Unsaturated behaviour of material from a vernacular eastern Croatia rammed earth house

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Abstract. The popularity of the rammed earth building technique has increased over recent decades due to its low ecological impact. Despite the presence of numerous vernacular rammed earth houses across eastern Croatia, research on their properties and behaviour is still in its early stages and appropriate standards to assess vulnerability do not exist. Despite local interest in repairing deterioration that has occurred in some of these houses, without proper knowledge, an important part of Croatian cultural heritage will be lost. To investigate the problem, in this study, laboratory tests of rammed earth material from a rammed earth house in eastern Croatia was collected and tested. The strength of the material was determined at different moisture contents (4-12%) and characterised based on UCS and soil water retention (suction) test results. Results were compared with other studies, and similar behaviour was observed. The influence of moisture content on strength was noted, as was a reduction in suction's contribution to strength beyond a certain moisture content. The strengths determined by the UCS tests corresponded to values recommended in the literature. With this research, an insight into the unsaturated behaviour of the vernacular rammed earth buildings in eastern Croatia was reached. However, to get a complete understanding of the behaviour, further research is necessary.

Keywords: rammed earth, unsaturated behaviour, eastern Croatia

1 Introduction

Earthen construction has gained the interest of the scientific community in recent decades due to its potential as one of the options for sustainable buildings of the future. Despite the prevalence of "conventional" building materials (i.e., concrete, fired brick, etc.), 30 to 50% of the global population still live in earthen houses [1], [2], [3], [4].

Croatia has many vernacular buildings dating from more than a hundred years ago. Earthen houses, usually built using adobe (cro., *ćerpič, prijesna cigla*) or rammed earth (cro., *naboj, nabijača*), are mostly situated in eastern parts of the country [5], [6]. However, since those houses were built using mostly empirical knowledge, little is known about their behaviour under specific loads and material properties. The first attempt to scientifically comprehend these vernacular earthen structures in Croatia appeared at the beginning of the 2020s with the "RE-forMS" research project [7] whose focus is the seismic behaviour of traditional rammed earth (RE) structures. However, in the scope of the project, other properties, such as material composition, strength, and thermal properties, are studied as well. To gain a better understanding of the life cycle of these structures, the hydro-mechanical behaviour must be comprehended as well, as stated by Chauhan et al. [8].

One of the publications to point out the relationship between suction and strength of RE structures was Jaquin et al. [9], in which principles of unsaturated soil mechanics were applied to RE material. Following this, several researchers used similar approaches [8], [10], [11], [12], [13], [14]. The main argument in favour of the approach was that soil in RE structures is never completely dry since it would collapse if that was the case. Jaquin et al. proved the parallel relationship between suction and compressive strength [9] and the relationship between moisture content and compressive strength [15]. Bui et al. [16], [17] observed that mechanical properties remained constant when the moisture content in the materials they studied was 4% or less. With that, they implied that moderate rainfall complemented with a proper roof structure could not induce collapse in RE structures, although care should be taken to assume that the findings apply to any and all RE materials.

For this study, original material from an existing RE house in eastern Croatia was collected and tested. Compressive strength and suction were tested on a wide range of gravimetric moisture contents, from 4 to 12%.

2 Rammed earth houses in eastern Croatia

In the scope of the research project RE-forMS, intensive field observations were performed. Thirty villages and two towns were explored, and earthen houses were noted. Earthen houses in the area are mostly built using RE, adobe, or a combination of both techniques. While the majority of the houses are in a deteriorated state, almost all of them are still in use. Those in a better state are still used for living or at least occasional occupancy, while those in a worse state are used as storage space. Several ethno-villages (e.g., Karanac, Kneževi Vinogradi, Zmajevac, Erdut, Vardarac, etc.) were observed as well, since those villages comprise a large number of earthen houses.

The floor plan of the vernacular earthen houses encountered was generally the same: the one-story houses comprised three connected rooms and a porch along the longer side of the house. Usually only one room faced the street, and the other two rooms were placed in sequence. The walls were typically 40 to 60 cm thick, while the RE layer thickness varied from 6 to 12 cm.

During the field observation, material samples were collected and used for laboratory testing on several levels. For the purposes of this study, material collected from a RE house (Figure 1) in Aljmaš, Croatia, was used. The house was selected due to the possibility to collect a large amount of samples. According to the owners, the house was built at least a century ago, but the specific year of the build was not known. As shown in Figure 1, the house was encountered in heavily deteriorated state, and it was not used as a residential dwelling.

Fig. 1. The RE house in eastern Croatia observed in this study

The RE house was documented and photographed with the owner's permission. Material was collected following the procedure described by Gomes et al. [18] and tested, which will be described in subsequent sections.

