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DESIGN PROPERTIES OF A CONSTRUCTION LAYERED ELEMENT MADE OF POLYMERIC COMPOSITES THERMAL CONDUCTIVITY STUDY CASE

BY

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Abstract. Buildings are built to serve the common needs of human society, and the use of advanced polymer composites in building construction allowed engineers to achieve outstanding performance in safety and durability requirements of buildings. Polymer composites, and in particular, polyester resins reinforced with glass fibres, offer many advantages compared with traditional materials in construction sector.

The paper presents the design properties of a glass fibre reinforced polyester composite, in general, and, in particular, the methodology of determining thermal conductivities, in two directions, for a structural polymeric laminate material, each laminae made of polyester matrix reinforced with fabric of glass fibres type *E* (*E*-glass). For the thermal conductivity, theoretical results are compared with experimentally obtained values.

The experimental values are correlated with results from theoretical models for thermal conductivities. Results can be useful for future research on composite materials for various applications and highlight the importance and difficulty in analysis of thermal properties of a structural system made of polymeric composites.

Key words: polymeric composites; composite properties, thermal properties.

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1. Introduction

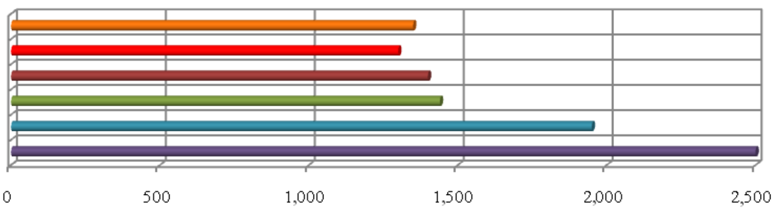
Polymeric composites are multi-phase materials produced by combining low-cost, light-weight, environmentally resistant polymer resins with reinforcing fibres to produce a bulk material with properties better than those of the individual base materials. Polymeric resins reinforced with high-strength, high-stiffness fibres in various forms are the most usual types of composites utilized for structural elements in construction.

Polymeric composites have high strength-to-density ratio, good resistance to various corrosive agents, and flexibility in fabrication of various elements, tailored properties and ease of applicability avoiding long disruption.

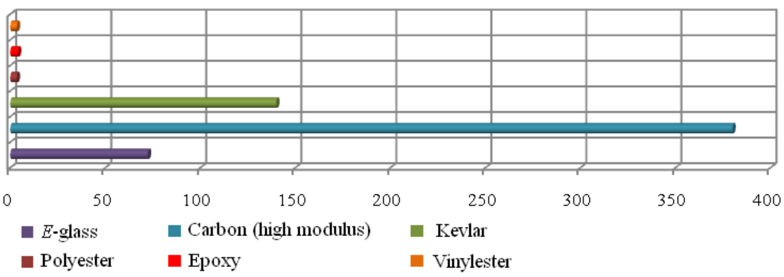
Advanced polymeric composites reinforced with fibres are increasingly being used in civil engineering structures. In particular these materials are utilized as structural elements due to their versatility and are easily applied on structural members made of steel, timber, reinforced and pre-stressed concrete for use in structural rehabilitation works where space constraints and time limitations are imposed.

2. Constituents of Advanced Polymeric Composites

Reinforcing fibres for advanced polymeric composites are fabricated from materials that are stronger and stiffer in the fibrous form than as a bulk material. Fibres used for structural applications must meet certain requirements



a



b

Fig. 1 – Typical properties of polymeric composite components: *a* – density, [kg/m^3]; *b* – Young's (elasticity) modulus, [GPa].

such as: high strength, high stiffness, convenient elongation at tensile fracture, high toughness, durability, acceptable cost and availability in suitable forms. There are three main types of reinforcing fibres utilized in polymeric composites for structural applications in civil engineering structures: glass fibres, carbon fibres and aramid (Kevlar) fibres (Barbero, 2010; Ţăranu & Isopescu, 1996).

Structural elements are mainly based on thermosetting resins, which are irreversibly formed from low molecular weight precursors of low viscosity. The most common thermosetting matrices used in advanced composites are polyester, epoxy and vinyl ester, which are briefly presented here (Restaino & James, 1995).

Some typical properties of glass, carbon and aramid fibres and maximum values of thermosetting resins properties are presented in Figs. 1 and 2.

