THERMAL INSULATION PROPERTIES AND FIRE RESISTANCE OF WALLS WITH STRAW BALE FILLING

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Summary: *One of the natural and traditional building materials is baled straw. The application of straw in the construction of buildings has caused many tests of this material. This paper deals with tests of thermal insulation properties and fire resistance of walls with baled straw fillings. In terms of thermal insulation properties, the walls with baled straw fillings have good properties in comparison to the classic wall structures, considering the cost of the structure. Unlike other types of tests, there is currently little scientific study of structures with baled straw in terms of fire resistance. Results of these studies are very encouraging and support the application of baled straw in construction.*

Keywords: *Straw bale, wall, thermal insulation, fire resistance*

1. INTRODUCTION

The construction industry is one of the largest environmental polluters. Recent research has shown that the construction industry is one of the world's three largest emitters of greenhouse gases and one of the world's five largest resource consumers [1, 2, 3]. This is, in first, the consequence of the use of conventional building materials for the construction, transport, installation and destruction of which it is necessary to spend a lot of resources and energy. The use of natural materials in the construction of buildings was negligible in the last century, but at the beginning of this century the situation is changing. One of the natural materials used in construction since ancient times is straw. In this work, straw refers to the stems of cereals produced in Serbia, such as: wheat, barley or oats. The possibility of using straw in the construction of objects is high, but these possibilities are not exploited sufficiently. Straw is often mixed with other building materials, for example mud or concrete, and these composites have good thermal insulation and mechanical properties [4, 5]. After harvest, straw is banned and it continues to be used in agricultural production, and more and more often in construction. Straw bales are very heterogeneous and porous and they can have a very large range of

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density and the baling process has a dominant influence on the layout of the stems, the fibers in the bale, which makes difficult the tests that are important for the application of baled straw in construction. This results in insufficient use of this material in the construction industry in addition to high potentials. Straw bale can be used to create structure walls of lower buildings [6], but it can be used as a fill in building structures, too. If baled straw is used as a filler in the structure of the object, then it is only an insulation layer. Application of baled straw as filling in structures is of interest and will be elaborated in more detail in this paper, primarily from the aspect of comparison of thermal insulation characteristics of baled straw with conventional thermal insulation materials used in Serbia in the function of the cost of the constituents in which they are used. As already mentioned, structures with filling of straw bales are rare, and as a consequence, in most countries there are no codes that recognize them. This applies in particular to the fire resistance of these structures. Until now, several tests have been done in the world on resistance to fire of straw-baled constructions, and all of these tests have shown very encouraging results regarding the use of baled straw as building materials. Some of them will be shown in paper.

2. PREVIOUS RESEARCH AND METHODS

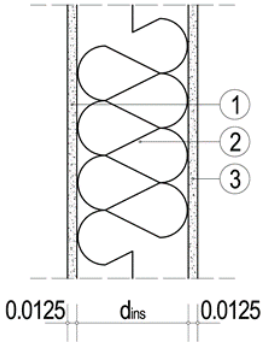
Thermal insulation properties of baled straw is one of the most investigated properties of this material, which is consequently to be baled straw commonly used as a filler in the construction of walls and roofs. One of the numerous studies of the thermal insulation properties of straw bales was done in France in laboratory conditions and results were compared with the results measured at a real object in which the straw was used as a filler in the wall structure [7]. Results of tests in laboratory conditions have shown that baled straw has very favorable thermal insulation properties. In straw bales which is embedded in the observed object there is no risk of condensation and that straw as an insulator allows good thermal performance and high thermal comfort. The thermal conductivity of baled straw primarily depends on the type of cereal, and then in the dominant orientation of the stems in the bale, the compaction of bales and the humidity of the straw. As the humidity of the straw changes during the exploitation period of the bale, the thermal conductivity of the bale is also changed. This has implications for the durability of the straw, as the change in humidity causes the development of microorganisms and the decay of the material. Tests carried out on the structure in New Mexico, which was built with wheat straw bales, and where straw bales are the main constructive element of the building, have also shown excellent thermal insulation properties of baled straw. In the thermal aspect, the baled straw has high thermal resistance, time lag and damping of the amplitude of the oscillation of the temperature, which makes it possible to achieve the optimal thermal comfort [8]. The application of baled straw in the construction of the objects in Serbia is at a very low level. There are no serious studies of this material by domestic researchers, nor national codes in the field of construction that recognize this material. The aim of this paper is to partly demystify straw as building material and promote its application in domestic construction. For this purpose, it will analyze the thermal insulation properties of baled straw and compare it with the thermal insulation properties of conventional thermal insulation materials in Serbia, such as stone wool, glass wool and extruded polystyrene (EPS). Then the price of

