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INVESTIGATION OF THE EFFECT OF THE "MADOR" MODIFIER ON THE STRENGTH AND WATER RESISTANCE OF CEMENT-REINFORCED DISCRETE MINERAL MATERIALS FOR ROAD CONSTRUCTION

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Statement of the problem. In the territory of the Russian Federation, a large number of cement modifiers are used to strengthen and stabilize soils during the construction and repair of highways. At the same time, the determination of the scope of modifying additives and their effectiveness requires a large number of laboratory studies, both according to GOST-normalized indicators and alternative methods, taking into account foreign experience. This circumstance led to the need to conduct a study of one of the additives to cement used to strengthen soils in road construction.
Results. The review of the results of studies of the effectiveness of the use of the modifier "MADOR" for non-cohesive mineral materials reinforced with cement for the construction of structural layers of pavement is given. The results of studies of strength characteristics, water resistance and water absorption of materials reinforced with cement together with the modifier "MADOR" are presented.
Conclusions. A significant positive effect has been established from the use of the "MADOR" modifier to strengthen the studied materials and soils in combination with cement. It is proposed to use the studied materials reinforced with the "MADOR" modifier together with cement in the structural layers of the road surface of highways.

Keywords: highways, soil reinforcement, cement, modifier "MADOR", compressive strength, tensile strength, water resistance, water absorption.

Introduction. The technology of highway construction and repair using cold recycling technology and soil reinforcement using inorganic binders has found wide application in the Russian Federation and abroad. Since the beginning of the last century, a large-scale study has begun on the possibility of using inorganic binders to stabilize and strengthen soils and industrial waste used in the structural layers of road clothing with standardized physical and mechanical properties. Based on the results of the research conducted in the Soviet Union, a number of regulatory documents were developed on strengthening soils for road construction, including those defining the scope of chemical additives. One of the disadvantages of the domestic regulatory framework regarding the selection of materials reinforced with inorganic binders, in contrast to the foreign one, is the limited amount of normative indices to predict the durability and reliability of road structures. In this study, apart from the mandatory regulatory characteristics, the authors conducted broader research of the physico-mechanical characteristics of both single-component and multicomponent mineral systems reinforced with cement.

In the Russian Federation, crushed stone and crushed stone-sand mixes are mostly used for construction of pavement foundations [8, 15] which are expensive road construction materials. According to [5, 16], while performing road construction work, there is a shortage of high-quality materials suitable for the construction of structural layers of road surfacing. One of the promising ways to address this is to strengthen local and man-made soils, including asphalt granulate, by means of various mineral binders. The efficiency of this method of road construction has been proved in [1—4, 6, 7, 9—12]. The results of a variety of studies [14—22] indicate the possibility of using local soils reinforced with cement in combination with various additives for the construction of structural layers of pavement. This paper showcases the results of experimental studies of the effect of the MADOR modifier on the strength characteristics of cement-reinforced soils. The results of the research on the effect of the MADOR modifier have shown the possibility of its use to regulate technological operations for strengthening soils with cement, as well as to increase the reliability and durability of road surfacing structures.

1. Laboratory studies of the effect of the MADOR modifier on the rate of strength gain. In the course of road construction work to strengthen soils or install structural layers of road surfacing using the cold recycling method, in order to increase the pace of construction, it becomes necessary to accelerate the strength gain time of the cement-reinforced road structure. In order to identify the effect of the MADOR modifier on the rate of strength gain of cement-reinforced mineral material, tests were performed in two ways.

Method 1. The tests were conducted on cement mortar in terms of bending and compressive strength on standard 4×4×16 cm beam samples that hardened under normal conditions at the ages of 2, 7 and 28 days according to GOST 310.4 "Cements. Methods for Identifying Bending and Compressive Strength". The results of the studies are shown in Table 1.

