Hydro-thermal Analysis of Building Envelope Walls with Cement-Stabilized Rammed Earth Structural Layer and Different Thermal Insulators and Their Positioning in Humid Continental Climate

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Abstract. The objective of the work is to analyse thermal insulation positioning in a building envelope wall with a load-bearing layer made of cement stabilized rammed earth (CSRE) in a humid continental climate. In the article CSRE is described and recommendations regarding the wall thickness of this material are presented. The results of the CSRE coefficient of thermal conductivity and current standard values of the heat transfer coefficient for external walls in various countries of a humid continental climate are also presented. On this basis, the thickness of the necessary thermal insulation in building envelope partitions with a load-bearing layer of CSRE is estimated. In the latter part of the article, the results of the simulation of hydro-thermal conditions occurring in partitions with a load-bearing layer of CSRE insulated with different types of thermal insulation placed in different parts in the partition are presented. The simulations have shown that in a humid continental climate the best solution is the use of thermal insulation on the external side of the building envelope.

1. Introduction

The objective of the work is the analysis of thermal insulation positioning in a building envelope partition with a structural layer made of cement stabilized rammed earth (CSRE) in a humid continental climate. CSRE is a technique used since antiquity to build monolithic load-bearing walls from locally available soil found under the layer of humus. This technique is composed of compacting layers of moist soil mixes in a formwork. After compacting a layer, subsequent layers are added until desired height of the element is reached. Compacted earth is distinguishable by its low energy usage as well as a low amount of waste produced by its construction [1], [2].

Recently, the topic of sustainable development in construction has become more and more popular. In this context, more and more attention is devoted to ecological building materials [3], [4]. The use of local soil reduces the overall cost of construction. Moreover, when the service life of the building comes to an end, the soil recovered from its demolition can serve as the raw material for another rammed earth construction, or simply be disregarded as unhararmful waste [5].
2. Recommended thickness for load-bearing walls made of rammed earth

Various international standards concerning rammed earth (table 1) include requirements for a minimum thickness for rammed earth walls. Some of the values for load-bearing layers depend on the number of stories in the building [6],[7], while others are based on exposure to atmospheric conditions [8]. For single-story buildings, the standards require a thickness of at least 200 to 325mm. It is worth noticing that in countries where the prevalence and rammed earth expertise is highest, e.g. Australia and New Zealand [9], the requirements in those standards for outer partitions are lower, in the range of 200 to 250mm in thickness. This may also be due to the climates of those respective countries.

| Country         | Document Name            | Source   | Minimum wall thickness t [mm] | Maximum wall height h [mm] | Wall slenderness h/t [-] |
|-----------------|--------------------------|----------|-------------------------------|----------------------------|-------------------------|
| Australia       | EBAA (2004)              | [11]     | 200                           | -                          | 15                      |
| Germany         | Lehmbau Regeln (2009)    | [8]      | 325                           | 3250                       | 10                      |
| India           | IS: 2110 (1998)          | [12]     | 300                           | 3200                       | 10.7                    |
| New Zealand     | NZS 4297 (1998)          | [13]     | 250                           | 3300                       | 6                       |
| Switzerland     | Regeln zum Bauen mit Lehm (1994) | [7] | 300 * | 3500                       | 11.6                    |
| USA             | 14.7.4 NMAC (2006)       | [6]      | 305 *                         | 2438-3048                  | -                       |

* For single-story house walls.

In the view of the authors, the thickness of building envelope walls of rammed earth should be based on the amount of stabilizer used. The authors also suggest taking into account the finishing layer, which protects the rammed earth against corrosion. Included in standards [6] and [7] are requirements which deal with the thickness of rammed earth walls based on the number of stories, showing that those authors were concerned not only with the durability of the material, but also its load-bearing capacity. Tests on the compressive strength [14], tensile strength under bending [16], as well durability [17], [18], demonstrate that in a humid continental climate, in a four-story residential building, load-bearing walls should be composed of soil mixed with 9% cement by mass and a thickness of about 25cm.

