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1 Rethinking Excavated-Earth Concrete: Water Transport 2 in Sustainable Earthcretes

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11

12 Abstract

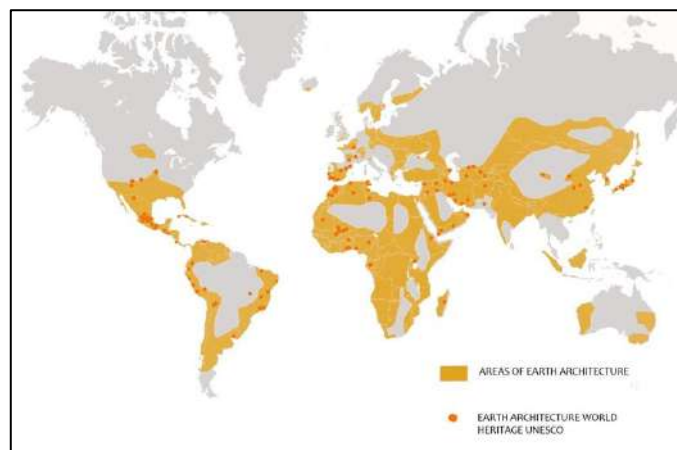
13 Durability is a critical—yet often underestimated—aspect of concrete technology and sustainable
14 construction materials. Parameters like CO₂-eq emissions (GWP) are key indicators of a Life Cycle
15 Assessment (LCA) and should be systematically evaluated over a structure's full-service life and its
16 depreciation time (economic life). This ensures that economic, environmental, and societal efficiency are
17 well-balanced. However, the length of a structure's service and economic life cycles depends on its
18 durability and reparability. Durability is therefore a key issue for ensuring structural integrity, long-
19 term functionality, environmental resilience, and economic sustainability. This study examines the
20 effect on the durability of the interaction between water and Shot-Earth, an innovative earth-based
21 concrete also applied to structural elements including reinforced walls, beams, vaults and slabs. Two
22 structural-grade Shot-Earth mixtures were evaluated in detail. The sorption coefficients were found to
23 be 0.8 kg/(m²h^{0.5}) and 3 kg/(m²h^{0.5}) over 24 hours, reflecting the influence of water-soil affinity, binder
24 content, porosity, and internal cohesion. Conversely, higher stabilizer content, reduced voids, and
25 higher density allow to reduce the coefficient to 0.2 kg/(m²h^{0.5}) such as for Ordinary Portland Cement
26 (OPC) concrete in comparison. It is also shown that Shot-Earth exhibits water permeability in the range
27 of 1.965×10⁻¹⁶ m² to 3.373×10⁻¹⁶ m², more than one order of magnitude higher than OPC concrete. The
28 experimental findings were supported by both FE modeling and a numerical simulation, providing
29 reliable tools to predict and optimize the durability of earth-based materials such as Shot-Earth.

30 *Keywords:* Shot-Earth, Earth-based Materials, Sustainability, Water Absorption, Durability, FE
31 Simulation

32 *Abbreviations:* SE2, Shot-Earth 772; SE1, Shot-Earth 771; SE1-2, Shot-Earth both mixtures 771 and 772;
33 C45, Ordinary Concrete (OPC) 45.5 MPa; IRA, Initial Rate of Absorption; FE: Finite Element

34 1. Introduction

35 Soil is one of the earliest building materials used by humanity. Formed through a long and slow physic
36 disaggregation processes promoted by natural weathering such as freeze-to-thaw cycles, rain, wind,
37 and manufacturing processes, soil has supported human structures since as early as 10'000 BCE in
38 Mesopotamia (the current Iraq, [1]) till recent years. Noteworthy techniques such as adobe [2,3], cob,
39 waffle and daub, torchis, pisé (or beaten earth), and rammed earth remain widely used nowadays,
40 providing shelter for an estimated 30–50% of the global population [4] (Fig. 1). These methods offer
41 significant ecological benefits including energy efficiency, resource conservation, and positive social
42 impact. The indoor well-being provided by earthen buildings is also a key factor that makes them a
43 preferable choice [5–7].



44
45

Fig. 1. World map for still-on-use earth – UNESCO Heritage

46 Cities such as Shibam, often referred to as the “Manhattan of the Desert” in Yemen [8], are located in
47 seismic zones and have withstood natural hazards for hundreds of years. Nevertheless, recent climate
48 change-induced flooding has severely challenged these traditional materials and revealed a critical
49 shortage of skilled workers able to repair them. Despite these ancient solutions, the improvement in
50 durability was considered nearly compulsory over the years by traditional builders that used natural
51 additives such as tree resins, cow dung, animal blood, and oils from plants or animals. These substances
52 helped make soil more water-resistant and durable, and they were low-cost and easy to provide.
53 However, these natural stabilizers became less effective. For this reason, the modern construction
54 industry still relies predominantly on concrete – a material associated with high environmental costs,
55 including CO₂ emissions, landfill accumulation, and intensive energy consumption. A growing issue is
56 the disposal of excavated soil in urban areas, which contributes to pollution, urban disruption, and
57 logistical complications. In response to these challenges, Shot-Earth has emerged as a promising
58 sustainable material. It combines soil, sand, and an optional amount of cement and it is applied at high

59 velocity to achieve dense compaction and early-stage green strength, thus eliminating the need of
60 conventional formwork [8–14] (Fig. 2a). Notably, the cement content is reduced up to 60% as compared
61 to that of an OPC concrete, making it an environmentally attractive alternative. Shot-Earth applications
62 are several: the main advantage of using dry shotcrete [15] technology lies in the high placement speed
63 to ensure good self-compaction. This promotes high density coupled with low permeability, thus
64 allowing to cast rapidly important volumes of earthen materials characterized by a significant strength
65 within the first curing stages. However, the variability of the characteristics of the excavation earth from
66 site to site is recognized as a major challenge for any earth-based material as it can potentially affect
67 various physical properties [16,17]. To overcome this drawback, the research activity also investigates
68 the technology of pressed-earth, which involves small cylindrical samples which are tested to predict
69 straightforwardly the engineering properties of Shot-Earth by means of suitable correlations [11]. Such
70 a technology, combined with Shot-Earth, was also used to experimentally evaluate long-term
71 viscoelastic behavior of earthen composites [18]. Shot-Earth can thus be concerned to the manufacture
72 of walls, slabs (Fig. 2b), beams, shells, domes, vaults [19], and other structural members for both repairs
73 and rehabilitations, as for reinforcement and replacing failed materials, as well as for surfaces
74 protection, even for geotechnical applications such as slope stabilization. Summarily, it can be either
75 employed in such situations in where other solutions, such as pressed-earth instead, would require
76 operational difficulties just as filling cavities, and walls behind pipes or other similar hurdles.



77
78 **Fig. 2.** (a) Shot-Earth projection leaned 45° over the horizontal direction (from [9]), (b) Test of a Shot-
79 Earth slab

80 Despite Shot-Earth's potential, its long-term durability has not been comprehensively studied,
81 especially in relation to water exposure, as well as for other earthen materials. Indeed, recent studies
82 have shown that moisture content strongly influences both the water absorption and the mechanical
83 strength in clayey and earthen materials, showing a considerable drop in performance as the water
84 uptake increases [20–23].

85 Durability [24] refers to the ability of a material or structure to retain its functionality and serviceability
86 over time when exposed to environmental stressors. For soil-based materials, whether stabilized or not,
87 water is typically the most harmful agent, leading to surface erosion, infiltration, and degradation
88 during extreme events such as floods. Additionally, other atmospheric factors—such as wind [25], frost
89 [20,26], solar radiation [27], fire [28], and chemical agents [24,29,30] — especially when acting
90 simultaneously, may significantly compromise the physical and mechanical performances of earth-
91 based materials and structures [31,32]. Knowledge of durability also guides contractors' material choices
92 and supports national strategies for achieving carbon neutrality by 2040–2050. An emblematic example
93 is Nsutam in Ghana, where an entire village was wiped away during a flood in 1970 [33]. It has been
94 one of the most detrimental examples of vulnerability of earthen structures by water-contact. Therefore,
95 this study aims to:

- 96 1. evaluate Shot-Earth under capillary rise, immersion, and pressurized absorption conditions;
- 97 2. compare its performance with ordinary Portland cement concrete (OPC);
- 98 3. develop and validate Finite Element (FE) simulations and simplified analytical models;
- 99 4. offer practical recommendations for implementation and design.

100 This study is capitally important for the sustainability profile of Shot-earth. Sustainability has been
101 defined through decades of studies, often shaped by painful lessons. The case of Thomas Midgley Jr. is
102 a well-known reference for understanding the risks of ignoring long-term environmental impacts. He
103 first developed tetraethyl lead (TEL), which was technologically efficient but caused widespread lead
104 poisoning (saturnism) [34–36]. Later, he co-developed Freon, a chlorofluorocarbon (CFC) that became
105 widely used in refrigeration and air conditioning. CFCs were later shown to be powerful ozone-
106 depleting substances and, at the same time, highly potent greenhouse gases.

107 It is important to note that ozone depletion and climate change are two distinct phenomena:

- 108 • Ozone depletion results from the breakdown of stratospheric ozone by CFCs and related
109 substances, which increases exposure to harmful UV radiation and is linked to higher rates of
110 skin cancer (e.g., melanomas).
- 111 • Climate change is primarily driven by the greenhouse effect, caused by the accumulation of
112 gases such as CO₂, CH₄, N₂O, and certain industrial gases (including CFCs).

