USE OF STRAW–CLAY MATERIAL IN WALLS

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ABSTRACT

The research aims to investigate the use of straw–clay material in wall construction, its load bearing and heat insulation properties. The main objective of this study is to get optimal straw–clay construction material, which could be used in load bearing external wall constructions of one–storey houses. The effectiveness of different kinds of straw and clay proportions in construction materials is determined by compression and thermal conductivity tests. To show the effectiveness of straw–clay material in load bearing external walls, a specific model of a one–storey house in the finite element analysis program Ansys is created. As a result of this study it is determined that straw–clay block construction material in right proportions can be used in one–storey house load bearing external walls with sufficient compressive strength and thermal resistance.

Key words: straw-clay wall, ecological housing, thermal resistance

INTRODUCTION

The use of straw in construction has had a long history. Initially, it was used for building shelters. The use of straw in a baled form for wall constructions was pioneered by the early settlers in America out of a desperate need to protect their farm animals from winter cold weather, and the practice was later extended to build houses for humans. That was more than a century ago. Recent rediscovery of straw bale construction is largely derived from the realization that our way of living is not sustainable if we keep doing things as we do now. Resources that support our materialistic lifestyle are depleting fast; animal species that are a vital part of our living environment are becoming extinct at an alarming rate. Providing safe shelters has always occupied a position of utmost importance in any culture and in any society, be it simple or complex. Construction activity is the single biggest contributor to global warming. Straw is a renewable resource. Compared with timber, which is regenerated typically every 20 to 30 years, straw is generated once or twice per year. As long as people need grain as a food source, straw will be generated as a by–product. Straw in many parts of the world is still regarded as a waste. Even its disposal has become an environmental issue, like burning in the field. On the other hand, straw has certain excellent properties as a building material, such as its thermal capacity. In baled form, it keeps its integrity reasonably well. Once rendered, straw is durable and strong. Straw bale building has seen a renaissance in recent years. It is spreading fast like a wildfire to every corner of the earth (Hodge, 2006).

Nowadays there is a great interest to develop construction technologies using straw and clay as ecological material in America, Europe, including the Baltic states. Not only straw bales, but also straw–clay material used in walls is with high potential. Building regulations for load bearing type of this material used in house building still develops and is noticed worldwide (Goodhew, 2005). The use of straw–clay material in construction grows mainly due to its good insulation, natural properties and economical reasons. Comparing with straw bales the straw–clay blocks provide higher fire resistance and smaller deformations.

Straw–clay or straw bale houses are constructed in one of three different methods. The first and oldest method is that of load bearing. The straw bales or blocks of straw–clay material support the roof. The second is infill construction. This has been particularly popular in the revival of straw–clay block building, as it has been easier to convince the regulatory authorities that this is a structurally sound system. This building type has either a steel or timber structure that is totally self–supporting with the blocks fitted between the supports to fill in the gaps (Duan, 2010). The third method is a combination of both of the above, and is referred to as structural infill. The structural infill home has a substructure to carry the vertical load of the roof and/or upper floor joists; however it is not self–supporting. As opposed to infill construction, it has no bracing to provide the lateral stability of the structure. This lateral stability is achieved through the installation of blocks into the walls (Hodge, 2006).

There are a lot of houses built using straw–clay material, but it is not researched enough to get convincing arguments for usage as a construction material. That is why it is necessary to investigate this material. The aim of this work is to investigate in the laboratory straw–clay material in order to promote the use of ecologically friendly materials in building construction.

EXPERIMENTAL INVESTIGATION

Material and mix preparation

Six straw–clay compositions were created and tested using different clay and cement proportions. The mix components are summarized in Table 1. The straw–clay cubes are shown in Fig. 1 and the straw–clay plate is shown in Fig. 2.

The mix with number 3 was selected as a compromise variant between strength and density, which could be used as constructive insulating material. That is why the plate was made with the same components and proportions as the third mix sample. The used barley straws were cut into small pieces – the length 30 mm to 40 mm, their diameter 1mm to 3mm. Illite type clay was used as a binding agent in the mix. The clay chemical composition results present the following oxides: SiO_2 60,72%, Fe_2O_3 6,08%, Al_2O_3 18,40%, TiO_2 0,9%, CaO 1,12%, MgO 3,22%, Na_2O 0,07%, K_2O 4,12%.

