Theoretical and Experimental Approaches Specific to Monolayer Composite Plates Obtained from Urban and Industrial Recycled Plastic Wastes and Proteic Fibres

ION DURBACA[1]*, NATALIA POPA[2], GHEORGHE VOICU[2], ADRIAN-COSTIN DURBACA[1]
[1]University Politehnica of Bucharest, Faculty of Mechanical Engineering and Mechatronics, Department of Equipments for Industrial Processes, 313 Splaiul Independenţei Str., 060042, Bucharest, Romania
[2]University Politehnica of Bucharest, Faculty of Biotechnical Systems Engineering, 313 Splaiul Independenţei Str., 060042, Bucharest, Romania.

This paper addresses the theoretical and experimental mechanical properties of specific to monolayer composite plates produced from urban and industrial recycling wastes with elastomeric matrix and fibrous protein reinforcement (leather, textile). Defining the theoretical model of composite material with its structural elements, as well as evaluating physical and mechanical characteristics essential to its default drive to an optimal and efficient design of all products made from such materials. By determining the theoretical and experimental parameters with maximum precision, which affects the properties of the composite structure, it is decided its use in specific technical industrial applications.

Keywords: composite material, reinforced lamina, recyclable waste, fibrous material.

In the context of ensuring sustainable development of society today, as fundamental goal of mankind, has developed the concept of integrated waste management in any way. Thus, amid national strategic problem solving waste management and prioritizing actions to minimize the production of waste, recycling, composting, energy recovery and organic storage, it was necessary the use of urban waste and / or industrial in for the achievement of new materials, such as for example composites monolayer plate made from recyclable waste plastics - polymer (*PET, PVC, ABS, PU, PMMA* etc.) or elastomeric (rubber) - reinforced with fiber waste proteinaceous (leather, textile, etc.).

The theory of the single-layer composite material, made by different manufacturing processes (injection, extrusion, Rolling etc.) consists of a single composite layer with the possibility of being able to be demonstrated by evaluating the efficiency of the mechanical characteristics of its structural components.

The basic unit for the composite materials with fiber reinforcement is the reinforced lamina (fig. 1), giving it multiple possibilities of composition and proper insertion of the characteristics of in the composite calculation. In the lamina, the fibers that embody the reinforcement are located and oriented so as to meet the desired characteristics in composite structural element.

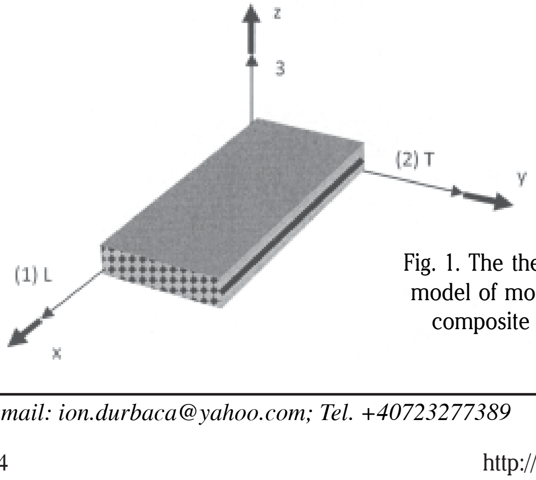

Fig. 1. The theoretical model of monolayer composite plate

The reinforced lamina is one of the most important parts of the composite material which consists of a sample matrix polymer / elastomer, reinforced with fibrous material in which the fibers are disposed according to the arrangement of these components in the composite assembly structure (randomly in space or plan) as shown in figure 2. In this case, those structures are considered 2-dimensional quasi-isotropy, where the fiber length, L is smaller than the thickness of the composite, t_c (fig. 2 a), and in the case of structural elements of composite fiber length is much greater than the thickness, achieving the 3-dimensional quasi-isotropy (fig. 2 b).