3. CSRE heat transfer coefficient

The value of a building material’s thermal conductivity coefficient depends on several properties, of which the most notable are its bulk density, structure, time to produce the material, as well as its moisture and temperature. These properties depend on the characteristics of the soil mix, the method of compaction, as well as exposure conditions. The authors measured the heat transfer coefficient of CSRE samples made from mixes of two different grain fractions. A three-digit symbol for the mixes, represents the percentage of select fractions in the following order: sand, gravel, and clay/silt. For instance, the mixture 613 contains 60% sand (0.063-2mm), 10% gravel (2-4mm), and 30% clay/silt (<0.063mm). Detailed soil fraction curves for mixes are shown in figure 1. The mineral and chemical composition of soil mixtures is written in [9]. Every mix had 9% Portland cement CEM I 42.5R added. Mixes were used with a humidity that was optimized for the maximum compaction of samples, and therefore most often the highest compressive strength and thermal conductivity. Hence, water was also added to the soil-cement mixture so that the samples would obtain their optimal moisture content for the assumed method of compaction.

Details of the preparation and the actual testing of heat transfer are found in [19]. The samples were 400x400 mm and 100 mm thick. Before the test, the samples were aged for 28 days. Testing was done based on recommendations in standard EN 12664 [20]. Tests were carried out at a temperature of 23°C and relative humidity of 50%. For this reason, the declared values of the heat conduction coefficient will be determined by the symbol $\lambda_{23,50}$. In accordance with the standard, if samples are found to have a
thermal resistance lower than 0.3 [(m²K)/W] or if the samples do not meet the requirements of the standard in terms of their slenderness, thin sheets of adequately compressible material should be placed between the surfaces of the sample and the plate of the measuring apparatus, to ensure there is adequate thermal contact between them. Concerning the uneven, rough surface, as well as a small expected value for thermal resistance of the samples, contact sheets of silicon rubber foam were used. In between the samples and contact sheets, a thermocouple was placed in order to show the differences in temperature during measurement. Eight measurements of thermal conductivity were conducted for each sample. Temperature on the upper and lower planes of the sample, the heat flux flowing through the sample, and the thickness of the sample were measured.

Values of the coefficient of thermal conductivity of each sample were found from the following formula:

$$\lambda = \frac{q \cdot d}{\Delta T}$$  \hspace{1cm} (1)

where:
- $\lambda$ – coefficient of thermal conductivity [W/(mK)],
- $q$ – heat flux flowing through the sample [W/m²],
- $d$ – total thickness of the tested sample [m],
- $\Delta T$ – difference in temperature [K].

Based on the obtained results it was possible to determine the thermal conductivity coefficient value based on EN ISO 10456 [21]. The declared value ($\lambda_{23,50}$) was determined after a statistical analysis of the results with a confidence level of 90% (table 2). With an approximate bulk density of around 2183 [kg/m³] for all tested samples, thermal conductivity coefficients with values ranging from 0.815 to 0.824 [W/(mK)] were obtained.

| Table 2. Declared values of thermal conductivity coefficients of CSRE samples |
|-------------------------------------------------|
| CSRE mixture | Average density [kg/m³] | $\lambda_{23,50}$ [W/(mK)] |
|---------------|------------------------|------------------------|
| 703           | 2186.5                 | 0.824                  |
| 613           | 2178.8                 | 0.815                  |
The declared thermal conductivity coefficients values obtained from laboratory testing results are given in table 2. Building material parameters are most often presented simply with their declared coefficient of thermal conductivity. The declared values are defined for standard operating conditions of the material and for the period immediately after its production. In reality, building materials operate under various circumstances, for which different parameters should be used. A common mistake in the determination of the U-value is the incorrect use of the declared value $\lambda_{23,50}$ as opposed to the design value ($\lambda_{\text{Design}}$) in calculations. During the design stage of partitions, the working conditions of the material should be predicted and convert the declared value $\lambda_D$ to the design value $\lambda_C$. In a temperate climate, building materials operate in conditions of both very high and very low temperatures.

Design value of the coefficient of thermal conductivity is determined by standard EN ISO 10456 [21], according to the formula:

$$\lambda_{\text{Design}} = \lambda_{10,\text{dry}} \cdot F_T \cdot F_M \cdot F_A$$

(2)

where:

- $\lambda_{\text{Design}}$ – design coefficient of thermal conductivity
- $\lambda_{23,50}$ – declared coefficient of thermal conductivity
- $F_M$ - conversion factor due to humidity
- $F_A$ - conversion factor due to ageing
- $F_T$ - conversion factor due to temperature

The values of individual conversion factors are determined on the basis of EN ISO 10456 [21]. As a result of calculations, the design values of the coefficient of thermal conductivity of the CSRE have been obtained, amounting to 0.91 [W/(mK)] for mixture 613 and 0.93 [W/(mK)] for mixture 703, respectively.

