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Research Paper

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In eastern Croatia rammed earth houses were traditionally built in the past. The choice of suitable soil for building rammed earth houses depends on several soil properties. Moreover, since there are no standards or recommendations for construction of rammed earth houses in Croatia, the construction and renovation of such houses is almost non-existent nowadays. With the aim of forming detailed recommendations for eastern Croatia area in near future, soil samples were collected from existing houses to test the physical properties of the soil. Obtained results showed that Atterberg limits are within the limits of the recommended values and published results in the literature, while particle size distribution differs from most recommendations and published results.

Key words:
traditional houses, rammed earth, particle size distribution, Atterberg limits, organic content, density

Prethodno priopćenje

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Fizikalna svojstva tla u zidovima tradicijskih kuća od nabijene zemlje u istočnoj Hrvatskoj

Na području istočne Hrvatske u prošlosti su se tradicionalno gradile kuće od nabijene zemlje. Pri odabiru tla za gradnju takvih kuća potrebno je voditi računa o njegovim svojstvima. U Republici Hrvatskoj ne postoje norme ili preporuke za gradnju takvih kuća, pa je danas njihova gradnja gotovo nepostojeća, a obnova postojećih kuća otežana. Obilaskom već izgrađenih objekata od nabijene zemlje prikupljeni su uzorci s ciljem ispitivanja svojstava tla i mogućim formiranjem detaljnih preporuka za područje istočne Hrvatske u skorijoj budućnosti. Rezultati ispitivanja Atterbergovih granica pokazali su dobro podudaranje s rezultatima objavljenim u literaturi i preporukama iz inozemstva, ali su uočena odstupanja u granulometrijskom sastavu.

Ključne riječi:
tradicijske kuće, nabijena zemlja, granulometrijski sastav, Atterbergove granice, organske tvari, gustoća

1. Introduction

Soil is one of the oldest materials used for building houses. The use of soil has several advantages. Soil is a readily available material that can be used multiple times [1, 2], and its disposal is simple (without special environmental requirements). If the source of the material is close to the construction site, the transportation costs are low, which reduces the carbon footprint. According to Lončar-Vicković and Stober [3], the thermal properties of rammed earth houses are also advantageous. According to Walker et al. [1], the thermal capacity of a 300-mm thick rammed earth wall with a dry density of 1.9 g/cm^3 is approximately equal to that of a 200-mm thick concrete block wall. Since rammed earth walls can transmit or absorb moisture from the air, another advantage of rammed earth houses is the quality of the air inside them [1, 2]. From an architectural point of view, soil can be an interesting building material because of its different colours and the possibility of surface treatment [1]. As no other materials were available in eastern Croatian villages in the past, the load-bearing walls of houses were constructed from rammed earth and adobe, ceilings were constructed from wooden beams, and roofs were mostly double-pitched with a wooden rafter construction covered with flat tiles. Traditionally, such houses were elongated with gables facing the street (Figure 1, left), and generally comprised three rooms lined up along an open porch: a large living room facing the street, a kitchen in the middle, and a smaller room at the back of the house (Figure 1, right). Over time, additional rooms were constructed as needed. Rammed earth houses are characterised by relatively thick walls (thickness ≥ 40 cm) constructed by compacting soil in the layers within the formwork. Compaction of soil layers was mostly performed manually, generally using wooden rammers. As part of this study, field research was conducted in eastern Croatia, where approximately 20 rammed earth houses were examined in detail, and it was found that the thickness of the built-in layers was mostly between 6 and 10 cm.

