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

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ABSTRACT

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

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1. Introduction

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

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

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

Traditional RE construction does not use additives but nowadays stabilisers are generally added to the earth mixture to improve its strength and erosion resistance. The addition of stabilisers, mainly Portland cement, jeopardizes the environmental benefits related to the use of a natural and virtually unlimited material such as raw earth [14]. On the other hand, traditional unstabilised rammed earth (URE) has a low compressive strength and questionable durability [15]. The environmental impact of cement is therefore considered as the price to pay for a stronger, more long-lasting material. Using waste products as alternative stabilisers has proved to be a viable solution to decrease the environmental impact of the rammed earth mixture while still providing enough strength and durability [16].

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

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

2. Materials and methods

2.1. Materials

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

The stabilisers used were cement (General Purpose Cement Type GP according to AS 3972 [24] composed of Portland cement and small amounts (<7%) of limestone), fly ash (FA) and calcium carbide residue (CCR). FA is the residue from a coal power plant and was classified as class F according to its calcium content [25]. CCR is the residue of acetylene production and was composed of calcium hydroxide with a small fraction of calcium carbonate. Cement, once mixed to the soil with water, forms hydrated compounds, typically hydrated calcium silicates and hydrated calcium aluminates, which link soil particles together [26]. The addition of calcium hydroxide gives rise to the same hydrated compounds on the long term by reacting with the silica and alumina dissolved from the clay structure [27]. The formation of these hydrated products is further enhanced when low-cost class F FA are added to the mixture and its siliceous and aluminous glassy components are activated by a cementitious agent such as cement or calcium hydroxide [26,28].

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

Except for P, samples used for hygroscopic testing were cut using a mitre saw from cylinders compacted at their Modified Proctor optimum water content and density [31]. Cylinders were cured either at standard conditions (S) (28 days in a climatic chamber at 96 %RH and 21 °C) or went through cyclic wetting-drying (WD) according to ASTM D559M standard [32]. After the respective aging conditions, cylinders were tested for compressive strength and remains were stored in sealed plastic bags for hygroscopic and microstructural analysis. P was cut directly from a wall erected by RE practitioners using soil from a demolished *pisé* farm in Dagneux, France. The wall was compacted below the standard Proctor optimum water content and the resulting density was about 1830 kg/m^3 [33]. Unstabilised mixes (P and ELS) were left to dry in ambient conditions for several weeks after manufacture; given the lack of stabiliser, curing conditions do not affect material hygroscopic properties beyond providing sufficient strength to maintain their material structure.

2.2. Hygroscopic characterization

2.2.1. Moisture Buffer Value (MBV)

Indoor RH exhibits significant daily and seasonal variations due to internal loads related to human activities such as heating, cooking or taking a shower. To moderate the daily RH variations the speed of moisture absorption and desorption is more important than the equilibrium moisture content [5]. For this reason, dynamic tests with a run time corresponding to a typical exposure are preferable to capture the passive air conditioning behaviour of a building material. A parameter that allows the humidity buffering potential of building materials to be compared was proposed for the first time by Rode in the Nordtest project framework and has been used since then by many authors to characterise building materials [34]. The value obtained

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

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[a]
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