Clay was mixed with water in order to obtain plastic consistence (water content 30%). The prepared clay paste was mixed with straw pieces in the laboratory mixer and then placed in forms. The mix with number 6 was prepared using Portland cement addition (type CEM I 42.5 N). All straw–clay test samples were placed in 20^{o}C temperature, humidity 50–60%.

Figure 1. Straw–clay cubes.

Figure 2. Straw–clay plate.

Moisture change measuring

During the drying process the prepared straw–clay samples were weighed and measured with accuracy ±0,1mm. The moisture percentage and shrinkage deformation of the material were determined. The diagram of straw–clay cube moisture change in time is shown in Fig. 3.

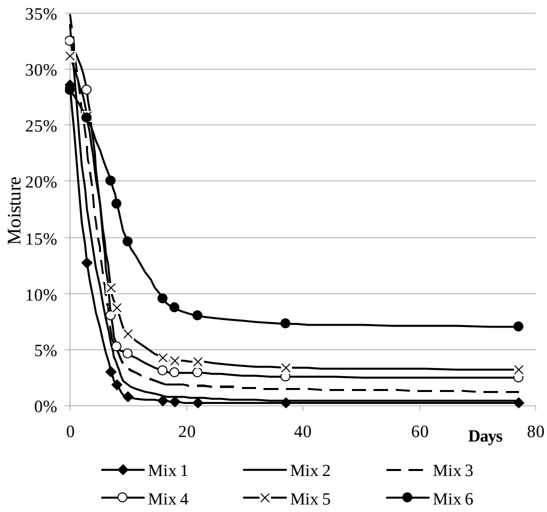

Figure 3. Moisture percentage change in time.

Table 1

Designed mix compositions in 1m^3

Mix number	1	2	3	4	5	6
Barley straw, kg	80	80	80	80	80	80
Clay, kg	300	400	500	700	800	400
Portland cement, kg	–	–	–	–	–	75
Water in clay, %	30	30	30	30	30	30
Additional water, kg	50	50	50	50	50	50

The material density was calculated considering the weight and actual dimensions of the sample. The density and shrinkage numerical results are summarized in Table 2.

Table 2

Material density and shrinkage results

Mix number	Density, kg/m^3	Shrinkage of cubes, %
1	345	10.0
2	393	10.1
3	470	10.1
4	638	10.2
5	728	10.2
6	487	4.9

The cubes with less density had some straw drop–outs. After 77 days the cubes with no Portland cement component had 10% shrinkage, the others with Portland cement component had 5% shrinkage.

Compression and thermal conductivity tests

The cubes were tested by the compression test using universal the testing machine Zvick 100 (Fig. 5) till their deformations became too big or the inner structure crushed (force determination accuracy ±10N, test speed 1 mm/min). Force–deformation diagrams were obtained. When straw–clay mix is put into moulds, straw fiber orientation becomes parallel to the bottom surface. In the compression test cube samples were placed with straw fibers oriented horizontal (variant 1) and for comparison some cube samples were placed on the edge (variant 2). The sketch is shown in Fig. 4. The numerical results including the gained elastic modulus from the cube compression test stress–strain curve are summarized in Table 3.
The obtained results indicate a significant impact of straw fiber orientation on the compressive strength and modulus of elasticity.

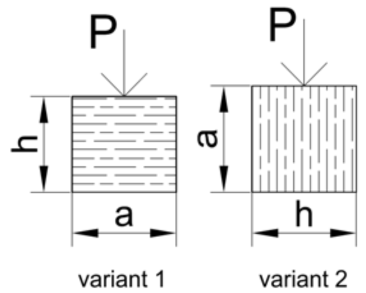

Figure 4. Cube orientation in compression test.

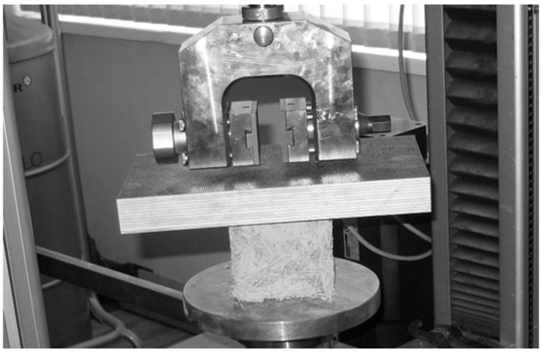

Figure 5. Compression test.

Figure 6. Thermal conductivity test.