3 Soil testing and material characterisation

The experimental in this study work consisted of an unconfined compressive strength (UCS) and suction tests, the latter using WP4C Dewpoint Potentiometer apparatus. Gravimetric moisture content ranged from 12%, at the time of making samples to about 4%. Particle size distribution (Figure 2) was determined by a combination of sieving and sedimentation (hydrometer method) [19].

The soil composition in Figure 2 was compared with soil composition recommendations (envelopes) from the literature [20], [21], [22]. The composition of soil used for this study fit well within the local envelope [23], as expected. However, the literature recommendations do not agree with the particle size distribution of the RE houses from eastern Croatia, as stated previously [23], and the same is true for the soil sample that forms the basis of this study.

The soil samples collected from the house in question were crushed and oven-dried at 105 °C for 24 hours to ensure there was no moisture in the soil. Samples for UCS and suction tests were made at a moisture content of 12%, as per the maximum dry density determined by the standard Proctor test results [24] (OMC = 12%, $\rho_{d,max}$ = 1839 kg/m^3). Wet soil was kept in plastic-sealed bags inside a humidity chamber for approximately 24 hours, to ensure the equilibrium of moisture within the material [11]. The goal was to test 10 groups of samples with moisture content ranging from 4 to 12%. The drying duration needed to reach the desired moisture content in the sample was determined by drying and weighing a set of samples every 5 to 15 minutes over the course of 8 hours.

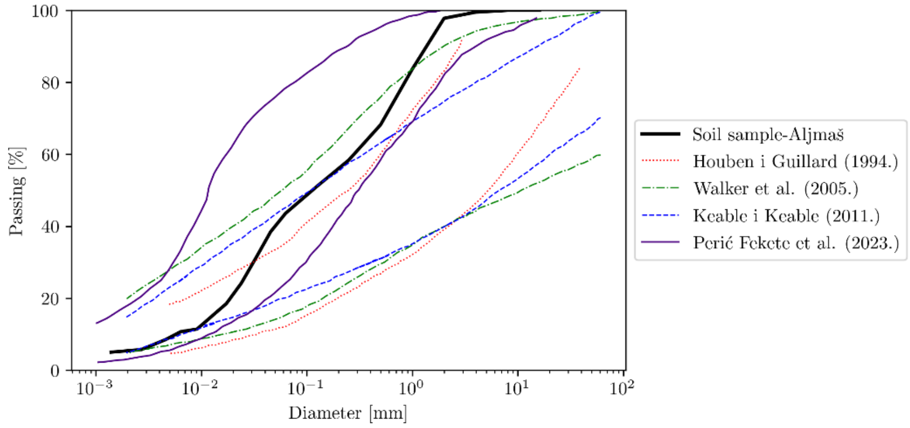

Fig. 2. Particle size distribution of the observed soil sample compared with literature recommendations and local envelope

3.1 Strength test

The UCS was tested on cylindrical samples with a diameter of 38 mm and a height of 76 mm. Cylindrical samples were compacted using a hydraulic press into six consecutive layers of the same height. After compacting, samples were wrapped in plastic and kept inside humidity chambers for an additional 24 hours. After equilibrating the moisture inside each sample, the air-drying process commenced. When the previously established drying period ended, wrapped samples were again kept inside a humidity chamber to ensure a homogenous distribution of moisture content inside the test sample prior to testing.

A Lloyd test machine with a 5 kN load cell was used for the UCS testing, with a loading rate of 0.1 mm/min. To check the moisture content in each sample, a small portion of the sample was taken after the completion of the test and dried in the oven for 24 hours at 105 °C. Also, a specimen for testing suction using the WP4C Dewpoint Potentiometer apparatus was gathered from each UCS tested sample.

According to test results (Figure 3), UCS is highly sensitive to moisture content in the sample, as expected based on a literature review. During the field observations in eastern Croatia, the moisture content of in-situ walls was determined. Measurements taken were in spring: during the dry period exhibited 2-5% of moisture content, while after rainfall moisture content increased to about 6.5-8 [23]. This research sheds light on the value of the compressive strength one could expect in the in-situ RE walls: about 2 MPa during the dry period and about 1.50 MPa after rainfall. According to Walker et al. [21], the unconfined compressive strength determined on a cylindrical sample should be at least 1 MPa or 2 MPa for load-bearing walls, which agrees with the experimental results in this study.

The drop in compressive strength with moisture increase is basically linear. Moreover, the influence of moisture content on stiffness and ductility was also observed. Specifically, as moisture content increased, the stiffness of the samples reduced while ductility increased.

