

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.

32

33 **Abbreviations**

34 CDW - Construction and demolition waste

35 FRA - Fine recycled aggregate

36 LH - Lime hydrate

37 LF - Limestone filler

38 RA - Recycled aggregate

39 w/c - water/cement

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41 **1. Introduction**

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

51 Most of the mortar mixes manufactured with higher percentages of recycled aggregate
52 presented lower mechanical properties than those of conventional mortar
53 [13,14,16,17,19,20]. However, certain authors have established that there were minor
54 influences on the properties of mortar mixes produced with a replacement ratio of up to
55 20% [21,22], 25% [19] or 40% [15] of recycled aggregate in substitution of natural
56 aggregate. According to several researches [23–26] the improvements on the mortars'
57 properties were also achieved when fine ceramic and concrete aggregates were employed
58 in the mortar production or the quality of the recycled aggregates were improved after
59 their treatment [27].

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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 m³ 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

92 main objectives of this research work. Two types of fillers were also used in the
93 manufacturing of the mortar; hydrated lime (recommended by Cuban standard) and
94 limestone filler (widely employed in the city due to its high availability). The physical,
95 mechanical and durability properties of the recycled aggregate mortar mixes were
96 analyzed and their results were compared with those of the results obtained from the
97 analysis of a standard conventional mortar, as well as with the minimum requirements as
98 defined by Cuban specification NC 175:2002 [31] (equivalent to ASTM C270-12 [32])
99 for type III masonry mortar production.

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101 **2. Materials**

102 **2.1 Cement**

103 An ordinary Portland cement P-350, which according to Cuban standard NC 95:2001 [33],
104 equivalent to ASTM Type I, was employed for all mortar production. It had a density of
105 3.12 g/cm^3 , specific surface of 3089 g/cm^2 and a compressive strength of 35 MPa at 28
106 days.

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108 **2.2 Fillers**

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

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118 **2.3 Fine aggregates**

119 *2.3.1 Production and composition of the recycled fine aggregates*

120 The recycled aggregates used in the present work were obtained from two different CDW
121 sources (CDW1 and CDW2). Both types of CDW were representative of the two most

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

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

136 The process adopted for the obtaining of the first type of fine recycled aggregates (RA1/2-
137 C) was carried out by firstly discarding all material finer than the 4.76 mm sieve from the
138 total volume of the CDW prior to it passing through the crushing stage. Secondly, the
139 total volume of the material greater than 4.76 mm was crushed via the employment of a
140 jaw crusher for the production of RA1/2-C fine recycled aggregates [14,29]. For the
141 production of the second type of fine recycled aggregates, RA1/2-F, the CDW material
142 which proved to be finer than the 4.76 mm sieve was used without undergoing any
143 crushing process. The third and last type of fine recycled aggregates, RA1/2-CF, were
144 obtained via the crushing of the total volume of the CDW to that of a finer material than
145 4.76 mm. In all three types of processes the material finer than 4.76 mm was separated
146 after every stage of crushing and the remaining fractions found to be coarser than that
147 size were submitted to a new crushing process. The crushing process was completed when
148 all the material accomplishment the desired particle size.

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150 *2.3.2 Fine aggregates properties*

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

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

162 Table 1 shows the physical properties of the natural and recycled aggregates. The density
163 and water absorption capacity were evaluated according to Cuban standard NC 177:2002
164 [37] (equivalent to ASTM C29/C29M-17 [38] specification). The bulk density and the
165 percentage of the material passing through No. 200 (< 75 µm) sieve were determined
166 following NC 181:2002 [39] (equivalent to ASTM C29/C29M-17 [38]) and NC 182:2002
167 [40] (equivalent to ASTM C117-13 [41]) specifications, respectively.

168 The water absorption capacity of all the recycled aggregates proved to be greater than that
169 of the natural aggregate (Table 1), a fact which has also been reported by other researchers
170 [13,17–19,22,26,42–44]. With respect to recycled aggregates, those obtained from
171 crushing the fine and coarse fraction of CDW1 achieved the highest and lowest absorption
172 capacity, respectively. The water absorption capacity of the three recycled aggregates
173 obtained from CDW2 was similar to or higher than that of RA1-C.

174 Table 2 shows the chemical composition of the recycled aggregates, which was
175 determined via Panalytical, Axios PW 4400/40 XRF spectrometers. The calcium and
176 silica content being the main differences between the CDW1 and CDW2 sources. The
177 recycled aggregates produced from the CDW1 source proved to contain approximately
178 50% of silica, as a direct consequence of its high percentage of ceramic material content.
179 The recycled aggregates produced from the CDW2 had a higher composition of calcium,
180 as they originated from concrete elements. The magnesium and aluminum content proved
181 to be the main difference between the composition of the coarse (-C) and fine (-F) fraction.
182 The RA1-F aggregates proved to have a high content of magnesium due to the presence
183 of limestone rocks, as the walls of the dwellings, which formed part of the material
184 sourced for CDW1, had a certain amount of dolomite content in them. In contrast, the
185 RA1-C aggregate proved to have a greater aluminum content, which was a direct result
186 of the influence of the coarse fraction of the ceramic roof material. With respect to the

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

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193 **3. Mortar Manufacture and Experimental Procedure**

194 **3.1 Mortar mixture proportions**

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

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

209 The manufacturing process was carried out following NC 173:2002 [46] (equivalent to
210 ASTM C348-14 [47] and ASTM C349-14 [48]) specifications. The total water content
211 added to each mortar was determined experimentally in order to obtain a consistency
212 index of 190 ± 5 mm in all mortar mixes, and in accordance with Cuban standard NC
213 170:2002 [49] (equivalent to ASTM C1437-15 [50]). The quantity of free water in the
214 paste of each of the mortar mixes defined the effective water cement ratio (see table 3).
215 The natural aggregates were used in dry condition while the recycled aggregates were
216 used in wet condition. The effective water absorption capacity of the fine aggregates was
217 determined via soaking them for 30 min (defined by DIN 4226-100 [51]). The method
218 used in the testing was that stipulated by the Cuban regulation NC 186: 2002 [52]

219 (equivalent to ASTM C 128-97 [53]) for the determination of the 24 h absorption capacity
220 of natural aggregates. The effective absorption capacity of the recycled and natural
221 aggregates was 80% and 50% respectively of their total absorption capacity.

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

227 The mortar specimens were de-molded at 24 hours and then, in compliance with
228 regulation NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14
229 [48]), cured in a humidity room until the testing stage.

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231 **3.2 Experimental procedure**

232 *3.2.1. Fresh state test*

233 The consistency and water retentivity properties were measured. The consistency of
234 mortar was fixed as 190 ± 5 mm for all the mortar mixes in accordance with NC 170:2002
235 [49] (equivalent to ASTM C1437-15 [50]) specifications. The mortar mixes which did
236 not achieve that requirement were rejected.

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

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244 *3.2.2. Hardened state tests*

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

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

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

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

265 The electrical resistivity was determined via the use of a model Vasmrk11 tester (see
266 Fig. 4). The measurements were taken with the specimens in a saturated condition which
267 was achieved by totally submerging the specimens in water for 24 hours after undergoing
268 28 days of curing.