Table 1

Amount of a modifier	Compressive/flexural strength per day *Rсж*/*Rизг*, MPa		
	2 days	7 days	28 days
Control composition (0 % modifier MADOR of the cement mass)	36,2/6,7	45,4/8,3	62,7/7,7
Modifier MADOR (3 % of the cement mass)	45,5/7,2	48,8/8,7	64,4/7,9

Method 2. The tests were performed on sand from crushing screenings of JSC PavlovskNerud in terms of compressive strength on cylinder samples with a diameter of 5 cm hardened under normal conditions for 2, 7 and 28 days. The test samples were prepared and tested in accordance with GOST 23558 "Mixes of Crushed Stone-gravel-sand and Soils Treated with Inorganic Binders for Road and Airfield Construction". The samples were tested on day 2 and 7 in a dry state; on day 28, the samples were tested in a water-saturated state after 2 days in water in accordance with regulatory requirements. The results of the studies are shown in Table 2.

Table 2

Amount of a modifier	Compressive strength per day *Rсж*, MPa		
	2 days	7 days	28 days
Control composition (0 % modifier MADOR of the cement mass)	5,57	6,21	7,01
Modifier MADOR (3 % of the cement mass)	6,40	7,48	7,09

The studies conducted in two different ways have shown that the introduction of the MADOR modifier in a volume of 3% of the cement weight into the cement-reinforced material enables a compressive strength index to be reached on samples hardened under normal conditions for 2 days equal

to the strength index for 7 days on samples without a modifier. Due to the fact that the regulatory requirements of SP 78.13330.2012 "Highways" regulate that the movement of construction vehicles along a layer of reinforced base or coating for further road construction work is allowed 5—7 days following the installation, depending on the brand strength of the cement-reinforced material, the above quality of the modifier can be employed to accelerate the pace of construction, subject to approval technologies for the production of works with the customer.

2. Laboratory studies of the effect of the MADOR modifier on physical and mechanical parameters. In order to identify the effect of the MADOR modifier on the physical and mechanical properties of various cement-reinforced mineral systems, strength tests were conducted for various hardening periods from 7 to 85 days, water absorption, water resistance, density and swelling. In order to carry out the above investigations on the effect of the MADOR modifier on cement-reinforced soil, the following materials widely used in road construction in the Voronezh region were used: sandy soil according to GOST 25100; sand from crushing screenings (JSC PavlovskNeurd); a mix of mineral materials from sandy soil according to GOST 25100 and sand from crushed stone screenings at the Obukhov quarry; a mixture of asphalt-concrete granulate with residual binder and sand from crushing screenings (JSC PavlovskNerud). Laboratory studies of cement-reinforced materials were conducted both in accordance with Russian regulatory documents in force at the time of testing, and additional physical and mechanical characteristics considering foreign experience.

Composition 1. Sandy soil according to GOST 25100, cement 42.5H — 10 % of the mineral part, water — 14.3 % to achieve optimal humidity, MADOR modifier — 3 % of the cement weight. The test samples were prepared and tested according to PNST-322 "Soils Stabilized and Reinforced with Inorganic Binders. Technical Specifications". Due to the lack of methods for identifying the volumetric density and parameters of water saturation and water absorption of cement-reinforced material in the specified standard, the indicators were identified using a similar test procedure in accordance with GOST 12801 "Materials Based on Organic Binders for Road and Airfield Construction. Test Methods". The water absorption index was identified following water saturation of the samples in vacuum for 2 days in water. The water resistance index was defined as the ratio of the compressive strength of samples saturated with water for 2 days to the strength of dry samples. The results of the studies are shown in Table 3.

The studies of the effect of the MADOR modifier on sandy soil reinforced with cement have shown that samples with the MADOR modifier have higher physical and mechanical properties. The water absorption following complete saturation of the samples with the MADOR modifier differs by 6.9 times less compared to those reinforced with cement alone with no modifier. The samples of sandy soil reinforced with cement in combination with a modifier have higher compressive strength, tensile strength, water resistance and bulk density than samples reinforced with cement alone with no modifier (Table 3).

