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DETERMINING THE EFFECT OF THE AMOUNT OF POLYPROPYLENE FIBER AND PLASTICIZER ON THE STRENGTH AND ABRASION RESISTANCE OF CONCRETES FOR RIGID PAVEMENT

Sergii Kroviakov
Corresponding author
Doctor of Technical Sciences, Professor,
Vice-Rector for Research*
E-mail: skrovyakov@ukr.net
Oleh Finohenov
PhD Student*
Andrii Ihnatenko
PhD, Associate Professor*
*Department of Highways and Airfields
Odesa State Academy of
Civil Engineering and Architecture
Didrihsona str., 4, Odesa, Ukraine, 65029

The object of this study is concretes and fiber-reinforced concretes for rigid pavements with polypropylene fiber and lignosulphonate type plasticizer. The task addressed is obtaining concrete with increased strength and wear resistance. Three compositions factors were varied in the experiment conducted according to the D-optimal plan: the amount of cement (300–380 kg/m^3), plasticizer based on lignosulfonates (0.6–1.0 %), polypropylene fiber with a fiber length 39 mm (0–3 kg/m^3). All concrete mixtures had equal mobility S1.

A set of experimental and statistical models was calculated. It was found that with an increase in the amount of plasticizer, the W/C ratio of the mixture decreases by 12–15 %, and the introduction of fiber has a negligible effect on W/C. Due to the use of fiber, the compressive strength of concrete at the design age increases by approximately 3.5 MPa, the early compressive strength practically does not change, the flexural strength increases by 0.5–0.6 MPa, and the abrasion resistance decreases by 0.07–0.08 g/cm^2 (17–19 %). The most noticeable changes in these properties occur already with the introduction of fibers in the amount of 2–2.5 kg/m^3. Increasing the amount of cement improves the strength and wear resistance of concrete, as well as the efficiency of using dispersed reinforcement.

When the amount of plasticizer is increased from 0.6 to 0.9 %, the compressive strength of concrete at the age of 3 days increases by approximately 2 MPa; at the design age, its strength increases by approximately 5 MPa, the flexural strength increases to a limited extent while the abrasion of concrete decreases (wear resistance increases).

Due to dispersed reinforcement and the use of a rational amount of plasticizer, concretes of rigid pavements with the required strength and increased wear resistance required for a given road category with reduced binder consumption were obtained, which could be used in practice

Keywords: polypropylene fiber, plasticizer, rigid pavement, concrete strength, concrete abrasion resistance, experimental and statistical modeling

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1. Introduction

The vast majority of highways in European countries are equipped with non-rigid asphalt concrete pavements. This practice has evolved historically and was mainly due to the availability in the past century of cheap and relatively high-quality raw materials for the production of asphalt concrete. However, in recent decades the cost of bitumen has been steadily increasing, while the load on highways is gradually increasing. Under such conditions, the competitiveness of rigid cement concrete pavements is significantly increasing. Therefore, this type of pavement is increasingly used in the construction and reconstruction of roads in many developed countries of the world, including Ukraine [1].

Rigid road pavements distribute the load from vehicles on the road base and soil better than asphalt concrete pavements, are not prone to the formation of ruts and waves and have a lighter color. The properties of rigid cement concrete pavements practically do not depend on air temperature. With fairly close installation costs, rigid pavements are much more durable compared to asphalt concrete. One of the confirmations of this is that according to the national Ukrainian standards [2], for example, for category II roads, the standard service life between major repairs of asphalt concrete road surfaces is 12–14 years. At the same time, the standard service life of cement concrete road surfaces according to these standards is 21 years.

The actual service life of road surfaces between major repairs is determined by many factors, one of the main of which is the properties of cement concrete. When producing concrete for the construction of rigid road surfaces, it is important to ensure their necessary strength, primarily tensile strength during bending, as well as durability. Under real operating conditions, the durability of road concrete is determined primarily by its wear resistance and frost resistance. One of the known methods of increasing the strength and durability of road concrete is dispersed reinforcement. The most common, relatively cheap, and corrosion-resistant variant of dispersed reinforcement is polypropylene fiber. To ensure the effectiveness of dispersed reinforcement, it is important to study its effect on the properties of concrete, in particular, taking into account changes in the properties of concrete mixtures and the concrete matrix as a composite material. Such studies should be carried out using cements, aggregates, and chemical additives available in local markets, similar to those used in real road construction practice. Therefore, the study of the effect of polypropylene fiber and plasticizer on the properties of concrete for rigid pavements and the determination of the rational amount of dispersed reinforcement remains an urgent scientific task. This task should be solved for each specific type of concrete mixture, taking into account the existing design requirements for the strength of concrete, its wear resistance, the type of cement used, etc. Due to this orientation, the devised technical solutions could be used in real road construction practice.

