Construction and Demolition Waste As Recycled Aggregate for Environmentally-Friendly Concrete Paving.

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Research Article

Construction and demolition waste as recycled aggregate for environmentally-friendly concrete paving.

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Abstract.

Recycled aggregates (RA) from construction and demolition waste (CDW) instead of natural aggregates (NA) was analysed in the manufacture of new eco-friendly concrete. Fine (FRA) and coarse (CRA) recycled aggregates were used in different percentages as substitutes of natural sand and gravel, respectively. The results revealed that the use of RA in percentages of up to 50 wt.% are feasible. Additionally, RA were used to produce paving blocks in accordance with industrial requirements. Thus, values of water absorption lesser than 6% and tensile strength upper than 3.6 MPa were obtained, which are similar to those of a reference sample. These results were achieved by reducing the

25   incorporation of cement, thereby saving production costs and minimizing environmental

26   impact.

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1. Introduction

The increase in population in emerging countries, together with the increase in residential development and the need for infrastructure improvements in developed countries has meant that the construction sector has grown at a moderate rate in recent years and that the long-term outlook at the global level is positive. Thus, in the next decade the Construction sector is expected to grow above the growth of the world's gross domestic product (GDP) according to the Eurostat (http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do). Within this sector, the demolition and rehabilitation works occupy an important parcel since the shortage of space in large cities often leads to a choice of demolition or rehabilitation works before undertaking a new construction project. However, this activity generates large amounts of construction and demolition waste (CDW). In 2016, 3.5×10^8 tonnes CDW were generated in Europe (http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do), being the largest waste stream and representing almost a third of the total waste originated (EU Construction & Demolition Waste Management Protocol 2016). In turn, the generation of CDW in the United States in 2015 was 5.8×10^8 tonnes according to the CDRA (https://cdrecycling.org/materials/), which is considered to constitute between 20 and 30% of the overall amount of municipal solid waste generated (Martín-Morales et al. 2011).

CDW are comprised of a broad range of materials, such as concrete, ceramics, brick, rock, metal, plaster, wood, glass, soil, asphalt, etc. (Medina et al. 2015; Villoria et al. 2011). The components of CDW are mostly non-hazardous. However, they may also contain harmful materials to both human health and the environment (U.S. EPA 530-R-98-010, 1998). In this regard, some studies highlight that certain CDW have significant amounts

56   of leachable heavy metals, specifically arsenic and lead (Tolaymat et al. 2004). Moreover,

57   the European Waste Catalogue (EWC) and Hazardous Waste List classifies this waste as

58   inert with code 17 01 07 (Commission Decision 2014/955/EU; Directive 2000/532/EC).

59   Currently, most developed countries have no specific recovery or recycling plan for

60   CDW, so their management is limited to controlled landfill disposal. The situation in

61   developed countries is even worse, as most CDW often end on illegal landfills or dumped

62   in urban areas or on roads, with the consequent environmental problem. In view of this

63   reality, in recent years governments have implemented environmental policies to

64   establish a regulatory framework that allows new recycling strategies. In order to carry

65   out a correct reuse and recycling of these CDW, the separation of the component such as

66   wood, glass, gypsum and other undesired material is a crucial step. The different

67   components of the CDW can be separated in-situ at the construction or demolition site.

68   However, the reality is the transport of the CDW to a recycling plant where the recycling,

69   separation and recovery of its parts takes place (EU Construction & Demolition Waste

70   Management Protocol 2016). In Europe, the average recycling rate of CDW is about 40%,

71   but in Spain, this rate is much lower and only 15% of the CDW generated is recycled

72   (Villoria et al. 2011), which represents a significant gap from the 70% target established

73   by the Integrated Waste Management Plan (Directive 2008/98/EC).

74   Nowadays, CDW has been successfully recycled as base and sub-base of road

75   construction (Bennet et al. 2000; Poon and Chan 2006a), paving projects (Arulrajah et al.

76   2014; Taha et al. 2002), footpaths projects (Arulrajah et al. 2013) and pipe-bedding

77   projects (Rahman et al. 2014; Taha et al. 2002). Nevertheless, it is still necessary to

78   develop new applications for the manufacture of new products, by developing originals

79   processes, by seeking and finding new markets in order to absorb and reduce the vast

80   volume of CDW worldwide production, and furthermore, to comply with the objective

81   established by EU (Commission Decision 2014/955/EU; Directives 2000/532/EC,

82   2008/98/EC).

83   Consequently, previous studies using RA obtained from CDW have developed new

84   applications mainly focused on the use of these sorts of materials as NA replacement in

85   concrete production (Falek et al. 2017; Favaretto et al. 2017; Idagu et al. 2017; Lau et al.

86   2014; Martín-Morales et al. 2011; Tabsh and Abdelfatah 2009; Sharmal et al. 2014; Silva

87   et al. 2014; Yang et al. 2011) and concrete materials manufacturing, i.e., concrete bricks

88   (Contreras et al. 2016; Poon et al. 2002; Rodríguez et al. 2016; Sadek et al. 2013) and

89   concrete block (Laiva et al. 2013; Poon et al. 2002, 2009; Sabai et al. 2013; Soutsos et al.

90   2011a). Moreover, several studies have focused on the application of the RA in the

91   production of concrete paving but without promising results (Jankovic et al. 2012; Juan-

92   Valdés et al. 2019; Poon and Chan 2006b, 2007; Soutsos et al. 2011b, 2012). Otherwise,

93   high levels of RA recycling were achieved by some authors (Juan-Valdés et al. 2018;

94   López Gayarre et al. 2013), which occurs at the expense of significantly higher production

95   costs, because of the addition of cement was increased, and cement is by far the most

96   expensive material in concrete manufacturing. Therefore, it is necessary to minimize the

97   consumption of cement, to achieve an economically realistic application.

98   This paper is part of an ambitious project that has been divided into two parts. The first

99   part consisted in the substitution of NA by RA, which were obtained from a specific pre-

100   treatment of CDW, in the concrete manufacturing. The second part, both the pre-treatment

101   developed and the potential results obtained were validated on an industrial scale

102   In light of the above, this aim of this paper is to develop a process that allows

103   simultaneously maximizing the incorporation of AR and reducing the cement requirement

104   necessary for the manufacture of concrete paving blocks, complying with the established

105 requirements. Therefore, the physical and technological properties were determined and

106 compared with standards materials according to the current regulations.

107 2. Materials and Methods

108 **2.1 Materials preparation**

109 Representative sample of CDW was provided from a recycling plant in the region of

110 Murcia (Spain). CDW was treated to obtain RA with physical and mechanical properties

111 similar to those of NA. Hence, the RA were obtained through mechanical pre-treatment

112 (crushing, grounding, sieving, and removal of impurities) of the CDW. Firstly, the

113 samples were crushed and passed through a sieve 12 mm. Secondly, the coarse fraction

114 was ground and sieved through a 4.8 mm mesh sieve. Finally, two different grain size

115 fractions were obtained, fine recycled aggregate (FRA) with a particle size < 4.8 mm, and

116 coarse recycled aggregate (CRA) > 4.8 mm, which were used in this research. Regardless

117 of the pre-treatment performed, RA showed a water absorption index higher than NA

118 (sand and gravel) due to the presence of porous materials such as mortar, ceramic, clay,

119 etc. (Poon and Chan 2006a, b; Yang et al. 2011). According to previous studies using RA

120 obtained from CDW (Contreras et al. 2016; Ferreira et al. 2011), the pre-saturation

121 (partial saturation of the superficial pores) of RA is an adequate method because of

122 provide the RA with an extra amount of water to solve the problem of their higher

123 porosity, and thus to achieve concrete mixtures with the calculated water/cement ratio.

