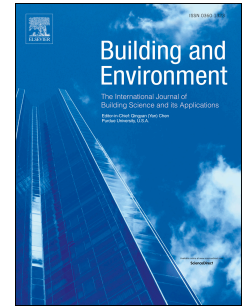


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Reduction of rammed earth's hygroscopic performance under stabilisation: An experimental investigation

Alessandro Arrigoni, Anne-Cécile Grillet, Renato Pelosato, Giovanni Dotelli, Christopher T.S. Beckett, Monika Woloszyn, Daniela Ciancio



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1 **Reduction of rammed earth's hygroscopic performance under**
2 **stabilisation: an experimental investigation**

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17 ABSTRACT

18 One of the acknowledged qualities of rammed earth (RE) is its moisture buffering capacity.
19 Recently, stabilisation of RE has become a common practice to improve the mechanical resistance
20 but very little is known about the effect that stabilisation has on hygroscopic properties. The present
21 study aims to fill this gap by understanding the role that stabilisation plays in the buffering and
22 sorption capacity of RE. The use of alternative stabilisers such as fly ash and calcium carbide
23 residue and a comparison with traditional unstabilised RE (URE) have also been investigated.
24 Moreover, the effect of weathering, simulated by cyclic wetting-drying, on hygroscopic
25 performance has been analysed. Moisture Buffer Value (MBV) testing, moisture and nitrogen
26 adsorption-desorption isotherms and mercury intrusion porosimetry were performed on stabilised
27 samples to examine microstructural phenomena responsible for behavioural changes. URE was
28 confirmed to be a good-to-excellent passive air conditioner according to the MBV scale but its
29 performance seemed to be highly influenced by the soil particle size distribution and mineralogy.
30 Based on the experimental outcomes of the mixtures investigated, stabilisation had a detrimental
31 effect on the moisture buffer capacity of rammed earth, likely due to the inhibition of the physico-
32 chemical interactivity between moisture and clays. Weathering had a variable effect on the
33 buffering capacity, depending on the availability of unreacted particles in the matrix.

34

35 KEYWORDS

36 Rammed earth; Stabilised rammed earth; Moisture buffer value; Hygroscopicity; Weathering;

37 Porosity

38 1. INTRODUCTION

39 Rammed earth (RE) is a thousand-year old construction technique in which soil is progressively
40 compacted in layers into formwork. The low environmental impacts of RE compared to traditional
41 wall systems (e.g. fired masonry) led to a renaissance of this building technique in many countries
42 around the world [1, 2]. Beyond sustainability, another acknowledged quality of RE is its passive
43 air-conditioning ability. Indoor comfort is fundamental for well-being in modern society, given that
44 people usually spend most of their time in enclosed spaces (e.g. about 90% in Western countries)
45 [3, 4].

46 Earthen walls and clay-based plasters guarantee thermal comfort through the passive moderation of
47 indoor temperature and humidity fluctuations [5-10]. Passive air conditioning reduces the energy
48 consumption and need for mechanical ventilation systems and dehumidifiers, with clear
49 environmental and economic benefits [11]. Buffering humidity variations is also particularly
50 important in situations where moisture generation does not balance the moisture extraction by
51 ventilation; high humidity environments (>60 %Relative Humidity (RH)) increase the abundance of
52 allergenic mites and the concentration of formaldehyde with potentially adverse health effects,
53 whilst low humidity environments (<40 %RH) increase the incidence of respiratory infections, the
54 severity of allergic and asthmatic reactions and indoor ozone levels [12].

55 Given the higher thermal conductivity of water ($\lambda_{water} = 0.6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) compared to air
56 ($\lambda_{air} = 0.026 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), the moisture storage capacity of a porous material is a fundamental
57 parameter for the thermal regulation of a building. In materials with low capillarity, high humidity
58 can also lead to fungus formation, detrimentally affecting thermal capacity [5, 13].

59 Traditional RE construction does not use additives but nowadays stabilisers are generally added to
60 the earth mixture to improve its strength and erosion resistance. The addition of stabilisers, mainly
61 Portland cement, jeopardizes the environmental benefits related to the use of a natural and virtually
62 unlimited material such as raw earth [14]. On the other hand, traditional unstabilised rammed earth

63 (URE) has a low compressive strength and questionable durability [15]. The environmental impact
64 of cement is therefore considered as the price to pay for a stronger, more long-lasting material.
65 Using waste products as alternative stabilisers has proved to be a viable solution to decrease the
66 environmental impact of the rammed earth mixture while still providing enough strength and
67 durability [16].

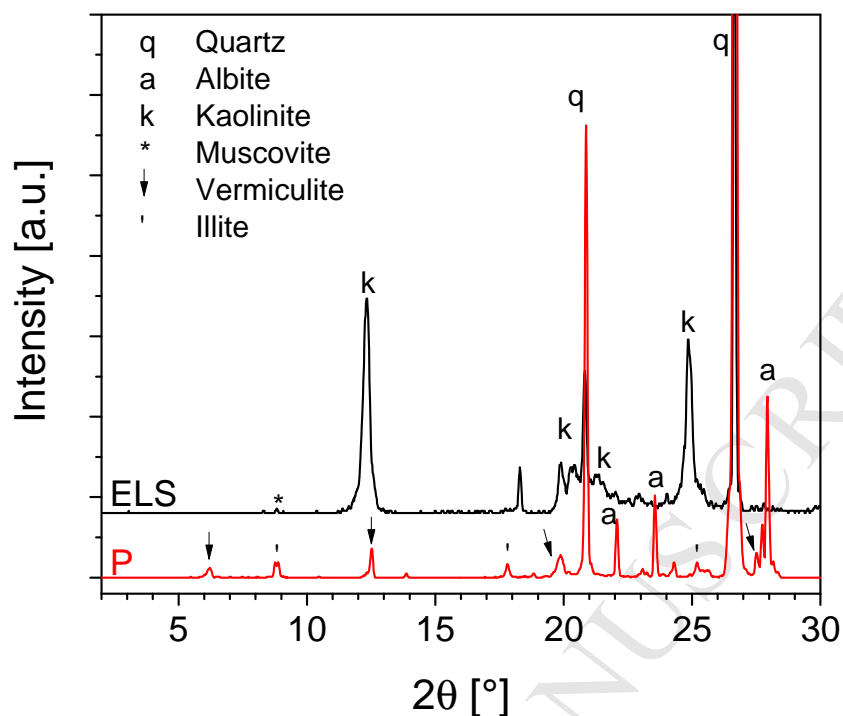
68 While the good hygrothermal performance of raw earth used in buildings is well understood and
69 acknowledged, less is known about the performance of modern RE buildings and in particular on
70 the influence that stabilisers may have on their hygroscopic properties [17]. A few studies have
71 recently been published focusing on the humidity buffering potential of stabilised rammed earth
72 (SRE) and compressed earth blocks, concluding that modern compressed earth can be a good
73 moisture buffering material [18-20]. Other authors studied earthen plasters and advised the addition
74 of aggregates in the mixture, such as natural fibres or synthetic gels, to enhance their hygroscopic
75 properties [21, 22]. Eires et al. evaluated the effect of certain stabilising agents (i.e. lime, oil and
76 sodium hydroxide) on the water vapour permeability of RE. Among the mixtures investigated, earth
77 stabilised with lime showed the best results, while oil seemed to reduce the vapour permeability.
78 Nevertheless, the buffering potential of the different mixtures was not investigated [23].

