INVESTIGATION OF PHYSICAL AND MECHANICAL PROPERTIES OF STRAW AS A BUILDING MATERIAL

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ABSTRACT

This article analyses how straw and straw buildings pass the Basic requirements given in Regulation (EU) No 305/2011 of the European Parliament and of the Council. The research was performed by analysing the various scientific works and test results carried out at accredited laboratories. The analysis reveals that perfectly prepared straw as well as buildings insulated with it can pass the Basic requirements. During the test of required pressure of rye, triticale and oat straw it was estimated that the type of straw and humidity have not influenced the compression. During the experiment, the following aspects were also estimated: the pressure to obtain an optimal density of 90...140 $kg \cdot m^{-3}$, the dependency between straw density and pressure deformations. The research of thermal conductivity confirmed the results of other scientific works, which state that increasing the straw's humidity increases the thermal conductivity coefficient as well. The thermal conductivity coefficient of dry straw is about 0.01...0.02 $W \cdot m^{-1} \cdot K^{-1}$ smaller than that of straw with 20 % of humidity.

Key words: straw, Basic requirements, density, pressure, thermal conductivity.

INTRODUCTION

Straw as barriers for thermal insulating and roofing material has been used for a long time. The usage greatly increased when the production of straw bale was started. In these latter years, straw has been used as a soundproofing and structural material. The increasing cost of traditional insulation materials, willingness to live in healthier ambience, environmental problems while producing energy-intensive building materials as well as access to information distributed over the Internet determined the wider use of pressed straw in Lithuania. The straw bales compared with traditional building materials, are ecological due to a low requirement for production energy and utilization. Recently, the considerable interest is being paid to straw bale, not only in popular literature but also on the internet and in the scientific publications (Ashour et al, 2011; Bainbridge, 2000, 2003; Czachor, 2002; Drack et al., 2004; Goodhew et al., 2004; Henderson, 2006; Korjenic et al, 2011; Lawrence, 2009; Simonsen, 1996; Sodagar et al, 2011; Taylor et al., 2006; Wieland et al., 2002). In a theme of construction from straw there are patents of inventions (Patent..., 2004, 2006, 2007 ir kt.), books (Hodge, 2006; Hollis, 2005; Karen, 2005, Bingham, 2007, King, 2006, Corum, 2005, Magwood, 2005). "The Last Straw Journal" has been published in USA since 1993. The PhD thesis about the use of renewable building materials in construction process was prepared (Ashour, 2003; Krick, 2008, Vejeliene, 2012; Milutiene, 2013). The material about construction from pressed straw is placed on the internet by associations, unions and corporations in many countries. All this suggests that the pressed bales of straw as a building material in the future should be used more widely.

The usage of straw as a building material is connected with the estimation of how buildings and their structures constructed from straw pass the Basic requirements stated in Regulation (EU) No 305/2011 of the European Parliament and the Council (Regulation..., 2011). When using straw it is important to know the thermal conductivity dependence on straw density, moisture content as well as their compression pressure. The aim of this work is to evaluate if the straw buildings pass the Basic requirements or not; to determine the pressure and density dependenc; to estimate the dependency between thermal conductivity and straw density, humidity.

MATERIALS AND METHODS

Evaluating straw as a building material the scientific works about the suitability to use pressed straw in construction were analyzed. During the analysis the pressed straw as a building material was reviewed according to the Basic requirements stated in Regulation (EU) No 305/2011 of the European Parliament and the Council (Regulation..., 2011).

For the pressing test - three types of straw (rye, triticale and oat) were used. The test was performed using a reinforced steel box. The box shape was rectangular with a cross-section area of 0.1 m^2. During the test, samples cut from straw bales according to the dimensions of box were used. For pressing a universal testing machine (Fig. 1) was used. The pressure to straw was transmitted through a rigid steel plate. The humidity was estimated according to the mass.