124 Moreover, García-González et al. (2014) showed that this technique reduces water

125 absorption during the cementation process, keeping the process water-free until the

126 cement hydration and achieving an appropriate consistency and workability.

127 On the other hand, other materials necessary for concrete manufacturing (sand, gravel,

128 cement and additive) were provided by the precast concrete company "Montalbán y

129 Rodríguez S.L.", placed in the region of Murcia (Spain). Eco-friendly mortars and paving

130 blocks were prepared using a high-activity water reducing/superplasticising additive

131 based on polycarboxylates MasterCast 731 supplied by BASF Company to improve

132 consistency.

133 Different percentage compositions (Table 1) of RA were mixed with NA (sand and

134 gravel), ordinary Portland cement (OPC) and additive. This OPC Type I is characterised

135 by a compressive strength of 32.5 N mm^{-2} and is composed of a mixture of clinker (97

136 wt.%) and natural gypsum (3 wt.%). The mixtures were moistened by spraying until a

137 w/c ratio = 0.45 was reached, which is the optimum index for obtaining adequate

138 consistency and a good workability used in the industrial process and which has been

139 provided by the precast company. The moistened materials were homogenized and placed

140 in steel moulds to obtain concrete cylindrical test specimens (ϕ = 150 mm, h $\approx$ 300 mm),

141 which were finally vibrated as described in the UNE-EN 12390-3 standard (2020).

142 Furthermore, hydrated mixtures were used in the manufacture of concrete pavements,

143 which were pressed in duplicate, utilizing a uniaxial hydraulic press at 30 tons in steel

144 moulds to obtain prismatic test specimens of 200 $\times$ 100 $\times$ 60 mm, in accordance with

145 industrial requirements (Figure 1). The samples were stored in open air with a temperature

146 of 22–30 ºC and a relative humidity of 65–75% (UNE-EN 12390-3, 2020).

147 ## 2.2 Characterization techniques

148 The particle size distribution was studied by means of a mechanical shaker using

149 Granutest model sieves (9.50 mm; 8 mm; 6.70 mm; 4.76 mm; 2.40 mm; 1.00 mm; 0.60

150 mm; 0.30 mm; 0.15 mm and 0.075 mm). The mineralogical characterisation of the CDW,

151 the recycled aggregates (fine and coarse) and the natural aggregates (sand and gravel) was

152 carried out using the XRD (X-ray diffraction) technique in a Shimadzu diffractometer

153 model XRD 6000, with Cuα radiation and operating at 1.2 kW (40 kV e 30 mA). The

154 diffractograms were registered in the interval of 5-60º 2θ, with a step size of 1º/min. The

155   main elements in the RCDs and in the natural and recycled aggregates were examined

156   using the energy dispersive X-ray fluorescence (EDXRF) technique in a Bruker S2

157   Ranger LE spectrometer fitted with a 50 W X-ray tube (50 kV, 2 mA), Pd anode, XFlash®

158   silicon drift detector with <135 eV resolution for Mn Kα and 100.000 cps, and equipped

159   with a Peltier type cooling system (liquid nitrogen is not required) and primary filter tool

160   changers with 9 positions possible. The trace elements were measured by inductively

161   coupled plasma mass spectrometry (ICP-MS) by using an HP computer model HP4500®.

162   The equipment was pre-calibrated with suitable standards.

163   The consistency (self-compacting) of fresh concrete was calculated using a V-funnel test

164   as established in the UNE-EN 12350-9 (2011) standard. In order to determine the physical

165   properties such as water absorption (WA), apparent porosity (AP) and bulk density (BD)

166   of the hardened specimens, tests were performed in accordance with the UNE-EN 12390-

167   3 (2020) standard for concrete, and the UNE-EN 1338 (2004) standard for concrete block

168   paving.

169   The test specimens and paving units were immersed in water at a temperature of (20 ± 5)

170   °C until they reached constant mass (immersed mass). Then, each specimen were dried

171   using a cloth until the surface of the concrete is dull (wet mass). Finally, the materials

172   were dried inside an oven at a temperature of (105 ± 5) °C until they reached a constant

173   mass (dry mass). WA, BD and AP were determined according to the following equations:

174 $$WA\ (\%) = \frac{(m_w - m_d)}{m_d} x100 \qquad (1)$$

175 $$AP\ (\%) = \frac{(m_w - m_d)}{(m_w - m_i)} x100 \qquad (2)$$

176 $$BD\ (kg\ m^{-3}) = \frac{m_d}{(m_w - m_i)} \qquad (3)$$

177   Where m_w is the wet mass, m_d is the dry mass and m_i is the immersed mass. Furthermore,

178   in the case of regular and rectangular pavers, the best method of determining the BD is

179   by using the m_d/mass volume ratio (volume of solid, open a close porosity), which is

180   calculated from the measured dimensions (ISO 5016, 1997).

181   For measuring specific gravity (SG) (or true density), the samples were finely ground (<

182   62 µm) in order to open the entire closed porosity. A weighted mass from this powder

183   was used to determine its true volume, and therefore its true density, by displacing a

184   distilled water inside a pycnometer (ISO 5018, 1983).

185    $$SG\ (kg\ m^{-3}) = \frac{Powder\ Dry\ Weight}{True\ Volume} \qquad (4)$$

186   The mechanical properties (compressive and tensile splitting strength) of the samples

187   were compared with the properties of standards (without CDW), determined according to

188   the requirements and test methods established in the UNE-EN 1338 (2004) standard, and

189   performed with an EMIC apparatus, model DL-2000 at 7 and 28 days of curing. The

190   mechanical test is carried out once the previous physical properties of the samples have

191   been determined. The first mechanical test to be performed was the tensile splitting

192   strength (T) test.

193    $$T = 0.637 * k * \frac{P}{S} \qquad (4)$$

194   Where T (MPa), P is the measured load at failure (N), S is the area of failure plane (mm^2)

195   and k is a correction factor (k=0.87) (UNE-EN 1338, 2004). Finally, the two parts of the

196   samples retained from the tensile splitting test were tested in compression strength (σ)

197   using the formula:

198    $$\sigma = \frac{P}{A} \qquad (4)$$

199   Where σ (MPa), P is the measured load at failure (N) and A is the resisting area (mm^2).

200 3. Results and Discussion

201 **3.1 Raw Materials Characterisation**

202 Attending to Figure 2, CDW used in this study are mainly composed by ceramic (30

203 wt.%), concrete (30 wt.%), mortar (30 wt.%) and others (10 wt.%). The morphology of

204 CDW was very irregular with a multitude of planes and angles. From the point of view

205 of its resistance to fragmentation, the coarser particles are surrounded by parts that

206 disaggregate when a force is applied to them, reducing the mechanical resistance.

