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BIOMASS-BASED AMIDES AS MULTIFUNCTIONAL ADDITIVES FOR ELASTOMERIC COMPOSITIONS

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Abstract

Study investigates the effect of diethanolamides synthesized from renewable plant raw materials (spent sunflower oil production adsorbent) on the properties of filled elastomeric compositions based on butadiene-α-methylstyrene rubber. It has been established that the studied amides are multifunctional additives that combine the properties of plasticizers, dispersing agents, activators, and secondary accelerators in sulfur vulcanization. Their use improves the technological characteristics of rubber compounds, reduces viscosity, and increases plasticity, thereby ensuring better processability of elastomeric compositions. It has been shown that the addition of amides significantly accelerates the sulfur vulcanization process: the cross-linking rate and the apparent rate constant of vulcanization increase by 2–4 times compared to traditional stearic acid, and the time required to reach the vulcanization optimum is reduced. A positive effect of amides on the formation of the vulcanization network structure has been established, which improves the heat resistance and thermal stability of rubbers. The highest effectiveness was demonstrated by glycerol-free fatty acid diethanolamide, which reduces the loss of strength properties after exposure to elevated temperatures by 25 % and provides a relative elongation at break that is 22 % higher than in rubber without additives. The results obtained confirm the potential of using plant-derived amides as environmentally safe, multifunctional ingredients for the production of modern elastomeric compositions and products made from them.

Keywords: elastomeric composition; fatty acid amides; bioingredient; sunflower oil production waste; environmentally friendly rubber; sulfur vulcanization; technological additive.

АМІДИ НА ОСНОВІ БІОСИРОВИНИ ЯК БАГАТОФУНКЦІОНАЛЬНІ ДОБАВКИ ЕЛАСТОМЕРНИХ КОМПОЗИЦІЙ

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Анотація

У роботі досліджений вплив діетаноламідів, синтезованих з відновлюваної рослинної сировини (відпрацьованого адсорбенту виробництва соняшникової олії), на властивості наповнених еластомерних композицій на основі бутадієн-α-метилстирольного каучуку. Встановлено, що досліджувані аміди є багатофункціональними добавками, які поєднують властивості пластифікаторів, диспергувальних агентів, активаторів та вторинних прискорювачів сірчаної вулканізації. Їхнє використання сприяє покращенню технологічних характеристик гумових сумішей, зниженню в'язкості та підвищенню пластичності, що забезпечує кращу перероблюваність еластомерних композицій. Показано, що введення амідів суттєво інтенсифікує процес сірчаної вулканізації: швидкість зшивання та умовна константа швидкості вулканізації зростають у 2–4 рази порівняно з традиційною стеариновою кислотою, а тривалість досягнення оптимуму вулканізації скорочується. Встановлений позитивний вплив амідів на формування структури вулканізаційної сітки, що забезпечує підвищення теплостійкості та термостійкості гум. Найвищу ефективність продемонстрували діетаноламіди жирних кислот без вмісту гліцерину, який зменшує втрату міцнісних характеристик після дії підвищених температур на 25 % та забезпечує відносне подовження під час розриву на 22 % вище, ніж у гуми без добавок. Отримані результати підтверджують перспективність використання амідів рослинного походження як екологічно безпечних багатофункціональних інгредієнтів для виробництва сучасних еластомерних композицій та виробів з них.

Ключові слова: еластомерна композиція; аміди жирних кислот; біоінгредієнт; відходи виробництва соняшникової олії; екологічно безпечна гума; сірчана вулканізація; технологічна добавка.

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Journal of Chemistry and Technologies, 2026, *34*(2), 448-458

Introduction

The widespread use of traditional elastomeric materials (rubber) is driven by their unique properties, primarily their high elasticity, good performance under dynamic loads, and ability to absorb and dissipate mechanical energy. These rubber properties are achieved due to the presence of a wide range of ingredients in their composition, in particular components of sulfur vulcanization systems, and a unique vulcanization process with the formation of a polysulfide spatial network [1; 2].

There are a significant number of inorganic and organic substances known to activate the vulcanization process. However, in practice, zinc oxide is usually used in combination with fatty acids (most often with stearic acid). In modern elastomer technology, there is a continuous update of the composition of rubber compounds that are potentially suitable for use as rubber ingredients. In particular, this applies to components of sulfur vulcanization systems such as organic activators. Recently, there has been a trend towards replacing this system with composite activators, so-called technological and technologically active additives with multifunctional action, the use of which opens up new opportunities for improving the formulation and manufacturing process of rubber compounds, increases the homogeneity and stability of rubber compounds and vulcanizates, and improves the quality of finished products [3–5]. When developing technological additives, considerable attention is paid to the environmental safety of production and the use of secondary raw materials in existing technological processes [6; 7].