Table 3

Mechanical properties of tested cube samples

Mix number	Loading variant (Fig. 4)	Compression strength, MPa	Vertical max. deformations, %	Elastic modulus, MPa	Moisture, %
1	2	0.038	1.9	2.500	0.3
2	2	0.094	3.5	5.200	0.5
3	1	0.499	20.0	3.082	2.4
4	1	0.543	16.3	3.235	2.4
	2	0.222	3.0	7.500	2.4
5	1	0.590	17.7	3.880	3.2
	2	0.289	4.5	11.850	3.2
6	2	0.118	3.0	5.500	7.1

Force added perpendicular to straw fibers gives higher compressive strength, but less modulus of elasticity and higher maximum deformations.

The mix number 1 and 2 having clay/straw proportions 3.75:1 and 5:1 correspondingly indicates low compressive strength. This material may be used only as heat insulating material.

The plate was tested by the thermal conductivity test using the device FOX600 (Fig. 6). The sample was fixed horizontally. During the test the temperature of the lower surface was +20°C and 0°C of the upper surface. The heat transmission coefficient was determined considering constant heat flow between two sides of the sample. The heat transmission test was carried out in different moisture conditions of the straw-clay plate: 43, 12 and 2.5%. The results are summarized in a diagram (Fig. 7).

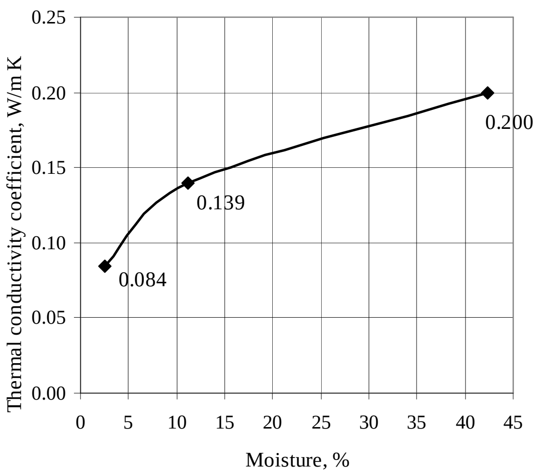

Figure 7. Thermal conductivity coefficient by various moisture.

The range of moisture between 2% and 5% may be considered as the corresponding value for real exploitation conditions of straw–clay walls.

MODEL OF ONE–STOREY HOUSE

External and internal walls of this one–storey house model (Fig. 8) are made from straw–clay blocks (500x240x250mm). In external walls the blocks are placed so that the width of the load bearing wall would be 500 mm.

The block mechanical material properties are taken from the 3 mix sample and the thermal conductivity coefficient is taken from the plate thermal conductivity test. The material density is 500 kg/m^3, moisture 2,3% (maximum 5%), the ratio between clay and straw is 1:6. The weight of one block (Fig. 9) is 15kg, which is acceptable from the building technology point of view.

The external wall is rendered with lime 30mm thick on each side. The model of this house is made in the finite element analysis program Ansys.

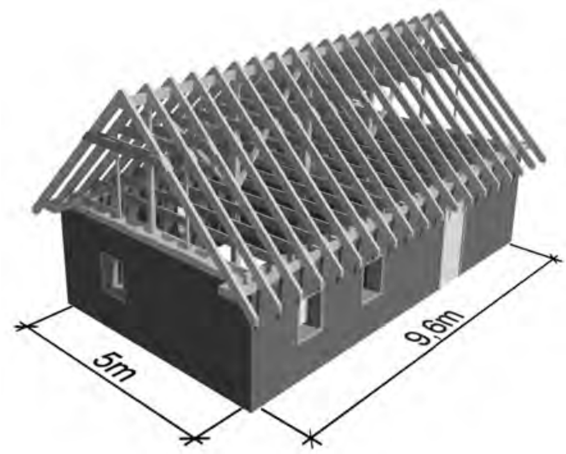

Figure 8. Model of one–storey house.

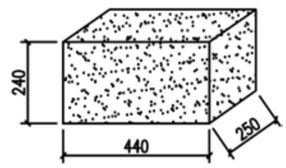

Figure 9. Straw–clay block.

The dimensions between the external walls are chosen 9,6m and 5m – according to the necessary timber element lengths for the roof construction. The height of the walls is 2,5m. In the middle of the building there is an internal wall (width 250mm), which provides total stability. The building stability is increased by the constructed roof construction, which bases on a specially designed wall–plate (Fig. 10, Fig. 11).

