Aspects Regarding the Optimal Control of Specific Mechanical Properties of Composite Materials Having the Polymeric or Elastomeric Matrix Reinforced with Protein Fibers

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The paper presents the results obtained by the authors for the mathematical modeling of the mechanical behaviour variation of the composite material with polymeric or elastomeric matrix and reinforced with protein fibers (CFP), depending on the concentration of the *reinforced material. The mathematical model of the main mechanical properties of a composite material allows optimal approximation variants of material that is as close to that required in a particular field. The method proposed in this article is generally applied to the composite materials and is valid not only for the case of mechanical properties dependence of a single parameter (the concentration of a constituent) but in the case of dependence on several parameters, case in which the possibilities of achieving a favourable variant are much larger and more accurate. In the category of free parameters of the mathematical model can enter all the constituents' concentrations, but, in addition, also important are the technological parameters: temperature in the manufacturing process, the reinforced material granulation, the degree of stirring, pressure, etc.*

Keywords: *CFP, mathematical model, variation, mechanical properties, optimal variants*

The control of polymeric or elastomeric composite materials production as well as the goods of any kind is linked inevitably to the accumulated knowledge about the structure of the products and the technology adopted. The control of the technological process of manufacturing, generally involves a minimal mathematical model which in fact is the first systemic description of the process. The systemic description includes separation of the parameters in the categories: input parameters, output parameters and control parameters. For the model to be functional from quantitative point of view, between these three categories of parameters are identified as many relationships, geometric, physics, chemistry and energy nature. The category of input parameters includes for example, concentrations of the composite material constituents as well as some of their quality parameters. The category of the output parameters should include those parameters which describe the quality of the material: mechanical, chemical, but also some more difficult quantifiable. The control parameters can be the constituents concentrations in the material, the physical parameters of the process (temperature, the substances concentration that come into contact with the product in the manufacturing process, pressure, mechanical and geometrical parameters of the installations that makes the production process, where applicable). Together with the identified relations between these parameters, in the system description also enter relations restricting of some parameters, relations called restrictions. These can have as subject the product quality indexes, energetic parameters, materials and energy consumption, etc.

Once obtained this mathematical model of the manufacturing process, using the relations and restrictions found can be seek solutions restricted by the beneficiary or the optimal solutions from the point of view of the substances or energy consumption.

Finally, after the model is validated and brought to a satisfactory accuracy, is trying algorithmization of the entire model and his writing as assistance program of the technological process, developed so that to obtain a product closer to the customer requirements in terms of consumption as small.

Such an approach is presented in this article. The mathematical model presented tries to describe the physico-mechanical behaviour of the composite material (CFP),depending on the reinforced material concentration: finite leather wastes in the form of grinding (particles with variable size of about 10 μm - 1 mm). CFP is a composite material obtained by reinforcement in a mass of rubber wastes of particle wastes from leather industry.

The mathematical model described in the paper had as a starting point a series of observations on the atypical behaviour of the composite material (CFP) at mechanical tests. More specifically, the variation of the mechanical properties with the leather concentration in the rubber matrix, is not monotone, generally, shows the maximum and minimum, phenomenon found by other researchers [1, 2].

Normally, this behaviour must be explained to the manufacturer to forecast material qualities depending on the concentration of fibrous leather waste mass from the elastomer matrix. From the investigations made, it results

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that there are some essential aspects in the manufacturing process, which should be clarified in order to explain this behaviour. Thus, in the temperatures range favorable for producing composite material (CFP), according to the indication of conception, the leather particles should be distributed as uniformly in the rubber matrix. However, until now has not been studied enough the structure of the final material in order to give answer to questions like these:

- which is the average size of the leather wastes acceptable in the process and which is the standard deviation admissible?
- which is the optimal temperature range and processing time during this period, so that the fiber protein to disperse homogeneously in the matrix?
- how it characterizes the structural composite material (CFP) in terms of the percentage of waste fiber protein particles dispersed and eventually dissolved in elastomeric matrix structure, of the homogeneity of thereof distribution and quantity of integrated unsuitable composite waste, respectively their role in the mechanical behaviour the material?

