UDC 51

M.V. Brailo[1], A.V. Buketov[1], S.V. Yakushchenko[1], O.O. Sapronov[1], L. Dulebova[2]

[1] *Kherson State Maritime Academy, Ukraine;*
[2] *Technical University of Košice, Slovakia*
(E-mail: yakushchenko.sv@ukr.net)

Optimization of contents of two-component polydispersed filler by applying the mathematical design of experiment in forming composites for transport repairing

The influence of two-component polydispersed filler on the elasticity modulus in flexure and impact resilience of the developed epoxy-polyester composite is analyzed. Regression equation by applying the mathematical design of experiment is found and dependence of output parameters on chosen variable factors is determined. It is proved that introduction of two-component polydispersed filler (in contents of mica – q = 20. . . 30 pts.wt., nitride boron – q = 40. . . 60 pts.wt.) in composite allows to increase significantly parameters of elasticity modulus in flexure to E = 7.2. . . 7.6 hPa with slight decrease of impact resilience to W = 4.6. . . 4.8 kJ/m^2. Theoretical analysis of the calculation results of functional relationships is carried out and mathematical model that properly describes behavior of the investigated material is found. Optimal content of main and additional fillers in composite for each property is established using found regression equations. It is determined that composite material in contents of mica q = 20. . . 30 pts.wt. and of nitride boron q = 40. . . 60 pts.wt. has optimal parameters.

Keywords: composite, epoxy-polyester matrix, two-component polydispersed filler, method of mathematical design of experiment, regression equation.

Introduction

Development of multicomponent system, which is a polymeric composite material (PCM), is a complex and long-lasting process. The composite with necessary properties can be formed by changing the content of single components, that is, changing the composition of multicomponent system. At the same time, to determine the structure of interrelationships of object parameters (properties) and to find quantitative constraint equation of outcome indexes and outcome parameters it is necessary to conduct set of experiments that requires high material costs. Therefore, an important task is to get necessary data with a minimum number of experiments. In order to optimize the results of multicomponent systems research, the mathematical design of the experiment is used for the required accuracy of results. Mathematical model receiving allows predicting material properties. Forecasting allows taking into account all factors that affect the functioning of heterogeneous systems, and provides the formation of technical object with high efficiency and quality [1, 2]. It is important to note that the use of the created bidisperse two-component composite material with improved properties in the complex during manufacturing and repairing the elements of marine transport (protective coatings for ship hulls, parts of friction units for ship machinery, etc.) allow significantly improve their operational characteristics.

During experimental studies different disperse fillers are added to binder to increase PCM outcome parameters [3, 4]. The issues of optimizing the composition and structure of highly filled epoxy composites containing additives of various dispersion are highlighted in works [5-8]. It should be noted that epoxy-polyester matrixes filled with dispersed fillers insufficiently investigated. The influence of disperse fillers (mica and nitride boron hexagonal) on the developed matrix (each component separately) is predetermined. The purpose of chosen disperse particles is to improve the PCM tribological properties. The multifactorial interaction of two-component polydispersed filler in complex with respect to composites properties remains unexplored. The method of simultaneous variation of several parameters in order to study their impact and the impact of interaction on the composites performance characteristics is used precisely in the integrated approach to establish the optimal content of mica and NB. During active experiment mathematical design exclude implementation of a large number of experiments and significantly reduces the timing of receiving the result.

Aim of work – to optimize the content of two-component polydispersed filler to improve the performance characteristics of composite material for its use in repairing the working elements of marine transport using the method of mathematical planning of the experiment.

Results and discussion

Design of experiment allows building a research strategy based on a sequence of clear and logically deliberated operations. Received mathematical model reflects the interconnection of the physical and mechanical properties of composites (elasticity modulus in flexure and impact resilience) from the content of bidispersed filler and gives an opportunity to study its influence on composition outcome parameters. The nature of changes of elasticity modulus in flexure and impact resilience as a result of addition of different amounts of main and additional fillers (mica and nitride boron hexagonal, respectively) is investigated. Particles dispersion according to granulometric analysis: mica – 20...40 micron, NB – 8...10 micron. For standardization, as well as for simplification of calculations, each component (filler) is encoded by conditional units taking into account variations (Table 1).

Table 1

Levels of variables on conditional and natural scale

Components	Factor	Average level, q, pts.wt.	Variation step, Δq, pts.wt.	Values of variables (pts.wt.), that corresponding to conditional units		
				-1	0	+1
Main filler – mica	x_1	30	10	20	30	40
Additional filler – nitride boron hexagonal	x_2	40	20	20	40	60

