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Laboratory research of granulated heat insulation material from coniferous forestry residue

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Abstract. The purpose of this research paper is to determine the heat conductivity of a granular heat insulation material made of coniferous greenery (fine twigs and needles), and the suitability of the material for application as heat insulation. In order to achieve the objective, a three-factor experiment plan was developed, and 11 samples produced. The thermal conductivity coefficient, moisture content, and density of the samples was determined. A full analysis of the experiment plan was compiled on the basis of the obtained results. The analysis results suggest that size composition, density, and tree species affect the thermal conductivity of the material. It was discovered that smaller spruce greenery insulation material pellets have a smaller thermal conductivity coefficient, which indicates a better capacity for retaining heat.

Key words: needles, coniferous, heat insulation, forestry residue.

INTRODUCTION

Bioeconomy has turned a new page in the development of using and evaluating biomass. It is important to find the right applications with the greatest added value (European Commission strategy, 2012). One of the fields where this can be done is increasing the energy efficiency of buildings. The question of the thermal insulation of buildings and development of innovative heat insulation materials as well as their introduction into everyday use is becoming more and more topical. It is essential for sustainably-minded people to have natural materials in their home, and for these materials to have minimal influence on climate change and cause the least possible harm to the environment and human health throughout their life cycle.

The environmental impact of a product during its full life cycle, including the production stage, can be reduced by using cleaner production strategies (Blumberga, 2010). A cleaner production strategy includes using resources sustainably, and striving towards non-waste production. This can be achieved if by-products or residues are integrated into the production processes where new products are made from by-products or residues. Using by-products or residues would reduce the consumption of new raw materials. This principle can be used for biomass resources. Therefore, raw materials and energy sources, their total volumes and impact on the environment are taken into account in the process of inventing new products so that after the industrial product is developed, its impact and unnecessary resource consumption are kept to a minimum (Haggar, 2007).

In Latvia, forests take up more than 51% of the total land area. Forest massifs are dominated by coniferous trees (54% of the total forest area) (NFI data, 2012). Forests, and coniferous trees in particular, are the largest natural resource in Latvia. As such, the resource is widely used in different industries and exported abroad (CSB Database, 2013). Despite the importance of this resource and the large cutting volumes, forest residues are still not properly used; neither are small branches. At the moment, the only industrial use of coniferous needles in Latvia is the production of coniferous extract. The maximal amount of needles utilized for extract production is 800 t per year (Pollution permit, 2010). Consequently, thousands of tons of coniferous greenery (fine softwood branches with needles) are left to decompose at the clearings. Taking into account the work volumes of the forestry section in the Baltic States, it would be technically possible to obtain about 700 thousand tons of coniferous greenery (needles and small branches) (Muizniece & Blumberga, 2015). Therefore, it is worth finding an economically and environmentally sound solution for the sustainable use of this biomass resource.

Consequentially, authors of this paper propose an innovative idea for the production of an ecological heat insulation material using the needles and small branches of coniferous trees (greenery). The proposed idea combines both the rational use of coniferous logging residue, and the production of an ecological heat insulation material, which is friendly to the environment and human health throughout its life cycle, while respecting the principles of cleaner production.