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270 **4. Results and Discussion**

271 **4.1 Fresh state properties**

272 *4.1.1 Consistency*

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

279 The higher absorption capacity of recycled aggregates with respect to natural aggregates
280 has a negative effect on the consistency of the mortar produced, as the recycled aggregates

281 absorb part of the mixing water [17,18,60,61]. Additionally, mixtures produced with
282 angular and rough-textured particles, such as those found in recycled aggregates, tend to
283 interlock and reduce inter-particle movement [62].

284 *4.1.2 Water retentivity*

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

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302 **4.2 Hardened state properties**

303 *4.2.1 Physical properties*

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

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

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

323

324 *4.2.2 Mechanical properties*

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

328 *Compressive strength*

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

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

341 The recycled mortars produced employing the aggregates obtained from the fine fraction
342 of the CDW (RA1-F, RA2-F) proved to achieve the lowest strength values. These mortars
343 achieved a reduction in strength value of up to 40% in the mortars produced with RA1-F

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344 and up to 35% in the mortars produced with RA2-F. It must be noted that although the
345 four mortars, RM1-F-LH, RM2-F-LH, RM1-F-LF and RM2-F-LF, were produced using
346 a lower w/c ratio to that of the other recycled mortars (in order to obtain adequate
347 workability). A determining factor on the compressive strength of the four mentioned
348 mortars was the poor quality of the recycled aggregates employed in their production. It
349 is known that with respect to conventional mortars the low w/c ratio produces higher
350 strength values. However, this water/cement ratio parameter cannot be considered as an
351 appropriate means of predicting recycled aggregate mortar's strength. This fact has also
352 been noted in other works [65,70].

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

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

364 *Flexural strength*

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

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

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

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

390 *Bond tensile strength*

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

394 Fig. 7 shows the bond strength results obtained by all the mortars as well as the two
395 restrictive values. All the recycled mortars were found to have obtained a lower bond
396 tensile strength than that of the mortars produced employing natural aggregates. The
397 recycled mortars manufactured with aggregates obtained from the CDW-1 source (mainly
398 of ceramic composition), were found to achieve higher bond strength values than the
399 mortars produced with aggregates from the CDW-2 source (heterogeneous source
400 containing mortar, low quality concrete composition and ceramic material). Moreover,
401 the use of recycled aggregates obtained via the crushing of the coarse material within the
402 CDW (RA1-C) achieved the highest property values. According to certain researchers
403 [14,16], recycled aggregate mortars achieve a lower bond strength capacity than that of
404 control mortars. In contrast, several researchers [42,67,69,72] have determined that
405 mortars produced employing 100% of recycled aggregate replacement ratio could achieve
406 a higher bond strength values than that of the control mortar.

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

414 All mortars achieved the 0.2 MPa value established by Cuban standard for rendering
415 mortars which are as suitable for employment on interior walls. However, the RM2-F-
416 LH, RM1-F-LF and RM2-F-LF mortars, produced employing recycled aggregates RA-F,
417 which were obtained from the fine CDW fraction, did not reach the minimum strength of
418 0.3 MPa needed for type III masonry mortar.

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420 *4.2.3 Durability properties*

421 *Capillary absorption*

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

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

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

440 Fig.8 and Fig. 9 denote the capillary absorption of the mortars produced employing
441 limestone filler (LF), which proved to have a higher capillary absorption capacity in the
442 early stages of testing than those of the mortars produced with hydrated lime (LH). The
443 reason for this difference in capillary absorption was due to the low transfer sorptivity
444 and high water retaining characteristics of hydrated lime [64]. Nevertheless, after 168
445 hours of testing it was determined that the capillary absorption of the mortars depended
446 on the type of aggregates employed in the mortar production and not on the type of filler
447 used. At 168 hours of testing, the capillary absorption values of all the mortars were
448 analyzed. The analysis was carried out by dividing the mortars into in three groups: Group
449 1 describes the mortars produced employing the RA1-F recycled aggregate, the RM1-F-
450 LH and RM1-F-LF mortars, which achieved the highest values; Group 2 describes the
451 behavior of all the other recycled aggregate mortars, which all proved to have achieved
452 similar capillary absorption; Finally, Group 3 describes the control mortars, CM-LF and
453 CM-LH, which achieved the lowest capillary absorption values of all the mortars tested.

454 The capillary absorption values of the mortars from group 1, 2 and 3 were 6, 5 and 4
455 g/cm² at 168 h, respectively. The test results imply that the final value of the capillary
456 absorption (at 168 h) depended directly on the water absorption of the recycled aggregate
457 which was employed in the mortar manufacture [60,63]. There was no significant
458 difference noted on the capillary absorption values when LH or LF filler was employed
459 for mortar production.

460 *Drying shrinkage*

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

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

1 470 achieved acceptable shrinkage values when compared to the same values obtained by
2 471 conventional mortars.

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4 472 Although the mortars produced using LH filler proved to have higher shrinkage values
5 473 than those of the mortars manufactured with limestone filler (LF), they were found to
6 474 achieve the minimum required workability using less water content than the mortars
7 475 incorporating LF. A comparative study between the LH filler and the LF filler showed
8 476 that the higher quantity of material finer than 75 μm in the LH filler and its water retaining
9 477 capacity proved to have a great influence on the increase of the shrinkage value. This fact
10 478 has also been described by other researchers [70,75].

11 479 All the recycled mortars produced using LF filler achieved similar shrinkage values in
12 480 spite of the different composition and properties of the recycled aggregates employed.
13 481 According to Miranda and Selmo [75], the use of different percentages of recycled
14 482 aggregates was influential on the mortars' shrinkage but not on their composition.

15 483 *Electrical resistivity*

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17 484 Fig. 12 indicates the electrical resistivity values of all the studied mortars. All the mortars
18 485 achieved a low resistivity value as a result of their high absorption capacity and low
19 486 mechanical properties. However, all the recycled mortars, with the exception of those
20 487 mortars produced employing RA1-F and RA2-F aggregates, achieved a higher resistivity
21 488 level than those of the control mortars.

22
23 489 In all probability, the presence of ceramic material in the recycled aggregates explains the
24 490 higher value achievement of the recycled mortars when compared to the same values
25 491 obtained from the control mortars. Similar results to those exposed have been reported in
26 492 a previous study [14]. The coarse fraction of the CDW contained a higher percentage of
27 493 ceramic material than the fine fraction. CDW-1 proved to have the highest amount of this
28 494 ceramic material, and it was this ceramic content which caused the highest electrical
29 495 resistivity levels in these mortars due to its inherent electrical insulating properties.
30 496 Consequently, the property of electrical resistivity is not an adequate form of assessing
31 497 the quality of mixed recycled aggregates mortars, as the values reported are more affected
32 498 by the content of siliceous material than by the saturated porous ramification.