In the construction of rammed earth walls, building materials must be selected by considering the suitability of the soil and its properties (for example, grading curve and Atterberg limits), the possibility of adding additives to improve the desired properties of the building material, moisture content during compaction and, among other things, compaction method, and compaction energy. Knowledge of rammed-earth house construction and selection of suitable soil in eastern Croatia has been passed down through generations; unfortunately, there are no complete and detailed records. Therefore, there are no standards for the construction of rammed-earth houses in Croatia. Owing to the lack of standards, the construction of new rammed-earth houses in the Republic of Croatia is difficult and/or restrictive, and the renovation of existing houses is challenging. However, a literature review reveals several international standards and recommendations for the construction of rammed earth houses (for example, NZS 4298 [4], NZS 4297 [5], HB195 [6], 14.7.4 NMAC [7], ASTM E2392/E2392M [8], SADC ZW HS 983 [9]). In order to gather knowledge about the properties and behavior of rammed earth houses, their construction and soil properties in the area of Slavonia and Baranja suitable for construction of structural elements, the 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 rammed-earth houses for analysis and comparison with the data and requirements published in literature, to serve for further recommendations. This paper presents the physical properties of three existing rammed-earth buildings in eastern Croatia. The mechanical properties of the soil for some of the rammed earth buildings observed in eastern Croatia can be found in [10, 11].

2. Materials and methodology

Samples were collected in eastern Croatia (Figure 2) from the villages of Bijelo Brdo (sample BB), Lug (sample LG), and Zmajevac (sample ZM). The years of construction is unknown for the buildings. For the building in Zmajevac, it is only known that it was built before 1969. However, it can be assumed that all three buildings are older than 50 years. The building in Bijelo Brdo was used for agricultural purposes, whereas the buildings in Lug and Zmajevac were used for residential purposes, with the house in Zmajevac still in use. The wall thickness in building BB is approximately 50 cm, and the thickness of the compacted layers ranges from 6 to 10 cm (Figure 2, right). House LG has a wall thickness of approximately 40 cm, with the thickness of the compacted layers ranging from 6 to 8 cm, whereas house ZM has a wall thickness of approximately 50 cm, with the thickness of the compacted layers ranging from 9 to 11 cm (Figure 2, right).

Figure 1. An example of a traditional rammed earth house in Baranja (left); Street facade (author's photo); floor plan [3] (right)

Figure 2. Position of the observed buildings on the map of the Republic of Croatia (taken from [12] and edited, left); Building BB and thickness of the compacted layer (author's photos, top right); House LG and the thickness of the compacted layer (author's photos, middle right); House ZM and the thickness of the compacted layer (author's photos, bottom right)

During sampling, the plaster (mainly a mixture of soil and chaff) and near-surface layer of the wall (approximately 3 cm thick) were removed from the walls of the buildings. It was not possible to obtain a larger amount of material from for the study because of the possible continuation or existing use of the structures. Since it was not possible to cut a part of the wall for testing, smaller parts were carefully sampled to obtain suitable samples for testing the bulk density. Some samples were obtained in bulk. The quantity of collected material was sufficient to investigate the basic physical properties of the soil. The particle size distributions, liquid limits, plastic limits, bulk densities, and organic contents of the samples were determined. The particle size distribution was determined by a combination of sieving and sedimentation using the hydrometer method according to HRN EN ISO 17892-4 [13]. Wet sieving was performed to separate particles larger than 0.063 mm. The process of (dry) sieving was performed for particles larger than 0.063 mm, using a standardised set of sieves. A sample of particles smaller than 0.063 mm was prepared according to a standard [13] and tested using a hydrometer.
The liquid and plastic limits were tested according to the HRN EN ISO 17892-12 [14]. The tests were performed on previously prepared samples passing through a 0.425-mm sieve. For the liquid limit tests, the fall cone method was used with an 80-g cone and tip angle of 30°, where the liquid limit was considered to be the moisture content at which the cone penetrated 20 mm into the specimen within 5 s, and the plastic limit was tested by rolling soil threads taken from the portion of the material prepared for the liquid limit test.
The bulk density test was performed according to the HRN EN ISO 17892-2 [15] using the fluid displacement method, that is, submerging the samples in a container filled with water. Owing to sampling difficulties from walls, there is a possibility of sample disturbances in a few cases. Therefore, the possible deviation in the bulk density determined from that of the walls should be considered. The moisture content of the observed samples was tested according to the standard HRN EN ISO 17892-1 [16], in order to determine the dry density of the samples. Additionally, the particle density was tested using the fluid pycnometer method following standard HRN EN ISO 17892-3 [17].
Organic content was tested by ignition according to ASTM D 2974 [18] on oven-dried samples (samples dried at 105 °C for at least 24 h). Ignition was conducted in a furnace at a temperature of 450 °C (with gradual heating to the required temperature), until no further loss of mass was observed.

