Rammed Earth incorporating Recycled Concrete Aggregate: a sustainable, resistant and breathable construction solution

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ABSTRACT

Construction and demolition debris, mainly concrete and masonry rubble, represent a significant share of municipal waste. Recycling crushed concrete aggregates and using them as substitutes for natural ones might therefore be determinant in reducing landfilling and mineral resource depletion. An innovative way to give new value to Recycled Concrete Aggregates (RCAs) is to ram them in layers to form load-bearing walls for stabilised Rammed Earth (RE) applications. However, the success of those few existing RE projects using RCA is mainly due to the knowledge and experience of the contractors rather than official standards or guidelines or scientific literature. The objective of this study was to further the knowledge of this building technique by determining the effect of different RCA replacements on the material's mechanical resistance, sustainability and hygroscopic properties: indicative of the structure's structural, environmental and hygrothermal performance. Mechanical resistance was assessed by means of the Unconfined Compressive Strength (UCS, commonly used for rammed earth-like materials), hygroscopic properties via Moisture Buffer Value (MBV) and sorption isotherms while the sustainability was assessed via consequential Life Cycle Assessment (LCA). Microstructural investigations via mercury intrusion porosimetry, nitrogen adsorption-desorption isotherms, scanning electron microscopy and X-ray diffraction were performed to understand and explain material mechanical and hygroscopic behaviour. The building technique, already proven to be durable, was demonstrated to be resistant (from 4 to 12 MPa at 28 days depending on the RCA replacement and cement content), sustainable (down to 25 kg CO_2-eq. of embodied carbon per square meter of load-bearing wall) and to have good moisture buffering abilities (0.88 g/(m2 %RH) for mixtures containing only RCA). Strength appeared to be more related to the particle size distribution of the mix rather than to the percentage of RCA added. The amount and type of stabiliser added to the mix and the distance covered by the RCA during its lifetime strongly affected the environmental sustainability of the mixture; to maximise the potential of this building technique, reducing the amount of cement in the mixture by using alternative stabilisers should be the main priority.

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47 ABBREVIATIONS

48	BET	Brunauer, Emmett and Teller
49	BJH	Barrett, Joyner and Halenda
50	CDW	Construction and Demolition Waste
51	CEM	Cement
52	CL	Crushed Limestone
53	ES	Engineered Soil
54	FA	Fly Ash
55	GHG	Greenhouse Gas
56	LCA	Life Cycle Assessment
57	LL	Liquid Limit
58	MBV	Moisture Buffer Value
59	MDD	Maximum Dry Density
60	MIP	Mercury Intrusion Porosimetry
61	OWC	Optimum Water Content
62	PL	Plastic Limit
63	PSD	Particle Size Distribution
64	RCA	Recycled Concrete Aggregate
65	RE	Rammed Earth

66	RH	Relative Humidity
67	RRCA	Rammed Recycled Concrete Aggregate
68	SRE	Stabilised Rammed Earth
69	UCS	Unconfined Compressive Strength
70	XRD	X-Ray Diffraction

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1. INTRODUCTION

Maximising reuse and recycling of waste materials is one of the main paradigms of a circular economy. To boost the transition towards more sustainable economic growth, different governments are adopting strategies to reduce the amount of waste landfilled and to increase recycling rates. The European Commission, for instance, adopted a Circular Economy Package, which includes legislative proposals such as targets for recycling 65% of municipal waste and to reduce its landfilling to a maximum of 10% by 2030 (European Commission, 2015): as it currently stands, only 35% of the non-compostable fraction of municipal waste is recycled and almost 30% is still committed to landfill (Eurostat, 2018).

A significant share of municipal waste is occupied by construction and demolition debris (approximately 35% in Europe (Eurostat, 2014)), which in turn mainly comprise concrete and masonry rubble. In Europe, it is estimated that roughly 1,350 Mt of concrete is produced annually (approximately 2.7 tonnes per inhabitant) and about 350 Mt of concrete debris are generated (European Commission and BIO Intelligence Service, 2011). Global figures are even more astonishing: worldwide concrete production was estimated to be 10 billion m^3 in 2012 (i.e. approximately 1.4 m^3 per person), with Asia and particularly China being the primary consumers (Miller et al., 2016). Data concerning global concrete waste generation and recycling is harder to obtain. Several developed countries already reuse or recycle most of the waste

88   originating from demolished structures: in the Netherlands, for example, more than 95% of the

89   Construction and Demolition Waste (CDW), mainly composed of concrete aggregates, is recycled (BIO

90   Intelligence Service, 2015). However, the same cannot be said for many other countries in Europe, where

91   only between 30% (Johnson, 2014) and 60% (European Commission and BIO Intelligence Service, 2011) of

92   concrete is in fact estimated to be recycled. Figures for CDW recycling have a wide geographical variation

93   in the rest of the world too: in Taiwan, for instance, the recovery rate is higher than 90% (Cement

94   Sustainability Initiative, 2009), while in Australia more than 30% is still disposed of by landfill (Randell et

95   al., 2014) and in China only about 5% of total CDW is reused or recycled (Duan and Li, 2016).

96   Concrete can be either re-used in its original form or, most commonly, it can be reprocessed into coarse

97   or fine aggregates. Once sorted and processed, coarse Recycled Concrete Aggregates (RCAs) can be used

98   for road works as base or sub-base (Paranavithana and Mohajerani, 2006), reintroduced into the

99   manufacturing of concrete as a substitute for natural aggregates (Fraile-Garcia et al., 2017) or used as

100 backfilling material in quarries, foundations, etc. (Vieira and Pereira, 2015). Incorporating RCAs in new

101 concrete structures may reduce the latter's enormous environmental impact (Hossain et al., 2016); more

102 than 4% of total greenhouse gas (GHG) emissions over the past decade were in fact related to concrete

103 manufacturing (IPCC, 2014). Although using RCA may not make significant CO_2 emission savings,

104 substituting natural aggregates with recycled ones might be determinant in terms of curbing waste

105 production and natural mineral resource depletion (Kleijer et al., 2017). Moreover, recovering the

106 demolished concrete leads to considerable cost advantages to the contractor by eliminating charges for

107 waste disposal (Mah et al., 2018). The environmental and cost benefits of employing RCAs might be

108 particularly true for cases where the supply of gravel is constrained (Ioannidou et al., 2017).

109 An innovative way to reuse demolished concrete is to ram it into layers to form load-bearing walls for

110 stabilised rammed earth (SRE) applications (Hall and Swaney, 2005). Rammed earth is an ancient

111 construction procedure where walls are built by compacting an earthen mixture between formwork. SRE

112 is a modern form of rammed earth that involves the addition of a (usually cementitious) binder to the

113 earth mix to improve the material's mechanical resistance (Walker et al., 2005). Right now, the most used

114 stabiliser is cement but alternative, more environmentally friendly binders such as by-products (e.g. fly

115 ash (da Rocha et al., 2014), calcium carbide residue (Arrigoni et al., 2017c)) or natural polymers (e.g.

116 (Achenza and Fenu, 2006; Eires, 2012)) are being explored. RCA can partially or entirely substitute the

117 sub-soil typically used for earthen construction. However, the success of those RE projects that have used

118 RCA is due to the knowledge and experience of the contractors involved in the projects (for example the

119 design of the deep elevated beam shown in Figure 1), rather than the presence of any official or rigorous

120 standards or guidelines on this topic. In contrast to concrete, where the use of RCA has been extensively

121 investigated (Behera et al., 2014), the research currently available in literature on the use of RCA for SRE

122 applications is almost non-existent. The first attempt to populate the scientific database with information

123 was done by Taghiloha, who explored the effect on the mechanical properties of SRE caused by a partial

124 replacement of the larger particles (i.e. gravel and sand) with RCA (Taghiloha, 2013). SRE mixes

125 incorporating RCA proved to have an acceptable (but lower) compressive strength than the counterpart

126 with natural aggregates. Advancing on the same topic, Jayasinghe et al. tested the compressive and

127 flexural strength of SRE incorporating building demolition waste in order to find an optimum proportion.

128 Results indicated a mix proportion of 1:5:5 of cement:soil:demolition waste (by mass or volume was not

129 specified) as the best combination to form a new building material with satisfactory load bearing

130 properties (Jayasinghe et al., 2016).

