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PERSPECTIVES ON USING BASALT FIBER FILAMENTS IN THE CONSTRUCTION AND REHABILITATION OF HIGHWAY PAVEMENTS AND AIRPORT RUNWAYS

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Abstract. With the ageing transportation infrastructure, many transportation agencies across the world are focussing on rehabilitating and improving existing pavements. This means more roadwork on pavements open to vehicular traffic. Considering the rapid increase in both traffic volume and intensity in recent years, the work conditions on pavements have become difficult. Thus, there is an important need to design and construct long-lasting pavements that possess high durability, appropriate roughness or smoothness, and that which helps achieve greater time interval between repairs. The use of basalt fibers has shown to improve the durability and mechanical properties of concrete and asphalt mixtures through dispersed reinforcement. This paper presents new data and insights on the use of basalt fibers in concrete and asphalt mixtures acquired from theoretical and experimental research studies that can be useful in the design, construction and rehabilitation of highway pavements and airdrome runways.

Keywords: durability, fiber, highway pavement, mixture, reinforcement filaments.

1. Introduction

A highway pavement is an integral part of a road-transport complex developed in various countries. Mobility and serviceable pavements are vital to a nation's economic growth as it is highly dependent on truck-freight transportation. Truck delays and poor road conditions add to the cost of fright shipments. In addition, traffic accidents affect economic costs (Ayuso *et al.* 2010; Pukalskas *et al.* 2015; Sivilevičius 2011; Toraldo *et al.* 2015; Ye, Li 2016).

As transportation infrastructure all over the world continues to deteriorate, many transportation agencies are focussing on rehabilitating and improving existing pavements. This means more roadwork on pavements open to vehicular traffic. Considering the rapid increase in both traffic volume and intensity in recent years, the work conditions on pavements have become difficult. Road pavements designed and constructed following traditional and locally adopted practices and specifications typically do not last through their service lives (Gopalakrishnan *et al.* 2013; Karaşahin, Terzi 2014; Krayushkina *et al.* 2012; Teodorovic, Vukadinovic 1998; Toraldo *et al.* 2015; Saraf 1998).

Thus, there is an important need to design and construct long-lasting concrete and asphalt pavements that possess the characteristics of high durability, appropriate roughness or smoothness, and that which helps achieve greater time interval between repairs (Baghini *et al.* 2014; Toraldo *et al.* 2015).

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The concrete pavement sustains multiple cyclic transport loads, oppose tensions that appear in the pavement layer as a result of variations in temperature and humidity and due to systematic freezing and defrosting of water in the pores of concrete in the autumn-winter period as well as support tensions generated by the deformations of the pavement caused by heaving of the subgrade foundation (Du *et al.* 2015; Gigineishvili 2014; Hendel *et al.* 2014; Soleimani, Ahmadi 2015). With the introduction of reinforcing fibers in concrete, these qualities have shown to improve to various degrees (Dzhigiris, Mahova 2002; Füssl *et al.* 2015a, 2015b; Krayushkina *et al.* 2012; Kurtaev *et al.* 1991; Rabinovich *et al.* 2001; Veselovskij *et al.* 2006).

The principal feature of concrete mixture reinforced with basalt fibers is its high durability at all kinds of stress conditions and the ability to sustain large deformations in elastic condition (Gribniak *et al.* 2015; Mahova, Grebenyuk 1980). At the same time, the relative deformation of basalt fiber reinforced concrete without cracking is about 0.7–0.9%. Such deformation magnitude exceeds the ultimate deformation of non-reinforced concrete 35–45 times. A considerable increase in the deformability, durability and abrasion properties of concrete happens due to the elimination of the stress concentration influences by basalt fiber in localized regions impaired by structural defects such as micro-cracks, delamination, etc. (Dzhigiris *et al.* 1989; Dzhigiris, Mahova 2002).

Currently, several types of basalt fibers are available that are being efficiently used for the reinforcement of concrete. Depending on the diameter, basalt fibers are divided into the following categories: micro-thin (with a diameter less than 0.6μ [microns]), ultrathin (0.6–1.0 μ), superthin (1.0–3.0 μ), thin (9–15 μ), thickened (15–25 μ), and rough (50–500 μ) (Dzhigiris *et al.* 1989; Dzhigiris, Mahova 2002).

