MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

Submitted: August 16, 2025 **Revised: September 15, 2025** **Accepted: October 23, 2025**

Influence of dispersed inorganic fillers on the properties of vulcanized rubber based on ethylene propylene diene monomer rubber SKEPT-40

E.N. Egorov ✉, **N.I. Kol'tsov**

I.N. Ulyanov Chuvash State University, Cheboksary, Russia

✉ enegorov@mail.ru

ABSTRACT

The influence of various powder inorganic fillers (carbon black P 803, P 324 and N 220, silica ZC-120) on the rheometric properties of the rubber compound, physico-mechanical and performance properties of vulcanized rubber based on ethylene propylene diene monomer rubber SKEPT-40, used for rubberizing metal surfaces, was studied. The rubber compound under study based on the above rubber included a vulcanizing agent (sulfur), vulcanization accelerators (2-mercaptobenzthiazole and tetramethylthiuram disulfide), vulcanization activators (zinc white and stearic acid) softener (industrial oil I-8A). It was found that vulcanized rubber with a content of 60.0 parts per hundred parts of rubber (phr) of carbon black N 220 has high physico-mechanical properties, the smallest changes in tensile strength, elongation at break and weight after exposure to aggressive acid-base environments and good frost resistance.

KEYWORDS

carbon black P 803, P 324 and N 220 • silica ZC-120 • ethylene propylene diene monomer rubber SKEPT-40 vulcanized rubber • rheometric • physico-mechanical and performance properties

Citation: Egorov EN, Kol'tsov NI. Influence of dispersed inorganic fillers on the properties of vulcanized rubber based on ethylene propylene diene monomer rubber SKEPT-40. *Materials Physics and Mechanics*. 2025;53(5): 132–139.
http://dx.doi.org/10.18149/MPM.5352025_11

Introduction

It is known [1–8] that dispersed inorganic fillers make it possible to regulate the technological properties of rubber compounds and the physico-mechanical properties of vulcanizates. In [1], the effect of Zeosil 1165 PM silicon dioxide modified with the organosilane coupling agent bis-(3-triethoxysilylpropyl) tetrasulfane (TESPT) on the rheometric properties of a rubber compound and the physico-mechanical properties of vulcanized rubber based on natural rubber (NR) was investigated. It was shown that the introduction of modified silicon dioxide into the rubber compound leads to an improvement in the rheometric, rheological of the rubber compound, and physico-mechanical properties of the vulcanized rubber. In [2], it was shown that binary fillers with a silica to graphite powder ratio of 1:1 in an amount of only 20.0 phr provide excellent mechanical properties and improved resistance to thermooxidative aging of composites based on NR compared to single fillers. In [4], the influence of hollow polymer microspheres Expancel 909 DU 80, Expancel 043 DUT 80, Expancel 920 DET 40d25, Expancel 920 DUT 40, Expancel 930 MB 120 and Lega Foam 120 MB in an amount of 5.0 phr on the rheometric properties of the rubber compound, the physico-mechanical and performance properties of oil-resistant rubber was studied. It was found that

© E.N. Egorov, N.I. Kol'tsov, 2025.
Publisher: Peter the Great St. Petersburg Polytechnic University
This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/li-censes/by-nc/4.0/)

vulcanized rubber containing Expancel 043 DUT 80 microspheres has the best physico-mechanical properties, high wear resistance and resistance to the effects of aggressive hydrocarbon environments. In [8], the influence of the amount of 5.0, 10.0, 15.0 and 20.0 phr was considered. The effect of montmorillonite on the physico-mechanical properties of vulcanizates based on a mixture of natural rubber/styrene-butadiene rubber in a ratio of 50/50 phr was studied. It was shown that the tensile strength of the filled vulcanized rubber reached its maximum value (11.2 MPa) when the montmorillonite content was 15.0 phr.

