Some physical properties of soil used in traditional Croatian rammed earth houses

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ABSTRACT

In eastern Croatia, houses were traditionally built using soil as the building material. The construction of rammed earth houses is carried out in layers within the formwork, and the choice of suitable soil depends on several properties, such as particle size distribution and plasticity. Unfortunately, the construction and renovation of such houses is almost non-existent nowadays since there are no regulations and recommendations for construction in Croatia. With the aim of forming recommendations, soil samples were collected from existing houses in order to test the physical properties of the soil. The comparison of obtained results with those published in literature and published recommendations, showed that bulk density and Attbereg limits are within the limits of the published values. However, particle size distribution differs from most recommendations and published results. Further research on soil properties from existing houses is needed in order to make recommendations for the area of Eastern Croatia.

KEYWORDS

Rammed Earth; Density; Atteberg Limits; Particle Size Distribution.

1. INTRODUCTION

Numerous materials can be used to build houses, and one of the oldest is soil. Soil is an environmentally friendly and easily accessible material with good thermal properties (Morel et al, 2001; Minke, 2006). In eastern Croatia, numerous houses were built in the past using soil. Even today, houses made of soil, older than 100 years, are still in use. Traditionally, houses in eastern Croatian villages are elongated, containing three rooms lined up along the porch: a living room facing the street, a small room at the back of the house, and a kitchen in the middle. Over time, additional rooms were added to this series. In Figure 1, a traditional rammed earth (RE) house in eastern Croatia can be seen. RE houses are characterized by very thick walls that are formed by ramming soil in layers within the formwork. When constructing such walls, it is important to choose the soil correctly (e.g., to choose proper grain size distribution and soil plasticity), prepare the soil at the adequate moisture content, and possibly add other materials in order to increase strength, and ultimately properly compact the soil. However, the knowledge of constructing and selecting suitable soil has not been noted in Croatia. Hence, there are no recommendations or regulations for the construction of RE houses like elsewhere in the world (e.g., NZS 4298 Materials and workmanship for earth buildings, NZS 4297 Engineering Design of Earth Buildings, HB195 The Australian Earth Building Handbook, 14.7.4 NMAC 2015 New Mexico Earthen Building Materials Code, ASTM E2392/E2392M – 10, SADC ZW HS 983:2014: Rammed earth structures – Code of practice). Due to that, construction of RE houses in eastern Croatia today is almost non-existent, while the renovation of existing buildings is somewhat difficult. In order to gather knowledge about the construction of RE houses and the requirements for the soil, a scientific project was initiated: Rammed earth for modelling and standardization in seismically active areas – RE-forMS. As part of the project, samples were collected from existing RE houses to analyse main soil properties, compare them with data, recommendations, and requirements available in the literature, and to serve to for further recommendations. Research of physical properties of soil from observed RE houses is one of the first of that kind in the Republic of Croatia, while recent research on thermal (Perić et al, 2021a) and mechanical properties (Perić et al, 2021b; Perić, 2021) was conducted.

Figure 1. Traditional rammed earth house in eastern Croatia

2. MATERIALS AND METHODOLOGY

Tested soil samples from the RE houses were collected in the eastern Croatia area (Figure 2), in the villages of Lug (sample LG) and Zmajevac (sample ZM). Both buildings are residential, with the house in Zmajevac still in use. There is no information on the year of construction for researched RE houses, but it is assumed that it is more than 50 years ago. The thickness of compacted layers for house in Lug (LG) ranges from 6 to 8 cm, while for the house in Zmajevac (ZM) it is between 9 and 11 cm (Figure 2).

Figure 2. Left: position of the researched houses on the map of the Republic of Croatia (map taken from Geoportal DGU and complemented with symbols); top middle and right: house LG; bottom middle and right: house ZM

From both houses, it was possible to take only a sufficient amount of soil to conduct basic physical property tests. During sampling, the plaster (mixture of soil and chaff) was removed if necessary, as in most cases, there was no plaster on the walls. Since it was not possible to cut out part of the wall for testing purposes, smaller parts were sampled, while taking care to obtain samples that could be used for testing bulk density. However, parts of the samples were obtained in bulk during sampling.