Responses more or less clear to these questions, requires very costly researches. These responses can lead to obtaining a structural model, possibly a mathematical model (differential or integral differential) of the manufacturing process, non-existent today. The phenomenological[1] mathematical model presented in this article is our alternative in order to put the basis of a CFP production with competitive qualities to match the market request.

Our approaches are not entirely unique, the study of the mechanical properties in general has been widely investigated for rubber and plastic materials [3-7] and the problem of their variations with concentration of some constituents was also approached, but not carried to complex applications of these variations [8, 9].

Experimental parts

Material and methods

Subject of given developments in this article refers to a composite material obtained by reinforcing a matrix elastomer (rubber waste) with protein waste (tanned leather) material called CFP [28]. For mathematical modeling of the mechanical characteristics of the composite as a function of main parameter influencing quality - protein leather waste concentration in elastomeric matrix, there were used the experimental data given in table 1.

In this table, reproduced from [28], the giving values of the mechanical characteristics of the composite CFP in five variants corresponding control sample and four samples of different concentrations of leather waste material. Also, in table 1 are given mechanical properties of the composite CFP, rolling out of the factory version and old version artificial material.

Physico-chemical and mechanical characterization of the composite variants was performed according to the actual standards. The physico-mechanical tests of the composite materials are regulated by standards [11-17]. In the figures 1 – 8, are plotted the experimental data obtained for the tested mechanical properties of the composite material (CFP), depending on the leather waste concentration in the rubber matrix.

Besides the experimental data have been plotted the variation of polynomial interpolation curves of grade 1, 2 and 3, in the experimental range of the leather waste concentrations in the rubber matrix.

Construction of the functional space

Functions that model the variation curves of mechanical characteristics in relation to the leather wastes concentration in the composite material (CFP), have already been introduced in a graphic form in figures 1 - 8.

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° 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

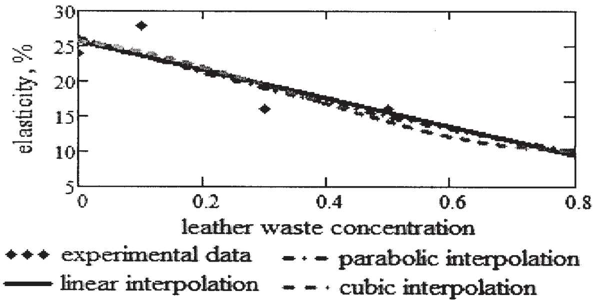

Fig. 1. The CFP elasticity variation depending on the leather waste concentration, experimental data and interpolations

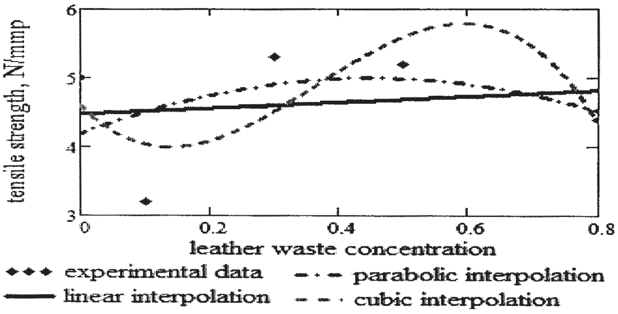

Fig. 2. The CFP tensile strenght variation depending on the leather waste concentration, experimental data and interpolations.