131 Building on these works, the mechanical behaviour of SRE samples with different RCA replacement

132 percentages was investigated here with the goal of understanding whether a diffusion of this innovative

133 technique might be desirable. Additionally, durability and environmental sustainability results, which

134 were first examined in a previous study (Arrigoni et al., 2017a), were integrated with new information

135   covering the hygroscopic and microstructural properties of the material to create a full characterization

136   of the construction technique.

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Figure 1. Example of a Rammed Earth house manufactured exclusively from RCA (with cement and oxides added for strength

and colour respectively) in Perth, Australia (credit: Hera Engineering (Hera Engineering Pty Ltd.))

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2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Recycled Concrete Aggregate

RCA was obtained from demolished structures in the metropolitan area of Perth, Western Australia. Aggregate sizes were predominantly between 0.6 and 19mm (i.e. sand and gravel grains). Specimens tested either comprised solely RCA and stabiliser or a mixture of RCA, "artificial" soil (described in the following sections) and stabilisers. The entire grading was used when RCA was the only constituent; when RCA was paired with soil, RCA size fraction smaller than 6 mm and greater than 19 mm were discarded for a better control of the final granulometry. X-Ray Diffraction (XRD) analyses on RCA samples (Figure 2) revealed the presence of Quartz (SiO_2), Calcite ($CaCO_3$), Anorthite ($CaAl_2Si_2O_8$), and traces of Larnite (C_2S, Ca_2SiO_4) phase. The latter indicates the presence of residual un-hydrated cement in the RCA, while the presence of Anorthite could be attributed to the presence of bricks or other ceramic contaminants (Ahmad and Iqbal, 2016).
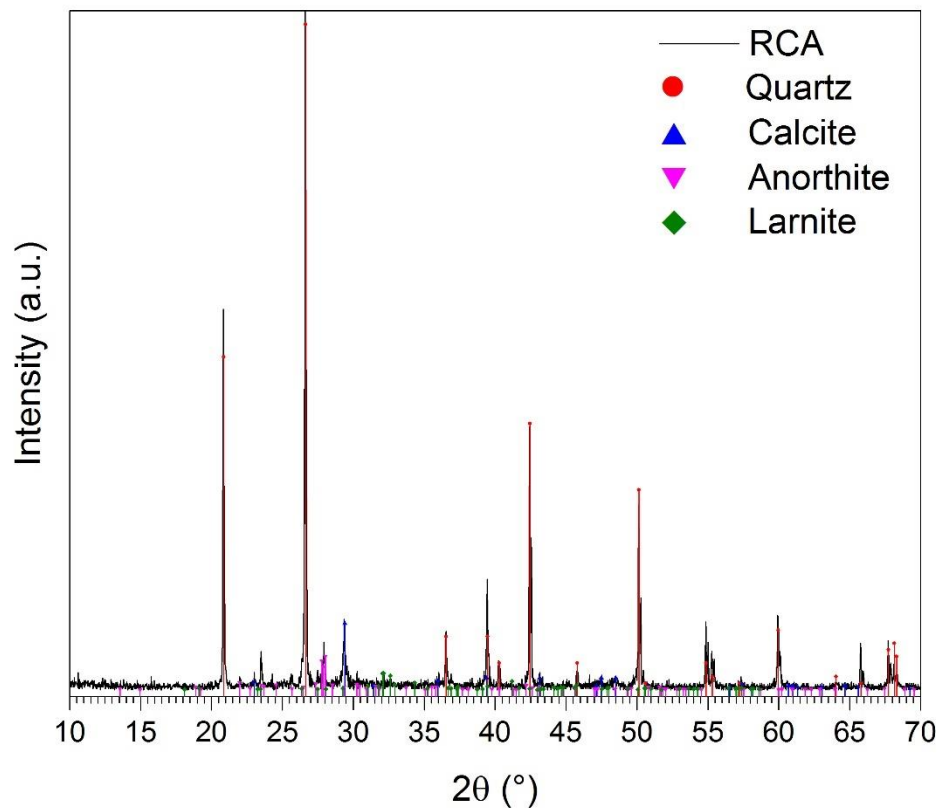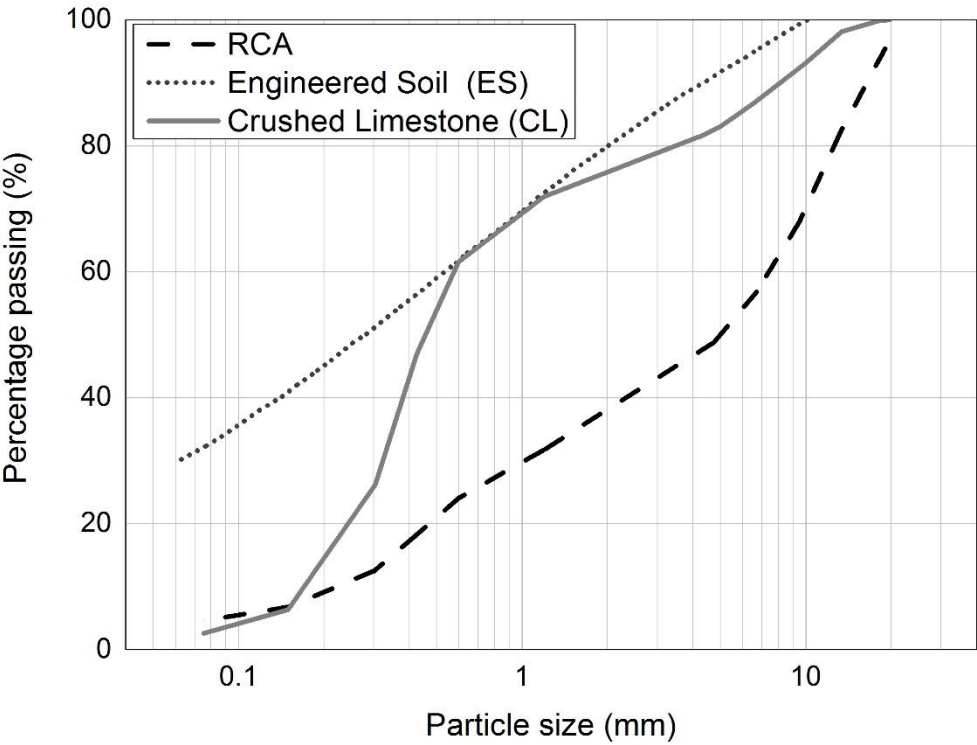
Figure 2. X-Ray Diffraction pattern of recycled concrete aggregates.

2.1.2. Mixtures

159 The primary constituent of traditional RE is inorganic sub-soil taken from deposits found beneath organic

160 topsoil. As soil characteristics are site specific and highly variable, for this study it was decided to create

161 artificial earth mixes to allow for repeatable results. To determine the effect of RCA substitution on RE

162 compressive strength two testing groups, each comprising one artificial soil and varying amounts of RCA,

163 were established, as shown in Table 1. Each group consisted of a benchmark mix (0% RCA replacement)

164 and 3 mixes with respectively 25, 50 and 75% by mass of RCA substitution. Furthermore, batches made

165 only of RCA were tested. A summary of all the mixtures prepared is also presented in Table 1. The first

166 benchmark was a Crushed Limestone (CL) typically used in Western Australia in RE projects, owing to its

167   ready availability. The second benchmark mix was an "engineered" soil created using Kaolin clay (10%,

168   PL=27%, LL=61% (Cocjin et al., 2014)), silica flour (to simulate silt particles, 20%), clean sand (50%) and 10-

169   mm blue aggregate (20%) and will be referred to as Engineered Soil (ES). The Particle Size Distribution

170   (PSD) curves of the benchmark mixes are reported in Figure 3. Portland cement (CEM, 7% by dry mass)

171   was added to all materials to improve the mechanical resistance of the mixtures. For the batches

172   comprising only RCA, additional mixtures comprising a different amount of cement (i.e. 10%) or by partial

173   replacement of cement with fly ash (i.e. 5% cement + 5% fly ash) were also investigated. Fly Ash (FA) is

174   the residue from coal power plants and its addition to the mixture was here considered due to its good

175   performance as cement replacement and its environmental friendliness (Xu and Shi, 2018). FA used in this

176   study was classified as class F according to its calcium content (ASTM, 2015). The chemical analysis showed

177   that the material comprised 58.7% SiO_2, 27.4% Al_2O_3, 8.1% Fe_2O_3, 1.6% TiO_2 and 0.9% CaO. Mixture labels

178   in Table 1 list that mix's constituent parts: for example, "100RCA + 5CEM 5FA" indicates a 100% RCA

179   substrate with an additional 5% Portland cement and 5% fly ash by mass.

