Capillary Barrier Effect in an Earthen Roof of Historical House

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Abstract. A capillary barrier is a widely used drainage system in recent years. It has been in practice since the end of the 1950s, and research over the past 60 years has provided valuable insight into its safe and economical design. Although capillary barrier application is not an old and traditional technique, it is possible to see its primitive application on earthen roofs of traditional buildings. One of these applications is in the earthen roofs of historical and protected houses in Kemaliye district in eastern Turkey. In this study, the capillary barrier behaviour of the earthen roof system of historical Kemaliye houses, which has existed for centuries, has been experimentally investigated. In this context, soil index properties and water characteristic curves were determined by conducting laboratory experiments on samples taken from the soil roof of a traditional Kemaliye house. In order to examine the capillary barrier behaviour of the roof in precipitation, 1D model infiltration experiments were carried out. In the light of the findings obtained from these experiments, it was concluded that the earthen roofs of traditional Kemaliye houses show varied capillary barrier behaviour depending on the initial conditions of the layers.

1 Introduction

A capillary barrier exists when there is a fine-grained of soil layer on top of coarse-grained of soil layer and restricts downward movement of the water into the lower layer by capillary tension. The capillary barrier was first mentioned by Kisch in 1959 and then this remarkable phenomenon has been of interest to researchers [1].

The barrier effect in a capillary barrier system arises due to the difference in the hydraulic properties of the two layers. In addition, coarse-grained soils are more impervious than fine-grained soils at high matric suction. The water infiltrating into the soil surface is held by capillary forces between the interface of the two layers.

Researchers widely studied experimentally, numerically, or analytically the mechanism of capillary barriers. In terms of effects of material types, grain size, heterogeneity of the soils, layer thickness, and slope angle or adding transportation layer on the performance and lateral diversion length of the capillary barrier have been investigated in numerous papers [2-14]. In addition field applications of capillary barriers such as preventing precipitation seepage into the solid waste landfills [14-19] or reducing precipitation-induced slope failures [20-24] have been examined by several researchers.

When the cover is subjected to infiltration, matric suction at the interface decreases and eventually water moves into the lower layer, which is called breakthrough. The lower layer has a significant effect on a capillary barrier. The breakthrough occurs in certain range of matric suction which is called the breakthrough head and is independent from the infiltration rate or fine layer properties [3].

While more uniform and coarse material at the lower layer increases the capillary barrier effect, the thickness of the coarse layer is seen to be ineffective if it is greater than the minimum thickness required to create the capillary break. The coarse layer properties influence the water storage capacity of the fine layer, infiltration rate and percolation [3, 25, 4, 26].

In this study, capillary barrier behaviour within an earthen roof system constituted with local materials and original construction techniques of historical houses that have survived for more than 100 years in Kemaliye, Turkey has been experimentally investigated.

The earthen roof of these historic houses are constructed with traditional methods. The lower layer material (silty sand soil) is placed in slurry form then the material is dried in the open atmospheric condition. After drying of the lower layer, the upper layer material (clayey sand) is placed and compacted with traditional equipment which is a cylindrical stone. Then stone particles are inserted into the clayey sand layer with water. Finally, the earthen roof is compacted again with a cylindrical stone (Fig 1).

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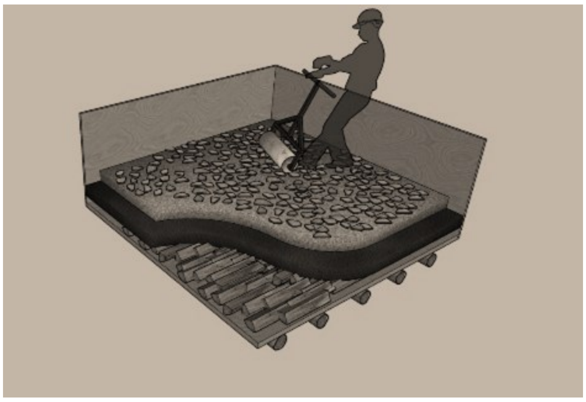

Fig. 1. Prototype of the earthen roof

The traditional earthen roofs of the Kemaliye Houses also have a specific drainage system. On the roof, there are two drainage systems. One is located on the corner of the upper layer with a slope surface and is provided to remove runoff. Another one is placed between the two layers at the facades of the roof [27] (Fig 2.).

