

Capillary absorption into CEBs and 2-layer composite building materials comprising of natural stone and CEBs.

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Abstract. Earth-based building materials have been used since antiquity for the construction of various structures. The main drawback of these materials is their vulnerability to direct contact with liquid water, such as rising damp. To protect earthen structures from rising damp, a stone foundation was used, resulting in composite masonry. In the current study, an experimental investigation of the capillary absorption of non-stabilized CEBs produced with soils sourced from different areas of Cyprus, as well as of 2-layer composite building materials comprising of natural stone and CEBs was carried out. The tests on CEBs indicated that the use of water as the wetting liquid led to the disintegration of the specimens and consequently to non-linear response. Thus, a non-reactive liquid was used instead to measure the capillary absorption coefficient of the materials. The test results showed that the capillary absorption coefficient of CEBs varied between 140-260 $\text{gr/m}^2\text{sec}^{1/2}$. In the case of the composites, capillary absorption with water as the wetting liquid showed perfectly linear response, following the $t^{1/2}$ law, with no disintegration of the specimens. The results showed that there are two distinct capillary absorption branches with different gradients, in line with the theory of capillary absorption into 2-layer composite materials.

1 Introduction

Earthen materials have been used for thousands of years to build several structures and monuments across the world [1]. For the past 50 years or so, however, earthen building materials have been sidelined by contemporary industrialized materials with superior physico-mechanical properties [2]. Recently, earth-based building materials have regained some of their lost interest, mainly because of their environmentally friendly nature [3]. The absence of firing process and the abundance of raw materials (e.g., soil) contributes to the low embodied energy associated with these building materials [4].

Compressed earth blocks (CEBs) are a relatively new form of earth-based building material. In fact, CEBs were first introduced in the 1950s and they are considered the evolution of the traditional adobe.

CEBs, as indeed the rest of earthen materials, are considered vulnerable to direct contact with liquid water. Thus, structures built with CEBs must be designed properly to mitigate the effect of water. To do that, stone foundation and roof overhangs were used in the past to eliminate the effect of rising damp and rain, respectively. Even so, problems associated with the presence of moisture are still evident in CEB structures. Therefore, the study of water transport, both in CEBs alone, and in composite natural stone-CEB specimens, is timely.

Water transport in CEBs, like in all porous building materials, usually takes place under unsaturated or partially saturated conditions and it is governed by the extended Darcy law [5,6]. Thus, water diffusion depends on the hydraulic conductivity, which, in turn, strongly depends on the moisture content of the material, rendering

the entire system rather complex [7]. The liquid properties, i.e., density, viscosity and surface tension, also affect the hydraulic conductivity; these change with temperature variations.

In the case of one-dimensional water absorption, hydraulic conductivity may be replaced by sorptivity, which expresses the tendency of the material to absorb and transmit water by capillarity [6]. The sorptivity is a relatively easy property to measure accurately and it depends on both the material and the test liquid. It also depends on the initial and final liquid contents. A very simple gravimetric, one-dimensional flow method may be used to measure the sorptivity [6]. Sorptivity measurements can be used to assess the effect of rising damp and rain penetration on construction materials [8-11].

Most of the experimental work published in the literature refers to homogeneous porous building materials [10-14]. Studies on multi-layered composites are rather scarce [15-18]. Such multi-layered problems, however, are common in building physics, since masonry structures, including earthen buildings, comprise of alternating layers of materials with different hydraulic properties. In this case, the properties of the different layers affect each other, with subsequent deviations from the properties of the materials themselves [6].

Griffin et al. [17] identified a surface layer in fired clay bricks, which makes them behave as layered materials, deviating from the expected square-root of time law during capillary liquid absorption. Wilson et al. [15,16], on the other hand, investigated the absorption of water into composite bars consisting of two materials with different sorptivities in hydraulic contact. Their method of

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analysis adopted a sharp wet front model, in contrast to numerical or finite element methods, which have also been employed in the field of soil science in the analysis of water movement through layered soils [7,19]. Sharp Front (SF) models are a simplified approach of unsaturated flow theory to modelling the liquid transport in porous materials by capillarity [20-22]. According to these models, the flow of liquids in a porous medium is controlled by permeability (K), porosity (f) and capillary potential (Ψ) [6,16]. In capillary absorption, the different hydraulic parameters of composite materials result in deviations from the square-root of time law, but a local sorptivity can still be obtained for the different layers [22]. For the case of absorption through a high sorptivity into a lower sorptivity material, Wilson et al. [15,16] concluded that the absorption of water into the composite is controlled by the properties of the lower sorptivity material.