Figure 1. Straw pressure test with universal testing machine

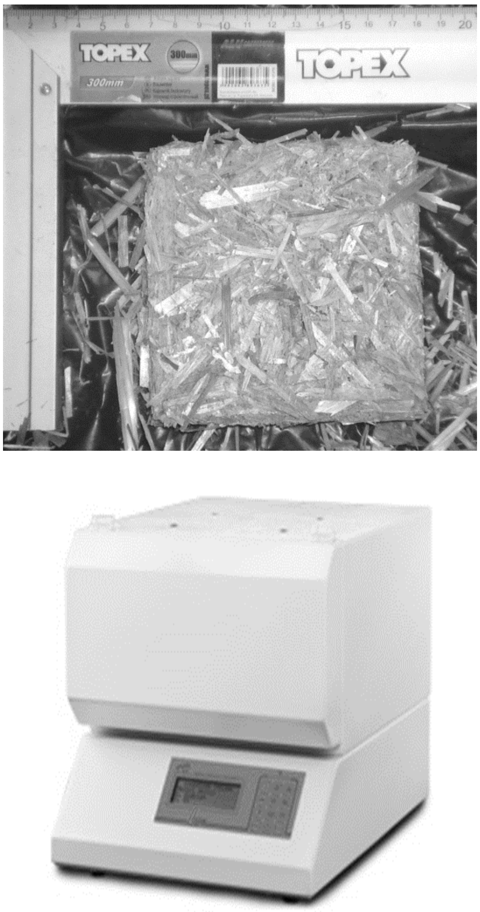

Figure 2 Straw sample for thermal conductivity test and „LaserComp“ FOX200 test apparatus

The thermal conductivity was estimated using shredded 50 mm long and differently pressed triticale straw according to standard methods (EN12667, ASTM C 518, ISO 8301) with „LaserComp“ FOX200 test apparatus. The straw was tested under dry and wet conditions. The heat flow was vertical to the straw's length (Fig. 2).

RESULTS AND DISCUSSION

Requirements for pressed straw bales as a building material, analysis of recently made investigations

The frequent usage of straw as abuilding material is associated with some distrust and fear: the building will burn, rot, mice or rats will attack it. In this article we will try to answer the above-mentioned fears by analyzing the scientific works: articles in refereed scientific journals, conformity assessment data carried out in independent laboratories.

Recently in the European Union there are undivided requirements for construction products. Each product, which is available on the market, shall have a declaration of performance. This is being performed according to standard methodology. Straw and manufactured construction products validation is possible after the establishment of the National Technical Assessment (NTA) or European Technical Assessment (ETA). In Germany in 2006 according to the Building from Pressed Straw Union order, a technical assessment was prepared and in 2014 Construction from Straw Directive (Strohbaurichtlinie..., 2014) and certificate (Allgemeine..., 2014) were prepared as well. These documents refer to particular requirements for pressed straw bales: dimensions, density, thermal conductivity, humidity, reaction to fire and others. The requirements for the construction process are given as well. Technical assessment describes the test methods, standards and periodicity of straw bales testing. Similar requirements for pressed straw are prepared in the USA and Belarus.

Assessing pressed straw bales and building structures from the basic requirement of mechanical strength and stability viewpoint, mechanical properties, particularly strength, are very important. The pressed straw is usually used for the frame building construction as insulation material for walls, roof, ceiling and loft. In this case, the load bearing structures are wooden frames, ceiling beams or rafters. In Germany, (Strohbaurichtlinie..., 2014) the length between the posts must not be longer than 1 m. The mechanical tests show that walls with wooden frames sustain quite great vertical and horizontal loads. An analogous test was carried out in Lithuania for legalization of wooden frames with external board filled with straw (straw shades (Fig. 3)) (National..., 2013). The test results proved that straw shades can be used for construction. According to this, it can be seen that straw is a suitable material for thermal insulation in wooden frame and shade buildings, where load bearing structures are wooden elements. Frameless walls from small straw bales can be used for simple building construction (when the length between the walls is less than 6 m). Using large straw bales for wall construction the length can be greater. We suppose that for the construction of frameless structures from straw bales it is necessary to perform further investigations. During the construction the visable surface of straw must be covered with plaster, therefore it is necessary to reach the required bond between straw and plaster. In Lithuanian National Technical Assessment (National..., 2013) the bond strength between straw and plaster must be not less than 40 kPa.