2. Use of fiber in cement concrete mixtures

One of the most effective methods for improving the mechanical properties of concrete used in the construction and rehabilitation of highway pavements and airport runways is to reinforce it with fiber, a special construction filament acting as a reinforcing component at the micro-level. The resulting fiber reinforced concrete (FRC) or fibrous concrete has improved fracture strength, impact resistance, high resistance to abrasion and other benefits

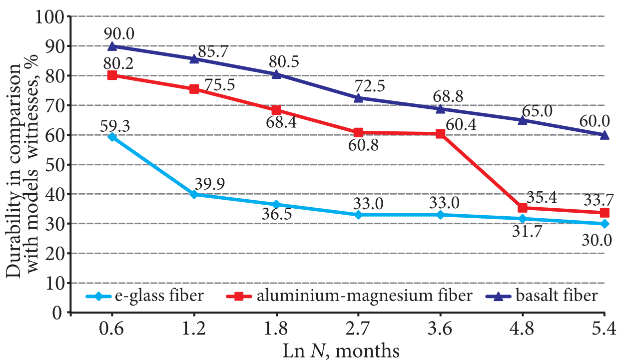

Fig. 1. Time dependence of durability losses of fibers in hardened Portland cement concrete

(Gigineishvili 2014; Gribniak *et al.* 2015; Holmyanskij *et al.* 1991; Talantanova, Tolstenev, 1999; Tapkin, Özcan 2012; Veselovskij *et al.* 2006).

The fibers used in fiber reinforced concrete include various metallic and non-metal fibers. Non-metal fibers typically include glass, polyamide, asbestos and basalt. A combination of different fiber types (such as metal and polymer, metal and basalt, etc.) have also been applied to maximize the benefits (Hajdukov *et al.* 1990; Kurtaev *et al.* 1991; Mihajlov *et al.* 1990; Rabinovich *et al.* 2001; Veselovskij *et al.* 2006).

For the last three decades, Ukraine has widely employed basalt fiber fabricated by melting basalt crumb at a temperature of 1450–1550 °C and passing through special filters from the derived melt. The strength of acid-proof basalt fiber with a diameter of 8 μ – 19 μ is 1800–2600 MPa and its density is 2.8–3.3 g/cm^3.

The results of numerous studies reported in the literature confirm a possibility of a wide-ranging use of permanent basalt fibers and rough fibers as reinforcing admixtures in concrete mixtures for construction purposes. However, studies have revealed that the use of smaller diameter basalt fiber may result in a reduction of stress in the concrete environment. The most intensive process of stress reduction occurs within the period of 3–6 months from the time of construction. Fig. 1 displays various levels of durability losses observed with the use of of e-glass, aluminium-magnesium and basalt fibers for concrete reinforcement.

3. Use of fiber in asphalt concrete mixtures

For pavement emergency repair and routine maintenance activities, both hot-mix asphalt concrete and cold-mix asphalt (also referred to as cold asphalt patch) have been used. Cold-mix asphalt mixtures are prepared at an ambient temperature without heating and even under complicated weather conditions with increased humidity and low temperature.

Over the last few years, the most widespread use of cold-mix asphalt in Ukraine has been found in liquidation pits and pot-holes. Since such repair work is typically carried out in cold weather at low temperatures, the use of cold-mix asphalt has proven to be very effective in achieving long-lasting repairs.

The mechanical properties and durability of both hot-mix asphalt and cold-mix asphalt has shown to improve through the addition of fibers (Ferrotti *et al.* 2014; Ye *et al.* 2009). The fibers used for the dispersed reinforcement of hot and cold-mix asphalt concrete mixtures are supposed to possess the following attributes:

- resistance to ageing under the action of increased temperatures;
- high rapture strength;
- durability under the action of corrosive mediums;
- humidity resistance;
- ability to mixed easily with other components without the formation of clots.

The functions of fiber as a tenacity regulator and reinforcement agent depend on their diameter, length, as well as the quantity of fiber added to bitumen. The optimal size of fiber is 4–6 μ in diameter and 4–5 mm in length. Thinner fiber easily brakes, which leads to the creation of very short fibers that almost have no influence on tenacity, whereas even thinner ones pose obstacles to uniform mixing.

