

# 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

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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 m<sup>3</sup> 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.

## 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  $3.12 \text{ g/cm}^3$ , specific surface of  $3089 \text{ g/cm}^2$  and a compressive strength of 35 MPa at 28  
106 days.

### 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  $2.1 \text{ kg/dm}^3$  and  $0.52 \text{ kg/dm}^3$  respectively, was considered to be an  
112 adequate filler for masonry mortar production. The LF, which had a dry density of  $2.58$   
113  $\text{kg/dm}^3$  and bulk density of  $1.14 \text{ kg/dm}^3$ , 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.

### 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

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  $190 \pm 5$  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  $190 \pm 5$  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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1 250 The mortar bond tensile strength was also determined, following the NC 172:2002 [56]  
2 251 specifications. The test, which was carried out over a concrete block surface via the use  
3 252 of a Dyna Haftprüfer Pull-off tester Z16 (as described in the previous work [14]), at 28  
4 253 days of curing and in similar conditions to those of the other test specimens.

5 254 The capillary water absorption capacity of each mortar was also determined after 28 days  
6 255 of curing according to NC 171:2002 [57] (equivalent to ASTM C1403-15 [58])  
7 256 specifications. All the surfaces of the specimens were sealed with an epoxy resin except  
8 257 for the top and bottom ends of 40 x 40 mm which were left untreated in order to ensure  
9 258 the one directional transport of the water as described by the regulation.

10 259 The drying shrinkage was determined according to ASTM C490/C490M-11 [59]  
11 260 specifications. The 25 x 25 x 285 mm mortar specimens, which had been fitted with a  
12 261 stainless steel stud at both ends, were de-molded after 24 hours of casting and kept in an  
13 262 environmental temperature of 28°C with a humidity of 80%. The initial length readings  
14 263 were immediately recorded via the use of a length comparator model 62-L0035/A. The  
15 264 length variation was measured over a period of 90 days.

16 265 The electrical resistivity was determined via the use of a model Vasmrk11 tester (see  
17 266 Fig. 4). The measurements were taken with the specimens in a saturated condition which  
18 267 was achieved by totally submerging the specimens in water for 24 hours after undergoing  
19 268 28 days of curing.

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## 21 270 **4. Results and Discussion**

### 22 271 **4.1 Fresh state properties**

#### 23 272 *4.1.1 Consistency*

24 273 It was necessary to vary the water content employed for the production of the mortars in  
25 274 order to obtain the required consistency of  $190 \pm 5$  mm. The variation of water content  
26 275 was carried out without using admixtures. Table 3 shows the consistency values obtained  
27 276 by all the mortar mixes produced. The recycled aggregate mortars needed more water  
28 277 than the control mortars in order to achieve the required workability values ( $190 \pm 5$  mm)  
29 278 established by Cuban regulation NC 170:2002 [49] (equivalent to ASTM C1437-15 [50]).

30 279 The higher absorption capacity of recycled aggregates with respect to natural aggregates  
31 280 has a negative effect on the consistency of the mortar produced, as the recycled aggregates

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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.

301

## 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.

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#### 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/cm<sup>2</sup> 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  $\mu\text{m}$  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  $\mu\text{m}$ ) 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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Recipient: Dr. Miren Etxeberria

## 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 <sup>3</sup> )	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 <sup>3</sup> )	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 <sub>2</sub> O <sub>3</sub>	MnO	TiO <sub>2</sub>	CaO	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	Na <sub>2</sub> 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 <sup>3</sup> )	Water absorption (%)	Porosity (%)
CM-LH	2086	13.8	25.3
RM1-C-LH	1864	23.3	35.2
RM1-F-LH	1779	28.9	39.8
RM1-CF-LH	1872	24.2	36.5
RM2-C-LH	1840	25.4	37.3
RM2-F-LH	1824	22.3	33.6
RM2-CF-LH	1861	19.3	30.2
CM-LF	2125	13.3	24.9
RM1-C-LF	1913	20.3	32.3
RM1-F-LF	1809	26.7	38.1
RM1-CF-LF	1896	22.1	34.3
RM2-C-LF	1888	22.7	34.9
RM2-F-LF	1880	20.7	32.2
RM2-CF-LF	1901	20.1	31.5

## LIST OF FIGURES

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

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

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Fig. 9. Capillary absorption as a function of time of lime filler mortars.