207 Therefore, a separation process was carried out intended to eliminate those fragile

208 particles. As a result, the percentage of hard fractions in the sample increases: concrete

209 aggregates (65 wt.%) and ceramic (35 wt.%).

210 Figure 3 presents the results of the particle size analysis of RA. The particle size profile

211 of the FRA indicated that the sample exhibited an asymmetric granulometric distribution

212 with a broad interval of particle sizes; therefore, it can be assumed that it is a sandy

213 material (from 4 to 0.075 mm). Figure 3a shows two main populations of particle size.

214 The first population corresponds to particles with an average diameter of about 149 μm.

215 The intermediate particle size fraction is the largest in this sample, with most particles

216 having an average size of 1 mm. Mixing particles with different sizes improves particle

217 packing, decreases porosity and water absorption, and increases concrete density (Shi et

218 al. 2016; Tam et al. 2007). The particle size study of CRA is shown in Figure 3b. It

219 presented a symmetrical distribution with a wide range of particle sizes in the interval

220 4.75-9.52 mm so CRA can be considered as gravel (from 4 to 20 mm). Figure 3b denotes

221 as main populations between 6.3 and 8 mm in diameter.

222 The major elemental analysis by XRF indicated a vast array of elements in CDW

223 composition (Table 2), mainly containing Si (75.5 wt.% as SiO_2), Al (9.76 wt.% as

224   Al$_2$O$_3$), Ca (6.10 wt.% as CaO), Fe (3.18 wt.% as Fe$_2$O$_3$), Mg (1.68 wt.% of MgO) and

225   Ti (1.11 wt.% of TiO$_2$). These results are similar to those found in the treated CDW

226   fractions, whose main constituent is SiO$_2$, 73.05 and 78.38 wt.% in FRA and CRA

227   respectively. Regarding the NA, sand is mainly composed of SiO$_2$ (90.60 wt.%) in the

228   quartz form and Al$_2$O$_3$ (3.83 wt.%), according to the mineralogical study, while the gravel

229   is mainly composed of SiO$_2$ (63.25 wt.%), CaO (10.46 wt.%), Al$_2$O$_3$ (4.84 wt.%) and

230   Fe$_2$O$_3$ (2.96 wt.%). On the other hand, Portland cement type I is composed of clinker and

231   gypsum and mainly contains CaO, SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$ (around 60, 21, 5 and 3 wt.%,

232   respectively).

233   Furthermore, the loss on ignition (LOI) in CDW and RA, ranged from 4.9 to 5.7 wt.%

234   (Table 2), and it was mainly associated with the release of volatiles; the liberation of water

235   from hydrated lime and hydrated calcium silicates; the emission of carbon dioxide from

236   carbonates; and the loss of water from phyllosilicates and other minor minerals present

237   in CDW (Sharma and Goyal 2020; Zhang et al. 2017). In addition, the increased CaO is

238   associated with the occurrence of CaCO$_3$ in the RA, which also leads to increased LOI

239   values, as its thermal decomposition produces CO$_2$ emission.

240   In order to study the contaminants existing in the CDW, the trace elements (below 0.1

241   wt.%) were studied by ICP-MS (Table 3). The main trace elements identified were of the

242   same order of magnitude as an unperturbed soil (Rudnick and Gao 2003). Similar results

243   to CDW were obtained by FRA and CRA. Consequently, they do not present dangerous

244   metals for both the materials and human health.

245   According to the XRD analysis (Figure 4), the CDW showed a complex mineralogical

246   composition. This is associated with the large diversity of components contained in them,

247   which include both amorphous and crystalline phases (coarse gravel or crushed rocks,

248   sand, lime, cement, fired clay minerals, etc.) (Malhotra et al. 1979). CDW are mainly

249   composed of quartz (SiO_2), calcite ($CaCO_3$) and portlandite ($Ca(OH)_2$). In addition, the

250   diffractograms indicate the presence of minor phases such as calcium silicate hydrate or

251   C-S-H   ($3CaO \cdot 2SiO_2 \cdot 3H_2O$),   gypsum   ($CaSO_4 \cdot 2H_2O$)   and   ettringite

252   ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$). These results agree with those reported in other studies

253   (Contreras et al. 2016; Menezes et al. 2002; Saiz-Martínez et al. 2016). Furthermore, the

254   XRD of the RA obtained by the CDW treatment, revealed the same mineralogical

255   composition than CDW. However, an increase in the intensity of peaks associated with

256   quartz was observed. In the opposite way, the intensity of calcite and portlandite were

257   reduced and even the low intensity peaks (C-S-H, gypsum and ettringite) almost

258   disappeared.

259   On the other hand, the natural sand used is mainly composed of quartz (Figure 5a) and

260   some low intensity peaks, in the XRD pattern denotes the presence of calcite and to a

261   lesser extent feldspar, such as microcline ($KAlSi_3O_8$). Gravel only includes quartz as

262   crystalline phase (Figure 5b).

263   Table 4 indicates that water absorption percentage (WA) of CDW was 7.6%.

264   Furthermore, it also reveals that the WA of both FRA and CRA (4.8 and 5.0%,

265   respectively) were quite lower than CDW although higher than NA (sand and gravel),

266   which were 0.8 and 1.3% respectively. By comparing the analysis results with the WA

267   limits from UNE-EN 12620 (2009), which specifies the required properties of natural,

268   mechanically processed, recycled or mixtures of aggregates to be used in concrete, it can

269   be said that both RA, in their current state, presented WA values within the limits

270   recommended by EHE-08 (below 5.0%). The increased WA values of RA when

271   compared to NA could be attributed to their higher porosity. The real density of NA is in

272   the range of ∼2500 kg m^{-3}, whereas the RA is significantly lighter, ∼2300 kg m^{-3},

273   regardless of the type of CDW. The UNE-EN 12620 (2009) requires aggregates with SG

274   greater than 2000 kg m^{-3}. Consequently, these two fractions (FRA and CRA) met this

275   requirement (see Table 4). In light of the above, the presence of attached mortar and

276   ceramic materials in the RA caused a reduction in density and increase in WA in

277   comparison with NA.

278   ### 3.2 Environmentally-friendly Concretes Characterisation

279   Once the RA and the natural constituents were characterised, concrete containing CRA

280   and FRA (Table 1) were manufactured and analysed (Table 5) according to the

281   established requirements. The physical and technological properties were summarised in

282   Table 5.

283   Before forming the cylindrical concrete specimens, the consistency was studied by the

284   Abrams cone according to the UNE-EN 1250-9, 2011. Table 5 shows all the values

285   obtained from the slump test, these do not follow any trend either with the addition of

286   cement or with the incorporation of RA. Figure 6 allows us to conclude that the viability

287   of the various mixtures was kept within the consistency range (9.6 to 12.8 cm). These

288   values were in accordance with other researches (Bermejo et al. 2010; Carro-López et al.

289   2018; Mefteh et al. 2013).

290   Moreover, the results obtained in the different tests carried out on cured concrete (Table

291   5) show that the replacement of NA by FRA and CRA affect the final properties of the

292   concrete. In general, the addition of CDW increases water absorption (WA) and apparent

293   porosity (AP), and antagonistic, it reduces both real density (SG) and resistance

294   (compressive strength (σ) and tensile splitting strength (T)). For this reason, these

295   properties will be specifically analysed.