So far, there are no scientific publications with information on an insulation material that is produced from needles or coniferous greenery. There is no information on the physical or mechanical properties of such a material. In previous studies (Muizniece et al., 2015) the thermal conductivity coefficient of this heat insulation material in the form of plates made of coniferous greenery has been determined to be $\lambda = 0.056$ W (m K)$^{-1}$, and the thermal conductivity coefficient of freely poured pine needles was identified to be $\lambda = 0.037$ W (m K)$^{-1}$. These values are similar to natural heat insulation materials already widely used in the market. For example, wood fibre panels ($\lambda = 0.045$ W (m K)$^{-1}$), cork panels ($\lambda = 0.043$ W (m K)$^{-1}$), hemp fibre panels ($\lambda = 0.041$ W (m K)$^{-1}$), coconut fibres ($\lambda = 0.045$ W (m K)$^{-1}$) (Ingrao et. al., 2014), flax fibres ($\lambda = 0.045$ W (m K)$^{-1}$) (Kymalainen & Syoberg, 2008) and cotton stalk fibres ($\lambda = 0.059$ W (m K)$^{-1}$) (Zhou et. al., 2010). Previous studies have revealed that freely poured pine and spruce needles have different thermal conductivity coefficients. This is explained by the difference in the dimensions of air gaps between the needles (Muizniece et al., 2015). There are no studies on the influence of the species of coniferous trees used for the production of the material on the thermal conductivity of the material in case it is produced from milled greenery. Such a study could determine whether the species of coniferous trees or their proportions in the greenery should be considered in producing heat insulation materials. However, there are several issues that should be studied. The most important of them is poor adhesion (without additional binding substances) of the heat insulation material in the form of plates, which limits its transportation, usage and dimensions. The decomposition and formation of fine dust fractures was observed in the case of freely poured coniferous needles. The fine fracture is denser and, therefore, has a lower capacity for retaining heat. As a solution for preventing this problem, it has been proposed to produce poured granular heat insulation materials from coniferous tree greenery. A three-factor experiment plan was developed, and the experiments were performed in order to determine the efficiency of such a material, as well as its properties and the factors influencing it.

MATERIALS AND METHODS

Experiments were planned carefully before the production and testing of the granular coniferous greenery heat insulation material – this allowed to determine the proportion and extent of the influence posed by selected factors in a more efficient manner, providing the best results. The thermal conductivity coefficient, the main indicator describing the efficiency of heat insulation materials, was selected for expressing the results of this experiment.

The thermal conductivity coefficient of a heat insulation material can be influenced by material bulk density, porosity, density, moisture content and other properties of the material (Popovs, 1990). Only three factors associated with the production of the granular coniferous needle heat insulation material that can directly or indirectly influence the thermal conductivity of the material were selected for the experiment. These factors are: granule size (granulometry), tree species (spruce or pine) used, and whether or not the material is washed and re-dried before the measurements.

Particles of milled greenery are not so fine that it would be possible to create very small granules. This must be taken into account when producing a granular heat insulation material from milled coniferous needle greenery. Also, smaller-sized granules would crumble faster. Therefore, the minimal value for this factor was set at 3–8 mm (fine granules) and maximal value at 16 mm (large granules).

Previous experiments showed (Muizniece, 2014) that granules produced from milled conifer greenery and potato starch do not disintegrate after being soaked and kept in water for a few hours. After re-drying, their mass decreases but volume and shape stay the same. This indicates that water washes out fine particles, while the material becomes lighter and more porous. Porosity is a very important factor that influences thermal conductivity. Light and porous materials retain heat better. Therefore, the third factor examined is whether the granules are washed and re-dried or not washed. First, the thermal conductivity coefficients were determined for coniferous pellets that had not been washed. The pellet samples were rinsed as follows: samples were soaked in clean water for 2 hours and occasionally lightly stirred, water was decanted and the samples were dried again. The processed samples underwent repeated heat flow measurements, and their thermal conductivity coefficients were determined.

Table 1. The experimental plan with factor values of the granular coniferous greenery heat insulation material

Factors	Sample No.								
	1	2	3	4	5	6	7	8	9,10,11
Size composition, mm	<8	>16	<8	<8	>16	<8	>16	>16	8–16
Species (pine or spruce)	pine	spruce	pine	spruce	spruce	spruce	pine	pine	mix 1/1
Washed or unwashed	unwashed	washed	washed	washed	unwashed	unwashed	washed	unwashed	mix 1/1

During the experiment, the maximal and minimal values of factors were varied in a number of ways, thus testing all possible combinations for a certain number of factors, see Table 1.

