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WASTE MANAGEMENT IN THE CONTEXT OF THE DEVELOPMENT OF SUSTAINABLE THERMAL INSULATION PRODUCTS FOR THE CONSTRUCTION SECTOR

Andreea HEGYI[1], Cezar BULACU[2], Henriette SZILAGYI[1], Adrian-Victor LĂZĂRESCU[1,3,*], Dumitru Eugen COLBU[4], Mihaela SANDU[5]

[1] NIRD URBAN-INCERC Sucursala Cluj-Napoca, 117 Calea Florești, Cluj-Napoca, 400524, Romania
[2] MINET SA, 12 Depozitelor Street, Rm. Vâlcea, 240426, Romania
[3] Technical University of Cluj-Napoca, 15 Constantin Daicoviciu Street, Cluj-Napoca, 400020, Romania
[4] Faculty of Geography and Geology, Doctoral School of Geosciences, Alexandru Ioan Cuza University of Iasi, 700506, Romania
[5] NIRD URBAN-INCERC, 266 Șos. Pantelimon, Bucharest, Romania, 021652

Abstract

The current global situation requires the efficient management of waste and the assessment of the potential for the implementation of the principles of the circular economy in order to conserve natural resources and reduce the negative impact on the environment. The aim of the research is to analyze the potential of non-woven products (mattresses) made of recycled polymer fibers, intended for use in the field of thermal insulation of buildings, in relation to their density and thickness. At the same time, the benefits obtained by combining them with products based on recycled waste and sheep wool were evaluated. The experimental results indicated good performance in terms of thermal conductivity coefficient and heat transfer resistance of the analyzed products, which can be successfully included in the category of heat-insulating materials. The correlation of thermal performance with the thickness and density of the products highlighted the need to deepen the analysis, these two parameters being insufficient for the design of such material. However, by combining mattresses made of recycled polymer fibers with mattresses made of recycled denim fibers and / or sheep wool, the benefits in terms of thermal insulation performance are obvious.

Keywords*: Plastic waste recycling; Thermal insulation; Natural resource preservation; Energy consumption reduction; Environmental protection*

Introduction

Huge amounts of plastics are consumed worldwide every year, mostly in the food packaging area – for example, in 2011 alone, a statistic from 27 EU states showed that, on average, each citizen generated around 159kg of waste from polymeric plastic packaging every year [1].

Globally, the requirement and production of plastics is increasing. As a result, huge amounts of waste are generated with a negative impact on water and land, considerable volumes of greenhouse gases are emitted, and non-renewable resources of raw materials and energy are consumed. According to Waste Directive 2008/98/EC, the objectives of waste management policies must aim at reducing the potential for waste generation, reducing resource consumption

* Corresponding author: adrian.lazarescu@incerc-cluj.ro

and making recycling more efficient, with regard to waste as a potential resource of new products with beneficial impacts on the environment and the health of the population. The most common waste plastics of polymer type are: polyethylene terephthalate (PET), polypropylene (PP), general use polystyrene (PS), polyvinyl chloride (PVC). Their recycling successfully responds not only to the need for quantitative reduction of polymer waste but also to obtain new products with low emission generation (Figs. 1, 2 and 3), and with the sustainable use of reserves of non-renewable raw materials and energy, it is known that current recycling technologies are able to provide quality-appropriate material [1, 2], largely used for fiber production - in 2016, 64% of all fiber production was synthetic fibers [3].

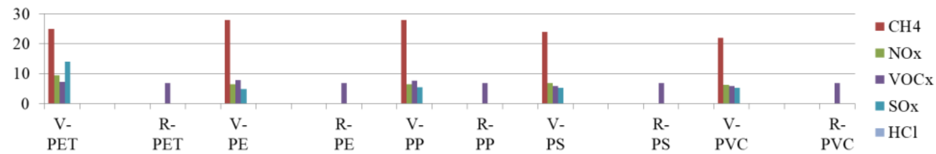


Fig. 1. Comparative analysis of pollutant emissions [1]

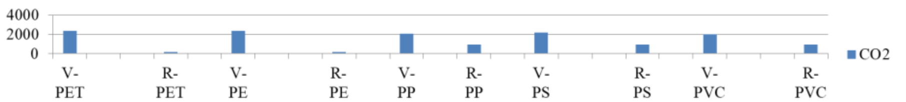


Fig. 2. Comparative analysis of CO_2 emissions [1]

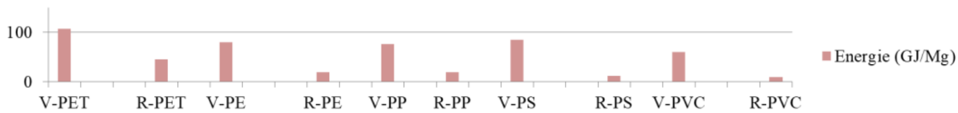


Fig. 3. Comparative analysis of energy consumption [1]

Polyethylene terephthalate is a material of great interest in the field of materials in general and, by implication, also in the field of building materials because it is 100% recyclable, the only material that is easier to recycle is aluminum. The cost of recycled polyethylene terephthalate (R-PET) is 20-60% lower than the cost of polyethylene terephthalate produced from Virgin raw material (V-PET), and the reduction in energy consumption is 50-70% and the consumption of petroleum raw materials is 50-60% [2, 4-7]. Worldwide, the main use of R-PET is in fibre production, accounting for more than 70% of the total polyethylene terephthalate fibre produced [4, 8].