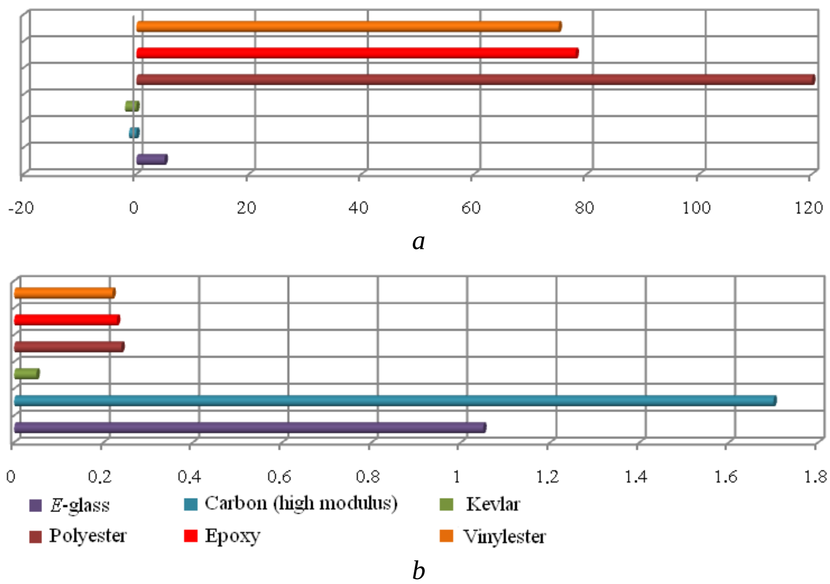


Fig. 2 – Thermal properties of polymeric composite components:
a – thermal expansion coefficient, [$10^{-6}/^{\circ}C$]; *b* – thermal conductivity, [W/m.K].

3. Design Properties of Unidirectional Fibre Reinforced Polymeric Composites

3.1. Micromechanics Techniques for the Effective Properties

Polymeric composites are typically organized in a laminate structure where each lamina (or flat layer) contains an arrangement of unidirectional fibres within a thin layer of polymer matrix material (Fig. 3).

Generally, material's strength is governed by its ability to sustain a load without excessive deformation or failure in combination with a good resistance to aggressive agents. The strength properties of polymeric composite lamina collectively make up one of the primary reasons for which civil engineers select them in the design of structures.

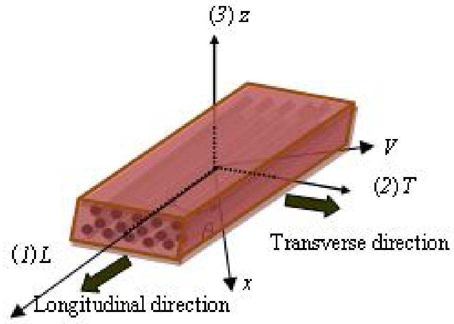


Fig. 3 – Unidirectional fibre reinforced lamina.

The design properties of polymeric composite materials can be determined by experimental measurements but these experiments are expensive, therefore a variety of methods, including micromechanical approach, are used to predict the mechanical characteristics of fibre reinforced polymeric composites. Micromechanic techniques are used to predict the effective properties and deformation response of the individual plies of the composite laminate. The laminate theory is then used to compute the effective response of the entire composite laminate. In the micromechanics, the effective properties and response are computed based on the properties of the individual constituents.

The common procedure is based on the analyse of a unit cell of the composite, the smallest material unit for which the response can be considered representative of the response of the overall composites (Barbero, 2010; Agarwal & Broutman, 1990; Daniel & Ishai, 1994). Analysis of composite structures made of fibrous composites is based on unidirectional lamina. An unidirectional lamina may be modelled by assuming fibres to be uniform in properties and diameter, continuous, and parallel throughout the polymeric composite. It may also be assumed that a perfect bonding exists at the interface, so that no slip occurs between fibre and matrix materials.

A unidirectional lamina (Fig. 3), has the strongest properties in the longitudinal direction, $L(1)$, which is the fibres direction. Any direction perpendicular to the fibres in the *2-3* plane is called the *transverse direction*, $T(2)$. The material behaviour in the other two directions (*2,3*) is nearly identical because of the random fibre distribution in the lamina cross section, therefore it can be considered transversely isotropic.

The properties of composite materials are determined by the properties of its phases and their distribution related to lamina's material axes (*1,2,3*). A key element in micromechanical analysis is the characterization of the relative volume or weight contents of the various constituent materials (Agarwal & Broutman, 1990; Bootle *et al*., 2001). Micromechanics equations can be developed from both equilibrium or compatibility relationships and assumptions about either stresses or strains in the representative volume element subjected to a simple state of stress (Gibson, 2011).