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

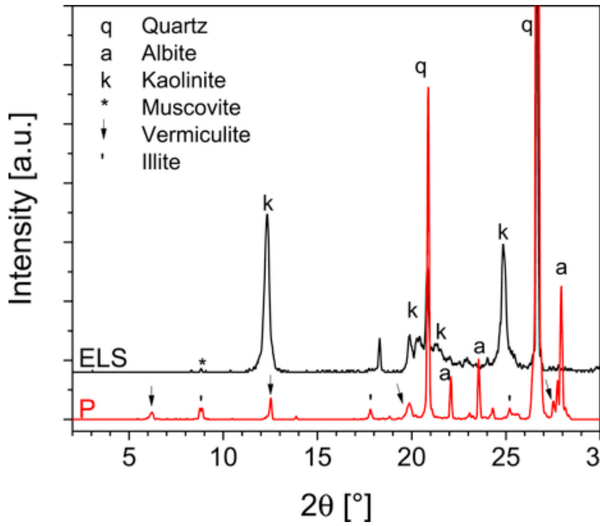


Fig. 1. XRD Patterns of Pisé soil (P, below, in red) and the clay fraction of ELS (ELS, above, in black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from the test is defined as Moisture Buffer Value (MBV), expressed in g/(m^2 %RH). The test consists of repeatedly exposing the surface of a specimen to a high humidity environment (nominally 75 %RH) for a period of 8 h and then to a low humidity environment (nominally 33 %RH) for a period of 16 h. For each cycle the average between the weight gain and loss is measured and the MBV is calculated from three consecutive quasi-steady state cycles (i.e. when the averages differ by less than 5%) [34]. Moisture states were quasi-steady as exposure times were purposefully shorter than those needed for full equilibration. Humidity conditions were regulated using saturated salt solutions (NaCl and $MgCl_2$ for the high and low RH levels respectively) inside two climatic chambers (Fig. 3). The two chambers were connected to a third, intermediate small chamber, which allowed the specimens to be moved from one chamber to the other without exposing them to external conditions. The temperature of the chamber was maintained at 23 °C by a thermostatic controller, a water convection heater and fans. The RH level in the chambers was monitored with sensors provided by Waranet solutions SAS (HygroPuces, accuracy ±3%). Two balances (Mettler XPE, accuracy ±1 mg) allowed specimens to be weighed inside each chamber. Specimens used for the test were either cylinders with dia. 100 mm or square prisms with 60 mm sides, both approximately 20 mm high. The influence of different dimensions of the exposed surface area

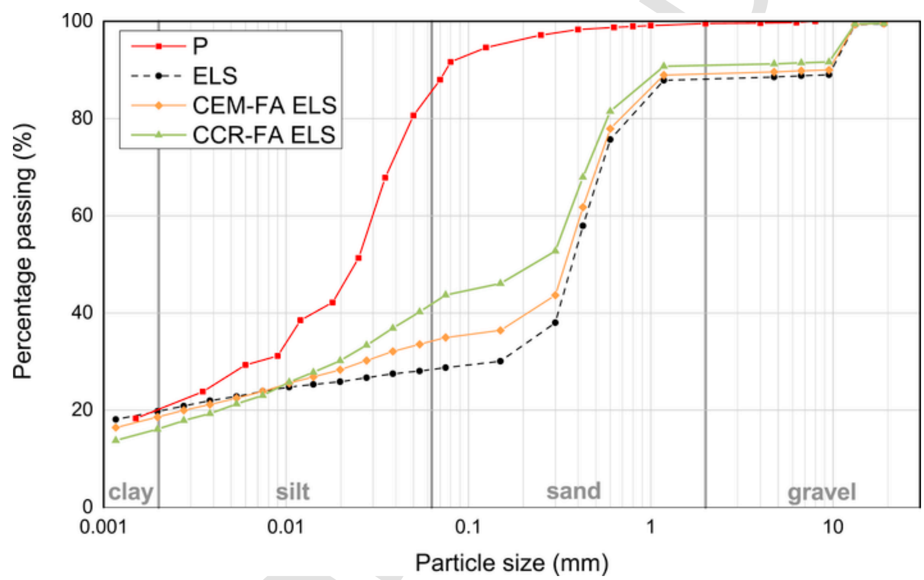


Fig. 2. Particle size distributions of the investigated mixes.

