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ENERGY SUSTAINABILITY OF RAMMED EARTH BUILDINGS

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ABSTRACT

Earth construction has long tradition in our civilization with wide distribution in various ways and techniques of application. When combined with other natural materials it is the material for construction of comfortable space for people. Increased need for energy efficient houses actualizes this type of construction in modern conditions as a holistic solution for modern buildings. In addition to many uses of earth as a building material, rammed earth wall came to consideration since it allows us to observe most of the advantages and disadvantages of this type of construction. Finding solutions to remedy observed disadvantages will lead to improved construction of adobe, wattle-and-daub, unbaked bricks, etc. This paper is aimed at proving energy efficiency of rammed earth wall and it points out possible research directions into improvements while preserving existing benefits. The most important issue is preservation of cost efficiency of earth building while using other natural supplements into the soil mixture.

Key words: *energy efficiency, earth construction, rammed earth, sustainable development*

INTRODUCTION

Experiences in building with earthen material are present on all continents and in almost all countries of the world. Tibet, Peru, Egypt, China, Europe and America provide many examples of construction with earthen material. It is estimated that about 1,7 billion people of the world's population live in houses made of earth. 50 % of them are in developing countries and at least about 20 % in urban and suburban areas. The oldest building made of earth is considered to be Ramasseum (Figure 1 - built of unfired earth elements - adobe), 3300 years old, in the old city of Thebes (Egypt). At the end of the nineteenth century the proficiency of building with earthen material had progressively disappeared and until the mid-twentieth century constructions made of earthen material had become marginal [1,2].

In harmony with the environment, people in Vojvodina for centuries have built their houses, barns, and outbuildings with earth and have developed a mastery of construction using earth as ubiquitous and inexhaustible resource.

Thanks to the basic raw material, walls made of rammed earth have excellent thermal accumulation potential, satisfying load-bearing capacity and they are long-lasting. Construction of rammed earth walls can be applied primarily in areas without enough wood for construction and where good quality earth for construction is in abundance. If the site lacks natural raw materials suitable for construction, artificial materials can be used but then remains the question of justification of such concepts (harmony of the building with its natural environment, increased construction costs, etc.).

Figure1. 3300 year old Ramesseum in Egypt

Heat accumulation capacity of the rammed earth walls does not need to be emphasized. Their homogeneous mass allows slow heating and cooling. In some cases, this feature of the rammed earth walls can completely eliminate the need for cooling and heating.

The heat, collected during the day, will spread in the room at night and will then collect cold air that will refresh interior space during the day. Density of rammed earth walls proved to be excellent for sound insulation. It is also necessary to reiterate earth's outstanding characteristics as firewall.

EARTH – THE ANCIENT MATERIAL

The walls of rammed earth can be adapted to different climates and different construction practices in the world in terms of finishing, types of insulation, wood paneling, plastering, etc. Maturation of the wall can take up to two years, depending on the thickness, climatic conditions and other factors. When developing process is complete, the wall of rammed earth has similar properties as the stone wall. To the mixture of the wall, some builders add crushed colored glass or pieces of wood to get a more interesting appearance to the wall.

The thickness of the wall is usually greater than 30 cm in order to ensure its strength. Today, using modern tools and machinery, formwork can be set to 10 ÷ 25 cm. Compression through pneumatic or hand tools is used to compact earth at about 50 % of its original height of the formwork. Compacting process is carried out in layers until it reaches the desired height and formwork can be removed immediately. Hence, it is not necessary to provide formwork for the entire building at once, but it can be built in stages without delays in construction until the wall completely hardens.

The techniques of using earth for architectural purposes depend on geological composition of the soil, the climate and the altitude. Earth material used for building is the result of long evolution process of rock. Earth material consists of gas, liquid, organic and inorganic solid substances of plant or animal origin, which affect the workability, structure and strength of the earth construction (Figure 2) [3].

For construction purposes the earthen material should include all kinds of granular sizes from the finest (clay and dust) to the largest (sand). Plasticity is a necessary ability for the earth to be formed. Compressibility is the ability of the earth to minimize its porosity. Finally, the grains are connected one to another through cohesion of clay.