Many studies [8–15] have shown that vegetable oils as technological additives are becoming important for replacing carcinogenic petroleum-based oils in the rubber industry. This trend has emerged as part of a general move towards more environmentally friendly and sustainable materials in various industries. Vegetable oils, such as soybean, rapeseed, palm, sunflower, and others, are defined as renewable resources, the use of which in the rubber industry reduces dependence on petroleum-based ingredients and contributes to the creation of more environmentally friendly materials and products. Vegetable oils and their modified forms can also improve the processing conditions of rubber compounds and bring positive changes to the properties of rubber and rubber products, such as increased elasticity and strength characteristics, heat resistance, rolling resistance, and others, which are important in the development of modern elastomeric compositions. Modification with vegetable oils of such industrial fillers of rubber compounds as silicon dioxide and calcium carbonate makes it possible to increase the compatibility degree of the inorganic component of the mineral filler with the organic component of the elastomeric matrix. In particular, the authors of [15] claim that silica-filled elastomeric compositions based on natural rubber in the presence of vegetable oils have a lower index of Payne effect than compositions with an equal mass content of petroleum-derived oils. This indicates a better level of silica dispersion in compositions with vegetable oils.

To a certain extent, even more promising additives to the sulfur vulcanization activator system may be amide derivatives of carboxylic acids synthesized from bio-based raw materials. Thus, the authors of [16] synthesized palmitamide from urea and palmitic acid (a product of palm oil) and used it in amounts of 2.0–8.0 wt.% as a plasticizer in butadiene-styrene rubber-based compositions filled with 30.0 wt.% of N 330 grade carbon black. Such application causes a decrease in the minimum torque values and an increase in the maximum torque, as well as an improvement in the degree of carbon black dispersion. In other words, palmitamide has the properties of both a technological additive (plasticizer-dispersant) and a vulcanization-active additive (positively affecting the degree of rubber crosslinking). Work [17] presents research results that indicate the possibility of using fatty acid amides and rosin (rosinamide product) as vulcanization activators for elastomeric compositions based on natural rubber. The studied amides showed a weak accelerating effect, accompanied by a reduction in the optimal vulcanization time and an increase in the vulcanization rate.

It has been shown [18–25] that the use of alkanolamide synthesized from palm stearin and diethanolamine in elastomeric compositions based on natural rubber filled with silicon (IV) oxide not only increases the vulcanization rate and reduces the sub-vulcanization time of mixtures, but also acts as a softener and improves the dispersion of the filler in the rubber matrix, increasing its reinforcing effect. Another environmentally safe nitrogen-containing ingredient of elastomeric compositions with softening and vulcanizing activity in the sulfur

vulcanization process is a product called oleamide, obtained from palm oil oleic acid and urea [25].

Taking into account the volumes of domestic sunflower oil production and, accordingly, the amount of environmentally hazardous waste accumulated during the winterization stage, which contains valuable organic products in the form of spent diatomaceous filter powder, we have determined the effectiveness and prospects of using the organic component of this waste as a technological additive to elastomeric compositions [26–28]. The mineral component of spent diatomaceous filter powder after selective purification or annealing can be used as a semi-reinforcing filler in elastomeric compositions based on carbon chain rubbers [29; 30].

Based on global trends in the use of environmentally friendly bio-ingredients from natural renewable raw materials in the rubber industry, the renewal of the range of ingredients in rubber compounds and the expansion of their list, in particular, the emergence of a class of technological active additives, this work aimed to study the effect of new diethanolamides synthesized from renewable plant raw materials on the overall set of properties of elastomeric compositions based on butadiene-α-methylstyrene rubber, comparing their effectiveness with traditional stearic acid. The non-stereoregular macromolecular structure of the proposed rubber causes its increased sensitivity to the introduction of new ingredients into the composition of rubber compounds, which manifests itself in changes in the rheological behavior of the composite, the nature of filler dispersion, the vulcanization kinetics, and the complex of physical and mechanical properties of the resulting rubbers.

Materials and methods of the study

The subject of the study was amide derivatives of fatty acids obtained from spent adsorbent used in sunflower oil production.

The first sample of diethanolamide (DEA G) was synthesized as follows: sunflower oil (washed from spent adsorbent), diethanolamine, and sodium hydroxide (as a catalyst) were loaded into a three-necked flask. The mixture was heated on a sand bath under stirring until the reaction mixture reached a temperature of 145°C and kept at this temperature for 2.5 hours while continuing to stir. Then the stirring was stopped and the mixture was cooled to a temperature of 25 °C. The result was a homogeneous, transparent liquid containing approximately 90–92 % of diethanolamide, 8–10 % of glycerin, and < 0.5 % of diethanolamine.

The second sample of diethanolamide (DEA) was synthesized from sunflower oil methyl ester and diethanolamine using a similar method. Sunflower oil methyl ester was obtained by alkaline catalysis of sunflower oil with methanol. The resulting methyl ester was separated from glycerol by washing with water and subsequent drying with calcium chloride. The reaction of sunflower oil methyl ester and diethanolamine in an alkaline environment yielded a homogeneous, transparent liquid containing approximately 99 % of diethanolamide and ≈1 % of diethanolamine (methanol evaporated during the reaction and after cooling the reaction mixture for 1 hour).

