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Antifriction fluoroplastic materials for sliding layers in bridge supports

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Abstract. The requirements for reliability and durability are increasing every year for the critical elements of bridge structures, as there is a steady increase in the number of vehicles and volumes of cargo movement. Such structural elements include bearing parts of spans of bridges, which perceive loads from the mass of spans, transport cargo and compensate for deformations from thermal expansion and contraction. Antifriction polymeric materials are used in all newly developed designs of bearing parts. The reliability and durability of bridges as a whole depend on the physical, mechanical and operational properties of such materials. The change in the length of spans due to temperature fluctuations is carried out due to sliding along the polymer layers. The article presents a critical analysis of the polymer and metal-polymer materials used as sliding supports. A review and analysis of standardized anti-friction materials for possible use as sliding layers in the bearing parts of bridges have been carried out. The most promising fluoroplastic composite materials capable of operating without lubricant are presented. An analysis of metal-fluoroplastic sheet materials was made, new metal composites were proposed, in which various mesh materials with a high polymer content in the working layer are used as an anti-friction layer. Such materials can be used as guides for the moving bearing parts of the bridge without the use of lubricants. It is shown that the use of the described modern wear-resistant anti-friction materials will significantly increase the bearing capacity and service life of sliding bearings.

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1. Introduction

The article presents a study on the bearing capacity of sliding elements in bridge sliding bearings. The object of the study is sliding elements in the construction of a linearly movable support part of the bridge. Currently, there is a significant increase in the load on transport facilities and their supporting elements [1–3], which is associated with a steady increase in the number of vehicles and the volume of goods, material and other tangibles movement around the world. In Russia, there is also an active development of land transport infrastructure aimed at efficient transport communication within the country and with neighboring states [4]. The requirements for strength, reliability, durability and non-repair periods of operation of transport structure elements in general and bridge structures in particular have increased significantly [5–7]. This has led to the increasing number of scientific and engineering developments in bridge building aimed at improving bridge structures [8–12], introducing new materials with improved performance properties [13, 14], changing the configuration of bearing parts, optimizing the thickness and position of sliding layers [15], etc. One of the critical elements of bridge structures are the supporting parts [16–18]. During operation, the bearing parts perceive various static and dynamic loads from superstructures, rolling-stock and deformations of steel spans of bridges associated with daily temperature changes. The movement of bridge spans from thermal expansion takes place in various ways. For example, compensation for the thermal expansion of old massive arch bridges of small length usually occurs due to joint deformation with the soil massifs of the banks. The progressive movements of the movable bearing parts are divided into three groups during implementation: deformation, rolling and sliding. Bearing parts that move due to rolling bearings are bulky and require constant care and lubrication control. Sliding bearings use polymeric materials [19–21] with high antifriction properties in the fluid friction mode. Not a single transport structure can do without polymeric materials used as thin sliding layers to move bridge spans. At present, more length of spans and higher cargo flows has increased the load acting directly on the steel-polymer sliding pair, leading to a change in the performance of bridges as a whole. Moreover, recommendations for the design and installation of polymer bearing parts of bridges[1] have not been reviewed for a long time.

The analysis of literary sources of the current state of bridge support elements and the introduction of new materials that can significantly increase the durability and reliability of the sliding support without structural changes to the assembly as a whole can be considered a useful and relevant task.

The purpose of the work is to summarize the literature data and patent sources on the bearing capacity and service life of sliding elements in the construction of a linearly movable bridge support part. Research objectives: 1) review of literature and patent sources on the bearing capacity of sliding elements in sliding bridge supports; 2) analysis of polymer materials to optimize the operation of critical sliding elements of transport and logistics systems; 3) choosing the optimal material for use in sliding bearings to change the supporting parts and increase the service life of sliding pairs due to increased wear resistance.

2. Methods

The collection of information began with studying the sources of printed materials, including the authors' articles. A selection of literature sources on antifriction fluoroplastic materials has been made and optimal composite, metal fluoroplastic materials have been proposed to be used in bridge structure supports. With the objective information on the study, a critical analysis of the materials used for sliding layers in bridge supports has been carried out. The data can be used to determine the required dimensions of sliding elements for newly created bridge structures for a load given. According to the research, fluoroplastic composites can significantly increase the bearing capacity and the service life of bridge structure sliding bearings.

