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OPTIMIZATION OF RECIPES OF DEVELOPED RUBBER MIXTURES TAKING INTO ACCOUNT THE EVALUATION OF PHYSICAL AND MECHANICAL PROPERTIES

Annotation: *Optimization of the composition of rubber compounds is a complex and multifactorial process due to the variety of components used and the complex relationships between them. Conducting a series of experimental studies to select the optimal formulation requires a significant investment of time, raw materials and laboratory resources. In this paper, an approach based on the use of mathematical modeling methods is proposed, which makes it possible to predict the properties of rubber compounds and determine their optimal composition. Special attention is paid to the use of natural zeolite and oil refining waste as modifying additives, which helps to increase the efficiency and environmental friendliness of production. The additives used include the organic fraction of oil sludge and natural zeolite from the Chankanai deposit. Based on a priori information, an experimental design was developed to enable the construction of adequate mathematical models using the least squares method. These models describe the relationships between the component composition and both performance properties and economic criteria. An optimization problem is then formulated based on these models, followed by an analysis of its features and the selection of the most effective solution method. The effectiveness of the proposed approach is demonstrated through an example of optimizing the rubber compound formulation. Modification of rubber compounds makes it possible to obtain composite materials with increased oil resistance, stable elastic and strength properties. This approach helps to reduce production costs by using affordable raw materials and simplifying the technological process. The developed computational model for determining the optimal composition of a rubber compound can be used both in scientific research and in industrial practice in the development of new formulations of elastomeric compositions.*

Key words: *multicomponent mixtures, rubber mixtures for sealing the hydraulic seals, optimization problem, conditional tensile strength, composition – cost.*

Introduction. Modern production of rubber, construction and other industrial products relies on the use of complex multicomponent systems, which include binders, fillers, resins, plasticizers and various chemical additives that provide the required performance characteristics of materials. These materials represent heterogeneous systems composed of particles and grains of varying dimensions. Their formulation can be mathematically described by a set of fractions zi, expressed in mass, volume, or molar terms, meeting the conditions $0 \le z_i \le 1$ and $\sum z_i = 1$. When the performance of such systems is governed exclusively by the ratios between individual components $z = (z_1, z_2, \ldots, z_n)$, and not by the overall quantity, processing methods, or external influences, they are referred to as multicomponent systems [1].

In the production of rubber products, it is often necessary to optimize the composition of multi-component mixtures so that certain properties of these mixtures reach the best values, while taking into account economic aspects. In the case of rubber mixtures, after developing the basic recipe, it is important not only to fix the initial ratios of the components, but also to optimize them in the process of further adjustment. This allows us to accurately determine such concentrations of individual components of the mixture, at which the key performance characteristics of the vulcanizate, determining the quality of the final product, will be expressed to the maximum. It is important that the technological requirements are met, and the material and energy costs for the production of the product remain minimal.

The composition of rubber mixtures is determined by the functional purpose of the product, the expected operating environment, and specific technical requirements. Such compositions are based on natural and synthetic rubbers, which are key products of oil refining [2-4]. Synthetic elastomers are mainly used in industrial production, among which synthetic isoprene rubber (SKI-3) is the most common. Despite the close similarity of its chemical structure to natural rubber, SKI-3 is inferior to its natural counterpart in a number of performance characteristics [3, 5]. In this regard, formulations of rubber compounds, as a rule, contain various modifying additives, and the search for new, more effective components remains one of the key areas for improving the durability and operational properties of finished products [6].

Since rubber compounds are complex multicomponent systems, the experimental determination of their optimal composition requires significant time and material costs associated with a series of laboratory tests. In modern conditions, mathematical modeling methods are increasingly being used to solve this problem. This approach allows not only to significantly reduce the duration of experimental studies, but also to predict the properties of final materials, as well as to use statistical models to assess the structural reliability of polymer composites [7-13]. Thus, mathematical modeling is becoming an important tool for optimizing technological processes and developing new materials in various industries.The present study focuses on modeling an optimal rubber compound formulation that incorporates industrial waste and locally sourced natural mineral components.

Materials and methods

The following were considered as objects of study:

– organic part of oil sludge (OPOS), previously extracted from waste of @PetroKazakhstan Oil Products@ LLP (Shymkent) by extraction method [14, 15];

– natural mineral zeolite of Chankanai deposit, Kazakhstan;

– rubber mixture for manufacturing rubber seals of hydraulic seals [16, 17];

– rubber mixture for manufacturing seals of hydraulic seals based on SKI-3, «ECO Shina» LLP (Table 1).