As a rule, fillers are used to improve the elastic-strength and performance parameters and the chemical resistance of vulcanized rubbers to the action of aggressive acidic and alkaline environments [9–22]. In the rubber industry, rubber compounds based on ethylene propylene diene monomer rubbers are of practical interest, which are characterized by a balanced resistance to the effects of temperatures [23] and oxidation by ozone [24–27]. Despite the achieved results, in connection with increasing requirements, it remains important to develop rubbers that are resistant to temperature effects and highly resistant to alkaline and acidic environments. To eliminate these shortcomings, dispersed powder fillers are introduced into rubber compounds, of which the effective are carbon black [28–34] and silica [35–38]. Therefore, research on the creation of high-quality rubbers based on ethylene propylene diene monomer rubbers, resistant to the effects of temperatures and aggressive environments, using dispersed inorganic fillers is relevant. In this article, the influence of carbon black P 803, P 324, N 220, and silica ZC-120 as fillers on the rheometric properties of the rubber compound, physico-mechanical, and performance properties of vulcanized rubber based on ethylene propylene diene monomer rubber SKEPT-40, often used in the rubber industry, was studied [39,40].

Material and Methods

The rubber compound included ethylene propylene diene monomer rubber SKEPT-40 with a Mooney viscosity ML_{1+4} (100 °C) = 38, ethylene and dicyclopentadiene content of 56 and 6 wt. %, as well as the following ingredients: vulcanizing agent (sulfur), vulcanization accelerators (2-mercaptobenzothiazole and tetramethylthiuram disulfide), vulcanization activators (zinc white and stearic acid), softener (industrial oil I-8A). Carbon black P 324, N 220 and P 803, as well as silica ZC-120 were used as fillers. Carbon black P 324 and N 220 are powders of a deep black color with a particle size of 0.028–0.036 and 0.024–0.033 μm, bulk density of 340 and 355 kg/m^3, a specific surface area of 75–82 and 106–114 m^2/g, and a dibutyl phthalate absorption of 100 ± 5 and 113 ± 7 cm^3/100 g, respectively. Carbon black P 803 is a dark gray powder with a particle size of 9–320 μm, bulk density of 320 kg/m^3, specific surface area of 14–18 m^2/g, dibutyl phthalate absorption of 83 ± 7 cm^3/100 g. Silica ZC-120 is a white powder with a particle size of 0.005–0.015 μm, silicon dioxide content of 97 %, specific surface area of 105–135 m^2/g, a pH (5 % aqueous suspension) of 6–8.

The rubber compound was prepared on LB 320 160/160 laboratory mills at a roll surface temperature of 60–70 °C for 25 min. The rheometric properties of the rubber compound were studied on an MDR 3000 Basic rheometer at 150 °C for 60 min in

accordance with ASTM D2084-79. To determine the physico-mechanical properties, the rubber compound was vulcanized at a temperature of 150 °C for 60 min in a PV-100-3RT-2-PCD vulcanization press. The elastic strength properties were determined according to [42] Shore A hardness was measured in accordance with [43]. Rebound elasticity was determined according to [44]. Relative residual compression deformation (RCD) was determined according to [45]. Change in tensile strength, relative elongation at break and hardness after thermal-oxidative aging in air was determined according to [46]. The change in conditional tensile strength, relative elongation at break and hardness after exposure to liquid aggressive environments was determined according to [47]. The change in mass after exposure to liquid aggressive environments was found according to [47]. The frost resistance coefficient for elastic recovery after compression was determined according to [48].

Results and Discussion

Four variants of rubber compounds were studied, containing carbon black P 324, N 220, P 803 and silica ZC-120 in the amount of 60.00 phr (traditional formulation). For each variant of rubber mixture, vulcanization curves were recorded at 150 °C for 60 min. The research results are shown in Fig. 1.

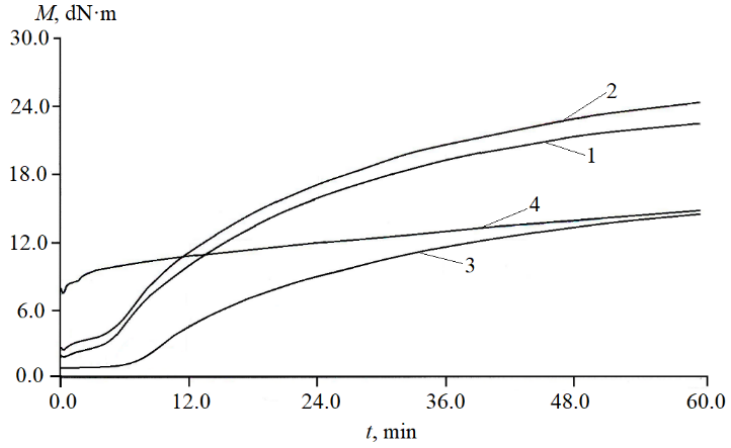

Fig. 1. Vulcanization curves of rubber compound (curve numbers correspond to variant numbers)

