BUILDING MATERIALS

HEMP SHIVES REINFORCEMENT INFLUENCE ON THERMAL CONDUCTIVITY AND PHYSICAL-MECHANICAL PROPERTIES OF FOAM GYPSUM

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ABSTRACT

Nowadays when energy reserves in the world are becoming limited, saving fossil energy resources and reducing CO2 emissions have become important issues. These issues are important in the building materials industry and their use in energy saving. The research presents thermal, mechanical and acoustic properties of foam gypsum with hemp shives reinforcement. The thermal conductivity of the material was determined by the company's LASERCOMP gauge FOX200 FOX600, which measures the samples according to ASTM C518-91 and the MBox RF1 equipment. The sound absorption coefficient was measured by the two-microphone method according to the standard ISO 10534-2 and the average sound absorption coefficient in the range of frequencies from 250Hz till 4400Hz was determined according to the standard EN ISO 11654. Bending and pressure parameters were obtained with the equipment Zwick Roell 2.5 TS provided with computer and software Test Xpert V9.01. It was determined that the main factor increasing thermal conductivity and mechanical strength of foam gypsum with hemp reinforcement was the volume density. The mechanical strength and sound absorption properties of the foam gypsum with hemp reinforcement depend on the length of hemp pieces in the composite. The sound absorption coefficient at an equal volume density value is higher for foam gypsum with short hemp reinforcement, but long shives reinforcement increases the foam gypsum absorption coefficient even more than short shives reinforcement. Our research shows that foam gypsum with hemp reinforcement in the range of volume density 250 - 450 kg m-3 can be used as heat and sound insulation material.

Key words: thermal insulation, heat transfer coefficient, foam gypsum, hemp shives reinforcement

INTRODUCTION

Energy saving for the production of housing and building materialsof is an important issue in Latvia and other countries. Huge primary energy consumption and CO2 emissions are characteristic of production of various modern insulation materials. Natural resources have been widely used for the production of building materials in many countries all over the world (Mathur, 2006; Akthar, Evans, 2010). The use of local materials, for example, gypsum in building materials and insulating building constructions, would be a significant contribution to Latvia's national economy. Gypsum is a local resource and its usage in Latvia's national economy is economically advantageous. Foam gypsum is one of the possible gypsum types for which it is possible in a wide range to vary the volume density and also such important parameters of building materials and composites as mechanical properties, sound absorption (Grubliauskas, Butkus, 2009; Laukaitis, Fiks, 2006), heat conductivity (Kymäläinen, Sjöberg, 2008; Skujans, Iljins et al., 2010) etc. Previous research (Skujans, Vulans et al., 2007) on foam gypsum showed that foam gypsum could be similar to other popular thermal and sound insulation materials such as mineral cotton, polystyrene, perlite, clay, etc. Gypsum obtains a high fire-resistance – the fire reactions class A in accordance with the European regulations (Ministry..., 2008). Fragility of the material could be mentioned as a certain disadvantage, which is why reinforcement of the material is needed (Chen, Sucech et al., 2010). Natural fibrous plants growing in the region could be used as a reinforcement. For example, palm plants in southern regions (Bacellar, D'Almeida, 2009) and hemp in Europe (Allin, 2005). Fibrous plants are relatively widely used in building, production of industrial products, in the sphere of vehicle production, agriculture and other fields (Yuanjian, Isaac, 2007). The research on this topic has been developed in Germany, France and Great Britain (Ulme, Freivalde, 2009). A lot of research has been carried out on the improvement of mechanical properties of compositions using different shives (Duval, Bourmaud et al., 2011; Khan, Chen et al., 2010; Khan, Chen et al., 2011; Yuanjian, Isaac, 2007). Nilsson (Nilsson, Gustafsson, 2007) and Duval (Duval, Bourmaud et al., 2011) have carried out research on the influence of shives diameter on their compressive and flexure strength. From the research it was observed that hemp fiber properties are highly dependent on the harvest year. Special attention is paid to the use of fibrous hemp in various sectors of the national economy, especially with the increase of hemp plants in Europe (Kymäläinen, Sjöberg, 2008). Composite material hemp concrete's grey energy is 90 kWh m^{-3} and it is very small by comparing with 430 kWh m^{-3} of normal concrete (Tran, Maalouf et al., 2010). Using cheaper gypsum instead of cement has to provide an economic benefit and increase energy efficiency. So far the usage of various fibrous plants in foam gypsum production as well as the production costs and ecological efficiency has not been evaluated.