The structure of the fatty acid amides of sunflower oil obtained in this work was studied by IR spectroscopy [31]. Analysis of the IR spectroscopy results for different types of diethanolamides showed that their spectra practically coincide with each other (Fig. 1). Analysis of diethanolamides (DEA and DEA G) spectra showed the absorption bands in the region of 3416 and 3367 cm^{-1}, which should be attributed to valence vibrations (associated vibrations) of alcohol OH groups and NH groups in amides; the DEA G sample is characterized by a greater number of peaks in this region, which is probably due to the presence of glycerol hydroxyl groups. In the region of 2925 cm^{-1} and 2854 cm^{-1}, there are absorption bands of asymmetric and symmetric vibrations of methyl groups. The band at 1742–1740 cm^{-1} refers to valence vibrations of C=O groups in amides (I amide band), the band at 1620 cm^{-1} refers to the deformation vibrations of NH groups (II amide band), the band at 1465 cm^{-1} is typical of C-N vibrations (III amide group), and the band at 1052 cm^{-1} characterizes the C-OH bond. In general, the spectra fully correspond to the structure of diethanolamides and are similar to the spectra described in [28].

Journal of Chemistry and Technologies, 2026, *34*(2), 448-458

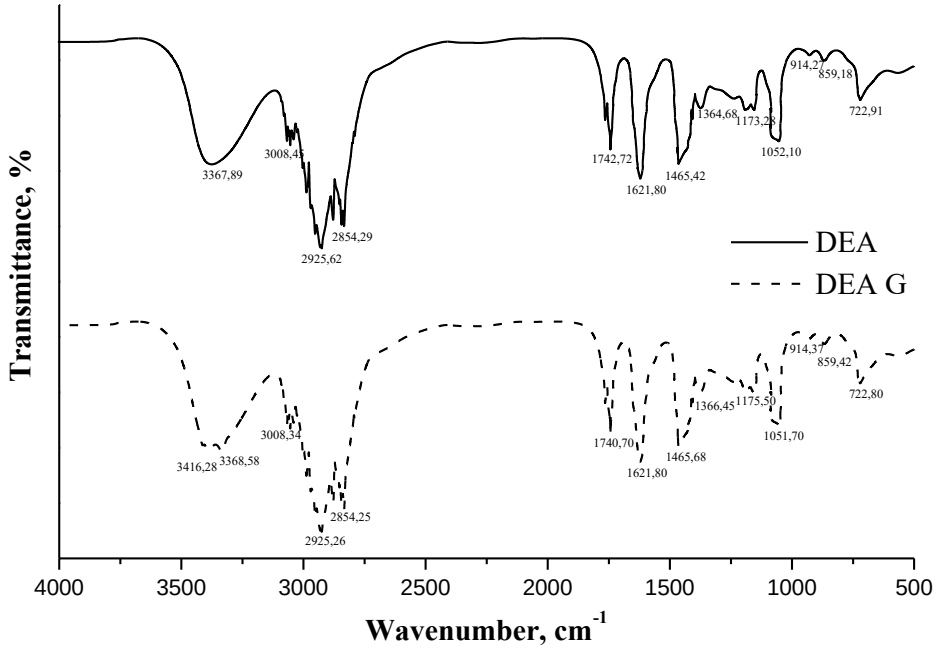
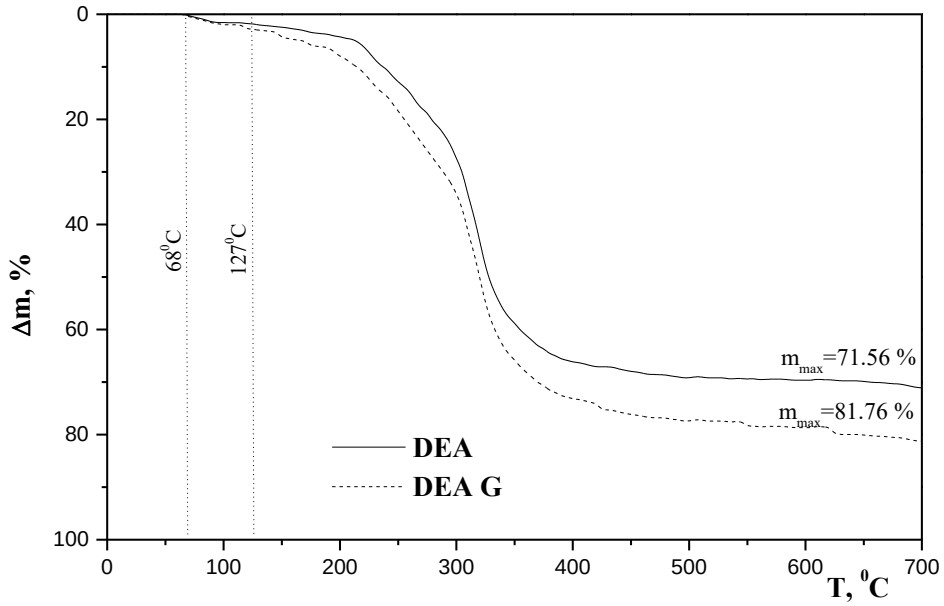