Fig 2 . Drainage gutter details of the roofs [28]

1D infiltration tests were carried out in the laboratory to investigate the capillary barrier behaviour on the earthen roof of traditional Kemaliye Houses. In the 1D infiltration tests, two different local materials namely clayey sand and silty sand were compacted in a cylindrical plexiglas tube with the same arrangement as the earthen roof of the historical houses. Infiltration was applied to the soil surface with a peristaltic pump with varied infiltration rates. The soil column was instrumented with TDRs (Time-domain reflectometer) and thermal sensors for measuring volumetric water content and soil suction. Runoff was accumulated in another container and percolation was measured by a tipping bucket. The capillary barrier effect investigated regarding with varied initial conditions of upper and lower soil layers.

2 Material Properties

Clayey and silty sand soils with the local names of yaşkuru and gavcin were used for the investigation of capillary barriers. Some routine laboratory tests (sieve analysis, hydrometer, pycnometer, falling head and constant head permeability tests were conducted for determination of the soil properties. The soils are classified as SC for gavcin and SM for yaşkuru according to the Unified Soil Classification System (USCS). The grain size distribution of the soils are given in Figure 3 and the other geotechnical properties of the soils are listed in Table 1.

In the traditional roofs, the soil surface is regularly compacted (especially during or after precipitation) with a cylindrical stone for preventing percolation. In order to consider this situation, compaction tests were carried out at different energies with the soil used in the upper layer (Fig. 4). In addition to the saturated permeability of the clayey sand soil with optimum water content at 200% 100% and 40% of the Standard Proctor (SP) energies, the permeability on the dry and wet side of the optimum water content were measured. In the traditional method, as the lower layer is not compacted directly, the soil structure does not change a lot.

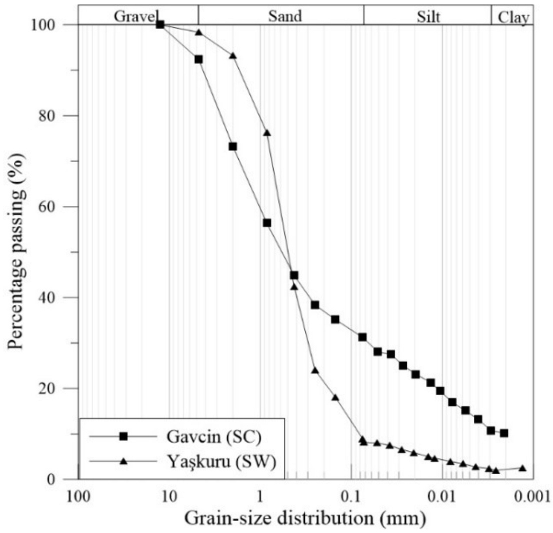

Fig. 3. Grain size distribution of the soils

Table 1. Geotechnical properties of the soils

	Gavcin (SC)	Yaşkuru (SM)
Gravel (%)	4	2
Sand (%)	70	89
Fine content (%)	26	9
D_{10} (mm)	0.002	0.08
Liquid Limit	28	-
Plastic Limit	20	-
Plasticity Index	8	-
Specific Gravity	2.73	2.7
Unified classification system (USCS)	SC	SM
k_{sat} (m/sec)	$4.14x10^{-8}$ -$1.85x10^{-7}$	$4.01x10^{-5}$

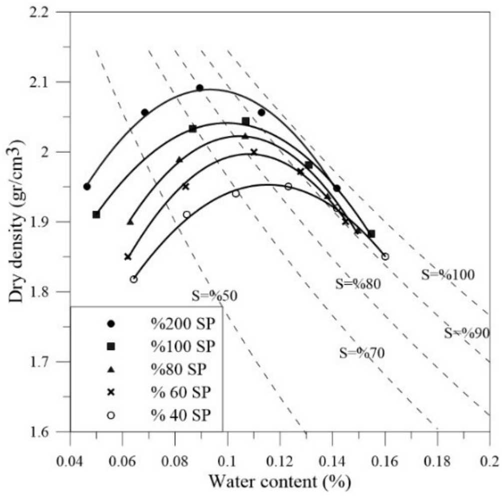

Fig. 4. Compaction curves of the clayey sand

The soil water characteristic curves of the local soils were measured with pressure plate and curves were fitted using the van Genuchten method (1980) (Fig 5) [29]. The best fitting parameters and SWCC properties of the soils are presented in Table 2.