4. U-value requirements in humid continental climate

European countries located in a humid continental climate change the requirements for the coefficient of heat penetration (U-value) every few years to more rigorous standards. Figure 2 presents the current requirements for select countries in this climate zone. The value of the coefficient of heat penetration for envelope walls in residential buildings in this climate ranges from 0.2 to 0.45 [W/(m²K)]. For all values in this range, a load-bearing building envelope partition made of CSRE requires an additional layer of thermal insulation.

![Figure 2](image-url)

**Figure 2.** Requirements for U-value for envelope walls in residential buildings in various countries in humid continental climate- status for year 2018 (based on [22], [23], [24], [25]).
5. Simulations of influence of thermal insulation location on thermal and humidity conditions inside partition containing structural CSRE layer

One of the most important issues when designing building partitions is to eliminate any risk of vapor condensation in the interior of the partition. The risk of its occurrence is affected, among other things, by the method of insulating the partition. In a humid continental climate, the primary source of humidity in a partition is from the internal humidity of the building. Simulations of thermal-humidity conditions were conducted for building envelope partitions with a load-bearing CSRE layer with a calculated coefficient of thermal conductivity of 0.93 [W/(mK)] and a diffusive resistance factor of 14.34 [26]. Simulations were conducted in the program Rockwool. Two variants of popular wall insulation materials - mineral wool and expanded polystyrene were considered in the simulations. These materials are characterized by similar computational values of thermal conductivity coefficient, $\lambda = 0.05$ [W/(mK)] for mineral wool, and $0.04$ [W/(mK)] for expanded polystyrene, and different values for the diffusive resistance coefficient $\mu$ equal to 60 for expanded polystyrene and 1.3 for mineral wool boards according to EN 12524 [27]. External climatic conditions, the average monthly temperature and relative humidity were adopted for Warsaw, and typical internal conditions for residential buildings (table 3).

### Table 3. Climatic conditions for residential building located in Warsaw.

| Month: | I  | II | III | IV | V  | VI | VII | VIII | IX | X  | XI | XII |
|--------|----|----|-----|----|----|----|-----|------|----|----|----|-----|
| External conditions: Temperature, $\Theta_e$ [°C] | -1.2 | -0.9 | 4.4 | 6.3 | 12.2 | 17.1 | 19.2 | 16.6 | 12.8 | 8.2 | 2.9 | 0.8 |
| Relative humidity, $\varphi_e$ [%] | 86.0 | 82.9 | 78.0 | 72.3 | 69.5 | 74.2 | 74.5 | 75.9 | 81.0 | 84.7 | 87.2 | 89.2 |
| Internal conditions: Temperature, $\Theta_i$ | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| Relative humidity, $\varphi_i$ [%] | 58.5 | 58.2 | 57.6 | 55.6 | 57.1 | 67.4 | 72.4 | 67.8 | 64.9 | 61.9 | 60.7 | 61.3 |

In the simulations, four arrangements of each of the above-mentioned thermal insulation materials were considered - on the outside of the partition, on the inside of the partition, between the two bearing layers of the compacted earth, and an arrangement in which the thermal insulation was placed on both sides of the load-bearing layer. Insulation thickness was chosen in such a way that all partitions had a U-value of around 0.20 [W/(m$^2$K)] (table 4). Rammed earth exposed to a humid continental climate has a debatable durability, hence the authors assumed that the walls would be finished with a layer of cement and lime plaster, characterized by its low diffusive resistance of 10 and a calculated heat transfer coefficient of 0.80 [W/(mK)].

The second group of simulations appertain to the temperature distributions in the building envelope walls of residential buildings for the extreme outdoor winter temperatures that may occur in Warsaw (value taken as -20°C taken from the national annex for norm EN 12831 [28]). Figure 3 and figure 4 present the results of the simulation of thermal and humidity conditions prevailing in a humid continental climate, in the coldest month of the year (January).

The simulations (figure 5) show that in the case of walls insulated internally or on both sides with mineral wool had a high presence of water vapour condensation. For building envelopes with mineral wool between two CSRE layers, the condensation was less intense. Apart from the case of internally insulating mineral wool, the water vapour accumulated in the partition will evaporate in the warmer parts of the year. Practically speaking though, the presence of even a small amount of moisture in the partition in cold months can affect the durability of the CSRE partition.