At the same time, around 5.8 million tonnes of textile waste are produced annually at EU level, of which only 25% are put into recycling and reuse processes, although the possibility of recycling is of 95% [3, 9, 10]. One of the possibilities of recycling is the transformation into fibers which, although not entirely corresponding to reuse in the area of the textile industry, can successfully become raw material in the sector of nonwoven materials for thermal insulation in the construction industry. The results of the research carried out to date [11, 12] have shown that recycled textiles have competitive thermal properties, thermal conductivity and thermal diffusivity and can be used as an alternative to commercial heat-insulating materials (extruded polystyrene or mineral wool) in the construction sector. According to reports from the literature [13, 14] curently the influence of the density of the product, the thermal insulation achieved by recycling of waste textiles, the coefficient of thermal conductivity are known, indicating a non-linear variation, identifying a range of densities for which the performance of thermal insulation are higher, in general (recycled textile waste mats having a low heat transfer coefficient around the value of 0,033W/mK).

Another insufficiently exploited source of raw materials, which often becomes dumped or burned waste, is sheep wool. According to research, the advantages of sheep wool mattresses are: natural thermo and phono insulating materials, easily renewable, recyclable, with a low impact on the environment and on people's health, they retain their shape and volume due to the genetic structure of the wires that tend to always return to their original shape, produces a recation that removes volatile organic compounds, they have a reversible hygroscopic character (under normal humidity absorbs water vapor, its humidity reaching 15...18% water vapor, and in conditions of increased humidity up to saturation, its humidity can reach up to 40%), exhibit a very good fire behavior, do not maintain combustion, have the ability to store energy at high temperatures and yield it at low temperatures [15-20]. Moreover, they are cheap materials. The raw material from which heat - insulating mattresses are produced is that coarse part of sheep wool that is not used in the textile industry - the main processing industry. Thus, the price of waste wool is less than 0.3$/kg of unwashed wool waste in the USA [8], respectively, about 1$/kg of ready-to-use washed wool in Romania. In addition, natural animal yarns can be combined with synthetic fibres from non-recyclable polyester waste to reduce environmental pollution [8] when producing them.

On the other hand, in Europe, around 30% of CO_2 emissions and 36% of total greenhouse gases are a direct or indirect consequence of the construction sector [21, 22]. At EU level it is estimated that 40% of energy consumption is due to public / private sector buildings [21, 23]. Therefore, it is essential to involve and prioritize the energy renovation of buildings, both for increasing indoor comfort and for reducing energy consumption and environmental impact (40% of total energy consumption, 36% of total CO_2 emissions, 25-30% of total waste generated) [13]. The analysis on the identification of the general requirements regarding the use of heat-insulating materials for construction revealed that in general, depending on their nature, heat–insulating materials are characterized by a coefficient of thermal conductivity, λ, with values ranging from 0.024-0.07W/mK. The thermal performance of insulation made of homogeneous, single or combined materials is usually evaluated by the following parameters: thermal conductivity, thermal transmittance, thermal diffusivity, specific heat and heat transfer resistance. At European and global level, thermal insulation of buildings is now a key element without which energy efficient design and construction can no longer be a question.

Studies have demonstrated the possibility of using polymer fibers from recycled materials for the purpose of heat-insulating non-woven materials for the construction sector, thus identifying the potential for conservation of natural resources and reducing environmental impact. In the case of mattress made of polypropylene (PP) and polyethylene terephthalate (PET), the thermal conductivity increases with the increase of the density, for the same thickness of the product, the heat-insulating non-woven fabric, the low density provides the potential for heat insulation, but for mechanical strength reasons, the density has to be controlled, taking into account the fact that the value of a density of 60kg/m^3, the heat transfer by convection becomes dominant and the thermal insulation performance decreases significantly [24-27]. Based on research, the quantifiable TIV indicator (Thermal Insulating Value) was identified, which indicates the efficiency as a thermal insulator of a product, depending on the coefficient of thermal conductivity of the material, the thickness of the product and the thermal emission performance of the surface. For heat-insulating products made of PET, the TIV coefficient varies between 41.21% and 52.15% for thicknesses in the range of

3.54 – 7.97mm and for heat - insulating products made of PP this coefficient ranges from 41.95% – 51.98% for thicknesses of 3.76 - 5.70mm, increasing with thickness increase [24-27].

