DESIGNING AND CONSTRUCTION OF ROADS, SUBWAYS, AIRFIELDS, BRIDGES AND TRANSPORT TUNNELS

UDC 625.7/.8

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DEVELOPMENT OF STONE MASTIC ASPHALT MIXTURES WITH ENHANCED WORKABILITY FOR INSTALLATION AND REPAIR OF ROAD SURFACES

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Statement of the problem. We consider the problem of the development of stone mastic mixes with improved deformation and durability in the installation and repair of road surfacings to allow one to arrange thin layers of asphalt concrete pavement or lay the mixture in the repair niche.
Results. The results of the full factorial experiment that was performed by means of the method of mathematical planning, the evaluation of the influence of the main structure-forming factors on the deformation-strength characteristics of stone-mastic asphalt concrete are presented.
Conclusions. The results of the analysis of the impact of major structure-forming factors on the deformation-strength characteristics and technological properties of stone mastic mixes are reported. The effective compositions of the stone mastic asphalt mixes with a maximum grain size of up to 10 mm with improved workability and required values of the deformation-strength characteristics for laying or maintaining thin layers of road surfaces.

Keywords: asphalt, bitumen, mineral powder, repairs, crushed stone-mastic mixture.

Introduction

One of the urgent problems facing the road industry is to improve the quality of the maintenance of asphalt concrete surfaces of highly-intensive highways [10]. The currently used technologies for maintaining and repairing asphalt concrete surfaces by means of rough surfacings or wear and tear layers, repairing with monolith or traditional thick asphalt concrete mixes have a number of great disadvantages: they are not compatible and not lasting, their physical and mechanical and (or) operational properties (strength, evenness, smoothness), etc. are not high [1—21].

The above disadvantages are not typical of crushed stone-mastic mixes (CSMMs). However, CSMMs are distinctly easy to lay in thin layers (2—3 cm) or for prefabricated repair voids. Improving this property would allow the quality of road maintenance and repair and the durability of asphalt concrete surfacings to be better [9].

1. Assumptions and problem statement, experimental methods

The strength, operational and technological properties of CSMMs are assumed to be completely dependent on their composition. Their original components as well as their percentage proportion in a mix might randomly fluctuate. Finally, determining the physical and mechanical characteristics (e.g., water saturation or limit compression strength) might be randomly erroneous as well.

Let us denote the numerical value of the investigated characteristics using Y and its functional dependence on the parameters using $F(X_1, X_2, X_3)$. The fact that there is random excitation in each experiment as stated above is reflected in an additive Z:

$$Y = F\left(X_1, X_1, X_3\right) + Z\,, \tag{1}$$

where according to the central limit theorem a random value Z is normally distributed with the parameters $M(Z) = 0$ and $\sigma(Z) = \sigma$. Taking the mathematical anticipation M from both parts, we get

$$M(Y) = M\left(F\left(X_1, X_2, X_3 + Z\right)\right) = F\left(X_1, X_2, X_3\right) + M\left(Z\right) = F\left(X_1, X_2, X_3\right). \tag{2}$$

The last equation means that the original functional connection $F(X_1, X_2, X_3)$ does not express Y itself but the mathematical anticipation for the specified values of the parameters X_1, X_2, X_3:

$$M\ (Y\ ) = F\ (X_1, X_2, X_3)\,. \tag{3}$$

Such a dependence is regressive and the law $F(X_1, X_2, X_3)$ is called the regression of Y using X_1, X_2, X_3. The experiment planning theory suggests how it is more effective to select combinations of the parameters X_1, X_2, X_3 (called plans or points) for further effective observation of the approximation of the regression function based on the experimental values Y determined for the selected plans.

The basis for the selection of a variety of plans for their further investigation was the planning method of a complete factor experiment supplemented by some plans in the centre of the variation range. The properties of the regression model were designed and investigated using the licensed software *DataFit* 7.1.