Figure 3. Straw shades (Source: http://grynasbustas.lt/produktai-ir-paslaugos/produktai/siaudu-skydai)

The evaluation of buildings with straw structures according to *Safety in case of fire* (second Basic Requirement) is very important. The design norms of construction works indicate structural fire resistance. The structure or element of structure (construction product) must have load-bearing capacity (*R*), thermal insulation properties (*I*) and be solid (tight, without cracks) (*E*) for a specific period of time. According to the reaction to fire construction products are divided into classes: A, B, C, D, E, F (A – nonflammable materials, F – flammable, easily flammable, materials). According to test results (Wandsysteme..., 2001; National..., 2013) pressed straw is flammable, normal flamemable material, which belongs to class E. The traditional thermal insulation material polystyrene with additives reducing flammability belongs to the same class.
In Austria, the flammability test of frame walls covered in plaster and filled with pressed straw was carried out (Wandsysteme..., 2001). The test shows that this wall withstands the 90 minutes long experiment (resistance to fire R90). Whereas in Lithuania the flammability test (National..., 2013) shows that straw shades covered with plaster are hardly flammable (B class), smoke and flaming particles were not formed during the test (s1 and d0 class). Walls with these properties can be used for construction for various building types. However fire is dangerous for uncovered straw. Therefore during construction it is necessary to keep the following fire safety requirements (no smoking, no use of open flames and regularly clean floors from straw residuals).
According to the test results it can be seen that buildings with pressed straw walls, which are covered with plaster or other nonflammable material pass the requirements of fire safety.
As fires in buildings are often caused by wiring faults, the electrical cables must be installed in special pipes or in la ayer of plaster. Also storage places of straw must be protected from lightning.
Evaluating pressed straw according to *Hygiene, health and the environment* requirement (third Basic requirement) the most important interest is rotting, growth of fungi, infestation of gnawers, quantity and toxicity of gas and smoke formation during a fire. In Austria, it was estimated that the rotting and growth of fungi in straw starts when the humidity in straw is higher than 18-20 % (Wandsysteme..., 2001). Therefore, the straw must be pressed when the weather is dry, protected from rain during transportation, storage and construction. The straw must be protected from ground capillary moisture as well. Also, the pressed straw must be ventilated. Selecting the plaster for finishing the walls and protection, vapor permeability must be considered. The interior plaster must be less permeable to vapor compared to the external plaster. In this type of wall, moisture will not accumulate. It is recommended to measure the humidity of the straw wall with special sensors (Lawrence et al, 2009). By design the straw will be ecological material, the grain can't be sprayed with herbicides or other chemicals before harvest. The straw for straw sheds produced in Lithuania must pass the requirements of (National ..., 2013): the humidity must be less than 20 % and the quantity of pesticides must be less than stated in Regulation (EU) No 305/2011 of the European Parliament and the Council (Regulation..., 2011).
Straw is completely common from other heat-insulating materials as a place suitable for gnawers. Therefore, it is necessary to protect pressed straw walls from the gnawers (mice and rats). One of the solutions is to use plaster or other covering material with a thickness of 20 mm or greater. Besides, the lower zone can be reinforced with the steel mesh. Experience has shown that gnawers do not like straw of winter crops. In all senses, it is necessary to use well-trashed straw.
According to the *Safety and accessibility in use* requirement (fourth Basic Requirement) the buildings from pressed straw do not present unacceptable risks for accidents.
Evaluating *Protection against noise* (fifth Basic Requirement), the acoustic valuation is being determined. In Austria, it was estimated that the

sound absorption coefficient of the frame wall insulated with pressed straw and covered with plaster, was 55 dB (Wandsysteme..., 2001). Similar results were obtained in Lithuania by testing straw sheds: the sound reduction index was 54 dB (National ..., 2013). These results show that external pressed straw walls insulate against noise well and are suitable for the highest acoustic comfort class A.

For buildings, where the interior temperature must be positive, *Energy economy and heat retention* requirement (sixth Basic requirement) is very important. According to this requirement, the amount of energy used to heat, depending on the local climate and the needs of the population, should not be greater than necessary. This depends on the parameters of barriers (heat transfer coefficient *U*, thermal resistance R_t). These parameters depend on the thermal conductivity coefficient λ of the material.

In Austria, Denmark, USA, Germany and other countries it was estimated that the thermal conductivity coefficient λ of pressed straw (density 70-150 kg·m^{-3}) is equal to 0.045-0.06 W/(m·K) when they are dry and equal to 0.054-0.072 W/(m·K) and when they are air-dry (Wandsysteme..., 2001; Ashour et al., 2003; 2011). The German Construction from Pressed Straw Directive states that the thermal conductivity the coefficient λ of pressed straw is 0.052 W/(m·K) (Strohbaurichtlinie..., 2014). In this case, the heat transfer coefficient of a wooden frame (evaluating influence of wood) wall filled with pressed straw and covered with plaster on both sides will be 0.13-0.14 W/(m^2·K) (total thermal resistance R_t = 7.7-7.1 m^2·K/W). These results show us that the heat transfer coefficient is less than required (till 2016 U_N = 0.2 W/(m^2·K) for residential buildings) by 43-54 %. The 40 cm thickness straw sheds (the density of straw 98...127 kg·m^{-3}) produced in Lithuania also have small thermal conductivity. The heat transfer coefficient is *U* = 0.15 W/(m^2·K) (total thermal resistance R_t = 6.65 m^2·K/W). Besides, it is possible to reduce this coefficient by additionally insulating the walls with wood fibre panels and getting energy effective buildings or passive buildings.

