THE THERMAL BEHAVIOR OF RAMMED EARTH WALL IN TRADITIONAL HOUSE IN VOJVODINA: THERMAL MASS AS A KEY ELEMENT FOR THERMAL COMFORT

by

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The traditional Vojvodina house represents an important part of the building stock of the northern Serbian province of Vojvodina. The research examines the thermal behavior of the rammed earth walls, which is the basic structural and façade element of traditional Vojvodina house.

Earth is a locally available, cheap, natural, environmentally friendly building material and has been used extensively for traditional family houses in Vojvodina. It has ecological and "green" characteristics, which can be assessed as very high quality, and they are of significant importance in the context of sustainable development and striving to reduce energy consumption today.

The research examines thermal behavior of rammed earth wall, including theoretical analysis of: the heat transfer coefficient U, the thermal resistance R and thermal conductivity λ. One of the basic elements of thermal behavior, the thermal mass, has been analyzed both theoretically and by measuring in situ. The in situ measurements were conducted on the traditional house in Vojvodina by measuring inside and outside surface wall and air temperature in summer. Analyses of rammed earth wall thermal performances have shown that the wall has low thermal conductivity, high heat capacity and significant thermal mass effect which is the key element enabling thermal stability.

The research indicates rather good thermal properties of the rammed earth walls. Potential of rammed earth wall in Vojvodina should be an issue of further analysis, although the possibility of improvement of existing facilities to meet current standards in terms of energy efficiency should be considered.

Key words: *thermal behavior, thermal mass, rammed earth, traditional house in Vojvodina*

1. Introduction

Traditional rammed earth houses are an important part of the building stock of north Serbian province of Vojvodina. According to statistical data, family buildings built before 1919 represent up to 7% of the total building stock of the province and most of them are made of rammed earth or adobe. Buildings constructed in the period from 1919 to 1945 represent 26% of the total building stock of the province [1]. There are no official data how many of them are made of rammed earth but in this period rammed earth and adobe were prevailing materials and common building techniques used for construction of typical single family houses in Vojvodina. Many of these houses are still used for residential purposes, although in relatively poor condition, neglected and not properly maintained. Home owners nowadays prefer to demolish old buildings and build a new one instead, rather than to rehabilitate and reconstruct them, due to the large body of knowledge which is needed for rehabilitation of these types of houses, especially in the domain of building technology. Also, uncertainty about the future performance of refurbished old houses often results in decision to demolish and build a new one.

The importance of the existing building stock of traditional buildings in Vojvodina is multiple. Besides the fact that traditional and historical heritage should be treated respectfully, existing ecological characteristics of rammed earth buildings can be assessed as very high, which is of significant importance in the context of sustainable development concept and contemporary striving to reduce energy consumption and live in more natural buildings in terms of used building materials. Considering those facts, the issue of energy performance of a rammed earth house thermal envelope should be treated with great care, since so far there are no conducted scientific or practical researches regarding the assessment of thermal envelope in a traditional rammed earth house in Vojvodina.

The goal of this research is to investigate the thermal behavior of the rammed earth façade walls in traditional single-family residential buildings in this region. The research includes both 1). theoretical analysis of: the heat transfer coefficient U, the thermal resistance R and thermal conductivity λ and 2) analysis by measuring *in situ* of the wall thermal mass, which is considered to be one of the basic elements of thermal behavior.

2. Traditional single family houses in Vojvodina

Under the concept of a traditional single family house in Vojvodina a unique architectural phenomenon is accepted: it is the house that has been created and developed in the period from the end of eighteen, during the nineteenth and early twentieth century in the entire province of Vojvodina. Regarding the origin of the house, theoretical expert attitudes are not harmonized, but most of them believe that this is a unique combination of German and local architectural tradition [2].

Development of the house proceeded chronologically from simpler structure to complex architectural layout shapes at the beginning of the twentieth century (Figure 1) [3]. The basic type and most common at the same time, is a three-part rammed earth house. The next step in house structure evolution derived from the previous one, is the four-part house, developed simply by adding one room longitudinally. The house structure continues to develop by adding rooms longitudinally or in the shape of letter ´L', and all the building types follow the same constructive logic (Figure 2). The most important common feature for all building types is a building material of structural walls, always made of earth or earth-based products locally available. Building material itself has also experienced an evolution from rammed earth, adobe blocks to brick, but the most common is rammed earth, with a significant number of houses still in use today [4].

Figure 1. Traditional house in Vojvodina, Pancevo.