The varying values were the following factors:

— X_1 is the content of a mineral powder in the mineral part of the mix, %;

— X_2 is the content of a large-grain filler (crushed stone) in the mineral part, %;

— X_3 is the content of bitumen in CSMMs, % (Table 1).

For all the investigated parameters of CSMMs the mathematical model was searched for as a full second-order multinomial from three variables:

$$Y = a_0 + b_1x_1 + b_2x_2 + b_3x_3 + c_1x_1x_2 + c_2x_1x_3 + c_3x_2x_3 + d_1x_1^2 + d_2x_2^2 + d_3x_3^2 \qquad (4)$$

followed by removal of insignificant summands.

In order to determine 10 original parameters a_0, b_i, c_j, d_k for each of the investigated characteristics Y three parallel series of 9 experiments were performed. In each experiment there was a certain mix that was prepared and investigated according to the guidelines of the complete factor experiment with three independent variable factors X_1, X_2, X_3.

The plan of the experiment and levels of the variation of the factors were identified based on the results of the preliminary experiments (Table 1, 2).

Table 1

Change range of three independent factors

Characteristics	Value of the code	Investigated factors		
		X_1, content of the mineral powder, %	X_2, content of crushed stone, %	X_3, content of bitumen, %
Main level (X_{0i})	0	15	70	6.5
Variation range (Δ_i)	ΔX	3.0	5	0.5
Upper level (X_i max)	$X_i = +1$	18.0	75	7.0
Lower level (X_i min)	$X_i = -1$	12.0	65	6.0

The response $Y = Y(X_1, X_2, X_3)$ for each point (X_1, X_2, X_3) of the plan of the experiment was an average arithmetic value of the corresponding values of Y observed in three parallel series of the experiments. This increased the accuracy by 1.7 times.

The CSMM mix-10 was researched. The mineral part was a granite crushed stone M 1000 and crushed screenings of granite M 1000 (Pavlovsk Ore Mining and Processing Enterprise of Voronezh region), non-activated limestone mineral powder (Voronezh). A road bitumen BND 60/90 manufactured at the Moscow Oil Processing Plant was used.

The major characteristics of CMMs to be investigated were

— the compression strength limit at the temperature 50 ºC of the dry samples (R_{50}, MPa) Y_1;

— average density, g/cm^3, Y_2;

— water saturation *W*, %, Y_3;
— porosity of the mineral part, %, Y_4;
— residual porosity, %, Y_5;
— depth of loading of the stamp at 40 ºC Y_6;
— shear adhesion at the temperature 50 °C, MPa, Y_7;
— limit tension strength during breakage at the temperature 0 °C, MPa, Y_8.

The plan of the experiment and natural values of the investigated factors at each point are given in Table 2.

Table 2

Plan of the experiment and natural values of the variables

Plan number	Plan of the experiment			Natural values of the variables		
	X_1	X_2	X_3	X_1, content of the mineral powder, %	X_2, content of crushed stone, %	X_3, content of bitumen, %
1	–1	–1	–1	12.0	65	6.0
2	+1	–1	–1	18.0	65	6.0
3	–1	+1	–1	12.0	75	6.0
4	+1	+1	–1	18.0	75	6.0
5	–1	–1	+1	12.0	65	7.0
6	+1	–1	+1	18.0	65	7.0
7	–1	+1	+1	12.0	75	7.0
8	+1	+1	+1	18.0	75	7.0
9	0	0	0	15.0	70	6.5

Generally the model of the investigated characteristics is as follows:

$$Y = a_0 + b_1 \times x_1 + b_2 \times x_2 + b_3 \times x_3 + c_1 \times x_1 \times x_2 + c_2 \times \\ \times x_1 \times x_3 + c_3 \times x_2 \times x_3 + d_1 \times x_1^2 + d_2 \times x_2^2 + d_3 \times x_3^2. \quad (5)$$

2. Results of designing the model

In all cases the coefficients d_1, d_2, d_3 were shown to be insignificant and thus assumed to be 0. The model of the index of the limit compression strength at the temperature 50° C Y_1 is as follows:

$$Y_1 = 1.15\,. \quad (6)$$

I.e. for all the suggested experimental data, the sufficient model is a constant.