2. Experimental part

At the previous stage of the research, we developed rubber mixtures based on SKI-3 for the production of seals for hydraulic seals, instead of white carbon black, we used zeolite as a filler, and the organic part of oil sludge as a softener, replacing PN-6Sh oil [16, 17].

2.1 Characteristics of materials

Synthetic cis-isoprene rubber $[C_5H_8]_n$ (poly-2-methyl-1,4-butadiene) grade SKI-3 [18] with a content of cis-1,4 units of at least 96% and a molecular weight of 100 thousand to 1 million g/mol was purchased from Russia (Figure 1).

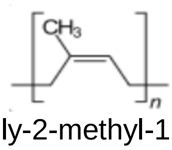


Figure 1 – Poly-2-methyl-1, 4-butadiene

OPOS – from the qualitative and quantitative analysis of oil sludge of «PetroKazakhstan Oil Products» LLP it was established that it contains organic compounds, solid inorganic components and water. Basically, the organic part of the oil sludge is represented by paraffins and asphalt-resinous substances. The presence of organic compounds in the oil sludge allows us to predict the manifestation of the plasticizing effect when introducing oil sludge into the rubber mixture.

Zeolite (TU38.10281-88) is a natural mineral. The general formula of zeolites is Mex/n [AlxSiyO2(x+y)]×zH2O, where Me is a metal, n is its oxidation state, x is the number of aluminum atoms, y is the number of silicon atoms, z is the number of water molecules.

2.2 Analytical control of raw materials

The group chemical composition was studied by liquid adsorption chromatography on a chromatograph with a mass-selective detector on a XEVO TQ-GC/GC-8890 device [14]. The study of functional groups in the organic part of the oil sludge by IR spectroscopy was carried out according to the standard technique on a single-beam IR Fourier spectrometer ShimadzuIRPrestige-21 with an attenuated total internal reflection (ATR) Miracle attachment from PikeTechnologie [14].

The recipe of the reference rubber mixture, as proposed by the authors of Ref. [19], along with the formulations of the studied rubber mixtures intended for the production of hydraulic seal components, is presented in Table 1.

Table 1 – Recipe for rubber mixture for making seals for hydraulic seals

Name of ingredients	Mass parts per 100 mass parts of rubber (*caoutchouc*)					
	Prototype	1	2	3	4	5
SKI-3 of the 1st group	100	100	100	100	100	100
Technical sulfur	4	4	4	4	4	4
Sulfenamide M	0,8	0,8	0,8	0,8	0,8	0,8
Santogard PVJ	0,2	0,2	0,2	0,2	0,2	0,2
Zinc white	5	5	5	5	5	5
Stearic acid	2	2	2	2	2	2
Pine rosin	2	2	2	2	2	2
Softener ASMG	3	3	3	3	3	3
PN-6Sh oil	**6**	**4**	**3**	**1**	**0**	**5**
OPOS	**0**	**2**	**3**	**5**	**6**	**1**
Protective microwax 3B-1	1	1	1	1	1	1
Acetonanil R	2	2	2	2	2	2
Diafen FP	2	2	2	2	2	2
Carbon black P – 220	60	60	60	60	60	60
White carbon	**20**	**15**	**10**	**5**	**0**	**17**
Zeolite	**0**	**5**	**10**	**15**	**20**	**3**
TOTAL	**208**	**208**	**208**	**208**	**208**	**208**

Rubber mixtures for manufacturing seals for hydraulic seals were prepared with full and partial replacement of PN-6Sh oil with the organic part isolated from oil sludge of «PetroKazakhstan Oil Products» LLP, as well as with simultaneous replacement of white carbon black with zeolite from the Chankanai field. The obtained mixtures were characterized by a satisfactory set of technological indicators, after which the properties of the vulcanizate were determined. OPOS was introduced into the mixture in a dosage of 1.0-6.0, and zeolite 3.0-20.0 parts by weight per 100 parts by weight of rubber (caoutchouc). Five samples of rubber mixtures were prepared.

