COMPOSITE MATERIALS BASED ON CLAY AND STRAW USED IN THE CONSTRUCTION OF WALLS IN CIVIL CONSTRUCTIONS

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ABSTRACT

In recent years, ecological buildings have become increasingly known and sought after, due to the pleasant and healthy environment inside, and also due to the low impact on the environment, compared to classic cement-based materials. In Romania, recently there has been an increasing interest in constructions made of natural materials in general, and especially in those made of straw bales and clay content. The choice and use of building materials involves a careful analysis; from the point of view of their impact on the environment, the ecological consequences can be found either in water, air and soil pollution, in the destruction of the natural habitat, or in soil erosion. Natural and biodegradable building materials based on straw and clay have many advantages, such as superior heat and sound insulation and respectively, an affordable price to the standard of Passive House

Keywords: ecological buildings; straw bales; clay.

REZUMAT

În ultimii ani, construcţiile ecologice au devenit tot mai cunoscute şi căutate, datorită ambientului plăcut si sănătos din interior și totodată datorită impactului redus asupra mediului înconjurător, în comparaţie cu materialele clasice pe bază de ciment. În România se înregistrează recent un interes crescut pentru construcțiile din materiale naturale în general și în mod special pentru cele din baloți de paie și conținut de argilă. Alegerea și utilizarea materialelor de construcții, implică o analiză atentă din punct de vedere al impactului lor asupra mediului; consecințele ecologice se pot regăsi fie în poluarea apei, aerului și solului, fie în distrugerea habitatului natural, fie în eroziunea solului. Materialele de construcție naturale și biodegradabile pe bază de paie și argilă au numeroase avantaje, precum izolarea termică și fonică superioară, respectiv un preț accesibil la standard de casă pasivă.

Cuvinte-cheie: construcţii ecologice; baloți din paie; argilă.

1. INTRODUCTION

In recent years, ecological buildings have become increasingly known and sought after, due to the pleasant and healthy environment inside, and also due to the low impact on the environment, compared to classic cement-based materials (Minke, 2005).

The choice and use of certain types of construction materials involves a careful analysis in terms of their impact on the environment. Pollution due to the technology of production of construction materials as well as the constructions themselves has an important effect on the environment and on climate change (Fabini, 2009).

The ecological consequences can be found either in water, air and soil pollution, in the destruction of natural habitat, or in soil erosion (Ciurileanu and Bucur Horvath, 2011).

One building option is the construction of prefabricated walls made of straw bales and clay. Starting with the late 19th century, at the same time as the industrial revolution and the invention of the first balers in the USA, the first buildings made of straw bales appeared. As time went by, the usage of straw ballots as building “bricks” became increasingly popular, thus enabling the development and refinement of construction methods. Practically, the architectural aspects have been improved, whilst obtaining a passive house standard (WEB, casedinbaloti.ro).

In the image below, different stages of the construction of such a structure are shown - in this case for a residential house in Virginia, USA (Fig. 1), built by Bob Hanson, the owner of Green BEES (Green Building for Economic and Environmental Sustainability). The structure is made of timber frames, with infill walls made of straw ballots. The owner confirms the quality of living in such a house, as a healthy and comfortable environment (Ciurileanu and Bucur Horvath, 2012).

Fig.1. Residential house built with straw ballots

In Figure 2, a two-story building, erected by Bath University (UK) is shown. These walls are constructed with a timber frame and straw bales, as well, this being an experimental building, for a case study of the material properties. As soon as the structure has been built, the monitoring has started for the heat transfer properties, humidity degree, air quality and acoustics performance (Suciu and Suciu, 2007).

Fig. 2. Two-story house, Bath, UK

In the past years, in Romania an equally increasing interest can be noticed in general for building made of natural materials, and especially for the straw bales structures (Suciu and Suciu, 2007).

The advantages of building using straw and clay prefabricates are as follows: superior thermal and acoustic performance, 100% natural and 100% biodegradable material, with a good behavior for seismic actions, building rapidity, accessible pricing at passive house standard. In Figures 3 and 4 several such buildings, built in Romania with straw bales, are shown (Moquin, 1994).