The applied normative loads: wind load 0,35kN/m^2; snow load 1,25kN/m^2; permanent load on the roof construction beams 0,265kN/m^2; permanent load on the roof ceiling beams 0,376kN/m^2. All construction self–weights are considered in the finite element program. The design values are calculated according to the European codes (Eurocode 0, 1996), considering the given partial safety coefficients and design combinations. For snow load the roof slope effect is considered, for wind load the aerodynamic coefficient and coefficient, which considers the height of the wall.

For walls in the finite element model the effective width of the load bearing external wall is taken 0,46m instead of real 0,5 m in order to consider imprecision.

The compression stress in the walls from the worst load combinations is shown in Fig. 12, but vertical deformations considering creep from the normative loads is shown in Fig. 13.

The compressive strength variant 1 (Fig. 4) is relative, because the test was stopped due to high vertical deformations. The masonry wall design compressive strength was calculated using the European codes (Eurocode 6, 1996).

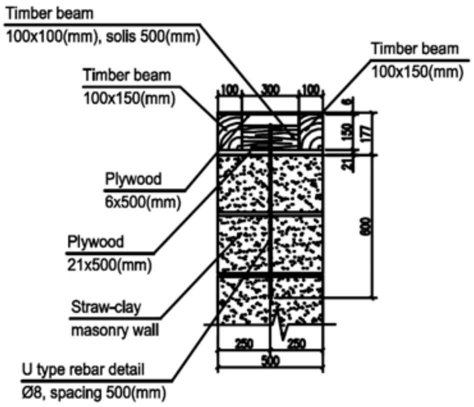

Figure 10. Straw–clay masonry wall connection with wall–plate.

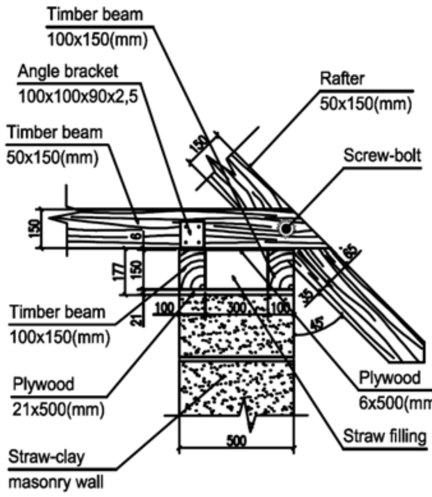

Figure 11. Rafter connection with wall–plate.

The straw–clay masonry wall construction design compressive strength can be calculated as

$$f_d = f_k \cdot \gamma_c \qquad (1)$$

where f_d – masonry wall design compressive strength, kN/m^2;

f_k – masonry wall characteristic compressive strength, kN/m^2;

γ_c – work condition coefficient.

$$f_k = K \cdot f_b^{0,7} \cdot f_m^{0,3} \qquad (2)$$

where K – constant, which considers element compressive strength transformation to masonry compressive strength;

f_b – element normalized average compressive strength along added loading, kN/m^2;

f_m – used mortar compressive strength, kN/m^2.

$$f_b = f_k \cdot \gamma_1 \cdot \gamma_2 \cdot \gamma_3 \qquad (3)$$

where f_k – experimental cube compressive strength;

γ_1 – constant, which considers tested element number;

γ_2 – constant, which considers cube to block size effect;

γ_3 – constant, which considers long term loading and moisture.

By the made calculations the masonry wall relative design compressive strength is more than 73,54kN/m^2. The thermal resistance of this one story house external wall is calculated according to the Latvian building standard (LBN 002–01).

$$U_{RN} = 0,3k \qquad (4)$$

where U_{RN} – overall normative heat transfer coefficient;

k – temperature factor (dependent on indoor and outdoor air temperature).

$$U = \frac{1}{R_T} \qquad (5)$$

where U – overall heat transfer coefficient;

R_T – overall thermal resistance value.