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500 5. Conclusions

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

503 *Recycled aggregates:*

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

513 *Fresh state of recycled aggregate mortars:*

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

519 *Hardened state of recycled aggregate mortars:*

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

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- 530 - The employment of LH filler as opposed to LF can result in 50% higher strength
 - 531 mortars than those of mortars made with LF employing the same type of recycled
 - 532 aggregates.
 - 533 - Although recycled aggregate mortars achieved a higher shrinkage value than that
 - 534 of conventional mortars, the employment of LF filler in recycled aggregate
 - 535 mortars reduced the shrinkage achieved by mortars produced with LH by up to
 - 536 25%.

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537 The recycled aggregates produced from the CDW composed of ceramic materials

538 achieved the best properties and were found to be able to produce recycled mortars with

539 adequate properties. However, in order to comply with the minimum quality requirements

540 established for recycled aggregate mortars, it is necessary to employ the coarse fraction

541 of the CDW in recycled aggregate production. Test results of the RA-F (recycled

542 aggregates produced using only the fine fraction of CDW) determined that it was only

543 adequate for the rendering or bonding of interior walls at or above ground level.

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544 Although the mortars produced employing hydrated lime achieved higher mechanical

545 properties than those of the mortars produced using limestone filler, it was established

546 that both, the physical properties and the shrinkage values, of the mortars produced

547 employing the limestone filler were more adequate. A finer grading distribution of the

548 limestone filler (only 40% of the available LF is finer than 75 μm) could be responsible

549 for improving both the retentivity and the mechanical properties of the mortars assuring

550 a general improvement of properties of masonry recycled mortars.

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557

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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.

- **40** (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.

“

Answer 40:

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 defined by standards and scientific references, which gave us the most valuable parameter.

- **43** (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.”

Answer 43:

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.

- **45** (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 different 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 an extended 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, spelling mistakes, 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 referred 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 is 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 modifications 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.

Table 2. Chemical composition of the recycled aggregates.

Table 3. Mix proportion of masonry mortars.

Table 4. Physical properties of the hardened mortars.

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 finer than 75µm (%)	1	13	11	13	12	7	11

Table 2. Chemical composition of the recycled aggregates.

Elements (wt %)	Fe ₂ O ₃	MnO	TiO ₂	CaO	K ₂ O	P ₂ O ₅	SiO ₂	Al ₂ O ₃	MgO	Na ₂ O
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

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

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



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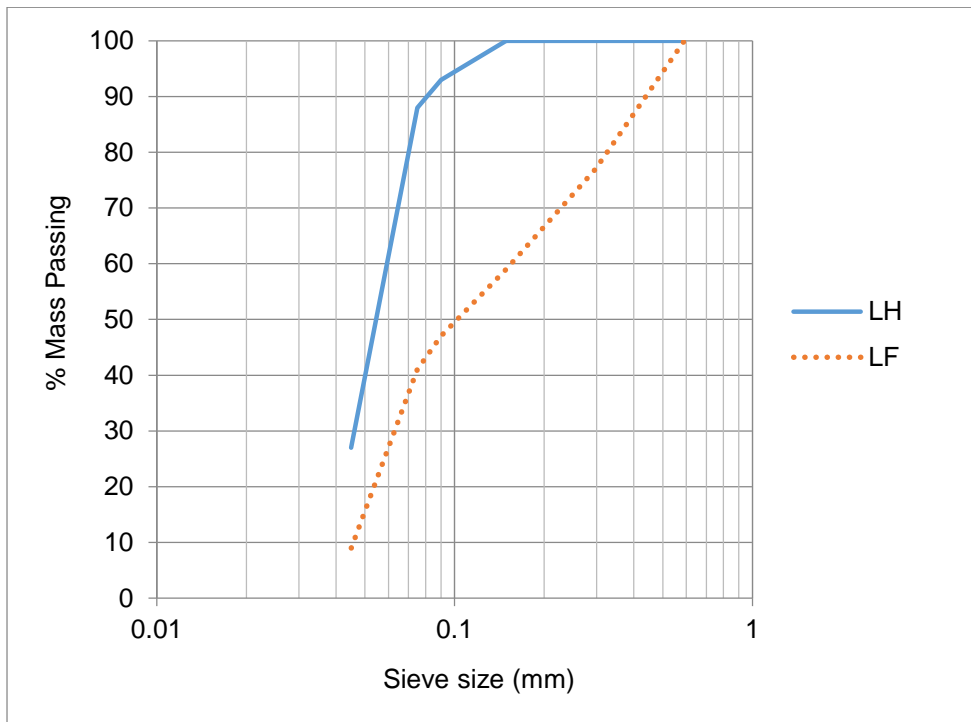


Fig. 2. Particle size distribution of the fillers used.

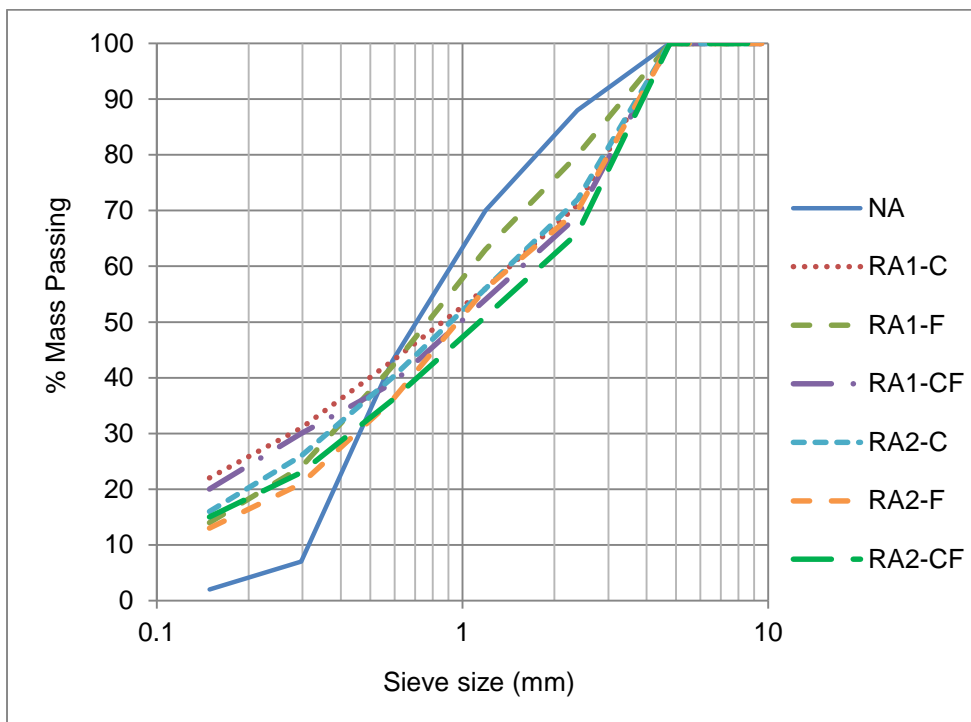


Fig. 3. Particle size distribution of the aggregates studied.