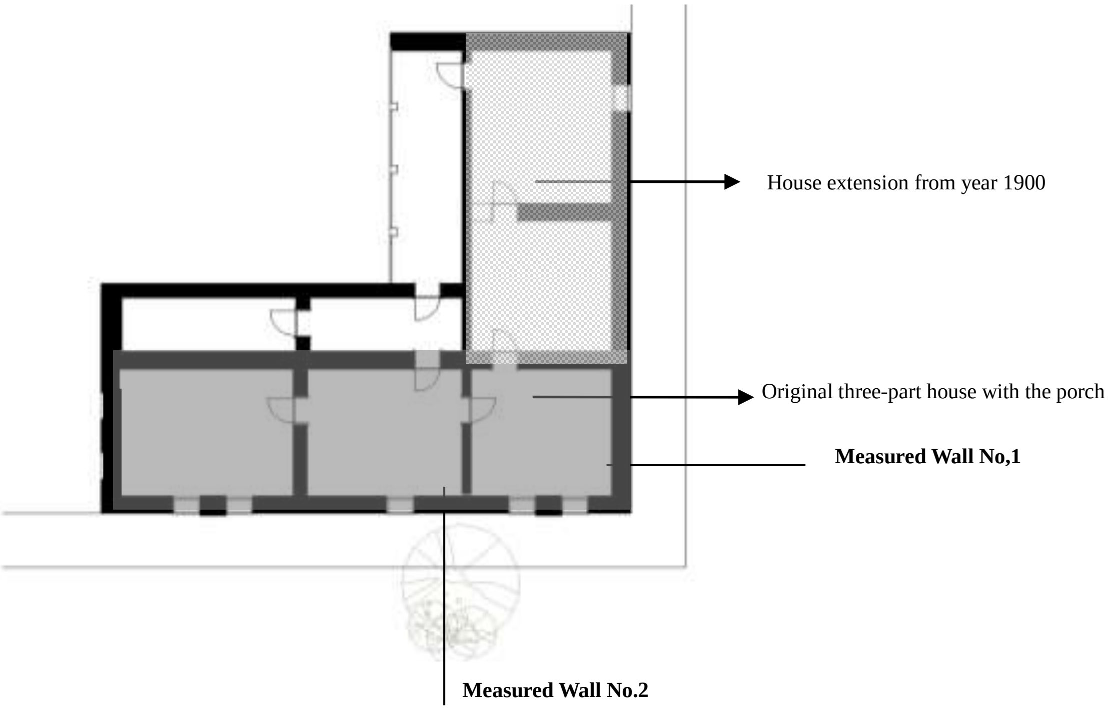

Figure 2. Ground floor plan of traditional house in Vojvodina, Pancevo. Ground floor layout in shape of letter ´L'. Marked measured positions of the walls.

Today, there are many types and subtypes that make up the entire building stock of traditional architecture very diverse. Up to now, many rammed earth houses are preserved but they are usually in poor condition, neglected, exposed to weather conditions and left to decay. Many of them have suffered a number of functional transformations and interventions on the walls itself. This research focuses on the thermal envelope of a rammed earth house, while the building type is not of crucial importance for this research.

2.1. The technique of construction of rammed earth walls

The choice of wall building materials of traditional and vernacular architecture, is based on the current situation and real needs, experience and knowledge and available means of the local population. As the result, rammed earth buildings were widely spread over the entire province, and in use for a very long period of time, from the beginning of the eighteenth century, through nineteenth century but also at the beginning of the twentieth century.

In their earliest stages of development, traditional houses of Vojvodina were built entirely of rammed earth. With the evolution of the application of this material use of building materials based on the local soil (clay, loam) but with higher degree of processing was developing, moving to use of adobe and finally brick [4]. Also numerous combinations of these building materials were applied. Traditional craftsmen, based on their own experience, used to combine different building techniques. The most common combination was to build foundations of bricks, to insure better structural stability of the building, and structural walls of rammed earth. Also, in some cases part of the walls, especially the north walls were built of bricks.[1] However, rammed earth walls are the most typical in a traditional single family house in Vojvodina and will be analyzed in this paper.

The masonry technique of the rammed earth wall was relatively simple: semi-dry, crushed earth was well mixed with chopped straw (chaff) which was used as reinforcement and then the earth was rammed between the two boards, which served as planking. The earth used as construction material was dug in a close proximity, usually in the garden of the house.

The best results could be obtained by first mixing the yellow and black loam and then mixing it with straw and chaff [5]. Also, only yellow clay could be used, mixed with straw and chaff [5]. The process of preparing the loam for construction is as follows: first the earth is well moistened and then mixed with straw and chaff. The mixture is stirred with a hoe or waded with feet, as long as the mud starts to be easily separated from the hoes [6]. The mixture is than compacted with hammers in layers of 20 cm (Figure 3), walls reaching the thickness of up to 60 cm [7]. As additional reinforcement for preventing cracking of the walls, chipped branches, vines or reeds, were used. The corners of the buildings were specially treated by putting branches at right angles. Rammed earth walls were later plastered with mud mortar on both sides (Figure 4).