The aim of this paper is to present experimental results regarding the coefficient of thermal conductivity, respectively the thermal resistance (important parameters for determining the thermal insulating character of a material) of non-woven products (mattresses) made of recycled polymer material fibers, intended for use in the field of thermal insulation of buildings, in relation to their density and thickness. At the same time, the benefits obtained by combining these analyzed materials, recycled plastic fibers, with recycled waste and sheep wool are evaluated.

Experimental

Materials

The heat-insulating materials tested were 11 mattress variants made of recycled polymer fibers, 1 type of mattress made of recycled denim fibers and 1 type of mattress made of sheep wool, presented and characterized by a nominal thickness (designed) according to Table 1. All these variants of mattresses were made by carding technology, with the addition of 20-25% bicomponent Bico polyester fibers. The addition of two-component fibers in the non-woven matrix was motivated by their good heat-sealing performance, so that conditions of dimensional stability, shape and structure of the product are achieved and maintained. The heat-insulating mattresses subjected to testing are coded as follows: Ax-B, where A represents the type of fibers (P - recycled plastics, d-recycled denim, W-sheep wool), x represents the number of type in the family of belonging and B - the percentage amount of Bico bicomponent fibers introduced through the manufacturing process into the non-woven matrix.

Table 1. Codificarea și grosimea nominală a saltelelor termoizolatoare

Code	Addition of two-component polyester fibres (%)	Nominal thinckness (mm)
P1-25	25	15±3
P2-25	25	45±3
P3-25	25	50±3
P4-25	25	55±3
P5-25	25	60±3
P6-25	25	70±3
P7-25	25	80±3
P1-20	20	30±3
P2-20	20	40±3
P3-20	20	45±3
P4-20	20	50±3
D1-20	20	20±3
W1-25	25	20±3

Methods

The selected analysis techniques are based on their suitability for the characterization of heat-insulating materials. Therefore, standardized, specific analysis methods were used according to EN 823:2013 for thickness determination, EN 1602:2013 for density determination and EN 12667:2002 for determination of thermal conductivity coefficient and heat transfer resistance. All tests were performed under laboratory conditions, at a temperature of 23±2ºC and relative air humidity 60±5%.

The thickness of the non-woven mattress type product was determined on samples with dimensions of 300x300mm, by direct measurement, under conditions of application of a compression force of 0.02kPa, according to EN 823: 2013.

The density of the material was determined on specimens with dimensions of 300×300mm, by referring the mass to the volume, according to EN 1602:2013.

The thermal performance of the individual specimens was determined by the hot plate method according to EN 12667:2002, using specimens with dimensions of 300×300mm. They were tested using a FOX 314 type conductivimeter at a temperature difference of 10ºC between the turntables, after having previously been dried at constant mass. Thus, the coefficient of thermal conductivity, $\lambda_{10,ct}$. and thermal resistance, R were recorded.

Subsequently, the thermal resistance in the field was calculated for the simulated cases of products made by overlapping 2 or 3 of the types of non-woven thermal insulation materials tested, according to the method specified by the standards in force.

Results and discussion

The results obtained experimentally for products of type heat-insulating mattress, made of recycled polymer material fibers, recycled denim fibers or sheep's wool, are shown in Figures 4 and 5 and in Table 2.

Table 2. Physico-thermal characteristics of heat-insulating mattresses

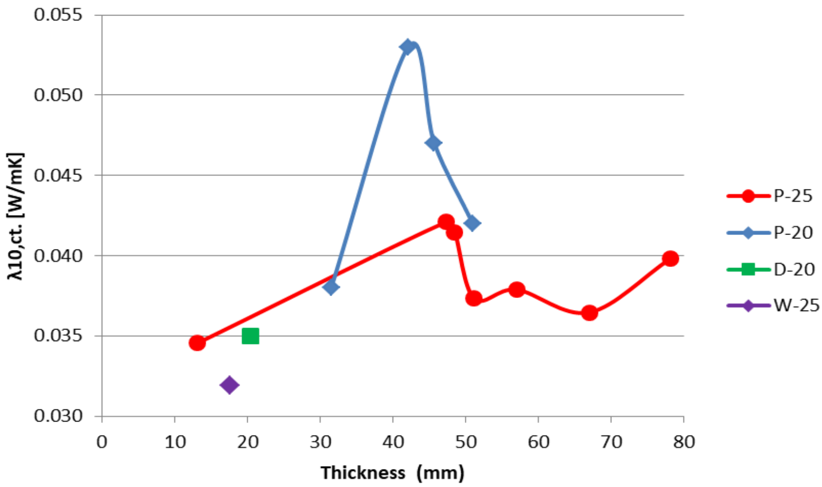
Code	Thickness (mm)	Density (kg/m^3)	Thermal conductivity coefficient, $\lambda_{10,ct.}$ (W/mK)	Thermal resistance, R (m^2K/W)
P1-25	13.08	60.9	0.035	0.38
P2-25	47.32	15.2	0.042	1.12
P3-25	48.52	15.8	0.041	1.17
P4-25	51.16	25.1	0.037	1.37
P5-25	57.00	27.7	0.038	1.45
P6-25	67.00	23.3	0.036	1.84
P7-25	78.18	18.8	0.040	1.96
P1-20	31.50	31.4	0.038	0.83
P2-20	42.10	10.6	0.053	0.79
P3-20	45.70	12.5	0.047	0.97
P4-20	51.00	19.7	0.042	1.21
D1-20	20.40	47.9	0.035	0.58
W1-25	17.61	44.5	0.032	0.55