The bulk density test was conducted in accordance with the standard HRN EN ISO 17892-2 by submerging the samples in a container filled with water (fluid displacement method). Three samples were tested for each RE house. In a few cases, there was a possible sample disturbance due to sampling difficulties. Hence, it is possible that the bulk density values determined on samples deviate from those in the original houses in-situ. Additionally, the moisture content was tested according to the standard HRN EN ISO 17892-1, in order to determine the dry density of the samples. Particle density was tested following standard HRN EN ISO 17892-3, by the fluid pycnometer method, during which the samples in the pycnometers were exposed to vacuum.

Laboratory tests of organic content were conducted in accordance with ASTM standard D 2974. The ignition of previously oven-dried samples was carried out in the furnace at a temperature of 450 °C, with gradual heating to the required temperature for 3 hours, until no further loss of mass was observed.

The liquid limit (LL) and plastic limit (PL) were tested following standard HRN EN ISO 17892-12. Testing was conducted on previously prepared samples passing through a 0,425 mm sieve. For LL testing, the fall cone method was used (cone of 80 g mass with a tip angle of 30°), where LL is considered to be moisture content at which the cone penetrates the sample 20 mm over 5 s. Testing of PL was carried out by rolling soil threads taken from the portion of material prepared for LL determination.

Particle size distribution was determined according to standard HRN EN ISO 17892-4 by a combination of sieving and sedimentation using the hydrometer method. Wet sieving was performed to separate particles larger than 0,063 mm from the sample. Particles larger than 0,063 mm were oven dried and dry sieving through a standard set of sieves was conducted. A sample of particles smaller than 0,063 mm was prepared following standard HRN EN ISO 17892-4, and was tested using a hydrometer. Hydrometer readings were taken at 0.5 min, 1 min, 2 min, 4 min, 8 min, 30 min, 1 h, 2 h, 6 h, and 24 h, and afterwards, particle size distribution was calculated.

3. RESULTS AND DISCUSSION

3.1. Bulk density

The bulk density of the LG sample had an average value of 2.02 Mg/m^3. With the moisture content of the samples determined, it was possible to calculate an average dry density of 1.97 Mg/m^3 for the LG sample. The ZM sample had the average bulk density of 1.89 Mg/m^3, while the calculated average dry density totals 1.84 Mg/m^3. Maniatidis and Walker (2003) report a wide range of dry density values for RE houses, ranging from 1.7 to 2.2 Mg/m^3. The values determined by this research are within the mean values defined by Maniatidis and Walker (2003).

As there are recommendations or regulations in other geotechnical constructions regarding the degree of compaction and moisture content during soil compaction, there are also recommendations for RE houses. According to NHS 4298, it is necessary to achieve a degree of compaction of 98%, while moisture content can be less than optimal by up to 4% and higher than optimal by up to 6% during compaction. Additionally, a recommendation is given regarding the thickness of the layers, which should be between 100 and 150 mm in the loose state. The New Mexico Code 14.7.4 NMAC instructs that the thickness of the layer should not exceed 200 mm, and each layer should be compacted to full compaction at optimum moisture content. The SADC ZW HS 983 states that the degree of compaction should be greater than 95% (for light compaction effort). Walker et al. (2005) instruct that the deviation from the optimal moisture content is allowed within ± 1 – 2% during the time of compaction, and the degree of compaction should not be less than 98% (by heavy manual compaction test). Since it was not possible to sample larger amounts of soil from LG and ZM houses, it was not possible to conduct Proctor test. Without knowing the maximum dry density, the achieved degree of compaction in researched houses cannot be determined. Due to the previous compaction of the soil (taken from RE houses) and the long period of exposure of the walls to external influences and long-term low moisture content, values of Proctor parameters should be taken with caution with respect to soil parameters before building RE houses. Nevertheless, the obtained densities provide a basis for further research and numerical modelling planned within the project.

3.2. Particle density

For sample LG, the determined particle density was 2.56 Mg/m^3, while for the ZM sample it was slightly higher, at 2.62 Mg/m^3. Particle density is not a property that is given in recommendations. However, knowing the values of particle density can help in determination of porosity and in modelling compacted soil constructions. Furthermore, lower value of particle density can indicate the presence of organic matter. Typically, values of particle density are in the range of 2.6 Mg/m^3 to 2.8 Mg/m^3 (Nonveiller, 1979).

