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Alternative Methods for Building Energy Preservation

Marian-Cătălin Grosu[1], Ioan Hossu[2], Emilia Visileanu[1], Florin Breabăn[3], Alexandra-Gabriela Ene[1], and Felicia Dondea[1]

[1]The National Research & Development Institute for Textiles and Leather, Bucharest, 030508, Romania
[2]"Gheorghe Asachi" Technical University of Iaşi, 700050, Romania
[3]Artois University, LGCgE. IUT Bethune, 62408 Bethune, France

ABSTRACT

This article deals with aspects of the thermo-physical efficiency of coarse textile wool fibers arranged in the form of fibrous layers. The advantage of exploiting a huge quantity of wool existing in Romania, currently less valorised, is the excellent wet-thermal and comfort properties of wool, concerning man and nature, 100% natural raw material, ecological and renewable, with a positive impact on man. By applying the technology specific to non-woven products, textile layers with layer density between 13 - 37 kg/m3 were made from wool with a fineness of 45–55 microns and a length of 150–220 mm. To analyze the simultaneous influence of the independent parameters textile layer density (kg/m3) and temperature (°C) on thermal parameters such as thermal resistance R - [m2K/W]; thermal conductivity λ - [W/(mK)] and the amount of heat stored in the sample Q - [J], an experimental design program using the rotating compound central factorial of order 2 was obtained. The highest thermal resistance value of 2.77 m2 K/W was obtained at a density of 13 kg/m3. Thus, the layer structure becomes more compact (the number of pores decreases, i.e. the amount of air in the structure decreases) causing the thermal resistance to decrease. Also, was identified that a significant decrease in thermal conductivity with the increasing layer density. In contrast, at a constant layer density (25 kg/m3), thermal conductivity increases insignificantly in the experimental range. Thermal conductivity decreases with increasing layer density and decreasing temperature. The lowest thermal conductivity value of 0.036 W/(mK) was obtained at a density of 37 kg/m3. The obtaining of a non-woven textile material with a higher value of the amount of heat stored in the sample depends primarily on the higher temperature difference to which the material is subjected and the decrease in the layer density.

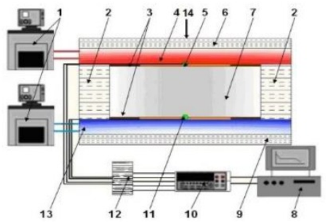
Keywords: Optimization, Heat resistance, Wool layers, Heat insulation

INTRODUCTION

From the perspective of sustainable development, the combined global efforts to reduce energy consumption and pollutant emissions into the earth's atmosphere require the promotion of research, development, and application of products with minimum negative effects. Products made from natural cellulosic (hemp, flax, wood) and protein (wool, flakes) fibers have thermal insulation properties close to those of established materials (mineral wool, glass wool, polystyrene (XPS -EPS)), but are nature-friendly (Hegyi et al., 2021). Among these, wool fibers are on an upward trend in use due to the major stunning advantages such as: natural, renewable and sustainable character, low embodied carbon, assure protection against moisture (Zabalza Bribián et al., 2011), (wool fiber absorbs the highest amount of water ∼30%), help control temperature, easy and safe in installation (has high resistance to compression due to its structure with crimps) (Lupu et al., 2013) is flame resistant (self-extinguishing character) (Hossu et al, 2015), thermal and sound insulation properties and lower price advantage (Hegyi et al., 2021). The energy savings that can be achieved in the construction sector, by insulating them are comparable to those of established materials with a strong environmental impact Corscadden et al., 2014), (Mansour et al., 2014. In the article, the results of mathematical modeling of the thermal characteristics of wool fiber nonwoven textile layers intended for thermal insulation of wall structures are analyzed. Thus, the contribution brought by these fibrous layers to thermal insulation is quantified, through two different aspects, namely: the increase of thermal and sound performance by wool textile layers (nonwovens) associated with concrete structures in the construction field.

MATERIALS AND METHODS

For the research, textile layers were made of nonwoven structure from coarse Romanian wool fibers, with a fineness of 45–55 microns and a length of 150–220 mm (Grosu et al., 2019). Following the thermal measurements made on the fibrous layer, under different temperature and density conditions, the values of the thermal parameters are within the limits of those obtained in the literature (Luc et al., 2012, Zach et al., 2012), and for a complete characterization of the influence of the structure of the layers on the thermal parameters, an experimental design was designed in a composite centered program, in which the fibrous layer is analyzed taking into account two independent variables: density and temperature. The densities were obtained by ensuring the height of the samples, according to the parameters of the experimental plan, the samples having a surface imposed by the measuring installation of 25X25 cm. The measurement of the heat fluxes related to the test temperatures, according to NF EN 12667, and NF EN 12664, used an experimental installation from the Laboratory of Civil and Environmental Engineering (LGCgE) of Artois University, IUT, France (Wu, 2011) (Fig. 1).