Table 3

Index	Index value		Change in the index of sample 2 in relation to sample 1
	sample 1 (MADOR — 0 %)	sample 2 (MADOR — 3 %)	
Compressive strength at the age of 28 days, MPa	3,11	3,21	+3,22 %
Tensile strength during splitting at the age of 28 days, MPa	0,33	0,42	+27,27 %
Water resistance	0,95	1,00	+5,26 %
Volumetric density, g/cm^3	1,95	1,98	+1,54 %
Water absorption over 2 days following complete water absorption, %	4,18	0,61	A decrease by 6.9 times

Composition 2. Sand from crushing plants (PavlovskNeur JSC), M400 cement — 10 % of the mineral part, water — 5 % to achieve optimal humidity, MADOR modifier — 3 % of the cement weight. The test samples were prepared and tested in accordance with GOST 23558. Compressive strength on day 7 was identified for the dry samples, while compressive and tensile strength during splitting were identified after 28 days of normal hardening in a water-saturated state. The water absorption index was identified after water saturation of the samples in vacuum for 2 days in water. The results of the studies are shown in Table 4. The studies of effect of the MADOR modifier on sand from crushing plants (JSC PavlovskNerud) reinforced with cement have shown that samples with the MADOR modifier have higher physical and mechanical properties. The water absorption after complete saturation of samples with the MADOR modifier differs 2.9 times less compared to those reinforced with cement alone with no modifier. Sand samples from crushing screenings reinforced with cement together with a modifier have higher compressive and tensile strength characteristics during splitting both in the initial and final hardening periods than those reinforced with cement alone with no modifier (Table 4).

Table 4

Index	Index value		Change in the index of sample 2 in relation to sample 1
	sample 1 (MADOR — 0 %)	sample 2 (MADOR — 3 %)	
Compressive strength of the dry samples at the age of 7 days, MPa	4,67	4,92	+5,35 %
Compressive strength at the age of 28 days, MPa	4,67	5,00	+7,06 %
Tensile strength during splitting at the age of 28 days, MPa	1,07	1,20	+12,14 %
Water absorption over 2 days following complete water absorption, %	5,92	2,04	A decrease by 2.9 times

Composition 3. A mix of mineral materials from sandy soil — 50 % according to GOST 25100, sand from crushed stone from the Obukhov quarry — 50 %, cement 42.5H — 10 % of the mineral part, water — 11.4 % to achieve optimal humidity, MADOR modifier — 3 % by weight of cement. The test samples were prepared and tested in accordance with GOST 23558. Due to the lack of methods for identifying the volume density and parameters of water saturation and water absorption of cement-reinforced material in the standard, the indicators were identified using a similar test method to GOST 12801. The compressive strength index was identified after 28 days of normal hardening in a water-saturated state. The water absorption index was identified after water saturation of the samples in vacuum for 2 days in water. The results of the conducted studies are shown in Table 5.

Table 5

Index	Index value		Change in the index of sample 2 in relation to sample 1
	sample 1 (MADOR — 0 %)	sample 2 (MADOR — 3 %)	
Compressive strength at the age of 28 days, MPa	2,00	2,21	+10,50 %
Volumetric density, g/cm^3	2,01	2,02	+0,50 %
Water absorption over 2 days following complete water absorption, %	9,06	1,10	A decrease by 8.2 times

The studies of the effect of the MADOR modifier on a mineral mix of 50 % sandy soil and sand from the crushing of 50% Obukhov quarry crushed stone reinforced with cement have shown that the samples with the MADOR modifier have higher physical and mechanical properties. The water absorption

after complete saturation of the samples with the MADOR modifier differs 8.2 times less compared to those reinforced with cement alone with no modifier. The samples of the material reinforced with cement together with a modifier have increased compressive strength and bulk density (Table 5).

Composition 4. Asphalt—concrete granulate with residual binder — 50 % (the content of residual binder is 6.4 % over 100 % by weight of the material), sand from crushing screenings (JSC PavlovskNerud) — 50 %, cement M500 — 8 % of the mineral part, water — 4 % to achieve optimal humidity, MADOR modifier — 3 % of the mass of cement. The test samples were prepared and tested in accordance with GOST 23558. Due to the lack of requirements for identifying the volumetric density and swelling of the cement-reinforced material in the standard, the indicators were identified using a similar test procedure to GOST 12801. The water absorption index was defined as the weight gain of the sample after it had been saturated with water for 2 days prior to the strength test in a water-saturated state. The water resistance index was defined as the ratio of the compressive strength of the samples saturated with water for 2 days to the strength of the dry ones. The results of the studies are shown in Table 6.