1 m² of wall will be analyzed depending on the applied thermal insulation material. The aim is to conclude which material is the most cost-effective for use in construction as a thermal insulation layer and the justification of the application of baled straw as a thermal insulation layer in buildings in Serbia from a financial point of view.

3. ANALYSIS OF THERMAL INSULATION PROPERTIES OF THE EXTERNAL WALL DEPENDING ON THE MATERIAL OF THE THERMAL INSULATION LAYER

The external wall which consists two layers of plasterboard and one layer of a thermal insulation material was analyzed.

Table 1. Hygrothermal properties of materials in the wall [9, 10]

Wall detail	Layers	Layer material	Thickness *d* *[m]*	Mass density *ρ* *[kg/m³]*	Thermal conductivity *λ* *[W/mK]*
	1	Plasterboard	*0.0125*	*900*	*0.21*
	2	Straw bale	*?*	*100*	*0.065*
	3	Plasterboard	*0.0125*	*900*	*0.21*

Based on the maximum permissible value of the overall heat transfer coefficient for elements of the thermal cover of the building for the external walls (U_{max}=*0.30 W/m²K*) [10], the required thickness of the layer of baled straw is calculated, so that the actual value of the overall heat transfer coefficient is lower or equal to the maximum allowed value.If the overall heat transfer coefficient through the construction *U* is calculated as:

$$U = \frac{1}{R_{si} + \sum_m \frac{d_m}{\lambda_m} + R_{se}} \quad (1)$$

where are: R_{si}=*0.13 m²K/W* and R_{se}=*0.04 m²K/W* thermal resistances of internal and external wall surfaces, and λ_m thermal conductivity of layer *m* with thickness d_m.
From the equation (1), the required thickness of the thermal insulation layer d_{ins} is calculated as:

$$d_{ins} \geq \left(\frac{1}{U_{max}} - R_{si} - \sum \frac{d_m}{\lambda_m} - R_{se}\right) \lambda_{ins} \quad (2)$$

Based on the presented calculation, the required thickness of baled straw in the wall is obtained. Then, conventional thermal insulation materials that can be found in Serbia: stone wool, glass wool and extruded polystyrene (EPS) were considered, instead of baled straw as a thermal insulation material.

Table 2. Hygrothermal properties of materials in the wall [9]

Layer	Layer material		Thickness *d [m]*	Mass density *ρ [kg/m³]*	Thermal conductivity *λ [W/mK]*
1	Plasterboard		*0.0125*	*900*	*0.21*
2	Thermal insulation	Stone wool	*?*	*100*	*0.033*
		Glass wool	*?*	*30*	*0.032*
		EPS	*?*	*25*	*0.041*
3	Plasterboard		*0.0125*	*900*	*0.21*

By implementing the same calculation, the required thickness of each thermal insulation material in the wall is obtained (Table 3).

Table 3. Required thickness of the thermal insulation material in the wall

Layer material	Required thickness of layer *d [m]*
Straw bale	*0.20*
Stone wool	*0.10*
Glass wool	*0.097*
EPS	*0.125*

On the basis of the required thicknesses of thermal insulation layers, the cost per m^2 of the wall is calculated for each of applied thermal insulation materials. Cost of materials per unit were taken as current average values in Serbia.