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Figure 3. Particle size distribution of RCA, Engineered Soil (ES) and Crushed Limestone (CL)

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184   *Table 1. Overview on the different mixtures analysed. wt. % indicates the weight percentage of dry substrate.*

GROUP	MIXTURE	SUBSTRATE			ADDITIVES		Optimum Water Content (OWC)	Maximum Dry Density (MDD)	Coefficient of uniformity	Coefficient of curvature
		RCA (Sieved (S)/Non-Sieved (NS))	Engineered Soil (ES)	Crushed Limestone (CL)	Cement (CEM)	Fly Ash (FA)				
		[wt. %]	[wt. %]	[wt. %]	[wt. %]	[wt. %]	[%]	[g/cm^3]		
1	100CL + 7CEM	-	-	100	7	-	8.2	1.97	3.4	1.1
	75CL + 7CEM	25 (S)	-	75	7	-	11.7	1.93	17	0.2
	50CL + 7CEM	50 (S)	-	50	7	-	12.4	1.93	30	0.2
	25CL + 7CEM	75 (S)	-	25	7	-	14.7	1.79	22	9.9
2	100ES + 7CEM	-	100	-	7	-	6.8	2.21	9.0	0.1
	75ES + 7CEM	25 (S)	75	-	7	-	9.6	2.06	29	0.1
	50ES + 7CEM	50 (S)	50	-	7	-	10.3	2.00	89	0.6
	25ES + 7CEM	75 (S)	25	-	7	-	11.9	1.89	62	28
3	100RCA + 7CEM	100 (S)	-	-	7	-	16.0	1.79	1.4	0.8
	100RCA + 10CEM	100 (NS)	-	-	10	-	12.7	1.98	34	0.6
	100RCA + 5CEM 5FA	100 (NS)	-	-	5	5	12.7	1.99	34	0.6

185

2.2. Methods

2.2.1. Mechanical resistance

Mechanical performance of concrete (Verian et al., 2018) and mortars (Raeis Samiei et al., 2015) containing RCAs is highly dependent on the quality of the aggregates; nevertheless, strength generally decreases with increasing RCA content (Fraj and Idir, 2017). The suitability and durability of rammed earth materials are qualified via their unconfined compressive strengths (UCSs). The effect of RCA replacement on UCS was therefore examined in this work to contrast results to those available in the literature for traditional cement-stabilised RE materials. Cylinders of 100-mm diameter and 200-mm height comprising five layers of equal mass and volume were manufactured following techniques described in previous works (Beckett and Ciancio, 2014). Specimens were manufactured at their Maximum Dry Density (MDD) obtained via the modified Proctor Test (Standards Australia, 2003). The MDDs and the Optimum Water Contents (OWCs) resulting from the modified Proctor test are reported in Table 1. Once manufactured, cylinders were placed in a curing room for 28 days at constant humidity (RH: $96 \pm 2\%$) and temperature ($21 \pm 1 \,^\circ$C). After curing, the cylinder UCS was tested using a soft-board sheet as contact material between the specimen and the machine platens to ensure a uniform application of the load; this was necessary as specimen ends could not be polished for fear of damage (Ciancio and Gibbings, 2012). At least 3 specimens for each mix were manufactured and the compression was performed at 0.3 mm/min displacement rate until failure (Ciancio and Gibbings, 2012). Specimen dry density and water content at the time of testing was calculated by measuring their weight and volume before testing and by transferring part of the crushed sample to an oven at 105 $^\circ$C and drying for 24 h.

2.2.2. Environmental impact assessment

The environmental benefits of using RCA as a substrate for RE structures in comparison with traditional and innovative earthen mixtures was presented by the authors in a previous work (Arrigoni et al., 2017a). Although the environmental sustainability of the analysed SRE mixtures was shown to be strictly related to the amount and type of stabiliser, attributional Life Cycle Assessment results confirmed the environmental benefits of using a waste material in comparison to quarried products. In the present work, the analysis is enriched with the assessment, from a consequential point of view, of the environmental benefits of partially replacing the substrate of traditional RE mixture with RCA. The consequential approach, in opposition to the attributional, aims to capture the environmental consequences due to a change in the system under study (Weidema, 2003). Moreover, it bypasses the discussion on the best way to allocate the impacts to "by-products" or "wastes" (Chen et al., 2010). In fact, when a by-product is used as an input to the system, which methodological approach to adopt depends on the constraints of the by-product market (Ekvall and Weidema, 2004). When part of the material is disposed, until an increase in the demand can be satisfied without affecting other consumers, the by-product can be classified as waste and be available burden free. Conversely, when the market is constrained and an additional demand for the material cannot be satisfied without affecting other consumers (e.g. more fly ash would not be produced even though there was a larger demand), its use should be modelled as if the unconstrained alternative on the market was used (in the case of fly ash this could be another cementitious product, such as cement (Crossin, 2015)) (Consequential-LCA, 2015). Since both the by-products considered in this research (i.e. RCA and fly ash) are still party landfilled in Western Australia (Arrigoni et al., 2017a) and RE building still occupies a niche of the construction sector market (Ciancio and Boulter, 2012), the by-products were modelled as waste, for which the credits from avoided landfilling were also accounted.

Together with global warming, new indicators (i.e. land use and water consumption) from the recently updated ReCiPe2016 method were used to assess the environmental impacts of the different RRCA

231   mixtures (Huijbregts et al., 2016). The approach of the study was "from cradle to gate" (i.e. limited to the

232   production stage of the mixtures (ISO, 2006)).

233   The reference scenario for the assessment was the most typical mixture used in Western Australia for RE

234   applications: crushed limestone as substrate and Portland cement as stabiliser (i.e. 100CL + 7CEM). Two

235   different functional units were considered in the analysis: i) 1 kg of SRE mixture and ii) 1 m^2 of finished

236   300-mm thick load-bearing wall. Different units were investigated considering that, even though one

237   mixture may be more sustainable by mass, the finished walls may differ in density and require different

238   amounts of base constituents. Since the impacts due to transportation depend on the location of the

239   building site with respect to the source of the base components, the same distance (equal to 50 km) was

240   considered to be covered by any good transported to the site. For comparison purposes, the base

241   constituents used for the engineered soil mixtures were assumed to be taken from site-excavated soil.

242   Although the comparison is interesting to understand the transportation role in the final environment

243   cost of the earthen structure, it is unlikely that the *in situ* soil, especially in Western Australia, would be

244   suitable for RE construction without needing additional components to improve its natural grading

245   (Ciancio et al., 2013).

246

247   2.2.3. Hygroscopicity

248   Hygroscopic performance of walls, closely related to their humidity buffering potential, is a key

249   contributing factor to indoor perceived comfort and a key asset used to promote earthen construction

250   (McGregor et al., 2016). Hence, hygroscopic performance, via Moisture Buffer Value (MBV) and moisture

251   adsorption-desorption isotherms, was examined here to determine any detrimental or advantageous

252   effects of RCA replacement on likely internal comfort. The mix tested, chosen as representative for RRCA,

253   was 100RCA + 10CEM (i.e. RCA as the only substrate material, stabilised with 10% cement).

254 Moisture buffering ability was tested according to the Nordtest standard (Rode, 2005) by alternatively

255 exposing the surface of a specimen to a 75% and 33% Relative Humidity (RH) environment. Specimens

256 used for the test were 20mm high cylinders with a 100mm diameter. Details on the climatic chambers

257 used for the test can be found in (Arrigoni et al., 2017b).

258 ISO 12571 was used as reference standard to determine the sorption and desorption isotherms (ISO,

259 2013). Two samples with a mass of approximately 50 g were used and, to avoid particle loss, they were

260 wrapped in a permeable and hydrophobic nonwoven fabric. Samples were first oven-dried to constant

261 mass and then placed consecutively in a series of environments at constant temperature (25 °C) and

262 increasing RH levels: 9%, 22%, 33%, 58%, 75%, 84% and 97%. The targeted humidity level was obtained

263 via saturated salt solutions and constantly monitored with HygroPuces sensors (accuracy $\pm3\%$ (Waranet

264 Solutions SAS)). When the samples reached a constant mass (i.e. the mass variation for three consecutive

265 days was lower than 0.1% of the sample weight), they were moved to the next environment in the

266 sequence. Once in the environment with a RH level of 97%, the reverse process was performed to obtain

267 the desorption curve.