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.



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



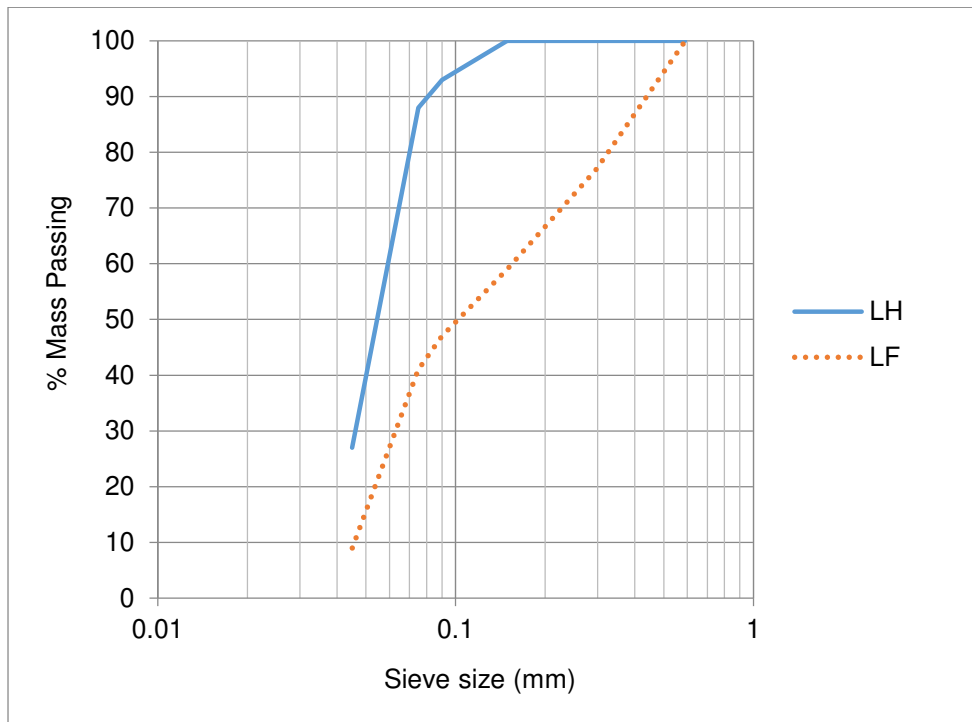


Fig. 2. Particle size distribution of the fillers used.

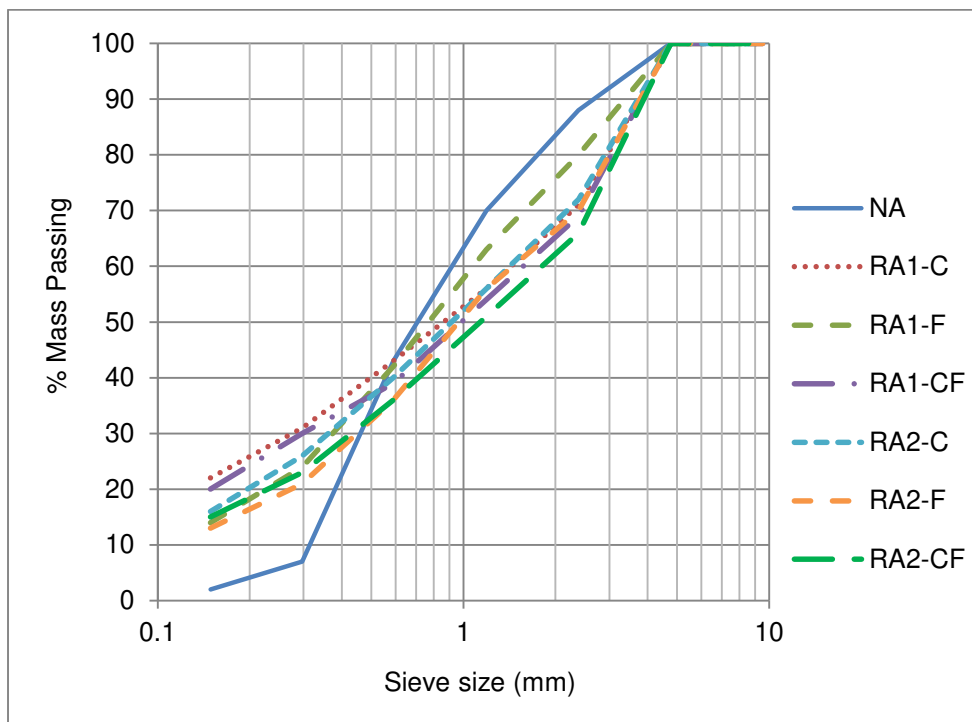


Fig. 3. Particle size distribution of the aggregates studied.