Fig. 1. Infrared spectra of the studied products (film based on AgCl)

To determine the thermal stability of the studied diethanolamides, thermogravimetric analysis was performed using a MOM derivatograph of Paulik-Paulik-Erdei system in the temperature range from 20 °C to 800 °C at a heating rate of 10 degrees/min (Fig. 2). It was found that both samples simultaneously begin to lose mass at a temperature of 68 °C. From a temperature of 127 °C, DEA G loses mass more intensively, probably due to the evaporation of glycerin, which is also observed in the change of the DTG and DTA curves' nature. At the specified temperature, an exothermic peak appears on the DTA curve, which is more intense for the DEA G sample. It means that with further increase in temperature, exothermic oxidation occurs, including glycerol. This phenomenon is in agreement with the literature data [32]. At a temperature of 200°C, the mass loss for DEA samples is 4.25 % and 8.0 % for DEA G. The peak of mass loss rate corresponds to 302 °C. The difference in maximum mass loss between the DEA G and DEA samples is 10.2 %, which indicates the quantitative content of glycerin in the DEA G sample.



Journal of Chemistry and Technologies, 2026, *34*(2), 448-458

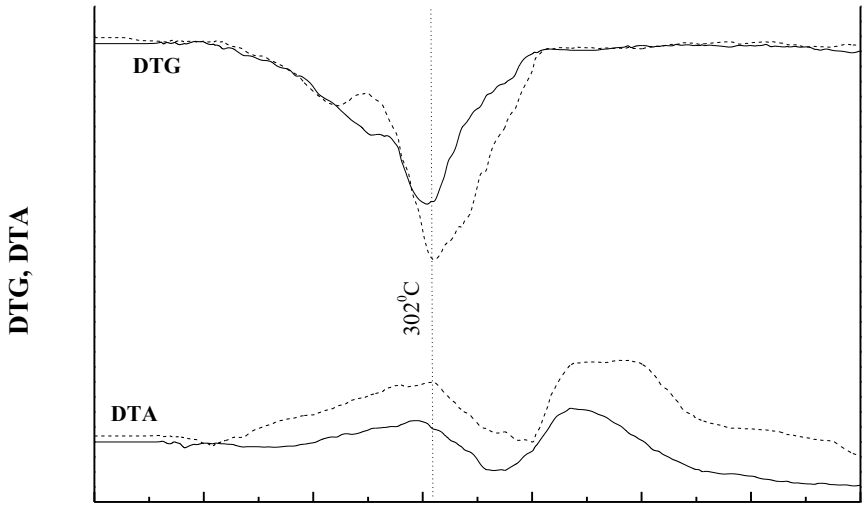


Fig. 2. Curves of differential thermal analysis of the studied diethanolamides (medium - air, heating rate 10 deg/min)

So, according to the results of thermogravimetric analysis, the sunflower oil fatty acid amides studied in this work are sufficiently thermostable at the temperatures of manufacture and processing of elastomeric compositions and should not cause complications in technological processes. Sunflower oil fatty acid amides are surface-active substances, where the long chain of fatty acid is hydrophobic, and the polar functional group of the amide and hydroxyl groups have hydrophilic properties. This fact gives the compounds the ability to reduce surface tension and stabilize various systems.

Research on diethanolamides was conducted in elastomeric compositions for the manufacture of small-diameter sealing rings (O-rings) based on KRALEX 1500 butadiene-α-methylstyrene rubber, filled with 40.0 phr of N 330 carbon black, with a sulfur vulcanization system. The effect of DEA and DEA G products was compared with that of stearic acid, as a technological additive and a component of the sulfur vulcanization system, under the condition of equal mass replacement of 1.5 phr per 100.0 phr of the rubber base.

The base rubber compounds were prepared using a 4.5/20-140 laboratory rubber mixer equipped with a mixing chamber volume of 4.5 dm^3, a working volume of 2.2 dm^3, and a pneumatic system pressure of 0.4–0.6 MPa. The additives under study and technical stearic acid (manufactured in Indonesia, a mixture of stearic acid with admixtures of palmitic, oleic acids, etc.) were introduced on Pd 320 160/160 laboratory rollers; rotation speed 23.0±0.5 rev/min, friction 1 : 1.25. The rubber and ingredients used in the work correspond to the actual standards.

Technological and physico-mechanical characteristics of rubber compounds and rubbers at the optimum vulcanization temperature of 165 °C were evaluated in accordance with current international standards and relevant methods [1; 33]. In particular, the study of the rheological and vulcanization properties of elastomeric compositions according to international standards DIN 53 529, ASTM D 6204, ASTM D 6601 was performed using a MDR 3000 Professional non-rotating rheometer manufactured by Mon Tech with Mon Control software.

Based on the analytical views on determining the vulcanization characteristics of elastomeric compositions presented in our work [34], the conditional constant of vulcanization rate (k_2) according to rheokinetic tests was determined by the following formula:

$$k_2 = \frac{1{,}608}{\mathrm{TC90} - \mathrm{TC50}}$$

where TC 50 and TC 90 is times corresponding to the vulcanization degrees of 50 and 90 %, respectively.