296 The WA of hardened concrete obtained according to UNE-EN 12390-7 (2020) increases

297 with the incorporation of the RA, being higher when the grain size of the RA is smaller

298 (Figure 7). In addition, the finer particles occupied the pores and most of the external

299 surface of the cylindrical specimens; therefore, WA was increased with the incorporation

300 of the FRA fraction. On the other hand, WA values decreased considerably with the

301 increase in the percentage of cement because the cementitious matrix increased and

302 therefore, the volume of pores present in the specimens was reduced. The WA values

303 range from 4.05% in the control specimen (0-0-7) to values slightly higher than 6.5%

304 (100-0-7 and 100-100-7). Although these values decreased with the increase of cement in

305 the mixture, even with the highest concentration of RA, reaching values close to 6% (100-

306 100-30).

307 The AP results shown in Table 5 indicate that the values ranged from 8.5 to 11.3%. The

308 AP decreased as the percentage of RA increased, especially with the incorporation of

309 FRA. This physical property is crucial, since it is related to the water absorption of the

310 cylindrical specimens (Bermejo et al. 2010; Gómez-Soberón 2002; Kumar and

311 Bhattacharjee 2003; Moon and Moon 2002). Therefore, this property follows the same

312 trend that water absorption (Figure 6), because both properties are directly related.

313 Similar to the properties previously studied, the real density (SG) increased in the

314 specimens with the highest cement content (Table 5), because their density is higher than

315 that of RA and likewise because the cement occupied the open pores. On the other hand,

316 density decreased with the incorporation of FRA and even more in the case of the CRA.

317 This can be observed by comparing the result of the control specimen (0-0-7) of 2.39 g

318 cm^{-3}, with those with the highest concentration of FRA (100-0-7) of 2.17 g cm^{-3}, and

319 finally with those contain 100 wt.% CRA (0-100-7) of 2.14 g cm^{-3}.

320 The most relevant technological properties for assessing the performance of a concrete

321 structure are compressive strength (σ) and tensile strength (T), as they are closely related

322 to its potential to support stresses over time without failure. Therefore, both strengths

323 allow a general assessment of the quality of the new concrete. Table 5 presents the

324 evolution of compressive strength at 28 days (UNE-EN 12390-4 2020) as a function of

325 the proportion of RA introduced into the concrete composition. It can be observed that

326 regardless of the type and granulometry of the recycled aggregate, the resistance

327 decreased in the samples with RA replacement by over 25 wt.% (Figure 8).

328 According to the results of σ, samples containing up to 25 wt.% of RA showed similar

329 values to those of the control specimen (ranging from 20.0 to 20.9 MPa) although the best

330 results were achieved by the specimens incorporating up to 25 wt.% FRA (Falek et al.

331 2017; Idagu et al. 2017; Tabsh and Abdelfatah 2009; Sharmal et al. 2014; Silva et al.

332 2014). In contrast, lower strength values were obtained for replacements greater than 25

333 wt.%, achieving a 15% reduction in the compressive strength of the materials prepared

334 by complete replacement of NA by RA. The heterogeneous composition of the RA and

335 the increase in total water/cement ratio due to the saturation of the RA necessary for their

336 incorporation into the concrete were responsible for these reductions in compressive

337 strength.

338 On the other hand, the specimens with a higher proportion of cement achieved the best

339 resistance results. This statement can be validated by observing how the compressive

340 strength values increase with increasing cement in the mixture: 17.2 MPa (100-100-7),

341 19.6 MPa (100-100-10), 21.5 MPa (100-100-20) and 26.3 MPa (100-100-30), Table 5.

342   Observation of the concrete specimens after the compressive strength test leads to the

343   inference that the load distribution during the test (Figure 9a) was homogeneous, as the

344   specimens exhibited a characteristic prismatic fracture.

345   Moreover, the characteristic tensile splitting strength at 28 days for concrete made with

346   RA (CRA and FRA) is shown in Table 5. The concrete specimens show values in the

347   range 2.55-2.08 MPa, while the reference material reached an average value of 2.58 MPa.

348   Therefore, a decrease of approximately 0-20% in the tensile splitting strength of concrete

349   elements with the incorporation of RA was observed (Figure 10). However, concrete

350   specimens processed by replacing 25 wt.% of NA with FRA show comparable strength

351   values (less than 5% variance) to those of concrete produced with NA. The presence of

352   bonded mortar, ceramic materials, etc., in the RA may have been responsible for the

353   observed loss in tensile splitting strength. Furthermore, as in the previous case, it should

354   be noted that the increase in the cement concentration in the mixture increased the T of

355   the specimens, as it is expected.

356   The cylindrical specimens after the tensile splitting strength test showed almost perfect

357   longitudinal fracture, which is characteristic of samples subjected to an uniform

358   longitudinal load distribution during the test (Figure 9b).

359   ## 3.3. Paving Blocks Characterization

360   After studying the influence of the incorporation of the RA in the production of

361   environmentally-friendly concrete, the possibility of replacing NA with RA in the

362   manufacture of constructive elements by using precast concrete elements such as paving

363   block was evaluated (Figure 1), whose physical and technological properties (after 28

364   days of curing) are shown in Table 6.

365 UNE-EN 1338 (2004) establishes two types of paving blocks, depending of the value of

366 WA: WA < 6%, called class 2 and mark B, where the paving is frost resistant (this is the

367 most demanding requirement) and the second if WA > 6%, called class 1 mark A. In this

368 sense, paving blocks containing up to 75 wt.% of RA can be considered as class 2, mark

369 B.

370 Table 6 summarises the results of tensile strength determined for concrete paver blocks

371 prepared with RA. Concrete pavers with up to 25 wt.% of RA (coarse and fine) showed

372 an average tensile strength of 3.9 MPa, the same value as that obtained for the reference

373 material (0-0-7) (De Brito et al. 2005; Mas et al. 2012; Özalp et al. 2016; Poon and Chan

374 2007), exceeding the average resistance of 3.6 MPa established in the EN-1338 standard

375 (2004), and the obtained results are not less than 2.9 MPa for any individual sample.

376 Moreover, paving units containing 50 wt.% FRA or CRA were shown not to have a

377 significant effect on the strength. On the other hand, paver blocks prepared with FRA

378 above 75 wt.% replacement did not exceed the tensile splitting strength threshold of 3.6

379 MPa. However, this research concludes that concrete specimens formulated with FRA as

380 a substitute for NA (up to 50 wt.%) or by a mixture of FRA and CRA (50 wt.% and 25

381 wt.%, respectively) comply the mechanical specifications for paver blocks. These results

382 allow us to conclude the viability of replacing NA with RA in the manufacture of concrete

383 paving blocks.

384 ### 3.4. Environmental implications

385 Throughout its service life, concrete has an environmental impact resulting from different

386 factors such as: the production of the raw materials, its manufacture, its use and

387 maintenance throughout its service life and, finally, its demolition. In this assessment, we

388 will focus on the impact associated with the production of raw materials, specifically

389 aggregates, assuming that the other variables are not significantly influenced by the use

390   of natural or recycled aggregates. According to Pimiento and Restrepo (2018), 0.008 tons

391   of CO_2 are emitted in the production of one ton of gravel or sand produced by open-cast

392   mining, while this emission is reduced to 0.001 tons of CO_2 emitted in the production of

393   one ton of aggregates from CDW.