113 Because different greenhouse gases have different warming effects, their emissions are expressed in
114 terms of CO₂ equivalents (CO₂-eq) using the Global Warming Potential (GWP) metric [37,38].
115 Switzerland ratified the Paris Agreement and, since 2019, has committed to achieving net-zero CO₂
116 emissions by 2050. For the construction industry, a key reference is the SIA 390/1 standard [39], which
117 focuses on CO₂. This standard applies a modular life-cycle assessment (LCA) approach to buildings and

118 extends the boundary beyond “cradle-to-gate” to also include the end-of-life phase. It expresses impacts
119 as a total amount of CO₂-eq per square meter and per year over the building’s reference service life.
120 This means that eco-materials must not only have a low embodied CO₂-eq content, but also demonstrate
121 declared performance characteristics, durability, reparability, and ease of maintenance. These aspects
122 are essential to ensure long-term sustainability and to avoid premature replacement, hidden emissions,
123 and unnecessary resource use. Furthermore, the standard requires accounting for cases where the
124 service life is shortened: if a building is reconstructed earlier than planned, the permitted CO₂-eq
125 allowance must be reduced pro rata. In addition, this standard — together with broader Swiss federal
126 policies such as the Climate and Innovation Act (LCI), the Code of Obligations’ compulsory non-
127 financial reporting, and the federal administration’s model role (which includes achieving net-zero
128 already by 2040) — requires that new construction materials demonstrate proven efficiency across
129 economic, environmental, social, and technical dimensions. Finally, the standard strongly promotes
130 circular economy principles. It requires defining a clear strategy for the end-of-life phase of buildings
131 and encourages the reuse of elements. Re-employed building components can be credited with a
132 reduction of up to 20% of the CO₂-eq impact compared to equivalent new materials. Shot-Earth has been
133 investigated primarily as a methodology rather than as a material [9]. A systematic approach has been
134 developed to prepare and optimize mixes, and structural calculation models have been studied to allow
135 structural engineers to design elements in reinforced Shot-Earth. The projection (spraying) method has
136 been designed to allow adjustments to the mix design during placement, without interrupting the
137 process. This characteristic is particularly important for walls, both structural and non-structural, since
138 the lower portion of a wall may require much lower water sensitivity than the upper portions. In
139 conventional earth-based construction, it is common to include an OPC concrete element at the base of
140 the wall to address this issue. Furthermore, Shot-Earth does not inherently depend on a specific binder.
141 If a zero-CO₂ cement is developed, it can be directly applied to Shot-Earth. Additional strategies have
142 also been studied to achieve near-zero-CO₂ Shot-Earth, even when a modest quantity of OPC cement is
143 used, thanks to the efficiency of the dry projection process. In this respect, Shot-Earth aligns with the
144 philosophy of the SIA 390/1 standard and, more broadly, with the net-zero objectives of Swiss federal
145 policies. In this study, the simplest version of Shot-Earth is used. Mixes 771 and 772, which contain pure
146 Portland cement, serve as the baseline for preparing and optimizing Shot-Earth for real applications. As
147 an example, a recent series of tests carried out for a construction project led to the optimization of the
148 mix design: starting from the standard 772, it was refined into a 10/4/2 mix containing a commercially
149 available low-clinker CEM II cement, without any loss of performance. Full-scale structural element
150 tests confirmed the robustness of the entire Shot-Earth methodology — from mix design to production

151 process, structural calculation, and detailing – and were validated through large-scale tests on wood–
 152 Shot-Earth composite beams (**Fig. 3**).



153
 154 **Fig. 3.** Example of a Shot-Earth and timber coupling: (a) Shot-Earth projection in wooden formwork to
 155 realize 9 m length beams, (b) surface flattening, and (c) Shot-Earth consolidation

156 **2. Materials and Methods**

157 **2.1. Materials**

158 Three materials were investigated in this study: Shot-Earth 772 (SE2), Shot-Earth 771 (SE1), and ordinary
 159 Portland cement concrete (C45). The Shot-Earth mixes were dry blends of excavated soil, coarse sand
 160 (0–8 mm), and Portland cement (CEM I 42.5N), with weight proportions of 7/7/2 and 7/7/1, respectively.
 161 Water was not added to the dry mix directly, but it has been introduced at the nozzle at 3% by volume
 162 during projection. The soil used in the present study contained less than 25% of clay and lime and over
 163 50% of sand and gravel, in compliance with requirements reported in previous studies [9–11]. Several
 164 specimens, including cubes, cylinders, and slabs, were fabricated and cured under laboratory conditions
 165 for 28 days prior to durability testing. The C45 was produced using a standard mix design of cement
 166 (340 kg/m³), aggregates (0–4 mm: 816.9 kg/m³; 8–16 mm: 427.9 kg/m³; 16–32 mm: 700.2 kg/m³), two
 167 superplasticizer additives (1.312 and 0.246 kg/m³), and water (164 kg/m³). Several cube specimens were
 168 tested after 28 days of curing, reaching an average compressive strength of about 45.5 MPa. Dry and
 169 apparent densities, and porosity were determined in compliance with relevant regulations [40,41],
 170 whereas compressive strength was assessed in accordance to EN 12390-3:2019 [42]. The modulus of
 171 elasticity has been evaluated by following to EN 13412:2006 [43], while Poisson’s ratio has been assessed
 172 in accordance with ASTM C469/C469M-14 [44], see **Table 1**.

173 **Table 1.** Resuming table of materials features concerning Shot-Earth durability assessment

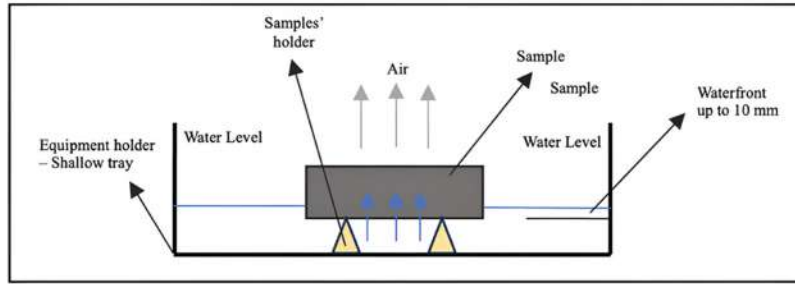
| | Bulk density _{dry} δ (kg/m ³) | Apparent density, (kg/m ³) | Compression strength, f_{cm} (MPa) | Porosity, ϕ (%) | Young module, E (MPa) | Poisson coefficient, ν |
|-----|--|---|---|-------------------------|--------------------------|-------------------------------|
| SE2 | 2050.58 ± 2.12 | 2495.95 ± 2.05 | 20.30 ± 1.27 | 17.84 ± 0.02 | 14923.90 ± 1989 | 0.2240 ± 0.16 |
| SE1 | 2027.56 ± 9.98 | 2496.15 ± 4.06 | 7.72 ± 0.33 | 18.77 ± 0.28 | 6198.12 ± 418 | 0.1938 ± 0.06 |
| C45 | 2327.98 ± 11.77 | 2597.53 ± 6.71 | 45.50 ± 3.0 | 10.37 ± 0.24 | 37485.54 ± 3974 | 0.2000 ± 0.03 |

174 Moreover, X-ray diffraction (XRD), X-ray fluorescence (XRF), and Scanning Electron Microscopy (SEM),
175 and particle size analyses were employed to characterise the mineralogical and chemical composition
176 of the Shot-Earth mixtures [45–48], as these properties may strongly affect their durability. In more
177 detail, XRD was employed to identify the mineralogical composition, which strongly influences water
178 absorption and, in turn, the development of cementitious phases in stabilized soils. For instance,
179 excessively high content of quartz, that is chemically inert and non-reactive with cement, does not
180 contribute to cementation and it reduces the formation of C–S–H gel to bind the matrix. This can increase
181 intermediate porosity, promote water penetration, and ultimately decrease the long-term durability of
182 the material [49]. For XRD, the analyses were conducted using a D2 Bruker SDD-160-1 detector to a
183 compound sample. The soil was previously dried at 105°C, finely grind, homogenized, and placed into
184 a circular holder. The results were conducted using the open-source software Profex [45]. Moreover, to
185 identify the oxides and other chemical elements in the compounds, providing essential information on
186 the presence of cementing or reactive, X-ray fluorescence spectroscopy (XRF) was also performed using
187 a Rigaku NEX DE spectrometer. As well as for XRD, the soil was oven-dried, finely grinded, and pressed
188 by using rounded holders in groups of three to guarantee homogeneity. Lastly, Zeiss EVO Scanning
189 Electron Microscope was deployed for SEM images combined with XRD. With the aim to quantify the
190 most microstructural details, it was decided to perform the following scan process: one scan at 1000X
191 regarding the matrix, one regarding the asperities or evident particularities to 1000X, and one of the
192 latter to 2000X. In addition, a granulometric analysis and Atterberg limit tests were also conducted to
193 assess the soil’s physical and mechanical properties in compliance with EN 933-1 [50] and SN 670 816a
194 [51]. Particle size analysis was conducted to determine the granulometric distribution by controlling
195 packing density, compaction, and also the water retention properties.

196 2.2. Experimental Approach

197 2.2.1 Initial Rate of Absorption (IRA)

198 Capillary absorption was tested following BS EN 13057:2002 [52] and AS/NZS 4456.17:2003 [53]. Nine
199 specimens were partially submerged (10 mm) in water, and mass gain was measured at fixed time
200 intervals—5 minutes, 12 minutes, 30 minutes, 1 hour, 2 hours—in which the water front was recorded
201 on each side of the samples, then 4 hours, and finally 24 hours (Fig. 4). Sorptivity coefficients (S) were
202 calculated for each mix and listed in Table 4.

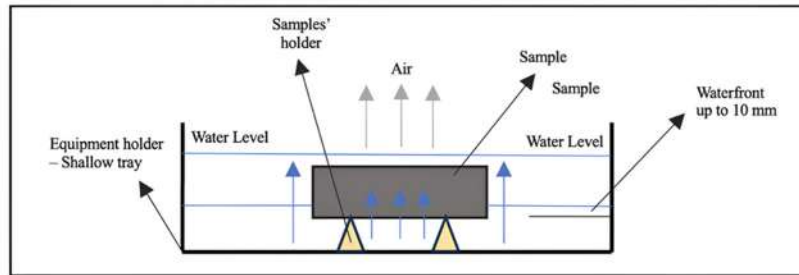


203
204

Fig. 4. Initial Rate of Absorption (IRA) test setup

205 **2.2.2. Immersion Test**

206 Following the IRA test, see Fig. 5, the same specimens underwent full immersion for up to 7 days. Mass
207 gain and water content were recorded daily. Saturation was reached rapidly in SE1, while SE2 and C45
208 showed slower uptake rates.