Fig.3. Residential house using straw bales in Valea Nucului, Buzău, Romania

Fig.4. Wall under construction, using straw bales infill walls, in Cluj County, Romania.

Straw panels stuck together with clay and cast inside the timber cassette are an optimal version for building houses on a timber frame structure with straw bales. An outstanding advantage of these panels is the rapidity of on-site assembly.

Due to the special conditions of the structure, the panels can be assembled without the help of special machines, the use of a drill machine being sufficient. The assembly of this new type of panel solves a few technical problems, for example the elimination of thermal cold bridging. At the joint of two panels, the lateral edge of the straw ball panel is sealed up against the lateral edge of the following panel (WEB, colibaverde.ro).

The aim of this work is to study the properties of the straw and clay infill that is aimed for usage inside the composite panels.

2. MATERIALS AND METHODS

We have used specimens manufactured from a homogenous mix of straw and clay, for which the following assessments have been made (by assimilation in conformity with standard requirements for thermal insulation materials, such as polystyrene, mineral wool, or masonry):

- dimensional and physical-mechanical characteristics, such as bulk density;
- bending strength;
- water absorption speed variation;
- traction strength;
- compression stress for a relative deformation of 10%;

After pouring/stripping, the specimens have been conditioned at 20°C and 50% RH.

2.1. Determination of bulk density

The determination of bulk density has been performed according to SR EN 1602 (ASRO, 2013). Figure 5 shows how a specimen measuring 200 × 200 × 60 mm is manufactured using a homogenous mix.

The density is the ratio between the mass and the volume of the tested specimen.

Fig.5. Appearance of the test specimen made to determine the density

2.2. Dimensional stability in normal conditions and laboratory constants

The dimensional stability in normal conditions has been determined in conformity with SR EN 1603 (ASRO, 2013), on specimens of 200 × 200 × 200 mm size.

The test consists in measuring the length, width and deviation from planarity of the specimens, at various time intervals, in normal laboratory conditions, until the achievement of a relative stability. The acceptable test conditions are: (23±2)ºC and (50±5)% relative humidity.

The length and width are measured at the start of the test (l_0, b_0) and after 28 days (l_t, b_t).

Dimensional variations are calculated in percentages, using relations (1) and (2),

$$\Delta\varepsilon_l = 100\frac{\Delta l}{l_0} \tag{1}$$

$$\Delta\varepsilon_b = 100\frac{\Delta b}{b_0} \tag{2}$$

where:

$\Delta\lambda$, $\Delta\beta$ – the difference between the initial and final length and width (mm)

l_0, b_0 – values of initial measured length and width, mm.

l_t, b_t – values of final length and width (mm)

Dimensional variations ($\Delta\varepsilon_\lambda$, $\Delta\varepsilon_\beta$) were rounded at the closest 0.1%.

2.3. Bending Strength

The test method consists of applying a force at a given speed, through a loading edge, in an axial direction, on the faces of the rectangular specimen positioned on two support edges.

The load is applied on the specimen at the mid-span between the two edge-supports.

Figure 6 shows a test specimen for bending, while Figure 7 shows the bending behaviour, determined according to SR EN 12089 (ASRO, 2013), on test tubes of 500 x 150 x 100 mm size.

The calculation of the bending strength, σ_x (kPa) is made using equation (3):

$$\sigma_x = 3x10^3 x\frac{F_x xL}{2xbxd^2} \tag{3}$$

where:

F_x – applied force, corresponding to displacement (N);

L – span between edge supports (mm);

b – specimen width (mm);

d – specimen thickness (mm).