For comparison there are calculated two kinds of straw–clay wall types – one with blocks, other with monolith filling. The thickness of the monolith filling is limited to 300mm because of the slow moisture drying, but the thickness of the masonry wall is taken from the previous calculated load bearing straw–clay wall. The overall heat transfer coefficient of both types is calculated with 2,3% moisture, density 500kg/m^3 and rendered lime is 30mm thick on each side. In the masonry variant the connection between the blocks is provided by straw–clay mixture (15mm thick) with thermal conductivity 0,4W/mK. Both variants – the variant with monolith filling between the timber elements and variant with blocks are considered as not homogeneous. The design value of the straw–clay thermal conductivity is gained from the experimental thermal conductivity 0,084W/mK summed with correction thermal conductivity coefficient 0,03W/mK. The calculated overall heat transfer coefficient of the masonry wall is 0,261W/m^{2}K, which is enough for one story house according to the Latvian building standard (with 17,67% reserve).

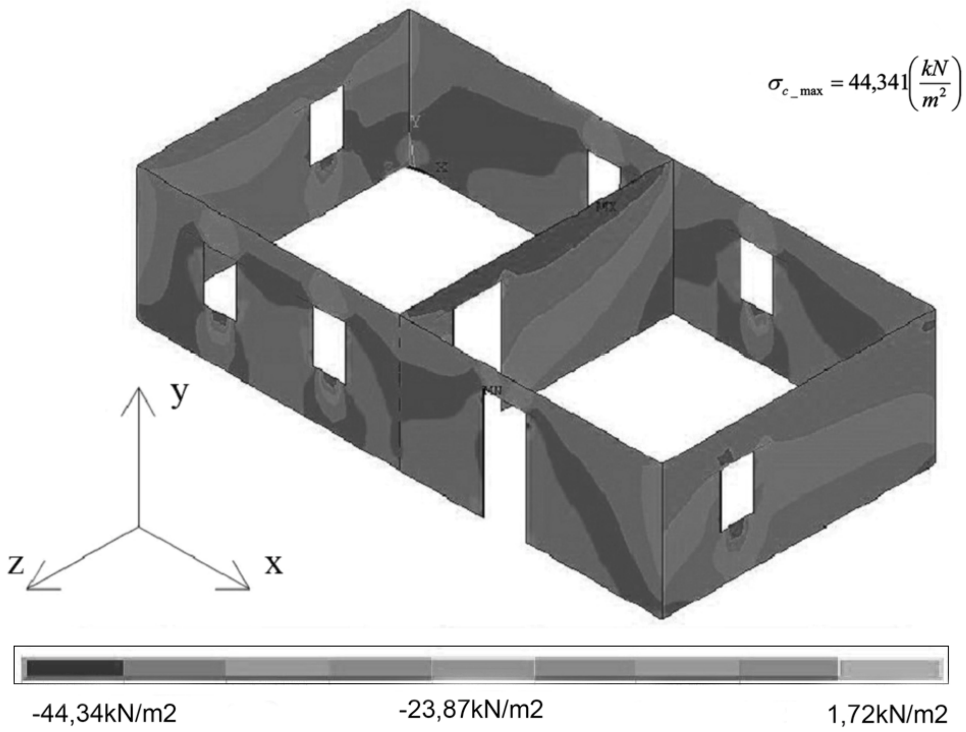

Figure 12. Compression stress distribution in walls, where σ_{c_max} – maximum compression stress value.