209
210

Fig. 5. Immersion test setup

211 **2.2.3. Water Permeability Test**

212 Water permeability tests were conducted under two pressure regimes following BS EN 12390-8 [42] and
213 DIN 1048-5 [54]. The first attempt (500 kPa for 72h) caused rapid failure in both SE1 and SE2: the applied
214 pressure has resulted too high to cause oversaturation of the surfaces of the cubes, thus leading to
215 formation of surface droplets. For this reason, the first attempt was not accomplished. Consequently, a
216 second attempt was carried out (200 kPa for 72h) and it was completed successfully. Penetration depths
217 were measured after specimen splitting (Fig. 6, Table 6) by Brazilian compression test [55]. Thus, real
218 intrinsic permeability and diffusivity coefficients were inferred for each material according to [15,52,56].



Fig. 6. Example of visible waterfront in SE1 after pressure exposure

2.3. Analytical and FE Modeling

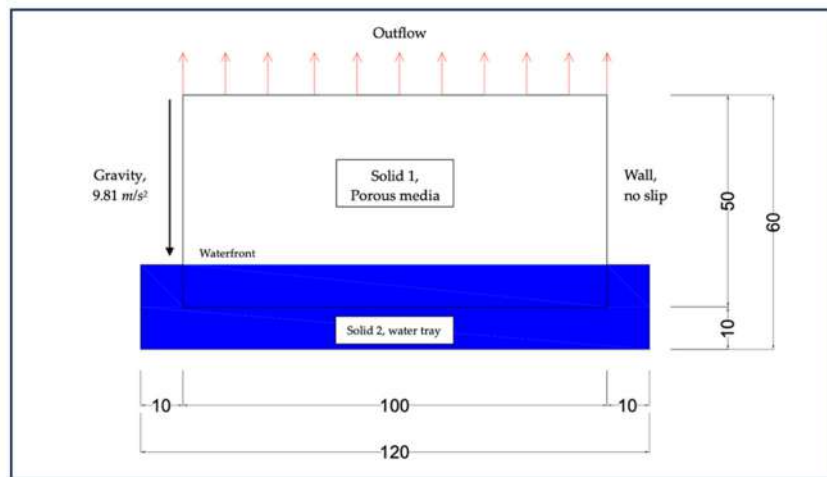
Although the transport of water in cementitious porous media has been widely studied, the development of reliable tools for simulating this phenomenon remains a significant challenge. This is particularly relevant when considering key transport properties such as capillary water absorption and gas permeability, which are essential for assessing the durability and mechanical performance of cement-based materials. These parameters influence how different substances move throughout the material, affecting hydration reactions, and long-term structural behavior. This dynamic process can create areas where the behavior of the material may vary unexpectedly. Models such as the *Brutsaert model* [57], the *Boltzmann* transformation approach [58], and the *Zhou model* [59] were developed to quantify the dependence of water absorption on the saturation level of porous materials. It is worth noticing that these models are based on empirical and theoretical basics drawn from soil mechanics, employing simplified geometries and being limited to unsaturated condition, which is unlikely to occur under real-world conditions in dealing with cementitious materials as concrete. While numerical modeling is widely available, finite element (FE) models for predictive purposes often require excessive boundary work, making the development of a feasible model more complex and time-consuming than necessary [60]. These challenges, along with numerous approximations, have discouraged many authors from continuing with this approach. Notwithstanding, an example of FE modeling to water absorption for capillary water-front rising for both SE1 and SE2, and C45 is given in this study. FE simulations were performed in ANSYS to model capillary water rise (Fig. 7). The Volume of Fluid (VOF) model was applied, and porous media behavior was approximated using Ergun's theory, later adjusted via *Darcy-Forchheimer* formulation [57–59]. The mesh resolution was 0.5 mm, yielding 26,202 nodes and

242 25,600 elements. Material porosity, particle size (D_p), and calculated permeability were calibrated
 243 against experimental data. Effective particle sizes were adjusted (e.g., 0.2–0.5 cm for SE1 and SE2) based
 244 on best-fitting results (see **Section 3.7**), as listed in **Table 6**. Moreover, a simplified analytical absorption
 245 model based on *Lin Yang's* assumptions [61,62] is also proposed as a polynomial relationship between
 246 degree of saturation and mass uptake based on IRA test data according to **Eq. (1)** and **Eq. (2)**:

$$247 \quad \frac{S_{i=1\dots n}(\Lambda)}{S_{i=0}} = 1 - 1.5 \Lambda + 0.5 \Lambda^2 \quad (1)$$

$$248 \quad \Lambda = \frac{m_x - m_d}{m_s - m_d} \quad (2)$$

249 where $S_{i=1\dots n}(\Lambda)/S_{i=0}$ depends on the degree of saturation, Λ , with the full-saturated mass, m_s , the full-
 250 dried mass, m_d , and the mass at any given time interval, m_x .
 251

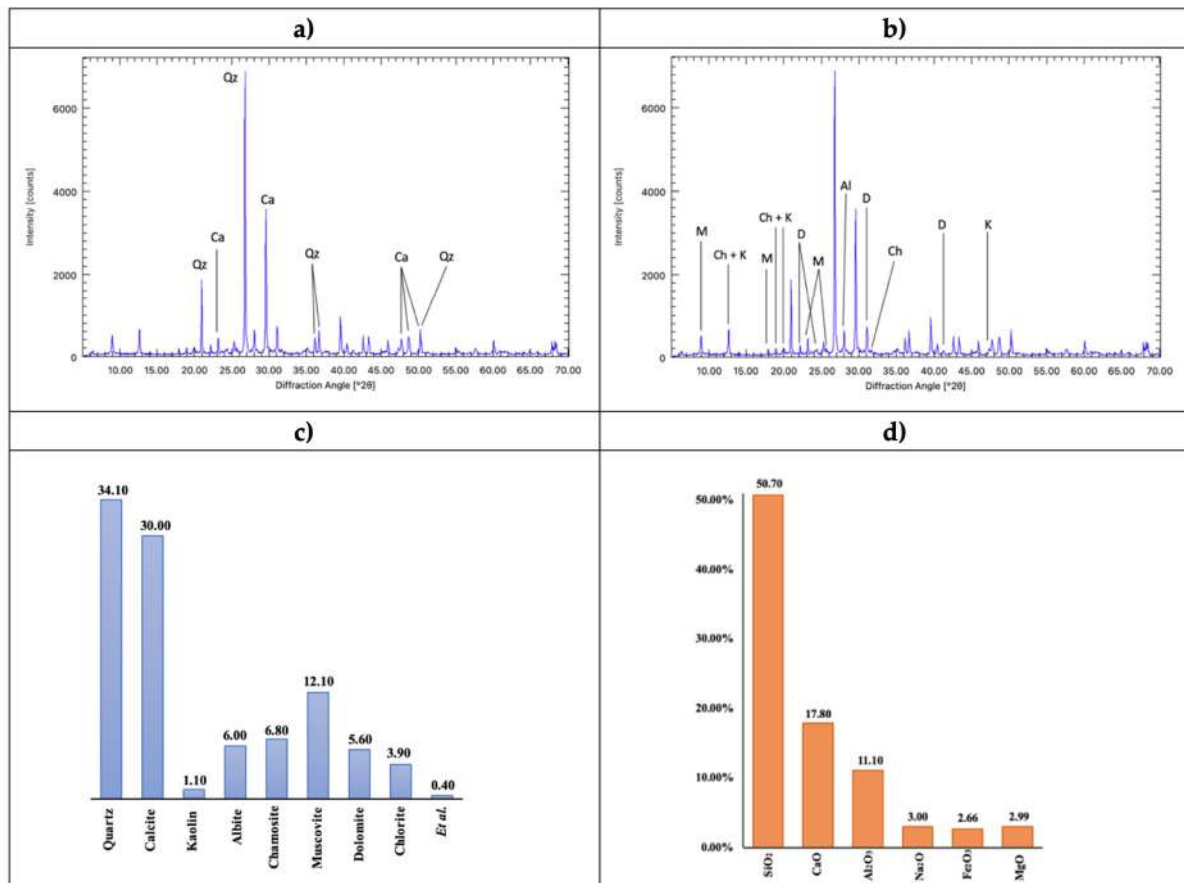


252 **Fig. 7.** Sketch of the FE model to assess the Initial Rate of Absorption; solid 1, porous media, and solid
 253 2 filled of water
 254

255 3. Results

256 3.1. XRD-XRF-SEM Images

257 The XRD's phases identification (**Fig. 8a-b**) has found a prevalence of quartz, calcite, muscovite,
 258 chamosite, albite, dolomite, chlorite, and kaolin. The high calcite content is optimal to guarantee
 259 intermolecular bonding and mechanical resistance [46–48], with minimal kaolin and no organic matter.
 260 XRF measurements confirmed high contents of silica oxide (SiO_2) and calcium oxide (CaO), both critical
 261 for mechanical strength and hydration potential (**Fig. 8c-d, Table 2**).