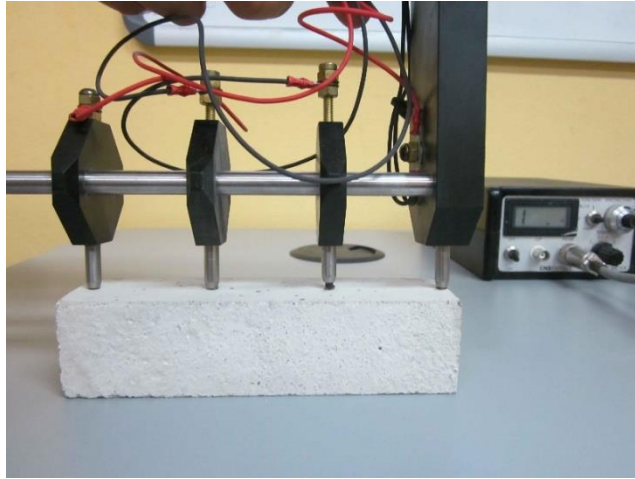


Fig. 4. Electrical Resistivity test.

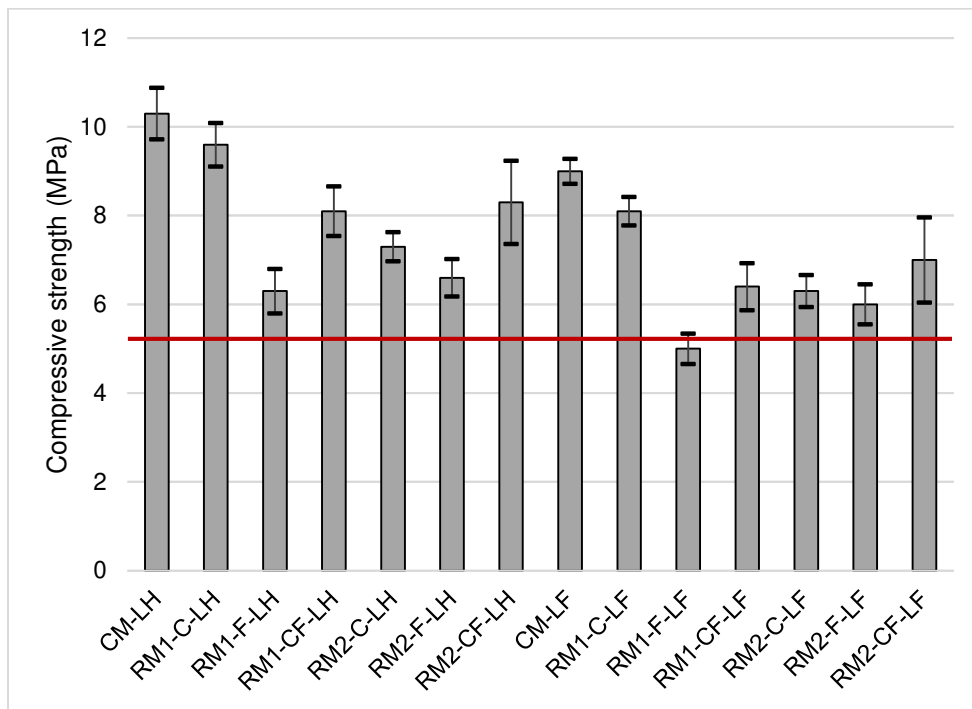


Fig. 5. Compressive strength (the standard deviation is presented at the top of each column) of the mortars studied. The horizontal line marks the minimum value (5.2 MPa) required by Cuban standard.