3. Results and discussion

3.1. Particle size distribution

One of the most important requirements in the selection of soil for the construction of rammed-earth houses, that is structural elements, is the soil particle size distribution. Although most construction has traditionally been conducted with soil from the immediate vicinity of the construction site, there is some empirical knowledge regarding the selection of suitable soil (for example, it is necessary for the soil to have a certain clay content to act as a binder [1, 2]). Currently, there are written recommendations and standards for the selection of suitable soil as well as for the testing procedure itself (e.g. [1, 4, 7, 9, 19-21]). The particle size distribution can be determined relatively easily using the combined sieving and hydrometer method, and the obtained results can be used to determine the suitability of the soil for use in rammed earth houses. If the soil available for construction does not have a satisfactory grading curve, corrections can be made in the form of the addition or deduction of certain fractions. In literature, recommendations and requirements are usually provided in terms of the clay, silt, sand, and gravel content in the soil and the maximum particle size [1, 4, 7, 9, 19-21]. The 14.7.4 NMAC [7] states that the soil should not contain particles larger than 38.1 mm, whereas NZS 4298 [4] states that it should not contain large particles that may affect the homogeneous structural performance of the wall. Walker et al. [1] did not specify a strict limit for the maximum particle size, but stated that 10 to 20 mm are common limits, although soils with larger particles (and even 100 mm) have been used successfully. Other recommendations and requirements are related to the clay, silt, sand, and gravel content of the soil suitable for the construction of walls using the compaction method. Walker et al. [1] recommended that the sand and gravel content in a sample should be between 45 % and 80 %, silt content between 10 % and 30 %, and clay content between 5 % and 20 %. A similar range of values is given in [9, 21], where it is recommended that the soil contain between 50 % and 70 % gravel and sand, 15 % and 30 % silt, and 5 % and 15 % clay. Compared to the above recommendations, Doat et al. [19] suggested a slightly lower sand and gravel content of 40–65 %, silt content of 20–35 %, and a slightly higher clay content of 15–25 %. Norton [20] recommended gravel and sand content of 45 %–75 %, silt content of 15 %–30 %, and clay content between 10 % and 25 %.

When examining the particle size distribution of the samples collected in situ in eastern Croatia, cohesive soil was found to be predominant in the observed samples (BB, LG, and ZM) (Figure 3). Sample BB contained 4.7 % gravel, 35.4 % sand, 50.1 % silt, and 9.8 % clay. Compared with sample BB, sample LG had a slightly lower content of non-cohesive soil with 0.8 % gravel, 24.3 % sand, 60.8 % silt, and 14.1 % clay, whereas sample ZM had a similar content with 2.7 % gravel, 36.8 % sand, 50.5 % silt, and 10 % clay. The maximum particle size of the BB and ZM samples was 16 mm, whereas that of the LG sample was 8 mm.

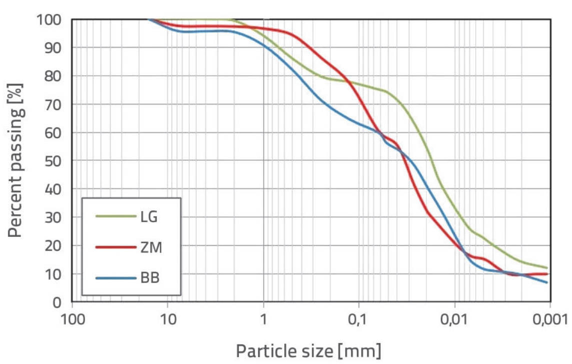

Figure 3. Grading curves for BB, LG, and ZM samples

It has been reported that samples collected from traditional rammed-earth houses worldwide show a wide range of particle size distributions. Thus, Perić et al. [22] state that in samples from rammed earth buildings, the average clay content is approximately 13 %, silt content is approximately 24 %, sand content is approximately 43 %, and gravel content is approximately 20 %. Comparing the above values with the particle size distributions of the BB, LG, and ZM samples, it can be observed that the gravel and sand contents in the samples of rammed earth buildings worldwide were higher than those determined for the observed buildings in Croatia.

