Research on New Structures to Replace Polystyrene used for Thermal Insulation of Buildings

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The paper proposes new structures to replace the polystyrene, which is well known to be a toxic and inflammable material, non-biodegradable, used on a large scale for residence and civil thermal insulation and for packaging. The proposed structures are intended to be light structures, easy to manipulate, easy to be cut at the sizes needed, compact enough to not be damaged during the transport or during the mounting time, easy to fix on the building walls and of course with similar thermal insulating properties as polystyrene. First agglomerated composites were proposed. The materials used in these structures are green and biodegradable, found as inserts of wood (flakes or fibers) and textiles (wool or jute) and binders as wheat flour, clay or ecological acrylic copolymers. The density and thermal conductivity coefficient were determined for each structure and compared with the expanded and extruded polystyrene values and finally the more appropriate structures were recommended. To some of the structures flakes of polyethylene were added, in order to constitute a steam barrier of the new product. The addition of the polyethylene proved to be a disadvantage for the thermal insulation property of the structure and also for its compactness and reliability. The agglomerated composites mentioned above were pressed at a normal temperature (20-22°C) and conditioned at a temperature of 40-50°C. Two other structures were also proposed in this paper for the same purpose: a sandwich one, obtained after pressing it at 200°C, containing jute, wood fibers and polyethylene granules for the core and beech wood veneers for the faces and a panelled board made of waste of polyethylene and jute core and fiberboard faces.

Keywords: *polystyrene, polyethylene, thermal insulation density, composites*

Polystyrene, as a petroleum-based plastic made from styrene monomer, classified as a possible human carcinogen by the International Agency for Research on Cancer was reported on 1986 to be the 5th largest creator of waste after identifying 57 released chemical polluting products during the combustion of polystyrene foam. It can not be recycled, being known that the plastics can take up to 400 years to break down in a landfill and has a high flammability. In order to reduce the flammability of polystyrene foam and to safeguard this material from accidental ignition, early research tests as corner test [4] were performed to show that the addition of any covering material having a better flame spread classification to the insulation was beneficial in terms of reducing the rate of early fire spread. In time the polystyrene products have improved from the flammability point of view, containing flame retardant additives to inhibit accidental ignition from a small source of fire, but continuing to have the maximum recommended operating temperature of 75°C. Despite its negative characteristics, polystyrene as a petrochemical product and plastic material it is used as an insulating material on the exterior walls of the buildings, saving 70% of the total heat loss and having also the advantage of the low weight. Thermal conductivity coefficient determined by plate method shows values between 0.036 and 0.046 W/mK for expanded polystyrene with densities in the range of 10-30 kg/m^3 [10]. The thermal conductivity coefficient is the main indicator of the thermal insulating property of any structure and thus it was determined using different methods for various materials and composites. It was found in the literature, for example, [5], that the thermal insulating property of the clay is improved approx. four times (0,06 W/mK against 0,250 W/mK) when mixing it with sawdust, instead of 75% (only 180 W/mK) when mixing it with ashes. Thus, composites started to satisfy better the requirements of thermal insulation rather than pure materials [1, 6]. Computer simulation and modeling of coupled heat and moisture transfer are becoming increasingly significant for accurate calculations of heat and moisture transfer. However, to solve the equations, the apparent thermal conductivity λ_{app} as a function of temperature, moisture content, and material structure is required, based on real determinations [8]. The technological process of polymers itself depends on the determination of the thermal conductivity coefficient. The thermal conductivity of polymers in the solid and molten phases, as functions of temperature and pressure, is an essential parameter to permit simulation of polymer processing by computer-aided engineering (CAE) [7]. Insulation performance of extruded polystyrene (XPS) foams proved to be improved by expanded them with various halogenated blowing agents [2]. As mentioned before, a variety of additives and chemical agents were mixed in its composition in order to improve some properties of polystyrene. But all these can not stop its properties of melting at low temperature and its lack of biodegradability. These reasons have motivated the research of the present paper on new structures able to