4. Experimental investigations and results

This research investigated the use of basalt fiber, that is a high-quality micro-thin filament, in cement and asphalt concrete mixtures. The appearance of micro-thin basalt fiber is shown in Fig. 2.

The composition of basalt mountain rock used for making micro-thin fiber is shown in Table 1. The physical-mechanical characteristics of basalt fiber are displayed in Table 2.

After characterizing the physical and mechanical properties of basalt fiber, cement and asphalt concrete mixtures incorporating basalt fiber were investigated.

For investigating the fiber reinforced cement concrete mixtures, the following materials were used:

- basalt fiber of 4–5 mm in length and 160.0 μ in diameter making 2.0–4.0% by mass of cement concrete;
- Portland cement M500 (650 kg) with normal density of 26%;
- river sand (1300 kg) with fineness modulus $M_k = 2.60$, density – 1260 kg/m^2;
- crashed stone with a fraction of 5–20 mm;
- chemical plasticizing and air-entraining additives produced by a commercial manufacturer in Slovenia.

The two most widespread technologies for mixing basalt fiber into the cement concrete mixture was utilized in this study as follows:

- *first:* fibers are added to the previously mixed combination of cement and water;
- *second:* first, fillers and fiber are mixed, and then, cement, water and additives are mixed.

The resulting mixtures were consolidated in standard forms using a laboratory vibro-table with the frequency of 3000 vibrations per minute. Physical-mechanical properties of the fiber reinforced cement concrete mixtures were determined after hardening at the seventh and twenty-eighth day. The results of compressive strength tests and mechanical durability tests are shown in Table 3.

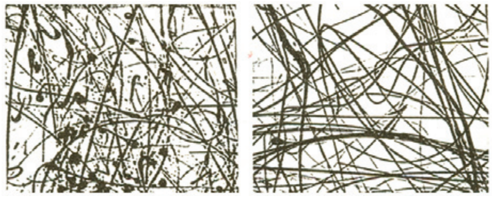

Fig. 2. The structure of micro-thin basalt fiber

Table 1. Chemical composition of basalt mountain rock

Title of oxide	Quantity of maintenance in fiber, %
SiO_2	46.5–51.5
Al_2O_3	15.0–19.0
MgO	4.0–10.5
CaO	7.5–11.5
$FeO+Fe_2O_3$	8.0–12.0
K_2O+Na_2O	3.0–6.0
TiO_2	0.3–2.5
Cr_2O_3	0.02–0.05
MnO	<0.1
Other	up to 100

Table 2. Physical-mechanical characteristics of basalt fiber

Title of index	Unit	Physical-mechanical qualities of basalt fiber
Basic diameter of fiber	μ	160.0
Quantity of non-fibrous additions	%	2–3
Solidity	g/cm^3	2.65
Temperature interval of usage	°C	(–269)–(+700)
Water resistance	%	99.6
Chemical stability:	%	
– 0.5H NaOH		93.4
– 2H NaOH		77.3
– 2H H_2SO_4		98.5
Water absorption	%	up to 1.0
Mechanical resistance	MPa	1800–4100
Modulus of elasticity	MPa	110–120
Elongation at rupture	%	3.1

Table 3. Compressive strength and durability tests results of basalt fiber reinforced cement concrete mixtures

No.	Type of concrete specimens	Quantity of fiber, % by mass of concrete	Compressive strength, MPa		Durability on stretching the bend, MPa	
			7 days	28 days	7 days	28 days
First technology						
1.	Reference specimen	–	19.8	22.4	4.6	5.9
2.	With basalt fiber	2.0	20.8	28.3	6.8	9.1
3.	With basalt fiber	4.0	18.8	23.2	4.9	7.2
Second technology						
1.	Reference specimen	–	19.9	22.2	4.6	5.9
2.	With basalt fiber	2.0	20.9	28.4	6.9	9.2
3.	With basalt fiber	4.0	18.6	23.3	5.0	7.1

The freeze-thaw durability and moisture resistance properties of basalt fiber reinforced cement concrete mixtures are displayed in Table 4.