The traditional house in Vojvodina was built of locally available building materials, earth (clay, loam) used from the building construction site with locally available additions (straw, chaff, chipped branches, vine branches or reeds, horse and pig hair). The difference in locally available building materials often caused the different composition of the rammed earth wall. Consequently, today is practically impossible to determine the exact composition of the wall without laboratory analysis. In other words, each wall has its own peculiarities in composition and structure and thermal performance may vary in a rather wide range, hence the thermal behavior of rammed earth wall would be analyzed in this paper.

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[1] North orientated walls, with the lack of direct sun insolation had a problem with moisture, so the rammed earth walls used to decay faster.

 

Figure 3. Cross section of the rammed earth wall, abandoned house in Ivanovo. Clearly defined layers of rammed earth.
Figure 4. Rammed earth wall with a large quantity of added straw (chaff) plastered with mud mortar, house in Vojlovica.

3. Thermal characteristics or rammed earth walls

Due to the fact that façades of analysed houses have rather small windows, the most important part of the building envelope, in terms of energy saving, is the façade wall. Buildings' energy gains and losses largely depend on its thermal performances. In this context, analysis of thermal performance of the external wall of a traditional house in Vojvodina is of great significance, especially as it is a completely unexplored field of research in Serbia. On the other hand, rammed earth houses represent a large part of the building stock in Vojvodina as artefacts of traditional architecture. There is an emphasis on their preservation, so the affirmation of their quality in terms of building physics and thermal building envelope should be examined and highlighted as an impetus for their rehabilitation.

The basic properties of the building thermal envelope materials, which will be analysed in order to define the thermal performances of a rammed earth wall are**:** the heat transfer coefficient U, the thermal resistance R, the thermal conductivity λ and the thermal mass as a key element for the specific thermal behavior of a rammed earth wall.

3.1. The heat transfer coefficient U

In terms of building physics the heat transfer coefficient U [W/($m^{-2}K^{-1}$)] is the parameter which represents the transfer of heat by transmission through a building construction element.

In 1996, Ervin Ginder considered certain parameters of thermal protection in his book *'Vojvođanske seoske kuće od naboja' (*eng: Traditional rammed earth houses in Vojvodina) [5]. For the rammed earth wall 50 cm thick without mud mortar, Ginder estimated the value for the coefficient of thermal conductivity k=0.87 W/(m^2xK) (equivalent to the heat transfer coefficient U). Literature review in Serbia show that these are the only data considering the heat transfer coefficient U of the rammed earth houses in Vojvodina. Recent publications that have considered traditional architecture in Vojvodina do not discuss the issue of rammed earth thermal performances [3].

Numerous international researches are considering the issue of rammed earth wall thermal performances, constructed both in traditional as well as contemporary rammed earth building techniques. It has been estimated that the value of the heat transfer coefficient for the 30 cm thick rammed earth wall should be expected in range from 1.9 up to 2.0 W/(m^2xK) or for 33 cm thick rammed earth wall U value is approximately 2.411 W/(m^2xK) (with the assumed density of the rammed earth 1540 kg/m^3) [6]. This practically means that to achieve the value U=0.5W/(m^2xK), which is still above the current maximum allowed for heat transfer coefficient for new construction (defined by the current Serbian Regulation U_{max} = 0.3 W/m^2K) and also above the values for the rehabilitated walls of existing buildings (U_{max} = 0.4 W/m^2K), the wall thickness of 1.6 to 1.8 m should be achieved [7], which is from the aspect of economy and rationality of a building structure very questionable.

It can be concluded that the thermal performances of a rammed earth, estimated by numerous theoretical research, expressed through the heat transfer coefficient U do not fulfill modern requirements for thermal insulation defined according to building regulations of the Republic of Serbia [8].

3.2. The thermal resistance R

The thermal resistance R [m^2KW^{-1}] of the building material is indirectly proportional to the value of the heat transfer coefficient (U-value). This practically means that for the 30 cm thick rammed earth wall with the estimated value for heat transfer coefficient U 2.0 W/(m^2xK), the thermal resistance R should be expected around 0.5 (m^2xK/W) [6].

A building material with a high R-value will certainly help keep the building thermal comfort, and reduce costs for heating and cooling. A rammed earth wall has relatively low estimated R-value and despite that fact, indoor temperatures remain stable during the summer and winter due to a great thermal mass of the walls. Several international researches are considering and trying to explain this fact [6, 7, and 9].

Published research on traditional earth walls shows that for thin walls (with maximum thickness d=45 cm) steady state thermal resistance has relatively low value [9]. For example, a typical adobe earth wall 30cm thick has a thermal resistance around 0.5 (m^2xK/W). But for the wall thicker than 45 cm, as is the case in most traditional houses of Vojvodina, cyclic state thermal resistance is high and increases exponentially with wall thickness (value for the cyclic thermal resistance R_{cyclic} is equal to R steady state divided by the decrement factor). For thick walls cyclic resistance increases rapidly, and this coupled with a great time lag means that for wall thicknesses greater than 45cm the heat flow through wall is negligible [9].