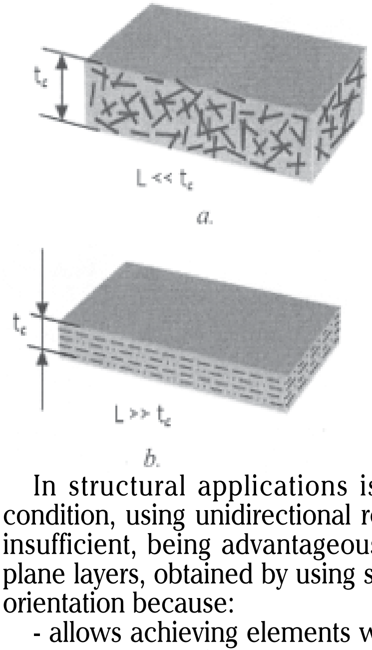

Fig. 2.The arrangement of fiber reinforced polymer matrix composite plate: *a* – random spatial orientation; *b* – random plane orientation

In structural applications is unpredictable stress condition, using unidirectional reinforced composites is insufficient, being advantageous to use quasi-isotropic plane layers, obtained by using short fibers with random orientation because:

- allows achieving elements with complicated shapes without any risk of damaging the model after the removal on forming device;
- can easily incorporate into fluid matrices so that the mixture can easily fill the cavity of many complicated shapes;

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* *email: ion.durbaca@yahoo.com; Tel. +40723277389*

- composites of randomly oriented short fibers may be considered to be approximately isotropic, while unidirectional reinforced composites are obviously anisotropic;
- have the advantage of a relatively low-cost price correlated with quasi-isotropic behaviour makes such composite structures to be most commonly used.

Mechanical properties of composites monolayer plates

In the case of composite materials reinforced with randomly oriented fibers, the physico-mechanical characteristics are determined by parameters such as fiber diameter d_f, fiber length L, the fraction volumetric of reinforcing w_f, the mode of alignment of the fibers in relation to the axis of the product and the manufacturing process.

To establish the physical and mechanical characteristics of composite lamina with polymer / elastomeric matrix and fibrous materials reinforcement it is initially chosen a system of axes of the lamina. Thus, in figure 1, above, schematically it is shown a lamina with unidirectional reinforcement: the parallel direction to the fibers L(1) is called longitudinal and the perpendicular to the fiber T(2) is called the cross/ transverse direction and can be consistent with any directions of the plane (2 3). The axes 1, 2, 3 are referred to as principal axes of the material.

The main mechanical features involved in the structural analysis of composite elements are *strength* and *rigidity*. These characteristics can be determined experimentally, but the tests are valid for one single fiber-matrix system obtained with a particular manufacturing process [1-3]. Therefore, it is recommended the use of theoretical and semi empirical models which allow the assessment of mechanical properties based on the parameters that influence the composite structure. Theoretical models are not always applicable, for direct design of elements some corrections are needed especially in the transverse direction, however, to study the mechanical characteristics in the longitudinal direction is considered that existing models in continuous unidirectional reinforcement composites are sufficiently precise.

Depending on the adopted axis system for fiber reinforced composite materials there are defined the following mechanical characteristics necessary for the design: $E_L = E_1$ - the longitudinal elastic modulus of the lamina (in direction parallel to the fibers); $E_T = E_2$ - transverse modulus of elasticity of the lamina (in a direction perpendicular to the fibers); $G_{LT} = G_{12}$ - shear modulus in the plane of the the lamina (L, T) or (1, 2); $n_{LT} = n_{12}$ and $n_{TL} = n_{21}$ - plane Poisson coefficients (L, T) or (1, 2); R_{tL} - tensile strength in the longitudinal direction of lamina; R_{tT} - tensile strenght in transverse direction of lamina; R_{cL} - compressive strength in the longitudinal direction of lamina; R_{cT} - compressive strength in transverse direction of lamina; $R_{f(LT)}=R_{f(12)}$ - the shear strength of the lamina in the (L, T) or (1, 2) plane.

For theoretical analysis of a composite material reinforced with randomly oriented fibers, it is often easier to use in the design calculations the traditional methods including specific reasoning to composite macro-mechanics with unidirectional reinforcement (rupture theories) and relations known from micromechanics analysis of continuous unidirectional reinforced fiber composites. Therefore, an acceptable estimate is obtained by using expressions from the literature for calculating modules of elasticity E, Poisson's ratio *í*, tensile strength R_t etc [1].