268

269 ### 2.2.4. Microstructural characterisation

270 To understand and explain the hygroscopic and mechanical behaviour of RRCA, the microstructure of

271 crushed samples was investigated by means of porosimetry and microscopy.

272 Pore size distribution and surface area were investigated via mercury intrusion porosimetry (MIP) and

273 nitrogen adsorption-desorption isotherms using an AutoPore IV 9500 Hg porosimeter and a TriStar 3000

274 analyser respectively (Micromeritics Instrument Corporation). The Barrett, Joyner and Halenda (BJH) and

275 the Brunauer, Emmett and Teller (BET) methods were used to derive respectively the pore size distribution

276 and the surface area from the nitrogen isotherm. The pore diameter range investigated with the mercury

277   intrusion technique was from 60,000 to 6 nm, while that investigated by the BJH method spanned from

278   300 to 1.7 nm. The techniques were chosen to cover most of the porosity belonging to the system

279   investigated. Moreover, according to the conjoined Kelvin-Laplace equation, results could partially justify

280   the behaviour of the different mixtures during the MBV test (Atkins and De Paula, 2006). In fact, although

281   the pores that likely remained filled even at the lowest humidities (i.e. pores with a radius below 10 Å)

282   could not be identified, the techniques allowed the larger pores that were gradually filled in the high

283   humidity chamber to be detected (Arrigoni, 2017). In a typical experiment, about 0.2-0.5 g of material was

284   tested. Before testing, samples were adequately deaerated.

285   A Cambridge Stereoscan 360 Scanning Electron Microscope was employed to investigate the morphology

286   of the samples. Fractured surfaces and polished samples (after being incorporated in an organic resin)

287   were observed. The samples were gold coated before the analysis to prevent charging effects.

288

289 3. RESULTS

290 3.1. Mechanical resistance

291   3.1.1. RCA

292   UCS results of the different mixes investigated here with respect to their RCA content are presented in

293   Figure 4. Although all mixes complied with the minimum 2.0 MPa compressive strength requirement for

294   stabilised earthen structures (indicated by the red line in Figure 4) according to the Australian Earth

295   Building Handbook (Walker and Standards Australia, 2001), it is evident that RCA replacement

296   detrimentally affected the UCS values of both mixes. Whilst the addition of RCA caused a decrease in

297   strength in the CL group compared with the specimens made without recycled aggregates (i.e. 100CL +

298   7CEM), the decrease was not linearly proportional to the addition of RCA; conversely, a clear trend was

299 not evident for the ES group. Certainly, other factors above RCA replacement percentage, for instance the

300 particle size distribution, should be taken into account to understand this mechanical behaviour. Although

301 the increase in strength with the addition of RCA in some soil mixes seemed to suggest that some optimal

302 PSD may exist, coefficients of uniformity and curvature for the different mixes (Table 1, describing the

303 shape of the PSD) did not exhibit a clear correlation with the compressive strengths. The same could be

304 said for the initial dry densities, depicted as rhombuses in Figure 4, which, while tending to decrease with

305 the increase in RCA content, did not present a clear correlation with strength. Rather, results agreed with

306 previous studies, which highlighted that dry densities cannot be a standalone proxy for strength when

307 more than one material and/or a binder are used (Beckett and Ciancio, 2014).

308 Mechanical properties of RRCA (i.e. rammed mixtures that had RCA as the only substrate) varied when a

309 different binding agent was used. When the amount of cement was increased to 10%, unconfined

310 compressive strength at 28 days went from 4.2 MPa to 8.4 MPa. More interestingly, a net increase was

311 noticed also when cement content was reduced to 5% and an additional supplementary cementitious

312 material was applied (i.e. 5% fly ash): after 28 days specimens exhibited an average UCS of 6.7 MPa.

313 Nevertheless, it must be noted that the mixtures with different binders, presented by the authors in

314 previous research (Arrigoni et al., 2017a), were tested starting from a different non-sieved RCA batch.
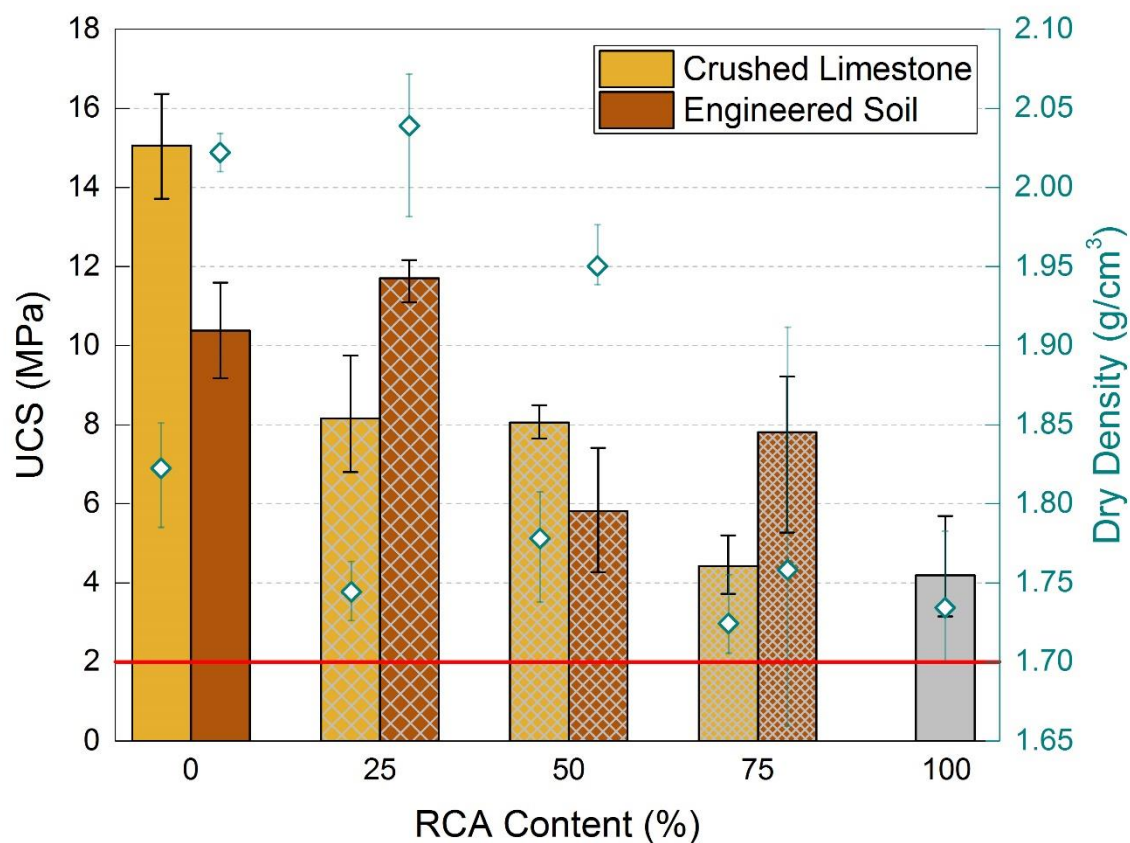
315

316

317 *Figure 4. Unconfined Compressive Strength (UCS) and dry densities (white-filled rhombuses) of cement stabilised rammed earth*

318 *mixture vs. RCA content. Error bars indicate the minimum and maximum measured for each mix.*

319

3.2. Environmental impact assessment

Results for the consequential LCA of the different mixtures are presented in Figure 5. Impacts referring to one kilogram of mixture are depicted using coloured columns while the impacts attributed to one square meter of finished wall are superimposed as a hatched pattern.

Global warming results were closely related to the amount of cement in the different mixtures: the worse mixture incorporated the highest percentage of cement (i.e. 100RCA + 10CEM) and the best one the least (only 5%). The cause of this close relationship was the massive CO_2 emissions associated with cement manufacturing (Barcelo et al., 2013). When the same amount of cement was employed, the advantage of using a waste material available on site (i.e. *in situ* excavated soil) emerged; the zero emissions for transportation made the 100ES + 7CEM mix the best solution. Next, the mix incorporating RCA performed slightly better than the reference case considering that RCA was available burden-free while quarry operations were needed to obtain the crushed limestone. The ranking changed when the square meter was considered as functional unit, due to the higher density of 100ES + 7CEM compared to the other mixtures. In this case, 100RCA + 7CEM emitted the least greenhouse gases (GHGs) during its life cycle.