The analysis of data in Table 4 shows that the introduction of basalt fiber improves the quality and durability of cement concrete. Due to the formation of a thick structural matrix resulting from the addition of basalt fibers, the indices of water absorption have declined and the indices of water resistance and frost resistance have risen.

For investigations on the hot-mix asphalt concrete mixture of type “B”, the following materials were used:

- limestone mineral powder was replaced with basalt fiber at quantities of 0.5%, 1.0% and 2.0%. In addition, bitumen volume – 7.0%, 7.0%, 7.5% respectively;
- granite crushed stone fraction of 5–20 mm – 42.5%;
- granite shorts fraction of 0–5 mm – 50.5%;
- limestone mineral powder – 7.0%;
- bitumen mark BMD 60/90 – 7.2%;
- polymer additions to bitumen – UDOM-2 and Butonal NS198.

The physical-mechanical properties of asphalt concrete mixtures mixed with basalt fiber are summarized in Table 5.

The analysis of data presented in Table 5 shows improvement in physical-mechanical properties of hot-mix asphalt concrete after the addition of basalt fiber. Note the significant increase in durability of basalt fiber reinforced asphalt concrete under compression conditions at a temperature of 50 °C which attests to its superior mechanical performance under hot weather.

Laboratory investigations on the cold-mix asphalt concrete mixture were implemented using mineral materials for the hot fine bituminous concrete of type “B”. Bitumen SG 70/130 modified with Wetfix-BE was employed.

The design of an optimal mixture for the cold fine bituminous concrete of type “B_x”, model II with addition of basalt fiber at concentrations of 1.0% and 2.0% was implemented as it is widespread for patchwork purposes. For comparison, a standard composition with limestone mineral fines has been used. The composition of mixtures is shown in Table 6.

The physical-mechanical properties of cold-mix asphalt concrete mixtures reinforced with basalt fiber are summarized in Table 7.

The analysis of data presented in Table 7 reveals that dispersed reinforcement of basalt fibers in cold-mix asphalt increases the durability of cold-mix asphalt concrete mixtures in comparison with the unreinforced ones by 40–45% before and after warming. The added benefits include reduction in water satiation and swelling properties.

Table 4. Freeze-thaw durability and moisture resistance properties of basalt fiber reinforced cement concrete mixtures

No.	Title of concrete specimens	Quantity of fiber, % by mass of concrete	Coefficient of frost resistance after the quantity of cycles			Water resistance, MPa	Water absorption, %
			100	200	300		
First technology							
1.	Reference specimen	–	0.840	0.760	0.710	4.8	5.3
2.	With basalt fiber	2.0	0.960	0.910	0.830	8.0	2.1
3.	With basalt fiber	4.0	0.901	0.860	0.792	8.0	2.3
Second technology							
1.	Reference specimen	–	0.850	0.750	0.680	4.3	5.5
2.	With basalt fiber	2.0	0.980	0.880	0.840	7.5	2.4
3.	With basalt fiber	4.0	0.890	0.840	0.790	7.0	2.7

Note: specimens have been investigated under the frost resistance of 100, 200, and 300 cycles of freezing and defrosting in 5% solution of NaCl.

Table 5. Physical-mechanical properties of asphalt concrete mixtures reinforced with basalt fiber

Type of mixture	Medium solidity, g/cm^3	Water satiety, %	Swelling, %	Compressive strength, MPa			Durability on stretching the bend, MPa	Water resistance factor, kV
				R 20	R 50	R 0		
Checking the fine-grained asphalt concrete of type “B” with limestone mineral powder (reference specimen)	2.36	2.13	3.17	2.6	1.4	10.5	4.8	0.90
Fine-grained asphalt concrete of type “B” with basalt fiber in quantity:								
– in 0.5%	2.35	2.52	0.79	3.8	1.9	9.6	4.9	0.92
– in 1.0%	2.34	3.44	1.21	4.2	3.2	10.3	5.2	0.90
– in 2.0%	2.32	4.21	2.07	4.6	3.8	10.9	6.6	0.86