For calculation of the mechanical characteristics of composite reinforced with randomly distributed short fibers, other than those reported in the literature [1], there are currently no acceptable mathematical models to assess their values comparable with those determined experimentally.

In the literature there are a number of studies on thermoplastic composites containing protein fibers [4]. The polymeric matrix may include plasticized *PVC*, acrylonitrile-butadiene-styrene (*ABS*) and polymethyl methacrylate (*PMMA*), where the modulus of elasticity *E* [MPa] shows different behavior. While composites *ABS* / leather and *PMMA* / leather presents decreased elasticity modulus *E* and a slight increase dependent to the ascendant in the percentage of leather composite fibers, *PVC* (polyvinyl chloride) / leather composites shows a similar behavior with *PVB* (polivilinil butyral / leather, namely, the elastic modulus is strongly influenced by the content of the fibers, especially in composites where the fiber content of the leather is beyond w_t = 30%, as shown in figure 3 [4].

It underlines that for such a composite material with leather fiber reinforced polymer matrix, the elastic modulus increases considerably with increasing the concentration of fibrous mass and the reduction of tensile strength can be attributed to a reduction in the capacity of deformation of the polymer matrix.

Experimental part

Materials and methods

It examines mechanical characteristics of a composite sample called CAUFIPEL (CFP), in which there is elastomeric matrix, as represented by co-acrylonitrile-butadiene rubber (NBR) reinforced with protein reinforcement found as semi-coarse crushed particles with varying sizes approx. 10 µm - 1 mm from waste tanned leather fibers [5]. Due to the presence of chromium in the reinforcement fibers, which requires processing at relatively low temperatures, it makes NBR elastomeric matrix represents a very interesting structural element for the development of composite case study for the CFP.

The experiments for the manufacture of composite plate structure in the CFP form have been carried out on a semi-industrial roller with a capacity of approx. 10 kg / h and the possibility of adjusting the temperature (fig. 4).

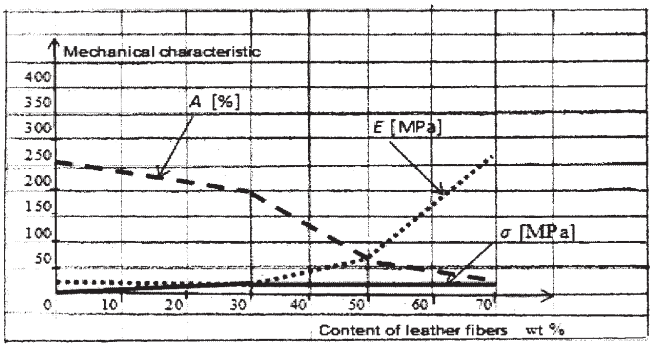

Fig. 3. The variation of mechanical properties (E, σr and A) of the composite PVC / leather, depending on the content of leather fibers [4]

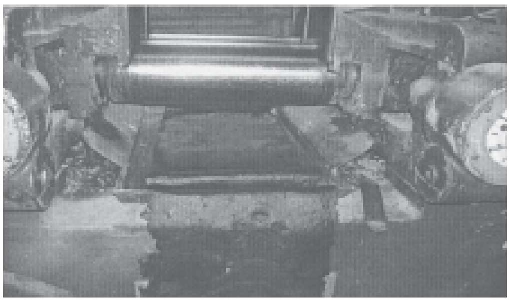

Fig. 4. Production of CFP composite plates on the roller [5]

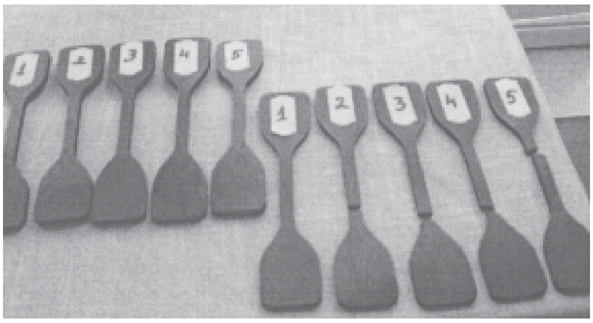

Fig. 5. CFP Composite material standardized test pieces [5].