Fig.6. Testing of the specimen to determine density

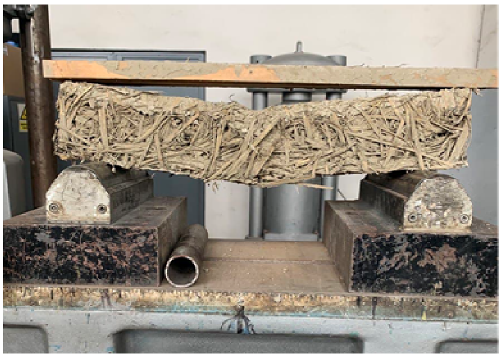

Fig.7. Determination of residual deformation from bending strength testing

2.4. Determination of the perpendicular traction on the faces

Figure 8 shows the assessment of the perpendicular traction on the faces, according to SR EN 1607 (ASRO, 2013), on the 300 × 300 × 50 mm specimens.

The specimen is fixed between two rigid plates, fitted into a traction test machine, and is subjected to tension at a given speed. The maximum traction speed resistance is recorded, and the traction resistance of the specimen is calculated. Resistance to perpendicular traction is calculated in kPa, with relation (4),

$$\sigma_{mt} = F_m / A = F_m / bL \qquad (4)$$

where:

F_m – maximal traction force (N);

A – cross sectional area of the specimen (m^2);

L, b – specimen length and width (m).

2.5. Assessment of the water absorption due to capillarity

The assessment of water absorption due to capillarity was performed according to SR EN 772-11 (ASRO, 2011) on 200 × 200 × 50 mm specimens.

Fig.8. Test of perpendicular traction

After drying to a constant mass, one face of the panel is immersed in water for 1 minute, and subsequently the mass increase is assessed.

The calculation of the water absorption coefficient due to capillarity, for each specimen of approximately 0.1kg/(m^2 × min) is done using equation (5):

$$c_{w.s} = \frac{m_{so.s} - m_{dry.s}}{A_s t} \times 10^3 \, (\mathrm{kg/(m^2 \times \ min)}) \qquad (5)$$

2.6. Assessment of thermal transfer resistance

The assessment of thermal transfer resistance has been performed in line with SR EN 1745 (ASRO, 2020), on 300 × 300 × 50 mm specimens.

The specimen is dried in the oven to a constant mass, and subsequently is placed in the machine. The thickness of the specimen is measured automatically by the conductivity meter.

The mean temperature between the plates is set to 10 degrees Celsius. After the temperature of the plates (hot and cold) stabilizes, the machine indicates the thermal conductivity of the specimen.

2.7. Assessment of permeability to water vapour

Figure 9 shows a specimen that has been subjected to testing for permeability of water vapour according to SR EN ISO 7783 (ASRO, 2019). The test was made on cylindrical specimens of 5 cm thickness and 17 cm diameter.

The specimen is sealed on the opening of the circular cup, as in Fig. 9, in which the vapour pressure is maintained constant by using a saturated solution of potassium nitrate, which ensures a relative humidity above 93%. The specimens are weighed at certain time intervals, and the transmission rate of the water vapours that pass through the specimen is determined through the weight difference of the cup, with reference to the time interval and transmission surface.

Fig.9. Specimen for the test for water vapour permeability

For each specimen, the variation of mass per unit time, G, in g/h, is assessed using relation (6):

$$G = \frac{m_2 - m_1}{t_2 - t_1} \tag{6}$$

Subsequently, the water vapour transmission rate (V), is determined using the relation (7).

$$V = 24 x \frac{p}{p_0} x \frac{G}{A} \tag{7}$$

where:

- A – area of the circular piece through which the steam transmission takes place (m^2);
- G – mass variation per unit time at a single determination (g/h);
- t_1, t_2 – time t_1 and t_2, respectively (hours);
- m_1, m_2 – the mass of the ensemble at time t_1, respectively t_2 (g);
- the p / p_0 factor corrects the water vapour transmission rate at the standard atmospheric pressure, $p / p_0 = 0.99$;
- the factor “24” converts G from g/h to g/day.

The permeability is computed from the average value of the permeability multiplied by the thickness of the specimen.

2.8. Compression behaviour

Figure 10 shows the determination of the compression behaviour according to SR EN 826 (ASRO, 2013) on 300 × 300 × 50 mm specimens.