According to the experiment planning scheme 9 experiments (N = 9) were conducted, each of which was repeated three times (p = 3) in order to exclude system errors (Table 2). In order that planning matrix to be orthogonal [9], the corrected values of E'level were entered, which were calculated by the formula

$$x_i' = (x_i)^2 - \frac{\sum_{u-1}^{N} x_{iu}^2}{N}. \tag{1}$$

Table 2

Scheme of experiment planning

No of experiment *(u)*	x_0	x_1	x_2	$E_3 = E_1^2 - d$	$E_4 = E_2^2 - d$	E_1E_2
1	2	3	4	5	6	7
1	1	-1	-1	0.33	0.33	+1
2	1	+1	-1	0.33	0.33	-1
3	1	-1	+1	0.33	0.33	-1
4	1	+1	+1	0.33	0.33	+1
5	1	0	0	-0.67	-0.67	0
6	1	+1	0	0.33	-0.67	0

Table continuation

1	2	3	4	5	6	7
7	1	-1	0	0.33	-0.67	0
8	1	0	+1	-0.67	0.33	0
9	1	0	-1	-0.67	0.33	0
$\sum_{u-1}^{N} x_{iu}^2$	9	6	6	2	2	4

The expanded matrix of planning of complete factor experiment (CFE) and its results are shown in Table 3.

Table 3

The results of investigation of the elasticity modulus in flexure and impact resilience PCM

No of experiment	Content of components, q, pts.wt.		Elasticity modulus in flexure, E, hPa	Impact resilience, W, kJ/m^2
	x_1	x_2	y_1	y_2
1	20	20	5.6	4.1
2	40	20	5.2	3.9
3	20	60	7.6	4.8
4	40	60	6.2	4.5
5	30	40	7.2	4.6
6	40	40	5.8	4.2
7	20	40	6.8	4.3
8	30	60	6.9	4.4
9	30	20	5.4	4.3

The mathematical model $y = f\ (x_1,\ x_2)$ was formed as a regression equation

$$y = b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2. \qquad (2)$$

The regression coefficients were determined by the formula:

$$b_i = \frac{\sum_{u=1}^{N} x_i y_i}{\sum_{u-1}^{N} x_{iu}^2}. \qquad (3)$$

Received coefficients of regression equation are given in Table 4.

Table 4

The coefficients of regression equation

b_0	b_1	b_2	b_{11}	b_{22}	b_{12}
6.80	-0.47	0.75	-0.3	-0.45	-0.25

As a result, in the analysis of the elasticity modulus in flexure, the following regression equation was determined:

$$y = 6.8 - 0.47x_1 + 0.75E_2 - 0.3E_1^2 - 0.45E_2^2 - 0.25E_1E_2.$$

For the statistical processing of experiment results, a test of reproducibility of experiments by the Cochran test was conducted:

$$G = \frac{S_{umax}^2}{\sum_{u=1}^{m} S_{ui}^2} \leq G_{(0,05;f_1;f_2)}, \qquad (4)$$

where S_{ui}^2 — dispersion of experiment results on combinations of few factor levels for m=3; m — number of parallel experiments; $S^2{}_{umax}$ — the highest dispersion in design line.

Dispersions of adequacy were determined by the formula:

$$S_{ui}^2 = \frac{\sum_{i=1}^{m} (y_i - \overline{y_i})^2}{m-1}, \qquad (5)$$

where y_{im} — value, received from each parallel experiment; $\overline{y_i}$ — average value y, received in parallel experiments.

Mean square error was determined by formula:

$$\sigma^2\left\{y\right\} = \frac{\sum_{i=1}^{N=9} \sigma^2\left\{y\right\}_i}{N(m-1)}, \tag{6}$$

where $\sigma^2\left\{y\right\}_i = \sum_{i=1}^{m=3}(y_i - \overline{y_i})^2$;

$$\sigma^2\left\{y_{av}\right\} = \frac{0^2\{C\}}{N}, \quad S_{b_0}^2 = \frac{S_0^2}{N}. \tag{7}$$

Dispersion values are shown in Table 5.

Table 5

Values of dispersions of adequacy (S_{ui}^2) and mean square error ($\sigma^2\left\{y\right\}_i$)

No	The dispersions of adequacy		The mean square error	
	conditional designation	value	conditional designation	value
1	S_{u1}^2	0.03	$\sigma^2\left\{y\right\}_1$	0.06
2	S_{u2}^2	0.04	$\sigma^2\left\{y\right\}_2$	0.08
3	S_{u3}^2	0.03	$\sigma^2\left\{y\right\}_3$	0.06
4	S_{u4}^2	0.01	$\sigma^2\left\{y\right\}_4$	0.02
5	S_{u5}^2	0.03	$\sigma^2\left\{y\right\}_5$	0.06
6	S_{u6}^2	0.01	$\sigma^2\left\{y\right\}_6$	0.02
7	S_{u7}^2	0.04	$\sigma^2\left\{y\right\}_7$	0.08
8	S_{u8}^2	0.03	$\sigma^2\left\{y\right\}_8$	0.06
9	S_{u9}^2	0.01	$\sigma^2\left\{y\right\}_9$	0.02

n this case:

$$\sum_{i=1}^{N} S_{ui}^2 = 0.23;$$

$$\sigma^2\left\{y\right\} = S_0^2 = 0.026.$$

Then the calculated value of the Cochran test at the 5% level of significance:

$$G_{calc} = \frac{S_{u_{\max}}^2}{\sum_{i=1}^{N} S_{ui}^2}; \tag{8}$$

$$G_{calc} = \frac{0,04}{0,23} = 0.174.$$

Testing the experiment results by the Cochran test [9] for a fixed probability $\alpha = 0.05$ confirmed the reproducibility of the experiments. Dispersion of experiment results on combinations of few factor levels: $S_{u\max}^2 = 0.04$. Calculated value of Cochran test: $G_{calc} = 0.174$.