This composite earthen materials are used for construction of: adobe (traditional, semi stabilized, fully stabilized, molded or fired adobe), rammed earth, mud plasters, etc. (Figure 3). These elements are produced using earth with a certain percentage of clay minerals. Clay minerals have particle sizes less than 0,002 mm. The surfaces and the volume of clay particles are increased by binding water. As these materials are processed and incorporated into a wet state, it must be considered that the volume after drying will be reduced. During the drying process it should not be wet or exposed to frost.

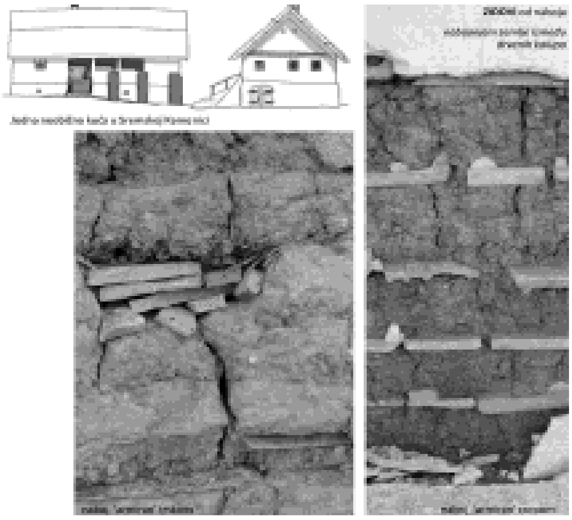

Figure 2. Rammed earth walls, Sremska Kamenica, Vojvodina - 18th century

For this reason, the construction can be carried out only in the period between May and September. In order to obtain a wall with better thermal properties but respecting the required strength and resistance to seismic effects, organic materials can be added which have to be in dry condition (chaff, straw, etc.), as well as inorganic materials (sand, gravel, crushed bricks) [4].

Figure 3. Preparation of earth for mud mortar

To increase resistance to water, stabilizers can also be added: cement, fly ash, lime, tar and bitumen, peat sludge materials containing proteins (caseins, albumin and various wastes of leather and alcohol industry), granulated slag mixed with a small amount of lime, gypsum, etc... Addition of cement can increase the resistance to weather conditions. Addition of lime makes hardening slower but gives a better permeability to gases. In some clay minerals such as montmorillonite it is more appropriate to use fly ash as a stabilizer instead of cement.

When tar and bitumen are used as additives, it is necessary to make a mixture of dense clay paste, followed by the raw material composite and earth. Mixing of these stabilizers is only possible if the raw composite is warm. Adding these stabilizers increases water resistance of raw material. For rammed earth wall buildings, raw material should be well minced and homogenized with about 12 % clay minerals. This composition provides good compacting ability and minimal shrinkage.

Raw materials which have up to 30 % of clay minerals are prone to shrinkage while those with less than 12 % of clay mineral may be used with the addition of fine sludge. The raw materials with more clay minerals can be optimized by adding sand. To create adobe (bricks made of raw earth), smoother clay with 40 % clay minerals is required, if the blocks are made with straw, as a regulator of the drying process, a higher quantity of clay minerals would be more advantageous.

Fibers for the reinforcement of natural earth are used for the raw materials containing a lot of clay minerals, in order to reduce shrinkage and increase insulating properties. Use of at least 4 % per volume of these fibers can give positive results regarding shrinkage and insulating properties of the walls. Usually fibers are used in an amount of 10 to 20 % per volume. Rammed earth walls durability can be significantly increased by a hydrophobic coating made of a 5 % water-glass solution in water. Stabilization of earth requires forced change in earth-water-air ratio. Many characteristics for different types of earth can be significantly improved with this method [5].

Some of the most common stabilization examples are with sand, plant fibers, lime (in case of earth with a higher percentage of clay) and cement (usually in addition between 6 ÷ 12 % mass, if the earthen material has a higher percentage of sand). Many other natural and synthetic products for stabilization are known to be applied: blood, fibers and animal skins, animal oils, casein, termite, eggs, wax, ash, vegetable fats and oils, tannins, vegetable juices, acids, salts, silicates, synthetic adhesives, soaps, plaster (Figure 4) [6].