The rheometric parameters determined on the basis of the obtained vulcanization curves are given in Table 1. It follows from Table 1 that for variant 3 of the rubber compound containing P 803 carbon black as a filler, a significant increase in the scorch time is observed, which may negatively affect the productivity and quality of the final product. At the same time, variant 4 is characterized by the lowest scorch time. The difference between the torques is directly proportional to the degree of chemical crosslinking of the vulcanizate. Thus, the vulcanizate of variant 2 containing N 220 carbon black as a filler should be characterized by a high degree of crosslinking and have better strength properties.

After vulcanization of the rubber compound, the main physico-mechanical properties of the vulcanizates were determined and are given in the Table 1. The Table shows that variant 2 demonstrates the better physico-mechanical characteristics compared to other variants of vulcanizates, which is explained by the smaller particle

Table 1. Results of the study of the properties of various variants of rubber compounds and vulcanizates

Fillers, indicators	Variants			
	1	2	3	4
Carbon black P 324, phr	60.0	–	–	–
Carbon black N 220, phr	–	60.0	–	–
Carbon black P 803, phr	–	–	60.0	–
Silica ZC-120, phr	–	–	–	60.0
Rheometric properties of rubber compound				
M_H, dN·m	22.51	24.33	14.37	17.51
M_L, dN·m	2.24	3.11	1.02	8.65
ΔM, dN·m	20.27	21.22	13.35	8.86
t_s, min	3.31	3.27	8.57	0.50
t_{90}, min	43.17	43.79	46.50	50.36
Physico-mechanical properties of vulcanizates				
f_p, MPa	14.6 ± 0.7	14.6 ± 0.6	6.0 ± 0.3	5.4 ± 0.3
ε_p, %	356 ± 17	362 ± 19	294 ± 14	682 ± 32
H, units Shore A	72 ± 1	77 ± 1	62 ± 1	68 ± 1
S, %	36 ± 1	37 ± 1	54 ± 1	40 ± 1
RCD at 25 % compression (125 °C × 24 h), %	32.0 ± 1.1	20.0 ± 0.7	30.0 ± 0.9	41.0 ± 1.4
Changes in the physico-mechanical properties of vulcanizates after aging in air (125 °C × 24 h)				
Δf_p, %	+(1.0 ± 0.1)	+(1.0 ± 0.1)	+(1.0 ± 0.1)	+(7.0 ± 0.3)
Δε_p, %	-(15.0 ± 0.6)	-(9.0 ± 0.4)	-(30.0 ± 1.3)	-(52.0 ± 2.1)
ΔH, units Shore A	+(9 ± 1)	+(7 ± 1)	+(8 ± 1)	+(10 ± 1)
Changes in physico-mechanical properties and mass of vulcanizates in a 20 % NaOH solution (23 °C × 24 h)				
Δf_p, %	+(6.0 ± 0.2)	+(3.0 ± 0.1)	+(5.0 ± 0.2)	+(10.0±0.4)
Δε_p, %	+(24.0 ± 0.8)	+(10.0 ± 0.3)	+(18.0 ± 0.6)	+(14.0±0.5)
ΔH, units Shore A	+(1 ± 1)	+(3 ± 1)	-(1 ± 1)	+(3±1)
Δm, %	0.17 ± 0.01	0.13 ± 0.01	0.18 ± 0.01	0.25 ± 0.01
Changes in physico-mechanical properties and mass of vulcanizates in a 20 % HCl solution (23 °C × 24 h)				
Δf_p, %	+(10.0 ± 0.4)	+(2.0 ± 0.1)	-(5.0 ± 0.2)	+(3.0 ± 0.1)
Δε_p, %	+(12 ± 0.4)	+(6.0 ± 0.2)	-(54.0 ± 2.1)	+(56.0 ± 2.3)
ΔH, units Shore A	+(1 ± 1)	-(2 ± 1)	-(1 ± 1)	-(7 ± 1)
Δm, %	0.43 ± 0.01	0.42 ± 0.01	0.46 ± 0.01	0.45 ± 0.01
Frost resistance of vulcanizates				
K_B	0.32 ± 0.01	0.34 ± 0.01	0.40 ± 0.01	0.31 ± 0.01