The requirement of *Sustainable use of natural resources* (seventh Basic Requirement) states that buildings must be designed, built and demolished in such a way that the use of natural resources is sustainable and, in particular, ensures the following:

(a) reuse or recyclability of the buildings, their materials and parts after demolition;

(b) durability of the buildings;

(c) use of environmentally compatible raw and secondary materials in the buildings.

Straw and others renewable raw materials mostly suit this requirement due to low energy required for production (Fig. 4), use and utilization (Sodagar et al., 2011; Vom..., 2014). Properly constructed and exploited buildings with pressed straw can be used for a long time. The longevity of straw sheds produced in Lithuania is 50 years (National..., 2013). In the world, there are straw buildings that were built more than 100 years ago.

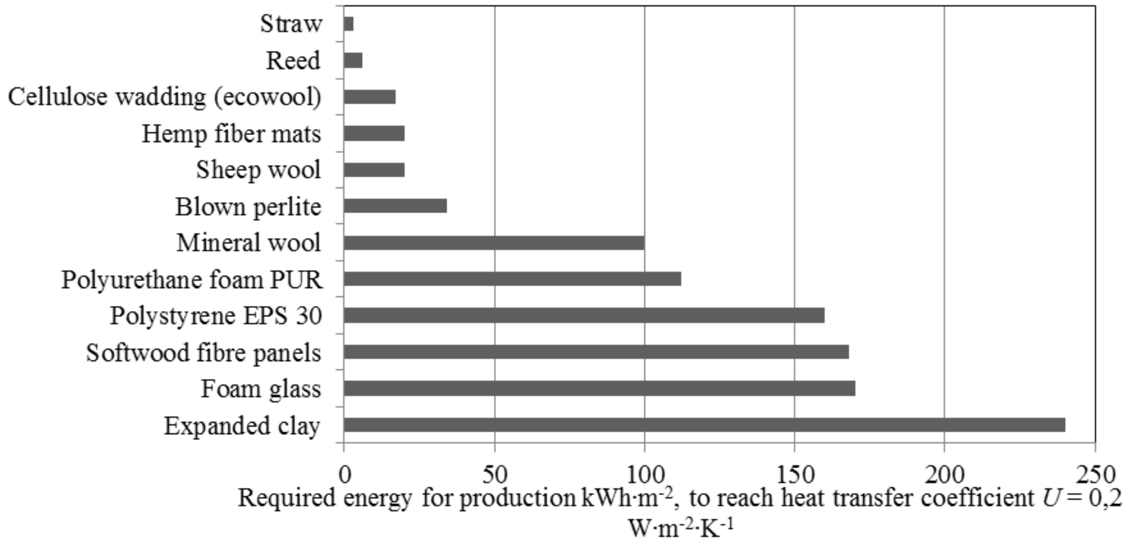

Figure 4. Required energy for material production, when heat transfer coefficient U = 0,2 W·m^{-2}·K^{-1} (Vom..., 2014)

The Numbers Above do not look proper Summarizing the test results of scientific works on pressed straw usage in construction and having compared them with requirements stated in Regulation (EU) No 305/2011 of the European Parliament and the Council (Regulation..., 2011), it can be stated that pressed straw as a natural thermal insulation material can be used for construction of buildings as it passes the Basic requirements.

Straw pressing test

When using pressed straw for building wall thermal insulation it should be properly pressed, so that the wall will be tight and the straw will not settle in the wall. During the pressing test of rye, triticale and oat straw, dependencies between deformations and pressure (Fig. 5, 6, 7), pressure and density (Fig. 8), deformations and density (Fig. 9, 10, 11) were estimated.The test results show that at the beginning of the test compression deformations run faster. The logarithmic equation characterizes this dependency. The dependency between the density and the pressure of different straw states that the highest density are oat straw with 24.1 % of humidity and rye straw with 19.2 % of humidity. It is estimated that in order to get the rye straw density to 120 kg·m^{-3} it is necessary to press them with 30 kPa of pressure. While triticale and oat straw must be pressed with 50 kPa and 55 kPa of pressure, respectively.