Table 4. Costs of materials per unit [11, 12, 13, 14]

Material	Unit	Thickness of the layer *d [m]*	Cost *[RSD]*
Plasterboard	*1 m²*	*0.0125*	*320.00*
Straw bale	*1 m²*	*0.20*	*200.00*
Stone wool	*1 m²*	*0.10*	*1476.00*
Glass wool	*1 m²*	*0.10*	*450,00*
EPS	*1 m²*	*0.14*	*709,56*

Based on the price analysis, the total cost per m^2 of wall is calculated (Table 5).

Table 5. Total cost of wall per unit m2 for applied insulation materials

Applied material for insulation layer	Cost *[RSD]*
Straw bale	*840.00*
Stone wool	*2116.00*
Glass wool	*1090,00*
Extruded polystyrene (EPS)	*1349,56*

In view of the data presented in Table 5, it follows that the application of baled straw as a thermal insulation layer in the construction of buildings is the most cost-effective.

4. FIRE RESISTANCE OF STRUCTURES WITH BALED STRAW

If baled straw is used as a thermal insulation layer in structures, the question of the resistance of these structures to the fire is raised. The conditions of fire protection are one of the most important requirements that people's facilities must satisfy. This implies that materials and structures must satisfy certain conditions, so that the facility meets the requirements of fire protection. Fire resistance is the ability of an object or part of it to meet the required load (R) and/or integrity (E) and/or thermal insulation (I) and/or other expected property for the specified time [15]. Testing of structures with filling of straw and straw structures in general on fire are very rare. The results of a small number of experiments give very encouraging results and support the application of baled straw in structures. The experiment which is carried out in France in 2004 related to the fire resistance of structures with filling of baled straw, namely concrete roofs and walls [16]. A wall model with a wooden substructure and a filling of straw bales with dimensions *1.85×1.90×0.44 m* was made.

The surface of the wall exposed to the fire load is plastered in two layers of *2 cm* thickness lime mortar over the plaster lath, while the other side is plastered in the same way, but with the addition of chopped hemp as a binding element in lime mortar. The thickness of the straw baled layer in the wall was *36 cm*. The model is equipped with thermometers that measure the temperature in the wall and which are arranged on the surface of the wall exposed to fire and inside the wall at a different distance from the that surface. The wall was exposed to the fire load in *85* minutes, with a temperature *800 °C* on the side affected by the fire. The temperatures measured inside the structure (in the straw baled layer) did not exceed *200 °C*. During the test, there was no collapse of the structure or a disturbance of its carrying capacity.

Similarly, a fire test of a roof model with a wooden substructure and a filling of straw bales with dimensions *1.80×2.0 ×0.39 m* was performed. The side exposed to the fire is covered with wooden three-layer panels with a thickness of *2.7 cm*, while on the other side there is a roofing paper and a roof panel. The model is equipped with thermometers on the surface exposed to fire and inside, at a different distance from the exposed surface. The roof model is exposed to a fire load in 20 minutes. The temperature of the side exposed to the fire was within limits of *800* to *900 °C*, while the temperature within the structure, in the layer of baled straw, did not exceed *230 °C*. After cessation of the

fire, it was determined that the three-layer panel was seriously damaged, but there was no burning of straw or a loss of structural stability.