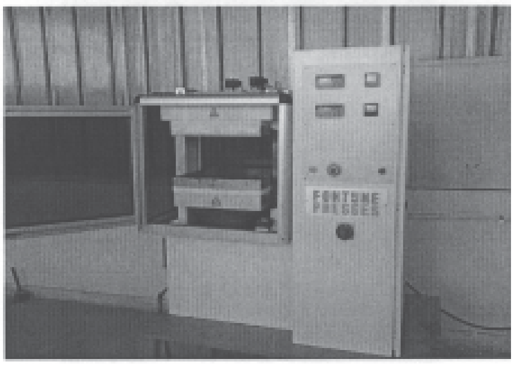

Fig. 6. Electrical vulcanizing press used for processing of finished products [5]

Table 1

Item no	Mechanical characteristics [MU]		Obtained values				
			CFP1	CFP2	CFP3	CFP4	CFP5
1	Hardness, Sh A		62	66	81	84	92
2	Elasticity, %		24	28	16	16	10
3	The modulus of elasticity N/mm^2	100%	1.3	2.1	3.6	-	-
		300%	2,6	-	-	-	-
4	Tensile Strength, N/mm^2		5	3,2	5,3	5,2	4.4
5	Ultimate elongation, %		500	273	300	100	80
6	Residual elongation, %		20	20	20	20	16
7	Tear resistance, N/mm		19	29	42	44.5	35.5
8	Density, g/cm^3		1.23	1.23	1,25	1,25	1.30
9	Wear, mm^3		215	210	250	234	356
Accelerated aging 70^o x 168 h							
10	Hardness, Sh A		62	67	83	87	94
11	Elasticity, %		20	22	14	14	10
12	The modulus of elasticity, N/mm^2		1.2	2.2	7	-	-
13	Tensile Strength, N/mm^2		3,9	3,8	7,1	5	4,4
14	Ultimate elongation, %		387	380	140	100	60
15	Residual elongation,%		18	24	20	22	14
16	Tear resistance, N/mm		20.5	27	46	45	43

The composite is discharged from the roll in the sheet form having a thickness of about 2.5 to 3 mm, and then punched according to dimensional forms specific to standardized test pieces used for physical and mechanical testing (fig. 5), or can volcanize in the press (fig. 6) at temperature of 1600°C and pressure of 0,5 MPa for 10 min to achieve the finished product.

Physicomechanical tests

In order to evaluate the mechanical characteristics of the CFP composite (5 Structural variations - CFP1 ÷ CFP5 – with different percentage compositions of the reinforcing filler), there are used the following standardized quantities: density, hardness, modulus of elasticity, tensile strength, elongation at break, residual elongation, tear strength, abrasion resistance, all of those ready-made material and also made on the material accelerated aging (70°C, for 168 h).

Summary of key experimental results obtained by standardized tests of mechanical characteristics of analysed CFP composite is given in table 1 - Summary of key experimental results [5].

Structural modeling and simulation

Using modern techniques of mathematical modelling and computer simulation to estimate the behaviour of the composite material analysed in relation to the matrix material and the presence of reinforcing material therein, is considering building a simple structural model, two-dimensional or three-dimensional, corresponding to a relatively thin layer of composite material. The simulation model is made of the mechanical behaviour of the composite (in particular, tensile and tear strength), the effects of reinforcement distribution in the matrix of the composite material, as well as simulating the effects of defective or incomplete interfaces between the matrix of the composite material and the reinforcement (manufacturing defects).

The basic structure of a CFP composite is defined geometrically by means of a simple rectangular plate with 30 x 10 x 3 mm dimensions and particles reinforcing grain exceeds 1 mm generalized diameter.