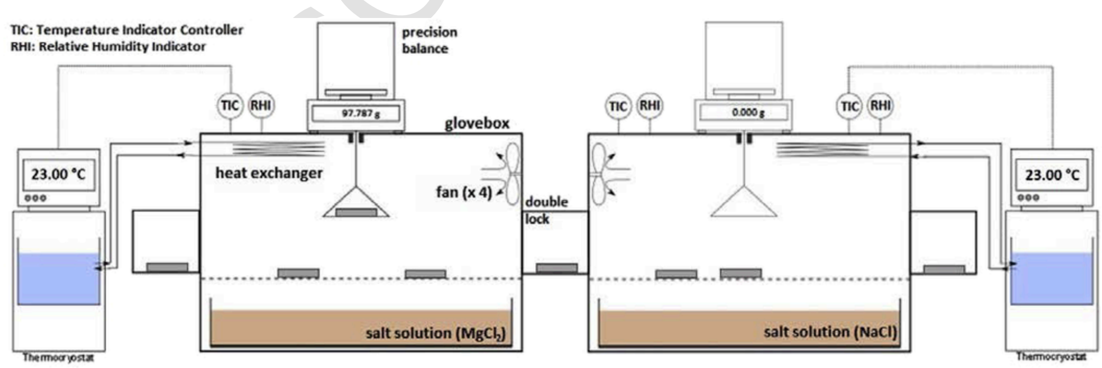


Fig. 3. Illustration of the custom-built climatic chambers used for the MBV test. On the left, the chamber at low RH environment and, on the right, the chamber at high RH environment.

was investigated and the variation of the results fell within the range of the experimental error. A thickness of 20 mm was considered to be greater than the moisture penetration depth in earthen specimens, according to previous studies [35], avoiding the risk of water fully penetrating the specimens and voiding the measured mass change. Specimens were covered with aluminium tape and only one surface was left exposed to the air. The exposed area was accurately determined by analysing scaled photographs using ImageJ software. The test was repeated at least three times for each specimen and at least two different specimens per mixture were tested. Both specimens cured under standard conditions and specimens that went through cyclic wetting-drying were tested.

2.2.2. *Moisture sorption isotherms*

ISO 12571 was used as reference standard to determine the sorption and desorption isotherms [36]. Isotherms are equivalent to water retention curves if reported in terms of total suction (calculated from RH and temperature using the Kelvin equation) and degree of saturation or volumetric water content (calculated using the specimen void ratio). Samples with a mass of about 20 g and a prismatic shape (typically 5 cm × 2 cm x 1 cm) were used, wrapped in a permeable and hydrophobic nonwoven fabric to avoid particle loss. Before testing, specimens were oven-dried at 105 °C to constant mass. Once dried, specimens were placed consecutively in a series of seven environments at different increasing relative humidity levels: 9%, 22%, 33%, 58%, 75%, 84% and 97%. The test atmospheres were created using saturated salt solutions: KOH, CH_3CO_2K, $MgCl_2$, NaBr, NaCl, KCl, K_2SO_4 respectively. Specimens were considered to be in equilibrium with the environment when a constant mass was reached. Once in the last test environment (97 %RH), the reverse process was performed in order to determine the desorption curve. Temperature was kept constant at 25 °C throughout the test. RH levels were monitored with HygroPuces sensors (Waranet Solutions SAS, accuracy ±3%). The test was conducted both on specimens cured under standard conditions and on specimens that went through cyclic wetting-drying.

2.2.3. *Porosity*

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

3. Results

3.1. *Moisture Buffer Value (MBV)*

Fig. 4 shows the cyclic moisture uptake and release per unit of exposed surface area of representative specimens from each RE mixture. The average MBV results for each mixture are reported in Fig. 5. Results show that a variation in the mixture's substrate and stabiliser led to different MBV values. The Nordtest sets the limits for the moisture buffering capacity of building materials and classifies the MBV values in five different categories: negligible, limited, moderate, good and excellent. Unstabilised mixes proved to be the ones with the best moisture buffering capacity: P had an excellent behaviour with an average MBV over 2 g/(m^2 %RH), while ELS fell in the "good" range with an average MBV of 1.53 g/(m^2 %RH). CEM-FA ELS (S) and CCR-FA ELS (S) showed a similar behaviour, with a reduced MBV compared to the corresponding unstabilised mixture. Both the mixes had a moderate buffering efficiency according to the Nordtest classification. The same mixtures tested after wet and dry cycles displayed reduced abilities: the MBV of CEM-FA ELS specimen slightly decreased from 0.82 g/(m^2 %RH) for CEM-FA ELS (S) to 0.76 g/(m^2 %RH) for CEM-FA ELS (WD); CCR-FA ELS mixes showed a more pronounced reduction going from 0.88 g/(m^2 %RH) for CCR-FA ELS (S) to 0.53 g/(m^2 %RH) for CCR-FA ELS (WD), but still remaining in the "moderate" class.