2.3 Tensile testing of rubber compound

To assess the practical effectiveness of using alternative fillers and plasticizers instead of traditional components, several SKI-3-based rubber compounds were prepared in the laboratory (Table 1). The tensile properties of the vulcanizates obtained were studied using a universal testing machine in strict accordance with GOST 270-75. This method allows you to obtain reproducible information about key parameters, including: tensile strength, elongation at break, and stress at specified strain levels.

The test equipment provided a high degree of accuracy: the error did not exceed ± 1% of the applied load, starting from 20% of the maximum range. The lengthening of the sample was constantly monitored, and the change in the distance between the control marks was measured using a precision instrument with a scale division of no more than 1 mm, which guaranteed the reliability of the results.

Throughout the stretching process, the load corresponding to the specified elongation levels was fixed. At the moment of fracture, both the breaking force and the final gauge length of the dumbbell-shaped specimens were registered. In order to maintain the validity of the data, results obtained from specimens that failed outside the working (narrowed) zone were discarded, as such fractures could introduce errors into the analysis.

During stretching, the load corresponding to selected elongations was fixed, while at the point of specimen rupture both the breaking force and the final gauge length were registered. Results obtained from fractures occurring outside the working section of the dumbbell-shaped samples were excluded, ensuring the correctness of the statistical analysis.

Vulcanizate tests were carried out according to GOST 270-75. The temperature resistance was determined after accelerated aging at 80 °C for 72 hours. The determination of tensile strength after thermal aging revealed how resistant the obtained materials are to prolonged exposure to high temperatures close to real operating conditions. Thus, the tests carried out not only provided accurate and repeatable results, but also showed that the developed rubber compounds have characteristics suitable for practical industrial applications.

2.4 Study of the vulcanization process

The vulcanization process was studied in order to gain a more detailed understanding of the mechanism and characteristics of the curing reaction of the studied rubber compounds. For this purpose, the main parameters of vulcanization were determined using rheological analysis, which allows us to trace the change in viscoelastic properties of the material over time and evaluate the dynamics of the formation of a spatial grid. This approach makes it possible not only to determine the optimal vulcanization conditions, but also to determine the effect of the mixture composition on the rate and degree of crosslinking of the rubber. The measurements were carried out on a Monsanto Rheometer 100S, which makes it possible to continuously record the torque generated during the cross-linking process and thereby construct rheological curing curves. Such curves show how the viscoelastic properties of the rubber compound change over time, and provide data showing the vulcanization process. The tests were carried out according to GOST 12535-78, which ensures the accuracy and comparability of the results. The samples were kept at 160 °C for 30 minutes (industrial elastomer curing conditions). The analysis of the rheological data obtained made it possible to determine the main parameters of the process, such as the optimal vulcanization time, the start of the reaction and the maximum torque, which in turn reflects the degree of crosslinking of the rubber. The above indicators helped to objectively assess the quality and technological properties of the developed rubber compounds.

3 Mathematical modeling

3.1 Factors under study

Modeling and optimization of the parameters for obtaining rubber compounds with specified properties was performed using a multifactorial probabilistic deterministic method. This methodology makes it possible to account for the combined influence of several variables while simultaneously ensuring statistical reliability of the obtained results.

As variable factors, two types of substitutions were investigated: the incorporation of the organic fraction of oil sludge (OPOS) as a plasticizer in place of the conventional PN-6Sh oil, and the introduction of locally available natural zeolite as a reinforcing filler instead of traditional white carbon. These substitutions were selected due to their dual significance: on the one hand, they contribute to cost reduction and resource efficiency, and on the other hand, they allow the evaluation of the functional viability of alternative raw materials under industrially relevant conditions.

As a result of the research, mathematical models were built that describe the influence of technological factors on the properties of materials. Based on them, optimal conditions for obtaining vulcanizates that meet the specified criteria were determined. The adequacy of the models has been confirmed experimentally. The values of the factors are shown in Table 1.

3.2. Matrix of the six-factor experimental design

Mathematical modeling of the optimal composition of the rubber compound was carried out using a six-factor experimental plan, which made it possible to identify patterns of influence of key technological parameters and their cumulative effect on the properties of the resulting material. This experimental matrix made it possible to study changes in the mechanical properties of rubber compounds depending on the selected composition parameters.

For this purpose, samples with different ratios of components were tested, allowing us to collect a sufficient amount of data and identify statistically significant patterns and relationships between the factors. Based on the results obtained, regression equations were constructed, which became the basis for further optimization of formulations of rubber compositions.