Table value of Cochran test: $G_{tab} = 0.478$.

So, the requirement is fulfilled (7):

$$G_{calc} = 0.174 \leq G_{tab} = 0.478.$$

Subsequently, the coefficients significance of regression equation was determined by analyzing the results according to the experimental design (Table 6).

Table 6

The experimental results of study of the elasticity modulus in flexure of materials

No of experiment	Elasticity modulus in flexure, E, hPa			Average value, E, hPa
	1	2	3	
1	5.4	5.7	5.7	5.6
2	5.0	5.4	5.2	5.2
3	7.4	7.7	7.7	7.6
4	6.3	6.1	6.2	6.2
5	7.1	7.4	7.1	7.2
6	5.7	5.9	5.8	5.8
7	6.6	7.0	6.8	6.8
8	6.7	7.0	7.0	6.9
9	5.3	5.5	5.4	5.4

Then the dispersions of regression coefficients (Table 7) were determined by the formula:

$$S_{b_i}^2 = \frac{S_0^2}{\sum_{u-1}^{N} x_{iu}^2}. \tag{9}$$

The significance of the regression coefficients was determined by the Student's test [10, 11]. Here with the table (t) and calculated criterion (t) of Student's test (Table 7) were determined.

Depending on freeness: f = N (n - 1) = 9 (3 - 1) = 18 the Student's test value were calculated, which is $t = 2.1$.

Calculated values of Student's test (t) and coefficients significance were determined: $t_0, t_1, t_2, t_{11}, t_{22}, t_{12} > t_T$. Moreover:

$$t_{i@} = \frac{|b_i|}{S_{b_i}}. \tag{10}$$

Table 7

Dispersion of coefficients of regression (S_b^2) and calculated values of Student's criterion (t)

No	Dispersion of coefficients of regression		Calculated values of Student's criterion	
	conditional designation	value	conditional designation	value
1	$S_{b_0}^2$	0.003	t_0	123.19
2	$S_{b_1}^2$	0.004	t_1	7.15
3	$S_{b_2}^2$	0.004	t_2	11.49
4	$S_{b_{11}}^2$	0.013	t_{11}	2.65
5	$S_{b_{22}}^2$	0.013	t_{22}	3.98
6	$S_{b_{12}}^2$	0.006	t_{12}	3.10

Calculated values of Student's criterion $t_0, t_1, t_2, t_{11}, t_{22}, t_{12}$ are larger than t_T, so it was considered that all coefficients of the regression equation are significant. As a result of rejection of insignificant coefficients, the following regression equation was received: $y = 6.8 - 0.47x_1 + 0.75E_2 - 0.3E_1^2 - 0.45E_2^2 - 0.25E_1E_2$.

The adequacy of the model was checked by Fisher test [3, 7]:

$$F_c = \frac{S_{u\max}^2}{S_y^2} \leq F_{(0.05;f_{0d};f_y)}, \tag{11}$$

where $S_{umax}^2 = 0.04$ — calculated value of dispersion of adequacy (Table 5);

$$S_y^2 = \frac{\sum_{i=1}^{N} S_{ui}^2}{N}, \tag{12}$$

$S_y^2 = 0.026$ — mean square error. So: $F_c = 1.565$.

$F_{(0.05;f_{0d};f_u)}$- table value of Fisher test in 5% significance level $f_1 = N - (k+1) = 9 - (6+1) = 2$, $f_2 = N(n-1) = 9(3-1) = 18$). So: $F_{(t)} = 3.55$ [10, 11].

Calculated value of Fisher test is less than table one, so the requirement (10)is fulfilled. It is possible to assume that equation adequately characterizes the composition.

Interpretation process of received mathematical model, as a rule, is not just determination of factors influence. A simple comparison of absolute value of linear coefficients does not determine the relative degree factors influence, since there are also quadratic squared terms and paired interactions. In a detailed analysis of the received adequate model, it is necessary to take into account the fact that for a quadratic model the degree of factor influence on the change of output value is not constant.

Dependencies that connect normalized and natural values of the variables are as follows:

$$x_i = \frac{q_i - q_{i0}}{\Delta q_i}, \tag{13}$$

where q_i — value of i experiment factor; q_{i0} — value of zero level; Δq_i — variation interval [9].

Substituting these values in accordance with the formula (13) into the regression equation and transforming it, we receive the following regression equation with the natural values of the variables:

$$E = 0.86 + 0.178q_1 + 0.16125q_2 - 0.003q_1^2 - 0.001125q_2^2 - 0.00125q_1q_2.$$

Given equation in natural values allows only predicting the output value for any point in the middle of range of factor variations. However, with its help it is possible to construct graphs of dependence of output value (elasticity modulus in flexure of composites) from any factor (or two factors). Geometric interpretation of the response surface is shown on Figure 1-3.