It should be pointed out that the current regulations and all codes of practice are based on the steady-state conditions where the difference in temperature across the material is kept steady, which is practically impossible situation in real terms. This statement can explain the significant difference in relatively low calculated values of the rammed earth wall thermal resistance R and great indoor comfort that people who live in rammed earth houses throughout Vojvodina can confirm. This perceived feeling of great comfort is achieved also due to advantages of thermal mass to reduce the swing in temperatures. Because of a significant contribution in keeping the indoor thermal comfort, a thermal mass will be analysed as the key element enabling thermal stability of a rammed earth house.

3.3. The thermal conductivity λ

The thermal conductivity *λ* [$Wm^{-1}K^{-1}$] is the thermophysical characteristic of a building material and depends on the type of the building material. The value is defined by the amount of heat which is transferred by conduction within 1s through the layer of construction material exactly 1 m thick, perpendicularly to its surface of $1m^2$ at a temperature difference of 1 ° C [10].

The thermal conductivity *λ* is determined experimentally for any type of building material as well as for rammed earth wall, and its value depends on the type and the structure of the building material, density (porosity) and moisture in building material.

In the only publication about rammed earth traditional Vojvodina architecture, published in Serbia, the thermal conductivity value is estimated as ***λ***= 0.64 W [5].

The thermal conductivity value is also estimated in numerous international regulations and standards, such as DIN which estimates rammed earth thermal conductivity as *λ*=1,2 W/(mxK) [11]. This standard was translated in Serbian language in 1985 and is in use under the title *'Pravila proračuna toplote potrebne za grejanje zgrada´* (eng: Rules for the calculation of heat required for heating buildings, Translation of DIN 4701 with comments) [12].

In an international research an estimated value for the thermal conductivity λ for all the layers within the rammed earth wall as well as for different local building techniques and with different additions (horsehair, straw, branches etc.). The thermal conductivity for mud plasters, which is the final layer of every rammed earth wall in Vojvodina, has an estimated value λ = 0.8 W/(mxK) [13].

It should be noted that, although rammed earth is widely spread building material on the territory of Vojvodina province, its treatment in the scientific literature and regulations is in general on a very low level in the Republic of Serbia. Therefore the current Serbian Regulation [8] provides very limited information for very limited number of traditional construction materials, while some common traditional materials are not even mentioned. The thermal conductivity for earth as a construction material is mentioned only as loose earth (wet), with thermal conductivity λ = 2.1 W/(mxK), while compacted dry earth, rammed earth or mud mortar is not mentioned at all.

The average value for the thermal conductivity for the rammed earth wall can be defined in range 0.7-1.25 W/(mxK) [14] which indicates relatively poor thermal performance of the rammed earth walls.

4. The thermal mass of a rammed earth wall

Thermal mass refers to the ability of a building material to absorb heat, retain it and then release it over time. Thermal mass basically represents a material's resistance to change in temperature as heat is added or removed. High-density building materials, such as rammed earth, brick, adobe and stone have a high thermal mass helping to moderate the thermal fluctuations within a house (room) to a significant extent.

Thermal mass is effective in improving building comfort in any place that experiences temperature fluctuations, both in winter as well as in summer. Vojvodina has continental climate with average daily temperature swings above 10 °C both in summer and in winter. During the summer days, direct heat gains from insolation and transmission heat gains, as well as internal gains (occupants, electrical appliances) are absorbed by the exposed thermal mass of the building, thus limiting the temperature rise which results in stable internal temperature within acceptable levels for human thermal comfort (below 26°C). During the winter, over the sunny period of the day with any direct sunlight on thermal mass, the heat radiation from the Sun will be stored within the wall, as well as heat absorbed from the increase in the ambient air temperature. After several hours, (depending on the time lag value, explained later) when the external air temperature begins to decrease, the stored heat within the thermal mass of the building is slowly released back into the interior helping to keep the building warm. This reduces the need to artificially heat the building. This phenomenon is known as passive heating which reduces the need to artificially heat the building. Basis of passive heating lies in the thermal mass phenomenon, which is explained in the next section.

4.1 Factors explaining thermal mass phenomenon

The four factors explaining the thermal mass phenomenon are: density of a building material [ρ], thermal capacity [c], specific heat [C] and time lag [ν].

Dense materials usually have a potential to store more heat. For rammed earth density depends on soil type, the moisture content during compaction and compactive effort. Rammed earth has an average density of 1400 do 2000 kg/m³ [9]. For uncompressed earth these values range from 1000-1500 kg/m³ and up to 1700-2200 kg/m³ for compressed earth. Such high density of a rammed earth wall should enable the storage of more heat compared to a usual contemporary building materials [15].