4. Results and discussion

4.1 Checking the optimality of the proposed rubber compound composition

To confirm the correctness of the proposed rubber formulation, a comprehensive assessment of the main indicators of its quality was carried out. The objective of the study was to ensure that the developed mixture meets the established standards and provides an optimal ratio of strength and elasticity. According to GOST 269-66, testing methods and equipment are adapted to the unique behavior of elastomers, which, unlike rigid materials, can undergo significant reversible deformations under relatively low stresses. In addition, their response strongly depends on testing conditions, including the duration of loading and temperature regime.

Another critical aspect is the susceptibility of rubber compounds to external non-mechanical factors. Prolonged exposure to elevated temperatures, ultraviolet light, ozone, oxygen, or other aggressive media can cause substantial degradation of mechanical properties. These features must be taken into account when evaluating the adequacy of the compound's composition, since they directly influence the durability and operational reliability of the finished vulcanizates.

4.2 Tensile testing of rubber

The experiments are carried out according to a pre-selected plan [1]. The experimental data obtained were processed using the least squares method, which allowed us to construct appropriate mathematical models. After checking their adequacy, we proceeded to the formulation and solution of the optimization problem.

To establish the optimal content of the organic part of oil sludge in rubber mixtures intended for the manufacture of hydraulic seals, which achieve the best conventional tensile strength of the vulcanizate, we used mathematical modeling and optimization methods.

The effect of the input parameters was studied: conventional strength (y1), relative elongation at break (y2), tear resistance (y3) and Shore A hardness.

The mathematical formulation of such problems in the general case is as follows:

$$\max(\min) y_j(z_1, z_2, ..., z_n),\ j=\overline{1,m};\ \max(\min) L_k(z_1, z_2, ..., z_n),\ k=\overline{1,p} \tag{1}$$

when $0 \le z_i \le 1$, $\sum_{i=1}^{n} z_1 = 1$, (2)

here yj (z1, z2 ,..., zn) j=1, m are functions of the properties of a multicomponent mixture, which are Scheffe polynomials constructed on the basis of experimental data conducted according to special plans [1], Lk (z1, z2 ,..., zn), k =1, p are economic criteria.

The solution of the multi-criteria optimization problem (1)-(2) in the general case is associated with serious mathematical difficulties, since usually the properties of the mixture, on the basis of which the selection of the component composition is carried out, are of a contradictory nature.

The choice of the method for solving the multicriterial optimization problem (1)-(2) and overcoming the mathematical difficulties that arise are possible only after developing the property functions yj(z1,z2,…,zn) for j=1, m for a multicomponent mixture, taking into account the specifics of the problem being solved, as well as the features of the economic criteria Lk(z1,z2,…,zn) when k=1,p. These functions yj(z1,z2,…,zn), j=1,m and Lk(z1,z2,…,zn), k=1,p form a mathematical model of the problem aimed at determining the optimal composition-property ratio of multicomponent mixtures. The implementation of this approach can be demonstrated using the example of the problem of selecting the optimal component composition of a rubber mixture used for rubber products (RP).

It is necessary to optimize the component composition of the rubber mixture consisting of PN-6Sh oil (x1), OPOS (x2) and zinc white (x3), zeolite (x4) in order to ensure the satisfaction of its physical and mechanical characteristics: conventional strength (y1), relative elongation at break (y2), tear resistance (y3) and Shore A hardness (y4) in accordance with the requirements of GOSTs or to achieve the maximum (minimum) values of these parameters. At the same time, it is necessary to minimize the cost of the mixture.

In this formulation, the optimization problem is multi-criterial. To solve it, the simplest approach is to use the method of identifying the main criterion, which is the cost of the mixture.

4.3 Classical multi-criteria optimization of rubber compound composition:

4.3.1. Formulation of the optimization problem

We have:

Variables (x) – proportions of mixture components:

- x1: PN-6Sh oil
- x2: OPOS
- x3: White carbon
- x4: Zeolite

Response functions (y) – physical and mechanical properties of the mixture:

- y1(x): Conventional strength (MPa)
- y2(x): Relative elongation at break (%)
- y3(x): Tear resistance (kN/m)
- y4(x): Shore A hardness

Objective function:

- C(x): Cost of the mixture (tenge/kg), which needs to be minimized.