79 The aim of the present work is to advance the understanding of the hygrothermal behaviour of SRE
80 by comparing the moisture buffering ability of an unstabilised earthen mixture with the
81 performance of the same mixture stabilised with traditional (cement) and innovative binders such as
82 fly ash and calcium carbide residue. The sorption capacity and the porosity of the different mixes
83 were investigated in order to provide a physical explanation of the moisture buffering behaviour.
84 Moreover, the study extends to the novel investigation of weathering's effect, simulated by wetting
85 and drying cycles, on the hygrothermal properties of stabilised earthen samples.

87 2. MATERIALS AND METHODS

88 2.1 Materials

89 A description of the mixes used in the study is given in Table 1. Engineered Local Soil (ELS)
90 represents an artificial mixture of different soils from Perth, Western Australia, mixed together to
91 form a suitable substrate for RE construction: 60 % local soil, 30 % clayey soil from a nearby
92 quarry and 10 % single sized gravel (10 mm). ELS represents the reference mixture for the study
93 and stabilisers were added to this soil mix in order to understand the effect of stabilisation on its
94 hygroscopic properties. On the other hand, P represents a typical soil mixture used for *Pisé* (French
95 name for RE) structures in the south of France. P was used in the present study to investigate how
96 changing soil type might affect the hygroscopic properties of RE. In fact, P and ELS possess very
97 different particle size distributions, with the former presenting a low percentage of coarse particles
98 (i.e. $>63 \mu\text{m}$). A comparison of the phase composition of P and ELS was assessed through X-ray
99 power diffraction (XRD). The XRD patterns were recorded on ground samples by means of a
100 Bruker D8 Advance diffractometer using a graphite monochromated Cu $K\alpha$ radiation. The
101 measurement range was $2-50^\circ 2\theta$ and the step was $0.02^\circ 2\theta$, with a counting time of 1 sec/step. The
102 low 2θ range of the patterns, where the reflections of the clay minerals were observed, is reported in
103 Figure 1. In the ELS sample, apart from quartz, a large amount of kaolinite and traces of muscovite
104 were detected. In the *Pisé* soil, apart from quartz and albite, illite and traces of vermiculite
105 reflections were identified. The analyses on oriented and glycolated samples revealed no presence
106 of expansive clays.



107

108 **Figure 1.** XRD Patterns of Pisé soil (P, below, in red) and the clay fraction of ELS (ELS, above, in
 109 black).

110

111 The stabilisers used were cement (General Purpose Cement Type GP according to AS 3972 [24]
 112 composed of Portland cement and small amounts (<7 %) of limestone), fly ash (FA) and calcium
 113 carbide residue (CCR). FA is the residue from a coal power plant and was classified as class F
 114 according to its calcium content [25]. CCR is the residue of acetylene production and was
 115 composed of calcium hydroxide with a small fraction of calcium carbonate. Cement, once mixed to
 116 the soil with water, forms hydrated compounds, typically hydrated calcium silicates and hydrated
 117 calcium aluminates, which link soil particles together [26]. The addition of calcium hydroxide gives
 118 rise to the same hydrated compounds on the long term by reacting with the silica and alumina
 119 dissolved from the clay structure [27]. The formation of these hydrated products is further enhanced

120 when low-cost class F FA are added to the mixture and its siliceous and aluminous glassy
121 components are activated by a cementitious agent such as cement or calcium hydroxide [26, 28].

122 Further information on the chemical characterization of the different substrates and binders can be
123 found in [16, 29] and an experimental application using P can be found in [30]. Particle size
124 distributions of the different mixes are presented in Figure 2.

125 Except for P, samples used for hygroscopic testing were cut using a mitre saw from cylinders
126 compacted at their Modified Proctor optimum water content and density [31]. Cylinders were cured
127 either at standard conditions (S) (28 days in a climatic chamber at 96 %RH and 21 °C) or went
128 through cyclic wetting-drying (WD) according to ASTM D559M standard [32]. After the respective
129 aging conditions, cylinders were tested for compressive strength and remains were stored in sealed
130 plastic bags for hygroscopic and microstructural analysis. P was cut directly from a wall erected by
131 RE practitioners using soil from a demolished *pisé* farm in Dagneux, France. The wall was
132 compacted below the standard Proctor optimum water content and the resulting density was about
133 1830 kg/m³ [33]. Unstabilised mixes (P and ELS) were left to dry in ambient conditions for several
134 weeks after manufacture; given the lack of stabiliser, curing conditions do not affect material
135 hygroscopic properties beyond providing sufficient strength to maintain their material structure.

136

137 **Table 1.** Description of the different mixes. wt % indicates the weight percentage of dry substrate.

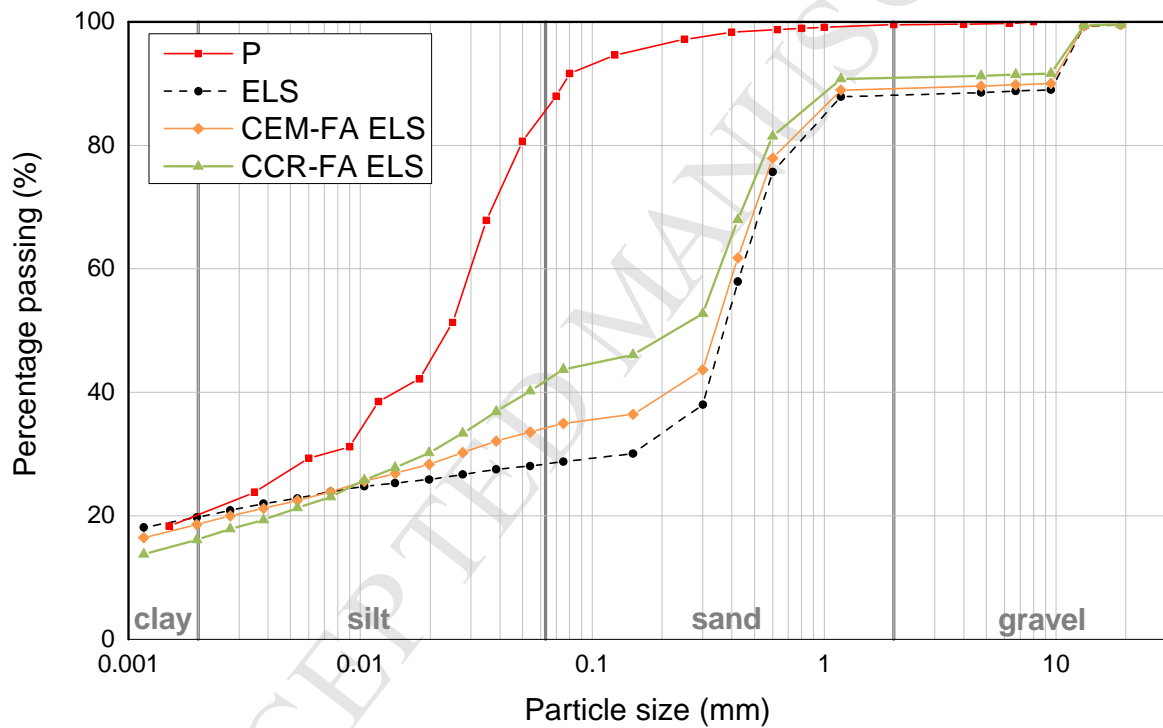
138 *Differently from the other mixtures, max dry density for P represents the standard Proctor dry
139 density to facilitate comparison [33].