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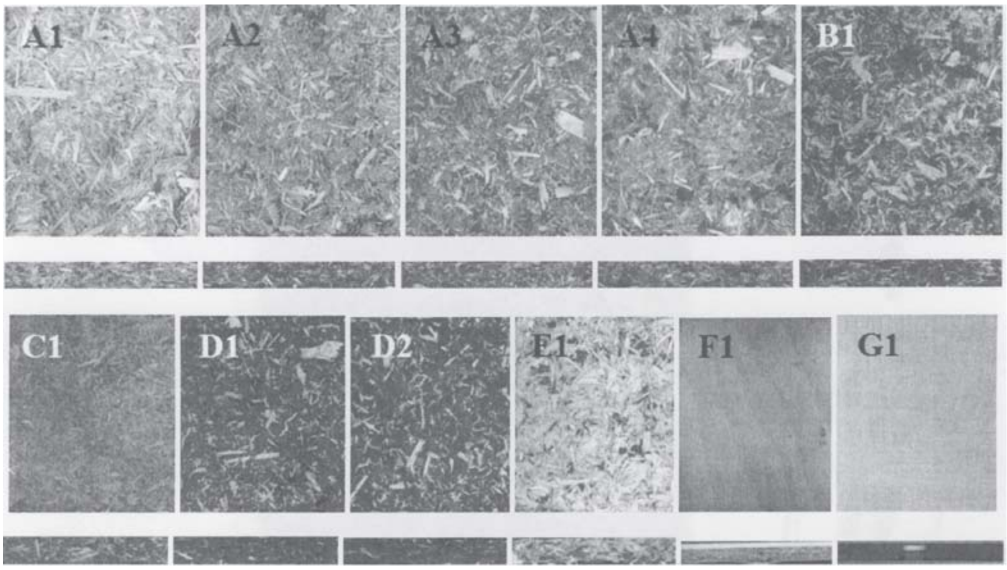

Fig.1. Proposed structures for the research

replace the polystyrene as thermal insulating material on building walls, as it is a continuation of the objective of introducing ecologic and biodegradable materials into the structures used nowadays in human close environment (interior arrangements, furniture, etc.) [3]. The research will focus on the determination of thermal conductivity coefficient for the proposed structures, compared with the polystyrene values, their flammable properties being the theme for a next research.

Proposed structures

The proposed structures are shown in figure 1.

They contain wood flakes, unwoven and carding wool or jute, polyethylene flakes and binders as acrylic polymers, clay, wheat flour or polyethylene. Characteristics of the proposed structures are shown in table 1 for agglomerated composites and table 2 for stratified ones.

All agglomerated structures presented in table 1 were formed in wooden molds with the interior sizes of 300 x 300 mm and height of 40 mm, provided with a fixed bottom plywood panel and a detachable top panel made of melamine faced chipboard, as seen in figure 2.

Table 1
CHARACTERISTICS OF THE PROPOSED AGGLOMERATED STRUCTURES

Code no.	Content and amount						
	Inserts, in g			Binders			
	Wood flakes, in *g*	Wool, in *g*	Polyethylene flakes, in *g*	White acrylic copolymer (Paint)	Ecologic acrylic copolymer (lacquer)	Clay solved in water	Wheat flour solved in water
A1	150	150	-	400 *ml* 60% water 40 % paint	-	-	-
A2	150	150	-	400 *ml* 40% water 60% paint	-	-	-
A3	150	150	-	400 *ml* 50% water 50% paint	-	-	-
A4	150	150	-	400 *ml* 55% water 45% paint	-	-	-
B1	150	150	-	-	-	-	300 *g* wheat flour 300 *ml* water
C1	150	150	-	-	-	800 g clay 500 *ml* water	-
D1	150	150		-	400 *ml*	-	-
D2	150	150		-	400 *ml*	-	-
E1	150	50	100	400 *ml*	-	-	-

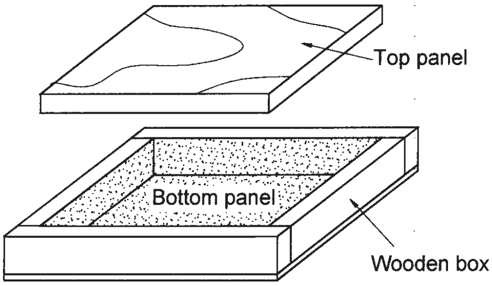

Fig.2. Wooden mold used to form the agglomerated structures

Table 2
CHARACTERISTICS OF THE PROPOSED STRATIFIED STRUCTURES

Code no.	Content and amount						
	Faces		Core			Adhesives	
	Hard fiberboard 4 *mm* thickness	Beech veneer 1.2 *mm* thickness	Polyethylene waste (cut from plastic bottles)	Wood fibers, in *g*	Jute, in *g*	Polyethylene granules, in *g*	Aderpren glue, in *ml*
F1	-	2 pcs	-	150	150	200	-
G1	2 pcs	-	9 pcs	-	50	-	100

The content of each structure have been mechanically mixed, poured into the mold and pressed at the environment temperature (approx. 20°C) only by the press upper plate weight during 24 h. After that, they were conditioned for another 48 h at a temperature of 40-50°C, until the water was completely removed from the mixture.