Thermal capacity [J/K] or a heat capacity is a physical property of a substance. It is an indicator of the ability of a material to store heat per unit volume; basically it is a scientific equivalent of thermal mass. The greater the thermal capacity of a material, the more heat it can store in a given volume per degree of temperature increase. Higher thermal capacity can reduce heat flow from the outside to the inside environment by storing the heat within the material. This is common for building materials with high thermal mass and their possibility to slow the heat flow from one side of the envelope to the other. This slowing of the heat flow due to the thermal mass is called "thermal lag" (or time lag), and is measured as the time difference between peak temperature on the outside surface of a building element and the peak temperature on the inside surface. In other words, the thermal mass keeps the internal room temperature stable due to the length of time required for heat to transfer through the walls. For example it is estimated that 300 cm thick rammed earth wall will take approximately 8 to 9 hours for heat to transfer through the wall to the other side. Thermal lag of rammed earth wall of traditional house in Vojvodina will be analysed by measuring in situ.

Both thermal capacity and specific heat describe an amount of energy needed to raise the temperature of substance (building material). The specific heat or the specific heat capacity is a measure of the amount of heat required to raise the temperature of given mass of material by 1ºC. It takes less energy input to raise the temperature of a low-specific-heat material than that of a high-specific-heat material. The specific heat capacity for rammed earth wall is approximately 870 J(kgK) up to 1260 J(kgK) [14]. Due to the high specific heat capacity of the soil used in its construction and achieved high density, rammed earth is a building material that provides excellent thermal mass.

4.2. Measuring thermal properties of a rammed earth wall

Results from any international study conducted on traditional buildings have shown that due to many variations and local specifics, the most reliable way to determine thermal characteristics_of this type of construction is by measuring them on site [16]. In Serbia, up to now, the thermal characteristics of rammed earth buildings were not the subject of research, especially not measurements in situ. This research, although limited only on thermal characteristics of rammed earth walls, represents, in the most general sense, the first research of energy performance of traditional single family houses in Vojvodina.

4.3. The process and methodology of measurements on site

Measurements for this research were performed in summer of 2014 on the rammed earth single family house still in use for residential purposes. Measurements *in situ* were conducted on one house during the period of three days. Two walls were measured in two different rooms.

The measurement was conducted with the device ALMEMO 5690-2 / Ahlborn (Figure 5). The device measures following parameters: external air temperature, external surface wall temperature, internal air temperature and internal surface temperature of the wall. The device consists of:

- set of sensors for surface (contact) temperature measurement,
- set of sensors for air temperature measurement,
- the device itself with display, commands and data saving storage.



Figure 5. ALMEMO 5690-2 / Ahlborn device
Figure 6. The set-up of sensors for internal wall surface temperature, wall No.1
Figure 7. The set-up of sensors for outdoor wall surface temperature, wall No.1

The sensors for measuring the thermal characteristics of the rammed earth wall are sensors for contact wall temperature, always set in the middle of the wall to avoid the zones around the windows and in the corners where significant thermal losses can occur due to two-dimensional heat transfer (Figure 6). When positioning the sensors on the external wall side, the direct impact of rain, snow, and wind should be avoided as well as direct impact of solar radiation, if possible (Figure 7). The device also has a possibility of measuring the heat flux, which was not an issue in conducted research.

Sensors for measurement of air temperature in the interior are set at half the distance between the walls and half the height between the floor and ceiling in order to avoid the influence of radiation of surrounding surfaces as much as possible.

After setting up the device and all the sensors, the measuring process started. First two hours of measuring are excluded from the analysed data because of the temperature swings, until all the sensors were stable.

Published researches that considered the thermal performance of traditional building walls recommend that the measuring process on traditional buildings should last longer, depending on the structure that is investigated [16, 17]. The period of up to two months will give absolutely relevant data. The recommendation is, when thick walls and massive structures are in question, that the measurement should last two to three weeks [17] which should be considered for the further thermal behavior researches of a traditional rammed earth walls in Vojvodina.

4.4. Selection of the sample - the house in which the measurement was carried out

For the measuring process, one house in Vojvodina was selected, based on following criteria:

- for façade load bearing walls rammed earth was used as construction material, the thickness of the walls should lie in average thickness range (60 to 65 cm),
- the building is in a rather good condition, still in use for residential purposes,
- the type/structure of the building is irrelevant (since most of the houses in building stock have suffered numerous transformations this criteria is irrelevant and focus is only on building material which is typically rammed earth).

The measured traditional house in Vojvodina was built in two steps. The first part of the house, where the measuring process had been conducted, was built with rammed earth walls around 1800, and the second one, built as an extension, with brick walls, around 1850-1900. A house has a ground floor plan in a shape of letter "L" (Figure 2). Information about the house, the measured walls and the measurement time period are given in Table 1.

Table 1: Information about the house, the measured walls and the measurement time period.