2.1. Sliding Knots and Materials Used

The structures of the supporting parts with movable sliding bearings are shown in Figs. 1 and 2. The slip plate rests on the middle support element, which is a cup cover (Fig. 1) and an upper balance bar (Fig. 2). A sliding element made of polished steel sheet is attached to the plate. Sheet polymeric material is fixed on the upper surface of the middle supporting element. Linear movements of the support units are provided by a sliding pair of polished stainless steel – fluoroplast. In spherical bearing parts, an additional polymeric anti-friction material is installed between the balancers. For smooth movement of the plates along the guide elements, metal-fluoroplastic material (MFL) is used, in the form of strips (Fig. 1, pos. 5 and Fig. 2, pos. 6).

[1] Rekomendacii po proektirovaniyu i montazhu polimernyh nesushchih chastej mostov [Recommendations for the design and installation of polymer load-bearing parts of bridges]. Rosavtodor. 20.02.2008. No. 73-r. Moscow, 2008. 115 p. [Online]. URL: https://docs.cntd.ru/document/1200062263 (reference date: 23.07.2024).

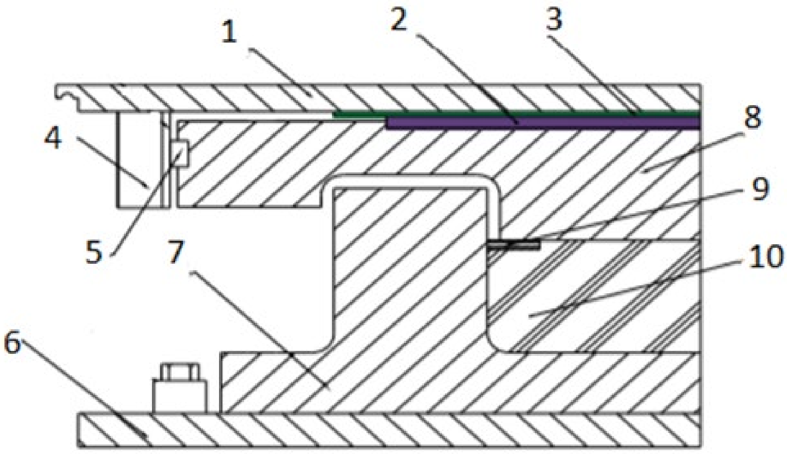

**Figure 1. Design of a linearly movable bearing part of the bridge:
1 – top plate, 2 – polished steel sheet, 3 – anti-friction gasket made of polymeric material,
4 – guide, 5 – metal-fluoroplastic strip, 6 – bottom plate, 7 – glass, 8 – cover, 9 – sealing rings,
10 – rubber insert.**

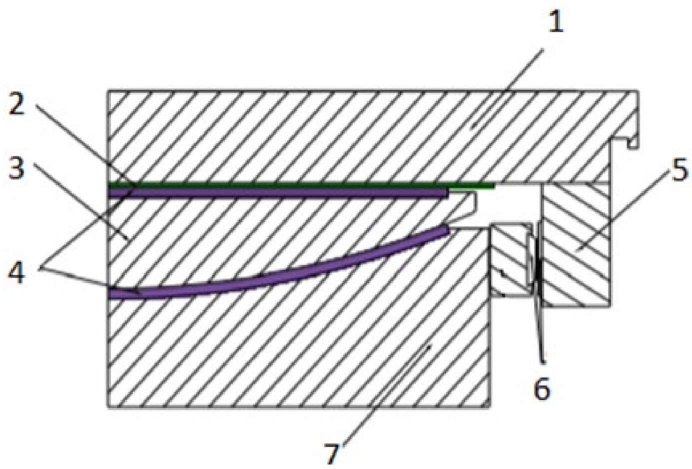

**Figure 2. Design of the ball segment bearing part of the bridge:
1 – sliding plate, 2 – polished steel sheet, 3 – upper balancer,
4 – anti-friction gasket made of polymeric material, 5 – guide, 6 – friction pair, 7 – lower balancer.**