1 - thermostatic baths, Huber 240-CC3 mini stat model; 2 - XPS thermal insulation on the samples contour; 3 - kapton guard rings; 4 - isotherm, warmly, upper thermal plate, Tmax; 5 - upper dissipative fluxmeter with temperature sensor, Φsup, Tsup; 6 - upper warm plate thermal insulation; 7 - sample; 8 - computer with specialized software; 9 - lower cold plate thermal insulation; 10 - data acquisition board; 11 - lower dissipative fluxmeter with temperature sensor Φinf, Tinf; 12 - Pt 100 thermal reference;13 - Al, lower, isotherm, cold, thermal plate, Tmin;14 - height adjusting samples system;

Figure 1: The principle scheme of the experimental measuring installation and measured parameters.

EXPERIMENTAL

Rotating Composite Centred Factor Program of Order II (RCFP II)

To follow and interpret the simultaneous influence of the independent parameters textile layer density (kg/m3) and temperature (°C) on the thermal parameters thermal resistance R - [m2 K/W]; thermal conductivity λ - [W/(mK)]; and the amount of heat stored in the sample Q - [J], samples were made and measured according to an experimental design using RCFP II. The limits of the ranges of the two variables, the true values and the coded values (see Table 1).

Table 1. Correspondence of independent parameters with true values.

Independent Variables		Levels of Variation					
coded values		−1,414	−1	0	1	1,414	U.M.
x_1 - layer density	(real values)	13	17	25	33	37	kg/m3
x_2 - hot plate temperature		20	26	40	54	60	°C

The designed matrix contains 13 sets of experimental combinations, 8 of which are distinct and 5 of which are the midpoint, and are made to determine the error value during the experiments. The empirical relationship between the independent process parameters and the obtained properties was obtained using the multiple regression technique. The interaction between the values of variables x_1 and x_2 is presented as a polynomial equation of order 2,

$$Y = b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2 \tag{1}$$

where Y is the dependent variable, b_0 is the regression constant, b_1 *şi* b_2 are the coefficients of the independent variables, b_{12} is the interaction coefficient of the independent variables, and b_{11} and b_{22} are the quadratic coefficients of the independent variables. The models obtained are based on the coded values of the independent variables, e.g. the minimum and maximum values of the range of the two variables x_1 and x_2 are denoted by −1.414 and 1.414. Thus the resulting value of Y depends on the interaction given by the polynomial equation at certain values of x_1 and x_2. In this case, Y successively represents R, λ, and Q (Table 2).

Table 2. Experimental matrix.

E	x_1	x_2	x_1Real [kg/m^3]	x_2Real [°C]	Y_1 R [m^2 K/W]	Y_2 λ [W/(mK)]	Y_3 Q [J]
1	−1	−1	17	26	2,15933	0,05604	10722,33
2	1	−1	33	26	1,56067	0,03845	11163,26
3	−1	1	17	54	2,30676	0,05245	91357,53
4	1	1	33	54	1,39476	0,04302	68241,58
5	−1,414	0	13	40	2,99341	0,05145	44923,54

(Continued)

Table 2. Continued

E	x_1	x_2	x_1Real [kg/m^3]	x_2Real [°C]	Y_1 R [m^2 K/W]	Y_2 λ [W/(mK)]	Y_3 Q [J]
6	1,414	0	37	40	1,55382	0,03475	39625,87
7	0	−1,414	25	20	2,12182	0,0377	9017,61
8	0	1,414	25	60	1,71681	0,0466	88170,22
9	0	0	25	40	1,81043	0,04419	39003,15
10	0	0	25	40	1,81646	0,04404	37581,47
11	0	0	25	40	1,70832	0,04683	38409,62
12	0	0	25	40	1,73152	0,0462	38134,23
13	0	0	25	40	1,64994	0,04849	43245,51

E – experiment number

EXPERIMENTAL

To establish the dependence relationship between the values of Y on the independent variables x_1 and x_2, a multiple regression analysis of the form of relation 1 was performed. The determination of the coefficients of the regression equation was carried out by the method of least squares minimizing the sum of the squares of the deviations of the calculated values from the measured ones, expressed by the relation 1.

$$Q = \sum_{i-1}^{n} (Ym_i - Y)^2 = \text{mimimum}(1)$$

Where: Ymi - measured values of the dependent variable under analysis; Y- experimental values of the dependent variable

The coefficients of the polynomial equation of order 2 determine the values of a predictable response $Y1 - 3$ and are presented in Table 3.