Table 6

Index	Index value		Change in the index of sample 2 in relation to sample 1
	sample 1 (MADOR — 0 %)	sample 2 (MADOR — 3 %)	
Compressive strength of the dry samples at the age of 7 days, MPa	3,83	5,00	+30,55 %
Compressive strength of the samples saturated with water for 2 days after 28 days of regular hardening, MPa	4,83	5,00	+3,52 %
Compressive strength of the samples saturated with water for 2 days after 60 days of regular hardening, MPa	5,17	6,00	+16,05 %
Compressive strength of the samples saturated with water for a long period (14 days) after 28 days of regular hardening, MPa	5,17	5,50	+6,38 %
Volumetric density after 28 days of regular hardening, g/cm^3	2,18	2,19	+0,46 %
Water absorption of 2 days in water after 28 days of regular hardening %	5,24	5,02	–4,20 %
Long-term water absorption (14 days in water) after 28 days of regular hardening, %	5,60	5,31	–5,18 %
Swelling after 28 days of regular hardening	0	0	0 %
Swelling after 28 days of regular hardening and long-term (14 days) water saturation	0,13	0	–100 %
Swelling after 60 days of regular hardening	0,19	0,10	–47,37 %
Volumetric density after 60 days of regular hardening, g/cm^3	2,16	2,18	+0,93 %
Compressive strength of the dry samples, after 60 days of regular hardening, MPa	5,25	5,92	+12,76 %
Compressive strength of the water saturated samples through a vacuum after 60 days of regular hardening, MPa	5,00	5,42	+8,40 %
Water absorption (2 days in water) after 60 days of regular hardening, %	1,60	1,38	–13,75 %
Water absorption after complete water saturation in a vacuum after 60 days of regular hardening, %	5,86	5,39	–8,02 %
Water resistance coefficient after water saturation for 2 days after 60 days of regular hardening	0,98	1,01	–2,92 %

The studies of the effect of the MADOR modifier on a mix of asphalt-concrete granulate and sand from crushing screenings (JSC PavlovskNerud) reinforced with cement have shown that the samples with the MADOR modifier have higher physical and mechanical properties. The samples with the MADOR modifier are characterized by a decrease in swelling to absolute zero, depending on the time of strength gain, a decrease in water saturation and water absorption, and an increase in the coefficient of water resistance to an absolute maximum compared to those reinforced with cement alone with no modifier. Also, the samples of reinforced material with the MADOR modifier have higher strength characteristics compared to those not modified with the MADOR preparation (Table 6). Also, during the studies of the effect of the MADOR modifier on reducing water absorption and water saturation on the samples from a mix of asphalt granulate and sand from crushing screenings (JSC PavlovskNerud), reinforced Using cement, the hydrophobic effect of the modifier was visually established after 28 days of regular hardening of the samples (Fig.). The hydrophobic effect was expressed in the fact that when a drop of 1—3 ml of water hit a sample of cement-reinforced material, the water was instantly absorbed, and when water hit a sample reinforced with cement together with the MADOR modifier, the water was not absorbed for at least 1 hour. This hydrophobic visual effect confirms the high rates of reduction of water saturation and water absorption, as well as increased water resistance on the laboratory samples.