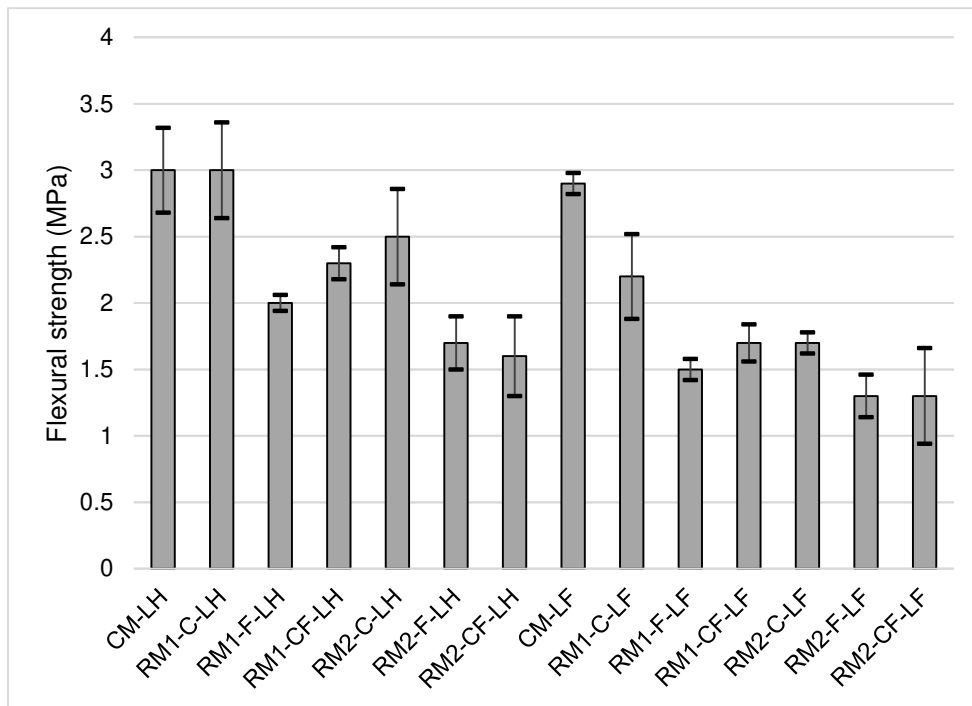


Fig. 6. Flexural strength (the standard deviation is presented at the top of each column) of the mortars studied.

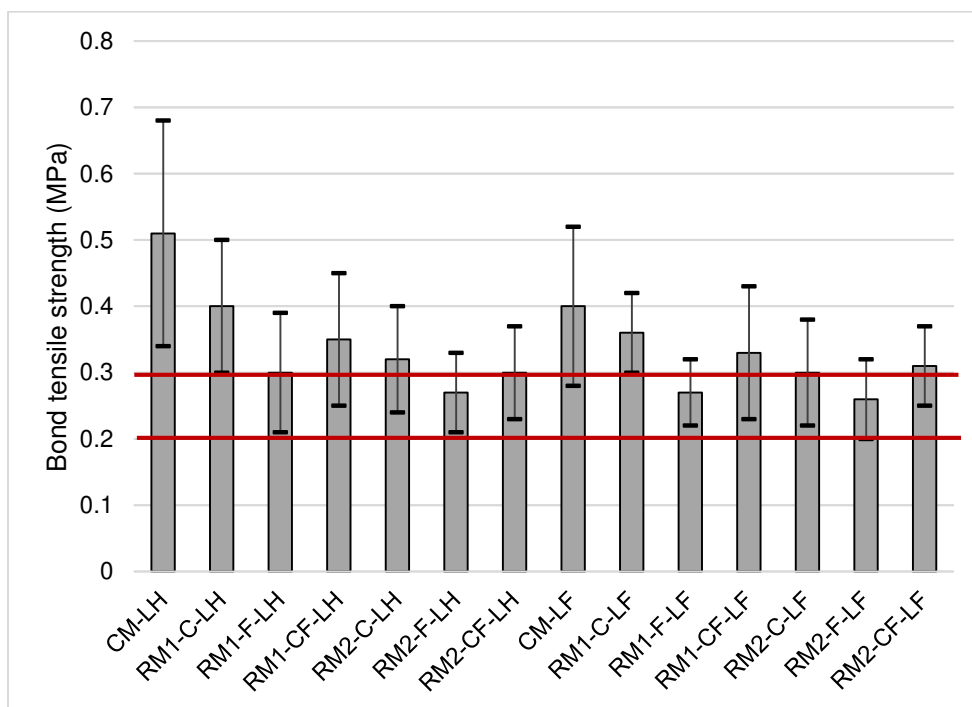


Fig. 7. Bond tensile strength (the standard deviation is presented at the top of each column) of the mortars studied. The horizontal lines mark the values (0.2 MPa and 0.3 MPa) required by Cuban standard to define the mortar application.