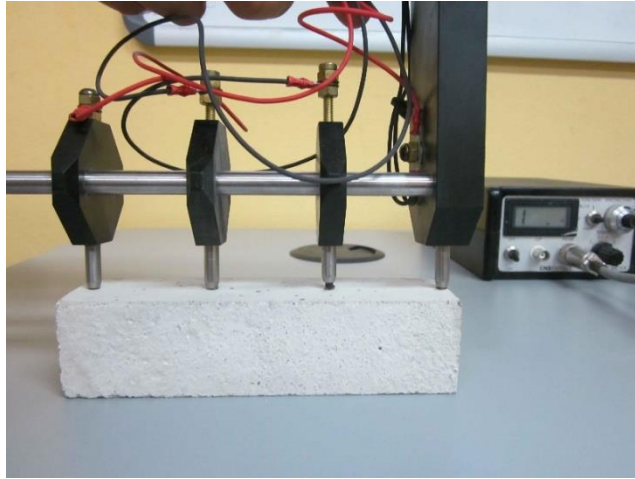


Fig. 4. Electrical Resistivity test.

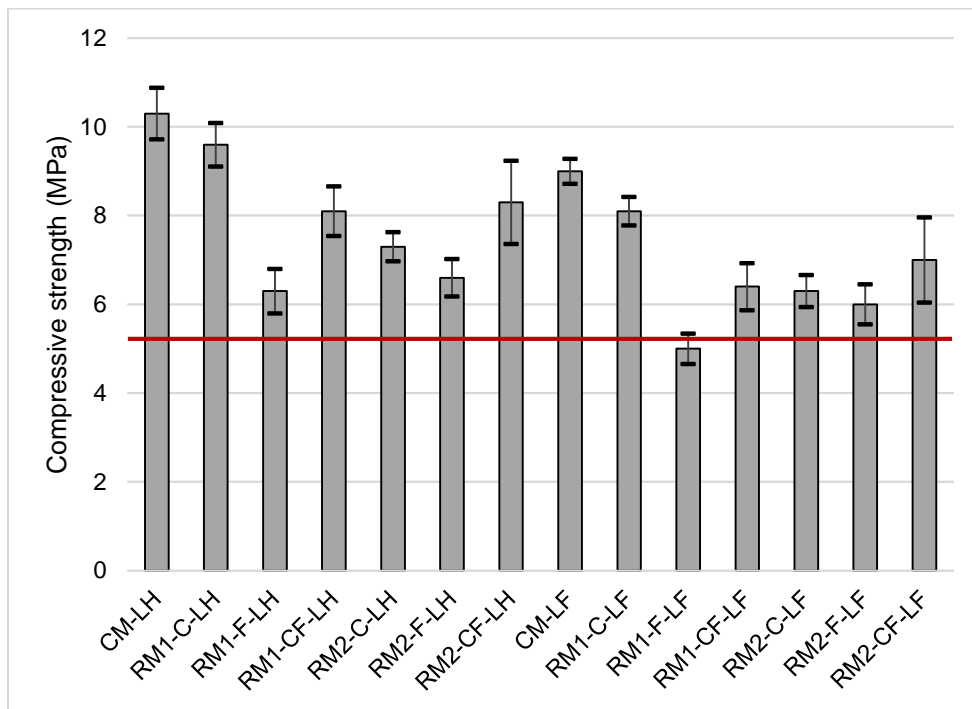


Fig. 5. Compressive strength (the standard deviation is presented at the top of each column) of the mortars studied. The horizontal line marks the minimum value (5.2 MPa) required by Cuban standard.

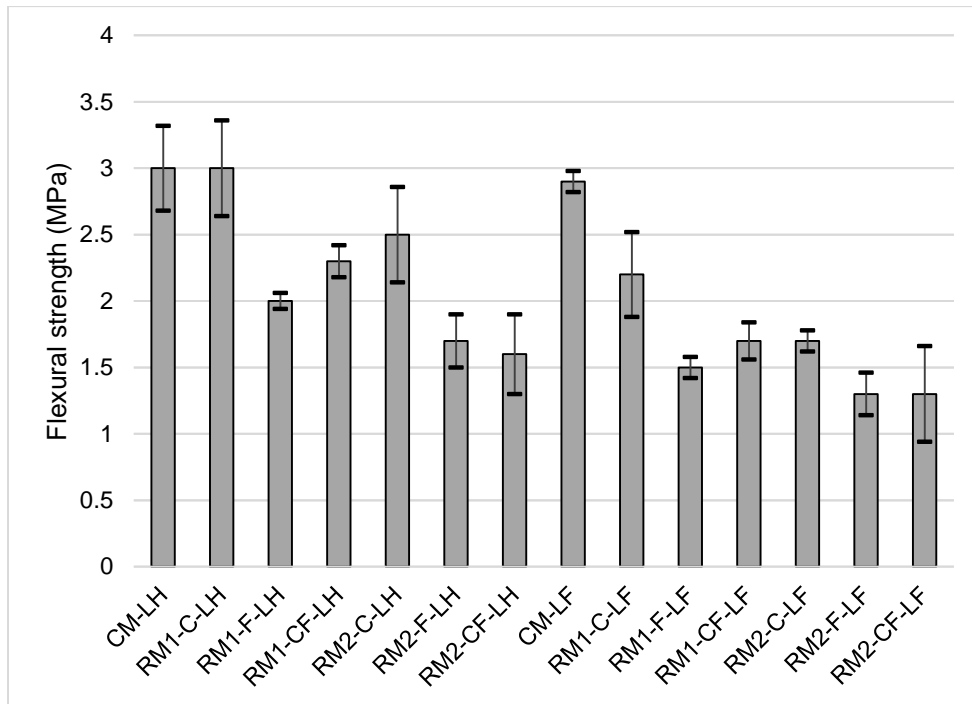


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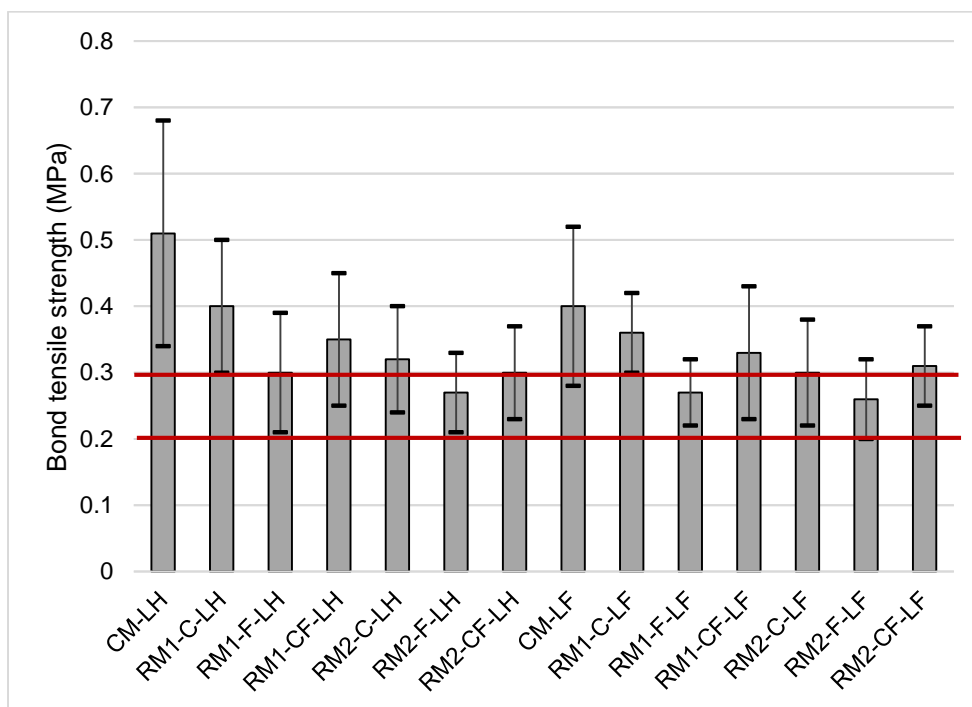