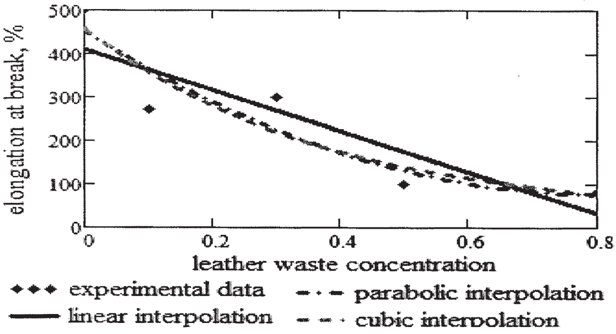

Fig. 3. The CFP elongation at break variation depending on the leather waste concentration, experimental data and interpolations

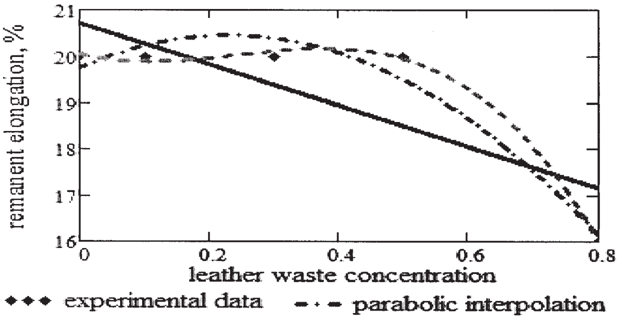

Fig. 4. The CFP residual elongation variation depending on the leather waste concentration

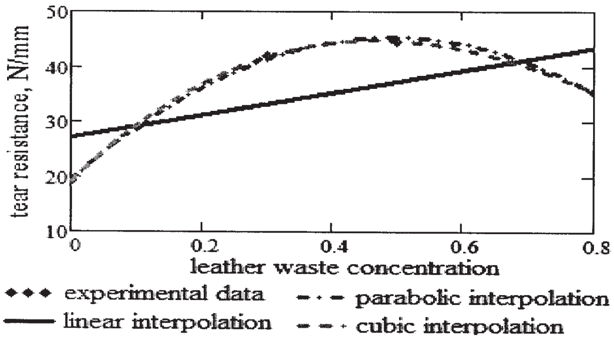

Fig. 5. The CFP tear resistance variation depending on the leather waste concentration, experimental data and interpolations

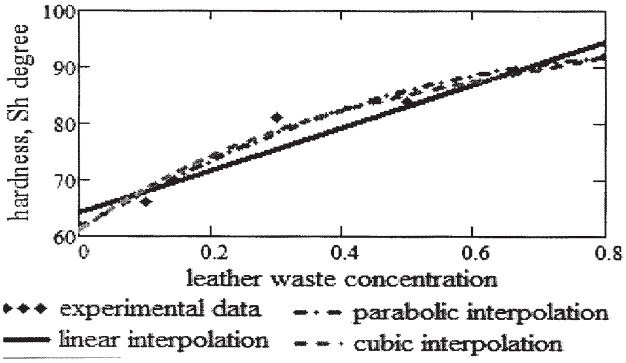

Fig. 6. The CFP Shore hardness variation depending on the leather waste concentration, experimental data and interpolations

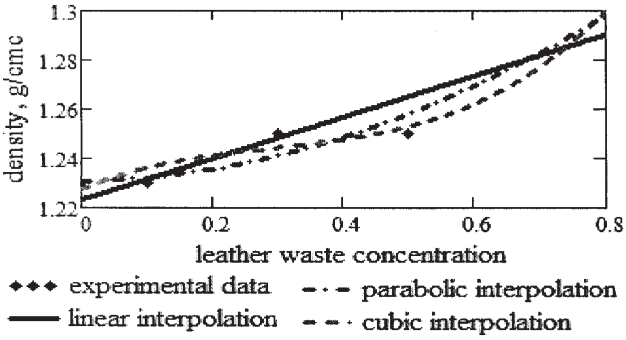

Fig. 7. The CFP density variation depending on the leather waste concentration, experimental data and interpolations

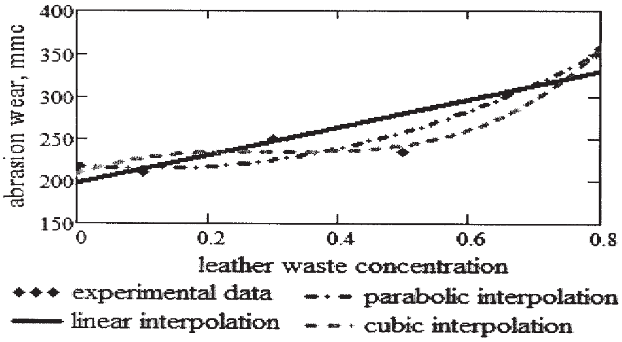

Fig. 8. The CFP abrasion wear variation depending on the leather waste concentration, experimental data and interpolations

The polynomial interpolation functions for each of the mechanical characteristics that were analyzed are given by their coefficients in table 2.