As seen in Table 2, heat-insulating mattresses from recycled denim fibres and sheep wool of comparable thickness were selected for testing, if a parallel is to be drawn to the specifications of the literature indicating that the thermal resistance increases with increasing thickness, but a thickness difference of up to 9mm does not induce significant changes on the thermal insulation properties of a material [28-31].

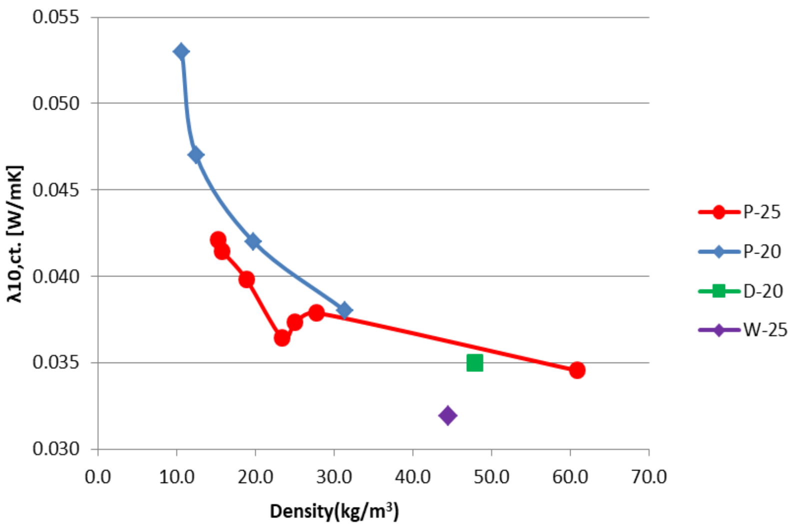
In the case of samples made from recycled polymer fibres, a nonlinear variation in the coefficient of thermal conductivity and thermal resistance is observed, depending on the thickness of the specimen or the density of the material, regardless of whether the samples were made with the addition of 20% or 25% bicomponent fibres. However, it can be said that in general two areas of influence can be identified. Thus, for the coefficient of thermal conductivity recorded, which is desirable to be as low as possible, values were recorded at least equal to 0.040W/mK for samples with low densities, even if the thickness of the product is large (See sample P7-25), the maximum being reached by the sample with the lowest density, P2-20.

Values of the coefficient of thermal conductivity of 0.035-0.38W/mK shall be recorded for specimens of higher density, respectively, a minimum of 23.3kg/m^3.

From the point of view of thermal resistance, a parameter that is desirable to be as high as possible, a generalized trend of increase is observed with the increase in the thickness of the specimen and a non-linear evolution, again with two trend zones, if the analysis is done according to density. Thus, for samples produced from recycled polymer fibers with 20% addition of bicomponent fibers, the maximum thermal resistance is recorded in the case of the sample with the largest thickness and an intermediate density, P4-20. In the case of samples produced from recycled polymer fibres with 25% added two-component fibres, this maximum thermal resistance shall be recorded for the sample with the highest thickness and relatively low density, below 20kg/m^3, P7-25.

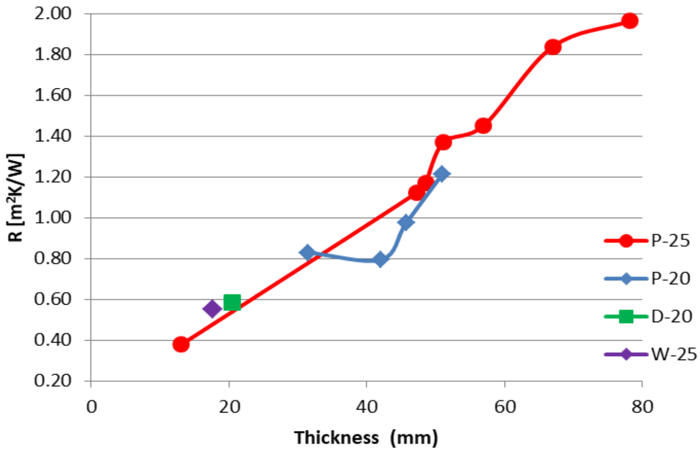


a)