Regarding rammed earth technology, an interesting solution would be to apply hard, double-sided thermal insulation as a permanent formwork. This type of solution would decrease the time it takes to build the partitions. In a humid continental climate, the durability of CSRE is decided by its resistance to cycles of freezing and thawing. In the case of a partition containing thermal insulation on both sides, the temperature of the rammed earth layer oscillated in its entirety around 0 °C, which is particularly dangerous for rammed earth in a humid continental climate. Only the partition system containing...
insulation on the external side ensures the stability of the layer of rammed earth at a temperature above 0°C. For this solution, for the simulation of January conditions, the dew point temperature falls in the thermal insulation layer, which results in the accumulation of water on the external side of the partition due to the low temperature of vapour condensation in winter.

Table 4. Building envelope walls considered in simulations.

| Mineral wool on the outside of the partition |  
| Layer | λ [W/(m·K)] | d [m] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Mineral wool | 0,05 | 0,225 | 4,50 |  
| Cement plaster | 0,82 | 0,015 | 0,02 |  
| External surface resistance | 0,04 |  
| U-value | 0,20 |  

| Styrofoam on the outside of the partition |  
| Layer | λ [W/(m·K)] | d [m] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Styrofoam | 0,04 | 0,18 | 4,50 |  
| Cement-lime plaster | 0,82 | 0,015 | 0,02 |  
| External surface resistance | 0,04 |  
| U-value | 0,20 |  

| Mineral wool on the inside of the partition |  
| Layer | λ [W/(m·K)] | d [cm] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Mineral wool | 0,05 | 0,225 | 4,50 |  
| Cement plaster | 0,82 | 0,015 | 0,02 |  
| External surface resistance | 0,04 |  
| U-value | 0,20 |  

| Styrofoam on the inside of the partition |  
| Layer | λ [W/(m·K)] | d [cm] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Styrofoam | 0,04 | 0,18 | 4,50 |  
| Cement-lime plaster | 0,82 | 0,015 | 0,02 |  
| External surface resistance | 0,04 |  
| U-value | 0,20 |  

| Mineral wool placed on both sides of the CSRE |  
| Layer | λ [W/(m·K)] | d [cm] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| Mineral wool | 0,05 | 0,115 | 2,30 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Mineral wool | 0,05 | 0,115 | 2,30 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| External surface resistance | 0,04 |  
| U-value | 0,20 |  

| Styrofoam placed on both sides of the CSRE |  
| Layer | λ [W/(m·K)] | d [cm] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| Styrofoam | 0,04 | 0,09 | 2,25 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Styrofoam | 0,04 | 0,09 | 2,25 |  
| Cement-lime plaster | 0,82 | 0,005 | 0,01 |  
| External surface resistance | 0,04 |  
| U-value | 0,20 |  

| Mineral wool between the two bearing layers of the CSRE |  
| Layer | λ [W/(m·K)] | d [cm] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,015 | 0,02 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Mineral wool | 0,05 | 0,215 | 4,30 |  

| Styrofoam between the two bearing layers of the CSRE |  
| Layer | λ [W/(m·K)] | d [cm] | R [(m²·K)/W] |  
|-------|--------------|-------|--------------|  
| Internal surface resistance | 0,13 |  
| Cement-lime plaster | 0,82 | 0,015 | 0,02 |  
| CSRE | 0,93 | 0,25 | 0,27 |  
| Styrofoam | 0,04 | 0,17 | 4,25 |  

Mineral wool placed on both sides of the CSRE

Mineral wool between the two bearing layers of the CSRE

Mineral wool between the two bearing layers of the CSRE

Mineral wool between the two bearing layers of the CSRE
Figure 3. Distributions of real water vapour pressure and saturated water vapour pressure in building envelope partitions with different thermal insulation positioning. Thermal insulation variants of mineral wool and expanded polystyrene. Climate data for Warsaw in January.
Figure 4. Distribution of temperatures in partitions with load-bearing layer of rammed earth at extreme outdoor temperature in January in Warsaw (-20°C).
Conclusions

CSRE is a building material with a declared coefficient of thermal conductivity of approximately 0.815 to 0.824 [W/(mK)]. In many European countries with a humid continental climate, the current requirements for the heat transfer coefficient range from 0.2 to 0.45 [W/(m²K)]. Such stringent requirements cause the envelope walls of residential buildings to require an additional layer of thermal insulation with a significant thickness.

Simulations of thermal and humidity conditions have shown that in a humid continental climate, the best solution for constructing building envelope partitions with CSRE load-bearing layers is a system with thermal insulation on the external side. Such positioning of thermal insulation prevents the rammed earth structural layer from freezing, as well as vapor from accumulating in the partition. Many popular materials can be used as thermal insulation in a partition with a CSRE load-bearing layer, both those with low and high diffusive resistance coefficients.

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