In this paper, an experimental investigation of the capillary absorption of non-stabilized CEBs and of a 2-layer composite building material comprising of a high sorptivity local limestone and a CEB was conducted, aiming to understand whether the entire process is controlled by the hydraulic properties of the first or the second material.

2 Materials and methods

2.1 Materials

In the current study, 5 soils sourced from different areas of Cyprus were used individually to produce non-stabilized CEBs. The granular composition of these soils was determined according to ASTM D422 [23] and is shown in Fig. 1, together with the limits set by CRaTerre-EAG [24] for the production of CEBs. It can be seen that only D-soil satisfied the limits, while A-, L- and T- soils presented high amounts of silt, and M-soil had a low amount of clay. According to the literature, though, soils that do not satisfy those limits can still be used for the production of CEBs [24].

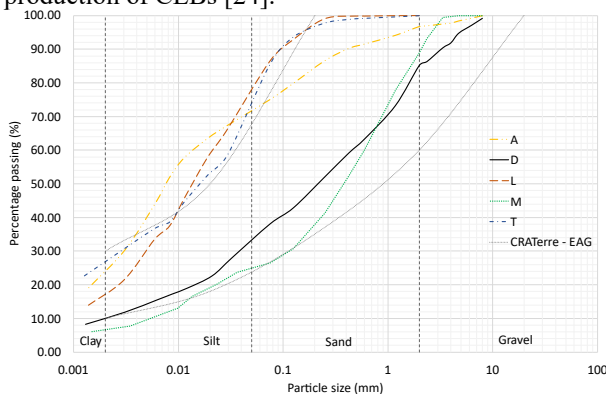


Fig. 1. Granular composition of the soils used to produce CEBs.

Atterberg limits and proctor compaction tests were also conducted according to BS 1377-2 [25] and BS 1377-4 [26], respectively, and the results are summarized in Table 1, together with the limits set by CRaTerre-EAG [24] for the production of CEBs. It can be seen that, in

terms of Atterberg limits, A-, L- and T-soils satisfied the criteria, while M- and D-soils failed to do so. The low value of M-soil plasticity index is attributed to the low clay content (Fig. 1). Regarding the compaction test, all soils presented satisfactory values of maximum dry density. M-soil presented the lower value of optimum moisture content; it was the only soil which satisfied the limits set by CRaTerre-EAG [24] and this is because of its low clay content. The other four soils presented high values of optimum moisture content, which can be attributed to their clay nature or to their granular composition.

Table 1. Atterberg limits and proctor compaction test results of the various soils. LL = Liquid Limit and PI = Plasticity Index.

	Atterberg limits		Proctor compaction test	
	LL (%)	PI (%)	Maximum dry density (kg/m ³)	Optimum moisture content (%)
A	36	15	1750	18
D	44	16	1680	20
L	29	9	1850	16
M	22	6	2090	10
T	41	17	1660	19
CRaTerre-EAG	25-50	3-29	1700-2200	≤15

The mineralogical composition of the various soils used is summarized in Table 2. A-, L- and M-soils presented a carbonaceous composition, while T-soil presented a bilateral composition, containing both carbonates and silicates. D-soil presented high values of silicates, which is characteristic of ophiolitic rocks from which it was formed. The chlorite content in A-, D- and T-soils is high and it is in line with the results of the Atterberg limits.

Table 2. Mineralogical composition of the soils.

Mineral	Raw material (%)				
	A	D	L	M	T
Calcite	81	4	80	59	30
Quartz	4	6	9	-	14
Dolomite	-	4	5	41	-
Alkali Feldspars	7	-	4	-	38
Chlorite	8	16	-	-	12
Plagioclase	-	34	-	-	-
Kaolinite	-	-	-	-	5
Talc	-	4	-	-	-
Enstatite	-	12	-	-	-
Goethite	-	8	-	-	-
Sodalite	-	6	-	-	-

A local limestone (Gerolakkos stone) was further used for the fabrication of a 2-layer composite building material. This stone is essentially a grainstone or unsorted biosparite quarried from the Pliocene-age Nicosia Formation [27]. It is a highly porous stone, which shows considerable volume of primary vug (up to 5 mm in size) and intraparticle porosity (up to 300 μm), while minor intercrystal type porosity (in the range of several microns) also appears within its matrix microsparry calcite grains [20]. Its porosity is ca. 50%, whilst its sorptivity is in the order of 1000 $\text{g}/\text{m}^2\text{sec}^{1/2}$ [27].