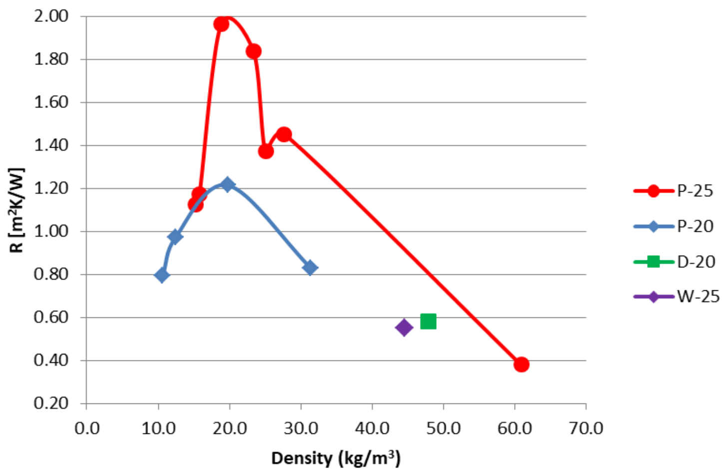


b)

Fig. 4. Variation of the thermal conductivity coefficient depending on: a) thickness and b) density



a)



b)

Fig. 5. Variation of the thermal resistance depending on: a) thickness and b) density

Considering that from the point of view of thermal insulation efficiency a low thermal conductivity and increased thermal resistance is desirable, it can be said that only on the basis of thickness and density control, one cannot identify a mathematical rule that would give the possibility to design an optimal insulating material. This can be explained on the basis of the difficult to control structure of the material, structure that includes fibers, arranged relatively orderly and air volumes between these fibers, and the thermal transfer is carried out by three mechanisms: conduction, convection and radiation. The thermal conductivity of a porous material, as in the case of non-woven heat-insulating products, is the sum of the characteristic air conduction from the pores, convection conduction, fiber conduction, radiation conduction and the interaction between air and fibers [32].

However, given the trend at European and global level, which shows that over time the thickness of the insulating material has continuously increased, both in the case of thermal insulation of walls and roofs [18], the possibility of increasing thermal insulation efficiency by overlapping two or even three different layers of thermal insulation products has been analyzed, since each type of material has advantages and disadvantages:

- thermal insulation products based on polymer fibers have the advantage of increased resistance to biological agents and do not have high water absorption;
- thermal insulation products based on denim fibers have the advantage of mechanical stability;
- heat-insulating products based on sheep wool have the advantage of increased permeability, energy storage/disposal capacity, absorption of harmful substances from the air (formaldehyde) and storage of water in the form of vapors, yielding it when needed to regral the humidity of the indoor air.

Thus, layered heat-insulating products were simulated, in which the nature of each layer is different in terms of the type of fibers that compose it. The results of this simulation, where two layers are superimposed, are shown in Figure 6. The evaluation of the benefits from the point of view of thermal insulation efficiency is shown in Figure 7.

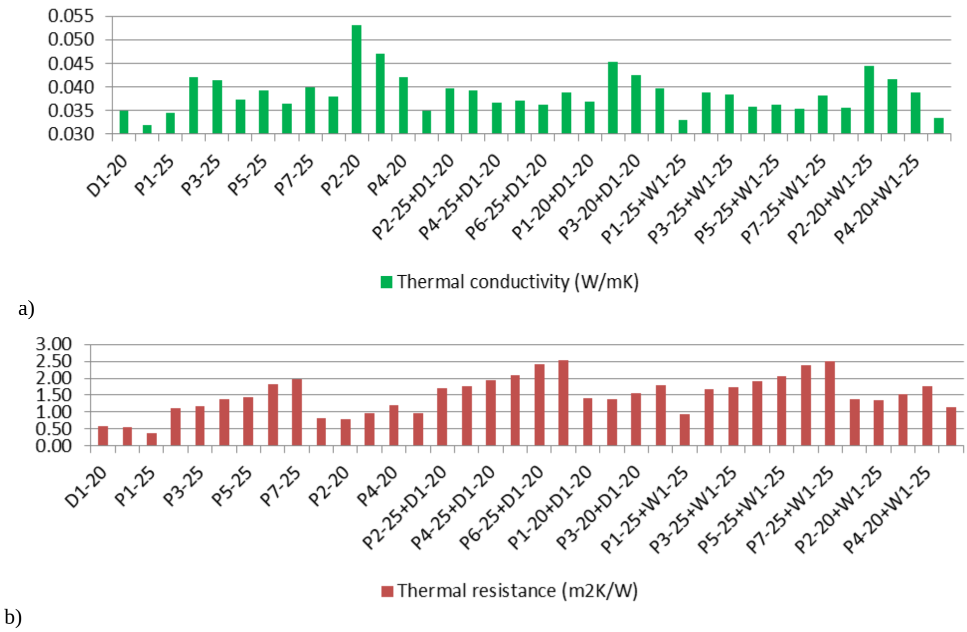


Fig. 6. Variation of the thermal conductivity coefficient by overlapping two layers of heat-insulating products of different nature (a) and variation of thermal resistance by overlapping two layers of heat-insulating products of different nature (b)