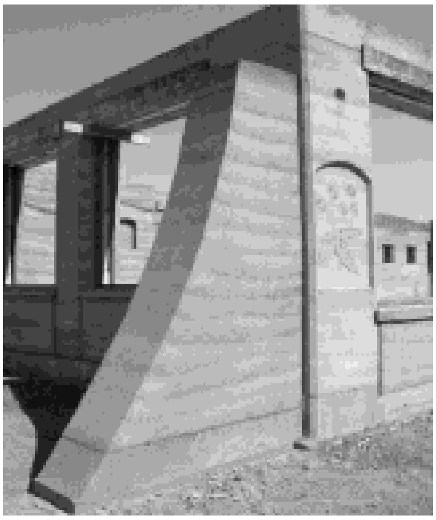

Figure 4. New type of construction

These characteristics are different for each earth and this diversity has led to development of numerous transformation of earth into construction material. The advantage of building using earth is primarily caused by its ubiquitous nature and high availability. Earth is healthy, warm and noble material, and easy to recycle. Construction of houses made of earthen materials does not consume energy and can be done DIY. Buildings made of earth have the ability of thermo-regulation of the inner environment and have high acoustic comfort, while at the same time they are also resistant to fire [7].

CONSTRUCTION OF RAMMED EARTH WALLS FOR BUILDINGS

The construction method of the rammed earth walls is based on the setting up of double-wall formwork into which the earth is compacted and so creating a wall panel (Figure 5 – formwork similar to ones used for concrete walls) [8]. The earthen material is compacted in layers between the formwork in vertical direction - wall construction and in horizontal direction - floors and slabs. After compaction, formwork can be removed immediately and will take a couple of hot and dry days to dry out the wall so it can gain the desired load-bearing strength.

The strength of rammed earth, similar to the strength of a concrete, in the process of maturation will continue to strengthen even after the start of using the building. Maturation of the wall can take up to two years, depending on the thickness, climate, etc. When that hardening process is complete, the rammed earth wall has similar features as a masonry structure made of stone. Some builders add crushed glass bottle cullet in color or pieces of wood to get a more interesting appearance of the surface of rammed earth wall.

Figure 5. Placing and ramming in wall forms

The thickness of these walls once was usually greater than 30 cm in order to ensure its strength, but today, using modern tools and machinery, formwork can be set even to 10 to 25 cm. For compacting, nowadays, a pneumatic or hand tools are used and earth is compacted to about 50 % of its original height in the formwork. Compacting process is carried out in layers until it reaches desired height, when formwork can be removed immediately.

This way it is not necessary to provide formwork for the entire building at once, but it can be built in stages, without retaining the construction until the wall reaches completely the designed state. It is necessary to remove the formwork from the wall as soon as compacting is finished, especially when the surface of the wall needs to be treated with sandpaper or wire brush on the grinder to obtain a texture on the surface, since after an hour it becomes too hard to be treated using common tools. The wetting of the exposed walls by atmospheric precipitation should only be avoided during construction (until the roof, eaves, insulation plinths, etc. are finished), although recent studies showed that slight increase in moisture content of dry rammed-earth walls will not affect the compressive strength significantly [9,10,11,12,13].

Today, rammed earth walls are placed along the classic strip foundation made of non- or lightly reinforced concrete or on a concrete slab. Insulation is usually placed between the walls of earth and concrete foundation (usually EPS, PU, etc.). Special advantage of the rammed earth walls is that they are easy to maintain during the entire lifespan of the building. It is easy to hammer a nail or place a screw into it and any damage can be easily repaired by adding fresh wet earth to the wall until it becomes homogenous with it.

PROPERTIES OF RAMMED EARTH WALLS

Good heat capacity of rammed earth walls is well known and probably should not be additionally emphasized. Their homogeneous mass provides their slow heating and cooling. In some cases, this feature of rammed earth wall can completely eliminate the need for cooling and heating of the inner space. Heat collected during the day will be transmitted in the room at night and cold collected at night will refresh the interior space during the day. Rammed earth walls can be, primarily due to the mass and density of the wall, characterized by having a high degree of sound insulation [13]. An example is given in the Table 1.