In sliding tribocouplers, it is recommended to use polymer plates made of fluoroplast-4 (polytetrafluoroethylene) grades P, PN, which are located in grooves (balancers, covers, plates)[1]. In sliding pairs with fluoroplast, sheet corrosion-resistant chromium-nickel steel Russian State Standard GOST 5582-75 with a polished contact surface is used. According to the analysis of the work, the recommended sliding pair can work with lubricant during the planned time in case when the amplitude of displacement of the bridge spans is insignificant. With a displacement amplitude of several tens of centimeters per day and an increased load, the service life of the sliding support may decrease due to the increased wear rate of polytetrafluoroethylene (PTFE) [20] and the cold flow of the material. Such movements are typical for bridges located in areas with a severe continental climate. In slip pairs, PTFE was chosen [1] because of its a low coefficient of friction. PTFE was also experienced in bridge piers located in European countries with a temperate climate. The undoubted prospect of using PTFE in sliding bearings is due to the presence of a number of unique properties: an anomalously low coefficient of friction among structural materials (0.04–0.05 for steel without lubrication), high thermal stability (decomposition onset temperature 4150C), high chemical resistance, excellent insulating properties. Along with these qualities, PTFE has insufficient wear resistance in tribocouplings (PTFE wear during friction is 4–5 times greater than that of caprolon, polyamide, polyethylene, and filled materials based on them) and increased creep (fluidity) under prolonged loads. It is known [22] that irreversible plastic deformation develops in PTFE products at low loads and at low temperatures (below the glass transition temperature). At room temperature and a load of 10 MPa, which is 2–3 times lower than the rupture strength of PTFE, its irreversible deformation develops within 100 hours (more than 200%) [23]. Unfortunately, the scientific literature review does not prove that there are practically any experimental studies of the stress-strain state of PTFE samples under compressive loads in a free or constrained state. Therefore, for a long time, researchers considered it impossible to use fluoroplastic in heavily loaded sliding bearings due to its cold flow (creep) [20]. A decrease in the creep of PTFE products in sliding bearings of bridges is observed due to design solutions in the form of placement of fluoroplastic plates in recesses – undercuts. To improve the wear resistance of PTFE in world practice, two main approaches have been developed, which can be defined as physical and chemical modification methods. The first one is based on the creation of composite materials by introducing finely dispersed (recently, ultrafine and nanosized) fillers (graphite, coke, chopped glass fiber and carbon fiber, metal oxides, nanodiamonds, etc.) into the fluoroplast [24, 25]. The second method is based on the copolymerization of tetrafluoroethylene with other partially or fully fluorinated monomers. Both methods made it possible to obtain a series of new materials with one or another improved characteristic, which are used mainly as structural materials.

Composite materials based on PTFE are distinguished by higher wear resistance and elastic properties, which leads to a significant increase in the durability and reliability of friction units. It is known that one of the most effective ways to ensure the reliability and durability of movable interfaces of mechanisms and minimize energy losses during operation is the use of lubricants. However, the use of lubricating fluids requires special devices, constant monitoring and maintenance, which leads to additional costs, while negatively affecting the environment. Based on the fact that recent years witness more attention to the environmental friendliness of friction units, in the long term, sliding bearings of bridge structures will work in tandem with polymeric materials with a low coefficient of friction and without the use of a lubricant.

Given the above, it is necessary to consider industrial fluoroplastic composite materials according to the following criteria:

– maintenance without the use of lubricants;

– higher wear resistance compared to that of the main polymer by at least 1000 times;

– the material works in pairs with steel;

– the coefficient of friction being equal to or slightly higher than the original polymer.

3. Results and Discussion

From more than three dozen standardized PTFE-based composites, we have selected the following materials, presented in Table 1.

Table 1. Comparative tribotechnical characteristics of industrial fluoroplastic composite materials.