Note: M_H is maximum torque; M_L is minimum torque; ΔM is difference between the maximum and minimum torques; t_s is scorch time; t_{90} is optimum cure time; f_p is tensile strength; ε_p is elongation at break; H is hardness; S is rebound elasticity; RCD is relative residual compression deformation; Δf_p, Δε_p and Δm are relative changes in the tensile strength, elongation at break and mass; ΔH is change in hardness; K_B is the coefficient of frost resistance by elastic recovery after compression.

size and larger specific surface area of the N 220 carbon black used in this variant compared to P 324 and P 803 carbon black, as well as by the poor dispersion of ZC-120 silica in the rubber matrix [41]. At the same time, vulcanizates of variants 3 and 4 have low values of conventional tensile strength and hardness, which limits their use in conditions where high strength and reliability of materials are required. However, variant 4 is characterized by a good indicator of elongation at break. Vulcanizate of variant 2, containing carbon black N 220 as a filler, is characterized by the lowest value of relative residual compression deformation, which indicates its high elastic properties.

The table also shows the results of the study of changes in the physico-mechanical properties and hardness of vulcanizates after thermal aging in air. As can be seen, the stable physico-mechanical properties are found in the vulcanizate of variant 2 of the rubber compound containing carbon black grade N 220. It shows a slight change in the tensile strength, as well as in the elongation at break after thermal aging in air.

The changes in the physico-mechanical properties and weight of the vulcanizates after exposure to aggressive environments were further investigated: 20 % aqueous solutions of NaOH and HCl at 23 °C for 24 h (see Table 1). The data obtained show that the best resistance in a 20 % HCl solution is demonstrated by the vulcanizate of variant 2, which is characterized by the smallest changes in strength and elongation.

Table 1 also shows the results of the study of the frost resistance of the vulcanizates, determined by their elastic recovery after a single 20 º% compression for 5 min at –50 ºC. As can be seen, all vulcanizates have high frost resistance coefficient values, which indicates the ability to maintain elasticity and physico-mechanical properties at extremely low temperatures, allowing them to be used in cold climates.

Conclusions

The objects of the study were a rubber compound and vulcanized rubber on its basis, obtained by sulfur vulcanization of ethylene propylene diene monomer rubber SKEPT-40 in the presence of vulcanization accelerators (2-mercaptobenzothiazole and tetramethylthiuram disulfide), vulcanization activators (zinc white and stearic acid), a softener (industrial oil I-8A) and various inorganic fillers (carbon black P 803, P 324, N 220 and silica ZC-120) in an amount of 60.0 phr. The rubber compound was prepared on laboratory rollers LB 320 160/160, and then its rheometric properties were determined on a rheometer MDR 3000 Basic. The vulcanized rubber was obtained by vulcanizing the rubber compound in a P-V-100-3RT-2-PCD vulcanization press. The resulting vulcanizates were tested for their physical and mechanical properties (elastic strength properties, Shore A hardness, rebound elasticity, and relative compressive strain), as well as their performance properties (changes in tensile strength, elongation at break, and hardness after thermal-oxidative aging in air, changes in mass after exposure to liquid aggressive environments, and frost resistance).

These results allow us to formulate the following conclusions:

1. The rubber compound containing N 220 carbon black exhibits a large difference between the maximum and minimum torques, which is directly proportional to the degree of chemical crosslinking and the strength properties of the vulcanizate.
2. The vulcanizate containing carbon black N 220 has better and more stable physico-mechanical properties compared to vulcanizates containing carbon blacks P 324, P 803 and silica ZC-120, which explained by the smaller particle size and higher specific surface area of carbon black N 220 compared to carbon black P 324 and P 803, as well as poor dispersion of silica ZC-120 in the rubber matrix. For the vulcanizate containing carbon black N 220, an insignificant change in the conventional tensile strength is observed, as well as the relative elongation at break after thermal aging in air, exposure to aggressive acid-base environments, and high frost resistance.

3. Recommendations for the practical application of the results: a rubber mixture consisting of ethylene propylene diene monomer rubber SKEPT-40 and containing 60.0 phr carbon black N 220, can be recommended for rubberizing the surfaces of tanks used for transporting and storing acid-base solutions.
4. A possible direction for further research is to study the effect of carbon black N 220 on rubber based on other ethylene propylene diene monomer rubbers, such as S 501A and S 505A.