Basic data about buildings	
Location	Pančevo
Address	Ive Kurjackog 68
Year of the construction	~ 1800-1850(1900)
Data about the measured wall	
Building material of the wall	Mud plaster Rammed earth Mud plaster
Wall thickness	65 cm
Orientation of the measured walls (marked on house ground floor plan in Figure 2.)	**Wall No.1 :** southeast / **direct sun radiation**
	Wall No.2 : southwest / **indirect sun radiation** (Tree shadow covering the entire facade)
Measurement period	
The period of measurement	74 hours
The start of the measurement	01.08.2014.
The end of the measurement	04.08.2014.

4.5. Results of the measuring process

The measured interval lasted for 74 hours, from 01.08.2014 at 15:21h to 04.08.2014 at 17:21h, and is characterized with a total of 445 sets of measured data for both walls (every ten minutes), presented in Table 2.

Table 2: Overview of parameters measured on site for *wall No.1* and *wall No.2*

WALL No.1		**External air temperature**		**Internal air temperature**		**Time delay***
date		*TIME*		*TIME*		
01.08.2014						
	Max T [°C]	*15:31*	**30.9°C**	*20:01*	**24.6°C**	***04:30h***
02.08.2014	Min T [°C]	*05:31*	**18.9°C**	*08:21*	**23.5°C**	
	Max T [°C]	*15:21*	**35.2°C**	*22:41*	**23.9°C**	***07:20h***
03.08.2014	Min T [°C]	*05:01*	**18.5°C**	*12:31*	**23.7°C**	
	Max T [°C]	*15:11*	**34.7°C**	*21:41*	**24.1°C**	***06:30h***
04.08.2014	Min T [°C]	*04:51*	**18.5°C**	*11:31*	**23.7°C**	
	Max T [°C]	*15:41*	**33.0°C**	/	/	/
	Min T [°C]	/	/	/	/	
Daily temperature oscillation		**12.0°C to 16.2°C**		**0.2°C to 1.1°C**		

WALL No.2		**External air temperature**		**Internal air temperature**		**Time delay***
date		*TIME*		*TIME*		
01.08.2014						
	Max T [°C]	*16:31*	**25.9°C**	*21:41*	**23.9°C**	***05:10h***
02.08.2014	Min T [°C]	*05:41*	**18.8°C**	*11:41*	**23.7°C**	
	Max T [°C]	*15:41*	**29.9°C**	*21:11*	**23.9°C**	***05:30h***
03.08.2014	Min T [°C]	*05:01*	**18.7°C**	*11:31*	**23.7°C**	
	Max T [°C]	*15:01*	**31.3°C**	*21:01*	**24.1°C**	***06:00h***
04.08.2014	Min T [°C]	*05:21*	**19.7°C**	*11:01*	**23.7°C**	
	Max T [°C]	*16:11*	**28.2°C**	/	/	/
	Min T [°C]	/	/	/	/	
Daily temperature oscillation		**7.1°C to 11.26°C**		**0.2°C to 0.4°C**		

The results are also presented on a diagram (Figure 8) which clearly shows the stable indoor air and wall surface temperatures while outside air and wall temperature swing. The diagram also shows time delay for both air and wall temperatures, which is in range from 4.30h up to 7.20h for both measured walls, with a maximum difference in indoor wall surface temperature of 0.6 °C and maximum indoor air swings of 1.1 °C. All data presented indicates extremely stable and comfortable indoor climate.