Land use results, which account for species losses caused by a specific use of land compared to a natural reference situation (de Baan et al., 2012), showed a similar trend to the one of global warming: the mix with higher contents of cement were the most impacting and, among the mixtures with the same amount of cement per unit mass, the mixture based solely on engineered soil was the most sustainable. Most of the cement impacts related to land use came from the occupation of soil by the trees that were logged to produce both the paper for packaging and the wood for heating. The additional soil occupation of the quarry made the mixture containing crushed limestone the worse in terms of land use.

Finally, the water consumption results are reported in the last group of columns in Figure 5. Although cement played an important role for this impact as well, a critical share of the final water footprint was

343   due to the water consumed for blending the components on-site, directly related to the optimum water

344   content of the different mixtures. Given its high water absorption capacity, the mixtures containing RCA

345   were those with the highest water consumptions. However, the mixture using alternative stabilisers (i.e.

346   100RCA + 5CEM 5FA) performed better than the reference scenario (100CL + 7CEM) for all the impact

347   categories considered, showing that reducing the amount of cement and using waste materials could

348   substantially reduce the environmental impacts and the water footprint of the mixture.

350   *Figure 5. Consequential LCA results for RRCA mixtures (100RCA + 7CEM, 100RCA + 10CEM and 100RCA + 5CEM 5FA) in*

351   *comparison with traditional rammed earth mixtures (100CL + 7CEM and 100ES + 7CEM). The impacts generated by the crushed*

352   *limestone mixture (i.e. 100CL + 7CEM) were considered as the base case scenario and the impacts of the other mixtures were*

353   *normalised (%) to the base case.*

355   GHG savings or expenditures by substituting part of the reference substrates (i.e. CL and ES) with RCA are

356   presented in Figure 6a and Figure 6b respectively, together with the variation in compressive strength of

357   the relative mixtures. For a constant amount of cement, substituting RCA produced a gradual saving in

358   GHG emissions but a corresponding strength reduction. Notably, the two pairs 75CL − 50CL and 25 CL −

359   RCA had very similar GHG emission and UCS results. These similarities highlighted the close dependence

360   of the mixtures' sustainability and resistance performances on the amount of cement used per unit

361   volume. In fact, cement was administered on a weight basis and the pairs mentioned had very similar dry

362   densities. Considering the pure RRCA mixtures, the higher environmental cost paid by increasing the

363   amount of cement from 7 to 10% was not compensated by a strength gain; on the contrary, strength

364   reduced compared to the base case but GHG emissions dramatically increased. Conversely, reducing the

365   amount of cement by using alternative stabilisers led to a substantial reduction of GHG emissions (more

366   than 15 kg of CO_2 equivalent per square meter of wall with respect to the ES base case) and to a

367   compressive strength lower than the reference cases but very close to those mixtures with only a partial

368   substitution of the substrate.

369   For the sake of comparison, if unreinforced concrete was used the cradle-to-gate emissions would be far

370   higher; considering an average 35 MPa concrete (Wernet et al., 2016), the wall could only be 60-mm thick

371   to equal the GHG emissions of the reference 300-mm thick SRE wall and 40-mm thick to have the same

372   life cycle impact of the most sustainable RRCA solution (i.e. 100RCA + 5CEM 5FA). Even if the very thin

373   concrete wall could support the imposed load, it is obvious that the wall would perform very differently

374   in terms of thermal regulation. A different functional unit must therefore be adopted for a fair LCA

375   comparison, which would likely lead to completely different results (Panesar et al., 2017). Contrastingly,

376   although outside of the scope of the present research, structural elements with the same functions could

377   be compared. For instance, if an SRE and a concrete beam were compared, considering a linear

378   proportionality between thickness of the beam and compressive strength and considering the same width

379   for the two beams due to reinforcement requirements, a beam made with traditional SRE mixture would

380   allow a saving of more than 40 kg of CO_2-eq. per linear metre. On the other hand, the 100RCA + 5CEM 5FA

381   mix would guarantee a lower saving (i.e. 10 kg CO_2-eq/linear meter) due to its lower mechanical
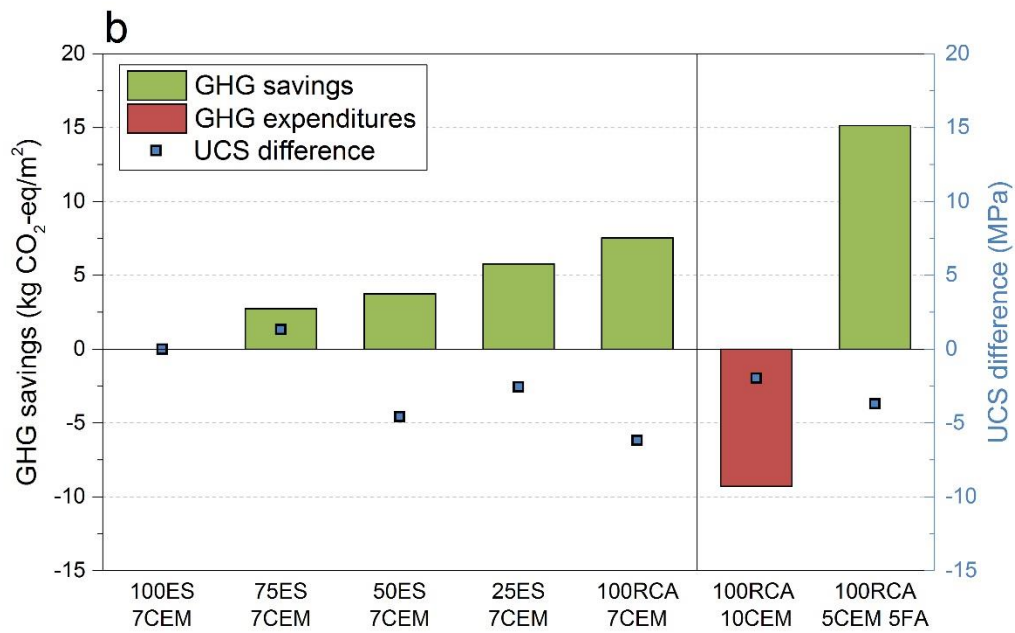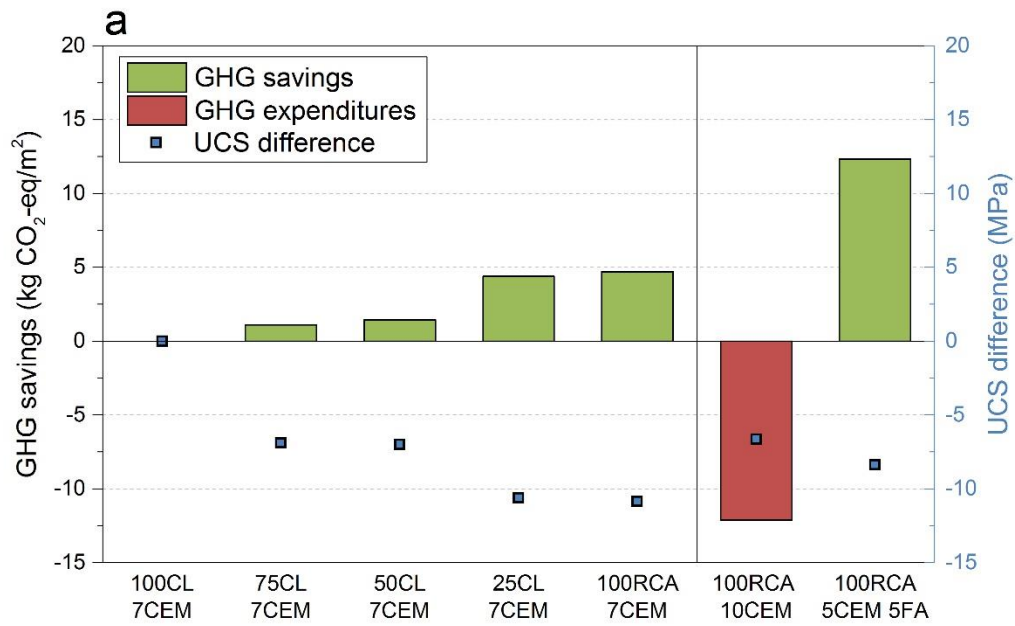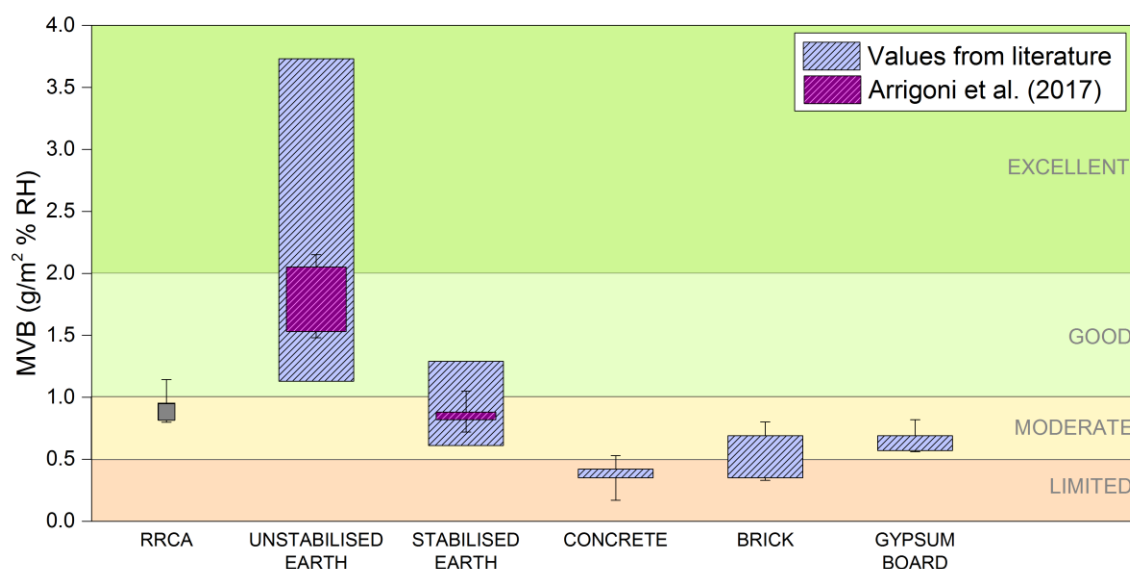
382   resistance.