According to Figure 6, it can be said that it is not easy, nor obvious to demonstrate the efficiency of thermal insulation capacity by overlapping. There is a decreasing trend in the coefficient of thermal conductivity, an increasing trend in thermal resistance, but, all this under the conditions that the thickness of new products is greater, respectively, is equal to the sum of the thickness of the individual insulating layers.

Therefore, it was considered much more useful to analyze the percentage variation of thermal resistance and coefficient of thermal conductivity in relation to these characteristic parameters for the recycled polymer mattress used, also taking into account the increase in thickness (Fig. 7).

It is observed according to Figure 7 that the thermal performance does not vary proprotionally with the variation of thickness. There are cases of substantial increase in thickness for which the benefits of reducing thermal conductivity are very small (P1-25+D1-20) or good but unspectacular (P1-25+W1-25). There are also cases where, although the increase in thickness is within average limits (30-40%), the benefit in terms of the decrease in the heat transfer coefficient is obvious, above 10% (P2-20+D1-20, P2-20+W1-25, P3-20+W1-25). On the other hand, the thermal resistance is strongly influenced by the increase in thickness. This parameter increases as the thickness increases; in all cases the percentage increase in thermal resistance is greater than the percentage increase in thickness. This trend is an indicator that confirms the further analysis of this hypothesis of the benefit of thermal insulation by overlapping layers of heat-insulating materials of different nature.

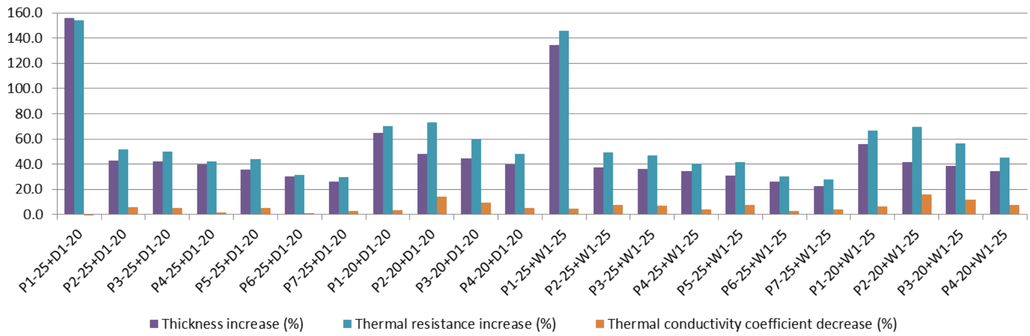


Fig. 7. Evaluation of the thermal insulation benefits obtained by overlapping two layers of thermal insulation material

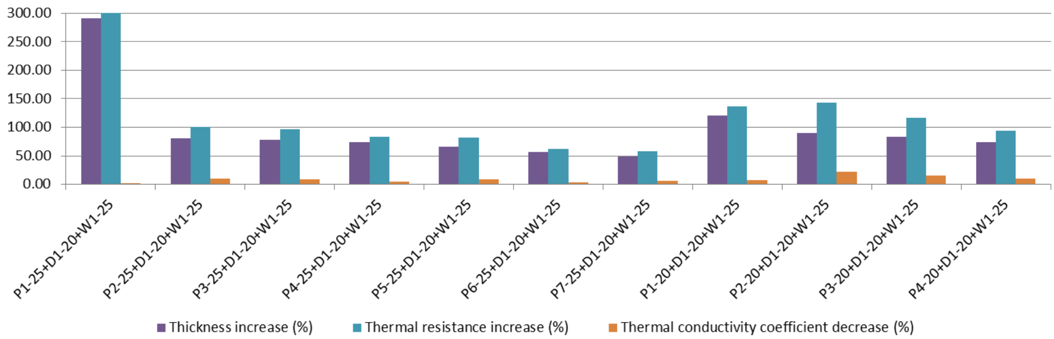


Fig. 8. Evaluation of the thermal insulation benefits obtained by overlaying three layers of thermal insulation material