2.2 Fabrication of CEBs and Composites

Five batches of non-stabilized CEBs, using one soil at a time, were produced, with the use of an AECT Impact 2001A hydraulic press. The dimensions of the end-products were 300 mm x 150 mm x 100 mm. For every batch, the soil was first mixed with 10% w/w water, following the producer's recommendation. After their production, the CEBs were stored in ambient conditions ($T=25^\circ\text{C} \pm 5^\circ\text{C}$, $\text{RH}=55\% \pm 10\%$) to cure for 3 months. Subsequently, they were dry-cut to form cubic specimens with 70 mm edge.

Cubic specimens with 70 mm edge were also dry-cut from full-sized blocks of Gerolakkos stone. The CEB specimens were then stacked on the stone specimens to form the composite material. A very thin mortar layer was inserted between the 2 layers of the composite material to ensure good hydraulic contact. The mortar was produced using the same soil used for the corresponding CEB.

2.3 Scanning Electron Microscopy

Scanning electron microscopy (SEM) analyses were conducted on gold-sputtered samples from all CEBs using secondary electron imaging mode. Samples were obtained from the surface of the CEBs that would have been exposed to outside conditions in a structure.

2.4 Capillary absorption into stone, CEBs and 2-layer composites

The capillary absorption of the natural stone used in this study was measured following the procedure described in EN 1925 [28]. The same test was also conducted on 6 cubic specimens from each CEB batch. The specimens were firstly dried in an oven at 65°C to constant mass. A non-reactive liquid, namely acetone, was used to determine their coefficient of capillary absorption, since water led to the disintegration of the CEBs and, subsequently, to a non-linear behaviour during the test. The same procedure was used for the capillary absorption into the composite materials; in this case, however, water was also used as the wetting liquid. All the tests were carried out under controlled environmental conditions at a temperature of 20°C .

3 Results and Discussion

3.1 Scanning Electron Microscopy

Figure 2 provides characteristic images obtained from the scanning electron microscopy (SEM) analyses conducted on samples of CEBs produced from all soils. The images indicate denser microstructure with smaller micro-cracks and voids for the specimens made of A-soil, M-soil and T-soil (Figs. 2a, 2d and 2e, respectively), compared to those made of D-soil and L-soil (Figs. 2b and 2c, respectively).

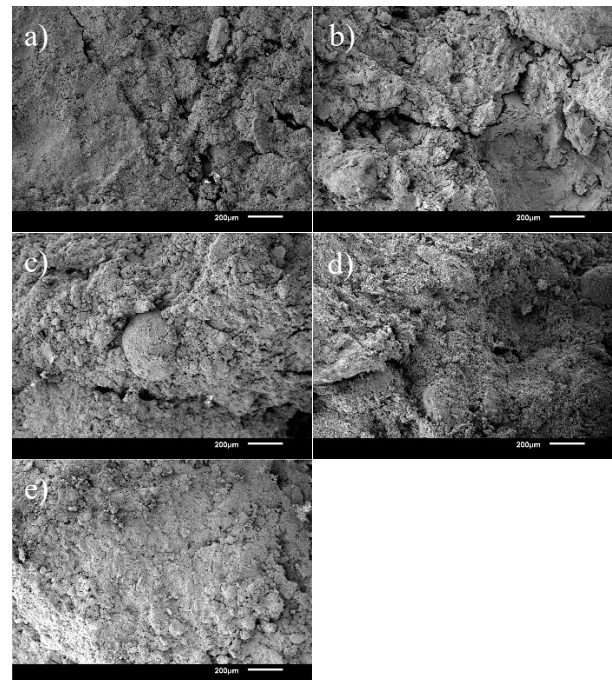


Fig. 2: SEM photomicrographs of CEB made of a) A-soil, b) D-soil, c) L-soil, d) M-soil and e) T-soil.

3.2 Capillary absorption into stone and CEBs

Fig. 3 shows characteristic i vs $t^{1/2}$ curves, where i is the cumulative mass of liquid absorbed by the specimens per unit surface area, for both CEBs and natural building stone. All the specimens demonstrated linear behavior with respect to the $t^{1/2}$ law. The average values of coefficient of absorption for the CEBs and the local limestone are summarized in Table 3. CEBs fabricated with M-soil demonstrated the lowest coefficient of capillary absorption, while CEBs produced with L-soil presented the highest value. These results can be attributed to the denser microstructure of CEBs produced with M-soil (Fig. 2), because of the better gradation of the raw material and production at their optimum moisture content (see Table 1), compared to L-soil. On the other hand, despite the fact that D-soil presented a satisfactory gradation, it contained high amounts of chlorite (see Table 2), which absorbs/desorbs water readily, thus resulting in CEBs with cracked microstructure (Fig. 2), and leading to higher absorption rates. The natural building stone (G) presented a much higher rate of absorption, compared to

the CEB specimens. Taking into consideration the viscosity and surface tension of the wetting liquid, the values hereby reported are in line with those observed in the literature [12-14].