3.2. *Moisture sorption isotherms*

Fig. 6 shows the sorption isotherms obtained for the different mixtures following the ISO 12571 recommendations. Fig. 6a shows how

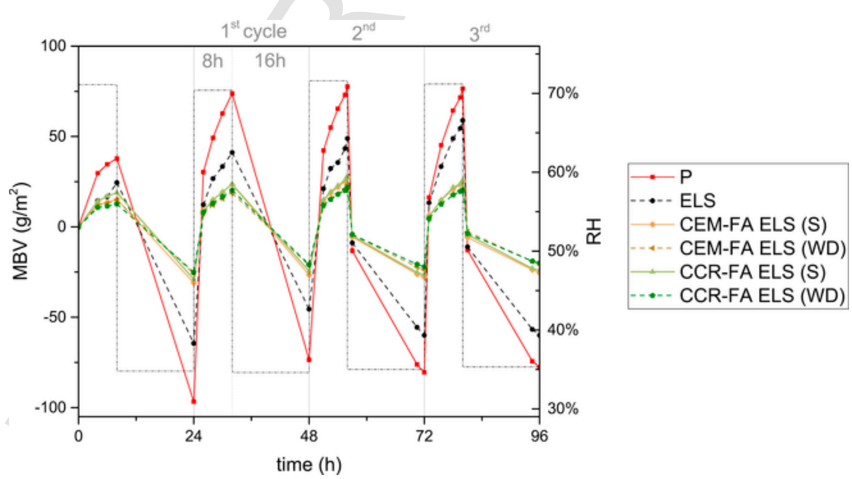


Fig. 4. Typical results of MBV testing. The 3 cycles highlighted represent the quasi steady state cycles used for the calculations. In the 2nd and 3rd cycle an additional measure soon after the transfer of the specimens in the low RH environment was performed. RH level during the test slightly differ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

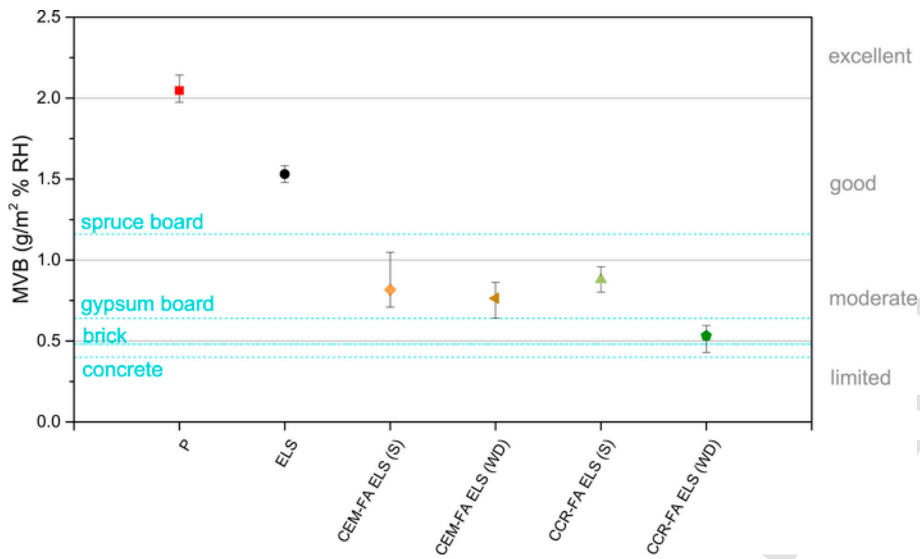


Fig. 5. Average MBV results. The subdivisions on the right y-axis follow the classification proposed in Ref. [34]. MBV values for traditional building materials (light blue dashed lines) from Ref. [34] are reported for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