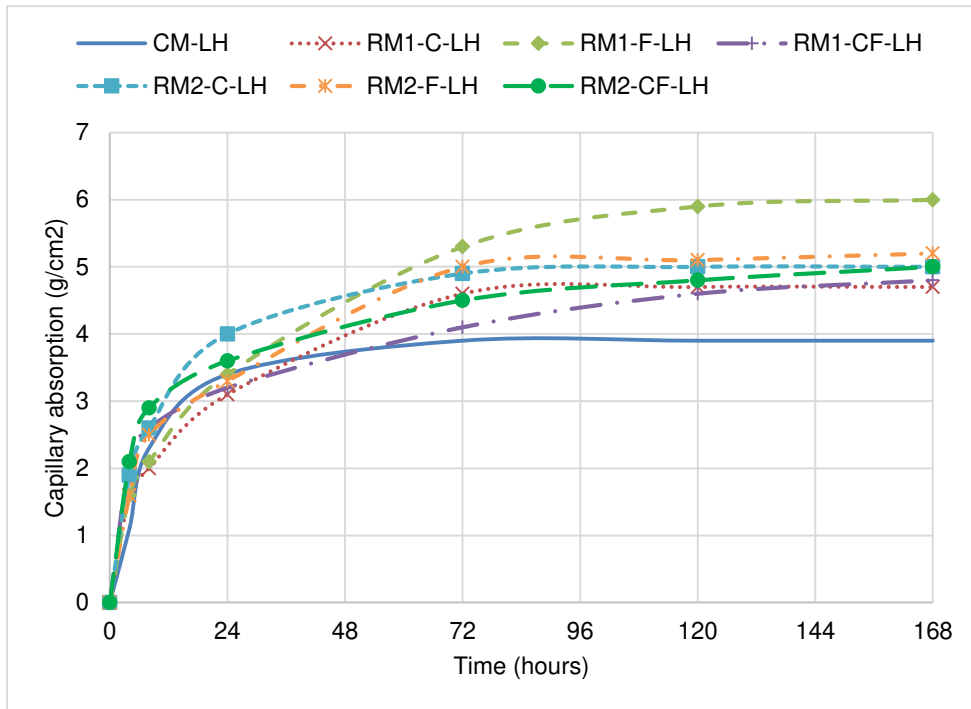


Fig. 8. Capillary absorption as a function of time of hydrated lime mortars at 28 days of curing.