The purpose of the research is – using hemp processing residues (hemp shives) to produce building material of foam gypsum composite (foam gypsum modified with hemp shives reinforcement) and determine the physical and mechanical properties of hemp shives and foam gypsum composite.

MATERIALS AND METHODS

Production technology of foam gypsum samples

The foam gypsum samples were produced using the dry mineralization method (Skujans, Vulans et al., 2007), mixing water, gypsum, a surface active substance (SAS) STAMEX F-15 FFFP 5%, and adding hemp reinforcement. As a foam producer the surface active substance is used in fire extinguishers. Foam gypsum binder – β $CaSO_4{\cdot}0.5H_2O$ was used in the experiments. In order to compare the indicators of thermal conductivity and mechanical strength, the former research results with high strength gypsum – α $CaSO_4{\cdot}0.5H_2O$ were used. The concentration of hemp shives used in foam gypsum is the amount of shives in grams per 1 kg dry gypsum binder (c, g kg^{-1}). The hemp shives concentration was varied within the limits of 15÷50 g kg^{-1}. Shive pieces of two lengths were used in the sample production, and they were added to the foam gypsum during its production process. Shives were prepared by chopping them into pieces and sifting in order to get pieces of two different lengths – 2.5÷5.0 mm (hereinafter – short shives) and with a length of 5÷10 mm (hereinafter – long shives). Beams of size 40×40×160 mm were produced from the foam gypsum and used for the bending and pressure resistance testing, pressing the material to the maximum breaking point. Foam gypsum beams for testing in an acoustic tube were processed using a round shape knife and a cylinder type sample with a 40 mm ∅ and a length of 160 mm. In order to obtain the heat transfer coefficient, samples with the dimensions of 300×300×40 mm were made.

Measurements of heat conductivity

The foam gypsum sample's heat conductivity was determined by heat flux method using the company's LASERCOMP measurement instruments FOX200 and FOX600. These instruments were designed according to ASTM C518-91 "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus".

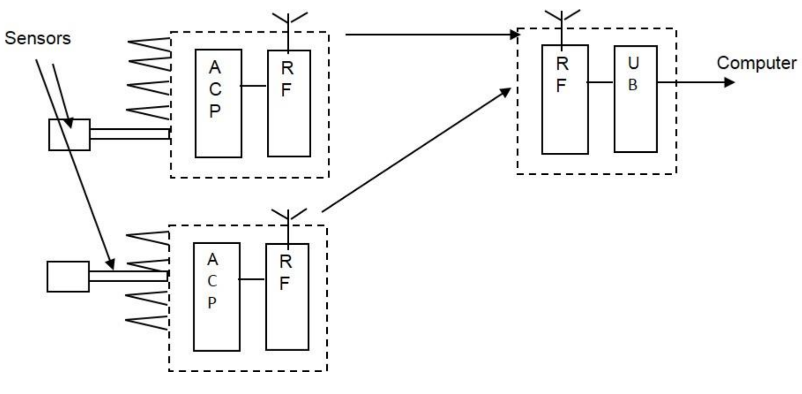


Figure 1. Block scheme of two-canal wireless heat flow and electronic measuring system MBox; ACP – analog-to-digital converter; RF – 2.4 GHz transmitter sending data to receiver module

A part of the thermal conductivity measurements was done with the two-canal wireless heat flow and electronic measuring system MBox RF1, developed at the University of Latvia. The block scheme of the measuring system is shown in Fig. 1. The equipment was used for long term temperature and heat flow measurements with a fixed time step and accumulating the acquired data in the computer. The measuring equipment ensures a total of eight thermo couples and two flow sensors connection to two measurement modules Fig. 1.
A wireless connection data transfer was ensured between the sensor modules and base module which was connected to the computer. The main components of the receiver module were a receiver (RF), which registers the data sent by the sensor modules, and a signal transformer for the computer input, using a USB port. 24 samples of every kind of foam gypsum (with and without shives) were made for heat conductivity measurements. Each sample was measured four times turning it 90 degrees after each measurement and repeating the measurement.