Analyzing the case in which three layers of different nature are superimposed within the same heat-insulating product (Fig. 8), it can be said that in general, the benefits are substantial and obvious. There are, however, two situations in which, although the thickness is to be increased by more than 100%, even 200%, the decrease in the thermal conductivity coefficient is less than 10%, respectively, for 2.28%, for the case of P1-25+D-1-20+W1-25 (where the thickness has increased by 290%), or 6.86% for the case of P1-20+D-1-20+W1-25 (where the thickness has increased by 120%). Therefore, for obtaining a low thermal conductivity coefficient, a large thickness of the product is not enough; this parameter is obviously influenced by other physical / structural characteristics. For all other analyzed cases, it is observed that, although the thickness increase percentage-wise with the lower values of the 95%, the thermal conductivity coefficient is reduced in a worst-case scenario, a 3% (sample P6-25+D-1-20+W1-25, which increase in thickness is less than 60%), and in the most favorable, 21% (sample P2-20+D-1-20+W1-25, which increase in thickness is 90%). From the point of view of thermal resistance, substantial increases are observed, even 2-3 times compared to the thermal resistance of the single product based on recycled polymer used in the composition of the structure. Also, the increasing trend of thermal resistance is similar, but more pronounced, compared to the increasing trend of thickness. In other words, the more the thickness of the layered product increases, the more its thermal resistance increases, and there is no case where the percentage increase in thermal resistance is less than the percentage increase in thickness. This trend can be assimilated to a positive cost-benefit ratio, where the benefits of thermal insulation are supposed to be assessed against the “costs” imposed by the use of a thicker product.

Conclusions

Based on those presented, it can be said that non-woven materials made from waste fibers of recycled polymer plastics, recycled denim fibers and sheep wool correspond in terms of thermal conductivity coefficient and thermal resistance in order to be used as heat-insulating materials.

Each of the three types of material analyzed, by their structure and nature, has advantages and disadvantages. However, the research carried out has highlighted both their performance in terms of thermal insulation and the benefits that can be obtained through their combined use. The correlation of thermal performance with the thickness and density of the products highlighted the need to deepen the analysis, these two parameters being insufficient for the design of such material. However, by combining mattresses produced with recycled polymer fibers with mattresses produced with recycled denim fibers and / or sheep wool, the benefits in terms of thermal insulation performance are obvious.

As a result, waste plastics of polymer type, textile fibers, in this case, denim, as well as sheep wool are sustainable sources of raw material that can contribute to the conservation of natural resuses and reduce the negative impact on the environment, thus:

- reducing the consumption of non-renewable natural raw materials for the manufacture of heat-insulating material by recycling waste;
- reducing the consumption of natural resources for energy production, by optimizing the energy efficiency of buildings;
- reduction of environmental pollution as a result of waste storage or burning;
- reduction of environmental pollution as a result of technological processes for the manufacture of new heat-insulating products.

Acknowledgments

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References

[1] S. Patachia, M. Tierean, L. Baltes, **Direcţii noi în proiectarea compozitelor pe bază de poliolefine în vederea creşterii eficienţei de reciclare**, POSDRU/159/1.5/S/134378, 2018.