The model of the average density of CMM Y_2 is as follows:

$$Y_2 = 2.395 + 0.0025 \times x_1 - 0.0125 \times x_2 - 0.0025 \times x_3 - 0.005 \times x_1 \times x_2\,. \quad (7)$$

The model of water saturation of CMM Y_3 is as follows:

$$Y_3 = 1.01 - 0.155 \times x_1 + 0.445 \times x_2 - 0.095 \times x_3 - 0.1125 \times x_1 \times x_2 + +0.1275 \times x_2 \times x_3. \quad (8)$$

The model of porosity of the mineral part of CMM Y_4 is as follows:

$$Y_4 = 17 - 0.05 \times x_1 + 0.35 \times x_3. \quad (9)$$

The residual porosity of CMM Y_5 is as follows:

$$Y_5 = 2.5 - 0.05 \times x_1 - 0.65 \times x_3. \quad (10)$$

The model of the index of the depth of loading of the stamp at 40 ºC Y_6 is as follows:

$$Y_6 = 2.236 - 0.0875 \times x_2 + 0.3125 \times x_3 + 0.0375 \times x_1 \times \times x_2 - 0.0375 \times x_2 \times x_3. \quad (11)$$

The model of the index of the shear adhesion at the temperature 50 °C Y_7 is as follows:

$$Y_7 = 0.21875 - 0.01125 \times x_2 - 0.05875 \times x_3 - 0.01125 \times x_1 \times \times x_3 + 0.01625 \times x_2 \times x_3. \quad (12)$$

The model of the limit tension strength during breakage at the temperature 0 °C is as follows:

$$Y_8 = 2.105 - 0.22 \times x_2 + 0.2625 \times x_3 - 0.09 \times x_1 \times \times x_3 - 0.0576 \times x_2 \times x_3. \quad (13)$$

The results of regressive modelling are in Table 3 where along with the original data obtained during the experiment there are the values calculated using the corresponding resulting regression model that are in brackets.

Table 3

Results of the experiment and modelling

Limit compression strength at 50 °C, MPa	Average density, g/cm³	Water saturation, %	Porosity of the mineral part, %	Residual porosity, %	Depth of loading of the stamp at 40 °C, mm	Shear adhesion at 50° C, MPa	Limit tension strength during breakage at 0 °C, MPa
1.07 (1.15)	2.40 (2.411)	0.98 (0.83)	16.7 (16.7)	3.2 (3.2)	2.0 (2.0113)	0.27 (0.2937)	2.54 (2.335)
1.52 (1.15)	2.42 (2.416)	0.64 (0.745)	16.6 (16.6)	3.1 (3.1)	1.9 (1.9363)	0.34 (0.2937)	2.52 (2.515)
1.20 (1.15)	2.39 (2.386)	1.36 (1.465)	16.7 (16.7)	3.2 (3.2)	1.8 (1.8363)	0.25 (0.2612)	2.07 (2.01)
1.06 (1.15)	2.38 (2.391)	1.53 (1.38)	16.6 (16.6)	3.1 (3.1)	1.9 (1.9113)	0.25 (0.2612)	2.34 (2.19)
1.27 (1.15)	2.40 (2.406)	0.48 (0.61)	17.4 (17.4)	1.9 (1.9)	2.7 (2.7113)	0.16 (0.1437)	2.19 (2.105)
0.89 (1.15)	2.41 (2.411)	0.25 (0.075)	17.3 (17.3)	1.8 (1.8)	2.6 (2.6363)	0.15 (0.1437)	2.05 (1.925)
0.93 (1.15)	2.38 (2.386)	1.93 (1.755)	17.4 (17.4)	1.9 (1.9)	2.4 (2.3863)	0.17 (0.1762)	1.73 (1.55)
1.26 (1.15)	2.38 (2.386)	1.09 (1.22)	17.3 (17.3)	1.8 (1.8)	2.4 (2.4613)	0.16 (0.1762)	1.40 (1.37)
0.94 (1.15)	2.41 (2.399)	0.95 (1.01)	17.0 (17.0)	2.5 (2.5)	2.3 (2.2363)	0.28 (0.2187)	1.72 (2)