Mix	Substrate	Portland cement	Calcium Carbide Residue	Fly Ash	Clay <2 µm	Silt 2-63 µm	Sand 63 µm-2 mm	Gravel 2-63 mm	Max dry density
		wt %	wt %	wt %	wt %	wt %	wt %	wt %	kg/m ³
P	Pisé	-	-	-	20	66	14	0	1870*

ELS	Engineered Local Soil	-	-	-	20	9	60	10	2160
CEM-FA ELS	Engineered Local Soil	5	-	5	20	9	60	10	2100
CCR-FA ELS	Engineered Local Soil	-	6	25	20	9	60	10	2010

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Figure 2. Particle size distributions of the investigated mixes.

144

145 2.2 Hygroscopic characterization

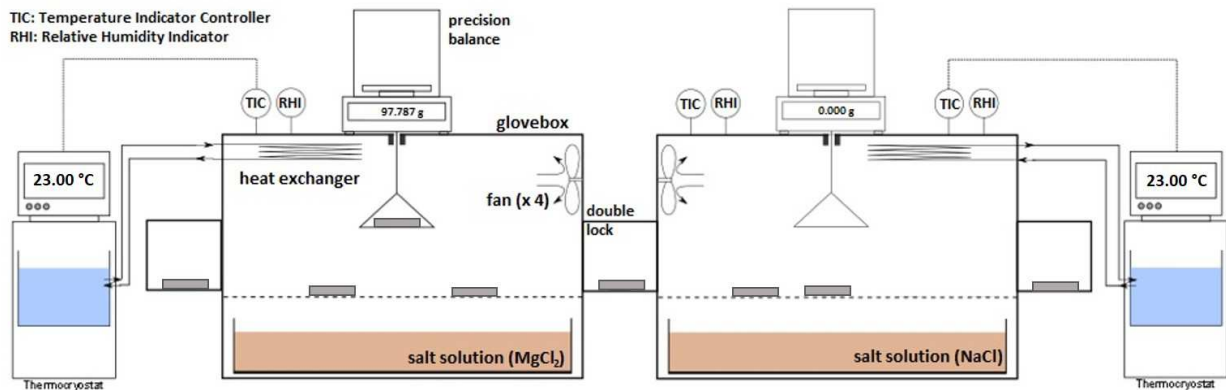
146 2.2.1 Moisture Buffer Value (MBV)

147 Indoor RH exhibits significant daily and seasonal variations due to internal loads related to human
 148 activities such as heating, cooking or taking a shower. To moderate the daily RH variations the

149 speed of moisture absorption and desorption is more important than the equilibrium moisture
150 content [5]. For this reason, dynamic tests with a run time corresponding to a typical exposure are
151 preferable to capture the passive air conditioning behaviour of a building material. A parameter that
152 allows the humidity buffering potential of building materials to be compared was proposed for the
153 first time by Rode in the Nordtest project framework and has been used since then by many authors
154 to characterise building materials [34]. The value obtained from the test is defined as Moisture
155 Buffer Value (MBV), expressed in $\text{g}/(\text{m}^2 \text{ \%RH})$. The test consists of repeatedly exposing the
156 surface of a specimen to a high humidity environment (nominally 75 %RH) for a period of 8 hours
157 and then to a low humidity environment (nominally 33 %RH) for a period of 16 hours. For each
158 cycle the average between the weight gain and loss is measured and the MBV is calculated from
159 three consecutive quasi-steady state cycles (i.e. when the averages differ by less than 5 %) [34].
160 Moisture states were quasi-steady as exposure times were purposefully shorter than those needed
161 for full equilibration. Humidity conditions were regulated using saturated salt solutions (NaCl and
162 MgCl_2 for the high and low RH levels respectively) inside two climatic chambers (Figure 3). The
163 two chambers were connected to a third, intermediate small chamber, which allowed the specimens
164 to be moved from one chamber to the other without exposing them to external conditions. The
165 temperature of the chamber was maintained at 23°C by a thermostatic controller, a water convection
166 heater and fans. The RH level in the chambers was monitored with sensors provided by Waranet
167 solutions SAS (HygroPuces, accuracy ± 3 %). Two balances (Mettler XPE, accuracy ± 1 mg)
168 allowed specimens to be weighed inside each chamber. Specimens used for the test were either
169 cylinders with dia. 100 mm or square prisms with 60 mm sides, both approximately 20 mm high.
170 The influence of different dimensions of the exposed surface area was investigated and the variation
171 of the results fell within the range of the experimental error. A thickness of 20 mm was considered
172 to be greater than the moisture penetration depth in earthen specimens, according to previous
173 studies [35], avoiding the risk of water fully penetrating the specimens and voiding the measured
174 mass change. Specimens were covered with aluminium tape and only one surface was left exposed

175 to the air. The exposed area was accurately determined by analysing scaled photographs using
 176 ImageJ software. The test was repeated at least three times for each specimen and at least two
 177 different specimens per mixture were tested. Both specimens cured under standard conditions and
 178 specimens that went through cyclic wetting-drying were tested.

179



180

181 **Figure 3.** Illustration of the custom-built climatic chambers used for the MBV test. On the left, the
 182 chamber at low RH environment and, on the right, the chamber at high RH environment.

183

184 2.2.2 Moisture sorption isotherms

185 ISO 12571 was used as reference standard to determine the sorption and desorption isotherms [36].
 186 Isotherms are equivalent to water retention curves if reported in terms of total suction (calculated
 187 from RH and temperature using the Kelvin equation) and degree of saturation or volumetric water
 188 content (calculated using the specimen void ratio). Samples with a mass of about 20 g and a
 189 prismatic shape (typically 5 cm x 2 cm x 1 cm) were used, wrapped in a permeable and
 190 hydrophobic nonwoven fabric to avoid particle loss. Before testing, specimens were oven-dried at
 191 105 °C to constant mass. Once dried, specimens were placed consecutively in a series of seven
 192 environments at different increasing relative humidity levels: 9 %, 22 %, 33 %, 58 %, 75 %, 84 %
 193 and 97 %. The test atmospheres were created using saturated salt solutions: KOH, CH₃CO₂K,

194 MgCl₂, NaBr, NaCl, KCl, K₂SO₄ respectively. Specimens were considered to be in equilibrium
195 with the environment when a constant mass was reached. Once in the last test environment (97
196 %RH), the reverse process was performed in order to determine the desorption curve. Temperature
197 was kept constant at 25 °C throughout the test. RH levels were monitored with HygroPuces sensors
198 (Waranet Solutions SAS, accuracy ±3 %). The test was conducted both on specimens cured under
199 standard conditions and on specimens that went through cyclic wetting-drying.