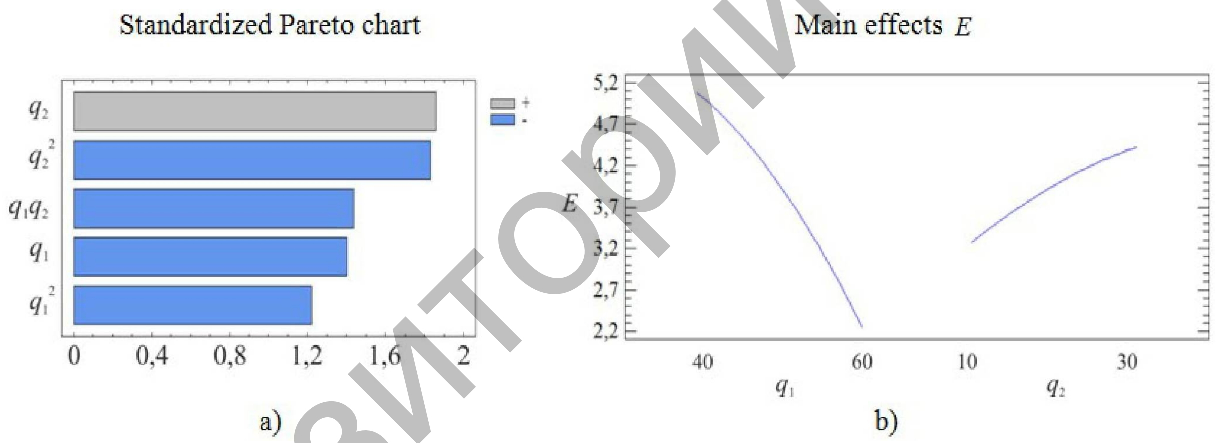


Figure 1. Standardized Pareto chart (a) and main effects (b)

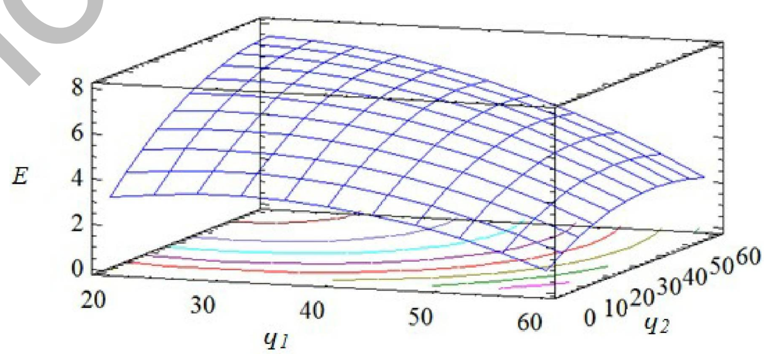


Figure 2. Estimated surface $E = f(q_1, q_2)$

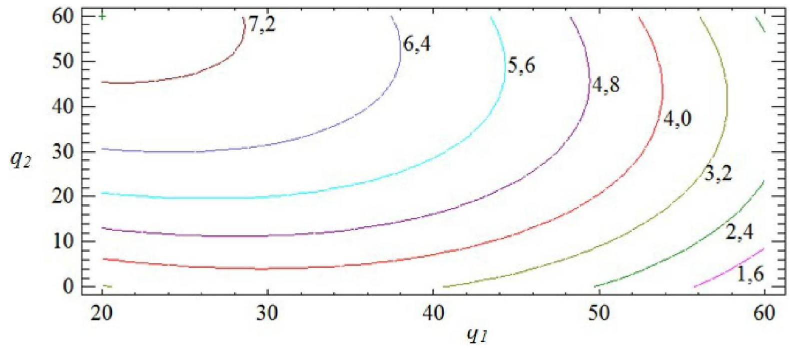


Figure 3. Contours of estimated response surface

Based on experimental studies it is set that both factors are significant. It should be noted that the effect of the additional filler content on the parameters of elasticity modulus in flexure is higher in comparison with the main one (according to Pareto chart). Analyzing the calculated response surface, it is determined that the optimum parameters of elasticity modulus in flexure have developed epoxy-polyester composite with two-component poly dispersed filler with the following content of particles: mica – 20...30 pts.wt., NB – 40...60 pts.wt. ($E = 7.2 \dots 7.6 hPa$).

Similarly to the above calculations scheme, the composition formula was optimized according to the viscosity index. The encoding of natural components values and the experimental design scheme are chosen according to Table 1 and Table 2.

In the process of study results analysis of composites impact resilience, the following values of the regression coefficients were received (Table 8).