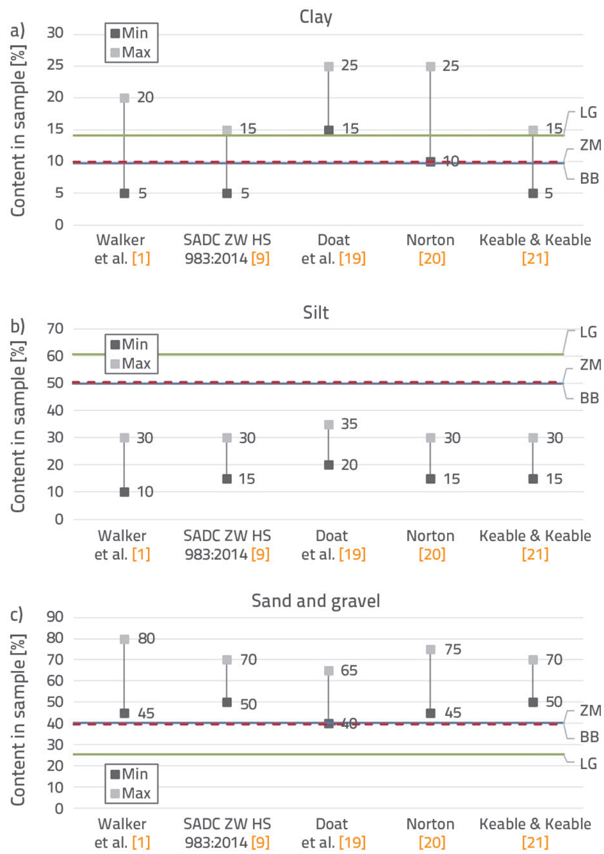

Figure 4. Recommendations for clay, silt, sand, and gravel contents and comparison with the results of BB, LG, and ZM samples: a) clay, b) silt, and c) sand and gravel

The maximum particle sizes in all the observed buildings were in accordance with the values given in [1, 7]. Figure 4 shows the recommendations from published literature in terms of particle size distribution [1, 9, 19-21] compared to the clay, silt, sand, and gravel contents of the BB, LG, and ZM samples. It can be seen that the clay content is satisfactory in all the studied samples, except for the recommendation given in [19]. The silt content was 15–25 % higher in the tested samples than in all the observed recommendations. The total sand and gravel content in the tested samples were lower than the recommended values, except for the recommendation in [19]. It can be seen that the particle size distribution of the tested samples does not correspond to the recommendations of other countries for silt content and total sand and gravel content. However, the observed buildings from which the BB, LG, and ZM samples were obtained still exist (although their age is believed to be more than 50 years) and may be or are in use. This shows that even soil with such a particle size distribution can be used for the construction of rammed-earth houses.

3.2. Liquid limit and plastic limit

In addition to the particle size distribution, soil plasticity is the most important requirement for the selection of a suitable soil for the construction of a rammed-earth houses. Cohesive soils can be classified using known Atterberg limits, and the plasticity index indicates the moisture content range in which the soil can be best shaped. In literature [1, 19, 23, 24], recommendations are generally provided in terms of a range of liquid limit and plasticity index values, and less frequently in terms of the plastic limit. Doat et al. [19] recommended that the liquid limit should be in the range of 25 % to 50 % (preferably 30 % to 35 %), plastic limit should be 10 % to 25 % (preferably 12 % to 22 %), and plasticity index should be in the range of 7 % to 29 % (preferably 7 % to 18 %). Houben and Guillaud [23] suggested a liquid limit in the range of 25 to 46 % and plasticity index in the range of 2–30 %. According to Walker et al. [1], the liquid limit should be less than 45 % and the plasticity index should be in the range of 2 % to 30 %. Delgado and Guerrero [24] suggested that the liquid limit should be in the range of 32 to 46 %, whereas they proposed a range of 16–28 % for the plasticity index.