Table 3. Regression equations for Y1, Y2 and Y3.

Y Values	Regresions	R^2
Y1	1,744-0,443*x_1 -0,074*x_2 +0,204*x_1^2 +0,027*x_2^2 -0,078*x_1*x_2	0,9477
Y2	0,046-0,006*x_1 +0,002*x_2-0,0001*x_1^2 -0,001*x_2^2 +0,002*x_1*x_2	0,9039
Y3	39,285-3,77*x_1 +31,205*x_2 +1,476*x_1^2 +4,635*x_2^2 -5,89*x_1*x_2	0,9904

They can have both positive and negative values that influence the experimental results. The significance check of the coefficients of the multiple regression equation was done using the Fisher Snedecor (F-ratio) test which is defined as follows (Serbulescu et al., 2002):

$$F = \frac{N - k - 1}{k} \cdot \frac{R^2_{Y \cdot x_1 x_2}}{1 - R^2_{Y - x_1 x_2}} \qquad (2)$$

Where: n is the number of experiments in the experimental matrix (sample volume), k is the number of independent variables, and R^2 is the multiple correlation coefficient.

The F-ratio is calculated for a 95% confidence level and two degrees of freedom ($f_1=2$, $f_2=10$ respectively) and then compared with the corresponding tabulated value. When the calculated F-ratios value exceeds the corresponding tabulated value it means that the independent variables have a significant influence on the dependent variable. The tabulated F-ratio value for a 95% confidence level is 4.1. The values of the multiple correlation R^2 coefficients (Table 3) between the experimental values and the calculated values illustrate a significant correlation.

The R^2 multiple correlation coefficients and F values, together with the polynomial equation obtained after testing the significance of the coefficients by applying the Student's test are presented in Table 4.

Table 4. Checking the significance of the coefficients of the regression equations Y1, Y2 and Y3.

Coefficient (C) and Its Signification (S or N)				Student Test Value (T)			
C	Y1	Y2	Y3	T	Y1	Y2	Y3
b_0	1,744 (S)	0,046 (S)	39,285 (S)	Tb_0	55,232	59,661	38,514
b_1	−0,443 (S)	−0,006 (S)	−3,770 (S)	Tb_1	−17,759	−10,379	−4,675
b_2	−0,074 (S)	0,002 (S)	31,205 (S)	Tb_2	−2,960	2,658	38,697
b_{11}	0,204 (S)	0,000 (N)	1,476 (N)	Tb_{11}	7,636	−0,168	1,706
b_{22}	0,027 (N)	−0,001 (N)	4,635 (S)	Tb_{22}	1,021	−1,066	5,359
b_{12}	−0,078 (S)	0,002 (S)	−5,890 (S)	Tb_{12}	−2,219	2,222	−5,165

S – with significative influence on Y; N- with non significative influence on Y

Y1 - Effect of Layer Density and Hot Plate Temperature on R

Analysis of the mathematical model described by equation Y1 of the thermal resistance - R [m2 K/W] in the experimental matrix (Table 2) indicates that x_1 - thickness of the textile layer (mm) and x_2 - temperature (°C) have a strong influence on the characteristics described by the equation. The coefficients of the linear part, of degree I, have the same sign (negative) which means that x_1 and x_2 exert an indirect influence and the same effect on the thermal resistance.

Thus, obtaining a non-woven textile with a higher or lower thermal resistance value must take into account both the layer density and the temperature difference to which the material is subjected. Figure 2a indicates that the response surface of the regression obtained is a quadric, as hyperboloid type, without critical point in the set range. x_1's direct (b11>0) and significant influence on Y1's is given by and interaction of the two independent variables x_1 and x_1 through the mixed term. The negative sign (b12<0) shows an indirect influence, i.e. a tendency for Y1 to decrease when x_1 and x_2 act together. The effect of x_1 and x_2 on Y1 is shown in Figure 2.