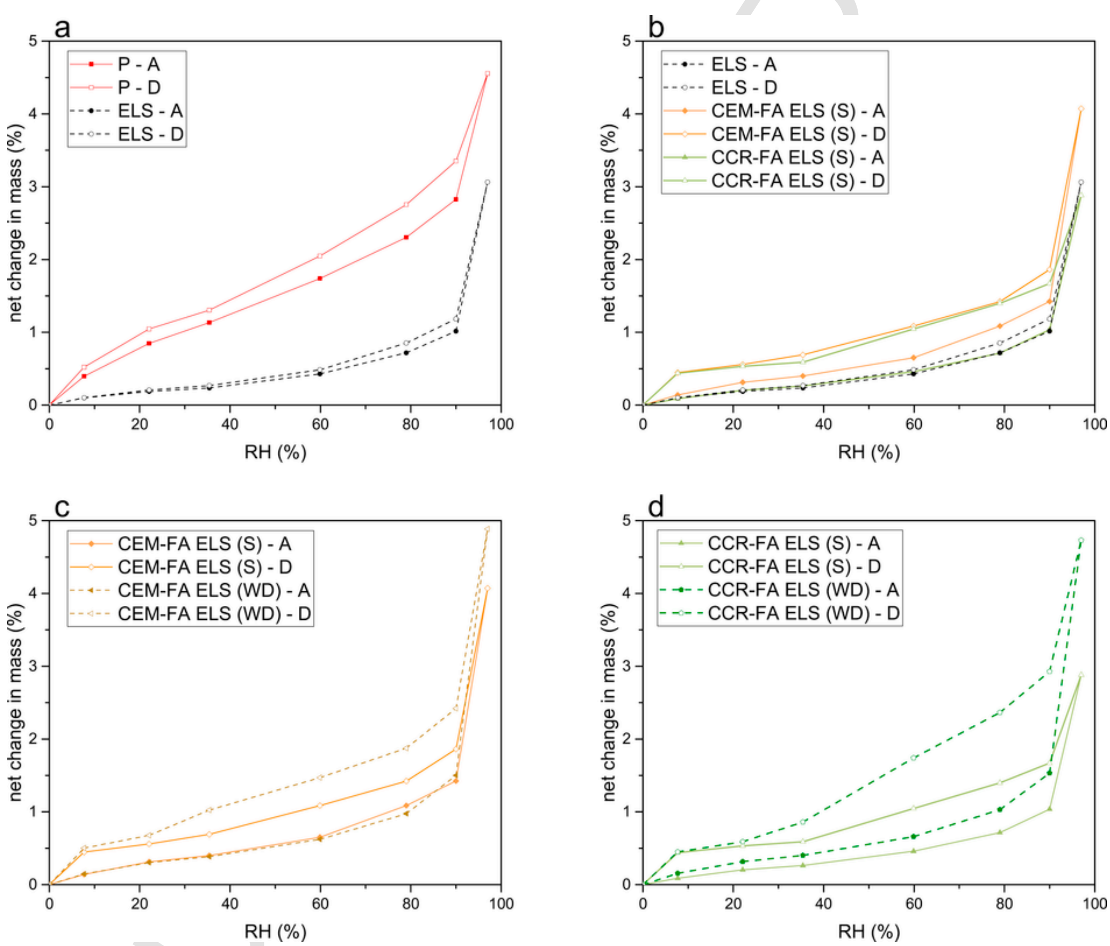


Fig. 6. Comparison of the isotherms results, according to ISO 12571. In a) unstabilised mixtures (P and ELS); in b) unstabilised (ELS) and stabilised specimens (CEM-FA ELS (S) and CCR-FA ELS (S)); in c) CEM-FA ELS cured at standard conditions (S) and after wet-dry cycles (WD); in d) CCR-FA ELS (S) and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

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

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

3.3. Porosity

3.3.1. Mercury intrusion porosimetry (MIP)

MIP results are reported in Table 2 and Fig. 7. Fig. 7a shows the incremental porosity of the unstabilised mixtures made from different substrates. Both the samples showed a unimodal distribution: the mode of ELS ranged from 100 to 2000 Å while the mode of P spanned mainly the interval of 1500–20000 Å. The size of these diameters may be attributed to mesopores and macropores separating tight agglomerates composed of quartz grains and clay particles [39]. In Fig. 7b pore size distributions for the unstabilised and stabilised soils are reported. CEM-FA ELS (S) showed a similar distribution to ELS, slightly shifted towards smaller diameters. A shift would be expected due to formation of cementitious products coating the agglomerates and reducing inter-agglomerate mesopore diameters [40]. Conversely, CCR-FA ELS (S) showed a more uniform distribution compared to ELS with a higher concentration of macropores. The more