The liquid limit determined for samples BB, LG, and ZM were 36 %, 38 %, and 32 %, respectively. According to the Unified Soil Classification System (USCS; [25]), the observed samples can be classified as low-plasticity soils (Figure 5).

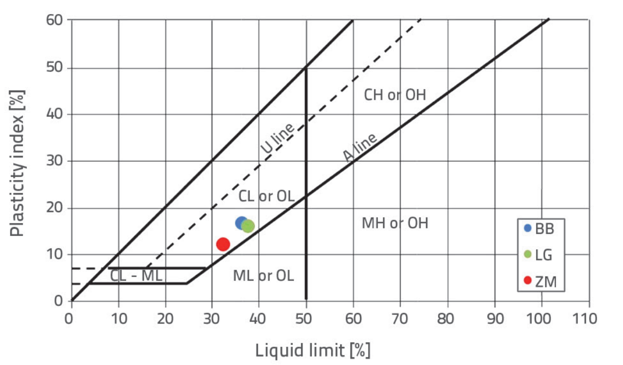

Figure 5. Plasticity chart for the USCS classification [25] with data for samples BB, LG, and ZM

For the samples BB and ZM a plastic limit of 20 % was determined, while for the sample LG is slightly higher at 22 %. The difference between the liquid and plastic limit values determines the plasticity index, which is 16 % for samples BB and LG and 12 % for sample ZM. Deviations are possible for the soil used as the construction material because the samples were obtained from buildings exposed to external influences, and had relatively low moisture content for a long period of time. The average moisture content of samples LG and ZM were 2.4 % and 2.8 %, respectively, whereas sample BB had the highest moisture content of 6.0 %. Therefore, it is necessary to take this into account when reproducing materials for research or construction.

In available literature, a wide range of liquid limit values was observed in soil samples from rammed earth houses, ranging from 14.8 % [26] to 57 % [27]. However, these values are generally above 25 % and below 45 % both in constructed buildings and published studies on soils for rammed-earth buildings [26, 28-31]. Previous studies indicate that in some rammed earth buildings, it was not possible to determine the plastic limit; that is, the observed soils were non-plastic [26]. However, in most cases, it was possible to determine the plastic limit (using samples from constructed buildings and soil used in published research), and most values were in the range of 15–30 % [26, 28, 30, 31]. The plasticity index values for soils from rammed earth buildings and research published in literature vary from 6 % to 25 %. Among the most frequently published values of the liquid and plastic limits in the literature are those of samples BB, LG, and ZM. The plasticity index values of samples BB, LG, and ZM were within the published range of the plasticity index values of samples from rammed earth houses in Portugal [26].

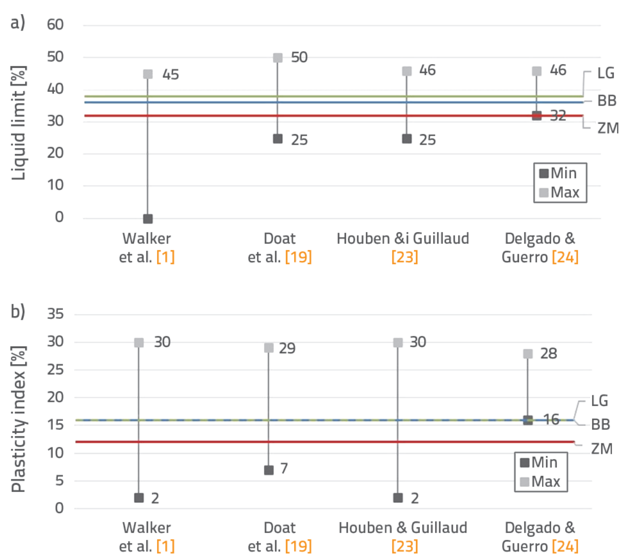

Figure 6. Recommendations for the range of values of the liquid limit and plasticity index and comparison with the obtained results of samples BB, LG, and ZM: a) liquid limit and b) plasticity index