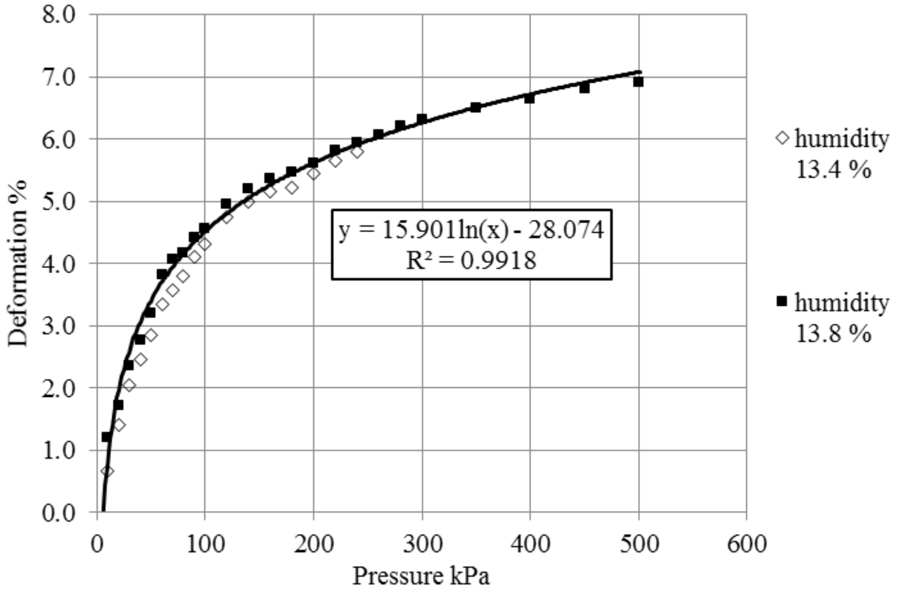

Figure 5. Dependency between deformations and pressure of triticale straw

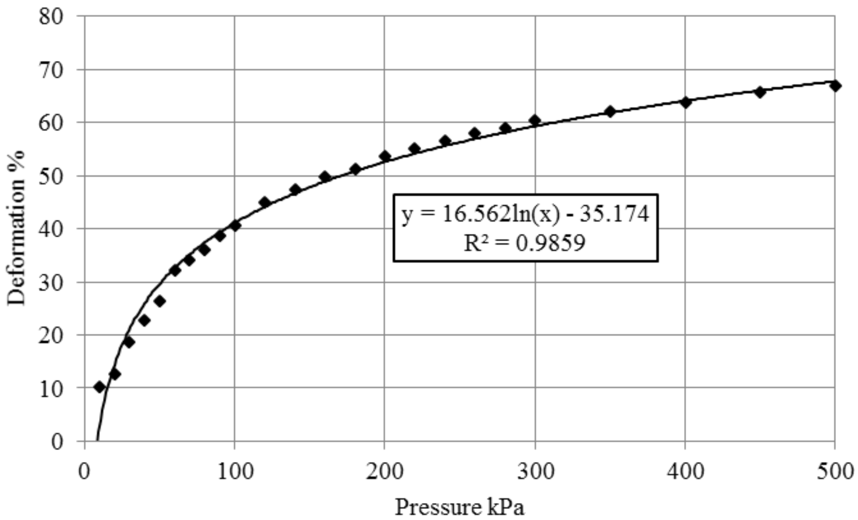

Figure 6. Dependency between deformations and pressure of rye straw

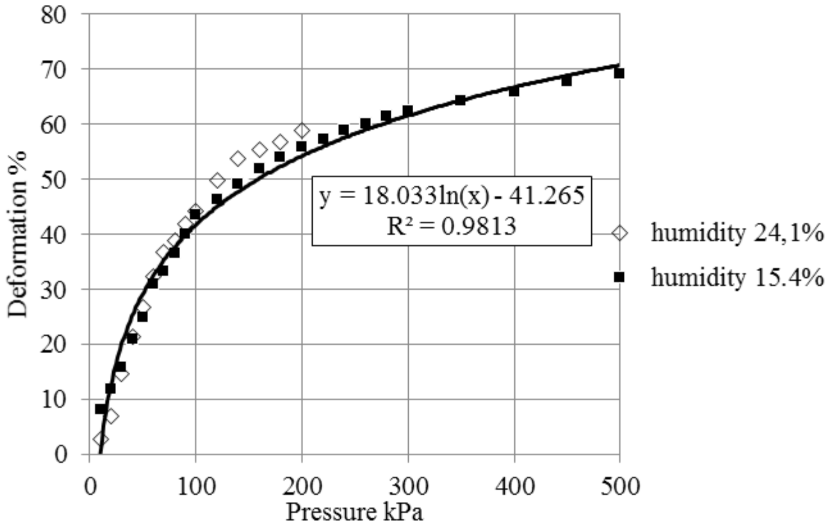

Figure 7. Dependency between deformations and pressure of oat straw