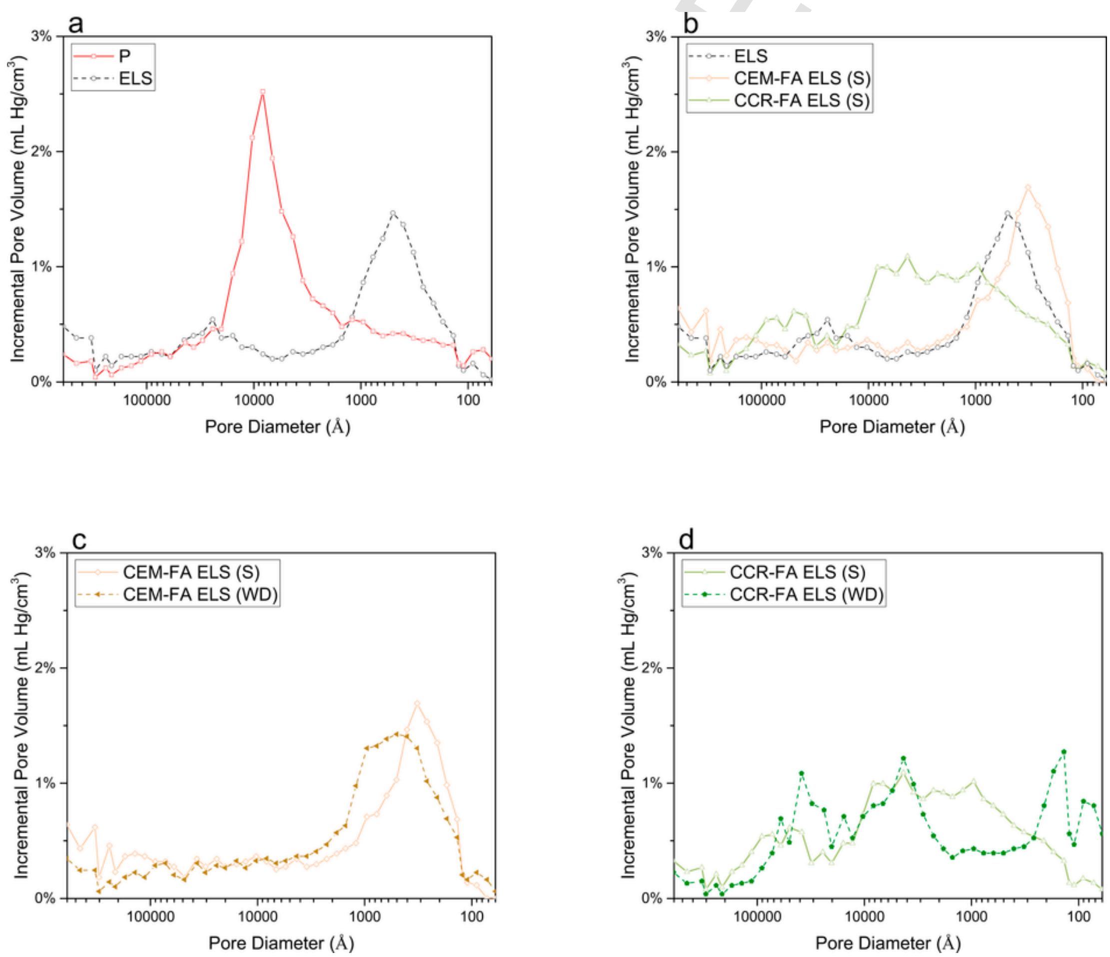


Fig. 7. MIP results for: a) unstabilised mixtures (P and ELS); b) unstabilised (ELS) versus stabilised specimens (CEM-FA ELS (S) and CCR-FA ELS (S)); c) CEM-FA ELS cured at standard conditions (S) and after wet-dry cycles (WD); d) CCR-FA ELS (S) and CCR-FA ELS (WD).

uniform distribution can be attributed to the material's broader particle size distribution arising from the high quantity of FA (particle diameters from few micrometres to more than 90 μm, with a median diameter of 15 μm) in this material, which increased the amount of silt-size particles of ELS (Fig. 2) and may have led to the formation of aggregates of variable dimensions as well as a reduced compacted density (higher optimum water content).