Most important mechanical properties involved in the design of polymeric composite structural elements are strengths and elastic parameters and they are determined with theoretical models which can be assessed based on parameters that affect system properties. The elastic properties of an unidirectional fibres reinforced polymeric lamina are: *elasticity modulus parallel to the fibres direction* (E_L), *elasticity modulus perpendicular to the fibres direction* (E_T), *shear modulus* (G_{LT}) and *Poisson's ratios* (ν_{LT}, ν_{TL}).

Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Exposure to high temperature above that of processing can also result in an initial (expansion) process, followed by degradation due to thermal effects. Therefore, the thermal conductivity and expansion of a material are of interest in the design process of any structural material.

The coefficients of thermal expansion, (α_L, α_T), of polymeric composites depend on the types of fibres, resin and volume fraction of the constituents. For the general case of orthotropic fibres (such as aramid and carbon/graphite) the longitudinal fibres modulus, E_{fL} , is different from the transverse modulus, E_{fT} , and so there are in the main directions also different linear thermal expansion coefficients such as α_{fL} and α_{fT} . The matrix is assumed to be isotropic therefore the parameter values are similar in any direction, α_m . The *E*-glass fibres are usually assumed to be isotropic.

Thermal conductivity, λ, is the intrinsic property of a material which relates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. The thermal conductivity is mainly a property related to the heat transfer perpendicular to the lamina plan which means a transverse direction. For homogeneous and isotropic fibres of thermal conductivity, λ_f **,** embedded in a resin matrix of thermal conductivity, $\boldsymbol{\lambda_m}$, the thermal conductivities, λ, are given by theoretical eqs. (Barbero, 2010; Ţăranu & Isopescu, 1996) which are used to predict the conductivity of polymeric composites. The most common used design properties of a unidirectional composite lamina are presented in Table 1.

Table 1
The Most Common Used Properties for Polymeric Composite Properties

1	Fibres ratio, i = [0; 100]	i
2	Volume fraction of j constituent ($j \equiv f,m$): $V_f = i/100$ and $V_m = 1 - V_f$	V_f, V_m
3	Density of the composite material	ρ
4	Elasticity modulus in longitudinal direction (parallel to fibres direction)	$E_{L(1)}$
5	Elasticity modulus in transverse direction (perpendicular to fibres direction)	$E_{T(2)}$
6	Shear elasticity modulus (in (LT) plan of unidirectional lamina)	$G_{LT(12)}$
7	Major Poisson's coefficient	$\nu_{LT(12)}$
8	Minor Poisson's coefficient	$\nu_{TL(21)}$
9	Coefficient of thermal expansion in longitudinal direction (parallel to fibres direction)	$\alpha_{L(1)}$
10	Coefficient of thermal expansion in transverse direction (perpendicular to fibres direction)	$\alpha_{T(2)}$
11	Thermal conductivity in longitudinal direction (parallel to fibres direction)	$\lambda_{L(1)}$
12	Thermal conductivity in transverse direction (perpendicular to fibres direction)	$\lambda_{T(2)}$

3.2. Design Properties of Composite Lamina

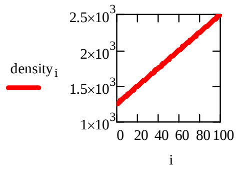
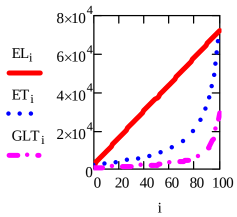
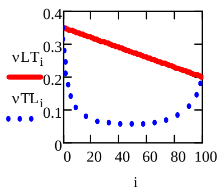
The design properties of a polymeric composite lamina related to fibres ratios variation are presented in Table 2 b,c for the case of an unidirectional lamina made of polyester resin reinforced with unidirectional *E*-glass fibres.