In table 2, for each mechanical characteristic are given on consecutive lines the interpolation polynomial coefficients of grade 1, 2 and 3, rounded to the second decimal place. Obviously, there are an infinite number of the interpolation functions, but in any analysis the polynomial interpolation functions of the first three grades, are the most common, especially because we have no physical reason to consider certain particular forms for the mechanical characteristics of the composite material CFP (exponential, logarithmic etc.).

For each interpolation function was calculated the standard deviation of the interpolated data on the experimental data set, and without exception, cubic interpolation gave the smallest deviation, so the best accuracy, as can be seen in the graphical representations.

Table 2

Characteristics	x^0	x^1	x^2	x^3
Elasticity	25.70	-20.29	0.00	0.00
	26.26	-26.37	7.62	0.00
	25.75	-10.71	-47.50	45.83
Tensile strength	4.47	0.43	0.00	0.00
	4.19	3.58	-3.96	0.00
	4.61	-9.46	41.95	-38.17
Elongation at break	20.71	-4.47	0.00	0.00
	19.74	6.20	-13.38	0.00
	20.05	-3.48	20.69	-28.33
Residual elongation	20.72	-4.47	0.00	0.00
	19.74	6.20	-13.38	0.00
	20.05	-3.48	20.69	-28.33
Tear resistance	27.11	20.27	0.00	0.00
	19.32	105.25	-106.62	0.00
	18.86	119.49	-156.73	41.67
Hardness	64.13	37.86	0.00	0.00
	61.42	67.41	-37.06	0.00
	60.90	83.64	-94.19	47.50
Density	1.22	0.08	0.00	0.00
	1.23	0.004	0.10	0.00
	1.23	0.11	-0.29	0.32
Abrasion wear	197.13	164.32	0.00	0.00
	218.23	-66.03	289.00	0.00
	207.29	272.92	-904.17	992.08

Let be the following notations for the chosen interpolation functions (polynomials of the same grade or other forms) in order to optimize the composite material (CFP): $f_e, f_{ts}, f_{ab}, f_{ar}, f_{tr}, f_h, f_d, f_w$, corresponding to elasticity, tensile strength, elongation at break, residual elongation, tear resistance, hardness, density and abrasion wear. For example, the polynomial interpolation functions of grade 1, 2 and 3 for the CFP composite elasticity, using data from table 1, are:

- for the first grade:

$$f_e(x) = -20.29x + 25.70 \tag{1}$$

- for the second grade:

$$f_e(x) = 7.62x^2 - 26.37x + 26.26 \tag{2}$$

- and for the polynomial of third grade:

$$f_e(x) = 45.83x^3 - 47.50x^2 - 10.71x + 25.75 \tag{3}$$

Further on, the question arises using this functional space (set or family of the interpolation functions of same variable), to obtain a minimal control on the final product of the composite material (CFP) obtaining process.

To define the problem, let us suppose we have a request for composite material (CFP) with qualities given by the *ideal vector,* vector that contains the desired values by the beneficiary for the mechanical characteristics of the material, in the order they are given and the interpolation functions:

$$z = (z_e, z_{ts}, z_{ab}, z_{ar}, z_{tr}, z_h, z_d, z_w) \tag{4}$$

Obviously, these values must be accepted with some tolerance, their simultaneously achievement using a single parameter being very probably impossible. Even more material parameters used for this purpose, does not guarantee obtaining the exact values required.