It is also considered the CFP composite as a linear elastic behaviour, characterized by the Young's modulus E, Poisson's ratio $í$, mass density - for the elastomeric matrix (rubber) and the fibrous proteinaceous reinforcement (natural leather), in table 2 - Linear-elastic characteristics of the CFP components.

To meet the widest range of applications requires a tool with which you can change in the manufacturing process, the mechanical characteristics of a plastic or composite. For the composite CFP material, a parameter whose choice gives to the desired properties is the concentration of leather waste in the elastomeric matrix. Most plastics and composites benefit from such a possibility of predicting mechanical concerned properties.

Thus, by using the structural modeling a three-dimensional geometrical model in which loads and restrains are shown in figure 7. Meshing was done using the SOLID3D elastic-plastic (Von Mises) finite element, which are found in the library of finite element structural analysis program COSMOS / M 2.8. The model contains 6265 nodes and 11956 finite elements.

Table 2

Material	E, MPa	ν	ρ
Rubber	10	0.45	1230
Leather	30	0.3	1000

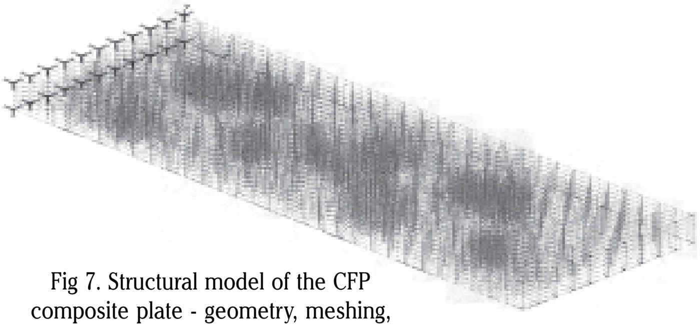

Fig 7. Structural model of the CFP composite plate - geometry, meshing, restraining and loading - for tensile test along the axis Ox

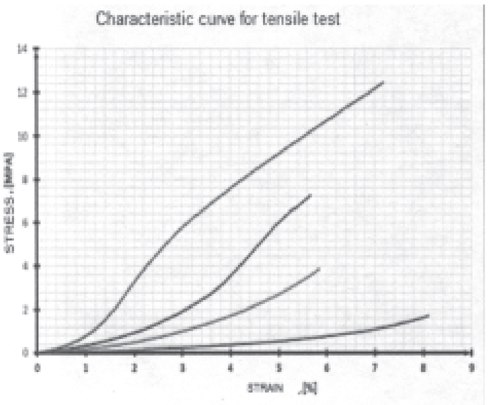

Fig. 8 - Stress-strain characteristic curves for tensile test.

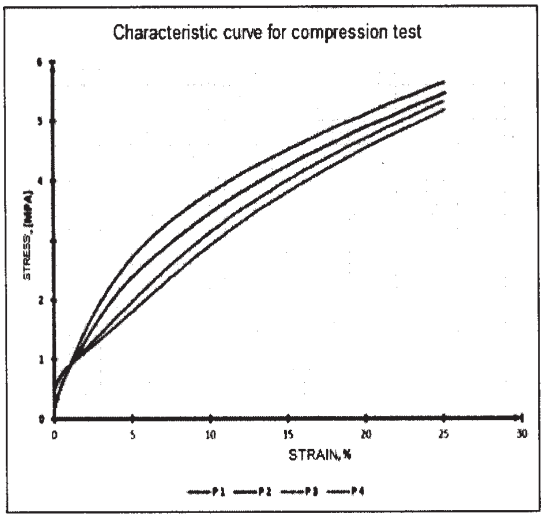

Fig. 9. Stress-strain characteristic curves for compression test

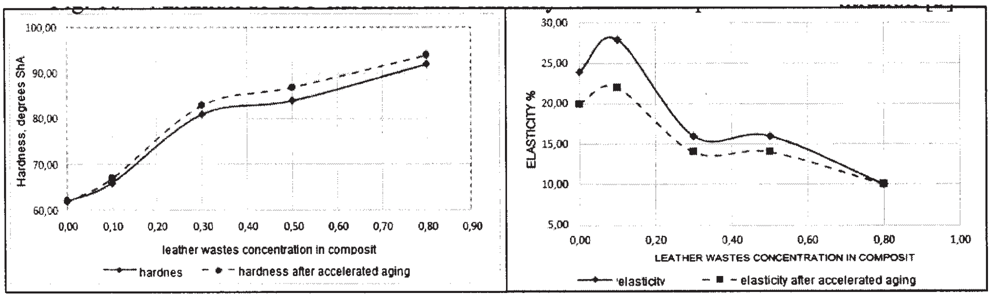

Fig. 10. Variation of CFP hardness and elasticity with fibrous particle concentration