CRediT authorship contribution statement

Evgeniy N. Egorov : writing – review & editing, writing – original draft, conceptualization, investigation; **Nikolay I. Kol'tsov** : writing – review & editing, writing – original draft, conceptualization, supervision, data curation.

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. Rombaldi SH, Pierozan NJ, Brandalise RN. Influence on mechanical and rheometric properties through different methods of chemical modification of silica applied to natural rubber compounds. *Journal of Elastomers and Plastics.* 2021;53(2): 165–187.
2. Alam MN, Kumar V, Potiyaraj P, Lee DJ, Choi J. Mutual dispersion of graphite–silica binary fillers and its effects on curing, mechanical, and aging properties of natural rubber composites. *Polymer Bulletin.* 2022;79(5): 2707–2724.
3. Shahamatifard F, Rodrigue D, Park KW, Frikha S, Mighri F. Natural rubber nanocomposites: effect of carbon black/multi-walled carbon nanotubes hybrid fillers on the mechanical properties and thermal conductivity. *Polymer-Plastics Technology and Materials.* 2021;60(15): 1686–1696.
4. Egorov EN, Sandalov SI, Kol'tsov NI, Voronchikhin VD. Study of the effect of polymeric microspheres on the properties of oil and petrol resistant rubber. *Journal of Siberian Federal University. Chemistry.* 2024;17(3): 376–382. (In Russian)
5. Marzocca AJ, Garraza ALR, Anbinder S, Macchi C, Somoza A. Changes in the mechanical, micro-, and nano-structural properties of reinforced vulcanized natural rubber compounds: their dependence on the SiO_2/CB ratio. *Rubber Chemistry and Technology.* 2022;95(1): 58–81.
6. Honorato LR, Visconte LLY, Nunes RCR. Effect of different cure systems on natural rubber/nanocellulose nanocomposites in rheological, physical-mechanical, aging, and mechanical properties. *Journal of Elastomers and Plastics.* 2022;54(5): 676–692.
7. Amrollahi A, Razzaghi-Kashani M, Hosseini SM, Habibi N. Carbon black/silica hybrid filler networking and its synergistic effects on the performance of styrene-butadiene rubber composites. *Polymer Journal.* 2022;54(7): 931–942.
8. El Mogy SA, Lawandy SN. Enhancement of the cure behavior and mechanical properties of nanoclay reinforced NR/SBR vulcanizates based on waste tire rubber. *Journal of Thermoplastic Composite Materials.* 2024;37(2): 520–543.
9. Zaeimoedin TZ, Aziz AKC, Kamal MM. Improving filler dispersion and physical properties of epoxidised natural rubber/silica compound by using dual fillers and coupling agent in mixing process. *Malaysian Journal of Analytical Sciences.* 2014;18(3): 604–611.
10. Shiva M, Akhtari SS, Shayesteh M. Effect of mineral fillers on physico-mechanical properties and heat conductivity of carbon black-filled SBR/butadiene rubber composite. *Iranian Polymer Journal.* 2020;29: 957–974.
11. Egorov EN, Kol'tsov NI. Influence of glass fibers on the physico-mechanical and performance properties of rubber based on general and special purpose caoutchoucs. *Materials Physics and Mechanics.* 2024;52(1): 126–131.
12. Kumar V, Alam MN, Manikkavel A, Song M, Lee DJ, Park SS. Silicone rubber composites reinforced by carbon nanofillers and their hybrids for various applications: A review. *Polymers.* 2021;13(14): 2322.
13. Roy K, Debnath SC, Potiyaraj P. A critical review on the utilization of various reinforcement modifiers in filled rubber composites. *Journal of Elastomers and Plastics.* 2019;52(2): 167–193.