394   According to the dosage used in this study, in the manufacture of precast concrete

395   elements (37.17 wt.% gravel, 55.78 wt.% sand, 6.97 wt.% cement) the CO_2 emission

396   associated with the extraction of the aggregates necessary to manufacture 1 ton of precast

397   concrete can be estimated as 7.44 kg. Considering the substitution of up to 50% of natural

398   aggregate by recycled aggregate, in the manufacture of 1 ton of precast concrete elements

399   with the incorporation of CDW, 4.18 kg of CO_2 will be emitted, which means a reduction

400   of 43.75% in the amount of CO_2 released into the atmosphere.

401   But in addition to the advantages derived from lower CO_2 emissions, other environmental

402   benefits associated with the replacement of natural aggregates with recycled aggregates

403   must be taken into account, such as: reduction of the volume of extraction of limited raw

404   materials, thus preserving natural resources; reduction of mining waste generated in the

405   extraction of reduction of landfill requirements for mining waste resulting from the

406   extraction of mining waste; and reduction of landfill requirements for mining waste.

407   Therefore, the precast concrete in this study can be considered as environmentally-

408   friendly. However, it is clear that, in order to ensure that the manufacture of concrete

409   incorporating recycled aggregates is assumed by the industry, it is necessary to ensure

410   competitive manufacturing costs. In this sense, the production cost of recycled aggregates

411   is 15% lower than that of gravel extraction and 27% lower than that of sand extraction.

412   Therefore, its implementation at industrial level is also viable from an economic point of

413   view.

4. CONCLUSIONS

The variability in the composition, the lower density and the higher water absorption make that a priori, CDW tends to be less resistant, more deformable, porous and permeable than NA. Moreover, in terms of the physical and mechanical properties studied, the addition of FRA and CRA increases the water absorption (WA) and the apparent porosity (AP) of concrete, reducing both its density and resistance. Additions of up to 50 wt.% of fine (50-0-7) or coarse (0-50-7) recycled aggregates or the substitution of 25 wt.% of each (sample 25-25-7), results in materials with similar properties to the reference materials. The WA around 4-6% and AP of 8.5% for both 0-0-7 (reference materials) and 25-25-7 samples. Similar WA and AP of 9.6% for samples using 50 wt.% of recycled aggregate with 7 wt.% of cement (50-0-7 and 0-50-7). Moreover, this values increase when the concentration of cement increases to 10 wt.%, showing values of 9.4% for the reference materials (0-0-10) and values below 11.3% for all analysed samples. The specific gravity decreased with the incorporation of FRA and CRA, slightly reducing the value of 2.39 g cm^{-3} for (0-0-7) until 2.17 and 2.14 g cm^{-3} for (100-0-7) and (0-100-7) samples, respectively. Additionally, the compressive strength (σ) and tensile splitting strength (T) of concrete were evaluated. The compressive strength for reference materials was 20.5 MPa, while samples containing up to 25 wt.% of RA (25-0-7, 0-25-7 and 25-25-7) showed similar values to those of the control specimen (ranged from 20.0 to 20.9 MPa), decreasing to 19 MPa when the percentage of substitution was up to 50 wt.% of RA. In relation to the tensile strength, the concrete samples showed values in the range 2.55-2.08 MPa, while the reference material reached an average value of 2.58 MPa for samples with 7 wt.% of cement. These values are slightly higher when the percentage of cement reaches 10 wt.%, with values of 2.95 MPa for reference material. In this sense, replacements of around 25 wt.% of RA were carried out similarly to the NA, and the

439 results were within the suitable range established by the EHE-08 for concrete

440 manufacture.

441 Finally, the technological properties of paving blocks manufactured with concrete with

442 50 wt.% of RA replacement, have a mechanical behaviour similar to that of the reference

443 material, with water absorption below 6% (class 2 and mark B) and tensile strength values

444 above 3.6 MPa, the minimum resistance established in the EN-1338 standard.

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663 Ethical Approval:
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665 Consent to Participate:
666 All the authors consent to participate in this research paper
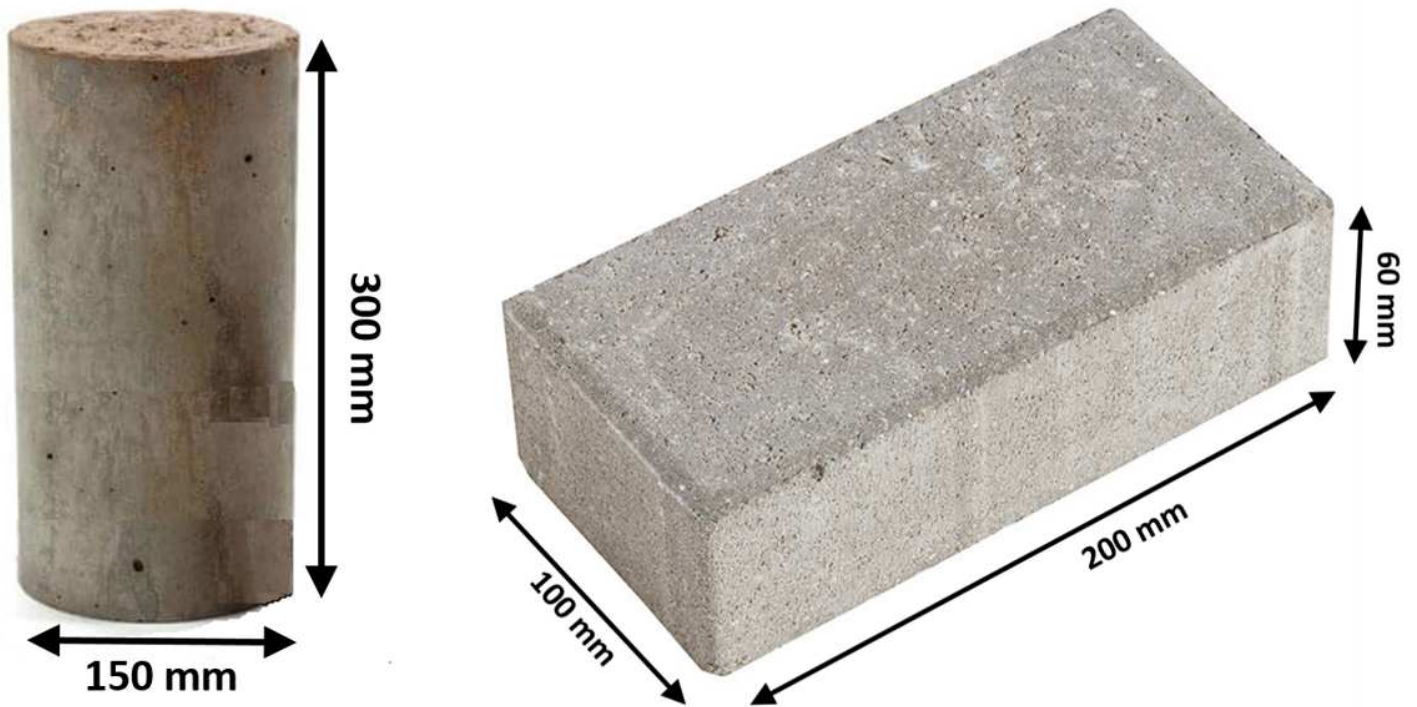
Figure captions:

Figure 1. General appearance and dimensions of the cylindrical test specimens (left) and
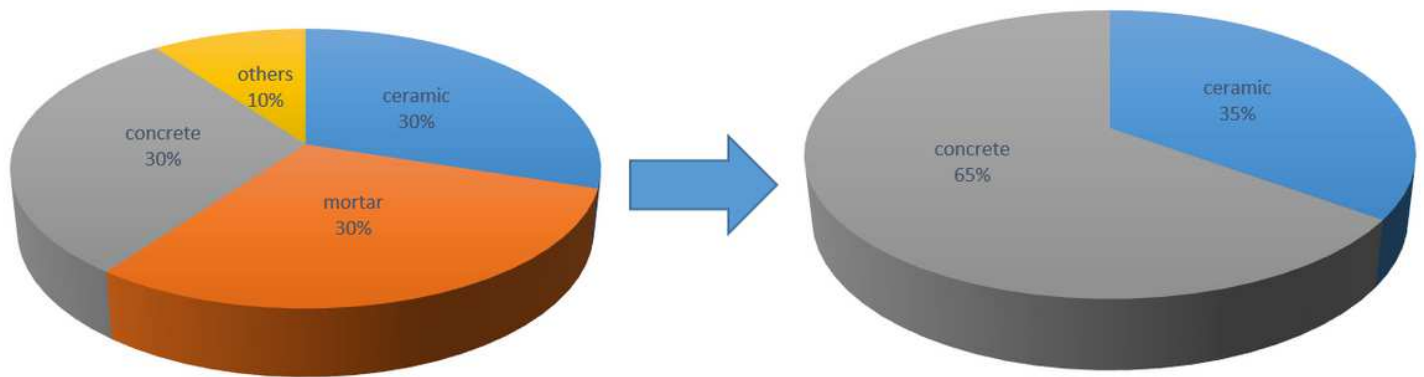
the paving blocks (right).

Figure 2. Material composition of CDW before (left) and after (right) the mechanical
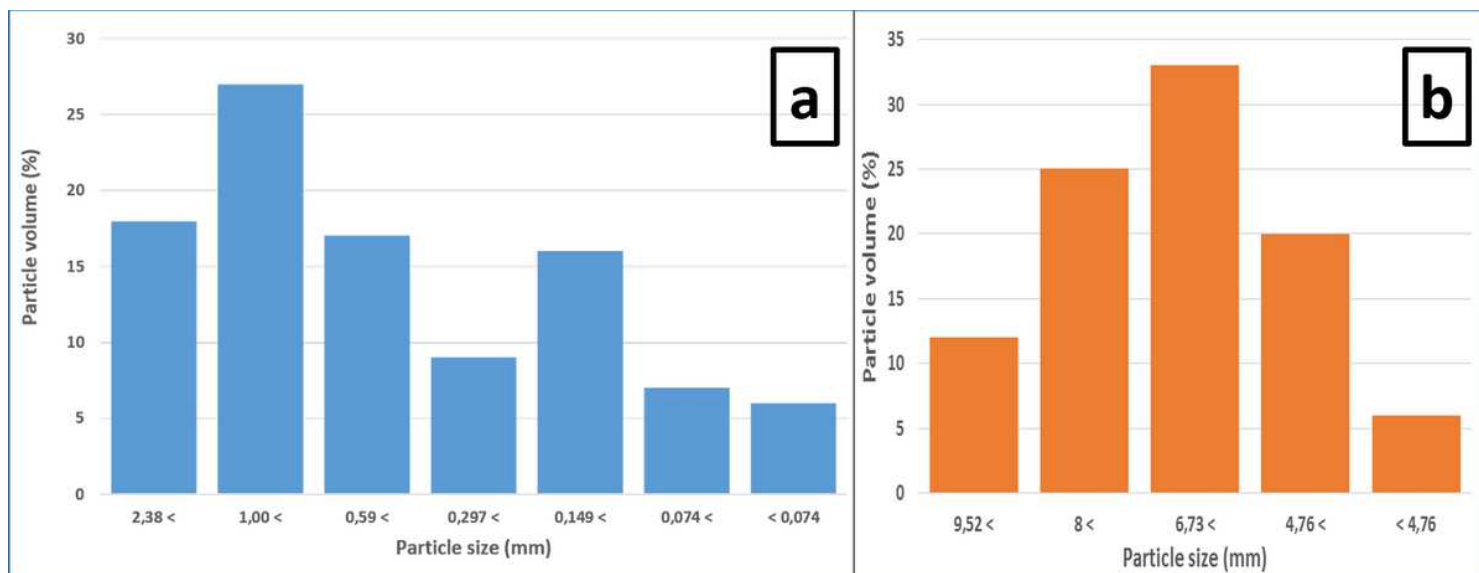
treatment.