200

201

202 **2.2.3 Porosity**

203 The pore size spectrum of earthen mixtures can be expected to span at least six orders of magnitude
204 (from less than 1 nm up to more than 1 mm [37, 38]). Mercury intrusion porosimetry (MIP) and
205 nitrogen adsorption-desorption isotherms at 77.35 K were selected to investigate the pore structure
206 of the different specimens, as together they reliably cover the majority of this spectrum: MIP covers
207 the pore range from 6×10^4 to 6 nm while nitrogen adsorption-desorption isotherms covers the finer
208 diameters (from 300 to 1.7 nm). MIP tests and nitrogen adsorption-desorption isotherms were
209 conducted using, respectively, an AutoPore IV 9500 Hg porosimeter and a TriStar 3000 analyser,
210 both from Micromeritics Instrument Corp. The Barrett, Joyner and Halenda (BJH) and the
211 Brunauer, Emmett and Teller (BET) methods were used to derive, respectively, the pore size
212 distribution and the surface area from the nitrogen isotherms.

213

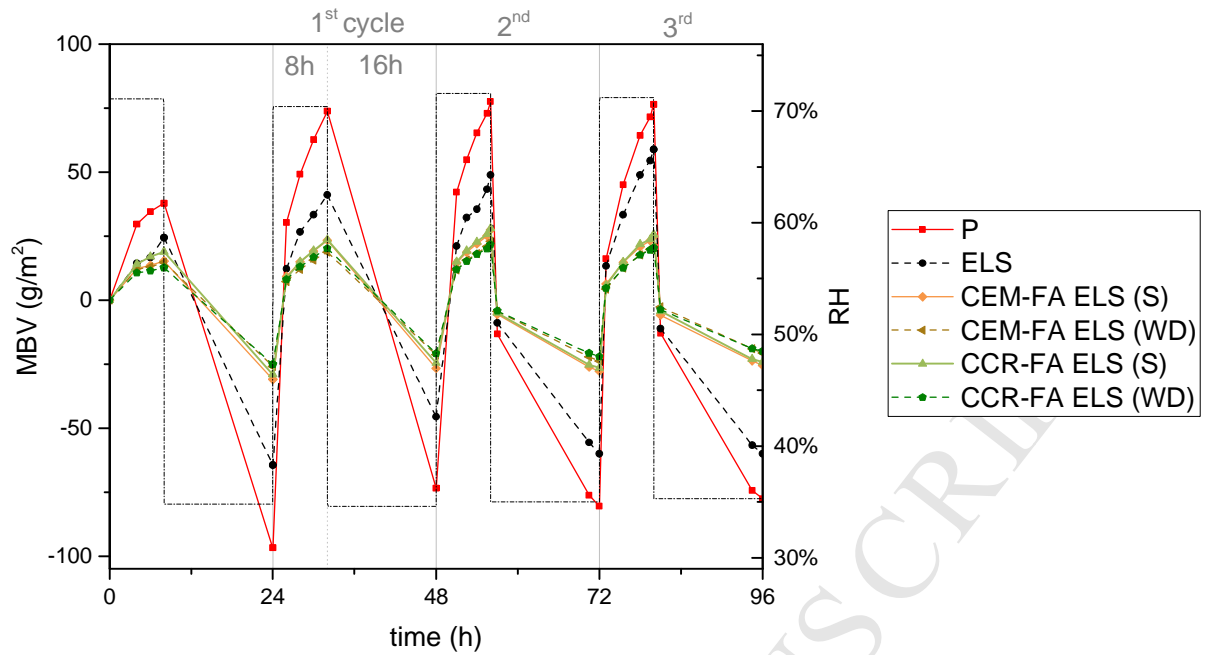
214 **3. RESULTS**

215 **3.1 Moisture Buffer Value (MBV)**

216 Figure 4 shows the cyclic moisture uptake and release per unit of exposed surface area of
217 representative specimens from each RE mixture. The average MBV results for each mixture are

218 reported in Figure 5. Results show that a variation in the mixture's substrate and stabiliser led to
219 different MBV values. The Nordtest sets the limits for the moisture buffering capacity of building
220 materials and classifies the MBV values in five different categories: negligible, limited, moderate,
221 good and excellent. Unstabilised mixes proved to be the ones with the best moisture buffering
222 capacity: P had an excellent behaviour with an average MBV over $2 \text{ g}/(\text{m}^2 \text{ \%RH})$, while ELS fell in
223 the "good" range with an average MBV of $1.53 \text{ g}/(\text{m}^2 \text{ \%RH})$. CEM-FA ELS (S) and CCR-FA ELS
224 (S) showed a similar behaviour, with a reduced MBV compared to the corresponding unstabilised
225 mixture. Both the mixes had a moderate buffering efficiency according to the Nordtest
226 classification. The same mixtures tested after wet and dry cycles displayed reduced abilities: the
227 MBV of CEM-FA ELS specimen slightly decreased from $0.82 \text{ g}/(\text{m}^2 \text{ \%RH})$ for CEM-FA ELS (S)
228 to $0.76 \text{ g}/(\text{m}^2 \text{ \%RH})$ for CEM-FA ELS (WD); CCR-FA ELS mixes showed a more pronounced
229 reduction going from $0.88 \text{ g}/(\text{m}^2 \text{ \%RH})$ for CCR-FA ELS (S) to $0.53 \text{ g}/(\text{m}^2 \text{ \%RH})$ for CCR-FA
230 ELS (WD), but still remaining in the "moderate" class.