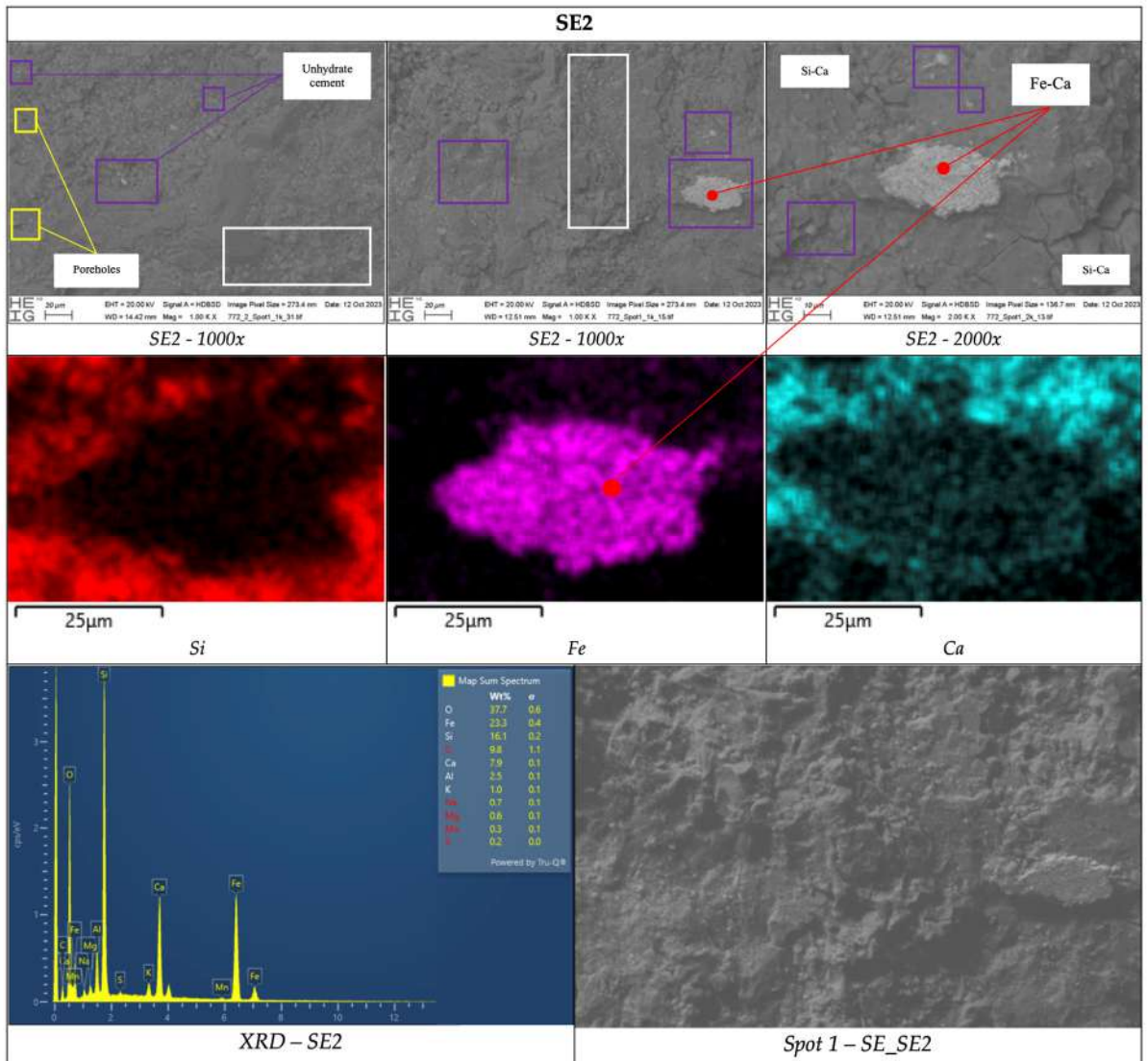
262
 263 **Fig. 8.** (a) XRD main peaks, (b) while complementary research has delineated traces of kaolin, albite,
 264 chamosite, muscovite and gibbsite; (c) phases were found with XRD, while (d) oxides were found by
 265 XRF: all of those are expressed in %-mass

266 **Table 2.** XRF chemical elements, on percentage of total mass (wt%). Reliability of results with XRD

| Elements | O | Si | Ca | Al | Fe | Na | Mg | K | Ti | P | S | Sc | Mn | Cl |
|----------|-------|-------|-------|------|------|------|------|------|-------|-------|-------|-------|-------|--------|
| % - Mass | 33.33 | 30.99 | 19.63 | 7.31 | 2.95 | 2.66 | 2.19 | 1.4 | 0.37 | 0.19 | 0.324 | 0.078 | 0.07 | 0.04 |
| SD | 2.89 | 1.37 | 1.24 | 0.22 | 0.29 | 0.06 | 0.06 | 0.08 | 0.032 | 0.015 | 0.015 | 0.016 | 0.005 | 0.0033 |

267 Moreover, SEM images coupled with XRD were adopted to better understand the microstructural
 268 evolution and phase composition of the samples, allowing correlations between hydration products,
 269 porosity distribution, and surface densities. From the morphological perspective, SE2 (**Fig. 9**) and C45
 270 (**Fig. 10**) displayed a dense and well-integrated matrix, while SE1 (**Fig. 11**) showed increased porosity
 271 and irregular bonding due to its lower cement content. For SE2 the predominance was of silicon, oxygen,
 272 and calcium. Localized concentrations of iron-calcium were also detected as white paddles ranging
 273 between 0.10–0.50 μm . According to *R.V. Balendran et al. [18]*, the hydration products of cement are
 274 complex and may be estimated as follows: 70% of fully hydrated cement consists of 80% calcium silicates
 275 and 20% calcium aluminates, 20% calcium hydroxide, and about 10% unhydrated cement, debris,
 276 calcium aluminate, or clinker residue [19]. Cement hydration up to 90 days was investigated using SEM,
 277 XRD, and EDXA techniques as proposed by *He et al. [63]*. XRD results showed ettringite formation
 278 during early hydration stages, which disappeared after 28 days (C-A-H). SEM analysis at later stages

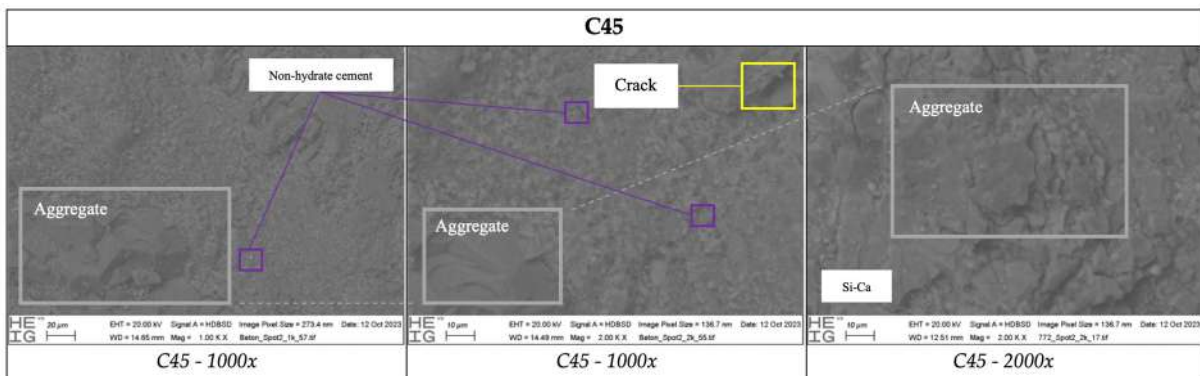
279 confirmed that ettringite needles were no longer observed, giving way to microstructural densification
280 as a rheological control mechanism. The C-A-H bonds contribute to microstructural densification but
281 only marginally to mechanical strength. Their role, however, may be fundamental to regulate the
282 absorption behavior and, in turn, to improve durability. As compared to C-A-H bonds, silicate
283 hydration increases more slowly. During curing, filamentous structures form and progressively
284 elongate until they intertwine and densify. These generate C-S-H bonds, which are crucial for the
285 mechanical properties of cementitious materials, although they also leave micro-cavities unfilled. In
286 SE2, the matrix appeared regular, homogeneous, and well-integrated with clasts and aggregates,
287 despite the intentionally reduced cement content (estimated over 20% less). The resolution of the images
288 did not allow a clear distinction of all hydration products [20]. However, calcium hydroxide was visible
289 and identifiable by its morphology as large flat crystals irregularly grouped on the surface. These
290 hydration products are responsible for mechanical resistance, compactness, and high density, possibly
291 linked to the absorption capacity of Shot-Earth. This behavior might be explained by the limited amount
292 of cement present in Shot-Earth. On contrary, no calcium-silicon hydrate spikes were identified.
293 Conversely, SE1 showed a higher degree of surface alteration due to its leaner amount of binder within
294 the mixture. As shown in **Fig. 9** indeed, the paste appeared more rarefied and less amalgamated,
295 producing large intermolecular voids highlighted in the yellow frames. Shadowed spots in the images
296 further underline this higher porosity, which had resulted crucial during the experimental campaign by
297 creating preferential channels, thus promoting absorption. Finally, minor concentrations of zirconium
298 (Zr) were detected.