Figure 6 shows a comparison of the recommendations in [1, 19, 23, 24] in terms of the results obtained for samples BB, LG, and ZM. From the comparison, it can be seen that all three samples have a liquid limit that is in accordance with the recommendations and range defined in the reviewed literature. The plasticity index was satisfactory for samples BB and ZM, according to the observed recommendations. For sample ZM, the plasticity index criterion was satisfied according to the recommendations in [1, 19, 23]; however, the plasticity index value was lower than that recommended in [24]. Considering that sample ZM belongs to a house that is still in use and that a lower value for the plasticity index is given [26] than the limit of 16 % according to Delgado and Guerrero [24]; perhaps a lowering of the lower plasticity index limits in the mentioned recommendation is possible.

3.3. Density

Bulk density, that is, dry density, is a property that depends on several factors, namely, soil type and compaction method, that is, moisture content during compaction and compaction energy. Similar to the recommendations for compaction and soil moisture content during compaction in geotechnical works, there are also recommendations for rammed earth houses. Generally, for this purpose, tests are conducted using the Proctor test [1, 2, 20, 32]. In literature [9, 20], the drop test (a ball of moist soil dropped from a certain height) is described as a procedure to determine the moisture content of the soil suitable for compaction in the walls of rammed-earth houses, that is, to control the moisture content of the soil during compaction. However, this method is not standardised as the Proctor test, and its accuracy is lower. According to NZS 4298 [4], a degree of compaction of 98 % is recommended, while the moisture content during compaction can be up to 4 % below the optimum moisture content and up to 6 % above the optimum moisture content. SADC ZW HS 983 [9], states that the required degree of compaction is greater than 95 %, while Walker et al. [1] state that the required degree of compaction is not less than 98 %, although the optimum moisture content may vary by ± 1 – 2 %. The 14.7.4 NMAC [7] specifies the full compaction of layers at optimum moisture content. In addition to the degree of compaction and moisture content required during compaction, there are also recommendations for the thickness of the compacted layers. According to 14.7.4 NMAC [7], the height of the layers should not exceed 20.3 cm, whereas NZS 4298 [4] states that the height of the layers should be between 100 and 150 mm in the loose state.

For the test samples presented in this paper, the average bulk density tested on three different samples was 1.81 g/cm^3 for the sample BB, 2.02 g/cm^3 for the sample LG, and 1.89 g/cm^3 for the sample ZM. With the moisture content of the samples determined, the average dry density of 1.71 g/cm^3 for the BB, 1.97 g/cm^3 for the sample LG and 1.84 g/cm^3 for the sample ZM could be calculated. In [32, 33], a wide range of dry density values for rammed earth buildings were reported from 1.75 g/cm^3 to 2.2 g/cm^3 and 1.7 g/cm^3 to 2.2 g/cm^3, respectively. Keable and Keable [21], state that a wall density of at least 1.8 g/cm^3 is required 28 days after compaction, and approximately 2 g/cm^3 is recommended. The values determined in this study are within the published range. As mentioned above, the thickness of the compacted layers varies within the observed buildings, BB, LG, and ZM, being 6-10 cm for BB, 6-8 cm for LG, and 9-11 cm for ZM. In literature [2, 3, 20, 34, 35], construction in layers of 10–15 cm in an uncompacted state has been recorded. The thicknesses of the compacted layers in buildings BB, LG, and ZM were within the published values [2, 3, 20, 34, 35] and recommended or required values [4, 7].

Since it was not possible to extract larger quantities of soil from the observed rammed-earth buildings, it was not possible to perform the Proctor test and determine the maximum dry densities. Therefore, it was impossible to determine the degree of soil compaction in the observed buildings. However, previous compaction of the soil from the observed rammed earth buildings and the long-time exposure to external influences and loads could potentially have influenced the test results. Although it was not possible to determine the degree of compaction, the determined soil densities provided a basis for further research and numerical modelling planned as part of the RE-forMS project. Another basis for further research as part of this project is the particle density. For the sample BB, the density was determined to be 2.51 g/cm^3, for LG 2.56 g/cm^3, while for the sample ZM a slightly higher value of 2.62 g/cm^3 was recorded. Although this property is not recommended, it can provide insights into the volume ratios in the soil as well as the presence of organic matter (lower density values).