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385

386 *Figure 6. Greenhouse gases (GHG) savings and expenditures and Unconfined Compressive Strength (UCS) resistance of the*

387 *different mixtures in comparison to: a) 100CL + 7CEM and b) 100ES + 7CEM*

3.3. Hygroscopicity

3.3.1. Moisture Buffer Value

Average MBV results for the RRCA samples tested (i.e. 100RCA + 10CEM) are presented in Figure 7. The material achieved a "moderate" to "good" moisture buffering ability according to the categories set by the Nordtest, with an average MBV of 0.88 g/(m^2 %RH). RRCA showed a lower buffering capacity than literature values for unstabilised earth (McGregor et al., 2014) but it performed better than most of the traditional materials tested in the Nordtest project, such as concrete, brick and gypsum boards (Rode, 2005). Results for RRCA are in line with literature values for stabilised rammed earth (Allinson and Hall, 2012) and performed slightly better than the SRE specimens made from engineered soil tested under the same operating conditions (with average MBVs ranging from 0.82 to 0.88 g/(m^2 %RH) (Arrigoni et al., 2017b)).

Figure 7. Moisture Buffer Value results for RRCA specimen in comparison with traditional earthen mixtures and building materials. The categories in which the results are subdivided and the values for the traditional building materials are taken from

406

3.3.2. Sorption isotherm

408   The average sorption isotherm for RRCA is shown in Figure 8 together with the isotherms of more

409   traditional RE mixtures presented in Arrigoni et al. (2017b). The lower part of the isotherms (distinguished

410   by filled symbols) and the upper parts (distinguished by empty symbols) represent, respectively, the

411   absorption and desorption results. RRCA showed an absorption curve similar to the one of the unstabilised

412   RE, absorbing much more moisture than the stabilised RE sample throughout the test. The reference

413   unstabilised RE represents a traditional soil used for *pisé* (an alternative term for rammed earth)

414   structures in the south of France composed mainly of silt and Illitic clay with a dry density of approximately

415   1.83 g cm^{-3} (El-Nabouch et al., 2018), while stabilised RE is an engineered soil (60% sand, 30% Kaolin clay

416   and 10% gravel) stabilised with 5% cement and 5% fly ash (dry density: 1.98 g cm^{-3}). RRCA showed a much

417   larger hysteresis loop compared to traditional RE mixes. Hysteresis is generally associated with pore

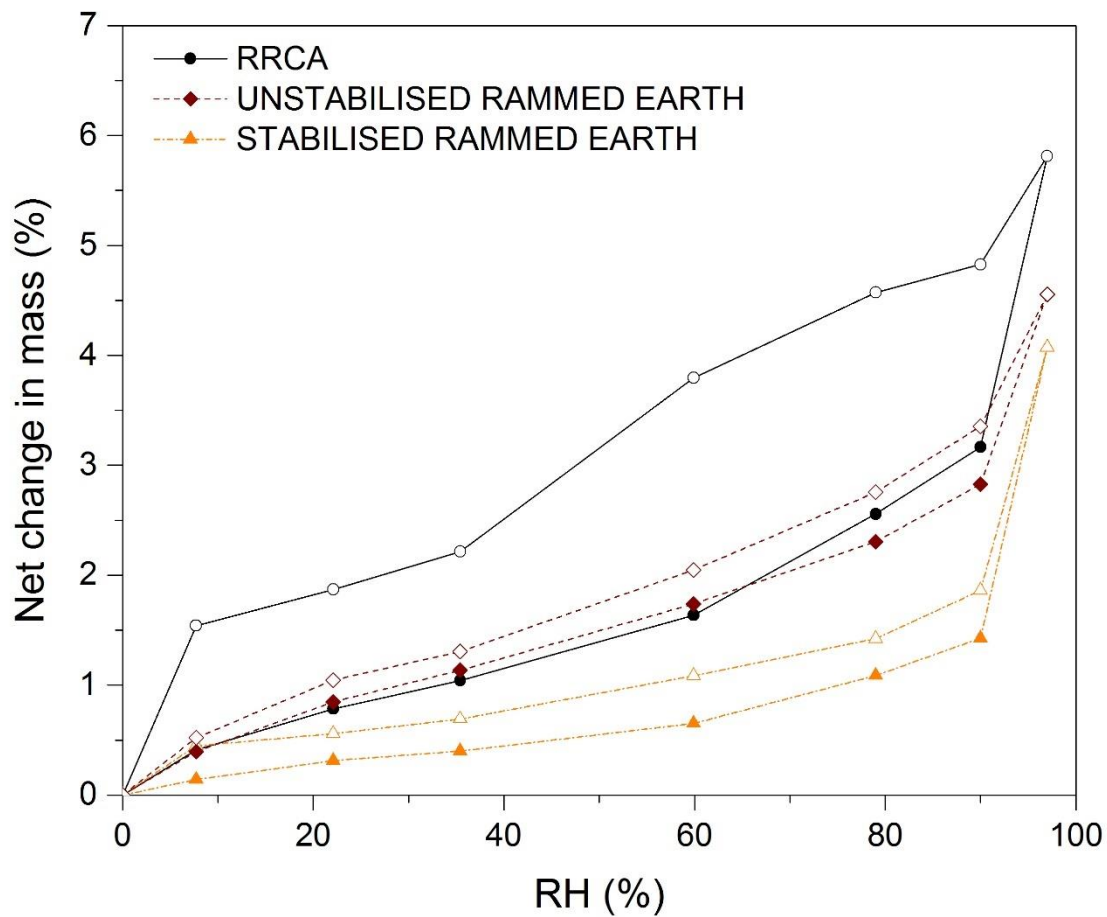418   interconnectivity; therefore, an extensive microstructural characterisation was performed.

Figure 8. Sorption isotherm result for RRCA compared to traditional RE mixes.

3.4. Microstructural analysis

3.4.1. Porosimetry

Porosimetry results for RRCA samples are presented in Figure 9 and in Table 2, together with the results obtained for traditional RE mixtures. Before drawing any conclusions on RRCA, it must be borne in mind that the specimens had a high heterogeneity due to the different origin and typology of the recycled aggregates in the mixture. Results may therefore be only partially representative of the whole system.

428   Moreover, the porosity investigated may originate both from the old system of concrete aggregates and

429   from the new RRCA system. Nevertheless, different samples from the same mixture were analysed and

430   the results reported are indicative of the recurring trends.