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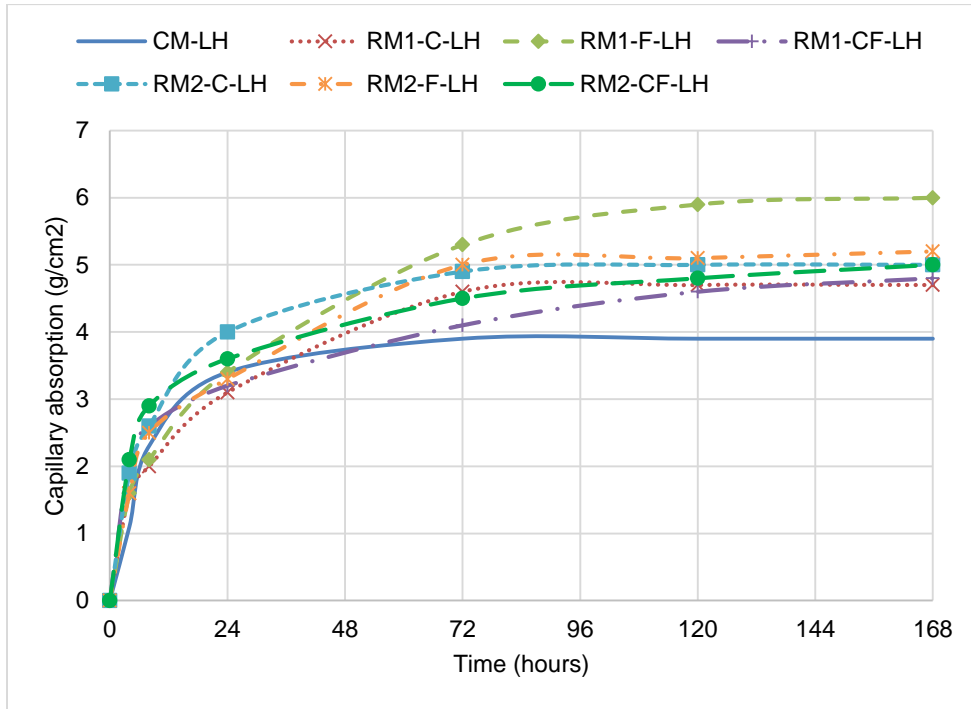


Fig. 8. Capillary absorption as a function of time of hydrated lime mortars at 28 days of curing.

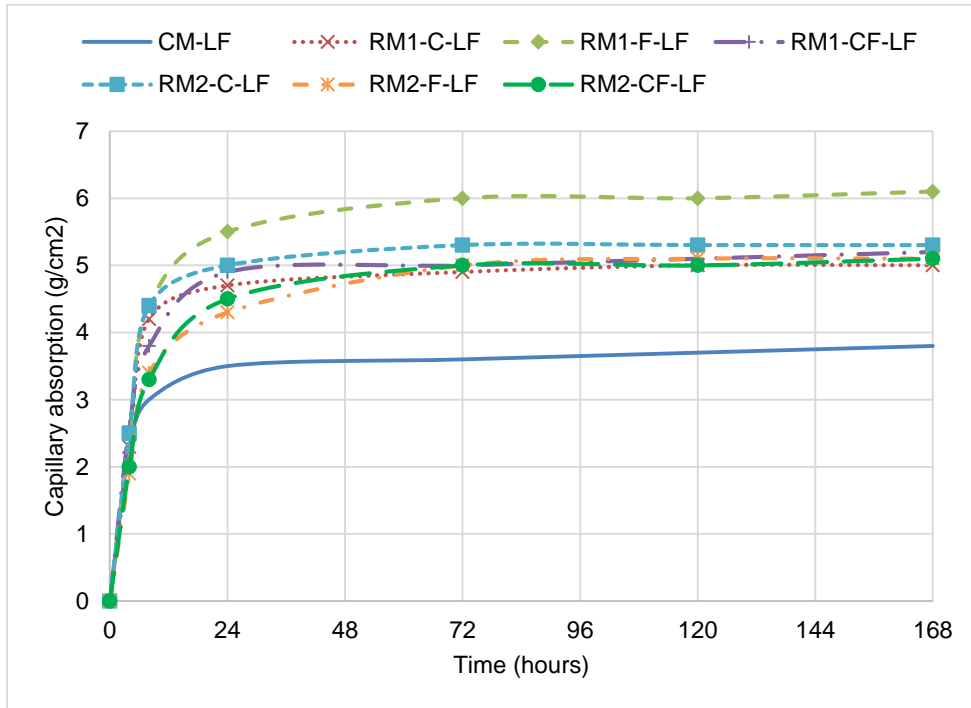


Fig. 9. Capillary absorption as a function of time of lime filler mortars at 28 days of curing.

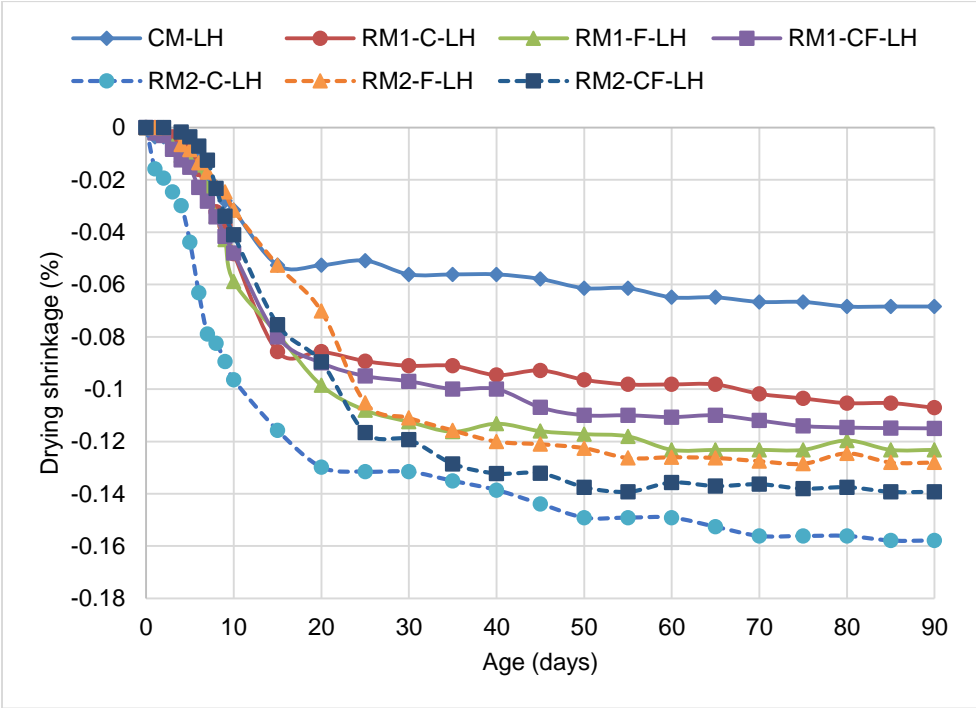


Fig. 10. Drying shrinkage of mortars produced with lime hydrate.