Table 8

The coefficients of regression equation

b_0	b_1	b_2	b_{11}	b_{22}	b_{12}
4.42	-0.18	0.32	0.02	-0.18	0.05

As a result, the following regression equation was found:

$$y = 4.42 - 0.18x_1 + 0.32E_2 + 0.02E_1^2 - 0.18E_2^2 + 0.05E_1E_2.$$

For statistical processing of experiment results, a test of experiments reproducibility was conducted according to the Cochran test [9].

Dispersions values that were calculated by formula (5-7) are shown in a Table 9.

Table 9

Values of dispersions of adequacy (S^2_{ui}) and mean square error ($\sigma^2\{y\}_i$)

No	The dispersions of adequacy		The mean square errors	
	conditional designation	value	conditional designation	value
1	S^2_{u1}	0.01	$\sigma^2\{y\}_1$	0.02
2	S^2_{u2}	0.04	$\sigma^2\{y\}_2$	0.08
3	S^2_{u3}	0.03	$\sigma^2\{y\}_3$	0.06
4	S^2_{u4}	0.03	$\sigma^2\{y\}_4$	0.06
5	S^2_{u5}	0.04	$\sigma^2\{y\}_5$	0.08
6	S^2_{u6}	0.01	$\sigma^2\{y\}_6$	0.02
7	S^2_{u7}	0.01	$\sigma^2\{y\}_7$	0.02
8	S^2_{u8}	0.03	$\sigma^2\{y\}_8$	0.06
9	S^2_{u9}	0.03	$\sigma^2\{y\}_9$	0.06

Moreover:

$$\sum_{i=1}^{N} S_{ui}^2 = 0.23;$$

$$\sigma^2 \{y\} = S_0^2 = 0.026.$$

Calculated value of the Cochran test at the 5% significance level was determined by formula (8):

$$G_c = \frac{0.04}{0.23} = 0.174.$$

Testing the experiment results by the Cochran test [10, 11] for a fixed probability $\alpha = 0.05$ confirmed the experiments reproducibility. Dispersion characterizing dispersal of the experiments results in combination of few factor levels: $S_{u\,\max}^2 = 0.04$. Calculated value of Cochran test: $G_{calc} = 0.174$.

Table value of Cochran test: $G_{tab} = 0.478$.

So, the requirement is fulfilled:

$$G_{calc} = 0.174 \leq G_{tab} = 0.478.$$

At the next stage, the coefficients significance of regression equation is determined, analyzing the results according to the experimental design (Table 10).

Table 10

The experimental results of study of the impact resilience of CM

No of experiment	Impact resilience, W', kJ/m^2			Average value, W', kJ/m^2
	1	2	3	
1	4.3	4.1	4.2	4.2
2	3.9	3.5	3.7	3.7
3	4.7	4.7	5.0	4.8
4	4.6	4.3	4.6	4.5
5	4.4	4.8	4.6	4.6
6	4.1	4.2	4.3	4.2
7	4.4	4.5	4.6	4.5
8	4.5	4.2	4.5	4.4
9	3.8	4.1	3.8	3.9

Subsequently, dispersion of regression coefficients is determined by formulas (9-10). The significance of regression coefficients is determined according to Student's criterion, which table value is $t_T = 2.1$ [10,11]. Calculated values of Student's criterion are shown in Table 11.

Table 11

Dispersion of coefficients of regression (S_b^2) and calculated values of Student's criterion (t)

No	Dispersion of coefficients of regression		Calculated values of Student's criterion	
	conditional designation	value	conditional designation	value
1	$S_{b_0}^2$	0.003	t_0	81.81
2	$S_{b_1}^2$	0.004	t_1	2.81
3	$S_{b_2}^2$	0.004	t_2	4.85
4	$S_{b_{11}}^2$	0.013	t_{11}	0.15
5	$S_{b_{22}}^2$	0.013	t_{22}	1.62
6	$S_{b_{12}}^2$	0.006	t_{12}	0.60

Calculated values of Student's criterion t_0, t_1, t_2 are larger than t, so it is considered that coefficients b_0, b_1, b_2 of regression equation are significant. Calculated values t_{11}, t_{22}, t_{12} are smaller than t_T, so coefficients b_{11}, b_{22}, b_{12} are insignificant. As a result, the following regression equation is received:

$$y = 4.42 - 0.18x_1 + 0.32E_2.$$

The adequacy of the model was checked by Fisher's test [10, 11].

Calculated value of adequacy dispersion: $S^2_{u\,\max} = 0.04$ (Table 9).