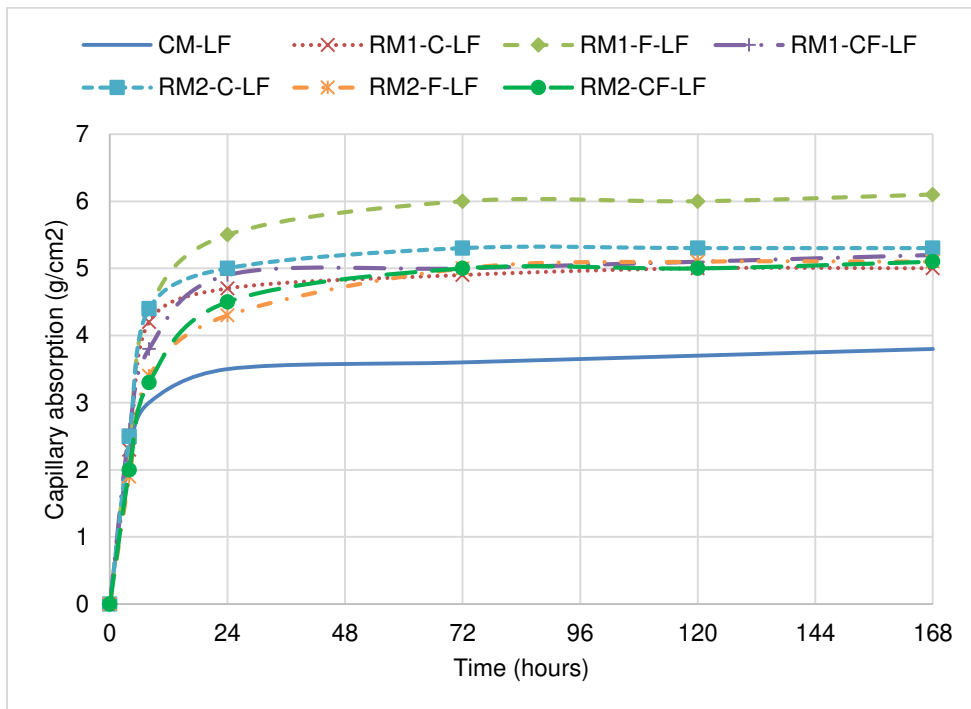


Fig. 9. Capillary absorption as a function of time of lime filler mortars at 28 days of curing.

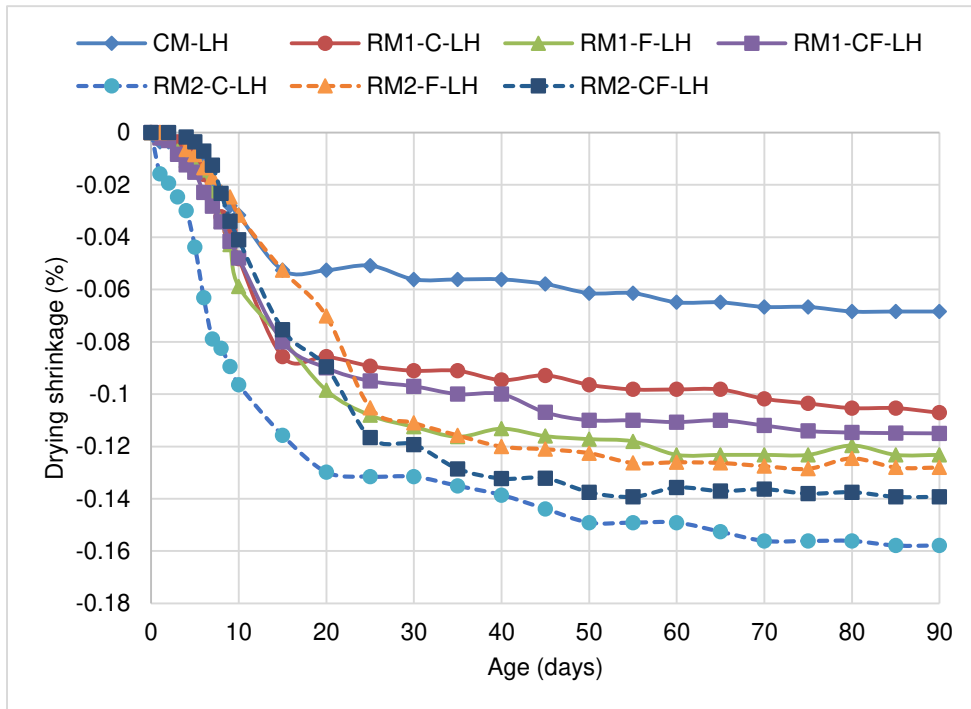


Fig. 10. Drying shrinkage of mortars produced with lime hydrate.