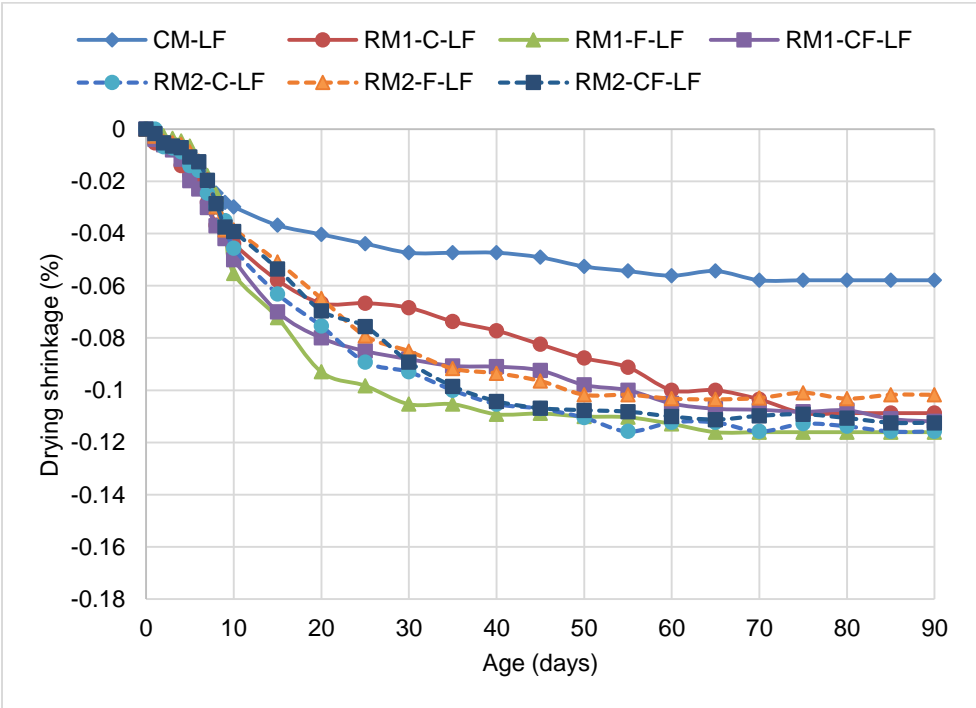


Fig. 11. Drying shrinkage of mortars produced with lime filler.

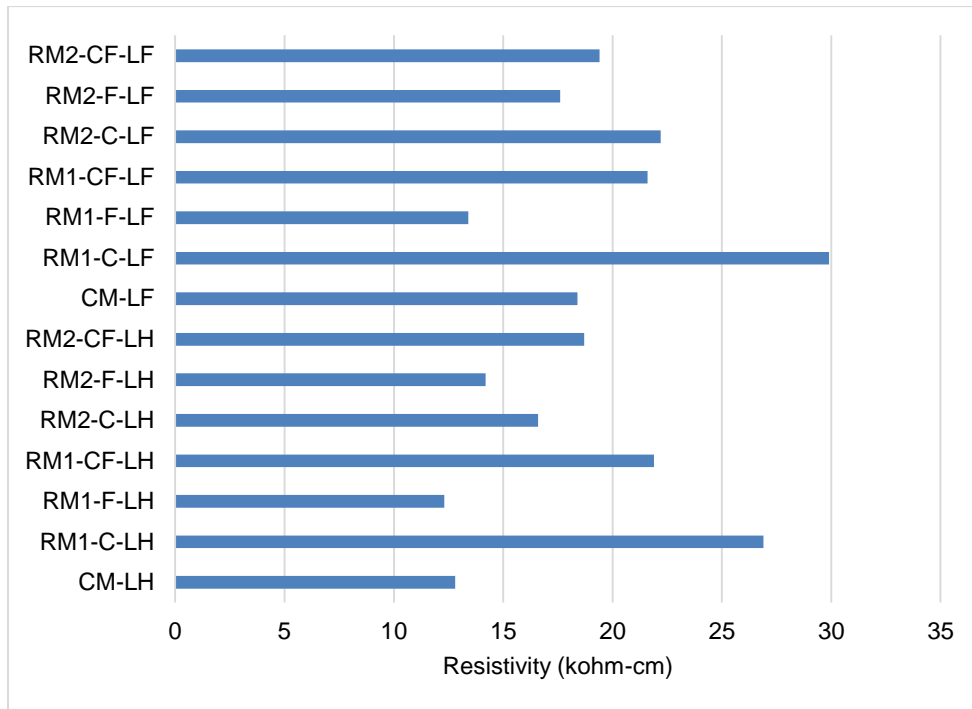


Fig.12. Electrical resistivity of mortars at 28 days.

1 **Influence of demolition waste fine particles on the properties of recycled aggregate** 2 **masonry mortar**

3

4 **Abstract**

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

19

20 **Highlights**

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

29

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

32

33 **Abbreviations**

34 CDW - Construction and demolition waste

35 FRA - Fine recycled aggregate

36 LH - Lime hydrate

37 LF - Limestone filler

38 RA - Recycled aggregate

39 w/c - water/cement

40

41 **1. Introduction**

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

51 Most of the mortar mixes manufactured with higher percentages of recycled aggregate
52 presented lower mechanical properties than those of conventional mortar
53 [13,14,16,17,19,20]. However, certain authors have established that there were minor
54 influences on the properties of mortar mixes produced with a replacement ratio of up to
55 20% [21,22], 25% [19] or 40% [15] of recycled aggregate in substitution of natural
56 aggregate. According to several researches [23–26] the improvements on the mortars'
57 properties were also achieved when fine ceramic and concrete aggregates were employed
58 in the mortar production or the quality of the recycled aggregates were improved after
59 their treatment [27].

60 The CDW, which can be recycled, is available in numerous countries as a result of human
61 intervention or natural disasters [28]. According to the information obtained from the
62 Cuban National Statistics and Information Office, approximately 1000 m³ of CDW is
63 generated per day in Havana. The largest volume of CDW being located in landfill sites,
64 which effectively makes it unusable for recycling due to the resulting mixing of materials
65 and consequent contamination [29]. In Cuba, uncontaminated waste is not recycled due
66 to deficiencies in adequate technological infrastructures as well as a lack of an adequate
67 policy with respect to the management of this type of waste [30].