In total, 11 samples were made (Fig. 1), from which three were made with the average factor values. First, fresh (water content at least 50%) coniferous greenery mass was milled with a milling machine (PM120 Vibrotehnik), then sieved with a sieve (mesh size 10 mm), then processed repeatedly with a fine sieve (mesh size 3 mm). The ground greenery mass was then manually mixed with a binder made from water and potato starch (1:10). The prepared mass was forced through an appropriate mesh (depending on the required granule size), then processed in the analytical screeners (Retsch analysensieb AS400) for 3–6 min, where the mass was rolled into spherical or elliptical granules. Granules were dried in a thin layer in a drawer-type drying stove (BMT ECOCELL) at 105°C for about 24 h. Once the pellets were dried, heat flow measurements were performed with the heat flow sensor Hukesflux DT01 in order to determine the thermal conductivity coefficient. Heat flow measurements were performed according to the standard method ISO 9869 Thermal insulation – Building elements – In-situ measurements of thermal resistance and thermal transmittance (ISO standard, 2014).

Figure 1. Samples of coniferous greenery granules (sample No. 1 on the left and sample No. 8 on the right).

Heat flow measurements were performed with a heat flow meter consisting of four thermocouples and two heat flow sensors. Parallel to measuring the samples, one pair of thermocouples and a heat flow sensor were attached to a reference surface with a known thermal conductivity coefficient for measurement reliability and accuracy control. In this experiment, the reference surface was extruded polystyrene with the theoretical conductivity coefficient value of $\lambda_{teor.}$ = 0.035 W (m K)$^{-1}$. The sample – freely poured coniferous granules – was placed in a vertical position between two 3 mm thick corrugated cardboard sheets with $\lambda_{teor.}$ = 0.18 W (m K)$^{-1}$. The experimental stand was placed in a closed chamber to avoid the influence of ambient conditions (wind and sun). Heat flow measurements were carried out at the average warm temperature (hereinafter warm environment) of +26 °C and at the average cold temperature (hereinafter cold environment) of -4 °C, the temperature range being 30 °C. Each of the samples was measured 3 times to verify the accuracy of results and obtain the average value of the thermal conductivity coefficient. Since freely poured coniferous granules were placed between sheets of corrugated cardboard, it was necessary to deduct its impact on the results.

In order to determine whether the obtained thermal conductivity results were reliable, measurement error was calculated for each result using the data processing program Statgraphics. The coefficient was $\tau_{95} = 1.412$ with the confidence probability of 95% in case of 3 measurements. If the proportion of the sum of differences between each measurement and the arithmetical mean compared to the standard deviation is smaller than τ_{95}, all measurements can be considered reliable. Regression analysis was performed to determine the correlation between the thermal conductivity coefficient and the selected experimental factors, i.e., density and moisture content.

Even though the granules were dried, they absorbed some moisture from air before and during the measurements. So the thermal conductivity was determined for an air-dry material. Therefore, moisture content, as it was at the time of the measurements, was determined (according to the standard method LVS EN 14774-2:2010) for all samples to identify the moisture content to which the certain thermal conductivity coefficients corresponded. Material density can also have an influence on thermal conductivity, so the average density of each freely poured coniferous needle granule sample was determined (according to the standard method LVS EN 15103:2010).

Insulation material samples were made out of coniferous (spruce and pine) forest residue granules. Small branches with needles were harvested in the 2014/2015 winter (felled forests). The median time period from the collection of coniferous forest residues to the production of insulation material samples was 1 month. The average moisture content for the raw material was 50%. The necessary materials for sample making were collected only from forest residues, not from growing trees (this will be also tried if industrial production is proved to be viable). Thus, the cleaner production principle was observed – the residues of another process were used as a raw material.

RESULTS AND DISCUSSION

The mean thermal conductivity coefficients of the granules, sample moisture content and density are summarized in Table 2. As you can see from the obtained results, the thermal conductivity of the samples is in the range of 0.0452 W $(m K)^{-1}$ to 0.0916 W $(m K)^{-1}$. Fine (<8 mm) washed and repeatedly dried spruce needle granules have the lowest thermal conductivity. The highest thermal conductivity was observed in case of large (>16 mm) unwashed pine needle granules. Granule size has a significant influence on the thermal conductivity of bulk heat insulation materials because the volume of the air gaps between the granules depends on granule size. The larger the air gaps, the higher the thermal conductivity coefficient of the material. Consequentially, smaller-sized granules retain heat better.