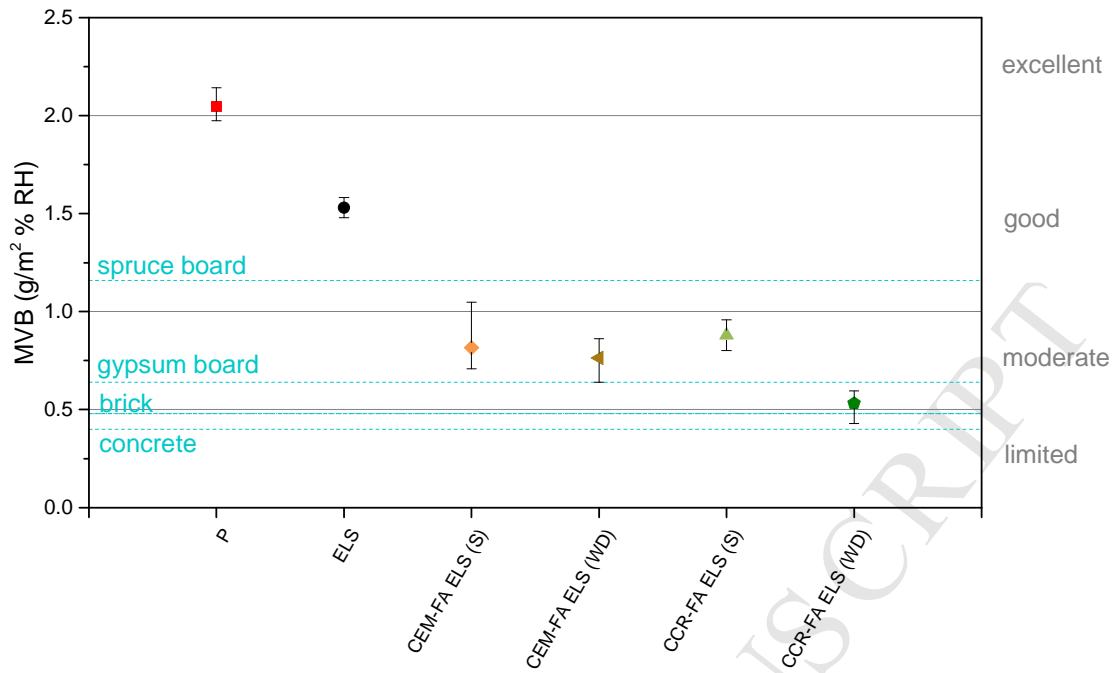
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233 **Figure 4.** Typical results of MBV testing. The 3 cycles highlighted represent the quasi steady state
 234 cycles used for the calculations. In the 2nd and 3rd cycle an additional measure soon after the transfer
 235 of the specimens in the low RH environment was performed. RH level during the test slightly differ
 236 from the nominal values due to the sensitivity of the saturated salt solutions to external factors.

237



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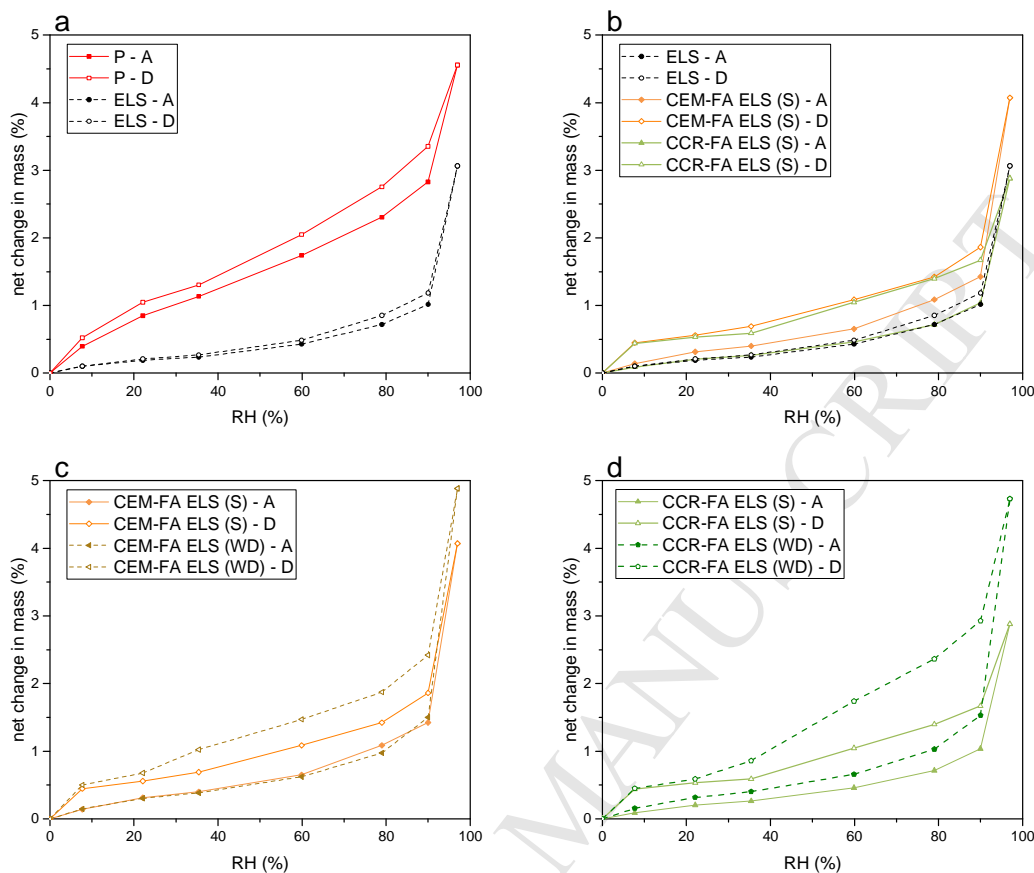
239 **Figure 5.** Average MBV results. The subdivisions on the right y-axis follow the classification
 240 proposed in [34]. MBV values for traditional building materials (light blue dashed lines) from [34]
 241 are reported for comparison.

242

243 3.2 Moisture sorption isotherms

244 Figure 6 shows the sorption isotherms obtained for the different mixtures following the ISO 12571
 245 recommendations. Figure 6a shows how different substrates led to very different curves: P absorbed
 246 much more moisture than ELS throughout the tests and showed a larger hysteresis loop. The effect
 247 of stabilisation on RE specimen is highlighted in Figure 6b where ELS sorption curves are
 248 superimposed on those of CEM-FA ELS (S) and CCR-FA ELS (S). The three materials showed
 249 similar adsorption isotherms but large hysteresis on desorption. The phenomenon was more evident
 250 for the sample stabilised with CCR and FA. In Figure 6c and d, the sorption isotherms of the mixes
 251 after exposure to wetting and drying cycles are compared with the same mixes cured at standard
 252 conditions. Samples after wet-dry cycles showed very similar adsorption curves to the samples
 253 cured at standard conditions but with a larger hysteresis. Again, the effect was more evident for
 254 CCR-FA stabilised ELS (Figure 6d).

255



256

257

258 **Figure 6.** Comparison of the isotherms results, according to ISO 12571. In a) unstabilised mixtures
 259 (P and ELS); in b) unstabilised (ELS) and stabilised specimens (CEM-FA ELS (S) and CCR-FA
 260 ELS (S)); in c) CEM-FA ELS cured at standard conditions (S) and after wet-dry cycles (WD); in d)
 261 CCR-FA ELS (S) and CCR-FA ELS (WD). A: Adsorption; D: Desorption.

