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Durability of Modified Fiber Concrete for Rigid Pavements

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Abstract

Modified concretes and fiber concretes for rigid pavements have been investigated. Four-factor experiment was conducted. The amount of Portland cement, polypropylene fiber, metakaolin and polycarboxylate superplasticizer varied in the experiment. All mixtures had the same mobility S2.

The active mineral additive metakaolin increases the compressive strength of concrete and its tensile strength in bending. The amount of metakaolin at the level of 15..20 kg/m^3 is rational. Due to a decrease in W/C with an increase in the amount of superplasticizer Coral ExpertSuid-5 to 0.9..1%, the compressive strength of concrete increases by 5..7 MPa, the tensile strength in bending increases by 0.5..0.6 MPa. Due to the introduction of polypropylene fiber, the tensile strength of concrete in bending increases by 0.6..0.9 MPa, the frost resistance of concrete increases by 50 cycles. Due to the use of a rational amount of superplasticizer and metakaolin, the frost resistance of concretes and fiber concretes concrete increases by 50-100 cycles. The use of a rational amount of modifiers and fiber reduces the abrasion of concretes by 40..45%.

The developed modified fiber concretes of rigid pavements, depending on the amount of Portland cement, have compressive strength from 55 MPa to 70 MPa, tensile strength in bending from 8 MPa to 9.5 MPa, frost resistance from F350 to F450, abrasion from 0.30 to 0.40 g/cm^2. Such strength, frost resistance and abrasion

resistance allows the use of fiber concretes in pavements with the greatest load and ensures high durability of the material and corresponds to the directions and tasks of the state scientific and technical program "National Transport Strategy of Ukraine for the period up to 2030"

Keywords: pavement, concrete, strength, durability, modifiers, fiber.

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Introduction

Cement concrete pavements are the most effective for increasing the bearing capacity, performance and durability of highways. These characteristics of the material are important due to the increase in traffic intensity, the level of dynamic loads and axle loads of heavy vehicles. In modern conditions, axle loads often exceed 115 kN. Cement-concrete pavements better distribute pressure to the substrate than asphalt-concrete pavements, since their modulus of elasticity is greater than that of asphalt-concrete. Cement concrete pavement is resistant to the formation of seclusion and waves. These properties reduce vehicle fuel consumption and help to protect the environment from pollution. The quality of work of rigid pavements is less dependent on the effect of high temperatures in the hot season (Vozny, 2017).

The durability of rigid pavements is determined not only by their strength, but also by frost resistance and abrasion of concrete. It is possible to obtain an economical material simultaneously with high durability and strength of concrete for rigid pavements only with the use of effective modifiers (Chen at al., 2018). In the modern construction industry, polycarboxylate superplasticizers are most widely used as modifiers (Neville, 2000). The molecular structure of polycarboxylates makes it possible to accelerate the hydration of cement, and the rapid adsorption of molecules on cement particles and the dispersion effect provide an increase in the surface of the hydration reactions (Liu at al., 2019).

For concrete of rigid pavements, an effective method of increasing durability is the use of active mineral additives of the pozzolanic type (Gupta et al., 2008; Kroviakov et al., 2019), including metakaolin (Busari et al., 2019; Salimi et al., 2020). Metakaolin affects the process of structure formation of the cement matrix in concrete, reduces the permeability and shrinkage of concrete, and also increases its frost resistance and corrosion resistance (Gupta et al., 2008; Busari et al., 2019; Salimi et al., 2020). However, metakaolin has a high dispersion and has a positive effect on the durability and shrinkage of concrete only at a low W/C mixture, that is, when using a mineral additive together with a superplasticizer (Salimi et al., 2020).

Also, an effective method of increasing the strength, crack resistance and abrasion resistance of concrete for rigid pavements is the use of fiber (Gupta et al., 2008; Shen et al., 2012). Improvement of concrete properties when using fiber is explained by its ability to perceive tensile stresses and reduce shrinkage and swelling deformations (Choi et al., 2011).

Thus, there is an actual task of developing fiber concrete modified with polycarboxylate superplasticizer and metakaolin for rigid pavements. Such concretes are able to provide the necessary strength and durability of the pavements.