Research methodology of the foam gypsum sound absorption measurements

The sound absorption measurements were carried out using impedance tube (Sinus) by the two microphone method. With the tube it was possible to measure the sound absorption coefficient in the range of frequencies from 250 Hz up to 4000 Hz, when the sound is reflected from the sample. The sound muffle coefficient (α) was determined by the formula:

$$\alpha = \frac{I_{abs}}{I_{fal}} , \tag{1}$$

where:
I_{abs} – intensity of absorbed sound, W m^{-2};
I_{fal} – sound intensity falling on the sample, W m^{-2}.

For all range of frequencies the mean value of the absorption coefficient was determined according to the standard of the European Union (International..., 1997).

30 samples of every kind of foam gypsum (without shives and with short and long shives) were made for sound absorption measurements. Each sample was measured three times.

Foam gypsum bending and compressive strength

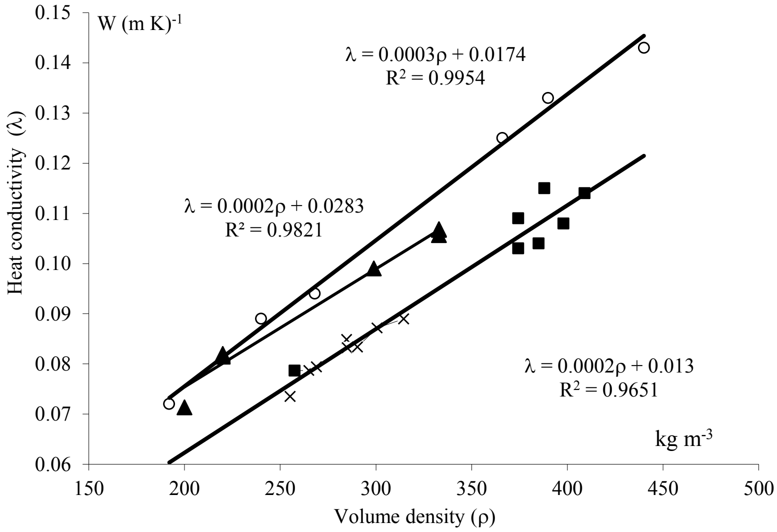
Research on bending and pressure resistance of the composite material (foam gypsum + hemp shives) was carried out using the device Zwick Roell 2.5 TS. The results were processed by the computer programme Test Xpert V9.01. As a result of the research, the maximum bending and pressure stresses of the material were determined depending on the length of the shives and the concentration in the composite. Samples were tested at three points-bending with 100 mm distance between supports. 30 samples of every kind of foam gypsum (with short and long shives) were made for bending strength measurements. Each sample was measured three times. For the pressure resistance measurement, the same samples from the bending strength measurements were divided into halves and used.
The results for bending and pressure resistance, sound absorption and heat conductivity were obtained using a qualitative research method. Processing of the data used an economically mathematical method - multivariated correlation calculation (using software SPSS-15 with $p<0.001$).

RESULTS AND DISCUSSION

By varying the composite production technology (ratio of water, gypsum and surface active substance), it is possible to obtain a foam gypsum of volume density from 250 kg m^{-3} to 1100 kg^{-3} (Skujans, Iljins et al., 2010), which significantly influences the entire foam gypsum and its composite materials' properties. Fig. 3 shows the foam gypsum heat transfer coefficient dependency on the material volume density. The figure shows heat conductivity for two types of foam gypsum. Marking the (Foam (α) alfa gypsum) data were taken from the corresponding publication (Skujans, Vulans et al., 2007) for foam gypsum, which is produced from α calcium sulphate hemihydrates (α $CaSO_4{\cdot}0.5H_2O$). The second series of measurements (Foam (β) beta gypsum) were obtained by the authors with β calcium sulphate hemihydrates (β $CaSO_4{\cdot}0.5H_2O$). At a volume density of 250 – 325 kg m^{-3} the measurements were made using the equipment FOX200, but at a volume density range of 375 – 425 kg m^{-3}, using the equipment MBox RF1 and FOX600. The differences between the measurement series can be explained by the fact that different α and β modification foam gypsum compositions were used. Thermal conductivity for hemp concrete where hemp shives with the density of 413 kg m^{-3} were used for reinforcement obtained by Tran (Tran, Maalouf et al., 2010) is 0.1 W $(m\,K)^{-1}$. For foam gypsum it is a better reason of thermal conductivity of matrix.
After processing the dependencies of the heat transfer coefficient by programme SPSS15, it was established that the volume density of the samples in a process of measurements and the concentration of hemp shives in foam gypsum were statistically significant (p 0.001), and the volume density of the samples to the average heat transfer coefficient value was more important than the concentration of hemp shives in the foam gypsum.