A compressive force is applied at a 10% deformation of the specimen at a given speed, in an axial direction perpendicular to the main faces of a square cross-section specimen and the maximum stress exerted by the specimen is calculated.

Fig.10. Test specimen subjected to compression stress

The compressive stress at a relative settlement of 10% is computed with relation (8):

$$\sigma_{10} = 10^3 \frac{F_{10}}{A_0} (kPa) \tag{8}$$

F_{10} – force corresponding to a relative deformation of 10% (N);
A_o – the surface on which the force acts.

2.9. Determination of the freeze-thaw resistance

The determination of the freeze-thaw resistance was done according to SR EN 12091 (ASRO, 2013), on specimens of 200 × 200 × 50 mm size.

The freeze-thaw resistance is determined as a change in the amount of water absorbed by a test specimen which is subjected to 300 successive cycles from dry conditions at -20°C to wet conditions at + 20°C.

The difference in water absorption is determined after the 300 cycles of thawing.

3. RESULTS AND DISCUSSIONS

The value of the density and the dimensional variations are presented in Table 1, and the residual deformation at bending and the resistance to bending in Table 2.

Table 1. *Density and dimensional variations*

Characteristic	*Density (kg/m³)*	*Dimensional variations (%)*	
		$\Delta\varepsilon_\lambda$	$\Delta\varepsilon_\beta$
Value	390	0	0

The bulk density of straw bales with clay is higher than the bulk density of extruded polystyrene, according to the literature. The advantage of prefabricated clay straw panels is that they can be used as masonry elements in the construction of the walls of a building; using polystyrene instead would mean just a thermal insulation that is applied on the wall built with other masonry elements.

There are no dimensional variations under normal conditions for prefabricated clay straw panels.

Table 2. *Tensile strength and residual deformation*

Charac-teristic	Tensile strength σ_x (kPa)	Bending de-formation (mm)
Value	302	200

The tensile strength is higher than that of expanded polystyrene EPS 100, which is around 100 kPa. Prefabricated panels made of straw with clay have the property of being elastic, which offers the walls made of these prefabricated units the advantage of good behaviour in seismic actions.

Table 3 shows the values of the mechanical resistances: tensile strength and compression behaviour, respectively.

Table 3. *Tensile strength and compressive stress at a relative displacement of 10%*

Charac-teristic	Tensile strength, σ (kPa)	Compression stress at a relative displacement of 10% σ_{10} (kPa)
Value	50	200

The tensile strength is comparable to that of expanded EPS 100 polystyrene, and the compressive stress at a relative displacement of 10% is 3-4 times higher than that of EPS 100 polystyrene.

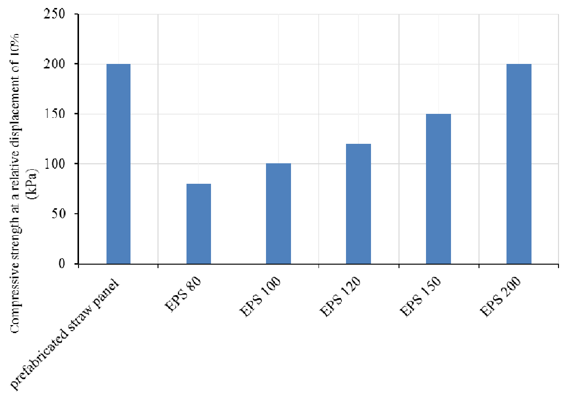

Fig. 11. Compressive stress of the clay straw panel compared to polystyrene of several types

It can be noticed in Fig. 11 that the compression stress of the straw with clay panel, is higher than that for all types of polystyrene, being twice larger as compared to the expanded polystyrene EPS 100. This shows a very good elasticity of the straw panel, due to the gap inside the straw.

The thermal conductivity and the water vapour transmission rate of the straw and clay panels are presented in Table 4.