Objective: Find such values of x1, x2, x3, x4 that:

1. Satisfy the requirements of GOST for parameters y1, y2, y3, y4
2. Minimize the cost function C(x)

4.3.2. Build regression models for the properties:

Based on the experimental data, build approximations:

$$\begin{cases} y_1(x) = f_1(x_1, x_2, x_3, x_4) \\ y_2(x) = f_2(x_1, x_2, x_3, x_4) \\ y_3(x) = f_3(x_1, x_2, x_3, x_4) \\ y_4(x) = f_4(x_1, x_2, x_3, x_4) \end{cases}$$

These can be linear or polynomial models of the second order, constructed using the least squares method.

4.3.3. We formulate restrictions:

- $y_1 \geq y_1^{GOST}$
- $y_2 \geq y_2^{GOST}$
- $y_3 \geq y_3^{GOST}$
- $y_4 \in \left[y_4^{\min}, y_4^{\max} \right]$
- $x_1 + x_2 + x_3 + x_4 = 1$
- $x_i \geq 0$

4.3.4. Cost formula:

$$C(x) = c_1 x_1 + c_2 x_2 + c_3 x_3 + c_4 x_4$$

where *ci* is the price of the components.

The results of the physical and mechanical properties of vulcanizates are given in Table 2.

Currently, traditional components – white carbon black and PN-6Sh oil, which are purchased abroad – are used to manufacture rubber seals for hydraulic seals at ECO-Shina LLC (Shymkent). The cost of white carbon black is 1850 tenge per unit, and PN-6Sh oil is 100 tenge per unit (Table 2). The price of one ton of rubber seals is 1.5 million tenge.

Mathematical modeling was performed using the Statistica 10.0 program, designed for statistical analysis and processing of experimental data. The program provides a wide range of tools for regression analysis, variance analysis (ANOVA), correlation analysis, and data visualization. In scientific and engineering research, Statistica is used to identify dependencies between variables, optimize compositions, and assess the influence of factors on output parameters [20]. Figures 3-5 show the results of modeling the «composition – cost» dependence of components, as well as the dependence of the physical and mechanical properties of rubber on the content and cost of the components of the rubber mixture.

Table 2 – Physical and mechanical properties of rubbers

Name of indicators	Standard according to TU 22.19.73-047-46028995-2018	Sample number					
		Proto type	1	2	3	4	5
Content of PN-6SH oil, m.p.		6	4	3	1	0	5
Content of organic part of oil sludge, m.p.		0	2	3	5	6	1
White carbon content, ppm		20	15	10	5	0	17
Zeolite content, ppm		0	5	10	15	20	3
Conditional strength, MPa	not less than 12.0	13,54	13,45	13,37	13,13	13,00	13,47
Relative elongation at break, %	not less than 350	420	420	422	425	425	422
Tear resistance, kN/m, not less than	not less than 40.0	53,96	53,21	52,30	52,06	51,21	53,15
Shore A hardness, conventional units, not less than	62 ± 5	60	60	60	59	59	60
Cost of each component (tenge/kg)	Unit price, tenge white carbon black = 1850 PN-6SH oil = 100 Zeolite = 102.60 OPOS = 15, 694						

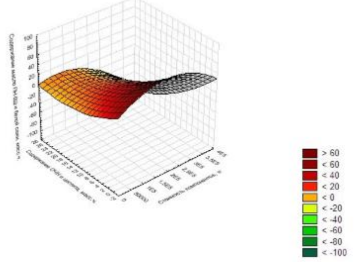


Figure 2 – Modeling the «composition – cost» relationship of rubber compound components

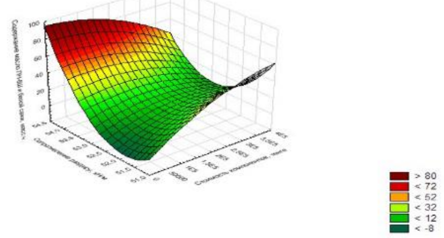


Figure 3 – Mathematical modeling of the dependence of the physical and mechanical properties of rubber on the content and cost of white carbon black and PN-6Sh oil