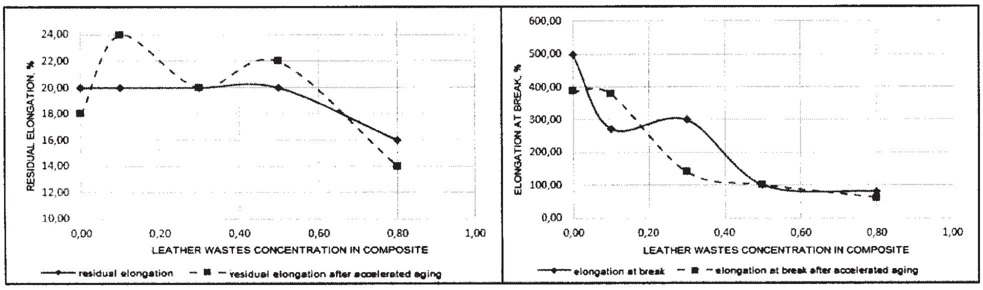

Fig. 11. Variation in ultimate elongation and residual elongation of the CFP composite with fibrous particle concentration.

Results and discussions

In the case of analyzed CFP composite material the specific mechanical characteristics curves confirm the particularities found in other experiments, that is, essentially, the behaviour varies depending on the quality and quantity of fibrous protein waste concentration (reinforcement) in the elastomeric matrix.

Stress- strain curves obtained experimentally for the four types of composite CFP (CFP2 ÷ CFP5), where the percentage content of protein fibers > 0% (excluding CFP1 structural variant, in which the percentage of the protein fibers = 0%) are shown in figure 8 for the tensile test, respectively in figure 9 for compression test.

The mechanical characteristics of CFP composite described in this paper are in accordance with the literature for hyperelastic materials [6-7].

For easier interpretation of the variation of CFP composite reinforcement properties with the concentration of protein fiber waste, these results are plotted in figures 10 -13 [5]. Representations are made based on the points whose coordinates are calculated or taken from Table 1. The percentage concentration of waste fiber in the composite is calculated as the ratio between the amount of protein and the amount of rubber waste (matrix composite).

Variation of the mechanical characteristics of the CFP composite, depending on the concentration of protein fiber waste in the characteristic curves shown in figures 10-13 is not simple, and these extreme points not negligible (residual elongation of the material aging, tensile strength). Other extreme mechanical characteristics are more

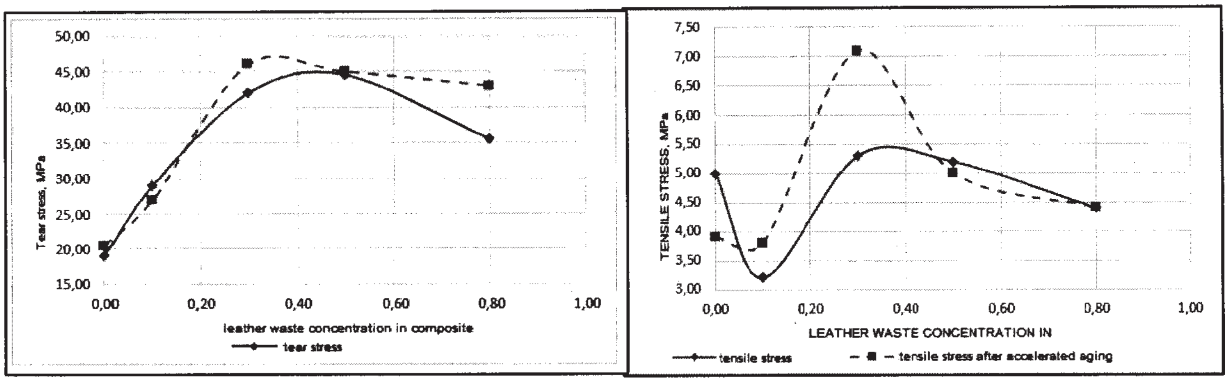

Fig. 12. Variation of fracture strength and tear resistance of the CFP composite with fibrous particle concentration.