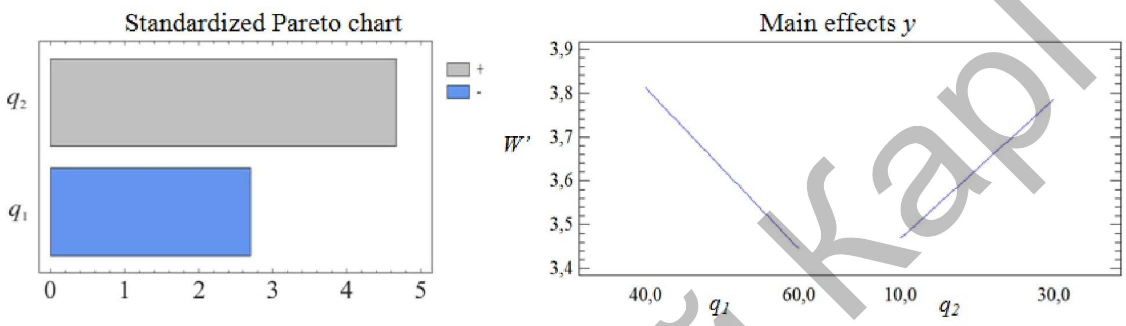
The mean square error: $S^2_y = 0.026$. So: $F = 1.565$. $F_{(0{,}05;f_W;f_u)}$ — table value of Fisher's test in 5% significance level ($F_{(t)} = 2.77$) [10, 11].

Calculated value of Fisher's test is smaller than table on, so requirement (11) is fulfilled. Consequently, the equation adequately shows the composition formula.

After transformations in accordance with formula (13), the following regression equation with the natural values of variables was received:

$$W' = 4.32 - 0.018q_1 + 0.016q_2.$$

Geometric interpretation of response surface is shown on Figure 4-6.



a) b)

Figure 4. Standardized Pareto chart (a) and main effects (b)

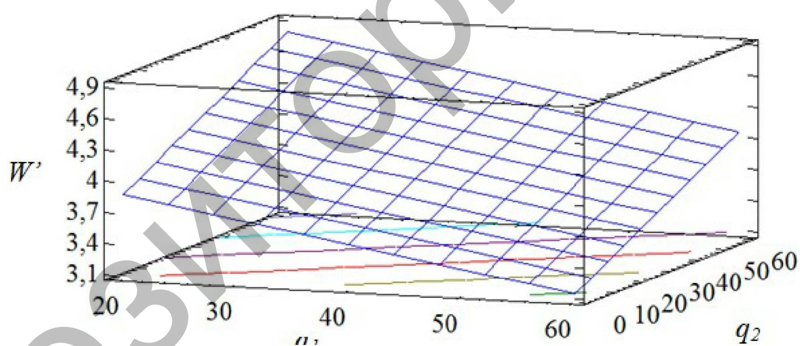


Figure 5. Estimated surface $W' = f(q_1, q_2)$

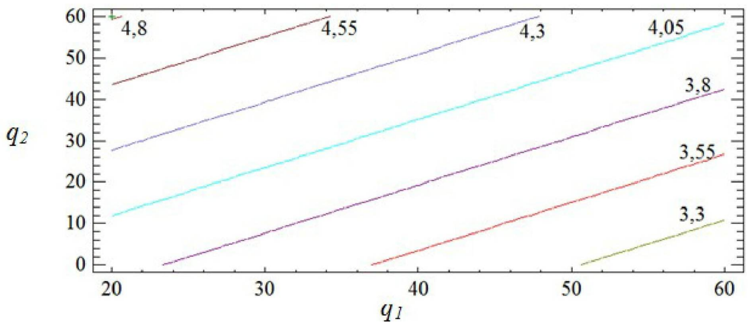


Figure 6. Contours of estimated response surface

Received results indicate that both factors of regression equation are significant. However, the output parameters of the composite are influenced only by linear dependencies of these factors. In the process of analysis, it was determined that the impact resilience values show maximum values for the fillers contents: mica – 20...30 pts.wt., nitride boron hexagonal – 40...60 pts.wt. (W' = 4,6…4,8 кДж/м^2). With further increase of particles in content the impact resilience degradation was observed. In our opinion, this happens due to aggregation of fillers in polymer matrix, which negatively affects the physical and mechanical properties of the material. Therefore it is advisable to add two-component polydisperse filler with the aforementioned content into modified epoxy-polyester matrix to improve performance in the repair of marine transport elements.

Conclusions

The analysis of set of experiments results in mathematical design of experiment showed that in regression dependences linear effects have more significant effect than interaction effects. This is especially noticeable in regression dependence in study of the composite material impact resilience. Received results are confirmed by Pareto charts and response surfaces. The optimum content of two-component polydispersed filler was set: mica is 20...30 pts.wt., nitride boron hexagonal is 40...60 pts.wt. The introduction of two-component polydispersed filler into the composite on the basis of epoxy-polyester binder can significantly increase values of elasticity modulus in flexure of composites to E = 7.2...7.6 hPa with a slight decrease of impact resilience to W' = 4.6...4.8 kJ/m^2. Received results allow getting materials with improved parameters of physical and mechanical properties. Due to the use of developed CM for protective coatings for ship hulls, repair of friction units of ship machinery, etc. it is possible to increase term between their overhauls and improve the performance characteristics in general.

The authors convey sincere thanks for opportunity of mobility and financial support during the research work at the Technical University of Košice (Slovak Republic) in accordance with the National Scholarship Program of the Slovak Republic (SAIA Programs).

References

1 Li X. Mathematical modeling and evolutionary algorithm-based approach for integrated process planning and scheduling / Xinyu Li, Liang Gao, Xinyu Shao, Chaoyong Zhang, Cuiyu Wang // Computers & Operations Research. — 2010. — Vol. 37(4). — P. 656–667.