The calculation of measurement error at a given confidence probability of 95% (coefficient τ_{95}= 1.412) showed that all the measurement results are reliable.

Table 2. Raw data and obtained thermal conductivity coefficients for coniferous forest residue granules

Sample No.	Thermal conductivity coefficient, W (m K)$^{-1}$	Moisture content, wt%, d	Density, kg m^{-3}	Size composition, mm	Species	Washed or unwashed
1	0.0674	5.24	205	<8	pine	unwashed
2	0.0767	4.63	175	>16	spruce	washed
3	0.0578	7.22	188	<8	pine	washed
4	0.0452	3.53	170	<8	spruce	washed
5	0.0821	5.89	192	>16	spruce	unwashed
6	0.0630	2.92	185	<8	spruce	unwashed
7	0.0637	5.27	208	>16	pine	washed
8	0.0916	9.68	225	>16	pine	unwashed
9	0.0654	6.64	203	8–16	0.5 spruce / 0.5 pine	0.5 washed / 0.5 unwashed
10	0.0666	6.64	205	8–16	0.5 spruce / 0.5 pine	0.5 washed / 0.5 unwashed
11	0.0687	6.64	205	8–16	0.5 spruce / 0.5 pine	0.5 washed / 0.5 unwashed

Regression analysis proved that a material's density has a significant influence on thermal conductivity. This was also observed in the experiment with insulation granules made of needles. As you can see in Fig. 2, less dense freely poured needle granules have a better (lover) thermal conductivity coefficient.

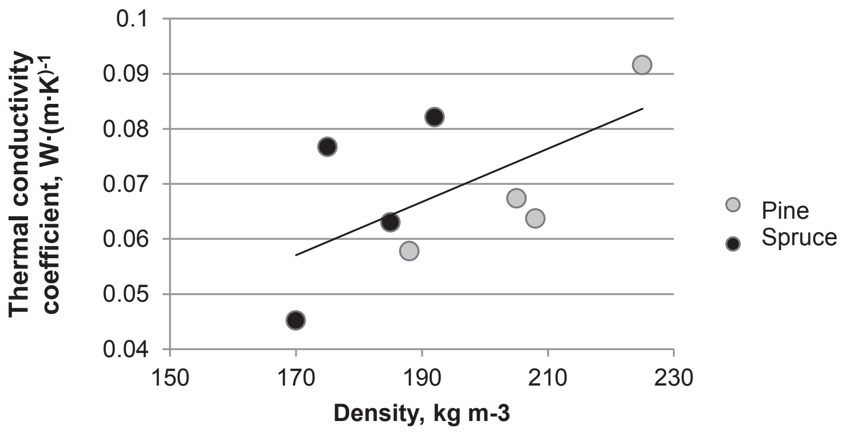

Figure 2. Correlation between thermal conductivity and the density of the material samples No.1–8.

This is demonstrated by the correlation coefficient, in this case 0.602, which indicates a strong causal link between the thermal conductivity coefficient and density. The fewer air gaps there remain between coniferous granules in the material, the better it retains warmth.

As it was mentioned before, the density of the sample material can influence the accuracy of determining the thermal conductivity coefficient. This was also observed in the performed experiment (Fig. 3) in case of the correlation coefficient 0.630, which indicates to a correlation between these two values.