Methodology

Investigation of properties of concrete for rigid pavements were conducted for the optimal 4-factorial (Jeff Wu et al., 2009). Such composition factors varied (Mishutin et al., 2020):

- X_1, amount of Portland cement (CEM II/A-S 42.5), from 400 to 500 kg/m^3;

- X_2, the amount of polypropylene fiber (length 12 mm, diameter 20 μm), from 0 to 2 kg/m^3;

- X_3, the amount of metakaolin (firing product of enriched kaolin clays), from 0 to 30 kg/m^3;

- X_4, the amount of polycarboxylate superplasticizer Coral ExpertSuid-5, from 0.6 to 1% by weight of cement.

Crushed stone of fraction 5-10 mm and quartz sand with a modulus of 2.7 were used as aggregates for fiber concretes.

The mobility of mixtures of all studied concretes and fiber concretes was equal (S2). This mobility provides the convenience of paving a mixture for rigid pavements. Respectively, W/C of mixture depended on the concretes composition.

The compositions of the investigated concrete and fiber-reinforced concrete of road surfaces are shown in Table 1.

Table 1

Compositions of the investigated concretes and fiber concretes of pavements (kg/m^3)

№	cement	crushed stone	sand	metakaolin	fiber	Super plasticizer	water
1	450	1115	655	15	1	3,6	183
2	400	1130	668	30	0	2,4	191
3	400	1135	692	0	2	4	193
4	500	1105	635	0	0	5	168
5	500	1100	603	30	2	5	181
6	500	1105	621	0	2	3	192
7	450	1115	617	30	2	2,7	206

8	450	1115	684	0	0	2,7	161
9	450	1115	651	30	0	4,5	164
10	500	1105	574	30	1	3	203
11	400	1130	691	0	1	2,4	192
12	400	1130	672	30	1	4	182
13	500	1105	601	15	0	3	199
14	400	1130	676	15	2	2,4	199
15	400	1135	702	15	0	4	158
16	500	1105	590	30	0	4	183
17	400	1130	662	30	2	3,2	189
18	400	1135	710	0	0	3,2	163

Properties of concrete were analyzed by experimental-statistical models.

Results

The W/C mixture varied depending on the composition of the concrete. Compressive strength, tensile strength in bending, frost resistance and abrasion were determined for all concretes (Table 2).

Table 2

W/C of mixture, compressive strength, tensile strength in bending, frost resistance and abrasion of the studied concretes and fiber concretes

№	W/C	compressive strength (MPa)	tensile strength in bending (MPa)	frost resistance	abrasion (g/sm^2)
1	0,406	59,4	8,32	400	0,35
2	0,471	49,3	6,97	250	0,53
3	0,474	45,2	7,21	300	0,41
4	0,336	66,1	8,72	350	0,47
5	0,361	65,0	9,22	450	0,29
6	0,384	54,4	8,73	400	0,36
7	0,455	51,1	8,49	300	0,36
8	0,358	54,8	7,91	300	0,50
9	0,364	65,4	8,22	350	0,45
10	0,406	55,5	8,47	400	0,39
11	0,478	41,8	7,35	250	0,45
12	0,455	49,1	7,46	300	0,41
13	0,398	56,6	8,07	350	0,46
14	0,484	46,3	7,78	300	0,44
15	0,396	60,9	7,61	300	0,49
16	0,366	65,2	8,24	400	0,43

17	0,469	51,1	7,62	300	0,42
18	0,408	49,4	7,07	250	0,48

Discussion

It was found that with an increase in the amount of Portland cement W/C is projected to decrease. The use of polypropylene fiber necessitates an increase in W/C to maintain the mobility of the mixture. When using metakaolin due to its additional water consumption, W/C mixture also increases. Increasing the amount of superplasticizer in the concrete composition from 0.6% to 0.9-1% significantly reduces the W/C of the mixture.