Table 6. Composition of mixtures

Number of composition	Title of mixture components	Composition concerning mass, %	Composition, kg
I	Granite crushed stone fractions of 5–20 mm in diameter	34.5	328.5
	Granite shorts fractions of 0–5 mm in diameter	59.0	562.0
	Limestone mineral powder	5.5	52.0
	Basalt fiber	1.0	9.5
	Bitumen SG 70/130 modified with Wetfix-BE 0.3% considering the mass of bitumen	5.0	48.0
	Altogether	105.0	1000.0
II	Granite crushed stone fractions of 5–20 mm in diameter	34.5	327.0
	Granite shorts fractions of 0–5 millimetres in diameter	59.0	559.0
	Limestone mineral powder	4.5	43.0
	Basalt fiber	2.0	19.0
	Bitumen SG 70/130 modified with Wetfix-BE 0.3% considering the mass of bitumen	5.5	52.0
	Altogether	105.5	1000.0

Table 7. Physical-mechanical properties of cold-mix asphalt concrete mixture reinforced with basalt fiber

Title of indexes	Objectives DSTU B V.2.7-119-2003	Type of the asphalt concrete mixture		
		Standard without fiber	Fiber 1%	Fiber 2%
Porosity of mineral skeleton, % capacity	20.00	19.00	18.50	18.00
Permanent porosity, % capacity	6.00–10.00	9.50	8.00	7.50
Water satiety before warming, % capacity	5.00–9.00	7.80	6.00	6.00
Swelling before warming, % capacity	2.00	1.50	1.20	1.20
Durability of compressive resistance, under a temperature of 20 °C:				
– before warming	1.30	2.50	3.80	4.00
– after warming	1.60	3.20	4.50	4.60
Coefficient of water resistance:				
– before warming	0.60	0.70	0.76	0.76
– after warming	0.80	0.85	0.88	0.90
Caking by the number of hits	10.00	9.00	8.50	8.50

5. Conclusions

1. Laboratory investigations on the use of basalt fiber for the dispersed (chaotic) reinforcement of cement concrete and asphalt concrete mixtures has been performed. The conducted investigation has showed the ability of the material to be effectively applied as reinforcement, which improves the physical-mechanical properties of dispersed reinforced materials.

2. The addition of basalt fiber into the cement concrete mixture resulted in the improvement of physical-mechanical properties (increase in compression strength by 20%, bending strength by 20–25%, frost-resistance and water resistance by 15–20% and abrasion).

3. The study established optimal basalt fiber concentrations, which include 2.0% by mass of cement concrete and 1.0% by mass of mineral fines for hot-mix and cold-mix asphalt concrete. Fiber filament provides three-dimensional hardening in comparison with traditional reinforcement making available two-dimensional hardening.

4. The addition of basalt fiber in hot-mix asphalt concrete mixture increases the fracture strength with the possibility of reducing the potential for reflection crack formation. It results in increased thermal resistance and a more stable structure resulting from the increased number of contacts between mineral grains. For this reason, the basalt fiber reinforced hot-mix asphalt concrete mixture has a higher durability index of bending strength and more stability of slide. The service life of the highway pavements and runway surfaces containing such mixtures is expected to increase 1.5 times.

5. Investigations on the use of basalt fiber in cold-mix asphalt concrete mixture showed increased compressive strength and resistance to cracking, about 40–50% more than the standard cold-mix asphalt concrete mixture. The coefficient of water resistance was found to be higher than

that of a traditional mixture. These findings seem to be indicative of higher life expectancy for asphalt concrete reinforced with basalt fiber.

6. Improvement in physical-mechanical properties points to a positive influence of basalt fiber on the structure of asphalt concrete that is expressed through changing matrix ductility in neighbouring layers. This will prevent the exfoliation of the matrix from the filament surface and inhibit water intrusion, especially during construction and repair activities.

7. The possibility of using the cold-mix fibrous asphalt concrete mixture is an important factor in road emergency repair carried out for securing uninterrupted traffic under intricate meteorological conditions – cold temperature and high humidity.