Table 2 (a,b,c)
The Design Properties Evolutions Related to the Fibres Ratio for an Unidirectional Lamina Made of Polyester Matrix and E-Glass Fibres

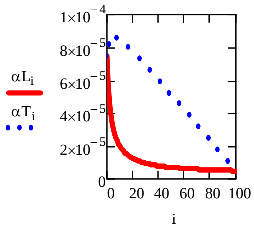
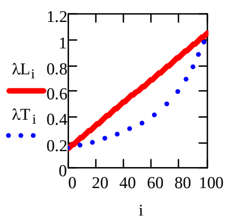
a) *Components Properties Used Values*

Constituents properties	Fibre: *E*-glass	Matrix: polyester
Density, [kg/m^3]	2,500	1,250
Young's elasticity modulus, [MPa]	72,400	2,200
Shear modulus, [MPa]	30,200	810
Thermal expansion coefficient, [10^{-6}/$^\circ$C]	5	75
Thermal conductivity, [W/m.K]	1.05	0.15
Poisson's coefficient	0.20	0.35

b) *Elastic Properties*

Property	Formulas used for properties evaluation	The design properties evolutions related to the fibres ratio of a composite lamina
ρ	$\rho_c = \rho_f V_f + \rho_m V_m$	
$E_{L(1)}$	$E_L = E_f V_f + E_m V_m$	
$E_{T(2)}$	$E_T = E_m \dfrac{1+\xi\eta V_f}{1-\eta V_f}$ $\quad \eta = \dfrac{(E_f/E_m)-1}{(E_f/E_m)+\xi}$ $\quad \xi = 2$	
$G_{LT(12)}$	$G_{LT} = G_m \dfrac{1+\xi\eta V_f}{1-\eta V_f}$ $\quad \eta = \dfrac{(G_f/G_m)-1}{(G_f/G_m)+\xi}$ $\quad \xi = 1$	
$\nu_{LT(12)}$	$\nu_{LT} = \nu_f V_f + \nu_m V_m$	
$\nu_{TL(21)}$	$\nu_{TL} = \nu_{LT} \dfrac{E_T}{E_L}$	

c) *Thermal Properties*

$\alpha_{L(1)}$	$\alpha_L = \dfrac{E_f V_f \alpha_f + E_m V_m \alpha_m}{E_f V_f + E_m V_m}$	
$\alpha_{T(2)}$	$\alpha_T = V_f \alpha_f + V_m \alpha_m + V_f \nu_f (\alpha_f - \alpha_L) + V_m \nu_m (\alpha_m - \alpha_L)$	
$\lambda_{L(1)}$	$\lambda_L = \sum_{i=1}^{n} \lambda_i V_i$	
$\lambda_{T(2)}$	$\lambda_T = \lambda_m \dfrac{1+\xi\eta V_f}{1-\eta V_f}$ $\quad \eta = \dfrac{(\lambda_f/\lambda_m)-1}{(\lambda_f/\lambda_m)+\xi}$ $\quad \xi = 1$	

The design properties of fibrous polymeric composite lamina in other directions (off-axis properties), are different from those in the longitudinal and transverse directions but related to them. The off-axis properties may be predicted by carrying out macroscopic analysis of a lamina using the principles of mechanics and assuming a lamina to be macroscopically homogeneous. From the mechanics standpoint, fibrous polymeric composites are among the class of materials called *orthotropic materials*, whose behaviour lies between that of isotropic and that of anisotropic materials. The number of elastic constants required for an isotropic material is only two for both two- and three-dimensional stress states. The increased number of elastic constants used for polymeric composite lamina due to its orthotropy, indicates the additional complexity of orthotropic problems. In general, the elastic constants will change with the transformation, but under some specific transformations, the elastic constants may remain unchanged as a result of an additional symmetries existing in the material properties (Daniel & Ishai, 1994).

4. Study Case: Thermal Conductivity for a Polymeric Composite Cross Ply Laminate Plate

4.1. Experimental Tests of Thermal Conductivity for a Laminate Plate

The experimental data were obtained in the laboratory test using a surface probe method. This gives the thermal conductivity for the heat flux vector normal to the plane of the surface. In this method, the sample is placed in the isothermal chamber. The data acquisition allows the recording of temperature rise of the sample and the time lapse after the start of heating.

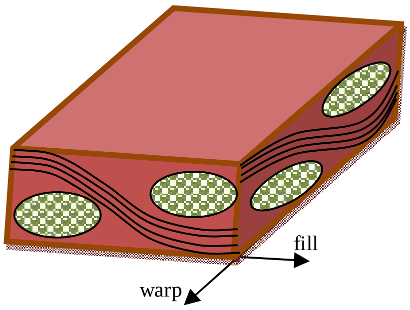


Fig. 4 – The schematic of the unit cell for the plain weave fabric.

When placed against a flat sample surface, this temperature rise depends on the thermal properties of the sample. The experimental measurements were performed in the laboratory of the “URBAN-INCERC” National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development, Branch of Iaşi.