299

300

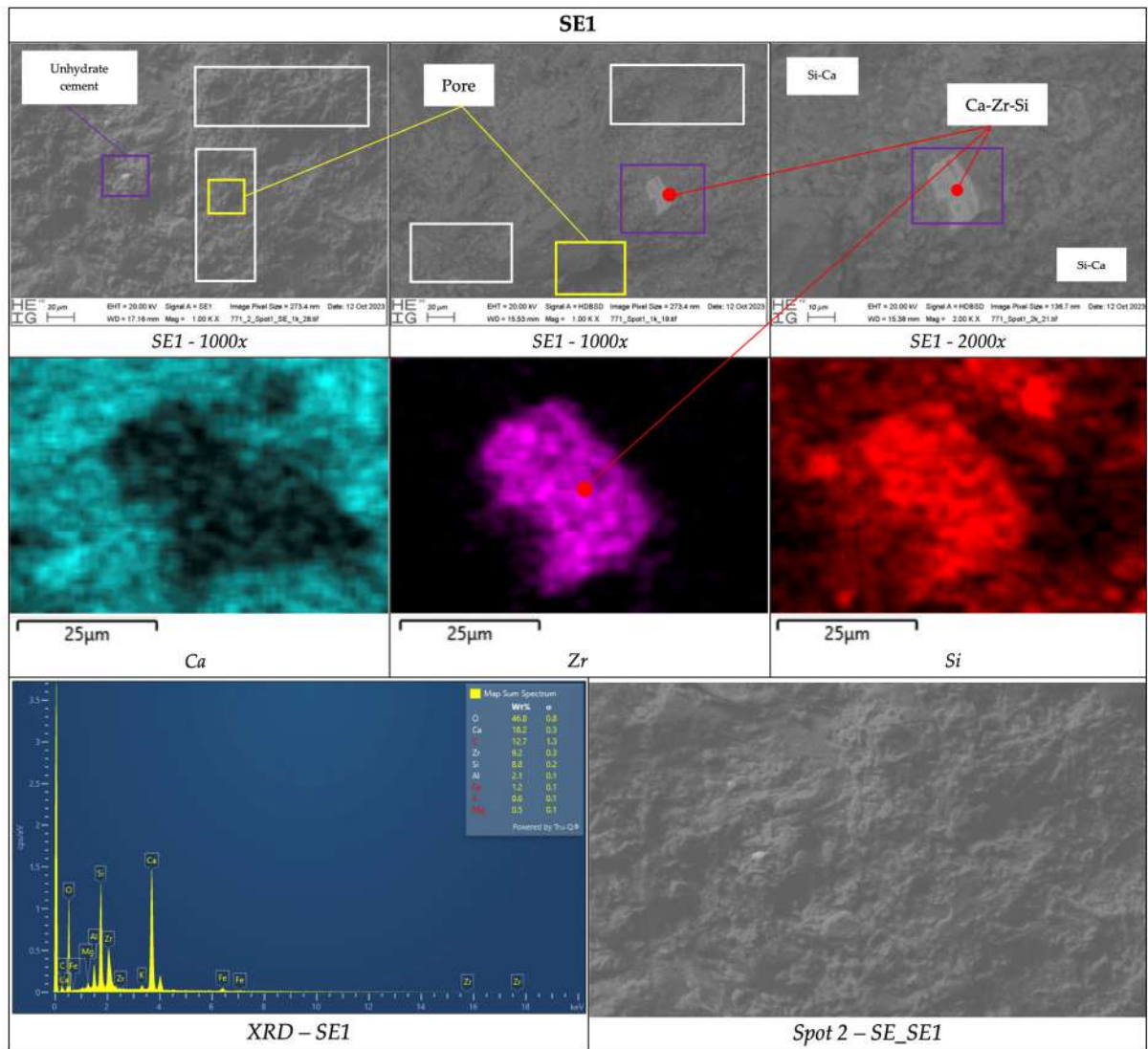
Fig. 9. SEM images for SE2 whom the XRD was applied on matrix, debris, and particularities



301

302

Fig. 10. SEM images for C45



303

304

Fig. 11. SEM images for SE1 whom the XRD was applied on matrix, debris, and particularities

305

3.2. Soil Classification

306

The soil was classified as CL (Clayey Silt with sand) according to the Unified Soil Classification System

307

(USCS), with approximately 75% of silt and clay content. Plasticity index and liquid limit are provided

308

in **Table 3**, whereas the particle-size distribution curve is shown in **Fig. 12**. The average particle

309

diameter, essential for subsequent modeling, was established to be 0.09 cm.

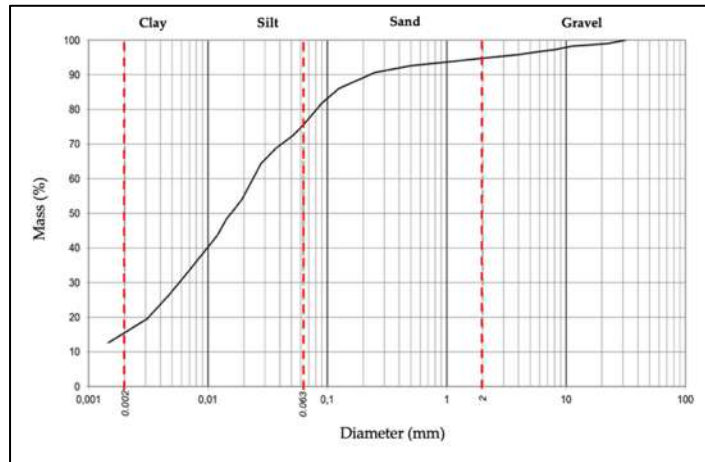


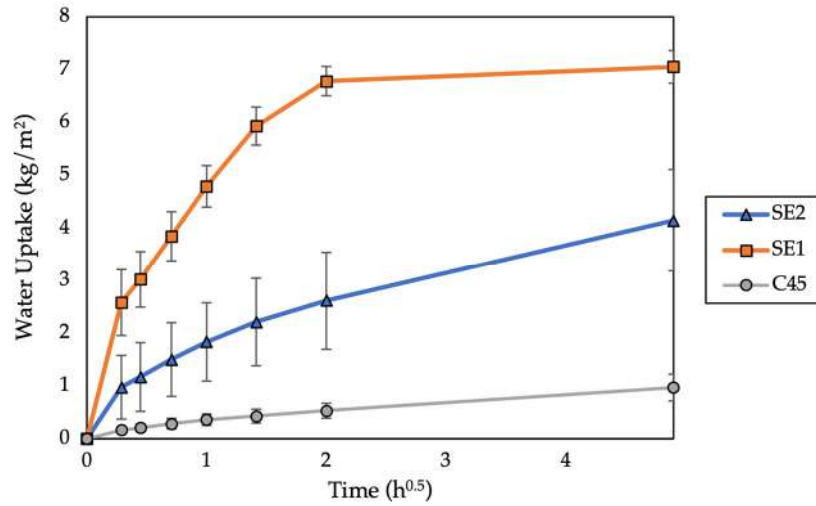
Fig. 12. Granulometric curve mass-passing sieve diameter (mm)

Table 3. Geotechnic parameters for soil used for Shot-Earth

| Atterberg limits | | |
|--------------------------------------|------|---|
| W_L | 21.5 | % |
| W_P | 14.5 | % |
| I_r | 7.0 | % |
| Soil percentages | | |
| Gravel (2-63 mm) | 5.2 | % |
| Sand (0.063-2 mm) | 19.3 | % |
| Silt + Clay (<math><0.063</math> mm) | 75.5 | % |
| Silt (0.002-0.063 mm) | 59.5 | % |
| Clay <math><0.002</math> mm | 16.0 | % |
| Classification USCS | CL | - |

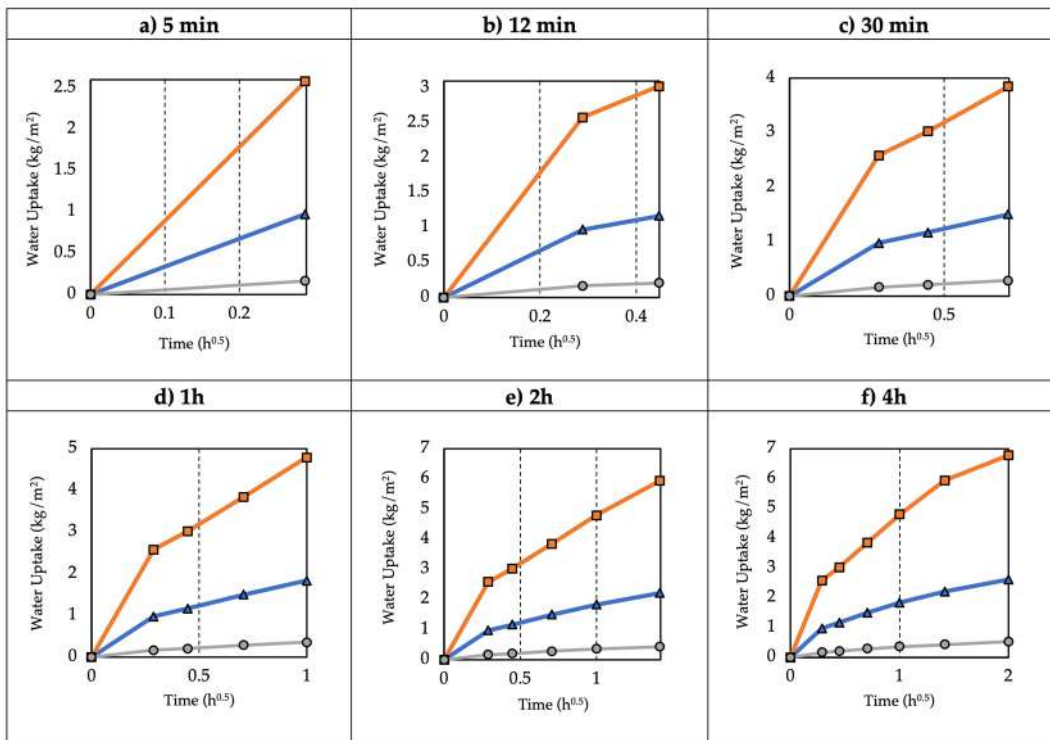
3.3. Initial Rate of Absorption (IRA)

The IRA test evaluated the water uptake behavior of SE1, SE2, and C45 over a 24-hour period under capillary conditions. As shown in Fig. 13, SE1 exhibited the highest initial sorptivity, followed by SE2, while C45 displayed minimal absorption due to its low porosity and high compaction. Only SE1 reached full saturation within the 24-hour. Sorption coefficients (S_5 for the 5-minute interval and S_{24} for 24-hour) were extracted for each mixture and listed in Table 5. Linear capillary behavior was observed for SE1, while SE2 and C45 showed nonlinear saturation curves [64]. Detailed water uptake trends at various time intervals are presented within Fig. 14a-f. In detail, the slope-derived sorptivity profile for SE1 is shown in Fig. 15. After 2 hours of partial immersion, the waterfronts were recorded and approximated to the nearest 0.5 cm, finding 35 mm, 50 mm, 20 mm, respectively, for SE2, SE1, and C45.