The problem of the function construction which leads to a result as close to that required by the beneficiary (*a feasible solution*) is a difficult problem, as evidenced by the issue of optimal multi-objective analysis. This type of analysis is also met as the multi-criteria analysis, vectorial optimization, multi-objective programming, Pareto optimization [17]. In this context, the optimal solution is not called in the proper sense optimal but *feasible solution*, namely the solution, which is situated at the "smallest distance" of that required by multiple criteria required. In our case multi-criterion is represented by the vector (4), which, in general, can be achieved with certain tolerances explained in the initial multiple criteria.

There are many methods to approach this very complex problem [17], as many software programs that perform such analyzes. The optimization method is used by many researchers in related fields at which we use in this article, [19-23].

In this article we do not deal in essence by this analysis so we will propose as an example one type of multi-criteria function, whose minimization condition is approximation of ideal vector (4) obtaining a feasible vector. Therefore, let be the function:

$$\begin{aligned}\Psi(x) = [&w_e(f_e(x) - z_e)^2 + w_{ts}(f_{ts}(x) - z_{ts})^2 + \\ &+ w_{ab}(f_{ab}(x) - z_{abe})^2 + w_{ar}(f_{ar}(x) - z_{ar})^2 + \\ &+ w_{tr}(f_{tr}(x) - z_{tr})^2 + w_h(f_h(x) - z_h)^2 + \\ &+ w_d(f_d(x) - z_d)^2 + w_w(f_w(x) - z_w)^2]^{\frac{1}{2}}\end{aligned} \tag{5}$$

In (5) can be taken for calculation any of the calculated interpolation polynomials (grade 1, 2 and 3) or other interpolation functions for each of the interpolation functions of the CFP composite material mechanical characteristics. Also in (5), factors w_i, $i=1...8$, positive, are components of a weight vector:

$$w = (w_e, w_{ts}, w_{ab}, w_{ar}, w_{tr}, w_h, w_d, w_w) \tag{6}$$

that satisfy the condition:

$$w_e + w_{ts} + w_{ab} + w_{ar} + w_{tr} + w_h + w_d + w_w = 1 \tag{7}$$

and express interest of the client for the mechanical properties of the composite material. If they are all equal ($w_1 = w_2 = ... = w_8$), then the interest is the same for achieving any value of the mechanical properties. If any of the weights is zero, this means that the customer is totally uninterested of that mechanical property of the composite material.

Results and discussions

To facilitate the understanding of the ideas presented earlier, is given an example that illustrates how to use the experimental data in order to control the manufacturing process of the composite material (CFP), of the elaboration of some structural variety of it, that correspond to the possible diverse requests of customers. Be ideal vector z in the first column of table 3 (the ideal vector and the feasible vectors obtained using polynomial interpolation function of grade 1, 2 and 3).

Minimizing the function (5), in which interpolation polynomial of grade 1, 2, 3 is used, is obtained feasible vector (namely the tangible values of the mechanical characteristics) given in table 2, columns 2, 3, 4. To obtain these results was used a weight vector (6) with all components equal to 0.125, meaning equal interest of the client for achieving value of each of the mechanical properties of the composite material (CFP).

As seen in figure 9, the three objective functions used have single points of minimum on the interval of waste

Table 3

Vector target, *z*	Optimal vector polynomial interpolation grade 1	Optimal vector polynomial interpolation grade 2	Optimal vector polynomial interpolation grade 3
14.00	21.54	22.80	23.60
3.50	4.562	4.60	4.00
340.00	314.53	336.92	331.14
18.00	19.80	20.34	19.89
37.00	31.26	31.70	32.05
82.00	71.88	69.925	70.44
1.25	1.24	1.23	1.24
300.00	230.77	214.60	229.89