Indicators	Trademarks of fluoroplastic composites					
	F-4	F4K15M5	F4K15UV5	Flubon-20	Fluvis-20	Fluvis-20 PHO
	GOST 10007-72	TC 6-05-1412	TC 6-05-041-781	TC301-05-16	RB 03535279.071	
Fillers, %	-	Coke – 15, MoS_2 – 5	Coke – 15, carbon fiber – 5	Carbon fibers UTM-8 - 20	Modified carbon fibers “Viscum” in plasma – 20	
Coefficient of friction on steel	0.04	0.1–0.39	0.08–0.35	0.05	0.05	0.05
Reverse friction pair	Steel	Steel	Steel	Steel	Steel	Steel
Relative wear resistance	1	1000	1000	2000	2000	3500
Working conditions		Moisture, condensation, no lubrication	In various environments without lubrication	Liquid, gaseous media, without lubrication	Aggressive media, without lubrication	

Table 1 shows that among the studied fillers, carbon and carbon fibers are promising ones, since they significantly increase the wear resistance of fluoroplastic composites. In addition to the presented materials based on fluoroplast-4, a new material has been developed, its structure changed due to joint temperature and radiation modifications. L.Ya. Karpov Research Institute of Physics and Chemistry manufactures F-4RK grade material [26, 27] produced according to TC 2213-103-00208982-2007, obtained by radiation modification of finished fluoroplastic products. This modification of PTFE made it possible to significantly increase the operational and wear-resistant characteristics of the polymer, which are shown in

Table 2. Modification of finished products is carried out by irradiation with gamma rays above the melting point of the crystalline phase of the polymer. After such processing, the operational properties of fluoroplastic blanks increase sharply. The F-4RK material obtained in this way has higher elastic modulus and yield strength compared to the initial material. Creep decreases up to 100 times, wear resistance increases 103–104 times, with a low friction coefficient [28].

Table 2. Comparative properties of materials F-4 and F-4PM.

Indicators	F-4	F-4PM
Density, kg/m3	2180	2200
Tensile strength, MPa	25	14.2
Relative elongation at break, %	350	125
Tensile modulus, MPa	350	630
Compressive stress at deformation 10%, MPa	15	25
Deformation in compression under a load of 14 MPa in 24 hours, %	16	6.8
Residual deformation 24 hours after unloading, 14 MPa	9.8	0.6
Coefficient of friction on steel	0.08	0.08
Wear intensity during friction on steel 30KhGSA under a load of 2.4 MPa and a speed of 0.3 m/s, mm/km	3.0	0.003
Brinell hardness, MPa	35	45
Maximum operating temperature, 0C	260	260

The search conducted showed that there are proposals from other companies offering antifriction fluoroplastic materials, without presenting their technical characteristics and disclosing methods of obtaining. Flontekh LLC [2] and RPE Arflon LLC [3] advertise wear-resistant polymer materials of the ARFLON brand (AR100 and AR200) obtained by high-temperature physicochemical modification of the original PTFE. Such materials can be used in the construction of railway bridges, road junctions and overpasses as a sliding layer for reciprocating and angular movements of span support units. Innovative fluoroplastic technologies LLC [4] produces a radiation-modified fluoroplastic – 4 called RAFLON, which is widely used in railway rolling stock. In our opinion, all the presented companies produce the same F-4RM material, but under different names, since any change in the irradiation dose entails changes in the properties of the material. Thus, when advertising a material called ARFLON, the company does not even report its radiation exposure, while the enterprise [27] RAFLON has a trademark that can be placed on all manufactured products. According to the authors of [29], the F-4RM material is widely used in various products and is manufactured at more than 50 enterprises. The Internet advertised the products of the company LLC "Konstanta-2":

– "Constaftor 300" – PTFE filled with the particles of chemically modified carbon fibers, which reduces creep under load, sharply increases wear resistance and strength at elevated temperatures;

– "Constaftor 400" – a highly filled composition based on F-4, characterized by an increased yield strength, heat resistance and very low creep, especially at elevated temperatures;

– "Constaftor 500" – a bronze-filled PTFE-based composition with low creep and high compressive strength, as well as good wear resistance.

Unfortunately, the company does not provide comparative technical characteristics of its materials in relation to industrial materials. In our opinion, the fillers used by this company, approved by many researchers, cannot lead to a significant increase in the performance characteristics of fluoroplastic composites compared to known materials.