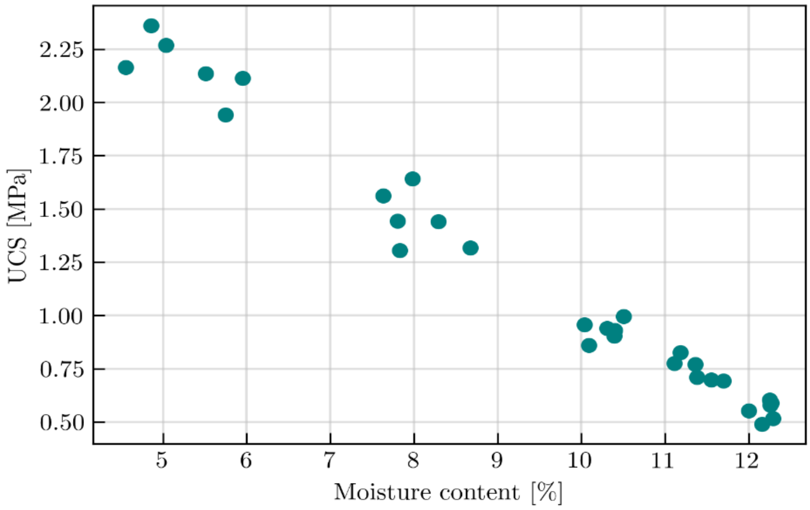

Fig. 3. UCS results at different moisture levels

3.2 Soil water retention behaviour

A suction test was performed on small disc shaped samples (*approx*. Φ 35mm, h = 0.8 mm), but also on fragments taken from each UCS sample after test completion. In total, 50 disc-shaped samples and 30 fragment specimens were tested. A wider range of moisture content was covered with the suction test than with the UCS test due to the amount of material needed for one disc-shaped sample that is 35 mm in diameter and 8 mm high. Suction values were gathered for moisture content ranging from 12 to about 2%.

The process of making samples was the same as for the UCS samples described above (section 3.1). However, due to the test apparatus, suction samples were kept inside small plastic containers. To ensure equilibrium inside the sample, it was kept in a closed plastic container at least an hour before the test.

Suction was determined according to the chilled mirror hygrometer method [25], based on the water potential of the soil specimen. After performing the test, specimens were oven dried (at 105 °C for 24 hours) to determine the relationship between moisture content and suction (Figure 4). As expected, based on the reviewed literature, suction values increased as moisture content decreased. Moreover, on the graph in Figure 4, two sets of marks can be observed. Circular marks represent suction test results obtained from fragments taken from UCS samples after test completion, while square marks represent suction test results from disc-shaped samples made solely for the purpose of the suction test. Since both marks combined form a relatively single file and the results complement each other, both sample shapes can be used for testing suction using WP4C apparatus. Moreover, the idea behind taking fragments for the suction test from each UCS sample was to gather both the UCS and suction values for the same moisture content. Thus, relationship between UCS and suction for corresponding moisture content could be observed.

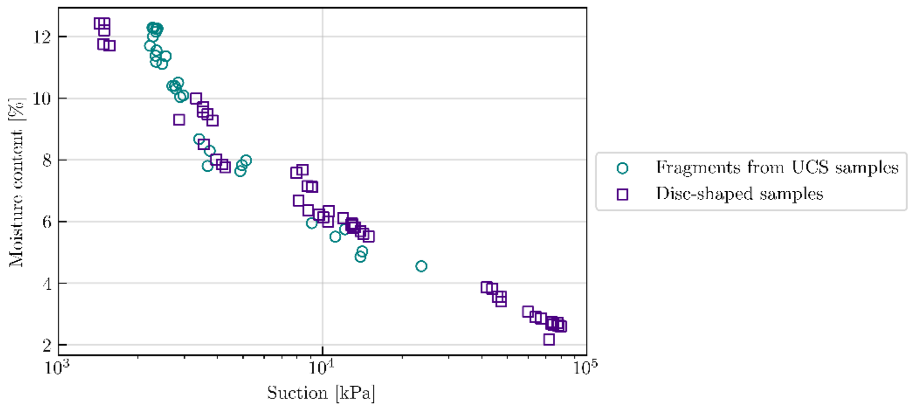

Fig. 4. Suction at different moisture content

3.3 The strength-suction relationship

To get insight into the hydro-mechanical behaviour of RE material collected from a house in eastern Croatia, suction results determined on fragments from UCS samples were plotted against corresponding UCS results (Figure 5).

An increase in suction was followed by an increase in compressive strength as moisture content decreased. However, after reaching about 104 kPa of suction, the compressive strength stopped increasing. The same plateau was observed by other researchers [15], [26], [27].

If the data plotted in Figure 5 are approximated by a line, the data gathered from testing suction on disc-shaped samples can be plotted against it (Figure 6). The square marks in Figure 6 have the same values as the square marks plotted in Figure 4. However, in Figure 6, square marks of suction values from disc-shaped samples indicate that if suction and moisture content are known, one could at least roughly predict the compressive strength of the material. However, the correlation should be made using more RE samples to confirm the effectiveness of the method.