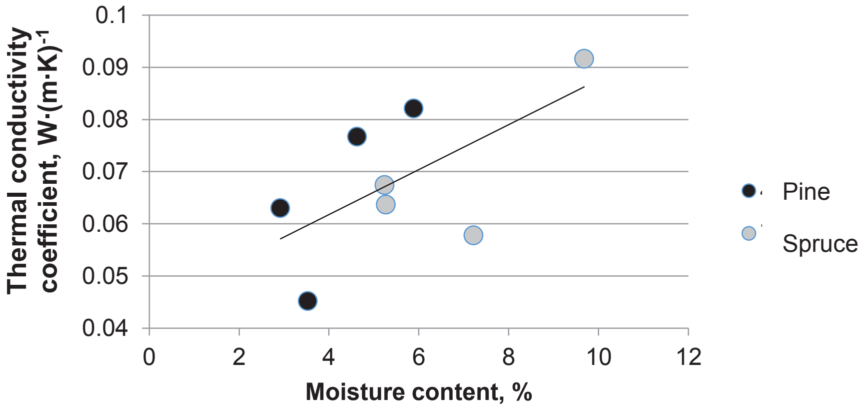

Figure 3. The dependence of thermal conductivity on the moisture content of material samples No. 1–8.

A strong correlation between the thermal conductivity coefficient and sample moisture content was observed during this experiment. In practice, the impact of the moisture content cannot be this high because the samples had low moisture content values (3–10%).

A regression analysis for the thermal conductivity coefficient and pellet size reveals a close relationship between the coefficient of thermal conductivity and bulk density of coniferous granules. A strong correlation was observed in this case, the correlation coefficient being 0.737.

The obtained results prove that the second experimental factor – species of coniferous tree – also affects thermal conductivity. Granules produced only from spruce greenery had better thermal conductivity coefficients than other materials of the same size, notwithstanding whether the granules were washed or not washed. However, regression analysis showed that this effect is very weak, as evidenced by the correlation coefficient of -0.123.

The results showed that rewashed granules had better thermal conductivity coefficients (0.554) in all cases, suggesting a moderate impact. Washing the granules had an impact on the thermal conductivity coefficient because the granule mass, and, therefore, the bulk density of granules, decreased. Mass, density and thermal conductivity changes due to sample washing are summarised in Table 3.

Washing leads to a significant decrease in granular mass – an average of 15.5% – which, in turn, decreases the density of bulk granules about 7.6–8.9% (8.2% on average). The reduction of the thermal conductivity coefficient is different for each sample, and it is not proportional to the decrease in mass and density. The highest thermal conductivity coefficient reduction was observed for large pine pellets, which had the highest coefficient of thermal conductivity.

Table 3. Mass, density and thermal conductivity changes (%) in granules as a result of washing

Sample	Difference in density, %	Mass difference, %	Difference in thermal conductivity, %
Fine pine granules (3)	8.3	-18.4	-14.2
Large pine granules (7)	7.6	-15.3	-30.5
Large spruce granules (2)	8.9	-11.5	-6.6
Fine spruce granules (4)	8.1	-16.8	-28.3
Average:	8.2	-15.5	-19.9

A full analysis of the experimental design was carried out to express pre-established correlations in the form of a single linear regression equation. Not all three factors studied in this experiment are expressed in numerical values. Therefore, in the second step (species) and the third step (washed and re-dried or un-washed granules) of calculations, the factors were given the maximal value of 1 and minimal value of 0 (spruce – 1, pine – 0, washed – 1, unwashed – 0). For the first factor, the minimal numerical value is 8 and the maximal is 16. The full regression equation after its simplification with the natural values of thermal conductivity coefficient λ (W (m K)$^{-1}$) can be expressed as follows:

$$\lambda = 0.06844 + 0.00252(g - 12) - 0.01518(sn - 0.5) + 0.00384(g - 12)(ep - 0.5)(sn - 0.5) \quad (1)$$

where: g is size composition (mm); sn is washed or unwashed material; ep is species (spruce or pine).

The experiment and analysis of the obtained data show that the thermal conductivity coefficient of granules produced from coniferous tree greenery is significantly influenced by the size of the granules (size composition), and whether the granules are washed or unwashed. The second factor (species of trees) also influences the thermal conductivity coefficient. Material made from fine (< 8mm) washed spruce greenery had the best thermal conductivity coefficient (λ_4 = 0.0452 W (m K)$^{-1}$). We can conclude that in order to make good heat insulation material from needles, its size composition must be up to 8 mm and it is preferable to use spruce greenery. The material must also be washed and re-dried.