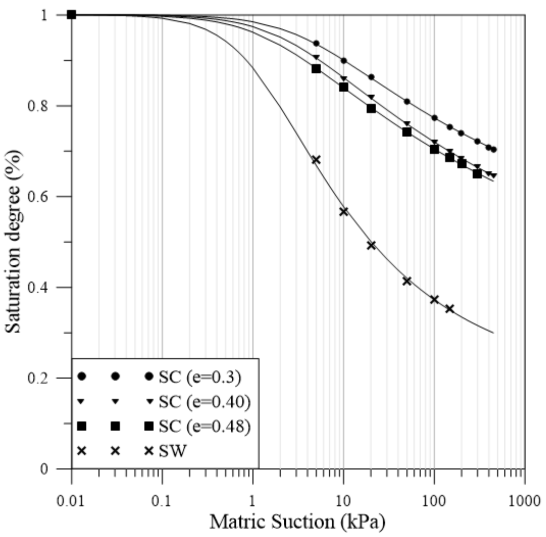

Fig. 5. SWCC of Gavcin (SC) and Yaskuru (SW) soils

Table 2. Parameters of the soil-water characteristic curves

Soil	θs	θr	α (kPa^{-1})	n
SC (e=0.48)	0.32	0.1	0.6941	1.1341
SC (e=0.40)	0.29	0.1	0.4273	1.1482
SC (e=0.30)	0.23	0.1	0.2873	1.1523
SM	0.44	0.08	0.9140	1.3229

3 Test Procedure

The test setup consisted of a transparent plexy cylindrical tube with a 16 cm diameter, peristaltic pump, TDRs, thermal sensors, tipping bucket, data logger and computer. The test set up scheme is shown in Figure 6. Several holes were drilled along the sidewalls of the Plexiglas tube for installing the instruments into the soil column. The thermal sensors were calibrated by a two-point method, based on temperature difference, while the sensor was totally dry and saturated. This data was used in a two-point calibration equation for obtaining negative pore water pressure. Unfortunately, it was observed that the two-point calibration method is not sensitive enough for measuring negative pore water pressure on the dry side. Very high and inappropriate negative pore pressures were measured in dry tests. The negative pore pressures could not be interpreted for the evaluation of the capillary barrier. Nevertheless, the results of the capillary barrier studies in the literature show that the volumetric water content-time and pore pressure-time graphs have same trends indicating the barrier effect.Therefore in this study, the capillary barrier effect was evaluated by volumetric water content data.

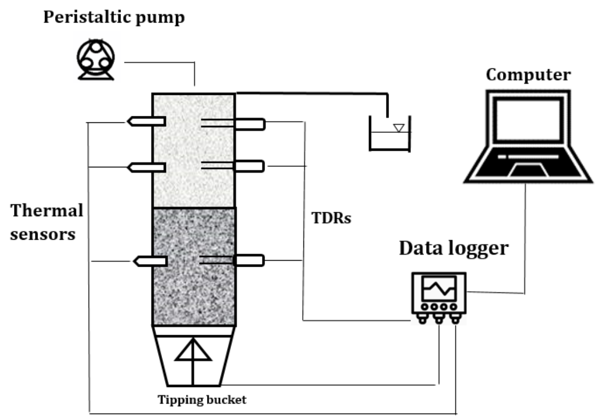

Fig. 6. Test set up scheme

Soil column tests were conducted with different initial conditions in terms of bulk density and water content of the upper layer. Additionally, for the consideration of the capillary barrier, the tests were performed in dry and wet conditions for the lower layer. The lower layer was constructed with a maximum water content that could be physically compacted in the wet tests, while compacted in air-dried water content in dry tests. In 1D two-layer tests, in order to achieve the targeted water content and dry density given in Table 3, clayey sand and silty sand were compacted in layers with 5 cm thicknesses by a Standard Proctor hammer.

Table 3. Initial conditions of the soil layers for soil column tests

Test Name	Dry density (Mg/m^3)		Initial water content (%)		Infiltration (mm/hr)
	SC	SW	SC	SW	
SC-2L-1	2.09	1.5	9	20	16
SC-2L-2	2.09	1.5	9	20	3
SC-2L-3	2.09	1.5	9	1	3
SC-2L-4	1.95	1.5	12	18	3
SC-2L-5	1.95	1.5	12	1	3

4 Results and Discussion

In the first soil column test, the lower layer was constructed in wet conditions. The upper layer was compacted at optimum water content by applying an energy two times higher than the Standar Proctor energy. The soil column was subjected to 16 mm/hr precipitation. The runoff and percolation were measured during the tests at certain time intervals. The measured volumetric water content variation during wetting process in SC-2L-1 test is presented in Figure 7.