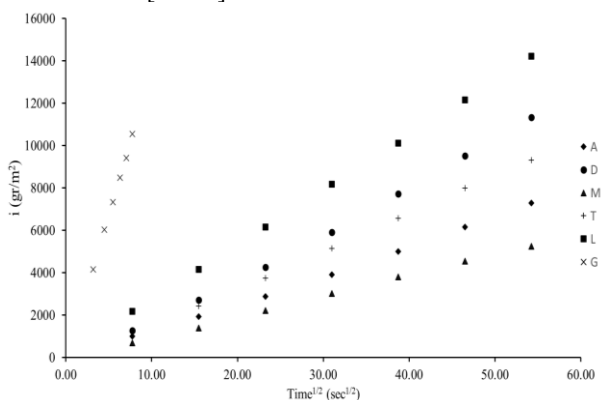


Fig. 3: Characteristic i vs. $t^{1/2}$ curves for CEBs (A, D, M, T, L) and natural building stone (G), using acetone as the wetting liquid.

Table 3. Average values of capillary absorption rates for the CEBs and the natural stone.

	Coefficient of capillary absorption, $\text{gr/m}^2\text{sec}^{1/2}$ (COV)
A	145 (14%)
D	229 (8%)
L	263 (9%)
M	99 (3%)
T	183 (11%)
G	1370 (30%)

3.3 Capillary absorption into composites

In the case of the composite materials, the capillary absorption test results showed two distinct branches in the i vs $t^{1/2}$ curve, irrespective of the wetting liquid (Figs. 4 and 5). The two branches presented perfectly linear behaviour, albeit with different gradients. This is in line with the theory of capillary absorption into layered composite materials [15,16]. The first layer, comprising of the natural stone specimen, presented the same capillary absorption coefficient in all cases, while the second branch of the curve presented different gradients depending on the CEB used. Composites made of CEBs produced with M-soil presented the lowest absorption rate, while composites made of CEBs produced with L-soil presented the highest absorption rates, irrespective of the wetting liquid. Thus, the results suggest that, after the wetting liquid passes the junction between the two layers, the capillary absorption of the composite sample is governed by the hydraulic properties of the second layer, which has the lower sorptivity. This is in line with the findings of Wilson et al. [16]. It is worth noting that the total amount of liquid absorbed per unit surface area was significantly higher in the case of water.

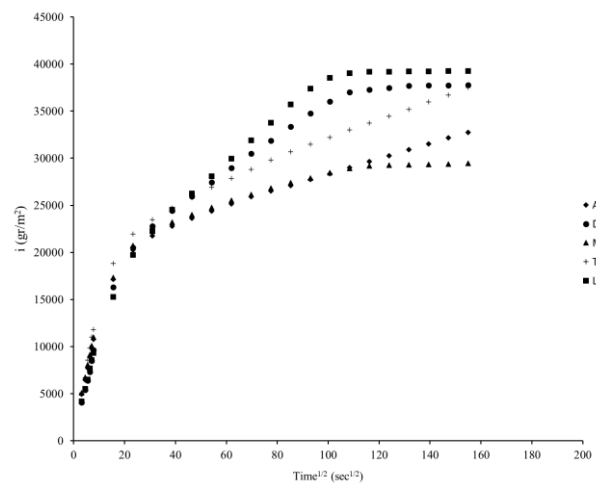


Fig. 4: Characteristic i vs. $t^{1/2}$ curves for composite building materials, using acetone as the wetting liquid.

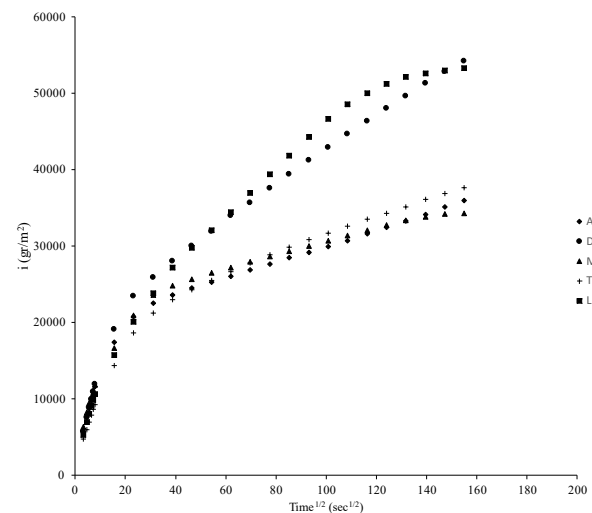


Fig. 5: Characteristic i vs. $t^{1/2}$ curves for composite building materials, using water as the wetting liquid.

