the shrinkage values, of the mortars produced employing the limestone filler were more adequate. A finer grading distribution of the limestone filler (only 40% of the available LF is finer than 75 µm) could be responsible for improving both the retentivity and the mechanical properties of the mortars assuring a general improvement of properties of masonry recycled mortars.

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