Table 1. Acoustic property of rammed earth walls

Rammed earth wall thickness / cm	R_w / dB
20	53
25	55
30	57
45	57

Load capacity – walls made of rammed earth have appropriate load bearing capacity and additional, even significant, stiffening can be provided [14]. Fire protection – since earth does not burn, rammed earth walls have high fire resistance. If the house is threatened by fire there is little fear that walls will burn or collapse. It is an ideal building material for suburbs and rural areas. CSIRO tests show that the rammed earth with wall thickness of 250 mm will attain 4 h fire resistance. Wall thickness of 150 mm, will score 3 hours and 41 minutes. The walls can easily be made even more powerful, 300 mm thick and monolithic. Resistance to insects - insects cannot eat walls of rammed earth, there are no hidden cavities in the wall where they could live undetected if there is no wooden frame that could be attacked. Easy maintenance - earthen walls should be used with natural finish, so paint/repaint job is eliminated, but it can be painted if desired. Soundproofing - 300 mm soil wall creates an excellent sound barrier. CSIRO tests provided sound rating of 50 decibels over the earthen walls of 250 mm. This is especially useful between the resting and living spaces as well as to block outside noise. Profitability - unlike some other forms of construction, earthen walls are simple to construct. They do not require plastering, painting or wallpaper. This saves money and energy used for the building [15]. Healthy and environmentally friendly - earthen walls are non-toxic and "breathable", thus creating healthy, friendly and very comfortable living space [16].

THERMAL ANALYSIS

As an example, a building made of rammed earth, which is made with clay and straw, woodchips or some other lighter material (Figure 6) is analyzed and compared with a common type of building (Figure 7) [11,17].

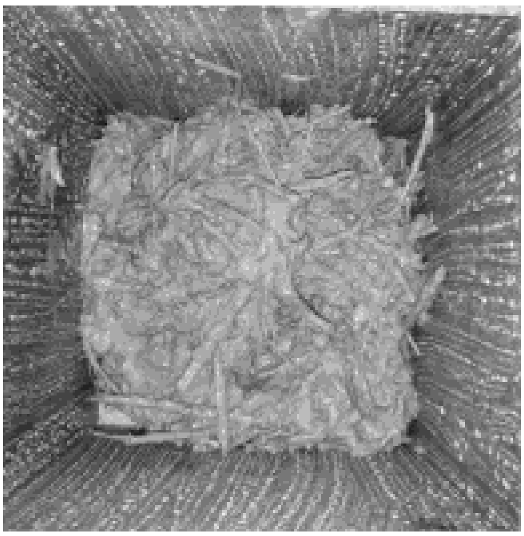

Figure 6. Placing of light clay

Figure 7. Floor plan of the analyzed example

CALCULATION OF THE STANDARD TYPE OF CONSTRUCTION

To present the possibility of energy efficient utilization of rammed earth building a common residential building was used as an example (Figure 7). The characteristics of the external walls are given in the following Table 2:

Table 2. External wall made of clay blocks - W1

Layer	Thickness / cm	λ / W/(m·K)
Plaster	1,5	0,850
Clay block	20	0,520
Simprolit®	10	0,044
Render	0,5	0,870
∑	32	

For the above detailed external wall, the overall heat transfer coefficient or *U* - value, calculated according to EN ISO 6946 - Eq. (1), is 0,351 W/(m^2·K).

$$U = \frac{1}{R_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} + \frac{d_4}{\lambda_4} + R_{se}}, \quad (1)$$

The ground slabs with layers detailed in Table 3. (except for the bathroom floor) has the overall heat transfer coefficient or *U* - value, calculated according to EN ISO 13370, of 0,368 W/(m^2·K).

Table 3. Layers of the floor – F1

Layer	Thickness / cm	λ / W/(m·K)
Parquet flooring	2,20	0,210
Wooden floor adhesive	0,30	1,000
Floor screed	4	1,400
Polyethylene foil	0,04	1,190
Styrodur®	5	0,034
Concrete slab	20	2,040
Water barrier	1	0,190
Concrete under-layer	10	2,100
Compacted hardcore	20	2,500
∑	62,54	

For bathroom floor detailed in Table 4., the overall heat transfer coefficient or *U* - value, calculated according to EN ISO 13370, is 0,357 W/(m^2·K).

Table 4. Layers of the floor in the bathroom – F2

Layer	Thickness / cm	λ / W/(m·K)
Ceramic tiles	0,80	1,000
Ceramic tiles adhesive	0,70	1,400
Floor screed	4	1,400
Polyethylene foil	0,04	1,190
Styrodur®	5	0,034
Concrete slab	20	2,040
Water barrier	1	0,190
Concrete under-layer	10	2,100
Compacted hardcore	20	2,500
∑	61,54	

For ceiling detailed in Table 5. the overall heat transfer coefficient or *U* - value, calculated according to EN ISO 6946 - Eq. (1), is 0,556 W/m^2K.