[2] C.C. Lin, *Recycling Technology of Polyethy1ene Terephthalate Materials,* **Macromolecular Symposia, 135,** 1998, pp. 129-135.
[3] D.G.K. Dissanayake, D.U. Weerasinghe, K.A.P. Wijesinghe, K.M.D.M.P. Kalpage, *Developing a compression moulded thermal insulation panel using postindustrial textile waste,* **Waste Management, 79**, 2018, pp. 356-361.
[4] V. Sinha, M.R. Patel, J.V. Patel, *Pet Waste Management by Chemical Recycling: A Review,* **Journal of Polymers and the Environment, 18,** 2010, pp. 8-25.
[5] L. Bartolome, M. Imran, G.C. Bong, W.A. Al-Masry, D.H. Kim, **Recent Developments in the Chemical Recycling of PET**, InTech. 2019, pp. 65-84.
[6] D.S. Achilias, G.P. Karayannidis, *The chemical recycling of PET in the framework of sustainabile development,* **Water, Air, and Soil Pollution: Focus, 4,** 2004, pp. 385-396.
[7] P. Santos, S.H. Pezzin, *Mechanical properties of polypropylene reinforced with recycled-pet fibres,* **Journal of Materials Processing Technology, 143–144,** 2003, pp. 517-520.
[8] A. Patnaik, M. Mvubu, S. Muniyasamy, A. Botha, R. D. Anandjiwala, *Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies,* **Energy and Buildings 92,** 2015, pp. 161-169.
[9] R. Drochytka, M. Dvorakova, J. Hodn, *Performance Evaluation and Research of Alternative Thermal Insulation Based on Waste Polyester Fibers*, **Procedia Engineering, 195,** 2017, pp. 236-243.
[10] A. Briga-Sá, D. Nascimento, N. Teixeira, J. Pinto, F. Caldeira, H. Varum, A. Paiva, *Textile waste as an alternative thermal insulation building material solution*, **Construction and Building Materials, 38,** 2013, pp. 155-160.
[11] A. Danihelová, M. Nemec, T. Gergel, M. Gejdoš, J. Gordanová, P. Scensný, *Usage of Recycled Technical Textiles as Thermal Insulation and an Acoustic Absorber,* **Sustainability, 11,** 2019, p. 2968.
[12] A. Hadded, S. Benltoufa, F.J. Fayala, *Thermo physical characterisation of recycled textile materials used for building insulating,* **Journal of Building Engineering, 5,** 2016, pp. 34-40.
[13] I.C. Valverde, L.H. Castilla, D.F. Nunez, E. Rodriguez-Senın, R. de la Mano Ferreira, *Development of New Insulation Panels Based on Textile Recycled Fibers,* **Waste Biomass Valor, 4,** 2013, pp. 139-146.
[14] S. Zeinab, Z.S. AbdeL-Rehim, M.M. Saad, M. El-Shakankery, I. Hanafy, *Textile fabrics as thermal insulators*, **Autex Research Journal, 6,** 2016, pp. 148-161.
[15] J. Zach, A. Korjenic, V. Petránek, J. Hroudová, T. Bednar, *Performance evaluation and research of alternative thermal insulations based on sheep wool,* **Energy and Buildings, 49,** 2012, pp. 246-253.
[16] A. Abdou, I. Budaiwi, *The variation of thermal conductivity of fibrous insulationmaterials under different levels of moisture content,* **Construction and Building Materials, 43,** 2013, pp. 533-544.
[17] M. Kehrer, H.M. Künzel, K. Sedlbauer, *Ecological insulation materials-does sorp-tion moisture affect their insulation performance?,* **Journal of Thermal Envelope and Building Science, 26,** 2003, pp. 207-212.
[18] A.M. Papadopoulos, *State of the art in thermal insulation materials and aims for future developments,* **Energy and Buildings, 37,** 2005, pp. 77-86.
[19] B. Hasselaar, *Vernieuwbare isolatie als Duurzaam Alternatief*, **Master Thesis**, TU Delft, 2003.
[20] K.W. Corscadden, J.N. Biggs, D.K. Stiles, *Sheep's wool insulation: a sustainablealternative use for a renewable resource?,* **Resources, Conservation and Recycling Journal, 86,** 2014, pp. 9-15.

[21] J. Ahlberg, E. Georges, M. Norlén, *The potential of hemp buildings in different climates. A comparison between a common passive house and the hempcrete building system*, **Bachelor Thesis**, UPPSALA University, Sweden, 2014, p. 59.
[22] N. Stevulova, J. Cigasova, A. Sicakova, J. Junak, *Lightweight Composites Based on Rapidly Renewable Natural Resource*, **Chemical Engineering Transactions, 35,** 2013, pp. 589-594.
[23] F. Asdrubali, S. Schiavoni, K.V. Horoshenkov, *A Review of Sustainable Materials for Acoustic Applications*, **Building Acoustic, 4,** 2012, pp. 283-312.
[24] S.A.R. Zeinab., M.M. Saad, M. El-Shakankery, I. Hanafy, *Textile fabrics as thermal insulators*, **Autex Research Journal, 6**(3), 2006, pp. 148-161.
[25] O. Jirsak, T*hermo-Insulating Properties of Perpendicular-Laid Versus Cross-Laid Lofty Nonwoven Fabrics,* **Textile Research Journal, 20**(2), 2000, pp. 121-128.
[26] G.J. Morris, *Thermal Properties of Textile Materials*, **Textile Institute Journal, 44,** 1953, p. 449.
[27] S. Sukigara, H. Yokura, T. Fujimoto, *Compression and Thermal Properties of Recycled Fiber Assemblies Made from Industrial Waste of Seawater Products*, **Textile Research Journal, 73**(4), 2003, pp. 310-315.
[28] V. Glombikova, P. Komarkova, E. Hercikova, A. Havelka, *How high-loft textile thermal insulation properties depend on compressibility*, **Autex Research Journal, 20**(3), 2019, pp. 338-343.
[29] G. Havenith, *Moisture accumulation in sleeping bags at sub-zero temperature: effect of semipermeable and impermeable covers*, **Textile Research Journal, 72**(4), 2002, pp. 281-284.
[30] J.T. Williams, **Textiles for cold weather apparel**, Woodhead Publishing, 2009, p. 432.
[31] G. Zhu, D. Kremenakova, Y Wang, J. Militky, *Study on thermal property of highly porous nonwoven fabrics*, **Industria Textila, 66**(2), 2015, pp. 74-79.
[32] R.S. Grewal, P. Banks-Lee, *Development of Thermal Insulation for Textile Wet Processing Machinery Using Needlepunched Nonwoven Fabrics*, **International Nonwovens Journal, 8**(2), 1999, p. 9.

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