The second bottleneck in sliding bearings are elements – guides, which must provide low friction and anti-seize properties during the movement of plates during the entire guaranteed service life. Such properties are typical for sheet MFLs. Traditional MFLs have been developed for plain bearings in various

[2] Technical characteristic of antifriction fluoroplastic materials of FLONTEKH LLC [Onljne]. URL: https://flonteh.ru/material/ (application date: 23.07.2024).

[3] Technical characteristic of antifriction fluoroplastic materials of NPP Arflon. [Onljne]. URL: http://www.arflon.ru/Products/properties.html (reference date: 23.07.2024).

[4] Technical characteristic of antifriction fluoroplastic materials of Innovacionnye ftoroplastovye tekhnologii LLC [Onljne]. URL: https://studylib.ru/doc/5000618 (reference date: 23.07.2023).

industries where the use of a lubricant is not desirable or acceptable. MFLs are produced in the form of metal strips, on which a porous layer of spherical particles of tin bronze is applied through a thin layer of copper. The protruding peaks of the outer bronze particles are covered with a polymer coating made from a mixture of fluoroplastic with various fillers, which acts as a lubricant. MFL production is automated and high-tech: plain bearings of various diameters, made from these tapes, in the form of rolled bushings, have a minimum running-in layer. In Russia, such bearings are produced at the machine-building enterprises of the country: Ftoroplast LLC, Bugulma, Promsnabkomplekt LLC, Promgleks-M CJSC, Kineshma. Foreign-made MFLs of the brands DU and DP (The USA) and MU (Italy) are also known. A comparative analysis of bushings made of MFL from various manufacturers, including Russian ones, showed that plain bearings made from grades DU and DP have the highest wear resistance [30]. The Russian MFL [31] loses to foreign products in terms of wear-resistant properties in dry friction due to the fact that the limiting wear of the fluoroplastic coating is concentrated in the surface layer with a thickness of 0.025–0.05 mm, which directly affects the durability of products as a whole. The wear limit is caused by the insufficient thickness of the fluoroplastic layer located in the pores of the bronze particles.

It can be stated that materials scientists failed to sufficiently firmly bond PTFE with a porous metal layer [32] (because of complete “unwillingness” of the polymer to stick to anything, the presence of a “shape memory effect” of the material during heat treatment, and a high coefficient of thermal expansion). In this regard, in most cases, these bearings provide the necessary resource of friction units when using lubricants. Bushings made of strip bimetallic materials are used in a wide variety of friction units (in pumps for pumping oil, various rotary mechanisms, hydraulic boosters, etc.). Based on these data, it can be stated that guides in the form of MFL platinum cannot ensure the guaranteed operation of this sliding unit without the presence of a lubricant. After the loss of the fluoroplastic coating, friction processes without lubricant are carried out along the tops of antifriction bronze particles with a possible loss of antifriction properties.

Thus, for the successful operation of the guides in the absence of lubrication, new anti-friction sheet materials are needed. There are known methods [33, 34] for producing MFLs in the form of plates where instead of the traditional porous bronze layer of spherical particles, various mesh woven materials are used, which are specially fixed on a metal surface. The polymer layer is fixed in the mesh pores after PTFE particles are pressed into the mesh space and sheet products are sintered in tightly compressed cassettes [32]. The resulting materials represent a metal composite with a heterogeneous structure. The working surface is a regularly alternating sections of a solid base (bronze mesh) and a polymer. The use of antifriction layers in the form of grids on the metal surface made it possible to increase the proportion of the polymer in the working layer. In the pores of bronze-brass meshes, the thickness of the fluoroplastic layer can be more than 1 mm. Such a thickness of the polymer layer makes it possible to significantly increase the durability and reliability of friction units without the use of a lubricant [35, 36]. Unfortunately, these metal-fluoroplastic mesh materials have not found proper application in plain bearings in the form of bushings. The main disadvantage is that at the initial moment of rotation, the contact between the sleeve and the shaft is carried out along the grid vertices, that is, along the minimum contour area, which leads to wear and, in most cases, when stable operation of the friction unit is achieved, the bearing clearances go beyond the limit value of the linear wear value.