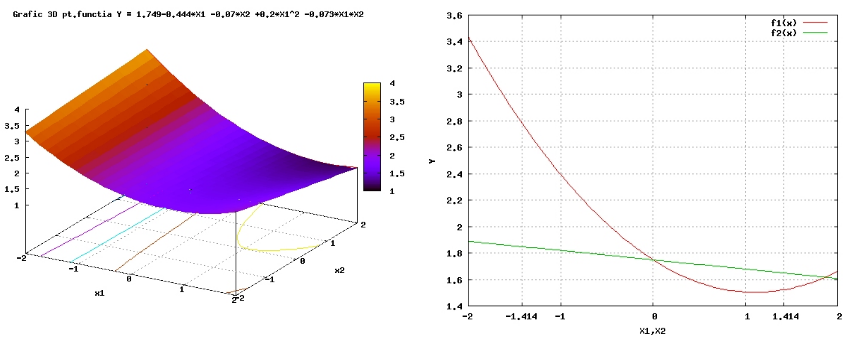


Figure 2: a) Quadric surface b) 2D surface response.

From the graph it can be seen that the thermal resistance Y1 decreases with increasing x_1 and x_2. The highest value of thermal resistance of 2.77 m2 K/ W was obtained at a density of 13 kg/m^3 and a hot plate temperature of 40°C. With increasing layer density (keeping the layer mass - g/m^2 constant) the layer thickness decreases. Thus, the layer structure becomes more compact (the number of pores decreases, i.e. the amount of air in the structure decreases) causing the thermal resistance to decrease. Figure 2b shows a more prominent decrease in thermal resistance at the same temperature (x_2 = 40°C) with increasing layer density. Also a decrease in thermal resistance, but not significant, is recorded with increasing temperature, when the layer density is kept constant (x_1 =25 kg/m^3). The temperature of the hot plate probably cannot significantly change the amount of air in the structure, as air is a good thermal insulator.

Y2 - Effect of Layer Density and Hot Plate Temperature on λ

The equation Y2 of thermal conductivity - λ in the experiment matrix (Table 2) indicates that the layer density x_1 and hot plate temperature x_2 exert less influence on the characteristic Y2 - thermal conductivity λ, than in the case of Y1. Moreover, the coefficients of the degree 1 terms have different meanings, indicating the inverse influence on λ (see Table 5).

Thus, obtaining a non-woven textile material from wool fibres with the lowest value of thermal conductivity is positively influenced with decreasing layer density and increasing temperature to which the material is subjected. Figure 3a indicates that the obtained regression response surface is of the quadric hyperboloid type with no critical point in the range. The choice of the direction of variation in the exprimental domain depends on the intended purpose in practical applications. The lack of 2nd degree terms leads to a not very well defined response surface in the exprimental domain. The interaction x_1 and x_2, through the presence of the mixed term, has a significant influence on the thermal conductivity. The positive sign of the mixed term (b12>0) leads to a direct influence, i.e. a tendency for the thermal conductivity to increase with the cumulative action of x_1 and x_2. The effect of x_1 and x_2 on Y2 is shown in Figure 3b.

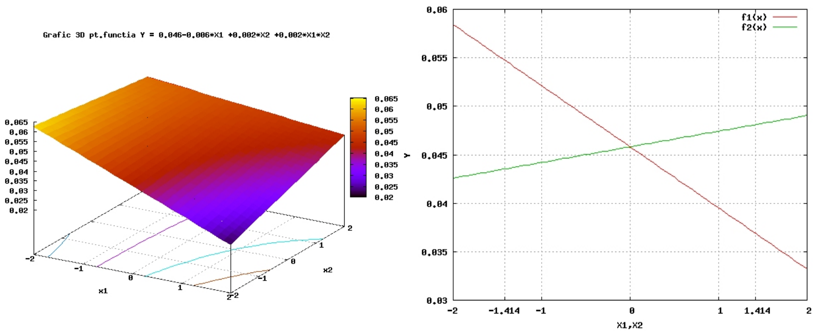


Figure 3: a) Quadric surface b) 2D surface response.

Analyzing the response surface (see Figure 3a), it is found that λ decreases with increasing layer density and decreasing temperature. The lowest λ value of 0.036 W/(mK) was obtained at a density of 37 kg/m3 and a temperature of 40°C.

At a constant hot plate temperature (x_2 =40°C), a significant decrease in thermal conductivity with increasing layer density is observed. In contrast at a constant layer density (x_1 =25 kg/m3), the thermal conductivity increases insignificantly in the experimental range (Figure 3b). A low value of thermal conductivity implies a high value of thermal insulation capacity.

Y3 - Effect of Layer Density and Hot Plate Temperature on Q

Equation Y3 of the amount of heat stored in the sample Q [J] in the experiment matrix (Table 2) indicates that x_1 - density of the textile layer (kg/m3) has a much lower and negative influence than x_2 - temperature (°C) on the characteristics described by the equation.