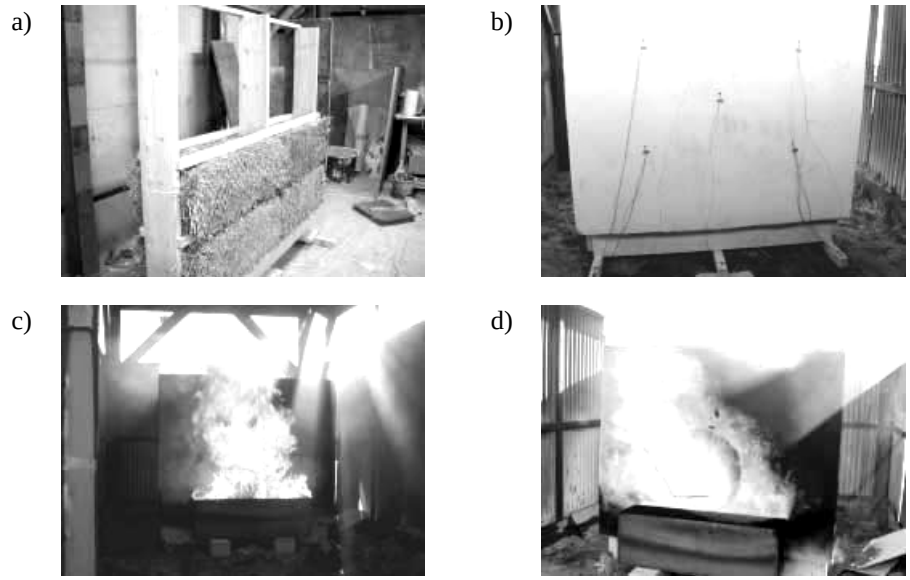


Figure 1. Wooden structure of a wall with baled straw filling (a), prepared wall for testing (b), wall exposed to fire load (c), the wall after cessation of fire (d)

Similar tests were carried out in the USA on two models of walls of varying thickness, with a fill of baled straw, of which thinner was plastered with compo mortar, and thicker with mud. The thick wall, which was plastered with mud, lasted a fire load of *60* minutes, and the temperature on the non-exposed side wall was not higher than *120 °C*. The thin wall, plastered with the compo mortar, exposed the fire load of *120* minutes, and the temperature on the non-exposed wall surface was not higher than *120 °C* [17, 18].

One of the interesting tests of straw resistance on fire was carried out with plastered blocks, which were made by straw bales plastered with a compo mortar of different mixing proportions [19]. The thickness of the blocks was *50 cm*, i.e. *45 cm* baled straw and two layers of *2.5 cm* mortar. Several blocks were made and exposed to a fire on one side for *120* minutes. On the other side a temperature sensor was placed. Due to the effects of fire load on blocks that were plastered with mortar with a higher proportion of lime, cracks appeared. There were no cracks, or they were much less on blocks that were plastered with mortar with a higher proportion of cement. During the entire test period, the temperature on the non-exposed side of the blocks was not higher than *5.5 °C*. The reason for this stability of blocks to the effect of fire should be because the lack of oxygen in the block, which prevents the straw ignition.

5. CONCLUSION

The use of baled straw in structures in Serbia, as a thermal insulation layer, is financially justified in comparison with other thermal insulation materials. On the other hand, due to the poor thermal insulation characteristics, larger thicknesses of the layer of baled straw than thermal insulation are needed compared with the other thermal insulation materials. The structures where it is used are thicker and this can have a negative effect on the aesthetic of these objects. Thermal conductivity and stability of baled straw as insulation material depends on humidity and further research should be oriented in that direction. On the other hand, straw-filled structures show surprisingly good resistance to fire load in terms of the time needed to collapse the structure from the moment of fire.

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ТЕРМОИЗОЛАЦИОНА СВОЈСТВА И ВАТРООТПОРНОСТ ЗИДОВА СА ИСПУНОМ ОД БАЛИРАНЕ СЛАМЕ

Резиме: *Један од природних и традиционалних грађевинских материјала је балирана слама. Примена сламе у изградњи објеката је проузроковала многа испитивања овог материјала. Овај рад се бави испитивањима термоизолационих карактеристика и ватроотпорности зидова са испуном од балиране сламе. У погледу термоизолационих својстава, зидови са испуном од балиране сламе имају доста добра својства у поређењу са класичним конструкцијама зидова, узимајући у обзир цену коштања конструкције. За разлику од других врста испитивања, тренутно постоји мало научних студија конструкција са балираном сламом у погледу ватроотпорности. Резултати тих студија су врло охрабрујући и иду у прилог примени балиране сламе у градитељству.*

Кључне речи: *Балирана слама, зид, термоизолациона својства, ватроотпорност*