The samples as cross plies laminated plates were made of isophtalic polyester P 4506 fireretardent, reinforced with plain weave fabric of *E*-glass fibres. A schematic of the unit cell for the plain weave fabric is shown in Fig. 4. Since the composite properties are highly influenced by the weave geometry, the fibres ratios must be known in both the warp and fill directions. Data from the laboratory measurements and tests are presented in Table 3.

Table 3
The Experimental Data

		Fibres ratios, *i* %		Experimental through-the-thickness thermal conductivities, λ_T W/m.K	
		warp	fill	–	10^{o}C
1	Sample 1	18.9	15.6	0.2675	0.2539
2	Sample 2	19.1	15.7	0.2529	0.2401
3	Sample 3	18.8	15.9	0.2545	0.2416
Average		18.933	15.733	0.2583	0.2452

4.2. Design Thermal Conductivity Evaluation of a Proposed Cross Ply Laminate Module

Analytical models help to predict the properties of a material without conducting any experiments. However, these models have to be extensively validated with experimental data before adopting them in practice on a large scale. Most of the literature on composite materials (anisotropic) dealt with mechanical properties and very few models were developed to predict thermal conductive properties in different directions (Nielsen, 1974).

Thermal conductivity of composites is anisotropic in nature. The knowledge of thermal conductivity of composites is needed for accurate design of thermal insulation of a construction. Thermal insulation is an important feature of any building. Apart from drastically reducing heating and cooling costs, it provides a comfortable uniformity in temperature throughout a structure. The heat flow through a building construction depends on the temperature difference across it, the conductivity of the materials used and the thickness of the materials. Together these parameters form the thermal resistance of the construction. The thermal resistance is an important technical parameter used in sustainable building design (Barbero, 2010; Ashby & Jones, 2011).

The thermal conductivity of a composite material depends on the fibre, resin materials, fibre volume fraction, orientation of the fibre, direction of heat flow and operating temperature. As the thermal conductivity of a polymer composite is based upon the conductivity of fibre and resin, being dominated by fibre material (Fig. 2 *b*). The compactness of fibres per unit area influences the conductivity of the composite. Fibre packing in a composite depends on the method of manufacturing.

The theoretical approach brings a more generalized eq. for a two dimensional steady state heat flow. Various theoretical approaches are used to yield the thermal conductivity of a composite material so that the heat flow in anisotropic composite material in any direction can be estimated (Ţăranu & Isopescu, 1996; Daniel & Ishai, 1994).

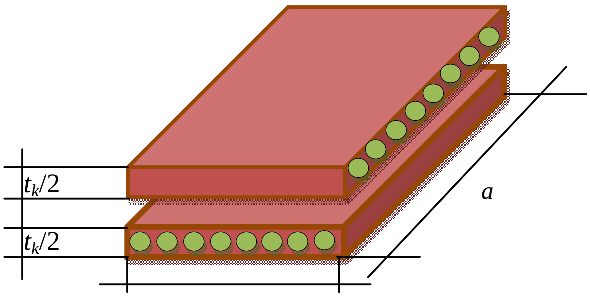


Fig. 5: The cross ply laminate module [0°/R/90°]

In the next evaluation it will be presented an analytical model for determination the thermal conductivity in a polymeric composite structural material made of polyester resin with *E*-glass fibres reinforcement. The thermal conductivities through-the-thickness (transverse direction) and longitudinal directions will be calculated using the theoretical models described in Table 4 c.

Consider a cross ply laminate module [0°/90°] (Fig. 5), based on two unidirectional plies made of polyester resin matrix and *E*-glass fibre, with the same thickness. The module plies have the same thickness, $t = t_k/2 = 0.05$ mm. It may also be pointed out that the basic ply constituent materials (matrix and fibres) are considered isotropic materials.

The values for thermal conductivities could be obtained using *the effective fibres volume fraction*, V_{fe}. Bellow is presented the calculation of the effective fibres volume fractions.

The effective fibres volume fraction can be calculated using eq.

$$V_{fe} = \left(V_{fe}\right)_{\mathrm{warp}} + \left(V_{fe}\right)_{\mathrm{fill}}, \tag{1}$$

where: $(V_{fe})_{\mathrm{warp}}$ is the effective fibres volume fraction for warp bundles; $(V_{fe})_{\mathrm{fill}}$ – the effective fibres volume fraction for fill bundles.