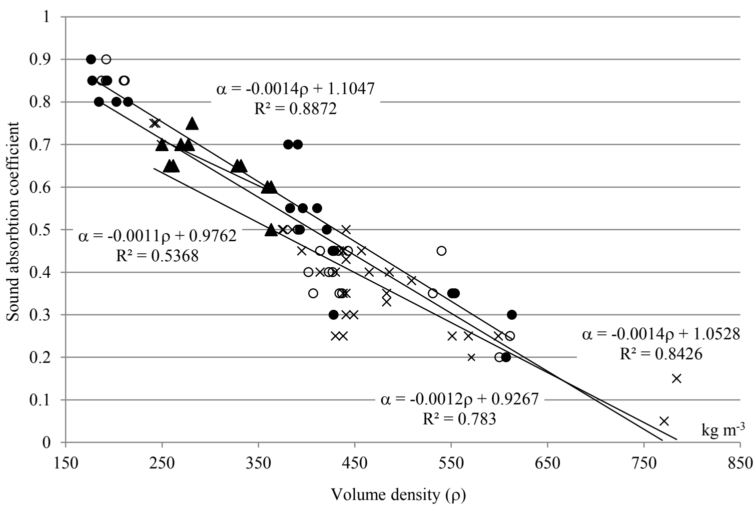
Hemp shives in foam gypsum at the concentration used in the research do not relevantly affect the thermal conductivity Fig. 2. It does not correspond to the hemp concrete investigations by Arnaud (Arnaud & Gourlay, 2012), where Thermal conductivity is between 0.6 W (m K)$^{-1}$and 0.12 W m K)$^{-1}$ depending on the mix formulation. For this phenomenon the authors have the opinion that thermal conductivity of foam gypsum matrix is better than cement paste matrix and for that reason cement paste matrix needs less hemp additives to change thermal conductivity.

The common sound absorption coefficient α tendency depending on the volume density is that α increases if the foam gypsum volume density decreases (Skujans, Iljins et al., 2010).



○ - Foam alfa gypsum (Skujans, Vulans et al., 2007), ■ - Foam β- Fogypsum, × - Foam β gypsum with hemp, ▲ - Alfa foam gypsum

Figure 2. Foam gypsum thermal conductivity dependence on the volume density. The data marked with (Foam α gypsum) have been taken from the corresponding publication (Skujans, Vulans et al., 2007) for foam gypsum, produced from α calcium sulphate hemihydrate (α $CaSO_4 \cdot 0.5H_2O$).
The second series of measurements (Foam β gypsum) were obtained by the authors with β calcium sulphate hemihydrate (β $CaSO_4 \cdot 0.5H_2O$)



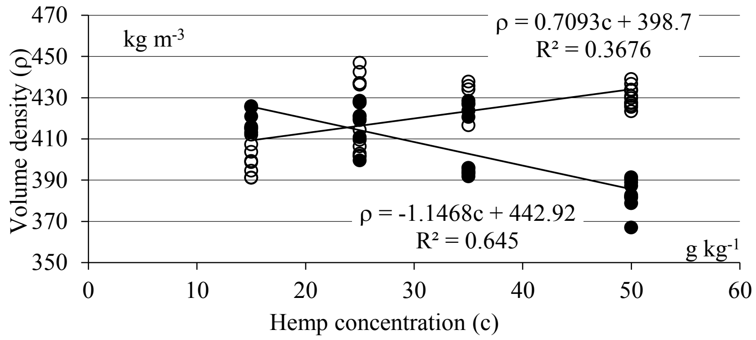
○ - Short shives, ● - Long shives, × - Without shives (Beta foam gypsum), ▲ - Alfa foam gypsum

Figure 3. The value of sound absorption depending on the volume density

This tendency has been observed also when modifying foam gypsum with hemp reinforcement. It is possible to obtain a better sound absorption coefficient of the α material at equal foam gypsum volume density (Fig. 3). This index is better for the foam gypsum with long shives. The foam gypsum sound absorption coefficient with short shives is higher compared to the composition without shives, but lower compared to the foam gypsum with the long shives at equal volume density value.