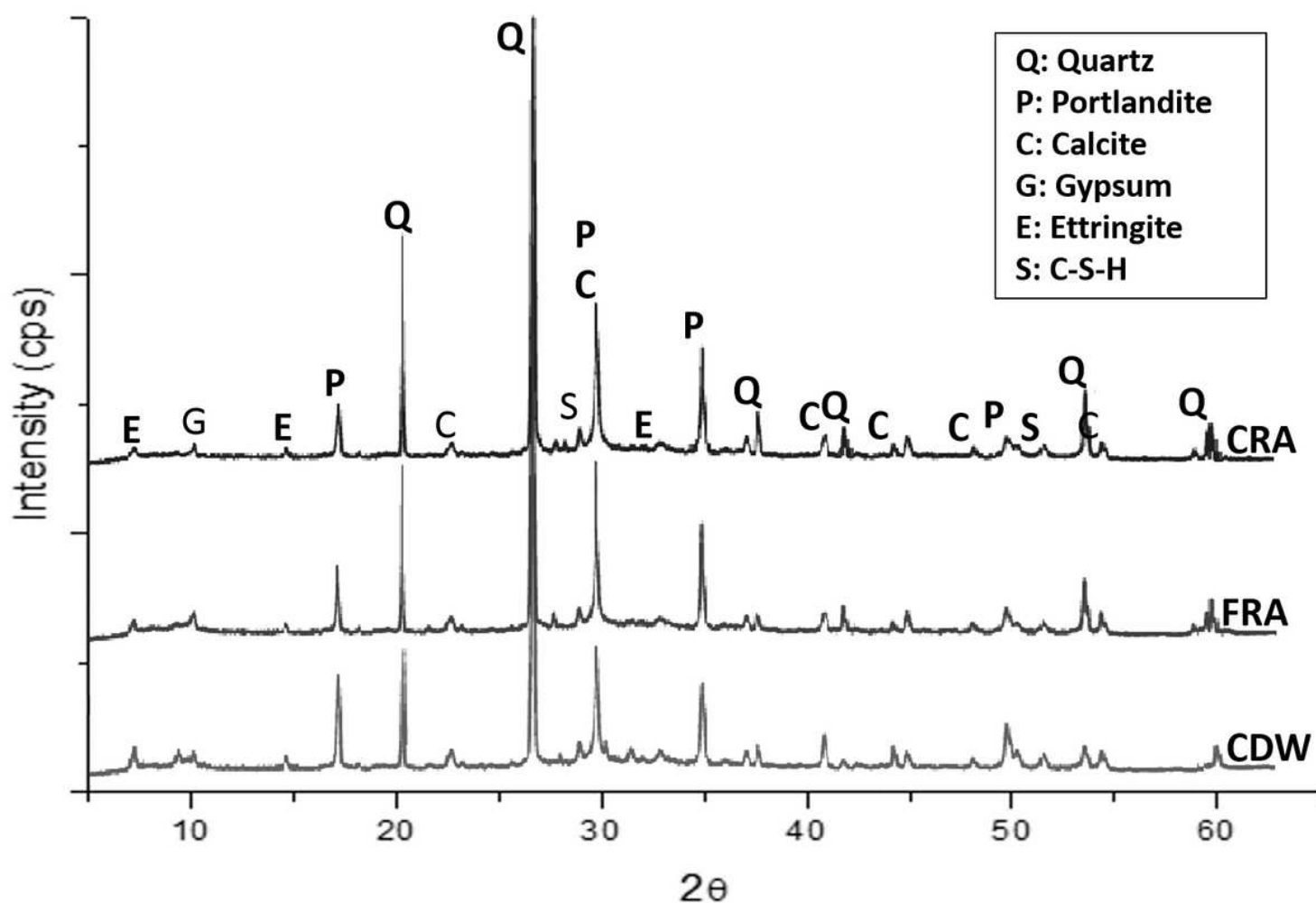Figure 3. Particle size distribution of FRA (a) and CRA (b).
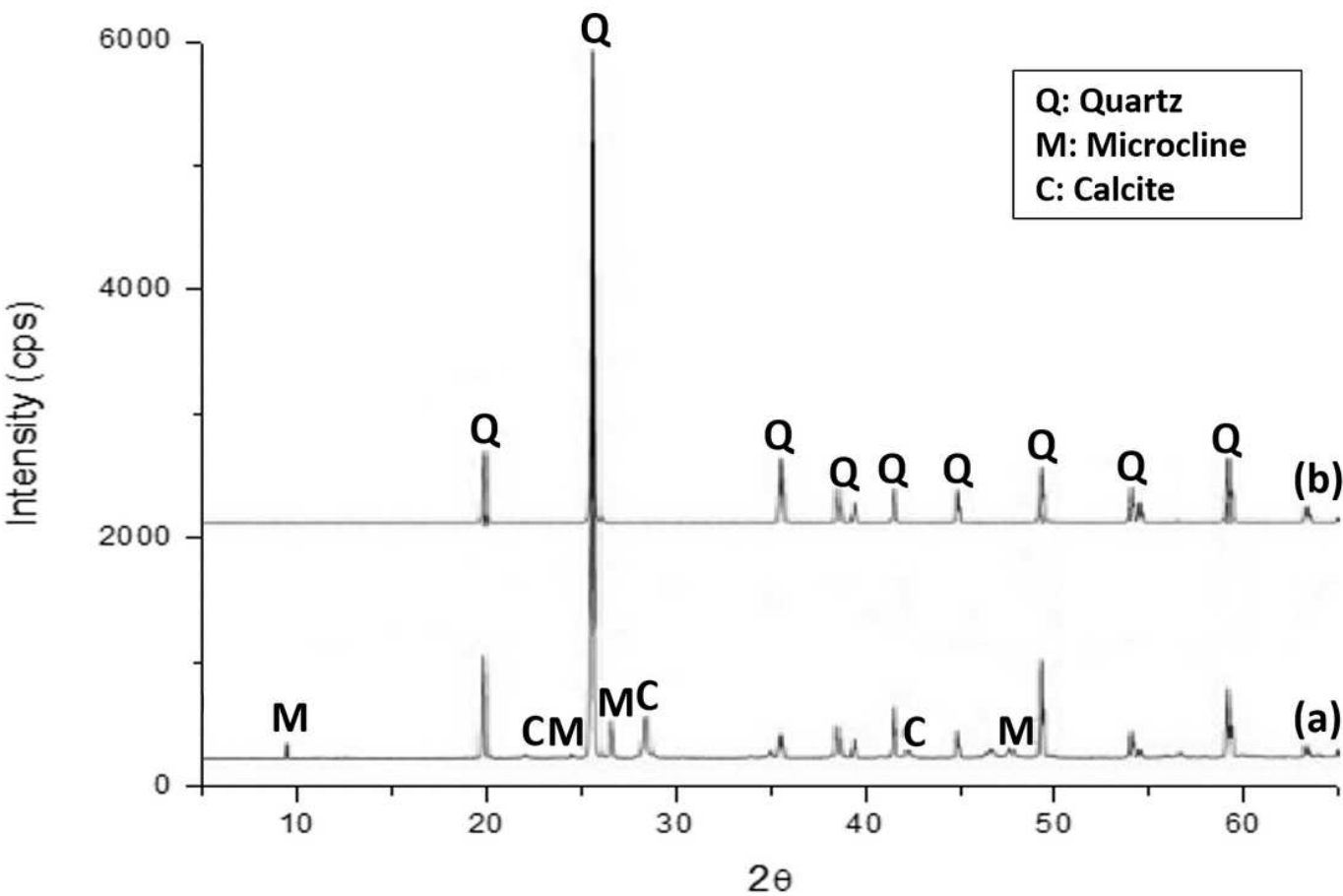
Figure 4. XRD pattern of CDW, FRA and CRA.

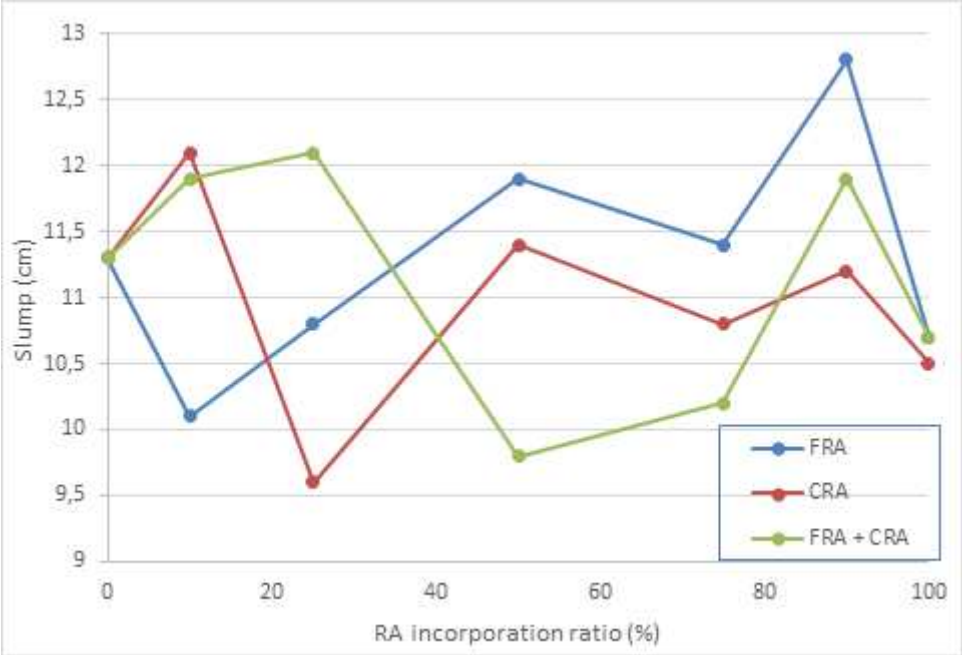Figure 5. XRD of natural sand (a) and gravel (b).