In our opinion, this material is promising for sliding units for guide plates, since changing the dimensions of the interface by a few hundredths of a mm will not affect the operation of the unit as a whole. In addition to traditional MFLs and bearings, fundamentally new imported metal-polymer bearings of the Fritex type made by Technymon appeared [5]. These bearings are rolled bushings from a three-layer system consisting of a bronze substrate with a thickness of 0.50 to 2.70 mm and a fluoroplastic fabric adhesively connected to it. The fabric, woven with special fibers, has a thickness of 0.40 mm. This thickness of the fluoroplastic coating in the form of a woven material may indicate the long-term operational reliability of the bearing. In terms of technical characteristics, when operating without lubrication at maximum allowable load and operating temperatures, Fritex bearings are not significantly inferior to MFL (Russia). The operating temperature range of such bearings is in the range from –100 to + 260 ^{0}C. A similar material, consisting of a metal substrate, an adhesive sublayer, and a fluoroplastic layer reinforced with fiberglass, is also advertised by Konstanta-2 LLC [30]. Technical characteristics of the material, unfortunately, are not provided by the producer. In our opinion, it is possible to adhesively connect a fluoroplastic fabric with a metal surface only if fabrics are created in the form of three-dimensional woven structures. Such fabrics consist of bulk layers intertwined with various threads in a special way into a single structure [37], where fluoroplastic fibers are on the surface, and the carrier threads, made of another synthetic material, have strength properties and increased adhesion to adhesives.

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[5] Technical characteristics of FRITEX-B [Onljne]. URL: https://technymon.com/product/self-lubricated-bearings/fritex-b/ (reference date: 23.07.2024).

4. Conclusion

1. The paper presents wear-resistant polymeric materials with hundreds and thousands of times increased operational characteristics when working in friction units in the absence of lubrication compared to the original polymer. This fact suggests that the replacement of sliding elements made of PTFE-4 with the materials described above in the sliding bearings will optimize the operation of the critical sliding elements of transport and logistics systems, significantly increasing their bearing capacity and service life.
2. The most promising material to replace PTFE is radiation-modified PTFE grade F-4RK (TU 2213-103-00208982-2007), then industrial fluoroplastic composite materials grades Fluvis-20PHO, Flubon-20, Fluvis-20, F4K15M5 and F4K15UV5.
3. Among PTFE materials, the longest non-lubricated mating work can be done with DU or DP materials. Promising materials can be metal-fluoroplastic sheets where various mesh materials with an increased proportion of polymer in the working layer are used as an anti-friction layer.
4. Further clarifications, calculations and more detailed research and experimental studies are needed to search for and select antifriction materials that are optimal in terms of wear resistance and reliability when operating without lubrication, providing the required service life of sliding elements in bridge sliding bearings.