3.3. Organic content

In constructions with soil, and also in RE houses, the use of organic soil is avoided, due to adverse consequences for the construction. When building RE houses in Croatia, available soil from the immediate vicinity of the house was usually used (e.g., material obtained by basement excavation or wells). However, empirically, the humus layer was discarded and was not used as a building material. Occasionally, plant fibre added at the contact of the layers acted as micro-reinforcement. In the observed LG and ZM houses, no residue of organic matter was present at the layer contacts. The presence of organic content from both houses was determined by testing three samples. The average organic content for the LG facility is 2.0% while for the ZM sample is 2.6%. An organic content range, published in literature, was from 0.9 to 5.4% in Portugal (Gomes et al, 2014). The share of organic matter in LG and ZM does not deviate from the mentioned range.

Recommendations regarding organic content are descriptive for the most part. Thus, NHS 4298 states that soil containing organic matter that may rot or break inside walls must not be used in the construction of RE houses. Both New Mexico Code 14.7.4 NMAC and the SADC standard ZW HS 983: 2014 state that the soil should be free of organic matter. Maniatidis and Walker (2003) point out that organic matter should be avoided. Walker et al. (2005) state that the share of organic matter, soluble salts, and other harmful substances cumulatively should not exceed 1 to 2%. Both LG and ZM have organic content values greater than or equal to 2%, hence according to Walker et al (2005), this soil would not meet the selection criteria. However, it should be noted that both RE houses still exist today, and the ZM house is still in use. Houben and Guillaud (2006) allow the limit of the marked effects of organic matter from 2 to 4%, which can justify the use of soil in the case of LG and ZM houses.

3.4. Liquid limit and plastic limit

Based on the known Atteberg limits, cohesive soil can be classified. The plasticity index (difference between liquid and plastic limit; PI) indicates the range of moisture within which the observed soil can best form. The determined LL for the LG sample was 38%, while for the ZM sample it was slightly lower and equalled 32%. The PL for the LG sample was 22% (PI 16%), and for the ZM sample the PL was 20% (PI 12%). Deviations are possible regarding the soil used as building material due to the fact that the samples were taken from houses exposed to external influences and had low moisture content over a long period of time. Therefore, it is necessary to keep that in mind when reproducing materials for research or construction purposes. A review of the literature revealed a wide range of LL, in samples from RE houses, ranging from 14.8% (Gomes et al, 2014) to 57% (Huang and Peng, 2015). However, more often these values are higher than 25% and lower than 45% both in soil samples from RE houses and in soil from suitability research for RE houses (e.g., Silva et al, 2013; Gomes et al, 2014; Lin et al, 2017; Tinsley and Pavia, 2019, Zhou and Liu, 2019). It has been noted in the literature that it was not possible to determine the PL for certain RE houses, i.e., that the tested soils were non-plastic (Gomes et al, 2014). However, the PL could be determined in most cases (on soil samples obtained from RE houses and soil used in suitability research) and more frequent values ranged from 15% to 30% (Silva et al, 2013; Gomes et al, 2014; Tinsley and Pavia, 2019; Zhou and Liu, 2019). The results of Atteberg limits for LG and ZM samples were within most common recorded values in the literature.

A recommendation for LL in the range of 25 to 46% and for PL from 2 to 30% was given by Houben and Guillaud (1994; as stated in Delgado and Guerrero, 2007). Delgado and Guerrero (2007) suggest a LL in the range of 32 to 46% and a PI of 16 to 28%. Both LG and ZM samples meet the LL criterion. However, the criterion for PI according to the recommendation given by Delgado and Guerrero (2007) is not met for the facility ZM (a facility that is still in use today). Hence, for the territory of the Republic of Croatia it is necessary to further investigate the criterion of PI.

3.5. Particle size distribution

The particle size distribution of the soil for the RE houses is the most common requirement in the literature. Cohesive soil was dominant for LG and ZM samples (Figure 3), according to the particle size distribution test. In the LG sample, 0.8% of gravel, 24.3% of sand, 60.8% of silt, and 14.1% of clay was observed. Sample ZM had a slightly lower content of fine particles than the LG sample, with 2.7% of gravel, 36.8% of sand, 50.5% of silt and, 10% of clay. According to the literature, the particle size distribution of samples collected from RE houses in other countries show a wide range of content of soil particles. Perić et al. (2021) state that the average amount of clay in RE soil samples was 13.2%, silt 24.4%, sand 43.1%, and gravel 19.9%. Therefore, from the previously mentioned, a higher content of gravel and sand in the RE soil samples can be observed in other countries than in the case of LG and ZM samples.