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

3.3.2. Nitrogen adsorption-desorption isotherms

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

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

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

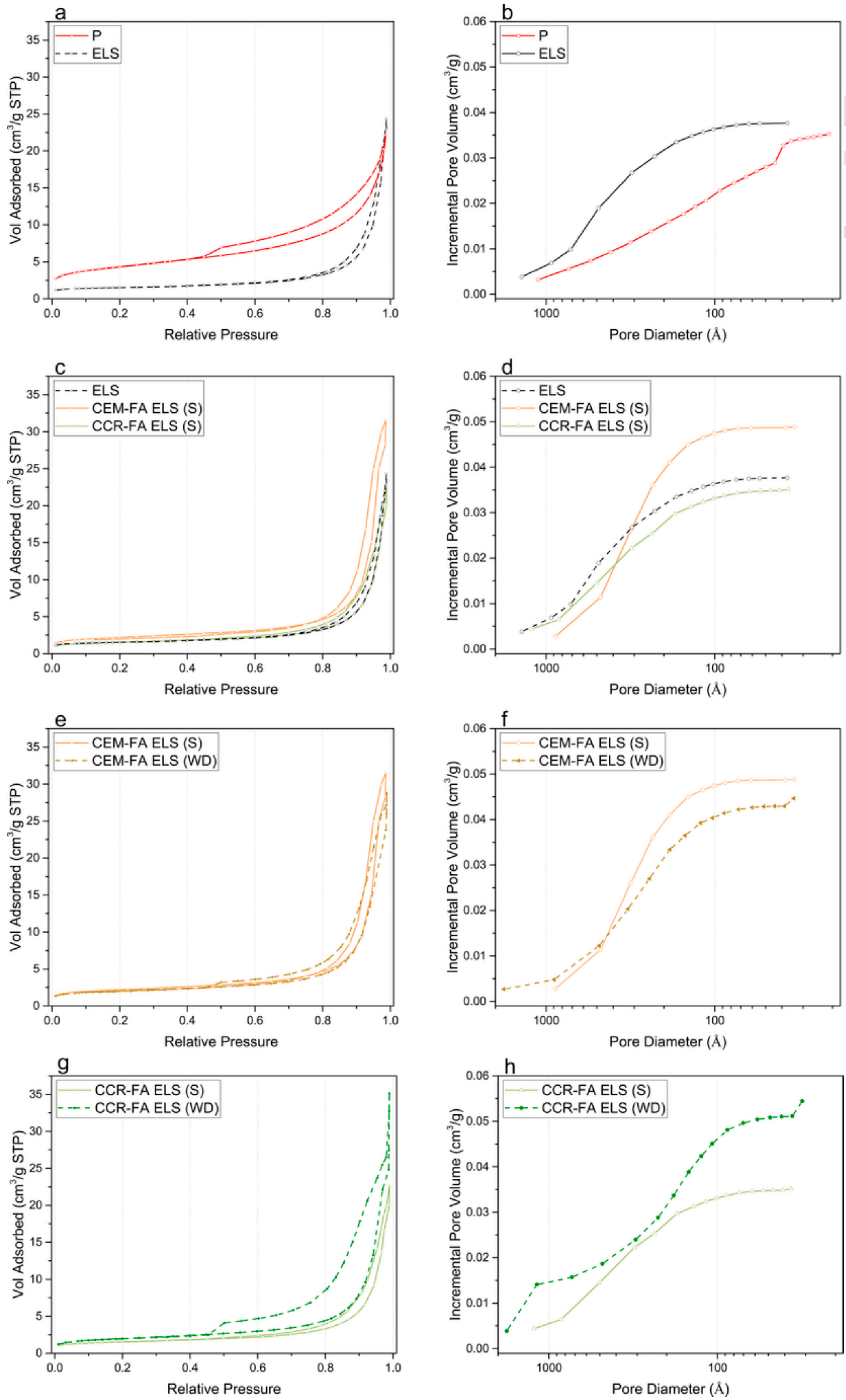
Isotherms of stabilised ELS after wet-dry cycles were coherent with MIP results. Average pore diameter was lower for both CEM-FA ELS (WD) and CCR-FA ELS (WD) compared to the same mixtures cured under standard conditions, suggesting that unhydrated particles reacted during the cycles and created narrower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