References

1. Proske, D. Bridge Collapse Frequencies versus Failure Probabilities. Springer. Cham, 2018. 126 p.
2. Ruzov, A.M. Ekspluataciya mostovogo parka [Operation of the bridge park]. Moscow: Akademiya, 2007. 176 p.
3. Singh, S., Martinetti, A., Majumdar, A., van Dongen, L.A.M. Transportation systems: Managing performance through advanced maintenance engineering. Springer Singapore. Singapore, 2019. 221 p. DOI: 10.1007/978-981-32-9323-6
4. Blinkin, M., Koncheva, E. A Forecast for Transport System Development in Russia. Springer. Cham, 2016. Pp. 273–293. DOI: 10.1007/978-3-319-47800-5_10
5. Ovchinnikov I.I., Majstrenko I.YU., Ovchinnikov I.G., Uspanov A.M. Failures and collapses of bridge constructions, analysis of their causes. Part 4. Russian journal of transport engineering. 2018. 1(5). DOI: 10.15862/05SATS118
6. Ye, S., Lai, X., Bartoli, I., Aktan, A.E. Technology for condition and performance evaluation of highway bridges. Journal of Civil Structural Health Monitoring. 2020. 10. Pp. 573–594. DOI: 10.1007/s13349-020-00403-6
7. Su, M., Wang, J., Peng, H., Cai, C.S., Dai, G.L. State-of-the-art review of the development and application of bridge rotation construction methods in China. Science China Technological Sciences. 2021. 64. Pp. 1137–1152. DOI: 10.1007/s11431-020-1704-1
8. Patent US no. 3349418 A,1965.
9. Beyer, Ye., Wintergerst, L. New bridge storage, new pillar shape. Der Bauingenleur. 1960. 35(6). Pp. 227–230.
10. Huang, W., Pei, M., Liu, X., Wei, Y. Design and construction of super-long span bridges in China: Review and future perspectives. Frontiers of Structural and Civil Engineering. 2020. 14. Pp. 803-838. DOI: 10.1007/s11709-020-0644-1
11. SHul'man S.A., Sluckaya M.N., Dvorkin N.Ya., Sovershaev I.V., Ivanov S.A., Antonov A.N. Opornaya chast' mosta [Bridge support]. Patent Russia no. 202383, 2021.
12. Sitnikov S.L., Sitnikov A.S. Opornaya chast' mosta i sposob ee izgotovleniya (Nesushchaya chast' mosta i sposob ee izgotovleniya) [Bridge support part and method of its manufacture (Bearing part of the bridge and method of its manufacture)]. Patent Russia no. 2731300, 2018.
13. Vasilev, A.P., Struchkova, T.S., Okhlopkova, A.A. Effects of Complex Fillers on the Mechanical and Tribological Properties of Polytetrafluoroethylene Composites. Materials Science Forum. 2020. 992. Pp. 739–744. DOI: 10.4028/www.scientific.net/MSF.992.739
14. Balyakin, V.B., Khatipov, S.A. Pilla, C.K. Experimental studies of tribotechnical characteristics of radiation-modified PTFE to use in rotor supports. Journal of Friction and Wear. 2015. 36. Pp. 346–349. DOI: 10.3103/S1068366615040030
15. Adamov, A.A., Kamenskikh, A.A., Nosov, Yu.O. Deformational behavior of the flat sliding layer of the spherical bearing. International Journal of Civil Engineering and Technology. 2019. 10(5). Pp. 99–107.
16. Eggert, H., Kauschke, W. Structural bearings. Ernst & Sohn. Berlin, 2002. 405 p.
17. Xue, J., Briseghella, B., Chen, B.-C., Zhang, P.Q. Optimal Design of Pile Foundation in Fully Integral Abutment Bridge. Springer Tracts on Transportation and Traffic. 9. Developments in International Bridge Engineering. Springer. Cham, 2016. Pp. 3–16. DOI: 10.1007/978-3-319-19785-2_1
18. Beben, D. Soil-Steel Bridges: Design, Maintenance and Durability. Springer. Cham, 2020. 214 p. DOI: 10.1007/978-3-030-34788-8
19. Yi, X., Du, S., Zhang, L. Composite Materials Engineering. 1. Fundamentals of Composite Materials. Springer Singapore. Singapore, 2018. 765 p. DOI: /10.1007/978-981-10-5696-3
20. Wang, Q.J., Chung, Y.W. Encyclopedia of Tribology. Springer New York. NY, 2013. 4139 p. DOI: 10.1007/978-0-387-92897-5
21. Spiridonov, A.M., Okhlopkova, A.A., Sokolova, M.D. Polymer Composite Materials Based on Ultra-High-Molecular-Weight Polyethylene Filled with Organomodified Zeolite. Polymer Science. Series D. 2020. 13(3). Pp. 311–314. DOI: 10.1134/S1995421220030181
22. Hatipov S.A., Cvelev V.M., Alekseev S.V. Aktual'nye voprosy proektirovaniya kosmicheskih sistem i kompleksov [Current issues in the design of space systems and complexes]. 6. Moscow: Block-Inform-Express, 2005. P. 53.
23. Khatipov, S.A., Artamonov, N.A. Creation of a new antifriction and sealing material based on radiation-modified polytetrafluoroethylene. Rossijskij Khimicheskij Zhurnal. 2008. 52(3). Pp. 89–96.