The average values of absorption rates for the composites are summarized in Table 4. In all the cases, the coefficient of variation for the CEBs was under 15%, while in the case of the natural stone it reached up to 40%. This is attributed to the varying microstructural properties of the natural stone hereby used. Its unusual pore size distribution, and in particular the presence of large pores, sometimes results in deviations in the measured sorptivity [20].

It is interesting to note that the average values of absorption rates in the case of composites are similar to the capillary absorption rates of the CEBs alone (Table 3), except for the CEBs produced with A- and T-soils. This is in accordance with the literature, whereby the 2nd layer of a composite approaches the absorption rate of the material alone after an intermediate period of suction [6]. In other words, the second material is, in hydraulic terms, effectively being preceded by a shorter length of itself, rather than the actual length of the first material [16]. The absorption of water into the composite is, therefore, controlled by the properties of the second material. For

the cases of CEBs made of A- and T-soils, a reduction in the absorption rate of ca. 40% is observed. This is attributed to an interfacial contact resistance between the 2 layers of the composite material.

The comparison of the composite's test results with water and acetone as the wetting liquids is not straightforward; surface tension and viscosity of the latter must be taken into consideration in order to draw valid conclusions. In any case, the absorption rates of the 2nd layers recorded with water are generally higher than those for acetone. This is attributed to the swelling and consequent microcracks formed during water penetration [29].

Table 4. Average values of absorption rates for the composite materials.

	Absorption rate, gr/m ² sec ^{1/2} (COV)			
	Acetone		Water	
	1 st layer	2 nd layer	1 st layer	2 nd layer
A	1294 (20%)	85 (12%)	1135 (27%)	95 (6%)
D	1206 (15%)	193 (15%)	1231 (37%)	215 (8%)
L	1154 (22%)	251 (6%)	1102 (38%)	295 (8%)
M	1303 (23%)	86 (11%)	1129 (15%)	88 (3%)
T	1532 (8%)	109 (5%)	935 (30%)	108 (7%)

4 Conclusions

In the current study, an experimental investigation of the capillary absorption of non-stabilized CEBs and of 2-layer composite materials comprising of natural stone and CEBs was conducted. The results suggest that the raw materials play a significant role in the quality of the hardened end-product. The granular composition of the soil affects the resulting CEB microstructure, as better gradation generally leads to denser microstructure and lower sorptivity. Furthermore, the mineralogy of the soils also affects the behaviour of the end-product against water penetration. Moisture-absorbing minerals may lead to sparser microstructure because of the formation of microcracks and voids. These may be caused either by water penetration during the service life of a structure or due to the water added during the production of CEBs.

Capillary absorption into CEBs alone showed that the latter are affected by direct contact with liquid water, resulting in disintegration of the specimens; thus, the use of a non-reactive liquid is recommended in such experiments. In this study, capillary absorption into CEBs using acetone as the wetting liquid showed perfectly linear behaviour with respect to the square-root of time law.

The results of capillary absorption into the composites produced with a high sorptivity limestone and CEBs showed that there is a deviation from the square-root of time law, as expected. The absorption curves consisted of two definite linear branches with different gradients, representing liquid absorption by two dissimilar materials. The absorption rate of the bottom layer corresponded to the sorptivity of the natural stone. When

the wetting liquid passed the interface between the 2 layers, the absorption rate reduced and approached the sorptivity of the top material (CEB). In all the cases, however, the gradient of the curve corresponding to the CEBs was lower than the sorptivity of the material alone. This is attributed to an interfacial contact resistance between the 2 materials.

The total amount of liquid absorbed per unit surface area was higher in the case of water, compared to acetone. This is attributed to the suction of the soil components and to microcracks and voids formed by water penetration, which increase the absorption rate and the total amount of liquid absorbed.

The present study is the first attempt to measure the capillary absorption of a layered composite material comprising of natural stone and earthen building materials. The results suggest that further exploitation of the effect of the hydraulic parameters of the different materials on the behaviour of the composite is needed. The effect that the interface between the two materials has on the latter also needs to be further investigated. In future work, the sharp wet front model will be used to describe liquid absorption into similar composites. This will certainly help understand the governing parameters of absorption in such cases.

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