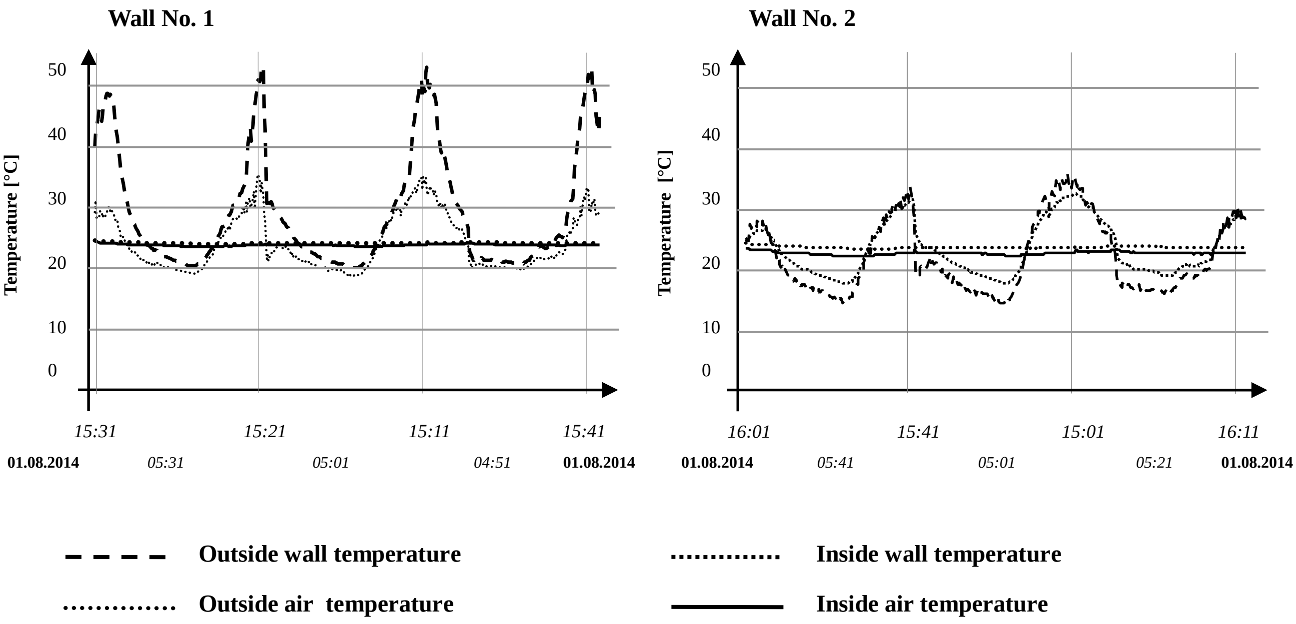

Figure 8: Diagram of the parameters measured *in situ*.

These results of *in situ* measurements correspond to the results of several published international researches, confirming that the thermal lag of 6 to 8 hours provide a stable indoor temperature. The results of the in situ measurements on the rammed earth house in Vojvodina also show that the high thermal mass of a rammed earth wall with an extremely large wall thickness d = 60-65 cm reduces the swing in temeperature which leads to a perceived feeling of greater indoor comfort. The daily inside air temperature swings range from ± 0.1°C to maximum ± 0.55°C which is basically negligible. Presented data also correspond to other research results that in rammed earth walls with thickness greater than 45cm the heat flow through walls is negligible [9].

5. The thermal behavior of rammed earth wall in traditional house in Vojvodina

As already explained, there are many local variations in building techniques of rammed earth walls in traditional Vojvodina houses. The structure of the wall consists of packed earth mixed with horsehair and a large amount of straw; the inside of the wall is plastered with the mud mortar with a large amount of added husk. Although those additions were mainly used to stabilise mud, together with the mortar, they certainly improve the insulating properties of the wall, depending on their quantity and variety. On the other hand, moisture can be present in the rammed earth walls and it also influences the thermal performance of the walls. As a result, it can be concluded that thermal performance of rammed earth walls in houses in Vojvodina varies and future research will be designed in a manner that investigates the variations of their thermal behavior.

Conducted theoretical research has shown, based on numerous international studies and reviews of conducted measurements, that thermal characteristics of rammed earth walls are extremely contradictory. As already explained, the average U-values were estimated in range from 1.9 up to 2.5 W/(m^2xK), and thermal resistances (R) indirectly proportional to those values. The values of thermal conductivity taken from different Serbian and international standards show thermal conductivity for compacted earth $\lambda = 1.2$ W/(mK) [12] and thermal conductivity for mud mortar (mud plaster): $\lambda = 0.8$ W/(mK) [13]. All of those values indicate rather poor thermal performances of rammed earth walls, based on theoretical estimations.

On the other hand, from the above measurements of thermal performances of two rammed earth walls, the following can be concluded:

- due to high thermal mass, inside air temperature in rammed earth houses is extremely stable. During the day there is a great outdoor air temperature swing, from minimum temperature of 18.9°C to maximum of 35.2°C for wall No.1, and 18.7°C to 31.3°C for wall No.2, while the inside air temperature stays in a range of ± 0.4°C for wall No.2. up to ±0.55°C for wall No.1. Average room air temperature is 23.7°C. Also, it should be noticed, that house residents do not open the windows during the night, and with the proper night ventilation inside air temperature during the day would be even lower;
- the inside wall surface temperature shows even smaller changes. During the day there is a great outdoor wall surface temperature swing from minimum temperature of about 15°C to maximum of 35°C for wall No.2, and even from 20.1°C to maximum of 53.2°C for wall No.1 which has the orientation towards direct sun radiation. In both cases inside wall temperature stays in a range of ± 0.3°C for both walls, about 23°C .
- measured time lag is in range from 4:30h up to 7:20h for both walls and air temperatures and the indoor air surface temperature swing is basically negligible.

The obtained measurements can be interpreted as the result of several factors. The key element of a thermal behavior of a rammed earth wall is a wall thickness d = 50-60 cm which has a high thermal mass influencing the slow flow of heat through the wall [9].

Published research on traditional rammed-earth walls shows, that in types of walls with large wall thickness (d = 50-60 cm), which is the case which applies to most cases of traditional houses in Vojvodina, steady state thermal resistance is low while cyclic state thermal resistance is high and increases exponentially [9]. On the other hand, the current building regulation and all calculation codes of practice are based on the steady-state conditions where the difference in temperature across the material is kept steady, which is practically impossible situation in real terms. This statement can explain significant difference in calculated values comparing to values measured in situ, as investigated by previous researches [16].