2. Literature review and problem statement

During operation, road surfaces are exposed to the influence of moving vehicles. Because of this, the direction of application of operational loads on the surface structures is constantly changing; in addition, the surface is subjected to a greater or lesser degree of dynamic influence. Under such conditions, the main physical and mechanical indicator that ensures the perception of loads by a rigid surface is the tensile strength of concrete at bending. For example, the Ukrainian national standard [2] regulates the minimum design class for tensile strength in bending, depending on the category of the road.

Traffic causes dynamic influences, accordingly, an important indicator of the quality of road concrete is wear resistance. For example, in [3] it is shown that abrasion of concrete by tires can cause the formation of ruts in the road surface. However, the work does not provide recommendations on methods for increasing the wear resistance of concrete surfaces.

A large number of studies confirm that dispersed reinforcement is an effective method for increasing the strength and durability of concrete for rigid road surfaces and other structures. The main mechanism of operation of dispersed reinforcement is that it is able to hold individual blocks of the internal structure of concrete as a coarsely heterogeneous material. This helps improve the performance of the material, namely in tension and under dynamic influences, in particular abrasion, transforming the quasi-brittleness of concrete into a more plastic behavior. In road construction, various types of fibers are used as dispersed reinforcement, but most often polypropylene, steel, basalt, and glass.

A significant increase in the tensile strength at bending and wear resistance of concrete pavements when using steel fiber is shown in particular in [4, 5]. In this case, in [4] it is recommended to introduce steel fiber simultaneously with macro-synthetic fiber. In [5], the use of 0.05 % carbon nanotubes and 1 % steel fibers made it possible to significantly improve the bearing capacity and crack resistance of the pavement, reducing its deflections under load. That is, in both of those works the effectiveness of disperse reinforcement with two types of fiber simultaneously is shown, which complicates the technology of concrete preparation. In [6], the use of steel anchor fiber in the amount of 80–90 kg/m^3 made it possible to almost double the tensile strength of concrete pavement at bending. In [7], the introduction of steel disperse reinforcement made it possible to increase the bearing capacity of structures by 10–70 %; in [8], it significantly increased the impact resistance. However, in works [6, 7] the issue of the possible impact of individual fiber fibers on tires of rolling stock and the case of abrasion of the protective layer of concrete was not considered. In work [8], the impact of the amount of fiber on the properties of concrete was not determined. The main undetermined issue in [6–8] is the lack of assessment of the economic feasibility of using steel fiber. The introduction of the amount of fiber recommended by researchers into the composition of concrete (from 70 to 100 kg/m^3) increases its cost by approximately two times. Under conditions of significant volumes of concrete operations in road construction, this is the main limiting factor for the use of this type of dispersed reinforcement.

Therefore, in practice, cheaper fiber options are increasingly used to improve the properties of rigid pavement concrete, primarily polypropylene, and less often basalt and glass. For example, in [9], a significant increase in the strength and impact resistance of rigid pavement concrete was achieved by using 1 % polypropylene fiber in combination with 1 % glass fiber. In [10], the maximum compressive and tensile strength in bending was achieved with the introduction of 0.4 % polypropylene fiber with a length of 12 and 20 mm. In study [11], the highest tensile strength was provided by reinforcement with 1 % fibers with a length of 9 mm. In [12], the most significant increase in the tensile strength of concrete was obtained when using polypropylene fiber with a length of 48 mm in an amount of 4 and 6 kg/m^3. In [13], reinforcement with polypropylene fiber in an amount of 0.5 % increased the modulus of elasticity of road pavement concrete and its compressive, tensile, and tensile strength. In [14], fiber in combination with a superplasticizer allowed for the production of fast-hardening concrete. As shown in [15], dispersed reinforcement with polypropylene fiber allows for reduced shrinkage and water absorption of concrete. In [16], dispersed reinforcement also allowed for reduced shrinkage of concrete in road structures, which reduced the risk of destruction of the corners of pavement slabs.

However, in [9, 11, 13–15], the feasibility of using polypropylene fibers of relatively short length (up to 12 mm) and small diameter was confirmed. In [10, 12], it is recommended to use fibers of longer length (20–48 mm) and larger diameter. In [16], a combination of two types of fibers is recommended, which is technologically more complex. There are also significant differences in information regarding the rational amount of fibers from the point of view of achieving greater strength and durability of road concrete.

Our review of the literature demonstrates that the issues that remain unresolved in the problem of obtaining effective concretes for hard coatings are largely related to the fact that the determination of the influence of fiber in the cited studies [9–16] was carried out without using the methodologies of experimental design and experimental-statistical modeling. This did not make it possible to determine the dependence of influence of the amount of dispersed reinforcement simultaneously with the influence of other compositional factors. The work of dispersed reinforcement in concrete is primarily due to its adhesion to the cement-sand matrix [17]. Therefore, it is important to study the effectiveness of fiber use while simultaneously varying the amount of cement and plasticizer, i.e., when varying the conditions of the joint operation of dispersed reinforcement and cement-sand matrix.