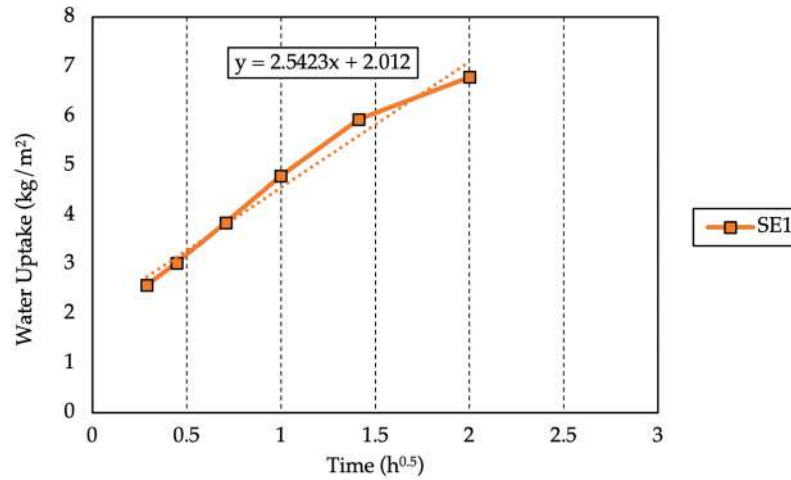
323
324
325

Fig. 13. Water uptake over 24 hours for SE1, SE2, and C45 during the IRA test. Standard error is provided



326
327

Fig. 14. IRA test results: Water uptake for (a) 5 min, (b) 12 min, (c) 30 min, (d) 1h, (e) 2h, and (f) 4h



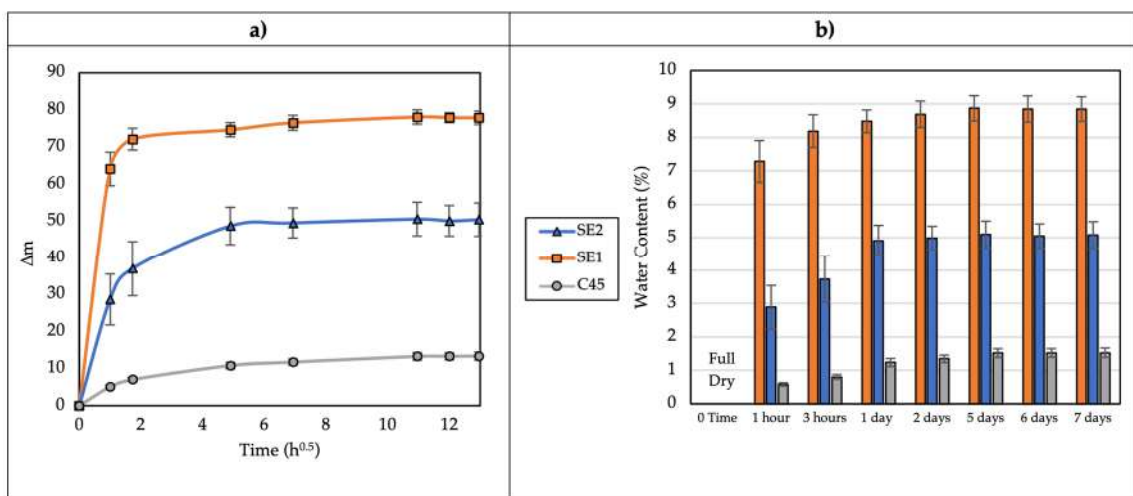
328
329 **Fig. 15.** Sorptivity coefficient (S) of SE1 derived from linear regression of water uptake

330 **Table 4.** Sorption coefficients at 5 minutes and 24 hours for SE2, SE1, and C45

| Sorption coefficients | | kg/(m ² h ^{0.5}) | kg/(m ² min ^{0.5}) | m/h ^{0.5} | mm/min ^{0.5} | Behavior |
|-----------------------|-------|---------------------------------------|---|--------------------|-----------------------|------------|
| SE2 | 5 min | 3.4 | 0.263 | 0.00324 | 0.419 | Linear |
| | 24 h | 0.8 | 0.062 | 0.00081 | 0.105 | Non-Linear |
| SE1 | 5 min | 8.9 | 0.689 | 0.00883 | 1.140 | Linear |
| | 24 h | 3 | 0.232 | 0.00142 | 0.184 | Linear |
| C45 | 5 min | 0.5 | 0.039 | 0.00277 | 0.053 | Linear |
| | 24 h | 0.2 | 0.015 | 0.00067 | 0.018 | Non-Linear |

331
332 **3.4. Immersion Test**

333 Specimens used in the IRA test were subjected to full immersion for 7 days. Mass gain was monitored
334 daily and normalized using \sqrt{t} to analyze non-linear absorption behavior. SE1 reached saturation
335 rapidly, with over 8% water uptake. SE2 and C45 absorbed more slowly (**Fig. 16**). As shown in the
336 following, these data turn out to be crucial to calibrate the FE model by $D_{p,corr}$ (see **Eq. (3)**).



337
338 **Fig. 16.** (a) Immersion absorption pattern, while (b) shows water content (%) over time, reflecting
339 saturation kinetics among the three materials

340 3.5. Water Permeability Test

341 Water permeability was assessed under two pressure regimes. The 500 kPa test resulted in structural
 342 failure of SE1 and SE2; therefore, a reduced 200 kPa test was applied successfully for 72 hours. C45
 343 showed the lowest permeability, while SE1 displayed the highest. Using test data, saturated and
 344 unsaturated permeability, K (m/s) and K_s (m/s), intrinsic permeability, κ (m²), and diffusivity, D (m²/s),
 345 coefficients were calculated according to [15,52,56], see **Table 5**.

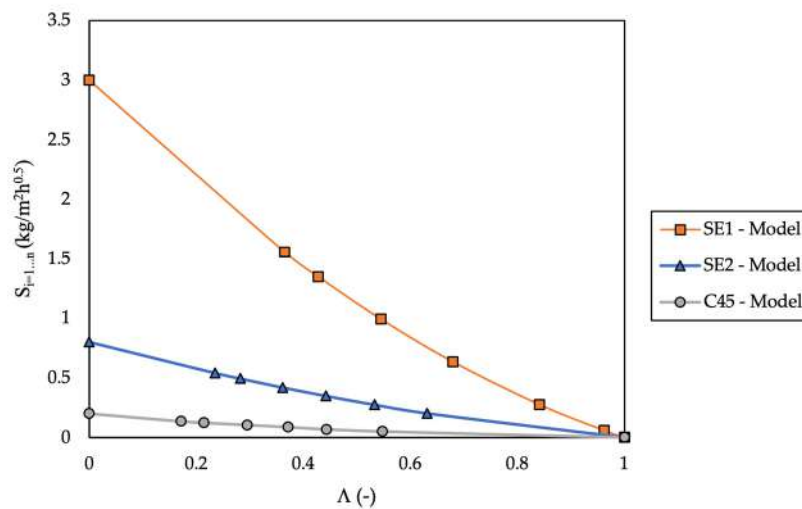
346 **Table 5.** Saturated and unsaturated permeability, diffusivity, and intrinsic permeability for SE1, SE2,
 347 and C45; ϕ and l_1 stand for porosity and waterfront rising over the test of time, respectively

| | l_1 (m) | ϕ | Water viscosity (Pa s) | P (kPa) | Time (s) | K_s (m/s) | K (m/s) | D (m ² /s) | κ (m ²) |
|-----|-----------|--------|------------------------|-----------|----------|-------------|-----------|-------------------------|----------------------------|
| SE2 | 0.084 | 0.17 | 0.001002 | 20.38 | 172800 | 2.026e-09 | 1.833e-09 | 1.300e-11 | 1.965e-16 |
| SE1 | 0.137 | 0.18 | 0.001002 | 20.38 | 172800 | 3.499e-09 | 3.166e-09 | 2.010e-10 | 3.373e-16 |
| C45 | 0.0145 | 0.15 | 0.001002 | 20.38 | 172800 | 3.086e-10 | 2.793e-09 | 1.135e-12 | 1.972e-17 |

348

349 3.6. Analytical Modeling

350 The simplified model was applied, and the relationship between the sorption coefficient S and degree
 351 of saturation is inferred for each material involved. IRA data were used to calibrate this model (see
 352 **Section 3.3**), which successfully predicted material behaviour across mixtures. As shown in **Fig. 17**, the
 353 curves for SE1, SE2, and C45 matched experimental absorption capacities. According to **Eq (1)** and **Eq**
 354 **(2)**, $\Lambda = 0$ corresponds to $S_i = 1 \dots n(\Lambda) = S_i = 0$, representing the maximum absorption capacity under
 355 initial full-dry conditions. Then, the degree of saturation is calculated by taking the positive solution of
 356 the quadratic equation. On the other hand, when $\Lambda = 1$, $S_i = 1 \dots n(\Lambda) = 0$, and this indicates that the
 357 material has reached full saturation and no further absorption occurs. Using the model, the initial
 358 capillary absorption ratio for any degree of saturation Λ can be straightforwardly calculated from the
 359 absorption ratio measured under fully dry conditions.