3.4. Organic content

In the construction of rammed-earth houses, the use of organic soil, which can have unfavourable consequences for the building, is avoided. In the construction of rammed-earth houses in Croatia,

Figure 7. Rammed-earth walls from eastern Croatia with organic material between compacted layers (author's photos): a) brushwood, b) reed and chaff

available soil from the immediate vicinity of the house was used, and brushwood, reeds, and cereal straw were sometimes added as reinforcements at the layer contacts inside the rammed-earth walls (Figure 7). Soil from the excavation of cellars, wells, or waterholes was generally used during construction. However, empirically, humus was discarded and not used as a building material.

Recommendations in literature regarding the organic matter content are mostly descriptive. For example, NZS 4298 [4] states that soil containing organic matter that may rot or break inside walls, must not be used in the construction of rammed-earth houses. The 14.7.4 NMAC [7] and SADC ZW HS 983 [9] state that soil should be free of organic matter. Maniatidis and Walker [33] indicate that organic matter should be avoided. Minke [2] stated that the soil should be non-humus and without plant matter, whereas Keable and Keable [21] stated that the soil should be free of organic matter and other substances, such as salts. Walker et al. [1] provided recommended values and limits, and stated that the organic matter content should be less than 2 % by weight of the soil mixture.

In the observed rammed-earth buildings BB, LG, and ZM, no remains of larger organic matter (for example, brushwood and reeds) were detected at the layer contacts. The organic content of each observed building was tested using three samples. The highest average organic content value (6.0 %) was recorded for sample BB. LG and ZM had slightly lower values 2.0 % (LG) and 2.6 % (ZM).

The results for soil samples BB, LG, and ZM did not comply with the recommendations of [1, 7, 9], because the organic content was higher than or equal to 2 %. According to the criterion given by Houben and Guillaud [23], where the limit of the marked effects of organic matter is 2–4 %, the use of soil could be justified in the case of houses LG and ZM but not for building BB. The range of organic content published in literature for existing rammed earth houses was found to be from 0.9 to 5.4 % in Portugal [26]. The organic content of samples LG and ZM did not differ from the reported range; however, sample BB had a higher value, and was the highest value recorded in available literature. Although it is advisable to select soil with as little organic matter as possible for the construction of rammed-earth houses, it has been shown that even with some organic content, the construction and durability of buildings is possible.

4. Conclusion

Field observations and soil sampling from rammed earth houses provided insights into the physical properties of the soil used in the past for the construction of rammed earth houses in eastern Croatia. As part of this research, the particle size distribution, liquid and plastic limits, density, and organic content were investigated for three rammed-earth buildings in eastern Croatia. The following are evident from the results:

- The maximum particle sizes of the samples were within the recommendations provided in literature. However, the percentages of gravel and sand content in the samples were lower than that recommended, and the percentage of cohesive soil was predominant. Since all three buildings can be or are still in use even after several years of existence, it is necessary to conduct more extensive research on the particle size distribution of the soil from rammed earth houses to make recommendations for eastern Croatia.
- The observed samples have low plasticity. The liquid and plastic limits of the studied samples were within most of the recommendations, although it should be noted that the tested samples were in conditions different from those in the soil itself. Nevertheless, it can be concluded that these recommendations are mostly applicable to rammed-earth buildings in eastern Croatia.
- Owing to the small number of samples, it was only possible to determine the bulk and dry densities of the samples and not to conduct a Proctor test. Therefore, it was not possible to determine the degree of compaction. The determined densities are in accordance with the recommendations reported in the literature.
- The organic content was tested by ignition, and it was determined that sample BB had the highest organic content of 6 %, whereas samples LG and ZM had lower contents of 2.0 % and 2.6 %, respectively. However, the presence of organic matter in soil is not recommended because of its negative consequences for buildings and human health.

The determined properties will serve as a basis for future research and the possible development of recommendations for soil properties required for the construction of rammed-earth houses.

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