Table 4. *Thermal conductivity and water vapor transmission rate*

Charac-teristic	Thermal conductivity λ (W/mK)	Water vapour transmission rate, V(g/m²d)
Value	0,076	181

The chart in Figure 12 shows some values of thermal conductivity for different construction materials, according to the literature.

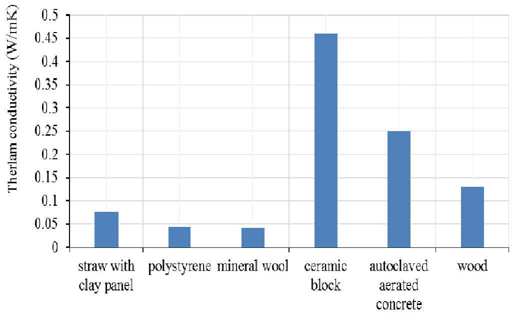

Fig.12. The values of thermal conductivities on different construction materials

The thermal conductivity of straw and clay panels is comparable to that of polystyrene and mineral wool. Compared to the other building materials shown in the chart, the straw and clay panels can be considered to be the best thermal insulators. Prefabricated clay straw panels, compared to polystyrene, have much higher water vapour permeability than polystyrene, which provides breathability to the wall made of straw bales. Wall breathing is the most important property that gives a healthy indoor environment. The thermal conductivity is comparable to that of polystyrene. Clay straw panels are good thermal insulators, and in addition to polystyrene have the quality of "breathing".

Table 5 shows the value of the water absorption rate before and after 300 cycles of thawing. These specimens subjected to freeze-thaw cycles have been previously plastered with hydraulic lime-based plaster compatible with the clay straw surface, because the first layer subjected to climatic conditions is plaster.

Table 5. *Water absorption speed before and after 300 cycles of thawing*

Charac-teristic	Before cycles	After cycles
	$C_{w,s}$ kg/(m^{2}xmin)	$C_{w,s}$ kg/(m^{2}xmin)
Value	91,8	96

Following the results of the frost resistance test, the variation of the water absorption speed is small, so, if the straw ball panel is plastered with a suitable plaster based on hydraulic lime, as used in this study, it can be considered as weather-resistant.

Fire resistance tests of straw bale walls are relatively rare in the world and are performed according to different standards. Virtually all the findings of such tests show surprisingly encouraging results.

For the fire to burn, air and flammable material are needed. There are only very small amounts of air inside the straw bales, since the straws are very well compressed and glued with clay. The walls of such a house are usually plastered on both sides. A layer of plaster with a thickness of 1.0-1.5 cm can withstand fire for half an hour. According to EU requirements, there is enough time to evacuate people (http://colibaverde.ro/casedinbalotidepaie/panouri-prefabricate-din-paie).

The manufacture of straw panels with clay is a more advanced method of using straw in construction. The straw and clay are placed in a wooden frame, usually the timber frame system, which forms a prefabricated panel ready to be transported to the construction site where the construction is assembled.

The construction technology with prefabricated straw panels is a modular technology that exponentially increases the efficiency with which straws are used in construction (unlike houses with simple bales), because they are processed using specialized equipment and the wood is cut automatically.

4. CONCLUSIONS

Natural and biodegradable building materials based on straw and clay have many advantages, such as superior thermal and sound insulation, and an affordable price at the passive house standard.

Prefabricated straw and clay can be used to build the exterior and interior structural elements of a building, having the advantage as observed in practice, of being themselves masonry units. Polystyrene, instead, has to be applied to walls made of other masonry units.

The panels can have different sizes depending on the project and are executed in the hall / enclosure, being subsequently transported to the assembly site. This reduces construction time, site work and associated risks and increases the performance of the entire building.

The use of prefabricated panels with straw and clay has gained momentum in the last 20 years. During that period, a huge investment has been made in their research and development.

Prefabricated structural walls filled with straw and clay can be later plastered with clay or lime plaster, although this requires extra work on site. However, they look beautiful, traditional and - most importantly - provide a healthy indoor space.

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