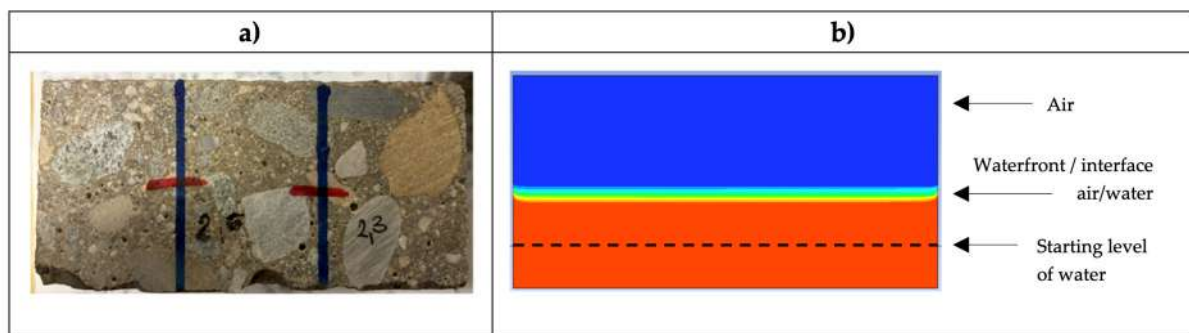


360

361 **Fig. 17.** Polynomial model fitting: relationship between absorption and saturation degree for SE1, SE2,
362 and C45

363 3.7. FE modeling and calibration

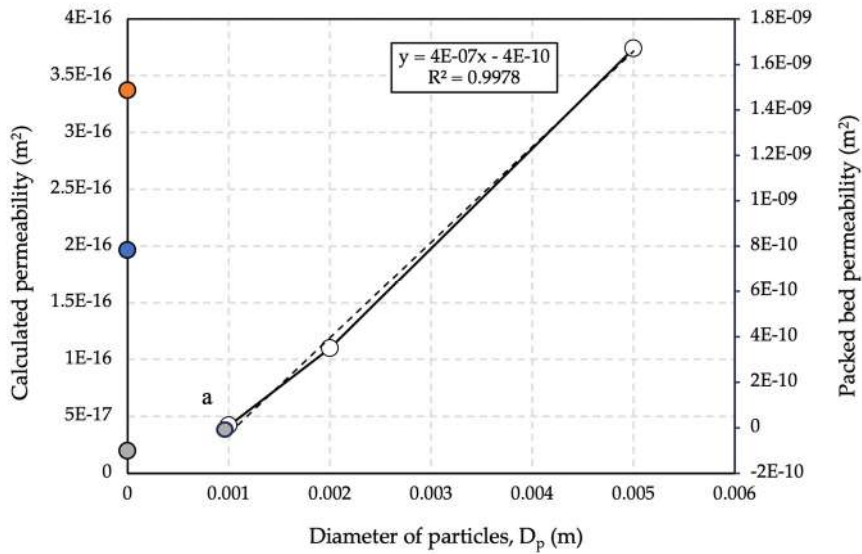
364 To allow comparison with IRA experimental data, the simulation covered a time interval of two hours,
365 after which the waterfront high was marked and compared with the experimental results. However, the
366 authors observed a significant discrepancy in the permeability values obtained using the simplified
367 Ergun theory among different materials. For instance, C45, while being the highest-performing material
368 in the present, also has the largest average particle diameter D_p , as it includes aggregates ranging from
369 16 to 32 mm size. Consequently, the average diameter was determined to be 0.8 cm. When applying
370 Ergun theory, the resulting permeability was found to be over four orders of magnitude higher than
371 expected, leading to the conclusion that this value is fundamentally incorrect and not representative of
372 the real material behavior in absorption. The permeability issue was addressed to *Felipe Montes et al.*
373 [65], who established correlations between the Ergun equation and the Reynolds number. By making
374 empirical assumptions about particle diameters, he determined that the optimal way to account for the
375 true density of concrete is to reduce the average particle size by an order of magnitude — from the
376 typical value of 1 cm for ordinary concrete to 0.1 cm. When this value was adopted as input data for
377 numerical analyses, as shown in **Table 6**, the simulation matches well the experimental data. **Fig. 18**
378 confirms the waterfront rise and the proper match between the experimental data and FE simulation
379 for C45.



380
381 **Fig. 18.** (a) Experimental waterfront vs (b) FE simulation rising for C45: the red portion indicates the
382 water, starting from 1 cm high, the blue region denotes the air that leaves the sample, and the green
383 region represents the interface

384 The triple-axis graph (**Fig. 19**) presented below shows that selecting an average diameter of 0.1 cm for
385 C45 is appropriate when considering the actual intrinsic permeability on the left-side y-axis. However,
386 this is not the case for the permeability of a packed bed predicted through the FE modeling on the right-
387 side y-axis. Notably, this low permeability results in a calculated value that is even negative, which
388 would theoretically suggest the use of a negative diameter. This underscores the critical importance of

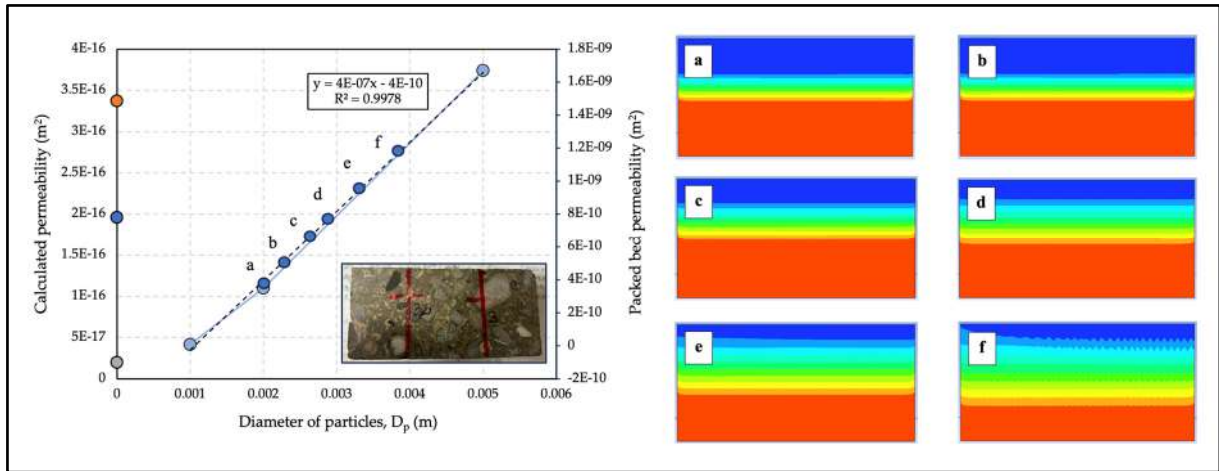
389 accurately representing the average particle size in modeling the porous media. Based on experimental
 390 data and material cohesion properties such as porosity and water capacity, two reference diameters
 391 such as 0.2 cm for SE2 and 0.5 cm for SE1 (Table 6) were both selected to establish a linear relationship
 392 between the three possible diameters and the values of permeabilities, and the equation has been
 393 extrapolated. On the left-side y-axis, the grey point stands for the actual intrinsic permeability –
 394 expressed in m² – of C45, while the blue and orange ones are for SE2 and SE1, respectively. However,
 395 the choice of 0.2 cm for SE2 reveals a significant deviation between the actual intrinsic permeability and
 396 the chosen diameter. In contrast, the 0.5 cm diameter for SE1 proves to be representative, as that for C45.
 397 These findings indicate the necessity of developing an exponential analytical relationship to correlate
 398 established values in the Literature with analogous values for other porous media, see Eq. (3). Thus, an
 399 exponential correlation is proposed, accounting for the maximum water content of each material
 400 (expressed in percentage) in compliance with the reference concrete with known modified average
 401 diameter.



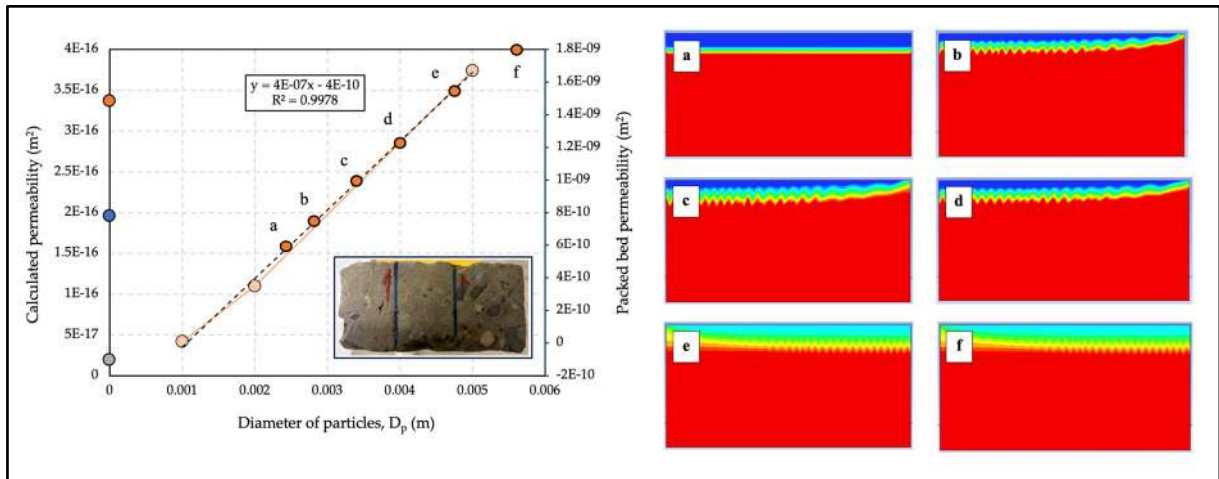
402
 403 **Fig. 19.** C45 matching experimental data by confirming $D_p = 0.1$ cm. Point *a* represents the position of
 404 packed bed permeability compared to the experimentally calculated one by 0.1 cm D_p

405

$$D_{p_{corr}} = D_{p_{real}} \left(\frac{W_{a,porousmedia}}{W_{a,concrete}} \right)^\alpha \quad \text{with } \alpha \in [0.5 - 1] \quad (3)$$



406
 407 **Fig. 20.** FE predictions and experimental data in terms of permeability for SE2 using corrected D_p . On
 408 the right: FE simulation of capillary rise as a function of the average particle size D_p : the red regions
 409 indicate water penetration into the sample, while blue regions denote the air leaving



410
 411 **Fig. 21.** FE predictions and experimental data in terms of permeability for SE1 using corrected D_p . On
 412 the right: FE simulation of capillary rise as a function of the average particle size D_p : the red regions
 413 indicate water penetration into the sample, while blue regions denote the air leaving

414 **Table 6.** Resuming table of FE modeling by Ergun's theory

| | D_p (m) | Porosity (-) | a, constant (-) | Constant of Forchheimer, k_1 (m) | k/k_{model} (m²) | α (m²) | C2 (1/m) |
|-----|-----------|--------------|-----------------|------------------------------------|--------------------|---------------|-------------|
| SE2 | 0.002 | 0.1784 | 150 | 7.898E-06 | 2.243E-10 | - | - |
| SE1 | 0.005 | 0.1877 | 150 | 2.326E-05 | 1.67035E-09 | - | - |
| C45 | 0.001 | 0.1037 | - | 7.10959E-07 | 9.25419E-12 | 9.25419E-12 | 126614.6426 |

415
 416 By varying both the ratio of water content relative to that of C45, taken as reference, and the
 417 corresponding α -values, a wide range of average particle diameters was generated for both mixtures.
 418 For SE2, the fictitiously assigned value aligns well with the experimental results, indicating its
 419 suitability. Additionally, as the average diameter increases, the waterfront propagation increases
 420 proportionally, as permeability does. However, all results remain within acceptable tolerance limits
 421 (**Fig. 20**). The same reasoning applies to SE1 (**Fig. 21**). Summarily, the diameters that best represent SE2
 422 were found to range from 0.18 to 0.33 cm, while for SE1, they ranged from 0.24 to 0.48 cm.