The hot plate temperature x_2 directly (b22>0) and significantly influences the thermal resistance by the presence of the second degree term.

A significant influence on Y3 is given by and interaction of the two independent variables x_1 and x_2 through the mixed term. The negative sign (b12<0) (see Table 5) shows an indirect influence, i.e. a tendency for the amount of heat stored in the sample to decrease when the two independent variables x_1 and x_2 act together.

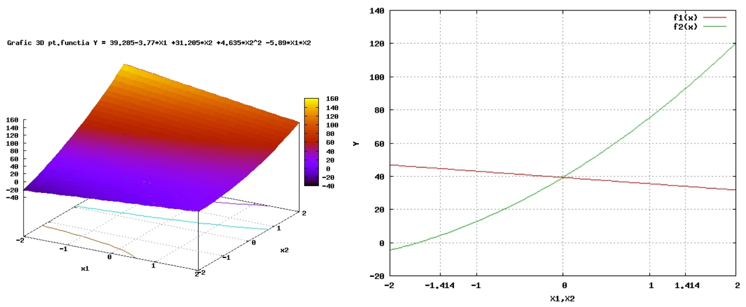


Figure 4: a) Quadric surface b) 2D surface response.

Thus, obtaining a wool textile non-woven designed for insulation with a higher value of heat stored in the sample depends primarily on the higher temperature difference to which the material is subjected and the decrease in the density of the layer. Figure 4a indicates that the regression response surface obtained is a quadric surface of hyperboloid type with no critical point in the range.

By checking the agreement of the mathematical model with the real process it is observed that the values of the difference between the real independent values (obtained from the 13 experiments) and the independent values calculated by the numerical modelling program, using relation 3:

$$A = \left| \frac{Ym - Yc}{Ym} \right| * 100 \tag{3}$$

Where Ym- average value of YR.

If the percentage differences are less than 10%, then the mathematical model is considered to be adequate, and when this value is exceeded, the influence of other factors leading to the actual values of Y, which were not considered in the experimental measurements, is considered to be present.

Table 5. Checking the consistency of the mathematical model with the real process.

E	Y1		Y2		Y3		AY1	AY2	AY3
	Y1R	Y1C	Y2R	Y2C	Y2R	Y2C			
1	2,159	2,387	0,056	0,052	10,720	10,595	10,549	5,820	1,165
2	1,561	1,657	0,039	0,036	11,160	14,835	6,187	6,581	32,931
3	2,307	2,396	0,052	0,052	91,360	84,785	3,868	1,233	7,197
4	1,395	1,353	0,043	0,043	68,240	65,465	3,011	0,131	4,067
5	2,993	2,779	0,052	0,055	44,920	44,616	7,150	5,996	0,677
6	1,554	1,526	0,035	0,037	39,630	33,945	1,805	6,054	14,322
7	2,122	1,848	0,038	0,044	9,020	4,428	12,889	14,777	50,905
8	1,717	1,639	0,046	0,048	88,170	92,675	4,512	4,198	5,110
9	1,810	1,744	0,044	0,046	39,000	39,285	3,678	3,821	0,731
10	1,816	1,744	0,044	0,046	37,580	39,285	3,998	3,798	4,537
11	1,708	1,744	0,047	0,046	38,410	39,285	2,079	1,513	2,278
12	1,732	1,744	0,046	0,046	38,130	39,285	0,712	0,529	3,029
13	1,650	1,744	0,048	0,046	43,250	39,285	5,691	4,906	9,168
Av	1,886	1,870	0,045	0,046	43,045	42,137			
			Coefficient of corelation				0,9477	0,9039	0,9904

YR – real value; YC – calculated value; A – adeqance of the model

CONCLUSION

The work focused on the analysis of the influence of some technological parameters of different textile wool fibre layers, in the form of unwoven textile structure (x_1: density of the textile layer - kg/m3) and (x_2: measuring temperature °C) on some very important parameters that are worked with in the field of thermal insulation, namely Y1 - thermal resistance R - [m2 K/W], Y2 - thermal conductivity λ - [W/(mK)] and Y3 - the amount of heat stored in the sample Q - [J]. For this purpose, a 2nd order factorial design was used using a mathematical modelling software of an experimental matrix with 13 experiments representing the technological margins subject to measurements.

It was found that the influence of the dependent parameters x_1 and x_2 on Y is different, for the particular cases thermal resistance, thermal conductivity and the amount of heat stored in the nonwoven wool textiles. The difference more than 10 percent, sign that in the real situation, the other additional factors influence the results.

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