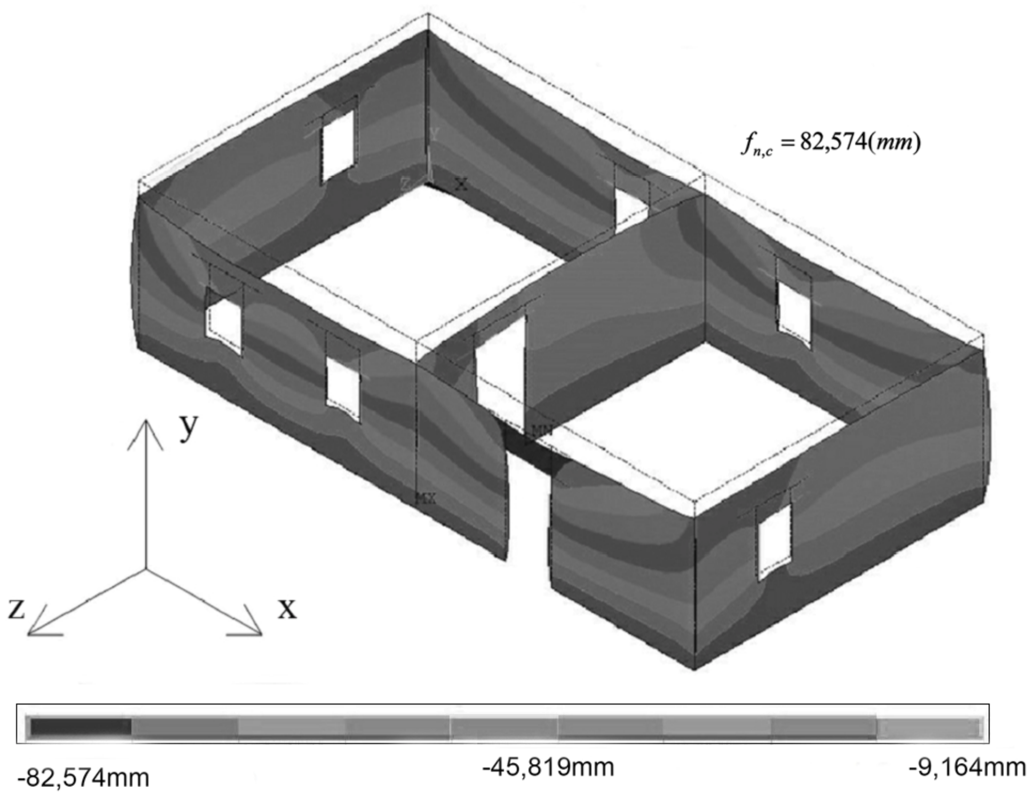

Figure 13. Deformation of walls in y axis direction considering creep, where f_n – maximum vertical deformation value.

According to the data in Fig. 6 the thermal resistance of this masonry wall would be enough even by 6…7% of moisture. The variant with monolith filling would provide the required thermal resistance with thickness more than 340mm, which is more than recommended due to moisture drying. That is why this variant is not recommended for using in external walls as the only heat insulating material.

RESULTS

Physical and mechanical properties of different straw–clay compositions were investigated. It is established that the material is non– homogeneous, its properties depend on the straw fiber direction. Straw–clay compositions have high drying shrinkage (up to 10%). Portland cement admixture in small amounts (75kg in cubic meter) decreases shrinkage to 5%. Use of specially produced precast straw–clay elements (blocks) allow to minimize the negative effect of shrinkage. The residual moisture content is dependent on the straw–clay material density. Portland cement component does not give much positive effect on the element compressive strength or deformation properties.

Heat insulating properties of straw–clay compositions depend on moisture of the material. In order to provide sufficient heat resistance and durability of straw–clay walls, the material must be in air–dry condition (moisture not more than 5%). That is the reason why the wall must be protected against water penetration.

The compression stress in masonry walls, created by the worst load combination of this one–storey house model is 44,34 kN/m^2, which gives more than 40,5% reserve. Theoretically masonry walls of this block material could be used for bigger vertical loading, but the vertical deformations are quite big (20mm and 83mm considering creep) and therefore the loading is limited. Because of the relative big deformations it is necessary to avoid concentrated load. That is why it is necessary to provide a wall–plate under the roof construction – it evens out the loading on the wall.

One of the straw–clay material biggest disadvantages is the moisture effect on its longevity as construction material. That is why it is important to investigate some ways to reduce the negative moisture effect and long time creep deformations.

CONCLUSIONS

Straw–clay material with the density 500kg/m^3 (weight ratio clay/straw 1:6, moisture 2–5%) used in blocks of the masonry wall with 500 mm load–bearing thickness plus 30mm rendered lime on each side of the wall provides thermal resistance enough for an one–storey house according to the Latvian building standard. The same block material used in load–bearing masonry walls of an one–storey house with overall dimensions 9,6x5x2,5m provides the necessary compressive strength with vertical wall deformations 20mm at first and 83mm considering creep. The thermal resistance will decrease because of the vertical deformation, that is why it is important to make the masonry wall with straw–clay blocks, which have moisture less than 5%.

In load bearing walls straw–clay blocks placed with straw fibers oriented horizontal give bigger vertical deformation, but at the same time bigger compressive strength. Thus, vertical deformation is the aspect which limits the usage of straw–clay blocks in load bearing walls.

Special attention must be paid to protection of straw–clay material against penetration of water, appropriate hydro insulation, drainage system and of course roof construction must be provided. Modifying straw–clay compositions with special mineral or organic admixtures is a way to increase the water resistance and dimensional stability of the material. This is a task for future investigations.

The obtained results of straw–clay compositions allow to conclude: ecologically friendly straw–clay material may be used in wall constructions of single storey buildings and provided investigation in this field must be continued.

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