Conclusions

1. The substantiated increase in the content of bitumen and mineral powder in CMMs with the maximum size of the grain of up to 10 mm allows high values of deformation and strength indices to be reached (shear adhesion at the temperature 50 °C, limit compression strength at the temperature 50 °C, limit tension strength during breakage at the temperature 0 °C) and necessary values of physical indices (average density, water saturation, porosity of the mineral part, residual porosity) as well as the depth of loading of the stamp at 40 ºC that are typical of viber monolith asphalt concrete mixes. The results of the experiment showed degrees of the influence of the main structural factors on the properties of foundation asphalt concrete mixes with the maximum size of the grain of up to 100 mm. The most significant factors are the content of bitumen or mineral powder with the amount of crushed stone in the mineral part of CMMs being less significant.

2. For laying thin layers of CMM surfacings with the maximum size of the grain in the mineral part of up to 10 mm it is recommended that mixes with a smaller content of bitumen and a higher content of mineral powder are used. For laying into repairing voids crushed stone mastic mixes with a high content of bitumen, optimal ratio of crushed stone and mineral powder in the mineral part should be used.

3. The results of the experiment show it possible to obtain effective compositions of CMMs with the maximum size of the grain of up to 10 mm that are better for laying and have higher deformation and strength characteristics by means of optimizing the content of the organic binder and components of the mineral part.

References

1. Barinov E. N. *Novye metody otsenki kachestva asfal'tobetonov* [New methods of assessing the quality of asphalt concrete]. Leningrad, Leningradskiy inzhenerno-stroitel'nyy in-t Publ., 1989. 55 p.

2. Gorelyshev N. V. *Asfal'tobeton i drugie bitumomineral'nye materialy* [Asphalt and other materials bitumomineraljnykh]. Moscow, Mozhaysk-Terra Publ., 1995. 176 p.

3. Gorelysheva L. A., Shtromberg A. A. Otsenka ustalostnoy dolgovechnosti asfal'tobetonnykh pokrytiy [Evaluation of fatigue life of asphalt concrete pavements]. *Nauka i tekhnika v dorozhnoy otrasli*, 2009, no. 1, pp. 25—26.

4. Zolotarev V. A. [Bitumens modified with polymers of the type SBS: Features of composition, structure and properties]. *Trudy Mezhdunar. nauch.-tekhn. konf. «Problemy povysheniya kachestva i resursosberezheniya v dorozhnoy otrasli»* [Proc. of International scientific-technical conference "Problems of quality improvement and resource saving in the road sector"]. Kharkov, KhNADU Publ., 2003. 17 p.

5. Zolotarev V. A., Bratchun V. I. [Modified bituminous binders, special bitumens with additives in road construction]. *Vsemirnaya dorozhnaya assotsiatsiya. Tekhnicheskiy komitet «Nezhestkie dorogi» (s8) [The world road Association* [The technical Committee is "flexible roads" (s8)]. Kharkov, KhNADU Publ., 2003. 229 p.

6. Iliopolov S. K., Seleznev M. G., Uglova E. V. *Dinamika dorozhnykh konstruktsiy* [Dynamics of road constructions]. Rostov-on-don, 2002. 258 p.

7. Zolotarev V. A. et al., Zolotarev V. A., Kosmina A. V. (eds.). *Ispytaniya dorozhno-stroitel'nykh materialov* [Testing of road construction materials]. Kharkov, KhNADU Publ., 2012. 368 p.