262

263 3.3 Porosity

264 3.3.1 Mercury Intrusion Porosimetry (MIP)

265 MIP results are reported in Table 2 and Figure 7. Figure 7a shows the incremental porosity of the
 266 unstabilised mixtures made from different substrates. Both the samples showed a unimodal
 267 distribution: the mode of ELS ranged from 100 to 2000 Å while the mode of P spanned mainly the
 268 interval of 1500-20000 Å. The size of these diameters may be attributed to mesopores and

269 macropores separating tight agglomerates composed of quartz grains and clay particles [39]. In
270 Figure 7b pore size distributions for the unstabilised and stabilised soils are reported. CEM-FA ELS
271 (S) showed a similar distribution to ELS, slightly shifted towards smaller diameters. A shift would
272 be expected due to formation of cementitious products coating the agglomerates and reducing inter-
273 agglomerate mesopore diameters [40]. Conversely, CCR-FA ELS (S) showed a more uniform
274 distribution compared to ELS with a higher concentration of macropores. The more uniform
275 distribution can be attributed to the material's broader particle size distribution arising from the high
276 quantity of FA (particle diameters from few micrometres to more than 90 μm , with a median
277 diameter of 15 μm) in this material, which increased the amount of silt-size particles of ELS (Figure
278 2) and may have led to the formation of aggregates of variable dimensions as well as a reduced
279 compacted density (higher optimum water content).

280 The effect of weathering on the stabilised samples is presented in Figure 7c and d. CEM-FA ELS
281 (S) and (WD) distributions were similar, with a marginal increase of pores from 400 to 2000 \AA and
282 60-100 \AA suggesting cracking of the hydrated matrix and some formation of additional hydrated
283 products from unreacted binder particles, respectively, during the wet-dry cycles. CCR-FA ELS
284 (WD), however, showed a marked increase of small pores (60-100 \AA) and, consequently, a
285 reduction of the average pore diameter and an increase of the total pore area (Table 2).

286

287 **3.3.2 Nitrogen adsorption-desorption isotherms**

288 Nitrogen adsorption-desorption isotherms results are reported in Table 2 in terms of surface area
289 calculated with the BET method and average pore diameters obtained with the BJH method.
290 Considering the existence of hysteresis between adsorption and desorption isotherms, desorption
291 calculations were used to analyse the distribution of mesopores' diameters [41]. The different
292 adsorption-desorption curves and the BJH desorption cumulative pore volume curves are presented
293 in Figure 8.

294 P exhibited the highest surface area, the lowest average pore diameter and an important hysteresis in
295 the adsorption-desorption isotherm (Table 2, Figure 8a). Conversely, ELS exhibited a very limited
296 surface area, a large average pore diameter and almost no hysteresis. The net difference between P
297 and ELS could be attributed to the different particle size distributions of the two unstabilised
298 mixtures: while P had a minimal percentage ($< 15\%$) of particles with a diameter larger than $63 \mu\text{m}$,
299 ELS was mainly composed of these particles (Table 1). The abundance of fine particles in P formed
300 a clayey-silt matrix with a high specific surface area and an intrinsic narrow porosity
301 interconnecting larger pores [38]. The sharp step between 30 and 50 \AA on the desorption isotherm
302 was considered to be a sign of this pores' interconnection (Figure 8b).

303 Surface area and average pore diameter slightly increased and reduced respectively when ELS was
304 stabilised. Newly formed hydrated products occupied previously larger pores, reducing the entrance
305 diameter and creating an ink-bottle effect which resulted in a slightly larger hysteresis compared to
306 the unstabilised mixture (Figure 8d and e). The higher surface area of CEM-FA ELS (S) compared
307 to CCR-FA ELS (S) could be explained by the higher degree of hydration of the stabilisers used in
308 the former case under standard curing conditions [29].

309 Isotherms of stabilised ELS after wet-dry cycles were coherent with MIP results. Average pore
310 diameter was lower for both CEM-FA ELS (WD) and CCR-FA ELS (WD) compared to the same
311 mixtures cured under standard conditions, suggesting that unhydrated particles reacted during the
312 cycles and created narrower pore entrances leading to adsorption-desorption hysteresis. The effect
313 was confirmed by the sharp step in the cumulative pore volume between 30 and 50 \AA and it was
314 particularly evident for CCR-FA ELS, most likely due to the high amount of unreacted FA particles
315 in the mixture (Figure 8f and h).

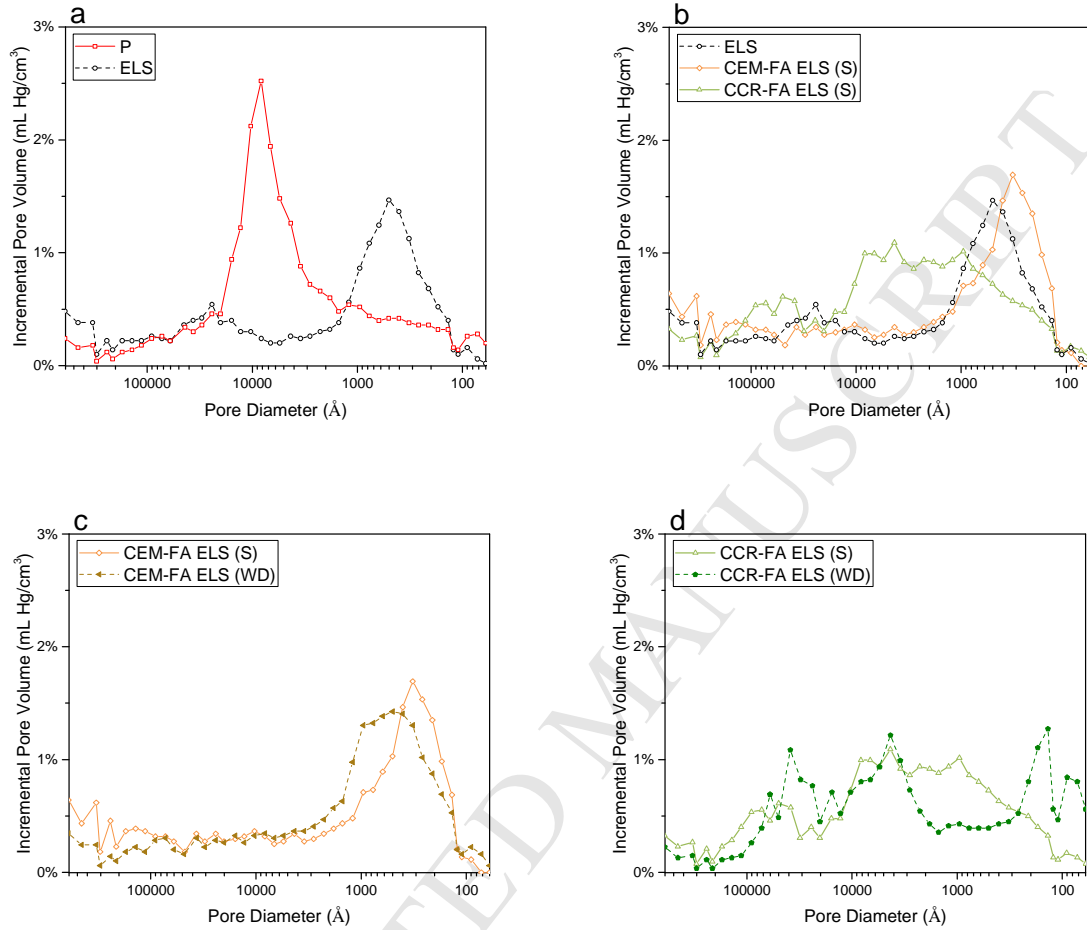
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317 **Table 2.** MBV and porosity results