4.2. The Thermal Conductivity of a Laminate Plate

The laboratory results were obtained for the thermal through-the-thickness (transverse direction) conductivity, on a polymeric composite laminate plate having the thickness H = 10.05 mm. Therefore the analytical model for cross ply laminate composite plate has the following arrangement of the plies: $[(0/90)_{100}/0]$, using a series of modules presented in Fig. 5. Considering, for reinforced plies, the fibres ratios presented in Table 3, the effective fibres volume fraction of composite plate evaluated with eq. (1) is V_{fe} = 0.3467. The calculated thermal conductivities for the composite plate with the evaluated effective fibres volume fraction, applying eqs. from Table 4 c, are

$$\lambda_L = 0.44853\,\text{W/m.K},$$
$$\lambda_T = 0.249348\ \text{W/m.K}.$$

4.3. Comparison of Experimental and Theoretical Results

Table 4
The Thermal Conductivities of the Polymeric Composite Laminate Plate

Theoretical thermal conductivities		Experimental through-the-thickness thermal conductivities, λ_T			
through-the-thickness λ_T	longitudinal λ_L	Sample 1	Sample 2	Sample 3	Average
0.249348	0.44853	0.2675	0.2529	0.2545	0.2583

Table 4 presents the calculated thermal conductivities and the experimental measurements for the polymeric composite plate. The comparison of the theoretical results with experimental data will be done. The theoretical values are correlated with results from experimental measurements.

5. Conclusions

Increasing use of composites for various applications highlighted its importance in the thermal property analysis of an engineering system. Thermal conductivity of a fibres reinforced polymeric composite can be measured by theoretical and experimental methods, but analytical eqs. are essential to predict thermal conductivities of a composite material due to the high cost of experimental tests. Information on the thermal properties of composite materials would facilitate the design of an engineering system made of fibres reinforced polymeric composite.

Comparing the results is found that the proposed analytical model for evaluating the calculated thermal through-the-thickness (transverse direction) conductivity led to obtain theoretical values similar to those obtained by experimental tests.

The small existed differences between theoretical and experimental results, presented in Table 4, could be explained by the theory of the nonlinear evolution in the thermal through-the-thickness conductivity with the increase of fibre volume fraction. The Halpin-Tsai eqs. use as the results have shown that, in the case of proposed analytical model, they are able to predict this non-linearity due to the interaction between fibre and matrix, with an admissible error (less than 5%).

The differences can be explained also by the range of temperature from room temperature to maximum service temperature, the fibre distortion, void content and the surface finish of the sample to acquire more accurate results.

In the case of composite plate, the assumed conductivity values in through-the-thickness direction show that the theoretical models are presenting reasonably values. The comparison between the theoretical values in both, through-the-thickness and longitudinal directions, reveals that the assumed value for thermal conductivity of polymeric composite made of polyester matrix with *E*-glass reinforcements along the axis of the fibre and transverse to the fibre are appropriate.

In the case of a polymeric composite structural element made of polyester matrix reinforced with *E*-glass fibres, the Halpin-Tsai eqs. can be used for theoretical appropriate prediction of the thermal conductivities.

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PROPRIETĂȚILE DE PROIECTARE ALE UNUI ELEMENT DE CONSTRUCȚIE STRATIFICAT DIN COMPOZITE POLIMERICE
Studiu de caz: conductivitatea termică

(Rezumat)

Clădirile sunt construite pentru a servi nevoilor comune ale societății umane, iar utilizarea compozitelor polimerice avansate în construcții au permis inginerilor constructori să atingă performanțe deosebite în cerințele de siguranță şi rezistență a clădirilor. Compozitele polimerice şi, în particular, răşinile poliesterice armate cu fibre de sticlă, oferă sectorului de construcții multiple avantaje în raport cu materialele tradiționale.

Se prezintă proprietățile de proiectare ale unui compozit polimeric armat cu fibre de sticlă, în general, şi, în particular, metodologia de determinare a conductivităților termice, după două direcții, pentru un material structural, compozit polimeric, alcătuit din lamele realizate din răşină poliesterică armată cu țesătură din fibre din sticlă tip *E*. Pentru conductivitățile termice, rezultatele de la modelele teoretice sunt comparate cu valorile obținute experimental. Concluziile şi validarea modelului utilizat pot fi utile pentru cercetări viitoare privind utilizarea materialelor compozite pentru aplicații diverse şi subliniază importanța, dar şi dificultatea, în analiza proprietăților termice ale unui sistem structural realizat din compozite polimerice.