8. Kalgin Yu. I. Dorozhnye bitumomineral'nye materialy na osnove modifitsirovannykh bitumov [Road bitumomineraljnykh materials based on modified bitumen]. Voronezh, Izd-vo Voronezh. gos. un-ta, 2006. 272 p.

9. Kalgin Yu. I., Strokin A. S., Mironchuk S. A. Otsenka ustoychivosti shchebenochno-mastichnogo asfal'tobetona s primeneniem polimernoy adgezionnoy dobavki k nakopleniyu ostatochnykh deformatsiy [Evaluation of resistance of stone mastic asphalt using polymer adhesive additives to the accumulation of residual strain]. *Nauchnyy vestnik Voronezhskogo GASU. Stroitel'stvo i arkhitektura*, 2015, no. 4 (14), pp. 107—115.

10. Kalgin Yu. I., Strokin A. S., Tyukov E. B. *Perspektivnye tekhnologii stroitel'stva i remonta dorozhnykh pokrytiy s primeneniem modifitsirovannykh bitumov* [Perspective technologies of construction and repair of road surfaces with the use of modified bitumen]. Voronezh, OAO «Voronezhskaya oblastnaya tipografiya», 2014. 224 p.

11. Kolbanovskaya A. S., Gokhman L. M., Davydova K. I. Regulirovanie protsessov strukturoobrazovaniya neftyanykh bitumov dobavkami divinil-stirol'nogo termoelastoplasta [Regulation of structure formation processes of bitumen additives butadiene-styrene thermoplastic elastomer]. *Kolloidnyy zhurnal*, vol. 34, no. 4, 1972, pp. 6—17.

12. Iliopolov S. K. e.a. *Organicheskie vyazhushchie dlya dorozhnogo stroitel'stva* [Organic binders for road construction]. Rostov-on-don, 2003. 428 p.

13. Rudenskiy A. V., Kalgin Yu. I. *Dorozhnye asfal'tobetonnye pokrytiya na modifitsirovannykh bitumakh* [Road asphalt coatings modified bitumen]. Voronezh, 2009. 143 p.

14. Bratchun V. I. et al. *Fiziko-khimicheskaya mekhanika stroitel'nykh materialov* [Physico-chemical mechanics of construction materials]. Donetsk, Noulindzh Publ., 2013. 338 p.

15. Carswel J., Noglia O. Etude des essais de fluage repetes comme method predictive de la resistance a l'ornierage des enrobes. RGRA, 2003, no. 817, pp. 55—59.

16. Chaussees a longue duree de vie et cas de reussite. Rapport du Comite Technique 4.3 sur Chaussees Routieres AIPCR, 2007. 42 p.

17. Hardzynski F., Such Ch. Modelisation du comportement rheologique des bitumes polymers. Le model autocoherant. Bull. des Labo P. et Ch., 1998, no. 214, pp. 3—18.

18. Heukelom W. Une methode amelioree de caracterisation des bitumen par leurs proprietes mecaniques / W. Heukelom. Bull. Liaison Labo. P. et Ch., 1975, no. 76, pp. 55—64.

19. Jolivet J., Malot M., Ramond G., Pastor M. Contribution des mesures rheologiques sur liants a la prevision l'ornierage en laboratoire. Bull. Liaison Labo. P. et Ch., 1994, no. 194, pp. 3—10.

20. Molenaar J. M. M., Hagos E. T., Van De Ven M. F. C. An investigation into the specification of rheological properties of polymer modified bitumen. Proc. 3rd Eurasphalt & Eurobitume Congress. 12—14 may 2004. Vienna, 2004, pp. 2080—2091.

21. Olard F., Chabert D. Developpement de l'essai de fatigue sur liants et mastics bitumineux. RGRA, 2008, no. 865. — P. 69—74.

22. Xue Y., Hou H., Zhu Sh., Zha J. Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: Pavement performance and environmental impact. Construction and Building Materials, 2009, vol. 23, iss. 2, pp. 989—996.