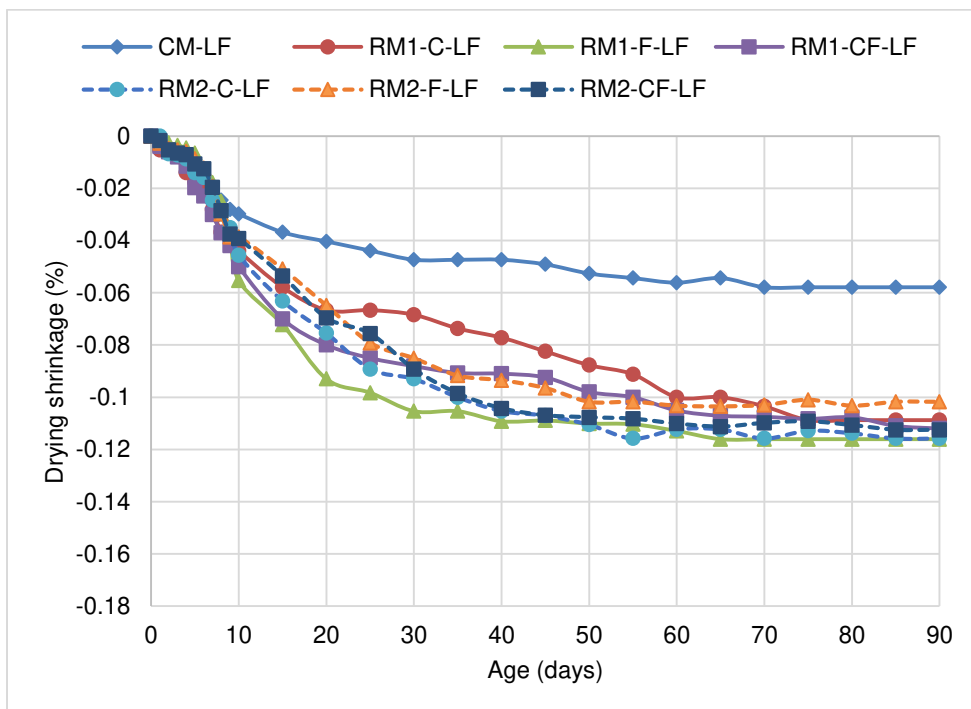


Fig. 11. Drying shrinkage of mortars produced with lime filler.

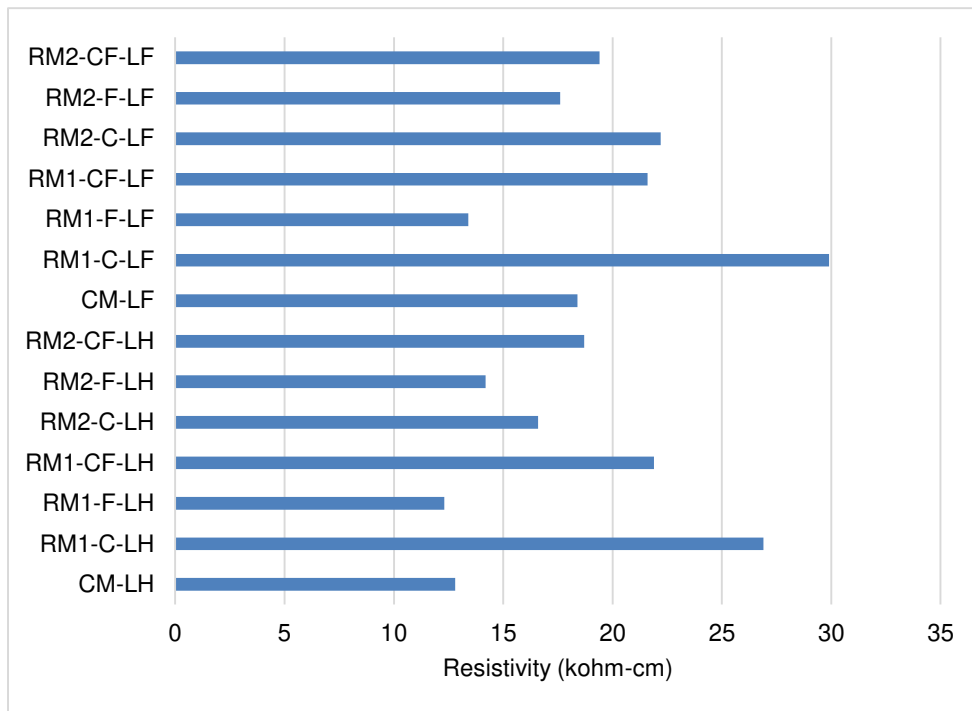


Fig.12. Electrical resistivity of mortars at 28 days.

# 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 m<sup>3</sup> 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  $3.12 \text{ g/cm}^3$ , specific surface of  $3089 \text{ g/cm}^2$  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  $2.1 \text{ kg/dm}^3$  and  $0.52 \text{ kg/dm}^3$  respectively, was considered to be an  
113 adequate filler for masonry mortar production. The LF, which had a dry density of  $2.58$   
114  $\text{kg/dm}^3$  and bulk density of  $1.14 \text{ kg/dm}^3$ , 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  $190 \pm 5$  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  $190 \pm 5$  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 Haftprufer 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  $190 \pm 5$  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 ( $190 \pm 5$  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  $\text{g/cm}^2$  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  $\mu\text{m}$  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 (<4.76mm) 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  $\mu\text{m}$ ) 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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