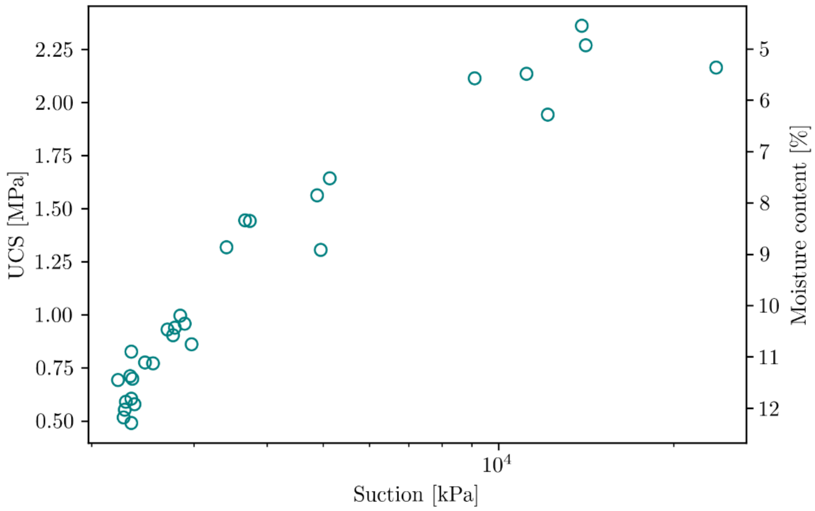

Fig. 5. Suction of fragment samples and strength at corresponding moisture content

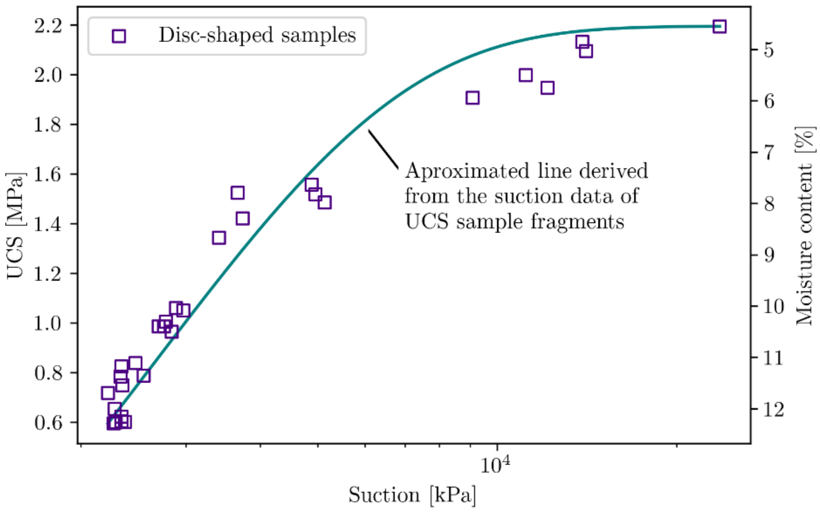

Fig. 6. Approximation chart for estimating the UCS based on suction and moisture content

4 Conclusion

Research into vernacular earthen architecture, specifically RE houses, from eastern Croatia is still in its early stages. Following field research, experimental tests in the laboratory were conducted to gain familiarity with the material and its properties and it should be noted that material from only one of the existing RE houses was studied here.

The particle size distribution of the used material differs from the recommendations for choosing suitable RE material, findings previously observed for other soil samples collected from RE houses in eastern Croatia.

Suction and unconfined compressive strength were determined to obtain insight into the hydro-mechanical behaviour, of a wide range of gravimetric moisture contents from 4 to 12%. A linear drop in compressive strength was observed with an increase in moisture content. However, for moisture contents that can be expected inside a RE wall during the usage phase (i.e., 4-7%), compressive strength values were 1.5 MPa or higher, which is enough, for routine design, according to recommendations in the literature.

Suction was measured on samples with moisture contents ranging from 2 to 12%. Again, a decrease in moisture content was followed by an increase in suction as expected. In order to connect compressive strength and suction at the same moisture content, fragments from each UCS sample were placed in the WP4C machine to get the suction value. The increase in suction and compressive strength was constant until suction of about 10^4 kPa was reached. Beyond that value, compressive strength reached a plateau and stayed relatively constant, despite further increases in suction. The same behaviour was observed by other researchers.

Finally, based on the UCS-suction relationship, a chart was created that could be used for rough estimation of compressive strength with known suction and moisture content in the sample. Since a suction test (using WP4C apparatus) is quicker and less soil is required to produce a test sample, an estimation of the UCS could be quickly obtained by this approach in the future when assessing strength of existing RE materials. Also, from even a small fragment gathered from an existing RE house, an estimation of UCS could be made. However, the experimental testing of this kind should be repeated with more RE mixtures of different compositions to confirm the applicability of the method. The results presented in this paper form part of a larger study described by the Authors in [28].

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