Mix	MBV results	MIP bulk porosity	MIP average pore diameter	MIP total pore area	BET surface area	BJH average pore diameter
	g/(m ² %RH)	%	Å	m ² /g	m ² /g	Å
P	2.05	24.2	1012	5.09	15.0	90.8
ELS	1.53	19.2	764	5.91	4.87	286
CEM-FA ELS (S)	0.82	21.9	649	6.73	7.37	235
CEM-FA ELS (WD)	0.76	21.5	636	7.61	6.72	181
CCR-FA ELS (S)	0.88	24.1	1041	5.31	5.00	241
CCR-FA ELS (WD)	0.53	24.7	437	13.1	6.79	150

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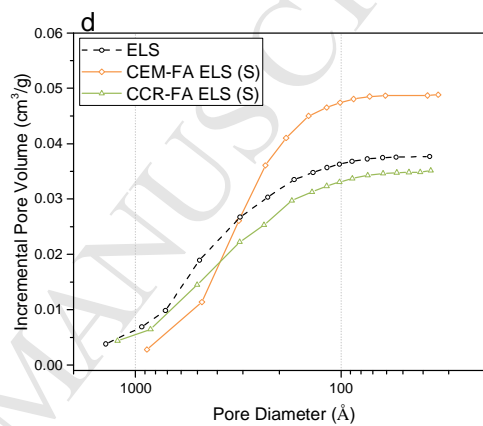
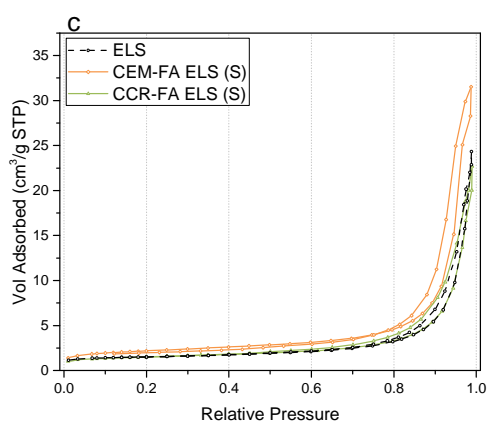
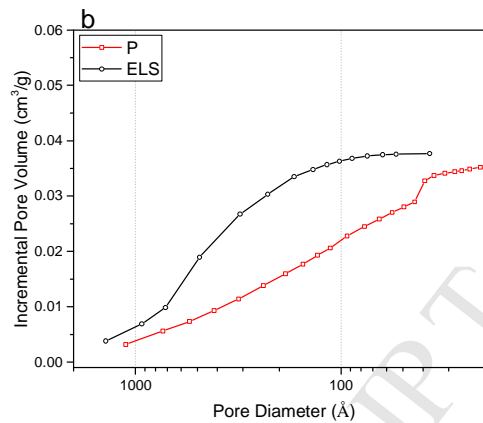
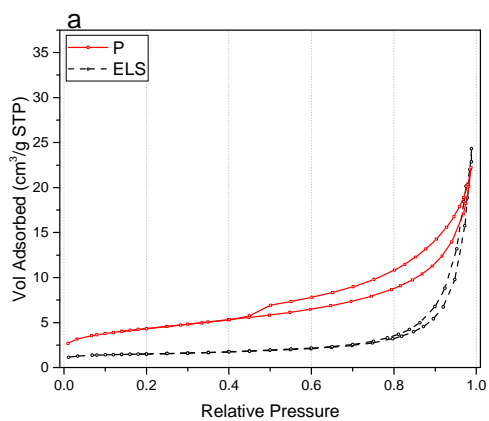
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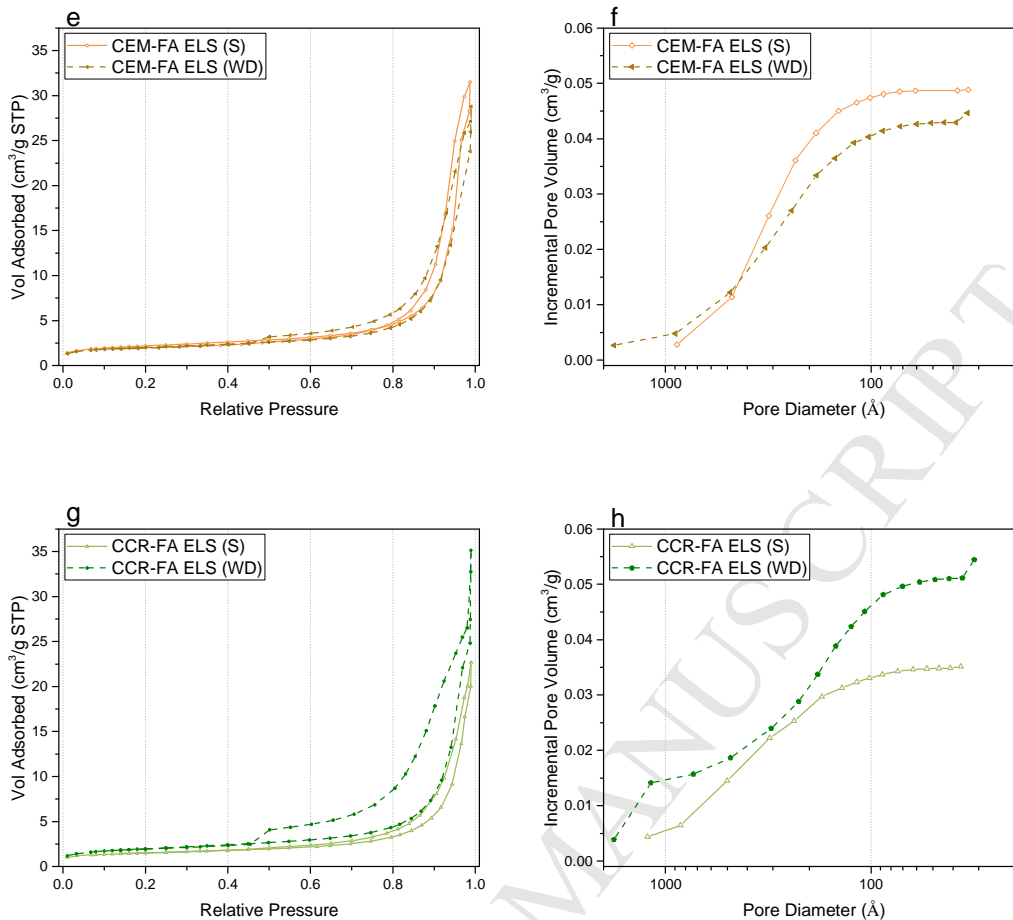
325

Figure 7. MIP results for: a) unstabilised mixtures (P and ELS); b) unstabilised (ELS) versus stabilised specimens (CEM-FA ELS (S) and CCR-FA ELS (S)); c) CEM-FA ELS cured at standard conditions (S) and after wet-dry cycles (WD); d) CCR-FA ELS (S) and CCR-FA ELS (WD).