F1 structure was obtained by melting the polyethylene granules at a temperature of 200°C applied at a specific pressure of 1 MPa to the structure composed of beech veneer for faces and jute fibers, wood fibers and polyethylene granules for the core. The second structure (G1) is a paneled board with faces of melamine faced hard fiberboard of 4 mm thickness and the core made of glued plastic bottle necks and jute fibers. The adhesive used to glue the bottle necks is Aderpren, made of chloroprene rubber and phenol resin with the addition of auxiliary substances and organic solvents.

Theoretical approach

The thermal conductivity is a physical parameter of a substance, that depends on temperature, pressure and nature of the substance and is usually determined experimentally.

It is determined from Fourier's equation:

$$\lambda = \frac{|\vec{q}|}{|grad\, t|}, \qquad (1)$$

being numerically equal to the amount of heat passing through unit area of the isothermal surface per unit time at a temperature gradient of unity. The results of measuring the thermal conductivity are used to calculate the processes of heat conduction. The thermal conductivities of construction and heat – insulating materials range from 0.023 to 2.9W/mK. Materials with a low thermal conductivity (below 0.25W/mK), commonly used for thermal insulation, are called heat – insulating materials.

For the construction elements with non-uniform structure, the unidirectional heat flux is calculated according to equation 2:

$$Q = qA = \frac{t_i - t_e}{R_T} A \; [W], \qquad (2)$$

where:

Q is heat flux, [W]

q- heat flux per unit area, [W/m^2]

A – the area of the heat transfer surface, [m^2]

t_i – the temperature of the inner air, [°C]

t_e – the temperature of the external air, [°C]

R_T – the equivalent thermal resistance of the construction element, [m^{2}K/W]

$$R = \Sigma \frac{\delta_k}{\lambda_k} \left[\frac{m^2 K}{W}\right], \qquad (3)$$

where:

δ_k is the thickness of a layer, [m]

λ_k - the thermal conductivity of the corresponding material layer, [W/mK]

Table 3
THERMAL CONDUCTIVITY (λ) FOR SOME MATERIALS USED IN BUILDING

Material	Density, ρ kg/m^3	Thermal conductivity, $(\lambda), \frac{W}{mK}$
Bricks dense	800	0.279
	1000	0.384
	1200	0.442
	1400	0.523
	1600	0.733
	1800	1.233
Brick work	1200	0.58
Paper	700	0.140
Plywood	600	0.151
Fiberglass	-	0.04
Oak wood	650	0.243
Fir, pine	450-500	0.16
Corkboard	-	0.043
Clay, dry to most	-	0.15-1.8
Glass, wool insulation	-	0.04
Wool, felt	-	0.07
Air	-	0.024
Plastics, foamed (insulation materials)	-	0.03-0.04
Polyethylene, *t=0.2 mm*	-	0.17
Polyethylene foam	-	0.43
Polystyrene expanded, *t=30 mm*	20	0.04
Polystyrene extruded, *t=20 mm*	-	0.035-0.036
PVC	-	0.19

and:

$$R_T = R_i + R + R_e = 0.125 + R + 0.042 \qquad (4)$$

and:

$$q = \frac{t_i - t_e}{R_T} \qquad (5)$$

where t_i = 20°C and t_e = 20°C are the inner and external temperatures.

Some of the thermal insulating materials are presented in table 3 together with their specific values of thermal conductivity and their densities [9]. The lowest values, both for density and for thermal conductivity coefficient belong to polystyrene, which is the most used material in building insulation, but with the disadvantages presented at the beginning of the paper.

Samples, experimental method and equipment

The sizes of the samples used to determine the thermal conductivity coefficient (λ) are as follows: Length L = 240 mm, width *l* = 240 mm and thickness t = 21 mm. The thermal conductivity was determined for all structures presented before.