TDR1 and TDR2 measurements showed that the volumetric water content increased almost simultanesously in the upper layer during the SC-2L-1 test. However the lower layer was seen to drain for nearly the first 45 hr. Then volumetric water content began to increase and not reach its initial value. The percolation was not observed in the SC-2L-1 test.

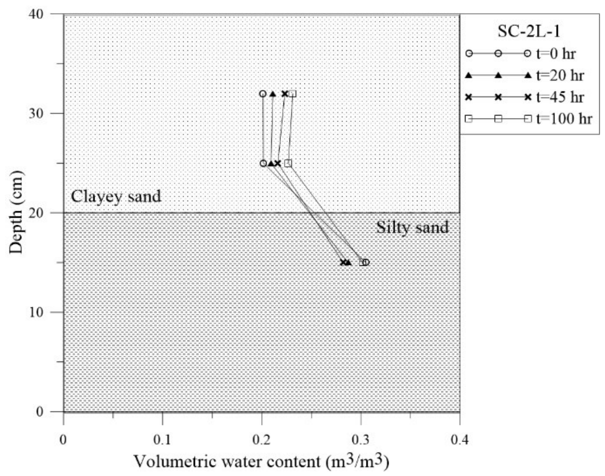

Fig. 7. Volumetric water content variation of SC-2L-1 test

SC-2L-2 test was conducted with a moderate precipitation rate (3 mm/hr) with the same initial conditions as the SC-2L-1 test. The runoff ratio was observed to reach 94% at the end of the test. Volumetric water content–time graph (Fig 8) indicates that test results are quite similar to the SC-2L-1 test. This was due to the saturated permeability of the upper layer, which was same in the both tests. The measured runoff ratio showed that the infiltration rate was approximately equal in both tests. The upper layer has seen to reduce the infiltration into its saturated permeability.

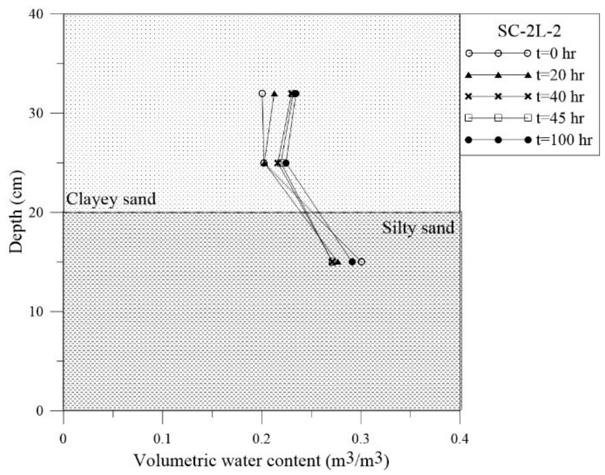

Fig. 8. Volumetric water content variation of SC-2L-2 test

In the SC-2L-3 test, the upper layer compacted at an optimum water content of 200% SP test, while the lower layer was in a dry condition for the observation of the capillary barrier. The upper layer was observed to get saturated with the same trends similar to SC-2l-1 and SC-2L-2 tests. However, an increase was observed in TDR3 readings nearly 55 hr after the test had begun (Fig 9). This increase could be attributed to that the water infiltrated into the soil column was held in the clayey sand layer and did not move into the silty sand soil layer. During the test, percolation was not observed. Runoff was measured to be 95% of the total precipitation.

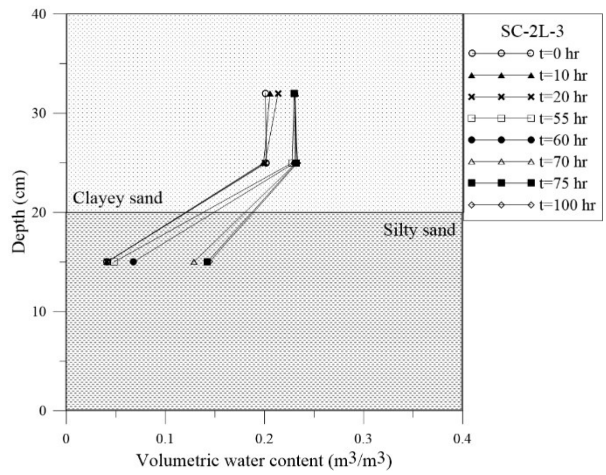

Fig. 9. Volumetric water content variation of SC-2L-3 test

In SC-2L-4 and SC-2L-5 tests, the upper layer is compacted with 40% of SP energy at optimum water content. Additionally, the lower layer was prepared in dry and wet conditions in the SC-2L-4 test and SC-2L-5 test, respectively.