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330 **Figure 8.** Nitrogen adsorption-desorption isotherm results (a-c-e-g) and BJH desorption cumulative
 331 pore volume curves (b-d-e-h) for: a-b) unstabilised mixtures (P and ELS); c-d) unstabilised (ELS)
 332 versus stabilised specimens (CEM-FA ELS (S) and CCR-FA ELS (S)); e-f) CEM-FA ELS cured at
 333 standard conditions (S) and after wet-dry cycles (WD); g-h) CCR-FA ELS (S) and CCR-FA ELS
 334 (WD).

335

336 4. DISCUSSION

337 MBV results confirmed that unstabilised RE is a good passive air conditioner and that this ability is
 338 highly affected by the soil's characteristics [18, 42, 43]: P and ELS had a very positive MBV but
 339 presented a marked difference between the results. The difference among the results was generated
 340 by the different porosity and soil mineralogy of the mixtures: P had both a higher bulk and very fine

341 porosity and a more hygroscopic clay fraction (mainly Illite, more hydrophilic than kaolinite, the
342 main component of the clay fraction of ELS [44-46]), improving its MBV over ELS. A marked
343 difference was also found between P and ELS isotherms: P adsorbed a much higher amount of
344 moisture and showed a larger hysteresis. The net difference in the hysteresis could be attributed to
345 the ink-bottle effect and to the capillary condensation caused by the presence of fine interconnecting
346 pores in the clayey matrix of P. The size of these pores ($< 100 \text{ \AA}$) corresponds in fact to the range of
347 critical pore radii for moisture condensation at the tested temperatures and humidities according to
348 the conjoined Kelvin and Young-Laplace equations, which describe the change in vapour pressure
349 due to a curved liquid-vapour interface [37, 47].

350 Stabilisation typically results in a reduction of clay's active surface area, due to the formation of
351 cementitious products covering the clay particles or a direct reaction between clay's constituents
352 and the stabiliser. A reduction of clay's active surface area generates a double effect on soils: i) an
353 increase in the sorptivity arising from reduced clay swelling [48, 49]; ii) a reduced physico-
354 chemical affinity for water, due to the inhibition of clay's high cation-exchange capacity [50].
355 Considering that no expansive clay was present, a lower active surface area only resulted in a
356 reduction of the soil's affinity for water. The effect was confirmed by the net decrease, up to 47 %
357 in the worst case, of the moisture buffer ability of stabilised ELS compared to the unstabilised
358 mixture. The results, in agreement with a previous study [51], were opposite to the trend in bulk
359 porosity, which was higher in stabilised specimens as supplementary fine material reduced their
360 Proctor dry densities, and in BET surface area, which was higher due to the formation of
361 cementitious gel. The different behaviour of the stabilised specimens compared to ELS was evident
362 in the sorption isotherms (Figure 6b), for which stabilised materials displayed greater hysteresis and
363 absorbed mass than the unaltered ELS. Greater absorbed masses were due to higher porosity.
364 However, increased hysteresis suggested an increase in the relative volume of trapped small pores
365 within the stabilised materials. Such an effect is expected if aggregates become inundated by
366 cementitious gel [26, 27, 52, 53].

367 Alternate wetting-drying cycles on stabilised samples led to a lower MBV compared to the same
368 mixture cured in standard conditions. Wetting-drying cycles have a double effect on stabilised soils:
369 i) the swelling and shrinking behaviour of clays has a detrimental effect on expansive soils, leading
370 to a destruction of the hydrated gel; ii) the availability of water and the relatively high temperatures
371 (71 °C) in the drying cycles triggers the hydration of unreacted stabilisers present in the mixture,
372 forming new cementitious products [54]. Renewed inundation of large pores by cementitious gel,
373 formed by the activation of large quantities of unreacted FA during wet and dry cycles, has
374 previously been demonstrated by the authors [29] and contributes to hysteresis via the ink-bottle
375 effect, where moisture becomes trapped inside large pores whose entrances are restricted [42, 55,
376 56]. Given the far higher FA and calcium hydroxide content of CCR-stabilised material,
377 opportunities for renewed hydration reactions were more likely in CCR-FA ELS. This effect was
378 captured in Figure 7b and Figure 8h as a sharp volume increase for fine porosity.

379 5. CONCLUSIONS

380 This article investigated the influence of stabilisation and weathering on the moisture buffer
381 capacity of RE specimens. From the experimental outcomes and the microstructural investigation,
382 the following conclusions were drawn from the study:

- 383 • The two unstabilised mixtures investigated confirmed the very good air passive conditioning
384 ability of URE. Nevertheless, the performance seems to be highly influenced by the particle
385 size distribution and by the mineralogy of the clay particles.
- 386 • Stabilisation considerably reduced the moisture buffering ability of RE, attributed to the
387 reduced physico-chemical affinity between water and clays. Nevertheless, although
388 performing worse than unstabilised mixtures, SRE mixtures performed better than most
389 traditional building materials (e.g. brick, gypsum board, concrete).
- 390 • Weathering, simulated by cyclic wetting-drying, further reduced the moisture buffer ability
391 of stabilised samples when unreacted particles were present and new cementitious products

392 could be formed. Conversely, it did not considerably affect the results when a low amount of
393 unreacted particles was present.

394 • Although stabilisation of RE is highly beneficial for the mechanical properties of the
395 structure and although particular attention to the choice of the additives could be paid to
396 reduce the environmental impacts, the addition of chemical binders seemed to reduce the
397 passive air conditioning ability of earthen walls.

398 • In order to understand if the main outcome of the present study represents a general rule, the
399 experimental investigation needs to be extended to different soil mixtures and alternative
400 stabilisation methods. On the same line, tests on samples exposed to real indoor conditions
401 need to be performed to validate the accelerated weathering results. From the environmental
402 point of view, using the minimum amount of low-impact stabilisers to reach the required
403 mechanical performance seems to be advisable, to reduce the effect on indoor building
404 comfort. However, a full life-cycle assessment of the different RE mixtures, which takes
405 into account the hygrothermal behaviour, would be necessary to obtain the optimal mixture
406 that minimises the environmental impact, guarantees a sufficient strength and safeguards the
407 occupants' health.

408

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HIGHLIGHTS

- Unstabilised RE (URE) was confirmed to be a very good air passive conditioner
- MBV of URE was highly influenced by particle size distribution and mineralogy
- Stabilisation considerably reduced the moisture buffer ability of Stabilised RE
- Clays' active surface area seemed to be the key parameter affecting MBV
- Weathering further reduced the MBV when unreacted stabiliser was present