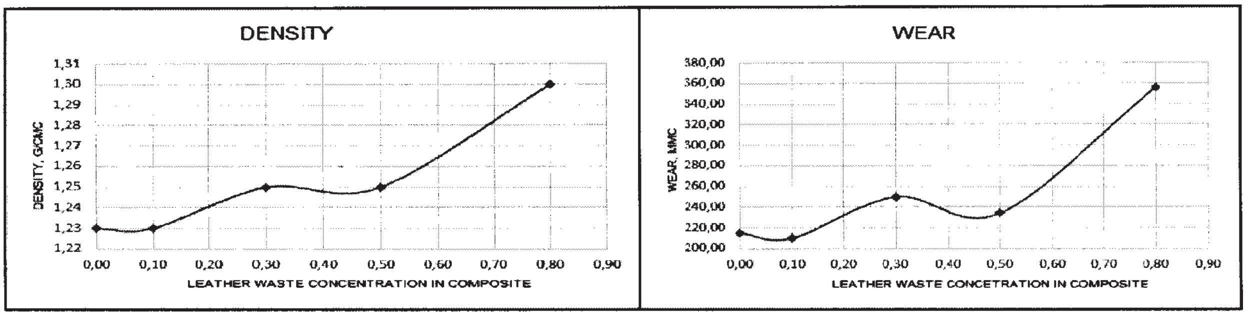

Fig. 13. Variation of density and CFP composite wear with fibrous particle concentration