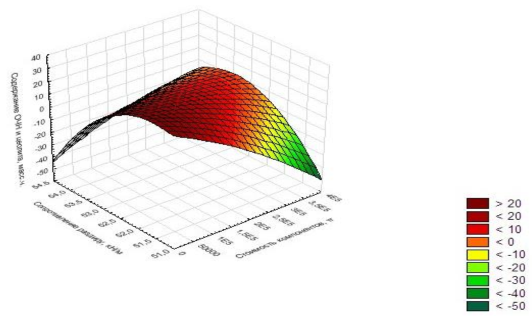
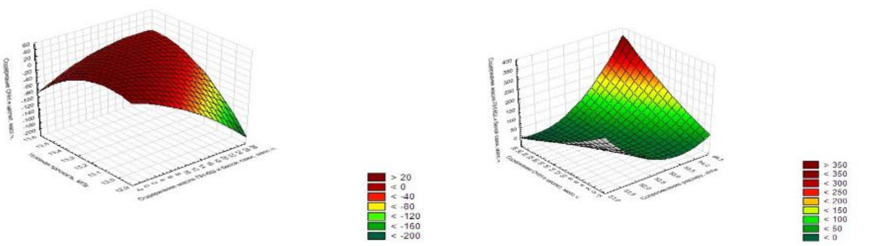


Figure 4 – Mathematical modeling of the dependence of the physical and mechanical properties of rubbers on the content and cost of OPOS and zeolites



a b

Figure 5 – Results of modeling the physical and mechanical properties of rubbers obtained using the 40℃×25 min mode: a – Conditional strength, MPa; b – Tear resistance, kN/m

This paper proposes replacing PN-6Sh oil with an organic component of oil sludge, and white carbon black with natural zeolite from the Chankanai deposit. The cost of the new raw material is 102.60 + 15.694 tenge per unit, while the cost of the traditional formulation is 1850 + 100 tenge per unit. Thus, the proposed formulation is significantly cheaper than the traditionally used one (Figures 2-4).

Figure 5 shows the results of modeling the physical and mechanical properties of rubbers depending on the content of OPOS and zeolite.

Analysis of the data in Figure 5 and Table 2 demonstrates that the performance characteristics of the experimental rubber samples are largely comparable with those of the reference (serial) compound, and in certain cases even surpass them. For instance, the nominal tensile strength (Figure 5a) and tear resistance (Figure 5b) under optimal vulcanization conditions (20 minutes) show values that are nearly equivalent to, or slightly higher than, those of the standard formulation. This effect can be attributed to the fine dispersion of zeolite particles, which, when evenly distributed within the polymer matrix, enhance interfacial interaction and consequently improve the mechanical performance of the compound.

It is noted that the elongation at break (Table 2) of the standard vulcanizate and sample № 1 was about 420%, while the experimental samples (No. 2-5) showed slightly higher values – 422-425%. This indicates that the modified rubber compounds are characterized by increased elasticity and are able to withstand large deformation until destruction. The slight increase in the indicator is probably due to the introduction of OPOS and zeolite from the Changkanai deposit, which improve the flexibility of the material by changing the structure of the polymer matrix.

The best physical and mechanical characteristics of rubbers intended for sealing hydraulic seals were achieved at a content of 6.0 wt. % OPOS and 20.0 wt. % of zeolite per 100 wt. % of rubber.

Thus, even small differences in composition indicate the positive effect of the proposed modifications, which increase the stretchability of the material without significantly reducing other mechanical properties.

Quantitative analysis shows that the incorporation of natural zeolite and oil-refining waste leads to an improvement of 1-3% in elongation at break and up to 2-4% in tensile strength relative to the conventional reference formulation. These changes, although moderate, demonstrate a measurable reinforcing effect attributed to the synergistic interaction between OPOS and the finely dispersed zeolite filler.

Among the evaluated approaches, the most effective was the optimization of composition by varying the content of zeolite and OPOS. The formulation containing 6 wt.% OPOS and 20 wt.% zeolite demonstrated the best balance of strength and elasticity. When transferred to industrial-scale production, this optimization strategy remains applicable and stable because it does not require modification of processing equipment and relies solely on adjusting the proportions of standard raw materials. The technological operations-mixing, molding, and vulcanization-retain their reproducibility, ensuring consistent mechanical properties across large production batches.