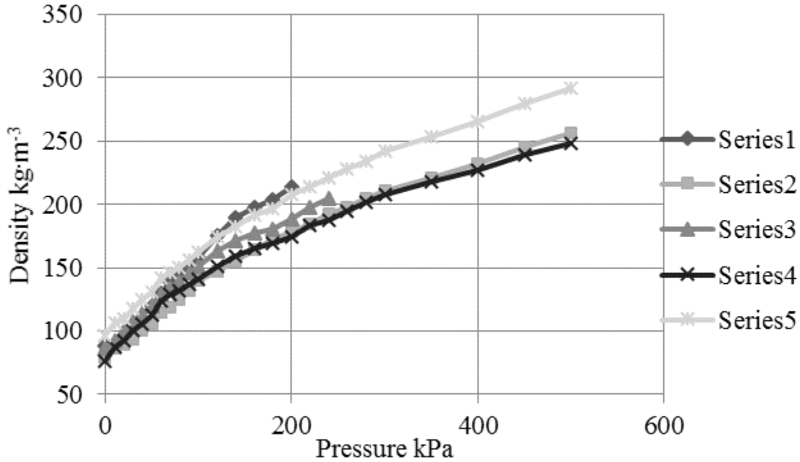

Figure 8. Dependency between density and pressure: 1 and 2 – oat straw, with 24.1 % and 15.4 % of humidity; 3 and 4 – triticale straw, with 13.4 % and 13.8 % of humidity; 5 – rye straw, with 19.2% of humidity

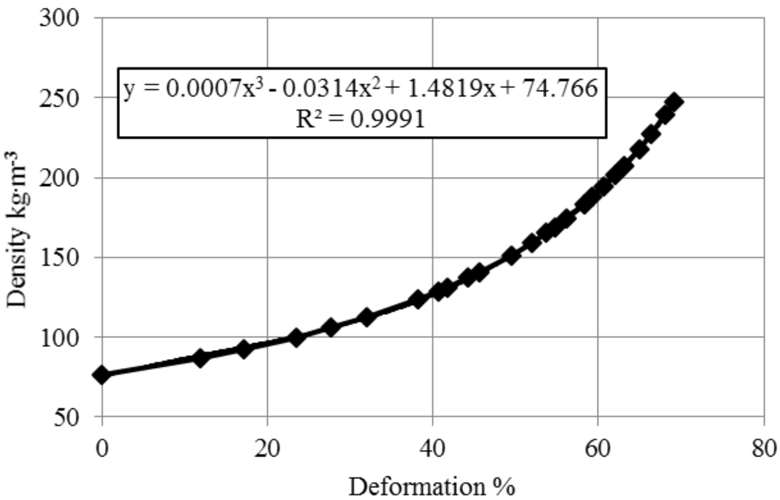

Figure 9. Dependency between compression deformation and density of triticale straw