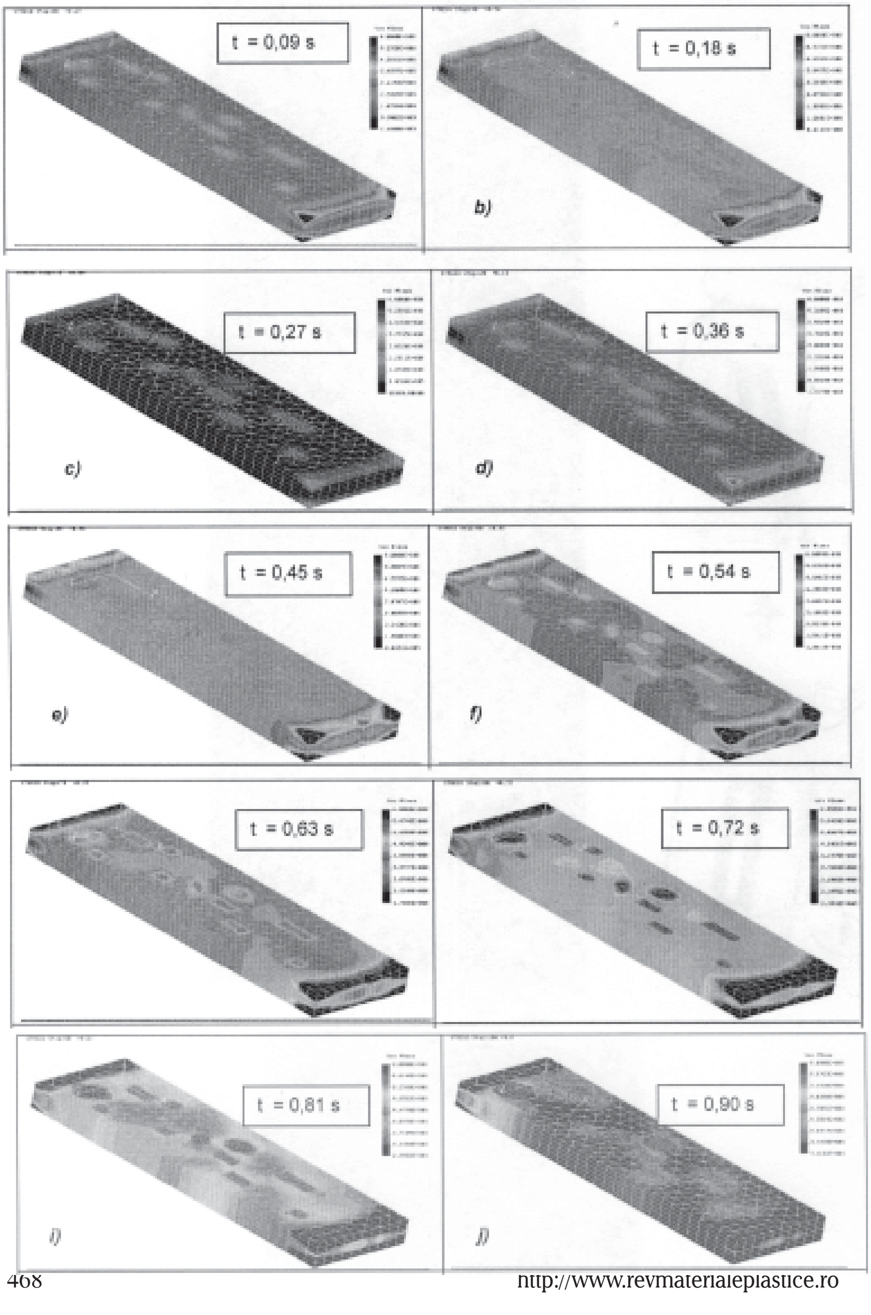

Fig. 14, a) – j) - Stress distribution in time pronounced, which may possibly be neglected in the calculation of interpolation (hardness, density, wear). The existences of these extreme nonmonotonic variations of features are interesting properties of composite materials - properties which can be explained by the internal structure of these materials. Such a mode of behaviour of the composite material was found by other researchers [8, 9].

Important for other applications are the ranges where the mechanical properties of the CFP composite are expressed in their overall variation. These features are important for producers to obtain materials with properties expected for use in certain areas. Mechanical tests of this type, carried out under similar conditions and advanced modern equipment are described in the literature [10, 11].

After conducting tests of structural analysis using the software COSMOS / M 2.8 and the mesh offered by finite element for three-dimensional geometric model of CFP composite, previously defined in figure 7, there were obtained a multitude of simulation results on the field values of the composite stress equivalent distribution in the composite material according to the concentration of fibrous particles relative to the volume of elastomeric matrix both in the linear elastic and in that the elastic-plastic. Thus, in figure 14 a - j [5], are presented colour maps of the distribution of equivalent stress values within the range of modelled CFP composite sample, on 10 equidistant points in time. Also other simulation tests revealed the effects of the distribution of reinforcement mentioned composite material matrix, in order to choose the optimal variant [5].

Therefore, combining the results of experimental tests of the CFP composite with the modelling-simulation tests, it is noted the achieving of a complete and deep analysis on specific mechanical characteristics mentioned composite.

Conclusions

Despite fact that the physicomechanical properties of the composite monolayer plate not match the experimentally determined acceptable by the analytical assessment, however it showed levels of appropriate use.

Experimental analysis performed may contribute decisively to obtain a composite material with features requested by the user. Since it is known the mechanical performance of the composite depending on the concentration of protein fiber waste, the producer can choose the concentration that gives the satisfactory physical and mechanical characteristics of the client. Furthermore, the manufacturer, within certain limits can choose the concentration that leads to minimum energy consumption.

For example, using a wide range of values of the mechanical characteristics of CFP composite, facilitated by the choice of concentration of protein fiber waste, it can provide an alternative composite material that meet the requirements for various products. It is also possible to try and obtain other composite materials using reinforcing elements as waste from the textile fiber, the properties of which have to be mandatory known primarily by technical requirements.

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Manuscript received: 19.03.2015