2 Букетов А.В. Применение методов математической статистики для оптимизации состава защитных покрытий / А.В. Букетов, А.В. Акимов, В.Д. Нигалатий, Н.В. Браило, Аль-Джавахери Али Андан Мансур // Вестник Карагандинского университета. — 2017. — № 1(85). — С. 17–27.

3 Sandler J. Development of a dispersion process for carbon nanotubes in an epoxy matrix and the resulting electrical properties / J Sandler, M.S.P. Shaffer, T. Prasse, W. Bauhofer, K. Schulte, A.H. Windle // Polymer. — 1999. — Vol. 40(21). — P. 5967–5971.

4 Hussain M. Mechanical property improvement of carbon fiber reinforced epoxy composites by Al2O3 filler dispersion / Manwar Hussain, Atsushi Nakahira, Koichi Niihara // Materials Letters. — 2010. — Vol. 26(3). — P. 185–191.

5 Buketov A.V. Investigation of the physico-mechanical and thermophysical properties of epoxy composites with a two-component bidisperse filler / A.V. Buketov, O.O. Sapronov, M.V.Brailo // Strength of Materials. — 2014. — Vol. 46(5). — P. 717–723.

6 Сапронов О.О. Оптимізація складу захисного покриття методом математичного планування експерименту // Загальнодержавний міжвідомчий науково-технічний збірник. Конструювання, виробництво та експлуатація сільськогосподарських машин. — Кіровоград: КНТУ, 2013. — № 43. — Ч. II. — С. 260–267.

7 Duleba B. Possibility of Increasing the Mechanical Strength of CarbonEpoxy Composites by Addition of Carbon Nanotubes / B. Duleba, F. Greskovic, L. Dulebova, T. Jachowicz // Materials Science Forum: Surface Engineering and Materials in Mechanical Engineering. — 2015. — Vol. 818. — P. 299–302.

8 Buketov A. Investigation of thermophysical properties of epoxy nanocomposites / A. Buketov, P. Maruschak, O. Sapronov, M. Brailo, O. Leshchenko, L. Bencheikh A. Menou // Molecular Crystals and Liquid Crystals. — 2016. — Vol. 628:1. — P. 167–179.

9 Бондарь А.Г. Планирование эксперимента в химической технологии (основное положение, примеры и задачи): учебник для студ. высш. учеб. завед. / А.Г. Бондарь, Г.А. Статюха. — Киев: Вища школа, 1976. — 184 с.

10 Грушко И.М. Основы научных исследований: учебник для техн. вузов / И.М. Грушко, В.В. Попов и др.; под ред. В.И. Крутова, В.В. Попова. — М.: Высш. шк., 1989. — 400 с.

11 Математические методы планирования эксперимента / под ред. В.В. Пененко. — Новосибирск: Наука, 1981. — 250 с.

Н.В. Браило, А.В. Букетов, С.В. Якущенко, А.А. Сапронов, Л. Дулебова

Көлік құралдарын жөндеуге арналған композиттерді дайындауда эксперименттің математикалық дизайнын қолдану арқылы екікомпонентті полидисперсті толтырғыштың мазмұнын оңтайландыру

Иілген және соққы тұтқырлық өңделген эпоксидті-полиэфир композит үшін бикомпонентті полидисперсті толтырғыштың серіппелік модуліне әсері талданған. Экспериментті математикалық жоспарлау әдісімен регрессия теңдеуі және таңдалған айнымалы факторлардан шағатын параметрлерден тәуелділігі алынған. Құрамға (слюда - q = 20. . . 30 мас. сағ.; NB - q = 40. . . 60 мас. сағ.) бикомпонентті полидисперсті толтырғышты копозитті енгізу, иілуі болмашы E = 7.2. . . 7.6 hPa дейін соққы тұтқырлығын азайтуға, болмашы W ’= 4,6 . . . 4,8 кДж / м^2 дейін соққы серпімділігін азайтуға серпімділік модулінің көрсеткіштерін едәуір көтеруге мүмкіндік беретіні дәлелденген. Зерттелетін материалдың өзгерісін сипаттайтын функционалдық тәуелділік есептеулері нәтижелерінің теориялық талдауы жүргізілген және математикалық моделі алынған. Шыққан регрессия теңдеулерінің көмегімен әр қасиет үшін композиттегі негізгі және қосымша толтырғыштардың оңтайлы құрамы алынған. Құрамы q = 20...30 мас. сағ. слюда және q = 40. . . 60 мас. сағ. бор нитриды болатын композитті материал жақсартылған көрсеткіштермен сипатталатыны көрсетілген.

Кілт сөздер: композициялық, эпоксид-полиэфирлі матрица, екікомпонентті полидисперстік толтырғыш, математикалық эксперименттерді жоспарлау әдісі, регрессиялық теңдеу.