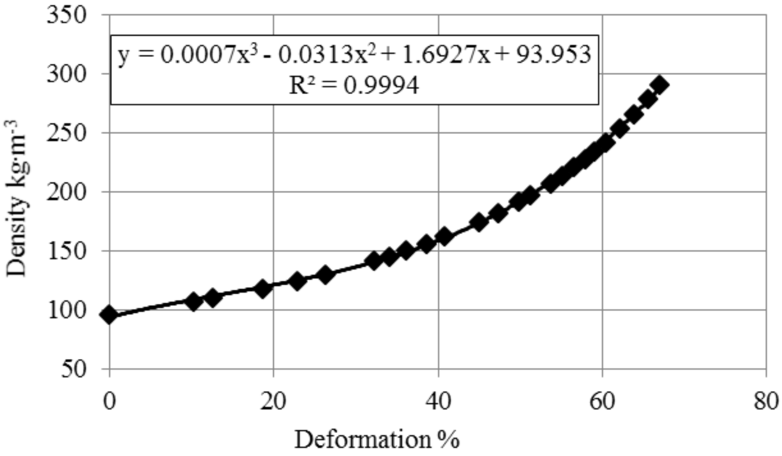

Figure 10. Dependency between compression deformation and density of rye straw

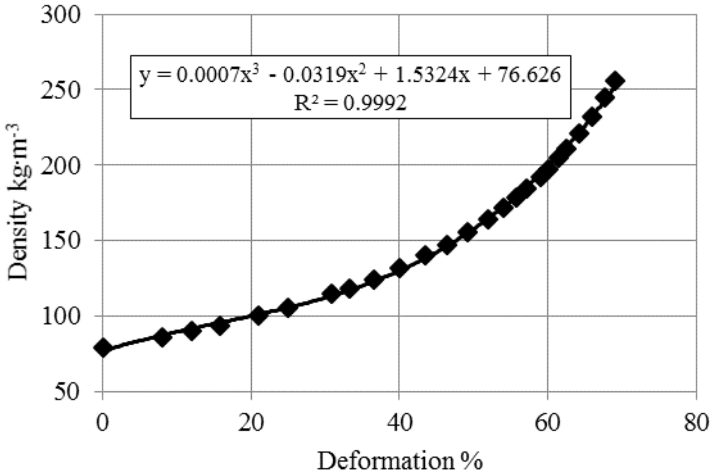

Figure 11. Dependency between compression deformation and density of oat straw

The polynomial equations characterize dependency between deformations and density. According to these equations the required density can be calculated. For example, to get 120 kg·m^{-3} of density triticale and oat straw, the compression deformation must be 35 % and for rye straw – 25 %.

Straw thermal conductivity test

Nowadays, as it was mentioned before, generally straw is used as a thermal insulation material. The thermal conductivity of straw was estimated using shredded 50 mm long and differently pressed triticale straw. The straw was dry and with a particular humidity. The results of the test are given in Table 1.

Table 1

Test results of thermal conductivity

Sample	Air-dry samples			Wet samples		
	Humidity %	Density kg·m^{-3}	Thermal conductivity W·m^{-1}·K^{-1}	Humidity %	Density kg·m^{-3}	Thermal conductivity W·m^{-1}·K^{-1}
1	1-1.5	46	0.048	22.1	57	0.058
2	1-1.5	63	0.048	18.8	79	0.067
3	1-1.5	53	0.046	44.3	91	0.071
4	1-1.5	128	0.048	21.6	151	0.057
5	1-1.5	139	0.049	13.0	209	0.061
6	1-1.5	134	0.053	-	-	-
7	1-1.5	425	0.061	3.6	694	0.081

The test results show that the thermal conductivity of dry straw depends on the density. This tendency is typical for other thermal insulation materials as well. The wet straw had a greater density and thermal conductivity coefficient. The increased humidity by 1 % increases the thermal conductivity coefficient by 0.0005...0.0011 $W \cdot m^{-1} \cdot K^{-1}$. Therefore, the maximum humidity (20 %) of straw increases the thermal conductivity up to 0.01...0.02 $W \cdot m^{-1} \cdot K^{-1}$ or by 19...42 %. It is also can be stated that in the range between 50 and 130 $kg \cdot m^{-3}$ there is a negligible influence of the density of air-dry straw on thermal conductivity. After this range the increasing density of straw weight increases the thermal conductivity.

CONCLUSIONS

Based on the obtained results the following conclusions can be drawn:

1. Wooden frame and shed walls insulated with pressed straw pass the Basic requirements.
2. The pressure of straw depends on the type and humidity of straw. In order to get 120 $kg \cdot m^{-3}$ of density of straw it is necessary to press rye straw with 30 kPa, triticale – with 50 kPa and oat – with 55 kPa of pressure; triticale and oat straw compression deformation must be 35 % and rye – 25 %.
3. Humidity of straw has a negative effect on the thermal conductivity coefficient: increasing humidity increases the value of the thermal conductivity coefficient. The maximum humidity (20 %) of straw increases the thermal conductivity to 0.01...0.02 W·m–1·K–1 or by 19...42 %.

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