References

Ayuso, M.; Guillén, M.; Alcañiz, M. 2010. The Impact of Traffic Violations on the Estimated Cost of Traffic Accidents with Victims, *Accident Analysis & Prevention* 42(2): 709–717. http://dx.doi.org/10.1016/j.aap.2009.10.020

Baghini, M. S.; Ismail, A.; Karim, M. R.; Shokri, F.; Firoozi, A. A. 2014. Effect of Styrene-Butadiene Copolymer Latex on Properties and Durability of Road Base Stabilized with Portland Cement Additive, *Construction and Building Materials* 68: 740–749. http://dx.doi.org/10.1016/j.conbuildmat.2014.06.061

Du, Y.; Wang S.; Zhang, 2015. Cooling Asphalt Pavement by a Highly Oriented Heat Conduction Structure, *Energy and Buildings* 102: 182–196. http://dx.doi.org/10.1016/j.enbuild.2015.05.020

Dzhigiris, D. D.; Mahova, M. F. 2002. *Osnovy proizvodstva bazal'tovyh volokon i izdelij*: Monografiya. Moskva: Teplojenergetik, 2002. 416 p. (in Russian).

Dzhigiris, D. D.; Mahova, M. F.; Sergeev, V. P. 1989. *Bazal'tovoloknistye materialy*. Moskva: VNIIJeSM, 72 p. (in Russian).

Ferrotti, G.; Pasquini, E.; Canestrari, F. 2014. Experimental Characterization of High-Performance Fiber-Reinforced Cold Mix Asphalt Mixtures, *Construction and Building Materials* 57: 117–125. http://dx.doi.org/10.1016/j.conbuildmat.2014.01.089

Füssl, J.; Kluger-Eigl, W.; Blab, R. 2015a. Mechanical Performance of Pavement Structures with Paving Slabs – Part I: Full-Scale Accelerated Tests as Validation for a Numerical Simulation Tool, *Engineering Structures* 98: 221–229. http://dx.doi.org/10.1016/j.engstruct.2014.10.054

Füssl, J.; Kluger-Eigl, W.; Eberhardsteiner, L.; Blab, R. 2015b. Mechanical Performance of Pavement Structures with Paving Slabs – Part II: Numerical Simulation Tool Validated by Means of Full-Scale Accelerated Tests, *Engineering Structures* 98: 221–229. http://dx.doi.org/10.1016/j.engstruct.2014.10.055

Gigineishvili, J. 2014. Results of Survey of Prestressed Concrete Beams Reinforced with Basaltplastic Bars, in *ECCE-GSCE-WCCE International Conference Seismics-2014 "Seismic Design and Rehabilitation of Buildings"*, 29–30 May 2014, Tbilisi, Georgia, 65–78.

Gribniak, V.; Arnautov, A. K.; Kaklauskas, G.; Tamulenas, V.; Timinskas, E.; Sokolov, A. 2015. Investigation on Application of Basalt Materials as Reinforcement for Flexural Elements of Concrete Bridges, *The Baltic Journal of Road and Bridge Engineering* 10(3): 201–206. http://dx.doi.org/10.3846/bjrbe.2015.25

Gopalakrishnan, K.; Agrawal, A.; Ceylan, H.; Kim, S.; Choudhary, A. 2013. Knowledge Discovery and Data Mining in Pavement Inverse Analysis, *Transport* 28(1): 1–10. http://dx.doi.org/10.3846/16484142.2013.777941

Hajdukov, G. K.; Volkov, I. V.; Laginov, A. H. 1990. Prochnost', deformativnost' i treshhinostojkost' steklofibrobetonnyh jelementov, *Beton i zhelezobeton* 9: 15–17. (in Russian).

Hendel, M.; Colombert, M.; Diab, Y.; Royon, L. 2014. Improving a Pavement-Watering Method on the Basis of Pavement Surface Temperature Measurements, *Urban Climate* 10(1): 189–200. http://dx.doi.org/10.1016/j.uclim.2014.11.002

Holmyanskij, M. M.; Kurilin, V. V.; Edneral, A. F. 1991. Stalefibrobeton s amorfnoj fibroj, *Beton i zhelezobeton* 6: 9–10. (in Russian).