The principle used to determine experimentally the thermal conductivity coefficient in steady – state conditions of heat transfer is based on the method of the heating plate with a single material sample. The material sample is placed between two metallic plates, the upper hot plate and the lower cold plate, maintained at constant temperatures. So, the difference in temperature between the plane surfaces of the sample is constant and uniform. Therefore, the surfaces of the sample are considered to be isothermal surfaces. The central part of the upper plate is heated by aid of an electric resistance, the rest of the plate is heated with water at the same temperature with that of the central part and serves as a protection plate. That is why, between the central part and the protection plate there is no heat transfer and the entire electric energy consumed is transmitted to the sample, representing the heat flow transferred normally through its isothermal surfaces. In these conditions, Fourier's law can be applied in order to determine experimentally the thermal conductivity coefficient. The equipment existing in the laboratory of the Department of Technical Thermodynamics and Fluid Mechanics is meant for the determination of the thermal conductivity coefficient of materials with values λ = 0.029....1.977W/mK. The scheme of this experimental equipment can be followed in figure 3.

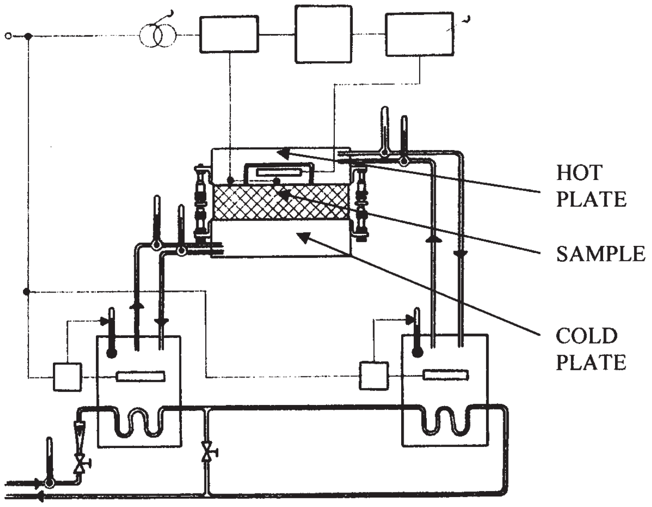

Fig. 3. The scheme of the experimental equipment used to determine the thermal conductivity coefficient of the proposed structures

Results and discussion

After applying the experimental method of determining the thermal conductivity coefficient, the results presented in table 4 were obtained. The table presents also the equivalent thermal resistance of the construction element (R_T), the final thermal resistance (R) and the heat flux (Q) transmitted into a wall with the thickness of the tested structure, from an inner temperature of 20°*C* to an exterior temperature of 0°*C*.

Table 4
THERMAL CONDUCTIVITY (λ) EXPERIMENTALLY DETERMINED FOR THE PROPOSED STRUCTURES

Code no.	Length L, *mm*	Width L, *mm*	Thickness, t *mm*	Volume V m^3	Mass, m *kg*	Density, ρ kg/m^3	λ, *W/mK*	R, m^2K/W	R_T m^2K/W	Q *W*
A1	0.252	0.252	0.030	0.0019	0.377	197.89	0.067	0.45	0.61	2.07
A2	0.252	0.252	0.037	0.0023	0.448	190.67	0.070	0.53	0.70	1.83
A3	0.252	0.252	0.027	0.0017	0.420	244.95	0.063	0.43	0.60	2.13
A4	0.252	0.252	0.037	0.0023	0.407	173.22	0.054	0.69	0.85	1.49
B1	0.252	0.252	0.034	0.0022	0.619	286.69	0.063	0.54	0.71	1.80
C1	0.252	0.252	0.030	0.0019	1.194	626.73	0.064	0.47	0.64	2.00
D1	0.252	0.252	0.038	0.0024	0.381	157.88	0.047	0.81	0.98	1.30
D2	0.252	0.252	0.030	0.0019	0.368	193.16	0.051	0.59	0.76	1.68
E1	0.255	0.255	0.030	0.0020	0.202	103.55	0.119	0.25	0.42	3.10
F1	0.252	0.252	0.010	0.0006	0.514	809.40	0.084	0.12	0.29	4.44
G1	0.250	0.250	0.020	0.0013	0.322	257.60	0.071	0.28	0.45	2.79

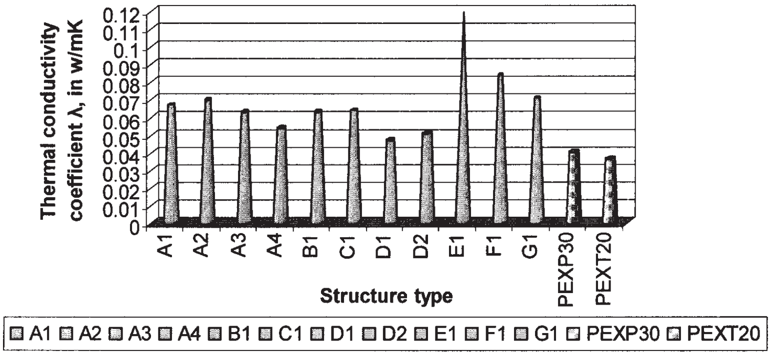

Fig. 4. The thermal conductivity coefficient λ determined for the proposed structures compared with polystyrene