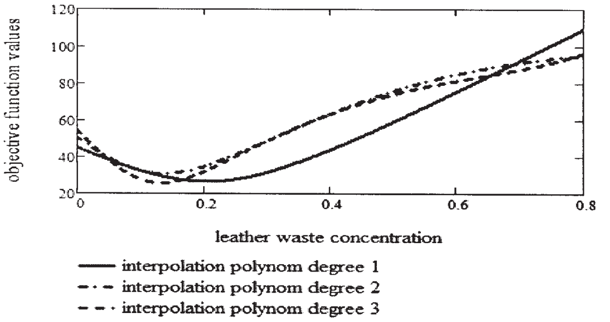

Fig. 9 The variation of objective functions type (5) formed with the three types of polynomial interpolation

leather concentrations in the used rubber matrix. The abscissa of the minimum point is not the same in each of the three variants of the objective function. For the objective function consists of polynomial interpolation functions of the first grade, the second and third are obtained minimal concentrations points with the values $c_1 = 0{,}205$, $c_2 = 0{,}136$, respectively, $c_3 = 0{,}133$ (or percentage, 20,5 %, 13,6 % and 13,3 %).

Conclusions

The researches related to the mechanical characteristics of the CFP composite have highlighted several important conclusions to increase the quality of this product, but also for other similar products from category of composite materials.

Firstly is observed that the manufacturing process of composite materials is controllable, the formulae used for control being derived, either a phenomenological model or a structural model. These models can be applied to a computer who runs the manufacturing process.

Using a single control parameter of the manufacturing process, in order to achieve a composite material with specified qualities, is a minimum example of using the process parameters that are available to researchers.

In this paper we used only leather waste concentration in the CFP composite material as an optimization parameter. Obviously, the set of optimization parameters should include in the future and other parameters: temperature, the particle size of the leather waste, pressure in the manufacturing process, the intensity of material mixing etc.

Researches have revealed the existence of some parameters that has not been taken into consideration before, the material recently developed. Discussions on the mechanical characteristics behaviour of the CFP material composite in relation to leather wastes concentration in the rubber matrix, have established to be important in future researches, the influences of the extent to which the leather is dispersed in the rubber matrix, of leather particle size of waste, of the limit work temperatures. All these issues must be addressed in the context of manufacturing technology adopted for the composite material.

Similar results can be obtained for the accelerated aged material by the same type of interpolation. It would be indicated a formula that includes the interpolation from the initial state and introduce an aging factor that depends on the parameters of the standardized accelerated aging. In addition it could be introduced aging parameters that can facilitate estimation of the material “age” and the “rest of life” left.

It should be pointed out an interesting aspect of the mechanical characteristics behaviour that generates possible beneficial phenomena for the multi-objective optimization. The curves of the second and third degree which interpolates the experimental data of some mechanical characteristics vary having the minimum and maximum, so that getting some target values for them is possible using several values of the leather wastes concentration in the rubber matrix.

However, these theoretical conclusions (strengthened by experimental data) must be checked in connection with the structure of the composite material and with the manufacturing conditions (temperature, the rate of temperature change in the composite mass, etc.).

From the point of view strictly physical, the functional (5) does not have a sense very correct because some of the terms in square brackets have different measurement units. However, even in these conditions, the specialists in multi-objective optimal analysis recommend the formation of a global objective function of the type (5), because it does not alter the coordinates of the minimum points, phenomenon that occurs when we would try to dimensionless terms inside the square bracket.

A large number of conclusions in this article introduces a number of research directions related not only to the CFP composite but also to other composite materials of the same type, as well as other types.

The used method of analysis and interpretation of the experimental data and especially their recovery in order to control the manufacturing process is also widespread for many composite materials.

In this research area are still many problems, firstly even in terms of multi-objective optimization. A production system of composite materials, equipped with such an optimal control program, becomes a *smart system* [24 - 26], able to satisfy for the customers particular quantitative requests but especially qualitative. Such an intelligent system can be “learned” not only to choose a combination of parameters favorable to an ideal vector (customer order), perhaps the most favorable, but even choose one that minimizes the energy and material consumption. Certainly these are future directions, approachable only to the extent that structural and technological process researches mentioned above will be thorough enough. These directions open the way of achieving composite materials with special qualities: intelligence, recognition, memory [27].

Considering the experimental data expressed above, we can say that the finite leather waste can be processed for achieving polymer composites used in the field of soles for shoes, seals, pavements etc. The elaborated technology is accessible to both enterprises of rubber and plastics processing as well as the tanneries and producers of finite leather.

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