Karaşahin, M.; Terzi, S. 2014. Performance Model for Asphalt Concrete Pavement Based on the Fuzzy Logic Approach, *Transport* 29(1): 18–27. http://dx.doi.org/10.3846/16484142.2014.893926

Krayushkina, K.; Prentkovskis, O.; Bieliatynskyi, A.; Junevičius, R. 2012. Use of Steel Slags in Automobile Road Construction, *Transport* 27(2): 129–137. http://dx.doi.org/10.3846/16484142.2012.690093

Kurtaev, A. S.; Sulejmenov, S. T.; Estemesov, Z. A. 1991. *Kompozicionnye materialy na osnove vjazhushhih*. Kiev: IPM, 21 p. (in Russian).

Mahova, M. F.; Grebenyuk, N. P. 1980. Dispersnoe armirovanie portlandcementa bazal'tovymi voloknami, *Cement* 2: 6–19. (in Russian).

Mihajlov, K. V.; Evgen'ev, I. E.; Aslanova, L. G. 1990. Primenenie metallicheskoj armatury v betone, *Beton i zhelezobeton* 4: 5–7. (in Russian).

Pukalskas, S.; Pečeliūnas, R. Sadauskas, V.; Kilikevičienė, K.; Bogdevičius, M. 2015. The Methodology for Calculation of Road Accident Costs, *Transport* 30(1): 33–42. http://dx.doi.org/10.3846/16484142.2015.1020871

Rabinovich, F. N.; Zueva, V. N.; Makeeva, L. V. 2001. Stojkost' bazal'tovyh volokon v srede gidratiruyushhih cementov, *Steklo i keramika* 12: 12–14. (in Russian).

Saraf, C. L. 1998. *Pavement Condition Rating System: Review of PCR Methodology*. Report No FHWA/OH-99/004. 126 p.

Sivilevičius, H. 2011. Modelling the Interaction of Transport System Elements, *Transport* 26(1): 20–34. http://dx.doi.org/10.3846/16484142.2011.560366

Soleimani, B.; Ahmadi, E. 2015. Evaluation and Analysis of Vibration During Fruit Transport as a Function of Road Conditions, Suspension System and Travel Speeds, *Engineering in Agriculture, Environment and Food* 8(1): 26–32. http://dx.doi.org/10.1016/j.eaef.2014.08.002

Talantanova, K. V.; Tolstenev, S. V. 1999. Kompozit – stalefibrobeton v dorozhnom stroitel'stve, *Avtomobil'nye dorogi* 9: 24–25. (in Russian).

Tapkin, S.; Özcan, Ş. 2012. Determination of the Optimal Polypropylene Fiber Addition to the Dense Bituminous Mixtures by the Aid of Mechanical and Optical Means, *The Baltic Journal of Road and Bridge Engineering* 7(1): 22–29. http://dx.doi.org/10.3846/bjrbe.2012.03

Teodorovic, D.; Vukadinovic, K. 1998. *Traffic Control and Transport Planning: a Fuzzy Sets and Neural Networks Approach*. Springer. 387 p. http://dx.doi.org/10.1007/978-94-011-4403-2

Toraldo, E.; Mariani, E.; Alberti, S.; Crispino, M. 2015. Experimental Investigation into the Thermal Behavior of Wearing Courses for Road Pavements Due to Environmental Conditions, *Construction and Building Materials* 98: 846–852. http://dx.doi.org/10.1016/j.conbuildmat.2015.08.047

Veselovskij, D. R.; Savickij, N. V.; Lyashenko, B. A.; Veselovskij, R. A.; Korotkov, O. S. 2006. Issledovanie prochnosti sistemy metallicheskaya podlozhka – armirovannoe polimernoe pokrytie pri izgibe i rastyazhenii, *Transportnoe stroitel'stvo* 12: 12–15 (in Russian).

Ye, H.; Li, S. 2016. The Imitation of the Road Surface Temperature Variation Characteristics Subjected to Periodical Ambient Conditions, *Applied Thermal Engineering* 92: 194–201. http://dx.doi.org/10.1016/j.applthermaleng.2015.09.086

Ye, Q.; Wu, S.; Li, N. 2009. Investigation of the Dynamic and Fatigue Properties of Fiber-modified Asphalt Mixtures, *International Journal of Fatigue* 31: 1598–1602. http://dx.doi.org/10.1016/j.ijfatigue.2009.04.008

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