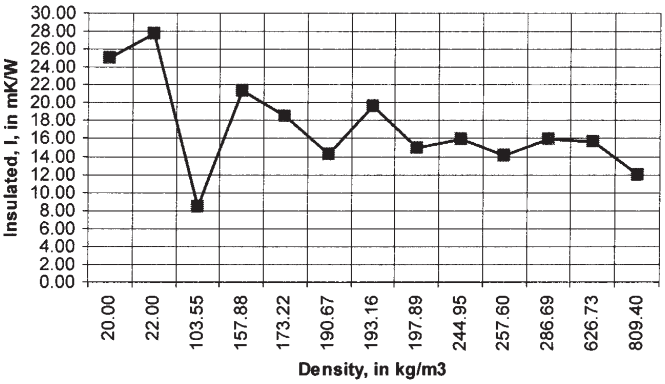

Fig. 5. Variation of the insulated capacity against the density of the proposed structures

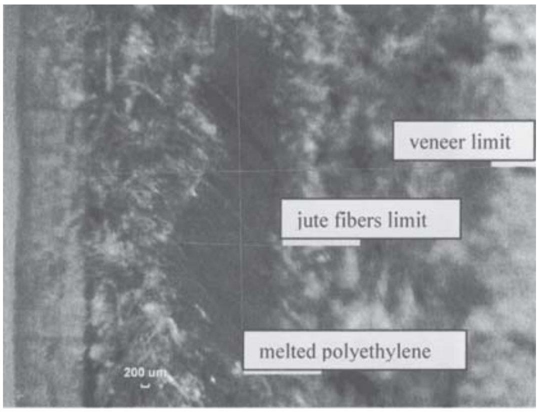

Fig. 6. Microscopic research on structure F1

The performance of the insulation materials can be described by the reciprocal of the λ value, and we will note with "*I*". Therefore, the higher the "*I*" value, the better the insulation quality. Comparing the obtained values of λ and I for the tested structures with those of expanded polystyrene of 30 mm (PEXP30) and extruded polystyrene of 20 mm (PEXT20), it can be observed that the better insulation quality of the proposed structures goes to structure D1, followed by structures D2, A4, B1 and C1. (fig. 4).

The variation of insulated *I* (reciprocal of λ) against the density of the material, shown by figure 5 has not a rule. It depends on the material capacity of insulation and on its thicknesses in the constant environmental conditions. For example a low insulated capacity has the structure E1, having polyethylene flakes in its composition, the polyethylene having a thermal conductivity coefficient of 0.17 W/mK, high enough to bring influence to the final value. It can be also observed that for the densities higher than 200 kg/m^3, the insulated capacity is quite narrow.

The presence of polyethylene into the proposed structures, with the advantage of constituting a steam barrier, unfortunately did not succeed to bring enough capacity of thermal insulation, proved by high values of the thermal conductivity coefficient (λ= 0.119 for structure E1, λ= 0.084 for structure F1 and λ= 0.071 for structure G1). A microscopic research at the interface veneer-jute fibers-melted polyethylene of the structure F1, presented in figure 6, shows a compact structure, obtained by melting the polyethylene granules as binder of the stratified structure, which succeeded to connect very closely the wood structure of beech veneer with that of the textile fibers. Maybe future research with an improved structure, with wool instead of jute, low pressure and longer time for obtaining a more porous material will bring better results. For G1 structure, improvements as using wool instead jute could bring also better results. E1 structure, which obtained the worst results proved also to be very fragile, the white acrylic copolymer used as binder being not efficient in creating the necessary connections between the components.

Otherwise, the tests proved that some structures as D1, D2, A4, B1 and C1 have good thermal insulating properties, being quite closed to those of the polystyrene (D1 having λ=0.47 W/mK compared with polystyrene having λ=0.36-0.40 W/mK). Improvements of these structures could improve the thermal insulating properties, bringing them to values almost similar to those of polystyrene, but eliminating the disadvantages of non-environmental and high inflammability material polystyrene has.

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