24. Kalistratova, L.F., Mashkov, Y.K., Egorova, V.A. Calculation of X-ray Density of Amorphous–Crystalline Polymer Taking into Account Degree of Ordering of Amorphous Phase. Inorganic Materials: Applied Research. 2018. 9(4). Pp. 687–692. DOI: 10.1134/S2075113318040147
25. Kornopoltsev, N.V., Rogov, V.E., Lenskaya, E.V., Kornopoltsev, V.N. Development of materials and coatings based on polytetrafluoroethylene. Chemistry for Sustainable Development. 2004. 12(6). Pp. 681–686.
26. Hatipov S.A., Sichkar' V.P., Voronina E.N., Ivanchenko V.K., Sobolev G.P., Bruk M.A. Sposob termoradiacionnoj obrabotki izdelij iz politetraftoretilena [Method of thermoradiation treatment of products made of polytetrafluoroethylene]. Patent Russia no. 2211228, 2003.
27. Artamonov, N.A. Sposob radiacionno-himicheskogo modificirovaniya politetraftoretilena i materiala na ego osnove [Method for radiation-chemical modification of polytetrafluoroethylene and materials based on it]. Artamonov N.A., Hatipov S.A. Patent Russia no. 2304592, 2007.
28. Hatipov, S.A., Konova E.M., Artamonov N. A. Politetraftoretilen, modificirovannyj radiaciej: struktura i svojstva [Radiation-modified polytetrafluorethylene: structure and properties]. Rossijskij Khimicheskij Zhurnal. 2008. 52(5). Pp. 64–72.
29. Sytyj, YU.V., Chursova L.V., Hatipov S.A., Sagomonova, V.A. Properties and application of F-4RM radiation-modified fluoroplastic (polytetrafluoroethylene). Aviation Materials and Technologies. 2012. 4(25). Pp. 48–55.
30. Bychkov S.A., Lavrenko I.G., Nechiporenko O.YU., Mladinov S.D. Issledovanie harakteristik metalloftoroplastov razlichnyh proizvoditelej dlya elementov aviacionnyh konstrukcij Open Information and Computer Integrated Technologies. 2013. 59. Pp. 343–354.
31. Mashkov YU.K., Ovchar Z.N., Bajbarackaya M.YU., Mamaev O.A. Polymeric compound materials in tribotechnique. Moscow: Nedra, 2004. 262 p.
32. Rogov, V.Ye Gur'ev A. M., Nikiforov S.O. Metalloftoroplastovye materialy dlya mashinostroeniya: osobennosti razrabotki, proizvodstva i primeneniya [Metal fluoroplastic materials for mechanical engineering: features of development, production and application]. Polzunovskij al'manah. 2010. 1. Pp. 51–57.
33. Buznik V.M., Kornopol'cev V.N., Kornopol'cev N.V., Mognonov D.M., Rogov, V.Ye Sposob polucheniya bimetallicheskogo materiala [Method for producing bimetallic material]. Patent Russia no. 2277998, 2006.
34. Kornopol'cev V.N., Kornopol'cev N.V., Rogov, V.Ye Mognonov D.M., Greshilov A.D. Sposob polucheniya bimetallicheskogo metalloftoroplastovogo materiala [Method for producing bimetallic fluoroplastic material]. Patent Russia no. 2212307, 2003.
35. Kornopol'cev V.N., Mognonov D.M., Ayurova O.Z., Buyantuev S.L. Novye tribologicheskie kompozity na osnove politetraftoretilena. Neorganicheskie materialy: prikladnye issledovaniya. 2017. 8(1). S. 108-111. DOI:10.1134/S2075113317010208
36. Kornopol'cev V.N. Sheet antifriction material with specified structure. Journal of Friction and Wear. 2010. 31(5). 359–363. DOI: 10.3103/S1068366610050077
37. Rogov, V.Ye., Bohoeva, L.A., Chermoshenceva, A.S. Reinforced composites with 3D fabric structures. Russian Engineering Research. 2021. 3. 71–74. DOI: 10.36652/0042-4633-2021-3-71-74

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