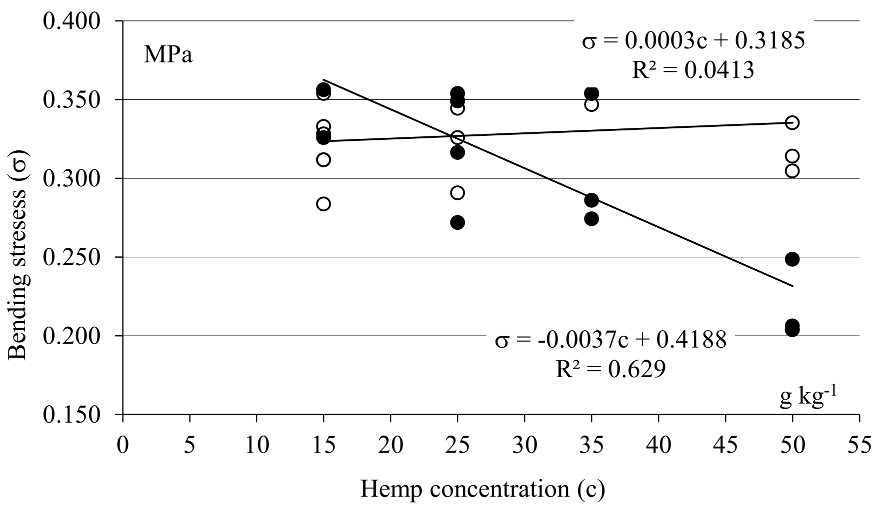
When the material is compared with hemp concrete developed by Gle (Gle, Gourdon et al., 2011) it has been established that the increase in hemp concentration increases sound absorption coefficient, but this material has a different binder.

The sound absorption coefficient within the limits of 0.75 – 0.30 is equal to the European standard (EN ISO 11654:1997) C, D class requirements (International..., 1997), and that is why the foam gypsum with hemp reinforcement within the volume density value of 250 – 450 kg m^{-3} can be used as a sound absorbing material.
In order to specify the shives' length and quantity impact on mechanical properties within the volume density value of 380 – 550 kg m^{-3}, samples with two types of hemp shives with lengths 2.5÷5 mm and 5÷10 mm were produced. Increasing short shives' concentration in the foam gypsum, its volume density value increases, but this coherence is opposite when producing foam gypsum with long shives' reinforcement (Figure 4).



○ - Short shives, ● - Long shives

Figure 4. The volume density of the composite material depending on long and short shives

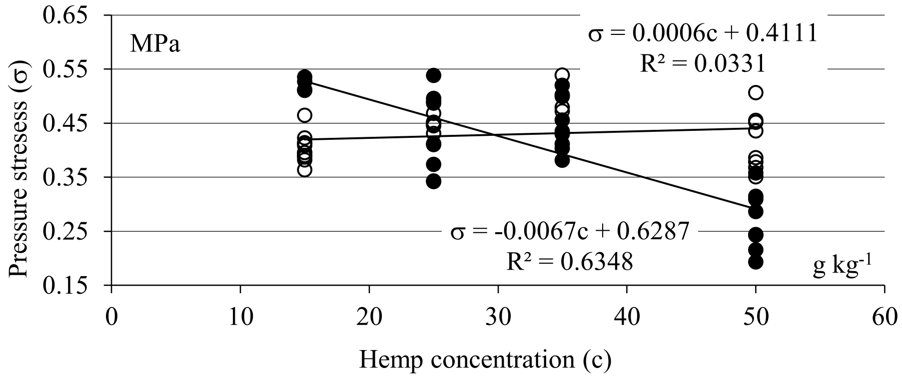


○ - Short shives, ● - Long shives

Figure 5. The value of bending stress in the composite material depending on concentration of long and short shives

Figure 5 reflects the bending stress of samples with long and short shives. Increasing short shives' concentration, the bending stress prevalently increases. Increasing long shives' concentration, the bending stress decreases. This coherence correlates with the volume density influence on material strength (Fig. 4), where increasing short shives concentration, the volume density increases, but in the foam gypsum with long shives the volume density value decreases.