Conclusion

Based on the conducted research, a mathematical basis was formed for determining the optimal composition of rubber compounds. Unlike traditional methods, the developed model takes into account the use of non-traditional components: the organic part of oil sludge (OPOS) and natural zeolite of local origin. Their introduction was examined not only as a means of resource utilization, but also as an effective factor in optimizing the course of vulcanization and improving the performance profile of elastomeric materials.

The integration of these additives has demonstrated tangible benefits. Rubber composites obtained under such conditions exhibit superior resistance when exposed to oil-containing environments, maintain stable elasticity and mechanical strength during operation, and show reduced dependency on costly polymer fractions. Also, simplification of the production cycle helps to reduce technological operations, which in turn leads to lower costs.

Thus, the developed mathematical model for selecting the optimal rubber formulation can be considered as a universal tool with practical value for industrial applications. It allows us to simultaneously solve the problems of improving the performance characteristics of materials and reducing the cost of production, and also serves as a methodological basis for further fundamental research in the field of polymer science and elastomer technology.

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ФИЗИКА-МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІН БАҒАЛАУДЫ ЕСКЕРЕ ОТЫРЫП, ӘЗІРЛЕНГЕН РЕЗИНА ҚОСПАЛАРЫНЫҢ РЕЦЕПТІН ОҢТАЙЛАНДЫРУ

Резина қоспаларының құрамын оңтайландыру – бұл қолданылатын компоненттердің әртүрлілігіне және олардың арасындағы күрделі қатынастарға байланысты күрделі және көп факторлы процесс. Оңтайлы рецептті таңдау үшін бірқатар эксперименттік зерттеулер жүргізу уақытты, шикізатты және зертханалық ресурстарды қажет етеді. Бұл жұмыста резина қоспаларының қасиеттерін болжауға және олардың оңтайлы құрамын анықтауға мүмкіндік беретін математикалық модельдеу әдістерін қолдануға негізделген тәсіл ұсынылған. Табиғи цеолит пен мұнай өңдеу қалдықтарын модификациялаушы қоспалар ретінде пайдалануға ерекше назар аударылады. Бұл өндірістің тиімділігі мен экологиялық тазалығын арттыруға ықпал етеді. Қоспалар ретінде мұнай шламының органикалық фракциясы және Шаңқанай кен орнының цеолиті пайдаланылды. Бастапқы ақпарат негізінде ең кіші квадраттар әдісімен барабар математикалық модельдер құруға мүмкіндік беретін эксперименттер жоспары жасалды. Бұл модельдер пайдалану қасиеттері мен экономикалық көрсеткіштердің қоспаның компоненттік құрамына тәуелділігін сипаттайды. Алынған модельдер негізінде оңтайландыру міндеті тұжырымдалды. Оның ерекшеліктері зерттелді және шешудің ең тиімді әдісі таңдалды. Ұсынылған тәсілдің тиімділігі резина қоспасының оңтайлы құрамын таңдау мысалында көрсетілген. Резина қоспаларының модификациясы майға төзімділігі жоғары, тұрақты серпімді және беріктік қасиеттері бар композициялық материалдарды алуға мүмкіндік береді. Бұл тәсіл қол жетімді шикізатты пайдалану және технологиялық процесті жеңілдету арқылы өндіріс шығындарын азайтуға көмектеседі. Резина қоспасының оңтайлы құрамын анықтаудың жобаланған есептеу моделін ғылыми зерттеулерде де, өнеркәсіптік тәжірибеде де эластомерлік композициялардың жаңа рецептін жасау кезінде де қолдануға болады.

Түйін сөздер: *көп компонентті қоспалар, гидравликалық тығыздағыштарға арналған резина қоспалары, оңтайландыру міндеті, шартты созылу беріктігі, құрамы-құны.*

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ОПТИМИЗАЦИЯ РЕЦЕПТУР РАЗРАБОТАННЫХ РЕЗИНОВЫХ СМЕСЕЙ С УЧЕТОМ ОЦЕНКИ ФИЗИКО-МЕХАНИЧЕСКИХ СВОЙСТВ