Н.В. Браило, А.В. Букетов, С.В. Якущенко, А.А. Сапронов, Л. Дулебова

Оптимизация содержания двухкомпонентного полидисперсного наполнителя путем применения математического планирования эксперимента при получении композитов для ремонта транспортных средств

Проанализировано влияние двухкомпонентного полидисперсного наполнителя на модуль упругости при изгибе и ударную вязкость разработанного эпоксидно-полиэфирного композита. Методом математического планирования эксперимента получены уравнения регрессии и установлена зависимость выходных параметров от выбранных переменных факторов. Доказано, что введение в состав композита двухкомпонентного полидисперсного наполнителя при содержании (слюда - q = 20. . . 30 мас.ч., NB - q = 40. . . 60 мас.ч.) позволяет значительно повысить показатели модуля упругости при изгибе до E = 7.2. . . 7.6 hPa при незначительном снижении ударной вязкости до W’ = 4,6. . . 4,8 кДж/м^2. Проведен теоретический анализ результатов расчета функциональных зависимостей, и получена математическая модель, которая адекватно описывает поведение исследуемого материала. С помощью полученных уравнений регрессии установлено оптимальное содержание основного и дополнительного наполнителей в композите для каждого свойства. Доказано, что улучшенными показателями характеризуется композитный материал по содержанию q = 20. . . 30 мас.ч. слюды и q = 40. . . 60 мас.ч. нитрид бора.

Ключевые слова: композит, эпоксидно-полиэфирная матрица, двухкомпонентный полидисперсный наполнитель, метод математического планирования эксперимента, уравнение регрессии.

References

1 Xinyu, Li, Liang, Gao, Xinyu, Shao, Chaoyong, Zhang, & Cuiyu, Wang. (2010). Mathematical modeling and evolutionary algorithm-based approach for integrated process planning and scheduling. *Computers & Operations Research, Vol. 37(4)*, 656–667.

2 Buketov, A.V., Akimov, A.V., Nigalatiy, V.D., Brailo, N.V., & Al'-Dzhavakheri Ali Andan Mansur. (2017). Primenenie metodov matematicheskoi statistiki dlya optimizatsii sostava zashchitnykh pokrytii [Application of methods of mathematical statistics to optimize the composition of protective coatings]. *Vestnik Karahandinskoho universiteta – Bulletin of Karaganda University, 1(85)*, 17–27 [in Russian].

3 Sandler, J., Shaffer, M.S.P, Prasse, T., Bauhofer, W., Schulte, K., & Windle, A.H. (1999). Development of a dispersion process for carbon nanotubes in an epoxy matrix and the resulting electrical properties. *Polymer, Vol. 40(21),* 5967–5971.

4 Manwar Hussain, Atsushi Nakahira, & Koichi Niihara. (2010). Mechanical property improvement of carbon fiber reinforced epoxy composites by Al2O3 filler dispersion. *Materials Letters, Vol. 26(3)*, 185–191.

5 Buketov, A.V., Sapronov, O.O., & Brailo, M.V. (2014). Investigation of the physico-mechanical and thermophysical properties of epoxy composites with a two-component bidisperse filler. *Strength of Materials, Vol. 46(5)*, 717–723.

6 Sapronov, O.O. (2013). Optimizatsiia skladu zakhisnoho pokrittia metodom matematichnoho planuvannia eksperimentu [Optimization of the composition of the protective coating by the method of mathematical planning of the experiment]. Zahalnoderzhavnii mizhvidomchii naukovo-tekhnichnii zbirnik. Konstruiuvannia, virobnitstvo ta ekspluatatsiia silskohospodarskikh mashin – National interagency scientific and technical digest. Design, manufacture and operation of machines, 43, II, 260–267. Kirovograd: KNTU [in Ukrainian].

7 Duleba, B., Greskovic, F., Dulebova, L., & Jachowicz, T. (2015). Possibility of Increasing the Mechanical Strength of CarbonEpoxy Composites by Addition of Carbon Nanotubes. *Materials Science Forum: Surface Engineering and Materials in Mechanical Engineering, Vol. 818*, 299–302.

8 Buketov, A., Maruschak, P., Sapronov, O., Brailo, M., Leshchenko, O., Bencheikh, L., & Menou, A. (2016). Investigation of thermophysical properties of epoxy nanocomposites. *Molecular Crystals and Liquid Crystals, Vol. 628:1*, 167–179.

9 Bondar', A.G., & Statyukha, G.A. (1976). *Planirovanie eksperimenta v khimicheskoi tekhnolohii (osnovnoe polozhenie, primery i zadachi) [Planning an experiment in chemical technology (main position, examples and tasks)].* Kiev: Vysshaia shkola [in Russian].

10 Grushko, I.M., Popov, V.V., & et al. (1989). *Osnovy nauchnykh issledovanii [Fundamentals of Scientific Research].* V.I. Krutova, & V.V. Popova (Ed.). Moscow: Vysshaia shkola [in Russian].

11 Penenko, V.V. (Eds.). (1981). *Matematicheskie metody planirovaniia eksperimenta [Mathematical methods of experiment planning].* Novosibirsk: Nauka [in Russian].