Several significant problems were discovered during the experiment. The most significant of them is forming chunks of fine granules; the essence of the problem is in the separation of fine particles rather than the disintegration of the granules themselves. It is possible that the granules would decompose completely with time. To avoid this problem, it is necessary to use stronger adhesive materials. In order to maintain the safety of the material to the environment, the new adhesive should be of natural origin and safe to the environment and human health throughout the product life cycle. The combustibility of the material is the second biggest problem. This can be solved by adding antipyrine. Additional studies are required in order to find solutions to address the brittleness of the granular coniferous greenery heat insulation material.

Scientific literature offers information about the physical properties of the different types of granular insulation materials, although information is not as extensive as in the case of board-type insulation materials. The production of granular insulation materials from vegetable raw materials is relatively rare but there is information on granular insulation materials produced from waste, most often glass. If it would be possible to avoid the crumbling of the natural granular insulation material, and if it would retain its physical properties, such granular insulation materials would already exist. The properties of some of them have been compared with the results of this study (see Fig. 4). As it can be seen, there are granulated insulating materials that have a much lower thermal conductivity coefficient, such as silicon-aerogel granulate and foam glass granules. However, the coniferous granular insulation material tested in this study has a lower thermal conductivity than the most widely known granular insulation material: expanded clay granules. Further research is needed to study the properties of this granular material.

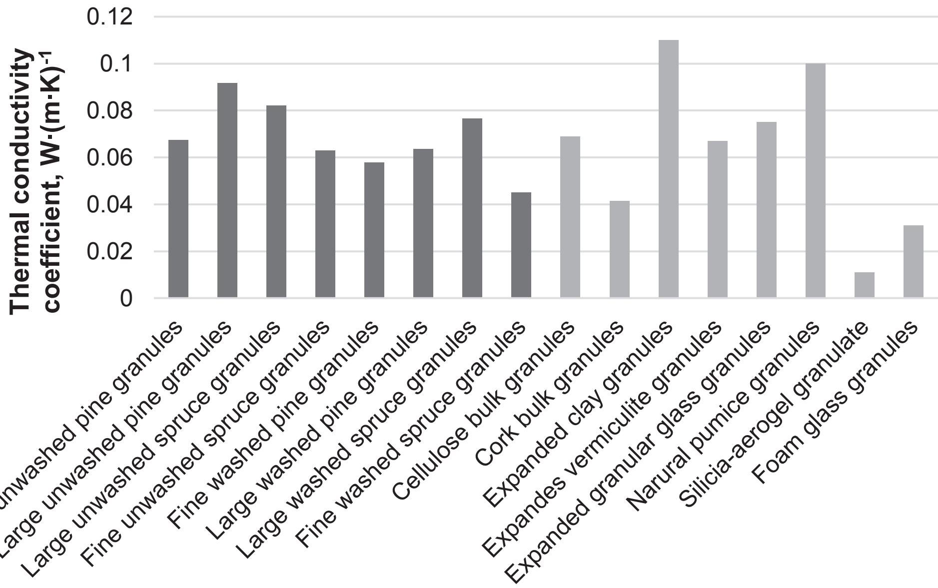

Figure 4. Comparison of the thermal conductivity coefficients of coniferous needle granules and other natural granulated heat insulation materials (Ayadi et al., 2009; Reim et al., 2004; Ingrao et al., 2014).

CONCLUSIONS

Thermal conductivity coefficients of granular coniferous greenery insulation materials and the factors influencing this indicator were studied by implementing a three-factor experimental plan.

The experiment showed that the thermal conductivity of freely poured heat insulation materials depends on the size of granules and whether or not the raw material is washed and re-dried (therefore reducing its density).

The thermal conductivity coefficient of the material made from fine (< 8 mm) washed spruce greenery granules (λ_4 = 0.0452 W (m K)$^{-1}$) is equivalent to existing and already widely used natural heat insulation materials. If solutions are found to prevent the disintegration of the granules and to reduce their combustibility while maintaining environmental safety throughout the life cycle in future studies, the physical properties of the material would be more advantageous in comparison to the heat insulation materials already on the market.

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