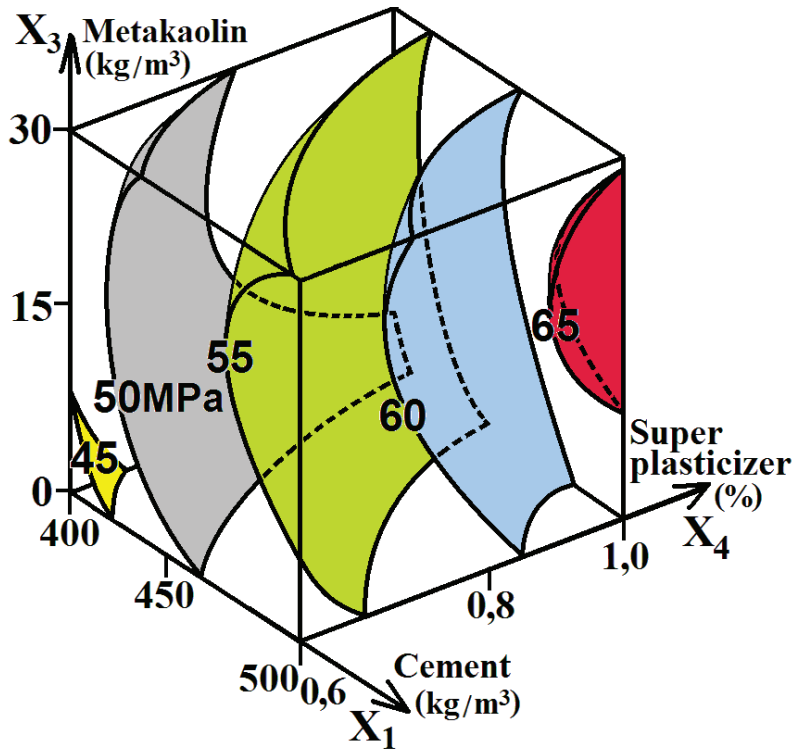
Also it was found that the amount of polypropylene fiber has a negligible effect on the compressive strength of the studied concretes and fiber concretes. Accordingly, Fig. 1 shows a diagram constructed on base of experimental-statistical model, which reflects the effect of the amount of Portland cement, metakaolin and superplasticizer on the compressive strength of fiber concretes.

The analysis of the diagram in Fig. 1 shows that when increasing amount of cement in the composition, the strength of concrete and fiber concrete is expected to increase. Metakaolin as an active mineral additive increases the strength of concrete. Rational for the strength of concrete is the amount of metakaolin from 15 to 20 kg/m^3. When increasing the amount of superplasticizer to 0.9..1%, the strength of concrete and fiber concrete increases by 5..7 MPa. The positive effect of the additive is more noticeable for concretes with metakaolin. Concretes and fiber concretes with a rational amount of modifiers depending on the amount of Portland cement in the composition have a compressive strength from 55 MPa to 70MPa, which corresponds to classes C35/40-C40/50.

For rigid pavements, important quality indicators are not only their compressive strength, but also tensile strength in bending. This is due to the multidirectional loads that the pavement receives during operation.

Figure 1

The effect of the amount of Portland cement, metakaolin and superplasticizer on the compressive strength of fiber concretes



Source: Author's illustration

The analysis shows that the tensile strength in bending of concrete and fiber concrete is significantly affected by the amount of Portland cement and the amount of polypropylene fiber. Due to the use of fiber tensile strength increases by 0.6..0.9 MPa. Thus, disperse reinforcement is an effective method of increasing the stability of cement concrete pavements under tensile loads. The tensile strength in bending of fiber concretes increases by 0.6..0.7 MPa due to the use of a rational amount of modifiers. Overall, modified fiber concrete, depending on the amount of cement in their composition has tensile strength in bending from 8 to 9.5 MPa. Such strength provides high bearing capacity of concretes in rigid pavements of highways.