6. Conclusion

The subject of research was thermal behavior of the traditional house in Vojvodina region, dominated by rammed earth façade walls. The research was conducted both theoretically and by measuring of wall's thermal behavior *in situ*.

The theoretical research contains analyses of the theoretical values of wall heat transmittance U, the thermal resistance R and the thermal conductivity λ. The estimated performance of rammed earth walls based on the data available in literature indicates relatively poor thermal characteristics of the walls, which are considered in the steady-state calculation methods.

On the other hand in situ measurement of the 60 cm tick wall results have shown much better thermal properties resulting in extremely stable indoor conditions: small indoor temperature swings (about ±0.5°C) in conditions of great outdoor temperature swings (up to ±16°C) and comfortable indoor environment (constant temperatures around 23°C). This only confirms theoretical assumptions and conclusions of previous researches on the significance of the great thermal mass, which is assumed to be the key element for a house thermal behaviour in dynamic calculation methods.

It may be concluded that the issue of energy performances of traditional rammed-earth buildings is complex and needs to be investigated further. The future research should include in situ measurements of a greater diversity of walls regarding types of materials which was used, their thickness and structure, and measurement plan for a longer period of time, both during summer and winter. In that way measured thermal properties could indicate the influence of different additions in the rammed earth walls, and other structural factors. Also, measured values would form the basis for potential rehabilitation of the rammed earth building stock in Vojvodina and their upgrade to current building regulations. Also, these results would provide the basis for the improvement of data of traditional building materials in the existing regulations.

7. References

[1] Jovanović-Popović, M. et al., Atlas of Family Housing in Serbia, Faculty of Architecture University of Belgrade and GIZ-Deutche Gesellschaft fur Internationale Zusammenarbeit, Belgrade, Serbia, 2012

[2] Janjetović, Z., Neprolazna svakodnevica: Nemački doprinos narodnoj kulturi Vojvodine [The Timeless Every Day Life: The German Contribution to Popular Culture in Vojvodina], *Tokovi istorije, Institut za noviju istoriju Srbije, 34* (2008), pp.214-224

[3] Kojić, B., Seoska arhitektura i rurizam teorija i elementi [Rural Architecture and Ruralism: Theory and Elements], Građevinska knjiga, Beograd, Srbija, 1973

[4] Vuletić, N., Narodno graditeljstvo u Vojvodini [Traditional Architecture in Vojvodina], *GRAĐA za proučavanje spomenika kulture, VIII-IX* (1978-1979), pp. 351- 357

[5] Ginder, E., Vojvođanske seoske kuće od naboja – material, konstrukcija i izvođenje [Traditional rammed earth houses in Vojvodina-materials, construction and building], PCESA, Novi Sad, Srbija, 1996

[6] Soerbato, V., *Analysis of Indoor Performance of Houses Using Rammed Earth Walls,* Eleventh International IBPSA Conference, Glasgow, Scotland, July 2009

[7] Geront, M., Building with Earth*:* Design and Tehnology with Sustainable Architecture, Birkhaüser Arhitekture 2nd rev. Edition, Berlin, Germany, Januar 16, 2009.

[8] *Правилник о енергетској ефикасности зграда [The Rulebook on Energy Efficiency of buildings]*. "Службени гласник Републике Србије", бр.61/2011

[9] Heathcote, K., The thermal performance of earth buildings, *Informes de la Construccion, julio-septembre 2011* . DOI No: 3989/ic.10.024

[10] Milić B., Elementi i konstrukcije zgrada, II deo, Univerzitet Crne Gore, Podgorica, Montenegro**,** 1999

[11] V. (1983). DIN 4701 *Regeln für die Berechnung des Wärmebedarfs von Gebäuden - Grundlagen der Berechnung.*

[12] Pravila proračuna toplote potrebne za grejanje zgrada, Prevod DIN 4701 sa komentarima [Rules for the calculation of heat required for heating buildings, Translation of DIN 4701 with comments], SMEITS, Belgrade, Serbia, 1985

[13] BS EN 12524. Building materials and products. Hygrothermal properties. Tabulated design values

[14] Rempel R. W. A., Rock, Clay Water, and Salts: Highly Durable, Infinitely Rechargeable, Eminently Controllable Thermal Batteries for Buildings, *Geosciences*, 3 (2013), pp. 63-101

[15] Thermal mass, www.paho.org

[16] Baker, P., U-values and traditional buildings. In situ measurements and their comparison to calculated values, Historic Scotland, Edinburgh, UK, 2011

[17] Baker, P., Reasrech Into the Thermal Performance of Traditional Brick Walls, Report, English Heritage Resreach, Glasgow Caledonian University, Glasgow, UK, 2011