431   When analysed via MIP, RRCA showed a more uniform pore distribution than traditional mixes (i.e. a

432   strong modal pore size was not evident, Figure 9a), most likely due to its aforementioned heterogeneity.

433   Moreover, RRCA exhibited a large total pore area compared, in particular, to the stabilised RE mixture.

434   The higher total pore area may be attributed to the high amount of cementitious gel, belonging to both

435   the old and the new system, with intrinsic narrow (i.e. <100 Å) porosity.

436   Nitrogen adsorption-desorption isotherms results are reported in Table 2 in terms of surface area

437   calculated with the BET method and of average pore diameters obtained with the BJH method from

438   desorption isotherms. Considering the existence of hysteresis between adsorption and desorption

439   isotherms, desorption calculations were used to analyse the distribution of mesopore diameters (Barrett

440   et al., 1951). RRCA demonstrated an intermediate surface area and average pore diameter when

441   compared to typical unstabilised and stabilised earthen mixtures. RRCA samples also exhibited a large

442   adsorption-desorption hysteresis loop, which could be attributed to the ink-bottle effect caused by an

443   irregular distribution of the pores (Arrigoni et al., 2017b). The sharp step between 30 and 50 Å on the

444   desorption isotherm was considered to be a sign of the pores' interconnection (Figure 9b). The ink-bottle

445   effect is typical in hardened cementitious paste, where capillary pores (>100 Å) can be interconnected

446   through finer connections (i.e. gel pores). These nanometre-sized pores represent the intrinsic porosity of

447   hydrated products such as CSH gel (Kaufmann et al., 2009). Cementitious paste, belonging to the original

448   crushed concrete or newly formed, was abundant in RRCA. Conversely, cementitious paste was limited or

449   absent in stabilised and unstabilised earthen samples respectively, due to the low (or null) amount of

450   cement in the mixtures. Although not containing any cementitious particle, the unstabilised mixture

451   exhibited the highest surface area, the lowest average pore diameter and an important hysteresis in the

452 adsorption-desorption isotherm, which could be attributed to the clayey-silt matrix with a high specific

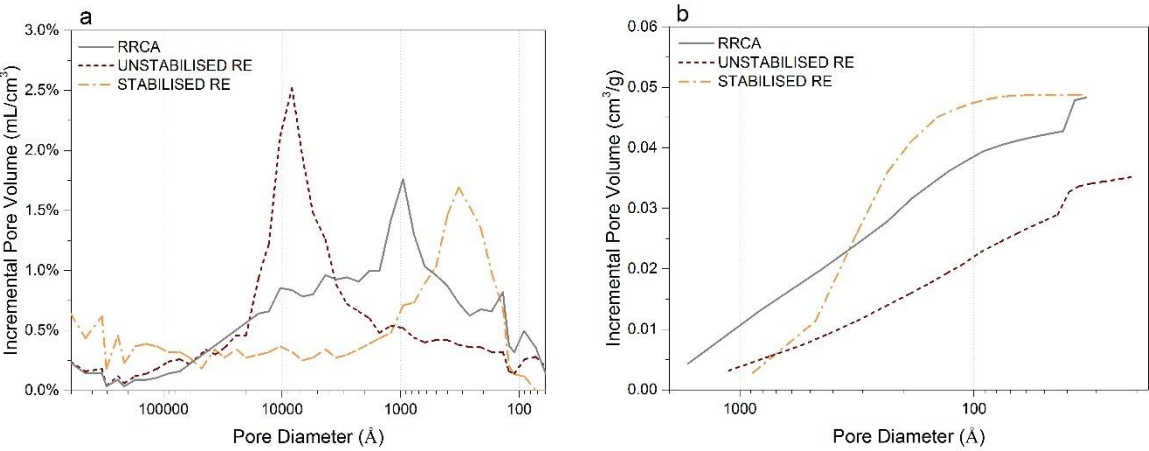453 surface area and an intrinsic narrow porosity interconnecting larger pores.

454

455

456 *Figure 9. Porosimetry results for RRCA compared to traditional rammed earth mixtures: a) incremental intrusion percentage*

457 *volume measured via mercury intrusion porosimetry; b) BJH desorption cumulative pore volume.*

458

459 *Table 2. Porosimetry analyses results for RRCA compared to traditional rammed earth (RE) mixtures.*

Mix	Dry density	MIP bulk porosity	MIP average pore diameter	MIP total pore area	BET surface area	BJH average pore diameter
	[g cm^{-3}]	[%]	[Å]	[m^{2}g^{-1}]	[m^{2}g^{-1}]	[Å]
RRCA	1.91	24.4	589	10.0	11.4	137
UNSTABILISED RE	1.83	24.2	1012	5.09	15.0	90.8
STABILISED RE	1.98	21.9	649	6.73	7.37	235

460

3.4.2. Scanning Electron Microscopy

Figure 10a and b show SEM images of the aggregate/binder interfaces of two different RRCA samples (i.e. 100RCA + 10CEM and 100RCA + 5CEM 5FA). The binding matrix of 100RCA + 10CEM resulted in rich hydration cementitious products (labelled "2" in the figure), identifiable in dendrites and needle-like phases that could be attributed to CSH gel and ettringite. The same phases were present, to a lower extent, in the 100RCA + 5CEM 5FA binding matrix. The minor concentration of these phases could be explained by the lower cement content in the mixture. On the other hand, in the 100RCA + 5CEM 5FA matrix, fly ash particles embedded in the matrix could be spotted (labelled "3" in the figure). The fly ash particle highlighted in Figure 10b had a smooth surface, suggesting that the particle did not react during the curing period. However, the presence of unreacted fly ash particles seemed to be minimal: as highlighted in Figure 10c, other fly ash particles seemed to be completely reacted and embedded in the matrix. Completely reacted fly ash particles are recognisable by the crystalline residues concentrated in a rounded shape area (Figure 10d), which represents the area previously occupied by the particle. The crystals could be attributed to the unreacted residues of the fly ash particle (i.e. quartz and mullite). In Figure 10c the interface between the original cementitious matrix (i.e. mortar) that surrounded the aggregates (labelled "4" in the figure) and the newly formed matrix (labelled "5") is also evident.
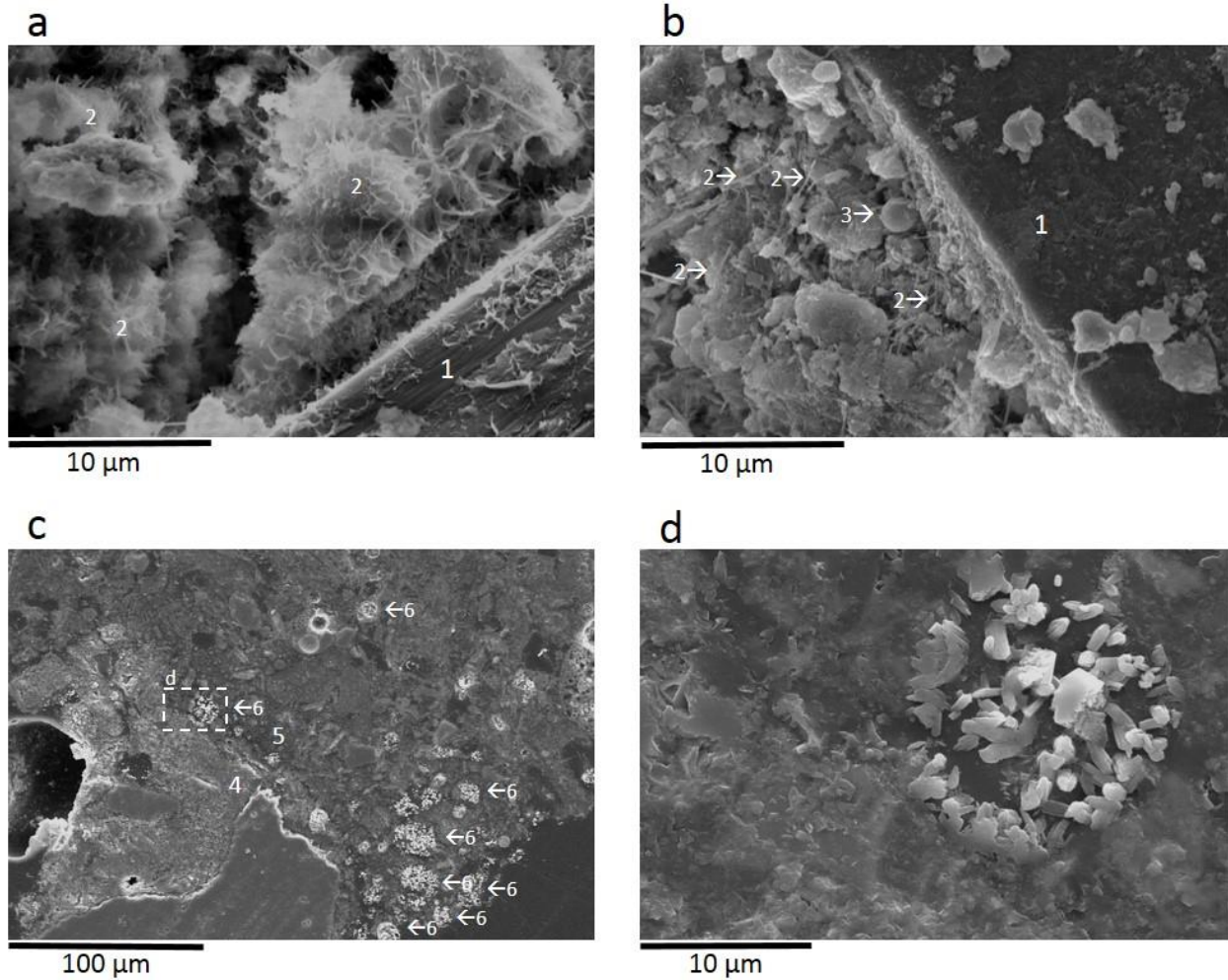
Figure 10. SEM images of RRCA samples (100RCA + 10CEM (a) and 100RCA + 5CEM FA (b, c and d)): a-b) aggregate/binder interface; c) original and new matrix at low magnification; d) detail of a reacted fly ash particle. In the figures "1" designates aggregate particles, "2" cementitious products (CSH gel and ettringite needles), "3" fly ash particles, "4" the original RCA (recognisable from a lighter colour in the figure), "5" the newly formed matrix (recognisable from the darker colour) and "6" reacted fly ash particles. The marked region in c) highlights one reacted fly ash and indicate the position of the zoomed image (d).