Frost resistance is an important condition for ensuring the durability of riding pavements. Concretes of pavements in the course of operation are exposed to repeated influences of freezing and thawing . The number of cycles of freezing and thawing of coatings can be much greater than the number of air temperature transitions through 0° C. Experimental-statistical model, which describes the effect of variable compositional factors (x_1-x_4) on frost resistance of the studied concretes and fiber concretes, has the form:

$$\begin{aligned} F\,(\text{cycles}) = 393 &+ 60x_1 \pm 0x_1^2 + 8x_1x_2 \pm 0x_1x_3 \pm 0x_1x_4 \\ &+ 23x_2 - 14x_2^2 - 10x_2x_3 \pm 0x_2x_4 \\ &+ 7x_3 - 29x_3^2 + 7x_3x_4 \\ &+ 19x_4 - 23x_4^2 \qquad (1) \end{aligned}$$

According to the model (2) diagrams such as "squares on squares" were built and shown in Fig.2. When building the diagram, the square in the x_3-x_4 coordinates (the

amount of metakaolin and the superplasticizer Coral ExpertSuid-5) was chosen as the bearing square. In the field of the bearing square 9 constructed squares reflect the effect of the amount of Portland cement and polypropylene fiber on the frost resistance of concrete and fiber concrete with the appropriate amount of modifiers.

The analysis of the diagram shows that the frost resistance of the studied concretes and fiber concretes is significantly affected by the amount of Portland cement and the amount of polypropylene fiber. Concretes with a Portland cement amount of 500 kg/m^3 have a frost resistance approximately 100 cycles higher than concretes with a binder amount of 400 kg/m^3. Frost resistance of concretes of rigid pavements increases by 50 cycles and more with use of fiber in the amount of 1,5-2 kg/m^3. Due to the use of a rational amount of modifiers (0.8-1% of superplasticizer and 15-20 kg/m^3 of metakaolin) frost resistance of concretes and fiber concretes increases by 50-100 cycles depending on the level of other compositional factors. In general, the developed modified fiber concretes of hard pavements depending on the amount of Portland cement in the composition have frost resistance from F350 to F450, which ensures their sufficient durability.

As noted above, the abrasion (abrasion resistance) of concrete is an important characteristic that largely determines the durability of road rigid pavements. Experimental-statistical model, which describes the effect of variable compositional factors on abrasion of concretes and fiber concretes, has the form:

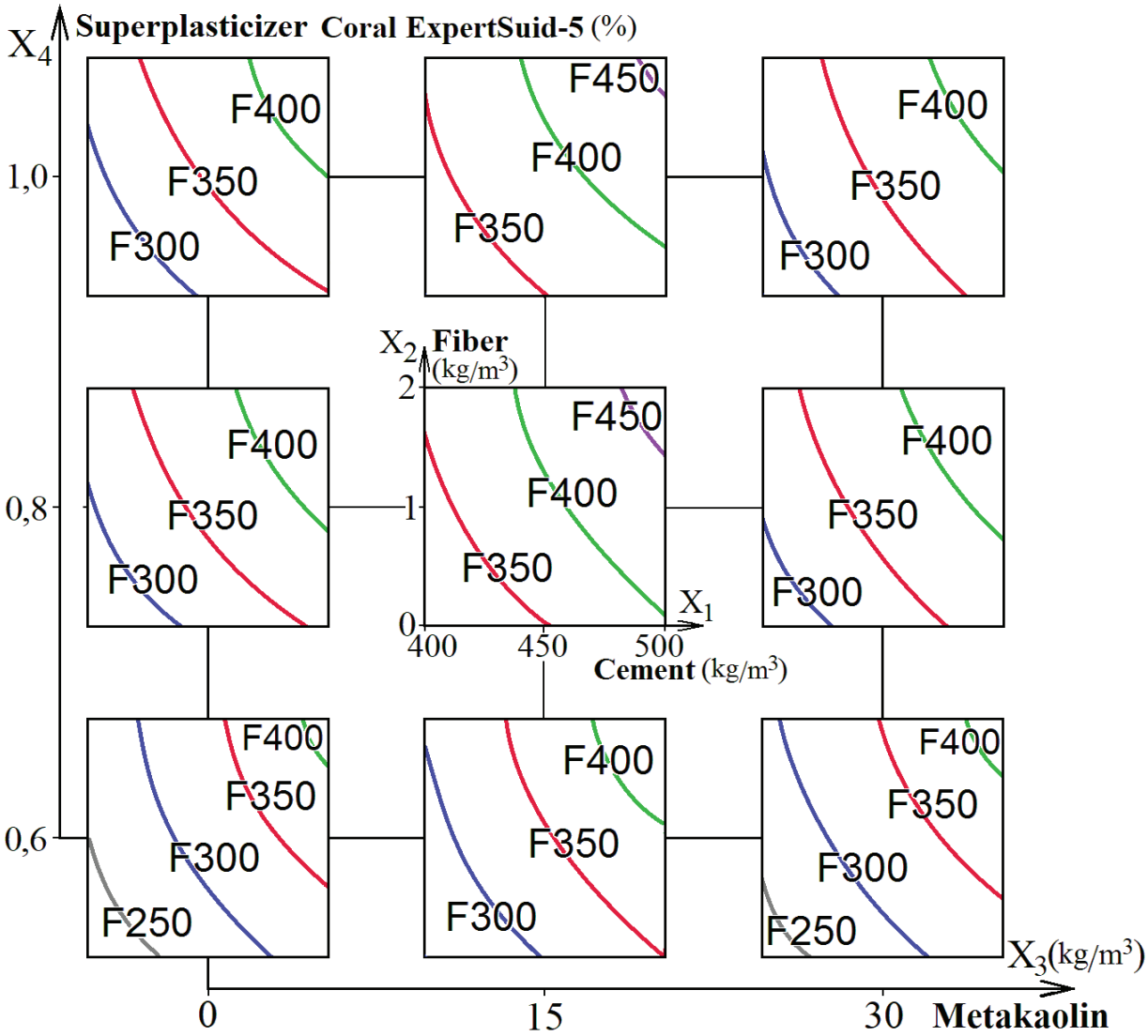
$$\begin{aligned} G\ (g/sm^2) = 0{,}350 &- 0{,}036x_1 \pm 0{,}020x_1^2 - 0{,}016x_1x_2 - 0{,}008x_1x_3 \pm 0x_1x_4 \\ &- 0{,}056x_2 + 0{,}030x_2^2 \pm 0x_2x_3 \pm 0x_2x_4 \\ &- 0{,}006x_3 + 0{,}012x_3^2 \pm 0x_3x_4 \\ &- 0{,}018x_4 + 0{,}022x_4^2 \quad (2) \end{aligned}$$

The analysis of the model has shown that the amount of fiber and Portland cement most significantly affects the abrasion of the investigated concretes of rigid pavements, and the amount of metakaolin does not significantly affect. Accordingly, Fig. 3 shows a diagram constructed on base of experimental-statistical model (2), which reflects the effect of the amount of Portland cement, fiber and superplasticizer on the abrasion of concretes and fiber concretes.

Analysis of the diagram (Figure 3) shows that dispersed fiber reinforcement significantly reduces the abrasion of concrete of rigid pavements, that is, increases their abrasion resistance. Due to the using of polypropylene fiber in the amount of 1.5..2 kg/m^3, the abrasion of concrete is reduced by 0.11..0.16 g/cm^2 (22..35%). With an increase in the amount of cement from 400 to 500 kg/m^3, the abrasion of concrete and fiber-reinforced concrete decreases by 0.07-0.10 g/cm^2. This is due to an increase in the strength of concrete with an increase in the amount of Portland cement. By increasing the amount of superplasticizer, the W/C of the mixture decreases, respectively, the strength of concrete increases and abrasion decreases. The combined use of fiber and a rational amount of superplasticizer reduces the abrasion of concrete by 40-45%.