Figure 6.Test for workability of the fresh eco-friendly concrete.

Figure 7. Graphical representation of water absorption vs. RA incorporation ratio.

Figure 8. Graphical representation of compression strength vs. RA incorporation ratio.

Figure 9. Exhibiting prismatic fractures of the specimens after compression (a) and tensile

splitting (b) strengths test.

Figure 10. Graphical representation of tensile splitting strength vs. RA incorporation

ratio.

Figures

Figure 1

General appearance and dimensions of the cylindrical test specimens (left) and the paving blocks (right).

Figure 2

Material composition of CDW before (left) and after (right) the mechanical treatment.

Figure 3

Particle size distribution of FRA (a) and CRA (b).

Figure 4

XRD pattern of CDW, FRA and CRA.

Figure 5

XRD of natural sand (a) and gravel (b).

Figure 6
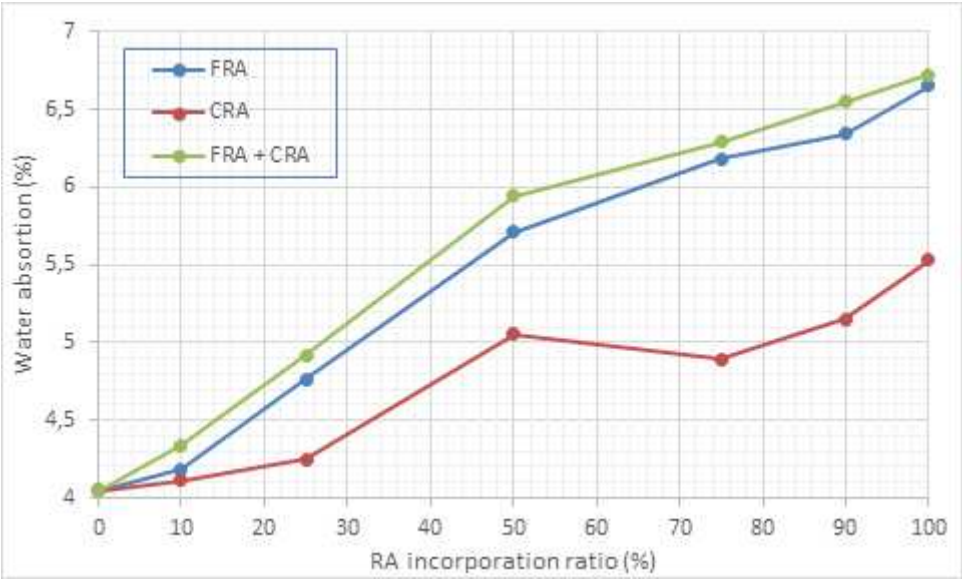
Test for workability of the fresh eco-friendly concrete.

Figure 7

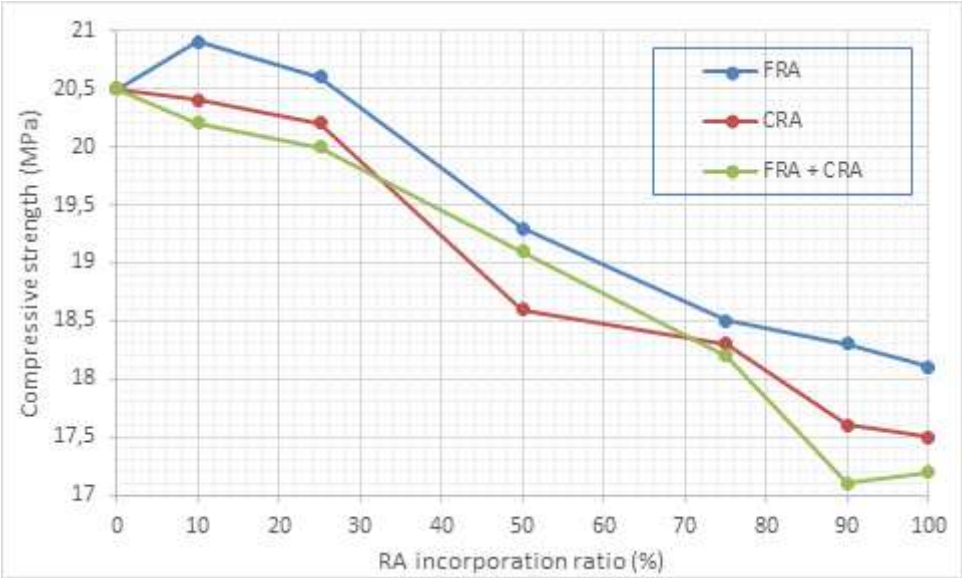Graphical representation of water absorption vs. RA incorporation ratio.

Figure 8

Graphical representation of compression strength vs. RA incorporation ratio.

Figure 9

Exhibiting prismatic fractures of the specimens after compression (a) and tensile splitting (b) strengths test.
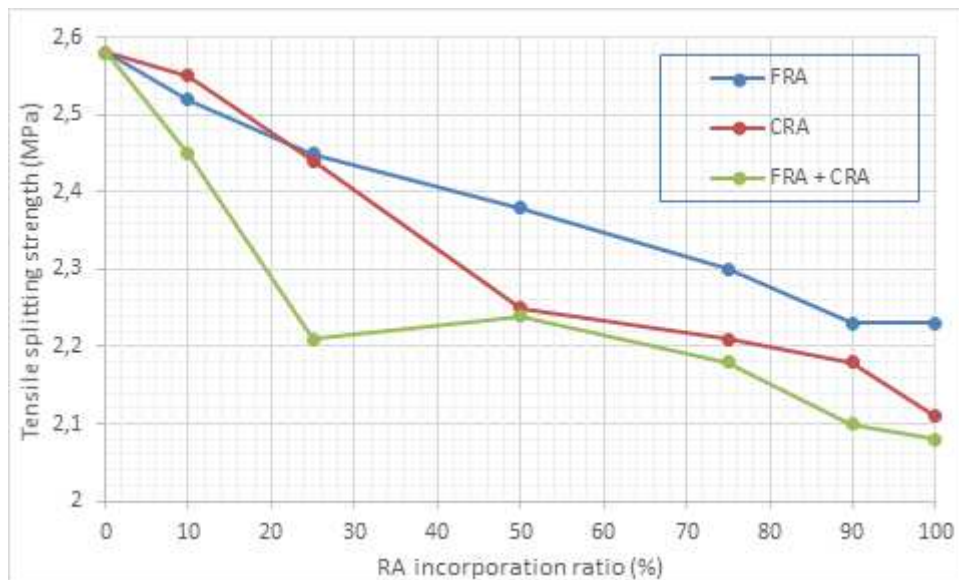
Figure 10

Graphical representation of tensile splitting strength vs. RA incorporation ratio.