For comparison, bending resistance of foam gypsum with gypsum β $CaSO_4{\cdot}0.5H_2O$ at ρ=400 kg m^{-3} equals to 0.30 MPa, and pressure resistance of 0.45 MPa. Using the composition with hemp shives of 35 g kg^{-1} equals to a bending resistance of 0.35 MPa, but a pressure resistance of 0.45 MPa. Using high strength foam gypsum α $CaSO_4{\cdot}0.5H_2O$ this bending measurement is proportionately at 0.90 MPa and pressure 1.15 MPa. Using hemp shive (1÷10 mm long) reinforcement with fibres content 7 % (in our investigations from 1.5÷5.0 %) in hemp concrete bending test results was 5.0 MPa (Sedan, Pagnoux et al., 2008). Lower compressive results are for lime-hemp concrete where using hemp shives with volume density 98 kg m^{-3} and hemp binder ratio 0.22÷0.33 (in our case 0.015÷0.05) composite with compressive strength from 0.22÷0.55 MPa was obtained (Bruijn, Jeppsson, et al., 2009). Higher results are obtained because of stronger matrix used in composite of concrete.



○ - Short shives, ● - Long shives

Figure 6. The value of pressure stress in the composite material depending on concentration of long and short shives

A similar bending stress is observed in research on pressure strength Fig. 6. By increasing hemp reinforcement concentration the pressure strength of the foam gypsum with short shives increases, but the pressure strength of the foam gypsum with long shives decreases. It correlates with Arnaud and Gourlay (Arnaud & Gourlay, 2012) researches where short hemp shives (average length 3.1 mm) are recommended to use in lighter concretes whose mechanical properties evolve more slowly due to reduction of macropores size but finally have higher modulus and compressive strength.

Investigating thermal conductivity dependence on volume density Fig. 2, the authors are of the opinion that one of the main foam gypsum components – the gypsum binding material, which makes walls of pores, leaves a significant effect on the coefficient of heat conductivity. As α and β foam gypsum binding materials differ in crystal structure and volume density, 2760 kg m^{-3} α gypsum and 2630 kg m^{-3} β gypsum (Vorobjev, 1983) (in our research 2670 kg m^{-3} α gypsum and 2550 kg m^{-3} β gypsum), then using α gypsum at the same volume density we obtain an increased strength together with increased thermal conductivity.

Foam gypsum and hemp shives reinforcement volume density dependence on shives concentration Fig. 3 is still an unclear and disputable issue. It is possible that hemp shives influence the growth of pores in foam gypsum, and the foam gypsum volume density value is changed when modified with hemp shives. The issue of hemp shives and foam gypsum structure correlation will be developed by further research on pore structure in foam gypsum modified with hemp shives. Differences in the sound absorption coefficient for the samples with hemp shives and without them at equal volume density value, is still an unanswered issue. It is possibly connected with the fact that hemp shives have the ability to transfer sound waves deeper into the material, thus increasing the sound absorption ability.

CONCLUSIONS

1. Foam gypsum reinforced by hemp shives at the volume density of 250 – 350 kg m^{-3} can be used as a heat insulation material λ=0.07-0.10 W (m·K)$^{-1}$.
2. Foam gypsum with hemp reinforcement of the volume density within 250 – 450 kg m^{-3} by its acoustic qualities corresponds to the standard EN ISO 11654:1997 C, D level requirements, and it can be used as a sound absorbing material.
3. The sound absorption coefficient at equal volume density value is higher for foam gypsum with short

hemp reinforcement, but long shives reinforcement increases the foam gypsum absorption coefficient α more than short shives reinforcement.

4. Increasing the concentration of short piece (2.5÷5.0 mm) shives reinforcement in the foam gypsum increases its volume density, but decreases the volume density for the foam gypsum with long piece (5÷10 mm) shives. The change of the volume density, in its turn, determines the bending and pressure stresses.

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