14. Braihi AJ, Jawad AJ, Kadhum AAH, Aljibori HSS, Al-Amiery AA. Chemical resistance of NR/SBR rubber blends for surfaces corrosion protection of metallic tanks in petrochemical industries. *Koroze a Ochrana Materiálu.* 2020;64(2): 65–71.
15. Kazemi H, Mighri F, Rodrigue D. A review of rubber biocomposites reinforced with lignocellulosic fillers. *Journal of Composites Science.* 2022;6(7): 183.
16. Wang Z, An Q, Jiao L, Lu P, Qu Y, Xu Z, Sun W, Li Y. Preparation and properties of fluorosilicone composites with thermal conductivity and chemical resistance through modification of filler and matrix. *Polymer Degradation and Stability.* 2024;225: 110823.
17. Omar MF, Ali F, Jami MS, Azmi AS, Ahmad F, Marzuki MZ, Muniyandi SK, Zainudin Z, Kim MP. A Comprehensive Review of Natural Rubber Composites: Properties, Compounding Aspects, and Renewable Practices with Natural Fibre Reinforcement. *Journal of Renewable Materials.* 2025;13(3): 497–538.
18. Egorov EN, Sandalov SI, Kol'tsov NI. Influence of basalt fibres on the physical-mechanical, performance and dynamic properties of rubber for rail pads. *Chemistry for Sustainable Development.* 2023;31(4): 362–366. (In Russian)
19. Ushmarin NF, Egorov EN, Kol'tsov NI. Influence of microspheres on properties of aggressive resistant rubbers. *Izvestiya vysshikh uchebnykh zavedeniy khimiya khimicheskaya tekhnologiya [ChemChemTech].* 2021;64(2): 49–55. (In Russian)
20. Zou Y, Yao YF, Zhang R, Zhao YH, Cao J, Xu YX. Biobased recyclable rubbers with shape memory, self-welding, and damping properties by cross-linking epoxidized natural rubber with succinic anhydride. *ACS Sustainable Chemistry and Engineering.* 2023;11(51): 18123–18130.
21. Ridho MR, Agustiany EA, Rahmi DnM, Madyaratri EW, Ghozali M, Restu WK, et al. Lignin as green filler in polymer composites: development methods, characteristics, and potential applications. *Advances in Materials Science and Engineering.* 2022;2022(1): 1363481.
22. Ushmarin NF, Egorov EN, Sandalov SI, Kol'tsov NI. Influence of polymeric microspheres on rubber properties for coating metal surfaces. *Russian Journal of General Chemistry.* 2023;93: 734–739.
23. Kumar SP, Prabhakaran G, Vishvanathperumal S. Influence of Modified Nanosilica on the Performance of NR/EPDM Blends: Cure Characteristics, Mechanical Properties and Swelling Resistance. *Journal of Inorganic and Organometallic Polymers and Materials.* 2024;34: 3420–3442.
24. Bizhani H, Katbab AA, Lopez-Hernandez E, Miranda JM, Lopez-Manchado MA, Verdejo R. Preparation and characterization of highly elastic foams with enhanced electromagnetic wave absorption based on ethylene-propylene-diene-monomer rubber filled with barium titanate/multiwall carbon nanotube hybrid. *Polymers.* 2020;12(10): 2278.
25. Costa NL, Hiranobe CT, Cardim HP, Dognani G, Sanchez JC, Carvalho JAJ, Torres GB, Paim LL, Pinto LF, Cardim GP, Cabrera FC, dos Santos RJ, Silva MJ. A Review of EPDM (Ethylene Propylene Diene Monomer) Rubber-Based Nanocomposites: Properties and Progress. *Polymers.* 2024;16(12): 1720.
26. Li C, Wang Y, Yuan Z, Ye L. Construction of sacrificial bonds and hybrid networks in EPDM rubber towards mechanical performance enhancement. *Applied Surface Science.* 2019;484: 616–627.
27. Ghoreishi A, Koosha M, Nasirizadeh N. Modification of bitumen by EPDM blended with hybrid nanoparticles: Physical, thermal, and rheological properties. *Journal of Thermoplastic Composite Materials.* 2020;33(3): 343–356.
28. Fan Y, Fowler GD, Zhao M. The past, present and future of carbon black as a rubber reinforcing filler–A review. *Journal of Cleaner Production.* 2020;247: 119115.
29. Robertson CG, Hardman NJ. Nature of carbon black reinforcement of rubber: Perspective on the original polymer nanocomposite. *Polymers.* 2021;13(4): 538.
30. Egorov EN, Sandalov SI, Kol'tsov NI. Study of the influence of dispersed fillers on properties of rubber for gaskets of rail fastening. *Materials Physics and Mechanics.* 2023;51(6): 119–126.
31. Zhang H, Wang C, Zhang Y. Preparation and properties of styrene-butadiene rubber nanocomposites blended with carbon black-graphene hybrid filler. *Journal of Applied Polymer Science.* 2015;132(3): 41309.
32. Jovanović V, Samaržija-Jovanović S, Budinski-Simendić J, Marković G, Marinović-Cincović M. Composites based on carbon black reinforced NBR/EPDM rubber blends. *Composites Part B: Engineering.* 2013;45(1): 333–340.
33. Xu T, Jia Z, Li J, Luo Y, Jia D, Peng Z. Study on the dispersion of carbon black/silica in SBR/BR composites and its properties by adding epoxidized natural rubber as a compatilizer. *Polymer Composites.* 2018;39(2): 377–385.
34. Ismail H, Omar NF, Othman N. Effect of carbon black loading on curing characteristics and mechanical properties of waste tyre dust/carbon black hybrid filler filled natural rubber compounds. *Journal of Applied Polymer Science.* 2011;121(2): 1143–1150.
35. Egorov EN, Ushmarin NF, Sandalov SI, Grigor'ev VS, Kol'tsov NI, Voronchikhin VD. Study of the effect of silica filler Silica 1165 on the properties of rubber for rail fastening gaskets. *Journal of Siberian Federal University. Chemistry.* 2022;15(1): 110–117 (In Russian)