423 **4. Discussion**

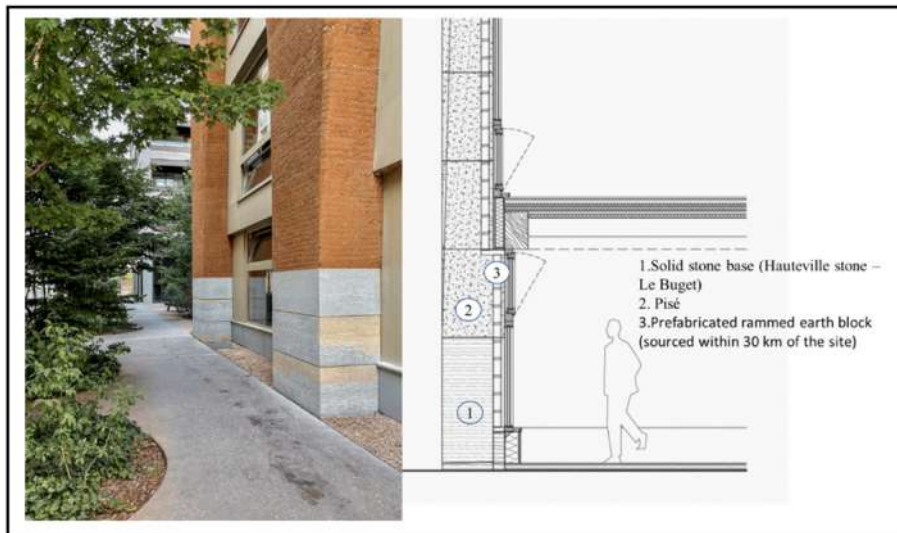
424 **4.1. Analytical and FE modelling**

425 The simplified analytical model successfully captured the absorption behavior of SE1-2 and C45, using
426 polynomial expressions based on the degree of saturation. This approach offers a fast and effective
427 method to predict water uptake from IRA data without requiring full-scale simulations. While more
428 complex, FE modeling proved to be a powerful tool for validating and extrapolating experimental
429 results. Starting the simulation with particle diameter (D_p) of 0.1 cm for C45 was crucial to interpolate
430 the correct permeability values for SE1 and SE2. Moreover, calibrating D_p based on experimental fitting
431 yielded more accurate representations of fluid flow in porous medium. The combined use of empirical
432 testing and modeling has proven effective in assessing non-standard construction materials.

433 **4.2. Durability Insights**

434 The findings of this study confirm that water remains one of the most detrimental environmental agents
435 impacting the durability of earth-based materials. Both capillary absorption and immersion tests
436 revealed that Shot-Earth — particularly the SE1 mix — exhibits high water uptake under saturated
437 conditions. While Shot-Earth offers excellent mechanical strength and early-age performance, its
438 vulnerability to moisture exposure is a legitimate concern. However, this concern must be viewed in a
439 broader architectural and historical context. Many traditional earthen materials—such as adobe and
440 rammed earth—also exhibit high water sorptivity, yet have endured for centuries, often in demanding
441 environmental conditions. Their resilience stems not from impermeability, but from careful design,
442 detailing, and construction practices that adapt to the inherent properties of the material. In this regard,
443 the present study provides a foundation for identifying where water-related durability challenges may
444 emerge and how they can be addressed through thoughtful planning. The results also show that
445 prolonged moisture exposure leads to a progressive loss of cohesion and mechanical integrity,
446 particularly in SE1. In capillary-driven scenarios—such as rising damp—SE1's rapid and linear
447 saturation behavior reflects its high affinity for moisture, likely due to its higher porosity and lower
448 binder content as compared to SE2 and C45. These findings highlight the critical importance of moisture
449 management when working with earthen materials, including the implementation of capillary breaks,
450 breathable coatings, elevated foundations, and proper drainage. Importantly, Shot-Earth is a highly
451 adaptable material system. Its dry application process allows for easy adjustment of the mix design,
452 facilitating transitions between SE1 and SE2 as needed. Moreover, the same projection equipment and
453 technique can be used to apply conventional concrete or shotcrete, offering exceptional construction
454 flexibility. Owing to its high green strength, different segments of a wall can be constructed using
455 tailored mix designs: for instance, a more water-resistant or cement-rich formulation can be applied at

456 the base, where exposure to rising damp is highest, while the level of stabilization can be gradually
457 reduced in the upper sections where moisture exposure is minimal. This stratified construction strategy
458 has long been employed across various materials and architectural traditions. A notable example is the
459 project illustrated in Fig. 22, adapted in [66], in which a rammed earth structural arch is supported by a
460 solid stone base. Such layered configurations enable practitioners to optimize both performance and
461 sustainability without altering the overall construction method.



462
463 **Fig. 22.** Lyon, Confluence II (France), stratified construction by using pisé and rammed earth blocks
464 [66]

465 5. Conclusion

466 This study evaluated the durability and water absorption behavior of Shot-Earth — a sustainable, soil-
467 based construction material — through comprehensive experimental testing and numerical modeling.
468 Two Shot-Earth mixtures (SE1 and SE2) were assessed and compared with conventional concrete (C45)
469 under capillary rise, full immersion, and pressurized water exposure. The key conclusions are as
470 follows:

- 471 • Moisture is the critical durability factor for earthen materials. A correlation exists between
472 compressive strength, density, and water absorption capacity: SE1 absorbed 8.85% (7.72 MPa),
473 SE2 improved to 5.09% (20.30 MPa), yet both remain above C45, which absorbed only 1.52%
474 (45.5 MPa). Denser, stronger matrices are more resistant to water absorption. SE2 marks
475 progress over SE1 but still requires stabilization to achieve concrete-level durability.
- 476 • Permeability remains a limitation. Shot-Earth permeability ($3.373 \times 10^{-16} \text{ m}^2$ for SE1 and
477 $1.965 \times 10^{-16} \text{ m}^2$ for SE2) is an order of magnitude higher than that of OPC concrete (1.972×10^{-17}
478 m^2). This may restrict its use in moisture-intensive environments unless appropriate protective
479 measures — such as base detailing, breathable coatings, or elevated foundations — are applied.

- 480
- The absorption capacity measured by the sorption coefficient S ($\text{kg}/\text{m}^2\text{h}^{0.5}$) can be analytically
481 evaluated using Eq. (1) and Eq. (2) at any time and at any degree of saturation once the initial
482 dry mass and the final fully saturated mass are known.
 - Using ordinary Portland cement concrete C45 as reference (1.52% maximum water content,
484 0.001 m particle size), the FE model shown that numerical simulations are a valid tool to predict
485 water transport in Shot-Earth. The computational procedure requires the adoption of a proper
486 reference diameter assessed through a best-fit scheme of the particle sizes through Eq. (3). The
487 corrected average particle size D_p turns out to be 0.002 m for SE2 and 0.005 m for SE1, while
488 porosity had limited influence. The proposed approach can be extended easily to other
489 cementitious materials.

490 Beyond durability, Shot-Earth demonstrates substantial environmental advantages. Excavated soil
491 accounts and aggregate have the same volume in all mixes studied, while binder content is reduced by
492 more than 20% in SE2 and 60% in SE1 compared to OPC concrete – enabling both structural and non-
493 structural applications. Moreover, in many cases (e.g., walls), only localized zones such as wall bases
494 require enhanced water resistance and thus heavier stabilization. The Shot-Earth spraying process
495 allows binder content or type to be quickly adapted *in situ* without halting construction. Its dry
496 application also greatly facilitates the incorporation of CO₂-negative additives, further reinforcing its
497 potential as a climate-positive construction technology. At the same time, further research remains
498 essential. While this study focused on water-related degradation, other durability factors – such as
499 freeze–thaw cycles, wet–dry cycles, salt crystallization, biological growth, and combined hygrothermal
500 effects, still require systematic investigation. Mesoscale approaches, such as time of wetness (TOW)
501 experiments, are carried out throughout the evaluation to the surface resistivity, rising damp, wet–dry
502 processes, carbonation, and real-aging conditions. Preliminary investigations indicate that Shot-Earth’s
503 response to these stressors is highly dependent on mix design and binder content, but standardized test
504 methods are often unsuitable for earthen composites. Developing adapted durability protocols
505 therefore represents a challenging next step to assess the long-term performance and to position earthen
506 composites such as Shot-Earth within building standards. Expanding the modeling framework to
507 account for coupled phenomena (e.g., hygrothermal transport, gas permeability) would also broaden
508 its predictive value. In conclusion, Shot-Earth and more broadly earthen materials is not yet a universal
509 substitute for concrete in durability-critical applications. However, its environmental benefits,
510 adaptability, and promising mechanical performance – combined with targeted protective detailing
511 and further research on durability mechanisms – position it as a credible candidate for climate-positive
512 construction technologies.

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516 d'un abri témoin en terre d'excavation et autres matériaux écologiques et indigènes en vue de la
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522 of new Shot-Earth technology in the construction industry (CUP: E93C24000250001)”.

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