Оптимизация состава резиновых смесей представляет собой сложный и многофакторный процесс, обусловленный разнообразием применяемых компонентов и сложными взаимосвязями между ними. Проведение серии экспериментальных исследований для подбора оптимальной рецептуры требует значительных затрат времени, сырья и лабораторных ресурсов. В данной работе предложен подход, основанный на применении методов математического моделирования, позволяющий прогнозировать свойства резиновых смесей и определить их оптимальный состав. Особое внимание уделено использованию природного цеолита и отходов нефтепереработки в качестве модифицирующих добавок, что способствует повышению эффективности и экологичности производства. В качестве добавок использованы органическая фракция *нефтешлама и цеолит Чанканайского месторождения. На основе априорной информации разработан план экспериментов, позволяющий построить адекватные математические модели методом наименьших квадратов. Эти модели описывают зависимость эксплуатационных свойств и экономических показателей от компонентного состава смеси. На основе полученных моделей сформулирована задача оптимизации, проведено исследование её особенностей и выбран наиболее эффективный метод решения. Эффективность предложенного подхода демонстрируется на примере подбора оптимального состава резиновой смеси. Модификация резиновых смесей позволяет получать композиционные материалы с повышенной маслостойкостью, стабильными эластичными и прочностными свойствами. Такой подход способствует снижению производственных затрат за счет использования доступного сырья и упрощения технологического процесса. Разработанная расчетная модель определения оптимального состава резиновой смеси может быть применена как в научных исследованиях, так и в промышленной практике при разработке новых рецептур эластомерных композиций.*

Ключевые слова: *многокомпонентные смеси, резиновые смеси для уплотнений гидрозатворов, задача оптимизации, условную прочность при растяжении, состав – стоимость.*

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ЭНЕРГИЯ САҚТАУ ҚҰРЫЛҒЫЛАРЫНЫҢ СЫЙЫМДЫЛЫҚ ӨНІМДІЛІГІН АРТТЫРУ ҮШІН MXENE МОДИФИКАЦИЯЛАУ ӘДІСТЕРІ

Аңдатпа: *Бұл шолу жұмысында екі өлшемді MXene материалдарын, ең алдымен $Ti_3C_2T_x$ және онымен байланысты қосылыстарды, суперконденсаторлар мен гибридті энергия сақтау құрылғыларында қолдану мақсатында олардың сыйымдылық сипаттамаларын арттыруға бағытталған заманауи модификациялау әдістері жан-жақты талданады және жүйеленеді. MXene материалдарының жоғары электрондық өткізгіштігі, қабатты құрылымы және химиялық белсенді беті оларды энергия жинақтау құрылғылары үшін перспективалы электродтық материалдар ретінде қарастыруға мүмкіндік береді. Алайда олардың практикалық қолданылуы қабаттардың қайта тығыздалуы, белсенді орталықтардың қолжетімділігінің шектелуі және ұзақ циклдік жұмыс барысында құрылымдық тұрақтылықтың төмендеуі сияқты бірқатар шектеулермен сипатталады. Осы шолу аясында MXene материалдарының электрохимиялық қасиеттеріне әсер ететін негізгі модификациялау стратегиялары, соның ішінде интеркаляциялау арқылы қабатаралық қашықтықты реттеу, беткі терминалдық топтардың функционализациясы, көміртекті наноматериалдармен және өтпелі металдардың оксидтерімен композиттер түзу, гетероатомды легирлеу, морфологиялық инженерия және әртүрлі кейінгі өңдеу әдістері қарастырылады. Аталған тәсілдердің иондық және электрондық өткізгіштікке, псевдоконденсация үлесіне және электрод материалдарының циклдік тұрақтылығына әсері салыстырмалы түрде бағаланады. Әдеби деректер негізінде меншікті сыйымдылық пен ұзақ мерзімді циклдік тұрақтылық көрсеткіштері бойынша жалпыланған талдау жүргізіліп, MXene негізіндегі электродтарды оңтайландыруға бағытталған практикалық ұсыныстар мен болашақ зерттеу бағыттары тұжырымдалады.*

Түйін сөздер: *MXene, суперконденсаторлар, энергия сақтау, беттік модификация, интеркаляция, псевдоконденсаторлар.*

1. Кіріспе

MXeнлер – $M_{n+1}X_nT_x$ жалпы формуласы бар екі өлшемді өтпелі металл карбидтері мен нитридтерінің класы, мұндағы M – ерте өтпелі металл (Ti, V, Nb, Mo және т.б.), X – C және/немесе N, ал Tx – беттік функционалдық топтар, негізінен –O, –OH және –F. MAX фазаларын селективті өңдеу және қабатты MXeнлерді дайындау бойынша алғашқы