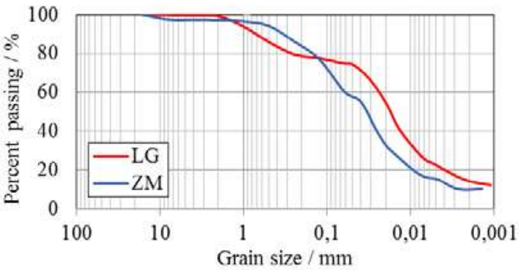

Figure 3. Grading curve for LG and ZM samples

Requirements are given in the form of the maximum grain size in the sample. For instance, New Mexico Code 14.7.4 NMAC states that soil must not contain particles larger than 38.1 mm. NHS 4298 states that soil must not contain large particles that can disrupt the homogeneous structural performance of the wall, without specifically referring to particle diameter. Other requirements are given in the form of particle percentage. For example SADC ZW HS 983:2014 states that the soil should contain 50-70% gravel and sand, 15-30% silt, and 5-15% clay. Maniatidis and Walker (2003) provide an overview of the recommendations for the lower and upper limits of individual soil groups (Figure 4). By comparing the above recommendations with the particle size distribution of LG and ZM samples, it can be concluded that the particle size distribution does not meet the required conditions. However, the LG and ZM buildings, of unknown age (the ZM building is known to be older than 1969), which still exist, show that even soil with such a composition can be used to build RE houses.

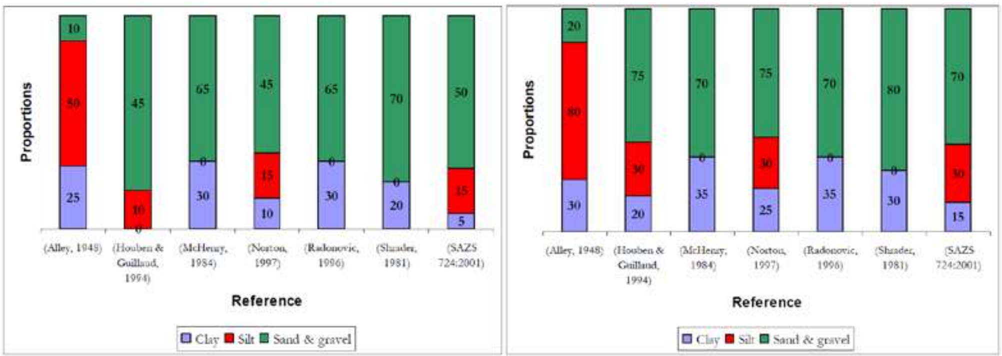

Figure 4. Particle size distribution for natural rammed earth, left: lower range limits; right: upper range limits (Maniatidis and Walker, 2003)

4. CONCLUSIONS

Field observation and soil sampling from the RE houses gave insight into the basic physical properties of soil used for the construction of RE houses in Eastern Croatia. Determined properties will serve as a basis for future research and possible development of recommendations for the required properties of the soil used for constructing RE houses. As part of the research, bulk density was tested, for which the values fell within the recommended published in the literature. However, without the known maximum dry density, it was not possible to determine the degree of achieved compaction. Particle density was slightly lower, which could indicate the presence of organic matter. The organic content was determined by ignition, and it was between 2% and 2.6%. Although the presence of organic matter in the soil is not recommended in the literature, both RE houses observed in this study still exist and can be used. Both the liquid limit and the plastic limit were within a wide range of values published and recommended in the literature. The exception was the plasticity index of the ZM sample, which proved unsatisfactory according to one criterion. However, it was found that the criteria (for LL and PL) published in the literature are applicable for RE houses in eastern Croatia. The particle size distribution of the tested samples was different from the average values published in the literature and given recommendations. It is necessary to conduct further research on the particle size distribution of soil used in RE houses in the Eastern Croatia area.

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