Figure 2

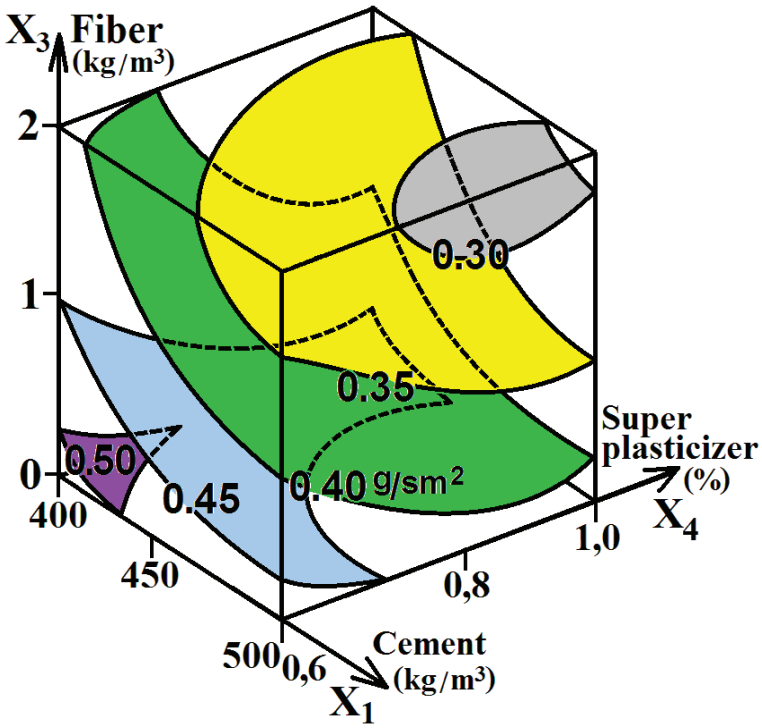
The effect of the amount of Portland cement, fiber, metakaolin and superplasticizer on the frost resistance of concretes and fiber concretes



Source: Author's illustration

Figure 3

The effect of the amount of Portland cement, fiber and superplasticizer on the abrasion of concretes and fiber concretes



Source: Author's illustration

Conclusion

Cement-concrete coatings are the most effective for increasing the bearing capacity, characteristics and durability of highways. These characteristics of the material are important in connection with the increase in traffic intensity, the level of dynamic loads and axle loads of heavy vehicles. In modern conditions, axial loads often exceed 115 kN. Cement-concrete pavements better distribute pressure to the base than asphalt concrete pavements, since their modulus of elasticity are higher than that of asphalt concrete. The durability of rigid coatings are determined not only by their strength, but also by the frost resistance and abrasion of concrete. It is possible to obtain an economical material simultaneously with high strength of concrete for rigid pavements only with the use of effective modifiers. Modified concretes and fiber-reinforced concretes for rigid pavements have been investigated. A four-factor experiment was carried out. The amount of Portland cement, polypropylene fiber, metakaolin and polycarboxylate superplasticizer was varied in the experiment. All mixtures had the same S2 mobility. The mobility of the mixtures of all investigated concretes and fiber-reinforced concretes was the same (S2). This mobility makes it easy to laying mix for rigid pavements. Accordingly, the W/C of mixture depended on the composition of the concrete. For rigid pavements, important quality indicators are

not only their compressive strength, but also their flexural tensile strength. This is due to the multidirectional loads that the road pavements experiences during operation. Frost resistance is an important condition for ensuring the durability of road pavements. Pavement concrete during operation is exposed to repeated effects of freezing and thawing. The number of freeze and thaw cycles for coatings can be much greater than the number of times the air temperature goes through 0 °C. The frost resistance of the concretes and fiber-reinforced concrete under study are significantly influenced by the amount of Portland cement and the amount of polypropylene fiber. Abrasion (abrasion resistance) of concrete is an important characteristic that largely determines the durability of rigid road pavements. Thus, a rational amount of modifiers for concretes of rigid pavements was identified: polycarboxylate superplasticizer 0.9-1% and metakaolin 15-20 kg/m^3. Due to the dispersed reinforcement with polypropylene fiber, the use of a rational amount of metakaolin and polycarboxylate superplasticizer Coral ExpertSuid-5 were obtained: fiber concrete rigid pavements with compressive strength up to 70MPa, tensile strength in bending up to 9.5 MPa, frost resistance up to F450 and abrasion less than 0.35 g/sm^2. High strength, frost resistance and abrasion resistance of modified fiber concretes allow their use in pavements with the highest load and ensure the durability of the material. Further research will analyze and develop modified fiber-reinforced concrete, as well as carry out industrial tests in Ukraine and Moldova.

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