Results and discussion

The results of determining the plasticity and elastic recovery of rubber compounds (Table 1) show that both diethanolamides, like stearic acid, have a positive effect on processability at a temperature of 70 °C. This also correlates with the results of determining the rheometric parameter of rubber compounds – the minimum torque (S_{min}) at temperatures of 155 °C and 165 °C. In the presence of diethanolamides, this

Journal of Chemistry and Technologies, 2026, *34*(2), 448-458

value decreases by 13–18 % relative to the values of the control composition without additives. The experimental product DEA has a more positive effect (even compared to the effect of stearic acid) on the technological characteristics. This softening effect of the studied amides has a certain impact on the maximum torque (S_{max}) and relative degree of crosslinking ($S_{max} - S_{min}$), which are lower than those in the control compositions with and without stearic acid (Table 1).

Table 1

Technological and vulcanization properties of elastomeric compositions for the manufacture of small-diameter sealing rings with various additives under investigation

Index	Type of additive			
	without additives	stearic acid	DEA	DEA G
Technological properties of rubber compounds				
Karrer plasticity, conv.unit	0.25	0.29	0.29	0.29
Elastic recovery, mm	2.2	1.9	1.9	2.0
Vulcanization properties (test conditions: T=155⁰C/165°C*; τ=60 Hz; H=1.67 Гц; ɣ=3.0⁰)				
Minimum torque (S_{Min}), dN·m	5.25/4.76*	4.75/4.36*	4.65/4.04*	4.76/4.39*
Maximum torque (S_{Max}), dN·m	57.40/51.82*	60.54/52.30*	56.03/48.30*	56.93/48.26*
Relative degree of crosslinking ($S_{Max} - S_{Min}$), dN·m	52.15/47.06*	55.79/47.94*	51.38/44.26*	52.17/43.87*
Scorching resistance (Scorch Time (TS 1)), min	1.70/1.00*	1.66/1.01*	1.43/0.81*	1.44/0.91*
Time to reach 90% vulcanization (TC90), min	28.83/17.00*	34.83/18.30*	15.73/5.21*	17.18/5.83*
Vulcanization rate (R_V=100/(TC90-TS1), min^{-1}	3.69/6.25*	3.01/5.78*	6.99/22.73*	6.35/20.33*
Conditional constant of vulcanization rate (k_2), min^{-1}	0.069/ 0.114*	0.056/ 0.104*	0.142/ 0.493*	0.127/ 0.448*
Temperature coefficient for indicator k_2, (K_{10}= $k_{2\,165}$/ $k_{2\,155}$)	1.65	1.86	3.47	3.53

Analysis of the sulfur vulcanization process using kinetic curves (Fig. 3 a, b) shows that the introduction of diethanolamides intensifies the crosslinking process, as demonstrated by a reduction in the induction period, a decrease in the slope of the kinetic curve in the main period, and an acceleration in reaching the optimum vulcanization, especially at a temperature of 155 °C.