4. DISCUSSION

In our previous studies, stabilised rammed earth mixtures incorporating RCA have already been shown to be highly durable even when they were stabilised with a minimal amount of cement (e.g. 5%) (Arrigoni et al., 2017a); when subjected to simulated extreme weathering conditions (i.e. prolonged high-pressure water jet and cyclic water-submersion and drying), samples, if properly compacted, lost little mass or strength. The experimental campaign presented here aimed at deepening the knowledge of these material in terms of mechanical resistance, hygroscopic properties and sustainability.

Unconfined compressive test results indicated that the presence of RCA in a rammed earth mix detrimentally affected the strength of the material. Nevertheless, the addition of RCA did not automatically translate into a decrease in characteristic UCS; most likely, the strength of the material is more closely related to the grading of the mix and the presence of contaminants rather than the percentage of RCA added alone (for example, X-ray diffraction analyses indicated the presence of bricks and ceramics in the recycled "concrete" aggregates as well as unhydrated cement). In order to avoid the creation of weak points leading to possible localised failure in the rammed earth, it might be convenient to remove these contaminants first. Given the significant effect that the quality and the characteristics of the material (which will vary from site to site) ostensibly had on the final behaviour, strength testing should be performed on the material prior to construction to ensure the required standards are met. Results found here were in line with the accessible works on SRE incorporating RCA: Taghiloha (2013) obtained a compressive strength at 28 days (on 177-mm high cylinders with a 152-mm diameter) between 6.7 and 8.2 MPa with mixtures containing recycled aggregates and 8.7% cement (on substrate dry mass), whereas the resistance of the cubes stabilised with 10% cement tested by Jayasinghe et al. (2016) ranged between 3.0 and 6.3 MPa. In both cases, the maximum RCA substitution tested was approximately 60%. In the present research, such strengths could be obtained using only recycled material and a lower cement content (e.g. 6.7 MPa at 28 days for 100RCA + 5CEM 5FA), highlighting the wide range of performance

509   expected of these materials. Even so, all batches tested here showed strengths exceeding 2 MPa and could

510   therefore be used in rammed earth construction according to the existing Australasian standards (e.g.

511   Standards New Zealand (1998); Walker and Standards Australia (2001)).

512   Incorporating RCA improved the sustainability of all tested mixes, save for that solely comprising soil

513   sourced on site. RCA performed better than quarried products in terms of both GHG emissions and land

514   occupation. Nevertheless, different distances between the building site, the natural quarry and the site

515   where RCA is sourced may affect the sustainability ranking (Fraj and Idir, 2017); for example, if RCA were

516   sourced 80 km farther than the natural quarry, it would be better to use the quarried material in terms of

517   GHG emissions rather than RCA. The gap reduced when land use was considered: the recycling site should

518   not be 35 km more distant than the quarry. Finally, in order to have a RRCA structure with a lower water

519   footprint than the base Western Australia case, the site where RCA is sourced should be at least 7 km

520   closer than the quarry. Overall, however, it was the amount of cement used in the mixture that was the

521   primary parameter affecting environmental impact.

522   Tests performed to evaluate the hygroscopicity of RRCA highlighted the relevant moisture absorption

523   capacity of the material. RRCA performed better than most of traditional construction elements in terms

524   of moisture buffering ability, so guaranteeing an improved indoor air quality (Fang et al., 1998) and

525   reduced energy consumption (Zhang et al., 2017). The good absorption capacity of tested RRCA was

526   probably due to the large surface area of the pores, comparable to that of unstabilised RE, which is typical

527   for cementitious matrices. However, the large hysteresis loop suggested an abundance of pores where

528   moisture was trapped because of restricted entrances (Issaadi et al., 2015). That the typical unstabilised

529   earthen mixture considered here performed better than RRCA could be attributed to the lack of clay

530   particles in the RRCA matrix, well-known for their optimal physico-chemical affinity with water (McGregor

531   et al., 2014).

532

5. CONCLUSIONS

533

534   This study highlighted the benefits (numerous) and drawbacks (few) of incorporating RCA into stabilised

535   rammed earth materials. The examination of the strength, sustainability and hygroscopicity of RRCA

536   complemented a durability analysis presented in a previous paper (Arrigoni et al., 2017a).

537   Cement stabilised RRCA exhibited acceptable compressive resistance according to available standards on

538   stabilised rammed earth. For the most part, RCA addition caused a decrease in unconfined compressive

539   strength compared to the traditional rammed earth mixes, although such substitution did not affect

540   durability. Decrease in strength was not linearly related to the amount of substitution. Rather, changes to

541   the mix particle size distributions and the quality of the recycled aggregates themselves appeared to affect

542   the strength of the final material more than the percentage of RCA added. Regardless, no mix achieved a

543   higher strength than the parent material alone.

544   Substituting part of the natural aggregates in the mixture with RCA slightly reduced the environmental

545   impact, but the need for each mix to contain cement largely offset any benefit. Using alternative stabilisers

546   alleviated this issue: including fly ash in the mixture and reducing the cement content to 5% led to a net

547   reduction of the life cycle greenhouse gas emissions of up to 15 kg CO_2-eq/m^2 without compromising

548   mechanical resistance or durability. SEM images of crushed RRCA samples showed how most of the fly

549   ash reacted to form new cementitious products that were perfectly incorporated in the new matrix. RRCA

550   exhibited "moderate" moisture buffering abilities: less than unstabilised earth mixtures but similar to

551   those of stabilised earth mixtures previously tested by the authors and better than many traditional

552   building materials (e.g. concrete and bricks).

553   Reusing demolished concrete aggregates definitely guarantees environmental benefits in terms of landfill

554   occupation and raw materials exploitation; both of these impacts, however, are difficult to capture with

555 the currently available LCA impact assessment methods. However, the environmental benefits of using

556 waste materials could be jeopardized by the surrounding conditions; if RCA had to cover longer distances

557 before reaching the new building site, it may be more sustainable for some impact categories (e.g. global

558 warming) to use natural aggregates.

559 To conclude, although the idealistic mixture made only from excavated *in situ* soil remains the optimal

560 rammed earth solution in terms of sustainability and moisture buffering ability, when the soil available on

561 site is not suitable for earthen structures or greater resistances are required, RRCA may represent a

562 worthwhile solution.

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