36. Liu H, Yang L, Liu X, Cao JP, Zhang J, Luo Z, Gao, Z. Silicon dioxide nanoparticle decorated graphene with excellent dispersibility in natural rubber composites via physical mixing for application in green tires. *Composites Part B: Engineering.* 2023;258: 110700.
37. Bera A, Sarkar K, Ganguly D, Ghorai SK, Hore R, Kumar N, Amarnath SKP, Chattopadhyay S. Recent advancements in silica filled natural rubber composite: A green approach to achieve smart properties in tyre. *Journal of Polymer Research.* 2024;31(4): 122.
38. Khan H, Amin M, Ali M, Iqbal M, Yasin M. Effect of micro/nano-SiO_2 on mechanical, thermal, and electrical properties of silicone rubber, epoxy, and EPDM composites for outdoor electrical insulations. *Turkish Journal of Electrical Engineering and Computer Sciences.* 2017;25(2): 1426–1435.
39. Kablov VF, Keibal NA, Kochetkov VG, Novopoltseva OM, Kryukova DA, Urzhumov DA, Tokar' VP. Research on Elastomeric Fire-and Heat-Protection Materials Containing Plasma-Treated Microspheres. *Polymer Science, Series D.* 2024;17: 286–290.
40. Davydova ML, Shadrinov NV, Fedorova AF, Khaldeeva AR, Sokolova MD. Studying the Stability of Ethylene-Propylene Rubbers under Thermocycling in Different Working Media. *Polymer Science, Series D.* 2025;18: 239–244.
41. Bokobza L. Elastomer Nanocomposites: Effect of Filler–Matrix and Filler–Filler Interactions. *Polymers.* 2023;15(13): 2900.
42. Russian State Standard. GOST 270-75. *Rubber. Method of the determination elastic and tensile stress-strain properties*. Moscow: Standardinform; 2008. (In Russian)
43. Russian State Standard. GOST 263-75. *Rubber. Method for the determination of Shore A hardness.* Moscow: Standards Publishing; 1989. (In Russian)
44. Russian State Standard. GOST 27110-86. *Rubber. Method for determination of rebound elasticity on the Shob type machine*. Moscow: Standards Publishing; 1987. (In Russian)
45. Russian State Standard GOST 9.029-74. *Unified system of corrosion and ageing protection. Vulcanized rubbers. Method of testing of resistance to ageing under static deformation of compression*. Moscow: Standards Publishing; 1982. (In Russian)
46. Russian State Standard. GOST 9.024-74. *Unified system of corrosion and ageing protection. Rubbers. Methods of heat ageing stability determination.* Moscow: Standards Publishing; 1975. (In Russian)
47. Russian State Standard. GOST 9.030-74 (method B). *Unified system of corrosion and ageing protection. Vulcanized rubbers. Method of testing resistance to attack by corrosive media in limp state.* Moscow: Standardinform; 2008. (In Russian)
48. Russian State Standard. GOST 13808-79. *Rubber. Method for the determination of low temperature resistance according to elastic rebound after compression*. Moscow: Standards Publishing; 1978. (In Russian)