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

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

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

85 In this research work the two different sources of CDW, which are most typical in
86 Havana, were treated for the production of fine recycled aggregates and their applicability
87 for masonry mortar was production analyzed. ~~The recycled aggregates were used in total~~
88 ~~replacement of natural aggregates.~~ Material taken from both of the CDW sources was
89 submitted to three different crushing processes, which led on to three types of recycled
90 aggregates being produced from each type of CDW under study. ~~A total of six types of~~
91 ~~recycled aggregates were employed in this work.~~ The influence of these processes on the

92 properties of the recycled aggregates, and their applicability, **in total replacement of**
93 **natural aggregates**, in mortar production were the main objectives of this research work.
94 Two types of fillers were also used in the manufacturing of the mortar; hydrated lime
95 (recommended by Cuban standard) and limestone filler (widely employed in the city due
96 to its high availability). The physical, mechanical and durability properties of the recycled
97 aggregate mortar mixes were analyzed and their results were compared with those of the
98 results obtained from the analysis of a standard conventional mortar, as well as with the
99 minimum requirements as defined by Cuban specification NC 175:2002 [31] (equivalent
100 to ASTM C270-12 [32]) for type III masonry mortar production.

101

102 **2. Materials**

103 **2.1 Cement**

104 An ordinary Portland cement P-350, which according to Cuban standard NC 95:2001 [33],
105 equivalent to ASTM Type I, was employed for all mortar production. It had a density of
106 3.12 g/cm^3 , specific surface of 3089 g/cm^2 and a compressive strength of 35 MPa at 28
107 days.

108

109 **2.2 Fillers**

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

118

119 **2.3 Fine aggregates**

120 *2.3.1 Production and composition of the recycled fine aggregates*

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

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

137 The process adopted for the obtaining of the first type of fine recycled aggregates (RA1/2-
138 C) was carried out by firstly discarding all material finer than the 4.76 mm sieve from the
139 total volume of the CDW prior to it passing through the crushing stage. Secondly, the
140 total volume of the material greater than 4.76 mm was crushed via the employment of a
141 jaw crusher for the production of RA1/2-C fine recycled aggregates [14,29]. For the
142 production of the second type of fine recycled aggregates, RA1/2-F, the CDW material
143 which proved to be finer than the 4.76 mm sieve was used without undergoing any
144 crushing process. The third and last type of fine recycled aggregates, RA1/2-CF, were
145 obtained via the crushing of the total volume of the CDW to that of a finer material than
146 4.76 mm. In all three types of processes the material finer than 4.76 mm was separated
147 after every stage of crushing and the remaining fractions found to be coarser than that
148 size were submitted to a new crushing process. The crushing process was completed when
149 all the material accomplishment the desired particle size.

150

151 *2.3.2 Fine aggregates properties*

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

155 Fig. 3 shows the particle size distribution of all the types of aggregates used in the present
156 study. They were determined following NC 178:2002 [35] specification (equivalent to
157 ASTM C136/C136M-14 [36]). ~~The range established by Cuban standard NC 657:2008~~
158 ~~[37] (equivalent to ASTM C 144 [38]) for aggregates for masonry mortar is also~~
159 ~~illustrated in the graph.~~ All the recycled aggregates were found to have a similar grading
160 distribution, however when compared to those of the recycled aggregates, the natural
161 aggregates were found to present a lower amount of finer aggregates than 0.297 mm, see
162 Fig. 3. Tests proved that the recycled aggregates not only presented a higher percentage
163 of material finer than 75µm, but that they also had lower amounts of passing material
164 through the higher grade sieve than those of the natural aggregates.

165 Table 1 shows the physical properties of the natural and recycled aggregates. The density
166 and water absorption capacity were evaluated according to Cuban standard NC 177:2002
167 [37] (equivalent to ASTM C29/C29M-17 [38] specification). The bulk density and the
168 percentage of the material passing through No. 200 (< 75 µm) sieve were determined
169 following NC 181:2002 [39] (equivalent to ASTM C29/C29M-17 [38]) and NC 182:2002
170 [40] (equivalent to ASTM C117-13 [41]) specifications, respectively.

171 The water absorption capacity of all the recycled aggregates proved to be greater than that
172 of the natural aggregate (Table 1), a fact which has also been reported by other researchers
173 [13,17–19,22,26,42–44]. With respect to recycled aggregates, those obtained from
174 crushing the fine and coarse fraction of CDW1 achieved the highest and lowest absorption
175 capacity, respectively. The water absorption capacity of the three recycled aggregates
176 obtained from CDW2 was similar to or higher than that of RA1-C.

177 Table 2 shows the chemical composition of the recycled aggregates, which was
178 determined via Panalytical, Axios PW 4400/40 XRF spectrometers. The calcium and
179 silica content being the main differences between the CDW1 and CDW2 sources. The
180 recycled aggregates produced from the CDW1 source proved to contain approximately
181 50% of silica, as a direct consequence of its high percentage of ceramic material content.
182 The recycled aggregates produced from the CDW2 had a higher composition of calcium,

183 as they originated from concrete elements. The magnesium and aluminum content proved
184 to be the main difference between the composition of the coarse (-C) and fine (-F) fraction.
185 The RA1-F aggregates proved to have a high content of magnesium due to the presence
186 of limestone rocks, as the walls of the dwellings, which formed part of the material
187 sourced for CDW1, had a certain amount of dolomite content in them. In contrast, the
188 RA1-C aggregate proved to have a greater aluminum content, which was a direct result
189 of the influence of the coarse fraction of the ceramic roof material. With respect to the
190 RA2-F aggregate produced from the CDW2 waste, it was determined that the high
191 magnesium value (limestone-dolomite aggregates were used for concrete production) was
192 a direct result of the high content of material obtained from the concrete roofing. In
193 contrast the RA2-C aggregate, which was obtained from ceramic wall waste, proved to
194 have higher amounts of aluminum content.

195

196 **3. Mortar Manufacture and Experimental Procedure**

197 **3.1 Mortar mixture proportions**

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

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

212 The manufacturing process was carried out following NC 173:2002 [46] (equivalent to
213 ASTM C348-14 [47] and ASTM C349-14 [48]) specifications. The total water content
214 added to each mortar was determined experimentally in order to obtain a consistency

215 index of 190 ± 5 mm in all mortar mixes, and in accordance with Cuban standard NC
216 170:2002 [49] (equivalent to ASTM C1437-15 [50]). The quantity of free water in the
217 paste of each of the mortar mixes defined the effective water cement ratio (see table 3).
218 The natural aggregates were used in dry condition while the recycled aggregates were
219 used in wet condition. The effective water absorption capacity of the fine aggregates was
220 determined via soaking them for 30 min (defined by DIN 4226-100 [51]). The method
221 used in the testing was that stipulated by the Cuban regulation NC 186: 2002 [52]
222 (equivalent to ASTM C 128-97 [53]) for the determination of the 24 h absorption capacity
223 of natural aggregates. The effective absorption capacity of the recycled and natural
224 aggregates was 80% and 50% respectively of their total absorption capacity.