Fig. Type of the samples after water penetration.
On the left is a sample with no modifier,
on the right is a sample with a MADOR modifier

Conclusions. The results of the experimental studies aimed at substantiating the possibility of using the MADOR modifier while performing work on cold recycling of road surfacing and strengthening soils with cement have proved to be efficient:

1. The construction of structural layers of road surfacing made of cement-reinforced materials with the MADOR modifier is one of the ways of replacing expensive stone materials and crushed stone-gravel-sand mixtures with local soils and reuse materials.
2. The use of the MADOR modifier as a drug that improves the quality of the cement-treated material enables a road structure made of cement-reinforced material to be obtained with the following enhanced characteristics:

– the MADOR modifier enables a compressive strength index to be achieved on samples that have hardened under normal conditions for 2 days equal to the strength index for 7 days on those with no modifier. This effect of the MADOR modifier to reduce the strength gain time from seven to two days makes it possible to accelerate road works;
– the MADOR modifier can considerably reduce water saturation and water absorption of cement-treated soils and increase water resistance compared to materials reinforced with cement alone with no modifier. Hydrophobization and water resistance of the structural layers of road surfacing directly affect the durability and service life of the highway;

- in mixes with asphalt-concrete granulate and sand from crushing screenings, the effectiveness of the modifier in reducing the swelling characteristics of the material is shown, and thus the effectiveness of the modifier in the combined use of cement and organic binder in the case of MADOR modifier in cold recycling of asphalt concrete pavements is proved.;
- reinforcement of mineral materials with cement together with the MADOR modifier enables a road structure with increased volumetric density to be obtained which, in turn, has a positive effect on increasing the bearing capacity in modulus of elasticity;
- the discrete materials reinforced with cement together with the MADOR modifier, both in the dry and in the water-saturated state, have higher compressive and tensile strength characteristics, i.e., over 25%. An increase in the tensile strength during splitting directly affects the reduction of cracking in cement-treated materials. Reducing the tendency to crack is one of the top priorities for cement-reinforced materials, especially for layers with high grade strength and high load-bearing capacity.

3. The studies have enabled us to identify a considerable positive effect from the use of the MADOR modifier on cement-reinforced material. According to the study, it is suggested that the MADOR modifier is used in combination with cement in order to increase the strength and water resistance of the structural layers of highway road surfacing.

References

1. **Bezruk, V. M.** Ukreplennye grunty (svoistva i primenenie v dorozhnom i aerodromnom stroitel'stve) / V. M. Bezruk, I. L. Guryachkov, T. M. Lukanina. — M.: Transport, 1982. — 231 s.
2. **Vasil'ev, Yu. M.** Trebovaniya k deformativnoi sposobnosti ukreplennykh gruntov / Yu. M. Vasil'ev // Primenenie ukreplennykh gruntov pri stroitel'stve dorozhnykh odezhd s ispol'zovaniem otkhodov promyshlennosti v kachestve vyazhushchikh i dobavok khimicheskikh veshchestv: Trudy Soyuzdornii. — 1981. — S. 145—151.
3. **Velichko, E. G.** Nekotorye aspekty fiziko-khimii i mekhaniki kompozitov mnogokomponentnykh tsementnykh sistem / E. G. Velichko, Zh. S. Belyakova // Stroitel'nye materialy. — 1997. — № 2. — S. 21—25.
4. **Vernigorova, V. M.** Sovremennye metody issledovaniya svoistv stroitel'nykh materialov / V. M. Vernigorova. — M.: ASV, 2003. — 239 s.
5. **Gorelyshev, N. V.** Tekhnologiya i organizatsiya stroitel'stva avtomobil'nykh dorog / N. V. Gorelyshev, S. M. Polosin-Nikitin, M. S. Koganzon. — M.: Transport, 1992. — 551 s.
6. **Kochetkova, R. G.** Uluchshenie svoistv glinistykh gruntov stabilizatorami / R. G. Kochetkova // Avtomobil'nye dorogi. — 2006. — № 3. — S. 25—28.
7. **Lanko, A. V.** Gidrofobizirovannye lessovye tsementogrunty v dorozhnom stroitel'stve / A. V. Lanko // Stroitel'nye materialy. — 2008. — № 4. — S. 27—30.
8. **Matvienko, F. V.** Prognozirovanie velichiny neobratimoi deformatsii dorozhnoi konstruktsii ot vozdeistviya transportnogo potoka / F. V. Matvienko, A. N. Kanishchev, V. N. Mel'kumov, V. V. Volkov // Nauchnyi vestnik Voronezhskogo GASU. Stroitel'stvo i arkhitektura. — 2010. — № 3 (19). — S. 81—92.
9. **Nikerov, N. S.** Dorozhnye odezhdy avtomobil'nykh dorog obshchego pol'zovaniya. Ch. 2. Konstruirovanie i raschet / N. S. Nikerov. — SPb.: Peterburgskii gos. un-t putei soobshcheniya, 2001. — 84 s.
10. **Petkyavichus, K.** Vozmozhnosti ispol'zovaniya mestnykh nerudnykh materialov pri stroitel'stve i remonte avtomobil'nykh i zheleznykh dorog / K. Petkyavichus, I. Podagelis, A. Laurinavichus // Stroitel'nye materialy. — 2006. — № 3. — S. 32—35.
11. **Pichugin, A. P.** Deformatsionnye protsessy v ukreplennykh gruntakh / A. P. Pichugin, V. A. Grishina, I. K. Yazikov // Ekologiya i novye tekhnologii v stroitel'nom materialovedenii: mezhdunar. sb. nauch. tr. — Novosibirsk, 2010. — S. 74—75.
12. **Pichugin, A. P.** Fiziko-khimicheskie protsessy v ukreplennykh gruntakh / A. P. Pichugin, V. A. Grishina, I. K. Yazikov // Stroitel'nye materialy. — 2009. — № 12. — S. 41—43.
13. **Podol'skii, Vl. P.** Issledovanie vliyaniya modifikatora "DORTsEM DS-1" na svoistva tsementa i fiziko-mekhanicheskie kharakteristiki tsementogrunta / Vl. P. Podol'skii, F. V. Matvienko, A. S. Strokin, A. E. Borisov // Nauchnyi zhurnal stroitel'stva i arkhitektury. — 2017. — № 1 (45). — S. 84—92.
14. **Podol'skii, Vl. P.** O vozmozhnosti rasshireniya resursnoi bazy dorozhnogo stroitel'stva za schet stabilizatsii i ukrepleniya gruntov / Vl. P. Podol'skii, V. L. Nguen, D. Sh. Nguen // Nauchnyi Vestnik Voronezhskogo GASU. — 2014. — № 1. — S. 102—111.