Table 5. Layers of the ceiling – C1

Layer	Thickness (cm)	λ (W/mK)
Screed	2	1,400
Styrodur®	5	0,034
Reinforced concrete slab	18	2,040
Plaster	1,5	0,870
∑	32	

For all windows and external doors (G1) made of PVC frame the overall heat transfer coefficient or U - value was adopted 1,3 W/m^{2}K.

The calculation of the average energy consumption for heating per annum for the average design temperature is given in the Table 6.

Table 6. Average energy consumption - standard building

Element	Overall heat transfer coeff. U / W/(m^2·K)	Area / m^2	Average temp. inside / °C	Average temp. outside / °C	U_e / W/(m^2·K)
W1	0,351	77,61	20	5	408,61
F1	0,368	50,94	20	5	281,18
F2	0,357	4,32	20	5	23,13
C1	0,556	55,26	20	5	460,86
G1	1,300	12,42	20	5	242,19
				∑E:	1415,97
Transmission heat losses: ∑e = 5097,49					
Transmission and ventilation heat losses: ∑e + 15 % = 5862,11					
Average annual heat loss per m^2: 106,1					

CALCULATION FOR RAMMED EARTH CONSTRUCTION

A building of the same surface area made of rammed earth construction, using light-clay, which is a combination of clay and straw, woodchips or some other lighter material with density of 900 kg/m^3 to obtain a thermal conductivity of 0,3 [10,18]. Our earlier studies already showed that light-clay materials can have good mechanical characteristic [10,12].The calculation of the average energy consumption for heating per annum for the average design temperature is given in the Table 7.

Table 7. Average energy consumption - earth construction

Element	Overall heat transfer coeff. U / W/(m^2·K)	Area / m^2	Average temp. inside / °C	Average temp. outside / °C	U_e / W/(m^2·K)
W1	0,300	77,61	20	5	349,24
F1	0,368	50,94	20	5	281,18
F2	0,357	4,32	20	5	23,13
C1	0,556	55,26	20	5	460,86
G1	1,300	12,42	20	5	242,19
				∑E:	1356,6
Transmission heat losses: ∑e = 4883,76					
Transmission and ventilation heat losses: ∑e + 15 % = 5616,32					
Average annual heat loss per m^2: 101,63					

Comparative analysis showed the variation in features between the rammed earth walls and sandwich wall with several layers of materials including a layer with enhanced thermal insulation characteristics.

By comparing these results, it can be noticed that in this example rammed earth walls are only slightly more energy efficient. However, energy efficiency and sustainable development must not be observed only through the exploitation of the building, but rather throughout its whole life span, starting from raw material, incorporation of it into the structure of the building and finally by exploiting (Figure 8).

Figure 8. Life span of the building

The energy consumption at each stage of this process, will affect the end result for the construction. By adding the energy consumption needed for demolition of the construction and recycling of the constituent materials, the total balance of energy efficiency can be obtained. It shows the full cost of the building.

Benefits of the rammed earth buildings can be also observed in the simplicity of the process. Raw material for construction is available at the construction site, preparation and construction itself is simple with low energy consumption and minimal mechanical or human labor.

The use of traditional materials with new technology leads to energy efficient buildings, where operating costs are minimized with respect to sustainability.

CONCLUSION

In different environments and in different regions, earth remains the most commonly used construction material. A third of the global population live in buildings made of mud, adobe, wattle and blocks of stabilized earth. Modestly or monumentally "earth architecture" shows the quality of everyday life and technical innovation. It corresponds to technical, social, cultural and economic challenges of the environment.

Building with earth respects diversity of culture and ambiance. It adapts and transforms the millennial knowledge and techniques and combines ancient materials with innovative architecture.

Main disadvantage of building with rammed earth walls is rapid degradation of this material if it is not properly used. Problems may occur as a result of uneven settlements of the ground, natural disaster, but mostly because of poor design concept and poor maintenance.

In general, it can be concluded that the use of earth as a building material has a bright future in the modern construction both in traditional form and also as an element of modern design. Today's knowledge and research capabilities can provide the opportunity in finding ways to eliminate deficiencies and preserve good performance and economy of construction.

It is necessary to consider natural fillers and additives, available in the immediate region of the construction site, which can improve rammed earth walls. The same applies to the use of natural aggregates and various fiber reinforcements.

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