SC-2L-4 and SC-2L-5 test results indicated that the fine layer was seen to get saturated gradually rather than homogeneously (Fig 10-11). In both tests, TDR1 and TDR2 measurements increased nearly the 3rd and 10th hr. For the dry and wet conditions, the shape of the wetting curves of the upper layer was quite similar except for the TDR-2 measurements. In the SC-2L-5 test, TDR-2 readings observed to be higher which was located above the interface. The volumetric water content increase in TDR-3 for SC-2L-4 and SC-2L-5 tests occurred nearly 23rd hr and 27th hr respectively. These results indicate that water breaking into the lower layer takes more time when the lower layer is in a dry condition. Percolation occurred in both tests at 38th and 52nd hr.

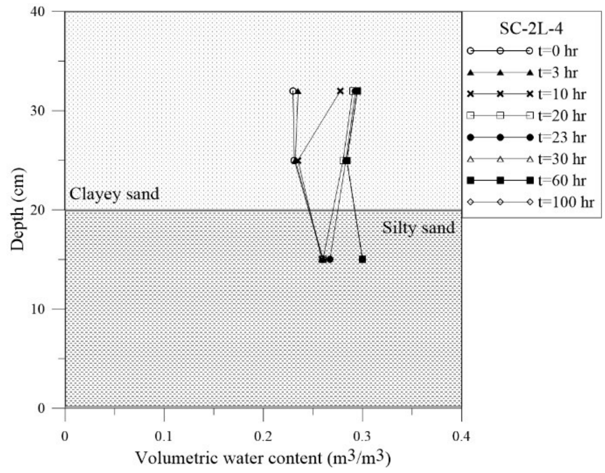

Fig. 10. Volumetric water content variation of SC-2L-4 test

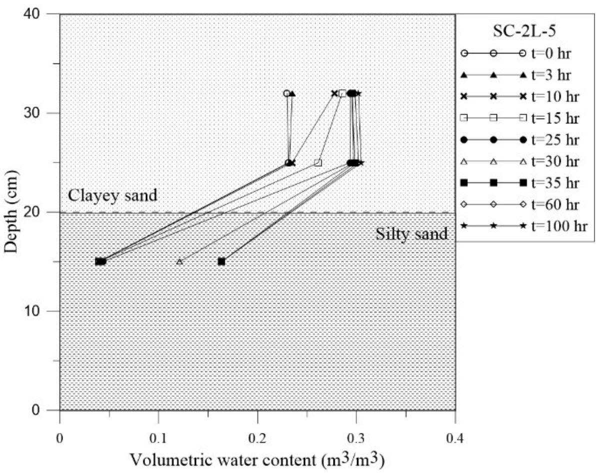

Fig. 11. Volumetric water content variation of SC-2L-5 test

Conclusion

In the light of the findings obtained from the experimental studies conducted to examine the capillary barrier behaviour of the earthen roof system of the historical Kemaliye houses, which have existed for centuries, the following conclusions can be drawn

1. It was observed that there is a capillary barrier effect on the historical earthen roof.
2. In the dry tests, the time required for the increase in volumetric water content of the lower layer is higher than compared with the wet tests. Additionally, volumetric water content measurements are greater near the interface in the dry tests. Therefore, more water stored in the upper layer in dry tests.
3. The tests carried out within the scope of this paper have shown that the top layer significantly affects the capillary barrier. The saturated permeability of the upper layer confines the infiltration into the barrier by reducing the infiltration rate to the saturated permeability. This results in a decrease in percolation and an increase in breakthrough time
4. The initial conditions of the upper layer also affects the wetting mode and barrier effects. The highly compacted upper layer get saturated homogenously and with lowering the compaction energy the layer is wetting gradually and wetting front take place.

Consequently, it can be deduced that residents of Kemaliye have taken advantage of the capillary barrier effect to protect the houses from precipitation. However, the roofs need to be maintained to restrict the percolation into the houses. Frost heave and/or desiccation cracks may occur in soils subjected to atmospheric conditions. Therefore, the permeability of the soils may change, and the barrier effect will be dissipated. The maintenance of the roofs, compacting by using cylindrical stone roller, may rehabilitate the soils in terms of hydraulic properties. The barrier effect on the historical earthen roof needs to be investigated further, considering atmospheric conditions.

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