15. **Podol'skii, Vl. P.** Optimizatsiya ob'emov dobychi kamennykh materialov i transportnoi skhemy ikh dostavki potrebitelyu / Vl. P. Podol'skii, V. V. Gasilov // Stroitel'nye materialy. — 1992. — № 11. — S. 41—44.
16. **Podol'skii, Vl. P.** Stroitel'stvo avtomobil'nykh dorog. Zemlyanoe polotno / Vl. P. Podol'skii [i dr.]. — M.: ITs "Akademiya", 2013. — 304 s.
17. **Fursov, S. G.** Effekt modifikatora "DorTsem DS-1" / S. G. Fursov [i dr.] // Avtomobil'nye dorogi. — 2011. — № 5. — S. 136—139.
18. **Brendel, G.** Tackling Indias coal ash problem / G. Brendel // Mining Eng. — 1999. — Vol. 51, № 10. — P. 44—45.
19. **Cheriaf, M.** Pozzolanic properties of pulverized coal combustion asch / M. Cheriaf, J. C. Rocha // Cem. and Concr. — 1999. — Vol. 29, № 9. — P. 1387—1391.
20. **Horiuchi, S.** Effective use of fly ash slurry as file material / S. Horiuchi, M. Kawaguchi, K. Yasuhara // J. Hazardous Mater. — 2000. — Vol. 76, № 2—3. — P. 301—337.
21. **Jingbang, Sh.** Fly ash utilisation in China / Sh. Jingbang // Proc. 20th Int. Miner Process. Congr., Aachen, 21—26 Sept., 1997. — Clausthal — Zellerfeld, 1997. — Vol. 5. — P. 109—111.
22. **Xu, A.** Potentials of high-volume fly ash utilization in concrete and cementations products / A. Xu, Sh. L. Sarkar // Proc. Amer. Power Conf. — Chicago, 1996. — Vol. 58, Pt. 1. — P. 651—656.