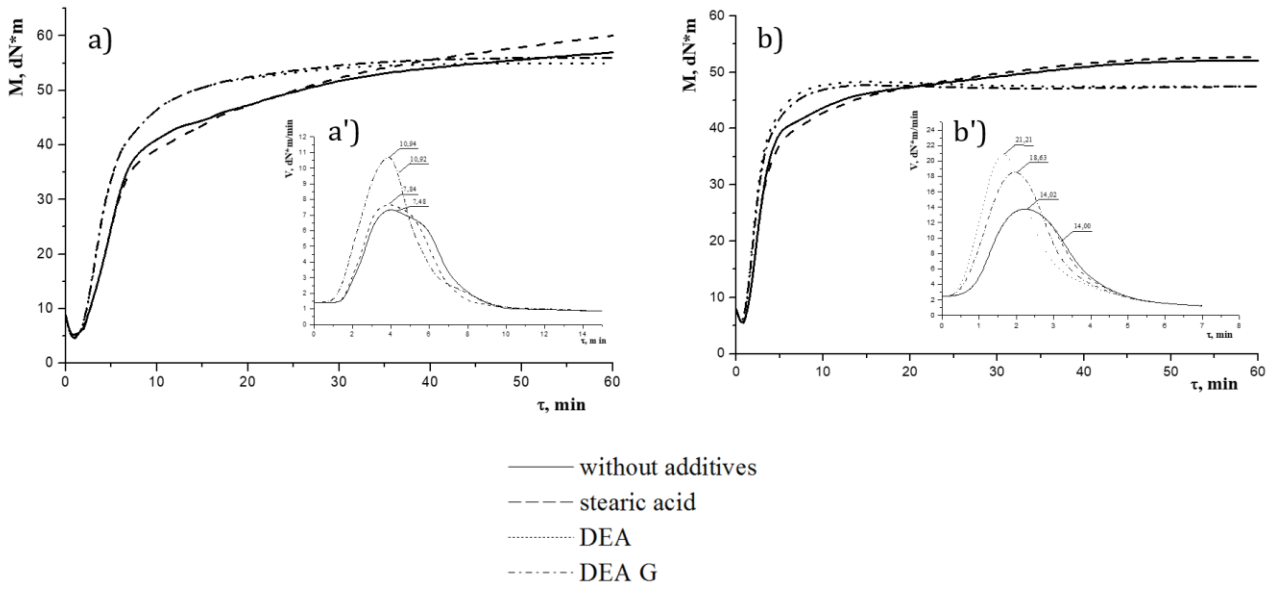


Fig. 3. Kinetic curves and vulcanization rates (at temperatures of 155°C –a, a' and 165°C – b, b', respectively) of elastomeric compositions with various additives

The maximum vulcanization rate of elastomeric compositions with diethanolamides at the same temperature is 1.5 times higher than that of compositions without additives and 1.4 times higher than that of compositions with stearic acid (Fig. 3 a'). An increase in the vulcanization temperature highlights the effect of different types of amides on the rubber

Journal of Chemistry and Technologies, 2026, *34*(2), 448-458

crosslinking process. At a temperature of 165°C (Fig. 3 b), DEA is characterized by greater activity compared to DEA G. The maximum vulcanization rate (Fig. 3 b') is observed for rubber with DEA. It exceeds the rate of rubber with DEA G by 1.14 times and the rate of rubber without the studied additives and stearic acid by 1.51 times. The change in the kinetic vulcanization curves' nature from a constant increase in the torque of elastomeric compositions in the presence of only zinc oxide and its combination with stearic acid, even at 165 °C sulfur vulcanization, to a faster achievement of a constant value on the vulcanization plateau for compositions with amide derivatives, probably indicates the influence of the latter on the mechanism of the process and the type of vulcanization bonds. This is confirmed by a 20–30 % lower content of free sulfur in rubbers in the presence of diethanolamides at the vulcanization optimum as a result of a possible increase in the sulfidity of their cross-links (Fig. 4) [35], which we also established in our previous work [28].

The reduction in the induction period is demonstrated on the kinetic curves when the studied amides were introduced. It is reflected in the calculated rheometric parameters, namely, resistance to scorching (Table 1) at both vulcanization temperatures. The acceleration of vulcanization is also observed in the calculated values. In particular, the time to reach the optimum vulcanization (TC90) of elastomeric compositions with amides is 2 or more times (depending on the vulcanization temperature) shorter compared to compositions without additives and stearic acid. Accordingly, the calculated vulcanization rate (Rv) and the conditional constant of vulcanization rate (k_2) demonstrate the above tendency. An increase in the vulcanization temperature naturally increases the vulcanization rate of all compositions and the difference in the calculated values. The advantage of amides at a temperature of 155 °C is on average 2 times, and at a temperature of 165 °C, almost 4 times.

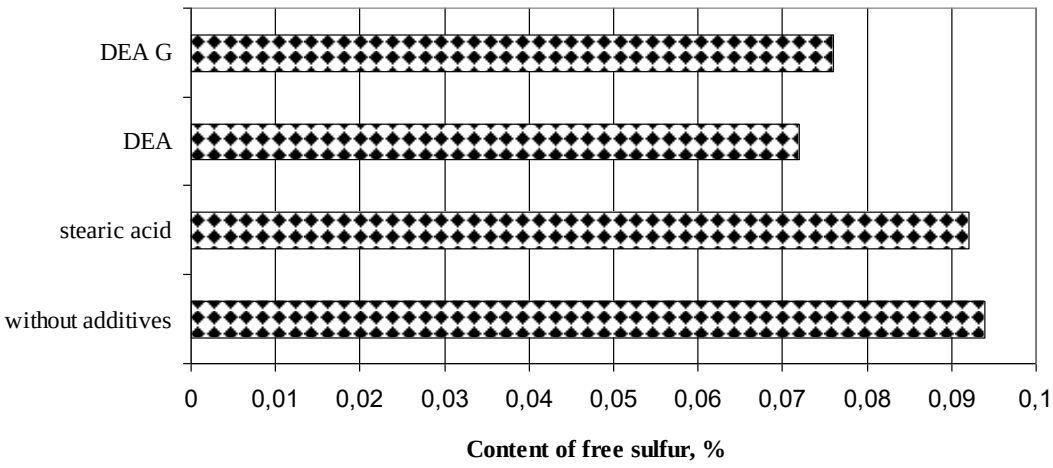


Fig. 4. Content of free sulfur in rubbers for the manufacture of small-diameter sealing rings with various additives

The conditional constant of the isothermal vulcanization rate of elastomeric compositions in the presence of diethanolamides is 2.3-2.5 times higher than that of stearic acid at a temperature of 155°C and 4.3-4.7 times higher at a temperature of 165°C. The temperature coefficient of vulcanization relative to the conditional rate constant (K_{10}) for compositions with stearic acid is 1.9 compared to 3.5 for compositions with DEA and DEA G. According to the kinetic characteristics of TS1, TS90, Rv, etc. (Table 1, Fig. 5), diethanolamides significantly affect the initiation of sulfur vulcanization, i.e., they are vulcanization-active additives. According to the specified rheometric parameters, DEA has an advantage over DEA G.