4. Discussion

MBV results confirmed that unstabilised RE is a good passive air conditioner and that this ability is highly affected by the soil's characteristics [18,42,43]: P and ELS had a very positive MBV but presented a marked difference between the results. The difference among the results was generated by the different porosity and soil mineralogy of the mixtures: P had both a higher bulk and very fine porosity and a more hygroscopic clay fraction (mainly Illite, more hydrophilic than kaolinite, the main component of the clay fraction of ELS [44–46]), improving its MBV over ELS. A marked difference was also found between P and ELS isotherms: P adsorbed a much higher amount of moisture and showed a larger hysteresis. The net difference in the hysteresis could be attributed to the ink-bottle effect and to the capillary condensation caused by the presence of fine interconnecting pores in the clayey matrix of P. The size of these pores (<100 Å) corresponds in fact to the range of critical pore radii for moisture condensation at the tested temperatures and humidities according to the conjoined Kelvin and Young-Laplace equations, which describe the change in vapour pressure due to a curved liquid-vapour interface [37,47].

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

Alternate wetting-drying cycles on stabilised samples led to a lower MBV compared to the same mixture cured in standard conditions. Wetting-drying cycles have a double effect on stabilised soils: i) the swelling and shrinking behaviour of clays has a detrimental effect on expansive soils, leading to a destruction of the hydrated gel; ii) the availability of water and the relatively high temperatures (71 °C) in the drying cycles triggers the hydration of unreacted stabilisers present in the mixture, forming new cementitious products [54]. Renewed inundation of large pores by cementitious gel, formed by the activation of large quantities of unreacted FA during wet and dry cycles, has previously been demonstrated by the authors [29] and contributes to hysteresis via the ink-bottle effect, where moisture becomes trapped inside large pores whose entrances are restricted [42,55,56]. Given the far higher FA and calcium hydroxide content of CCR-stabilised material, opportunities for renewed hydration reactions were more likely in CCR-FA ELS. This effect was captured in Figs. 7b and 8h as a sharp volume increase for fine porosity.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CEM-FA ELS (S)
CCR-FA ELS (S)
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e
CEM-FA ELS (S)
CEM-FA ELS (WD)
Vol Adsorbed (cm³/g STP)
Relative Pressure
f
CEM-FA ELS (S)
CEM-FA ELS (WD)
Incremental Pore Volume (cm³/g)
Pore Diameter (Å)
g
CCR-FA ELS (S)
CCR-FA ELS (WD)
Vol Adsorbed (cm³/g STP)
Relative Pressure
h
CCR-FA ELS (S)
CCR-FA ELS (WD)
Incremental Pore Volume (cm³/g)
Pore Diameter (Å)

5. Conclusions

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

- The two unstabilised mixtures investigated confirmed the very good air passive conditioning ability of URE. Nevertheless, the performance seems to be highly influenced by the particle size distribution and by the mineralogy of the clay particles.
- Stabilisation considerably reduced the moisture buffering ability of RE, attributed to the reduced physico-chemical affinity between water and clays. Nevertheless, although performing worse than unstabilised mixtures, SRE mixtures performed better than most traditional building materials (e.g. brick, gypsum board, concrete).
- Weathering, simulated by cyclic wetting-drying, further reduced the moisture buffer ability of stabilised samples when unreacted particles were present and new cementitious products could be formed. Conversely, it did not considerably affect the results when a low amount of unreacted particles was present.
- Although stabilisation of RE is highly beneficial for the mechanical properties of the structure and although particular attention to the choice of the additives could be paid to reduce the environmental impacts, the addition of chemical binders seemed to reduce the passive air conditioning ability of earthen walls.
- In order to understand if the main outcome of the present study represents a general rule, the experimental investigation needs to be extended to different soil mixtures and alternative stabilisation methods. On the same line, tests on samples exposed to real indoor conditions need to be performed to validate the accelerated weathering results. From the environmental point of view, using the minimum amount of low-impact stabilisers to reach the required mechanical performance seems to be advisable, to reduce the effect on indoor building comfort. However, a full life-cycle assessment of the different RE mixtures, which takes into account the hygrothermal behaviour, would be necessary to obtain the optimal mixture that minimises the environmental impact, guarantees a sufficient strength and safeguards the occupants' health.

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

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