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

230 The mortar specimens were de-molded at 24 hours and then, in compliance with
231 regulation NC 173:2002 [46] (equivalent to ASTM C348-14 [47] and ASTM C349-14
232 [48]), cured in a humidity room until the testing stage.

233

234 **3.2 Experimental procedure**

235 *3.2.1. Fresh state test*

236 The consistency and water retentivity properties were measured. The consistency of
237 mortar was fixed as 190 ± 5 mm for all the mortar mixes in accordance with NC 170:2002
238 [49] (equivalent to ASTM C1437-15 [50]) specifications. The mortar mixes which did
239 not achieve that requirement were rejected.

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

246

247 *3.2.2. Hardened state tests*

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

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

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

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

268 The electrical resistivity was determined via the use of a model Vasrmmk11 tester (see
269 Fig. 4). The measurements were taken with the specimens in a saturated condition which
270 was achieved by totally submerging the specimens in water for 24 hours after undergoing
271 28 days of curing.

272

273 4. Results and Discussion

274 4.1 Fresh state properties

275 4.1.1 Consistency

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

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

288 4.1.2 Water retentivity

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

305

306 **4.2 Hardened state properties**

307 *4.2.1 Physical properties*

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

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

327

328 *4.2.2 Mechanical properties*

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

332 *Compressive strength*

333 The type III masonry mortar (which is adequate for using at ground level and above, as
334 rendering or bonding material) must have a minimum compressive strength value of 5.2
335 MPa at 28 days in order to comply with the Cuban standard NC 175:2002 [31]. As shown

336 in Fig. 5, all the mortars achieved the minimum required strength value with the exception
337 of the RM1-F-LF mortar.

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

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

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

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

368 *Flexural strength*

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

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

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

394 *Bond tensile strength*

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

398 Fig. 7 shows the bond strength results obtained by all the mortars as well as the two
399 restrictive values. All the recycled mortars were found to have obtained a lower bond

400 tensile strength than that of the mortars produced employing natural aggregates. The
401 recycled mortars manufactured with aggregates obtained from the CDW-1 source (mainly
402 of ceramic composition), were found to achieve higher bond strength values than the
403 mortars produced with aggregates from the CDW-2 source (heterogeneous source
404 containing mortar, low quality concrete composition and ceramic material). Moreover,
405 the use of recycled aggregates obtained via the crushing of the coarse material within the
406 CDW (RA1-C) achieved the highest property values. According to certain researchers
407 [14,16], recycled aggregate mortars achieve a lower bond strength capacity than that of
408 control mortars. In contrast, several researchers [42,67,69,72] have determined that
409 mortars produced employing 100% of recycled aggregate replacement ratio could achieve
410 a higher bond strength values than that of the control mortar.

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

418 All mortars achieved the 0.2 MPa value established by Cuban standard for rendering
419 mortars which are as suitable for employment on interior walls. However, the RM2-F-
420 LH, RM1-F-LF and RM2-F-LF mortars, produced employing recycled aggregates RA-F,
421 which were obtained from the fine CDW fraction, did not reach the minimum strength of
422 0.3 MPa needed for type III masonry mortar.

423

424 *4.2.3 Durability properties*

425 *Capillary absorption*

426 Fig. 8 and Fig. 9 indicate the capillary absorption values of the different mortars tested.
427 According to the obtained results, the final capillary absorption value was greatly
428 influenced by the water absorption capacity of the recycled aggregates (see Table 1), a
429 fact which has also been verified by other researchers [18–20,69]. According to Lopez
430 Gayarre et al. [26], the recycled mortar produced with 100% of ceramic recycled
431 aggregates achieved lower capillary absorption capacity than those of the conventional

432 mortar due to the decrease in the amount of effective water. This decrease being a direct
433 result of an increase in the percentage of the ceramic recycled aggregates employed in the
434 production of the mortar.

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

444 Fig.8 and Fig. 9 denote the capillary absorption of the mortars produced employing
445 limestone filler (LF), which proved to have a higher capillary absorption capacity in the
446 early stages of testing than those of the mortars produced with hydrated lime (LH). The
447 reason for this difference in capillary absorption was due to the low transfer sorptivity
448 and high water retaining characteristics of hydrated lime [64]. Nevertheless, after 168
449 hours of testing it was determined that the capillary absorption of the mortars depended
450 on the type of aggregates employed in the mortar production and not on the type of filler
451 used. At 168 hours of testing, the capillary absorption values of all the mortars were
452 analyzed. The analysis was carried out by dividing the mortars into in three groups: Group
453 1 describes the mortars produced employing the RA1-F recycled aggregate, the RM1-F-
454 LH and RM1-F-LF mortars, which achieved the highest values; Group 2 describes the
455 behavior of all the other recycled aggregate mortars, which all proved to have achieved
456 similar capillary absorption; Finally, Group 3 describes the control mortars, CM-LF and
457 CM-LH, which achieved the lowest capillary absorption values of all the mortars tested.

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

464 *Drying shrinkage*

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

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

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

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

487 *Electrical resistivity*

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

493 In all probability, the presence of ceramic material in the recycled aggregates explains the
494 higher value achievement of the recycled mortars when compared to the same values
495 obtained from the control mortars. Similar results to those exposed have been reported in

496 a previous study [14]. The coarse fraction of the CDW contained a higher percentage of
497 ceramic material than the fine fraction. CDW-1 proved to have the highest amount of this
498 ceramic material, and it was this ceramic content which caused the highest electrical
499 resistivity levels in these mortars due to its inherent electrical insulating properties.
500 Consequently, the property of electrical resistivity is not an adequate form of assessing
501 the quality of mixed recycled aggregates mortars, as the values reported are more affected
502 by the content of siliceous material than by the saturated porous ramification.

503

504 **5. Conclusions**

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

507 *Recycled aggregates:*

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

517 *Fresh state of recycled aggregate mortars:*

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

523 *Hardened state of recycled aggregate mortars:*

- 524 - The use of recycled aggregates produced from the fine fraction of CDW1, which
525 was mainly composed of earth and limestone, increased the mortars' absorption
526 capacity of up to 100% with respect to that of conventional mortar. Consequently,

527 it was necessary to employ the ceramic material presented in the coarse fraction
528 of CDW for recycled aggregate production.

529 - Whereas the mortars produced employing recycled aggregate obtained from the
530 CDW1, which had ceramic as its main component, achieved similar mechanical
531 properties to conventional mortar, it was discovered that the use of the recycled
532 aggregates obtained from CDW2 (concrete with main component) achieved lower
533 properties than those of conventional one.

534 - The employment of LH filler as opposed to LF can result in 50% higher strength
535 mortars than those of mortars made with LF employing the same type of recycled
536 aggregates.

537 - Although recycled aggregate mortars achieved a higher shrinkage value than that
538 of conventional mortars, the employment of LF filler in recycled aggregate
539 mortars reduced the shrinkage achieved by mortars produced with LH by up to
540 25%.

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

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

555

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561

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