Journal of Chemistry and Technologies, 2026, *34*(2), 448-458

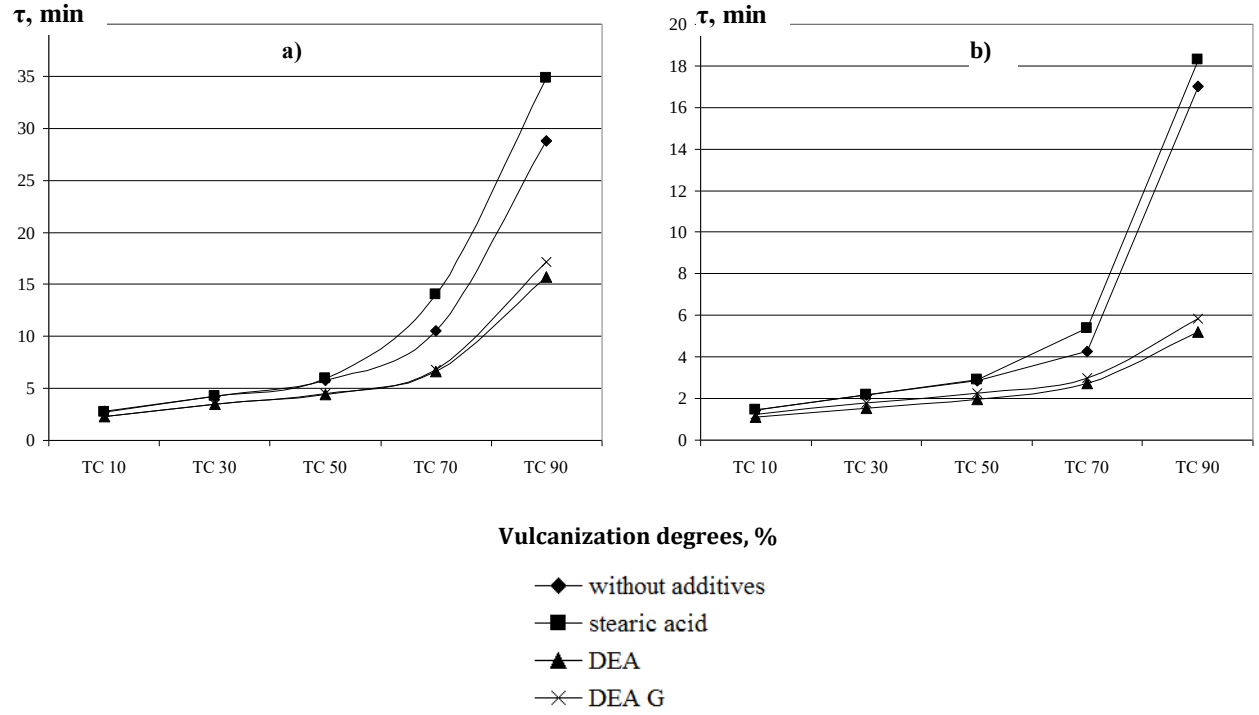


Fig. 5. The effect type of additive on the time required to achieve different vulcanization degrees of elastomeric compositions at a temperatures of 155°C (a) and 165°C (b)

That is, the studied amide derivatives of fatty acids are multi-purpose additives. As difil substances, from a chemical point of view, they have a positive effect on the technological characteristics of rubber compounds (as softeners-plasticizers). As organic activators and secondary vulcanization accelerators at a dosage of 1.5 mass parts per 100.0 mass parts of the rubber matrix, diethanolamides have a effect on the duration of the induction period of the sulfur vulcanization process and increase the kinetic parameters of the crosslinking by 2-4 times. This probably indicates an ionic mechanism of the actual vulcanization agent (AVA) formation with the participation of diethanolamides at the induction stage of vulcanization and a radical mechanism (with the synergistic action of diethanolamides in the AVA structure) for the formation of vulcanization cross-links [36]. Such specifics of elastomeric composition sulfur vulcanization in the presence of the studied diethanolamides will require further the adjustment of composition and dosage of the ingredients of the vulcanization system.

The use of the studied diethanolamides, as well as stearic acid, does not lead to radical changes in the basic physical and mechanical properties of rubbers compared to the sample without additives (Table 2), but demonstrates corrective effects, especially under thermal stress.

Table 2

Physical and mechanical properties of rubbers for the manufacture of small-diameter sealing rings with various additives (optimum vulcanization at a temperature of 165 °C)

Index	Type of additive			
	without additives	stearic acid	DEA	DEA G
Conditional stress at 300% elongation, f_{300}, MPa under normal conditions	16.2	17.0	16.5	16.7
Conditional tensile strength, f_p, MPa under normal conditions	24.3	24.5	24.5	25.1
at a temperature of 100 °C	7.2/0.30*	6.1/0.25*	9.0/0.37*	8.5/0.34*
after aging 100 °C×72 h	17.7	17.7	18.2	17.8
Relative elongation at break, ε, % under normal conditions	400	350	420	390
at a temperature of 100 °C	220/0.55*	230/0.66*	270/0.64*	270/0.69*
after aging 100 °C×72 h	220	180	240	210
Tear resistance, B, kN/m under normal conditions	53	65	65	58
after aging 100 °C×72 h	43	47	50	44

Continued from Table 2

Shore hardness A, H, rel.units under normal conditions	61	63	61	61
after aging 100 °C×72 h	66/1.08*	67/1.06*	66/1.08*	66/1.08*
Rebound elasticity, S, % under normal conditions	46	45	47	47
after aging 100 °C×72 h	45	45	46	47

Note: * – coefficient of temperature or heat resistance

DEA and DEA G additives increase the heat resistance of rubber, reducing the loss of conditional tensile strength at an exposure temperature of 100 °C by 25 % and 18 %, respectively. The diethanolamides allow maintaining high deformation properties of rubber, in particular, after exposure to 100 °C, the relative elongation at break of rubber with DEA and DEA G is 22 % higher compared to rubber without additives and 17 % higher compared to stearic acid. DEA, like stearic acid, increases tear resistance by up to 22 % under normal test conditions and retards the decrease in this value after thermal aging. Analyzing the values of heat resistance coefficients (Fig. 6), diethanolamides are more effective than stearic acid. The highest values of almost all coefficients are characteristic of rubber containing DEA.

Thus, the studied diethanolamides, in particular DEA, effectively increase temperature and heat resistance and preserve the elasticity and strength properties of rubbers without causing significant changes in other physical and mechanical characteristics.

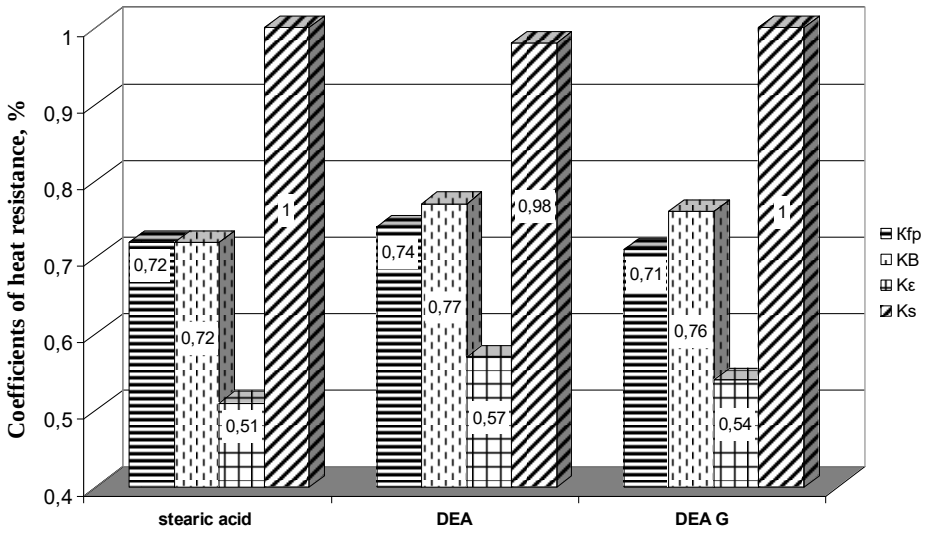


Fig. 6. Coefficients of heat resistance, calculated based on the main physical and mechanical properties (table 2) of rubbers for the manufacture of small-diameter sealing rings with various additives

Conclusions

In line with global trends in the production of elastomeric compositions and products made from them using environmentally friendly ingredients based on plant raw materials, amide derivatives of fatty acids from the organic component of spent sunflower oil adsorbent were synthesized in this work and characterized using instrumental methods.

The introduction of diethanolamides into the composition of filled elastomeric compositions for the manufacture of small-diameter sealing rings based on butadiene-α-methylstyrene rubber demonstrates a complex of positive effects, surpassing the traditional additive, stearic acid. The amides under study perform a multifunctional role: they improve the processability of rubber compounds and act as effective organic activators and secondary accelerators, accelerating the sulfur vulcanization process by 2–4 times. Shortening the induction period of the vulcanization when using diethanolamides will require further the adjustment of composition and dosage of the ingredients of the vulcanization system. A significant increase in the temperature and heat resistance of rubber was established: DEA and DEA G additives reduce the loss of strength characteristics after exposure to elevated temperatures by 25 % and 18 %, respectively, and provide a relative elongation at break 22 % higher than for rubber without additives. Among the additives studied, diethanolamide without glycerin proved to be the most effective,

providing optimal vulcanization kinetics and physical and mechanical properties of rubber under normal conditions and after heat exposure.

The obtained environmentally safe bio-ingredients can be recommended for extended testing and further implementation in sulfur vulcanization systems to produce elastomeric compositions for various purposes.

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