3. The aim and objectives of the study

The aim of our work is to determine the comprehensive effect of the amount of polypropylene fiber and lignosulfonate plasticizer on the mechanical properties of concrete for rigid pavements. This will make it possible to improve the durability and operational characteristics of road surfaces.

To achieve the goal, the following tasks were set:

– according to the optimal 3-factor plan, to conduct a study on the effect of the amount of lignosulfonate-type plasticizer, fiber, and cement on the W/C of the concrete mixture;

– to investigate the effect of varied composition factors on the compressive strength of concrete at early and design ages and on tensile strength during bending;

– to investigate the effect of varied factors on the wear resistance (abrasiveness) of concrete.

4. The study materials and methods

The object of our study is concretes and fiber concretes of rigid road surfaces with polypropylene fiber modified with a lignosulfonate plasticizer.

Based on the data from the reviewed literature, a working hypothesis of the research was defined to verify the possibility of solving the problem of obtaining concretes with increased strength and wear resistance by using a rational amount of dispersed reinforcement and plasticizer. To ensure the reliability of the resulting dependences and decisions made, it is necessary to use experimental and statistical modeling methods.

The following materials were used to prepare the studied concretes and fiber concretes:

– Dyckerhoff Portland cement PC II/A-S 500 R-N (CEM II/A-S 42.5 R), produced by Olshansky cement plant (Olshansky cement plant, Ukraine);

– granite crushed stone of fraction 5–20 mm. The origin of the crushed stone is Ukraine. Bulk density of crushed stone is 1345 kg/m^3;

– quartz sand with a particle size modulus of 2.4. Origin of sand – Voznesensky district, Mykolaiv oblast, Ukraine;

– plasticizer Sika® Plastiment®-1230 (based on lignosulfonates), produced by Sika, Switzerland;

– polypropylene fiber X Mesh. Fiber length is 39 mm, equivalent diameter is 0.45 mm (Fig. 1). Produced by TOV DIIF, Dnipro, Ukraine.

The choice of plasticizer was determined by the results of previous studies [18], which showed that for low-mobility concrete mixtures S1, the effectiveness of plasticizers based on lignosulfonates is approximately equal to the effectiveness of more expensive plasticizers of the polycarboxylate type. Fiber with a fiber length of 39 mm was selected taking into account the positive experience of using similar fibers to improve the physical and mechanical characteristics of concrete for rigid pavements [19].

Fig. 1. X Mesh polypropylene fiber with a fiber length of 39 mm and an equivalent diameter of 0.45 mm

The experiment was carried out according to the optimal 15-point 3-factor D-optimal plan [20, 21]. The following concrete composition factors were varied in the experiment:

X_1 – amount of cement, from 300 to 380 kg/m^3;

X_2 – amount of fiber, from 0 to 3.0 kg/m^3;

X_3 – amount of plasticizer, from 0.6 to 1.0 % of the mass of cement.

The mobility of all concrete mixtures was equal to S1 at OK from 2 to 3 cm. This meets the requirements of the national standard [2], according to which the mobility of mixtures for the arrangement of rigid road surfaces should be from 1 to 5 cm. The compositions of the concretes were adjusted taking into account the need to ensure their equal mobility. The remaining technological factors that could affect the structure and properties of the concrete remained unchanged during the implementation of the entire experiment.

The experimental plan and the compositions of the 15 studied concretes and fiber concretes are given in Table 1. The transition from natural to coded values of the levels of the varied factors was performed according to a stand procedure [21].

Table 1

Plan of the 3-factor experiment and compositions of the tested concretes and fiber-reinforced concretes

Point No.	Levels of factors			Concrete composition (kg/m^3)					
	X_1, Portland cement	X_2, Fiber X Mesh	X_3, additive Sika® Plastiment®-1230	Portland cement	Gravel	Sand	Fiber X Mesh	Additive Sika® Plastiment®-1230	Water
1	–1	–1	–1	300	1230	825	0	1.80	132
2	–1	–1	1	300	1230	840	0	3.00	118
3	–1	0	0	300	1230	833	1.5	2.40	123
4	–1	1	–1	300	1230	815	3.0	1.80	138
5	–1	1	1	300	1230	829	3.0	3.00	126
6	0	–1	0	340	1210	792	0	2.72	138
7	0	0	–1	340	1210	784	1.5	2.04	142
8	0	0	0	340	1210	788	1.5	2.72	136
9	0	0	1	340	1210	793	1.5	3.40	132
10	0	1	0	340	1210	788	3.0	2.72	136
11	1	–1	–1	380	1190	751	0	2.28	149
12	1	–1	1	380	1190	760	0	3.80	142
13	1	0	0	380	1190	752	1.5	3.04	146
14	1	1	–1	380	1190	746	3.0	2.28	153
15	1	1	1	380	1190	753	3.0	3.80	147

The properties of the concrete mix, concretes, and fiber concretes were determined according to standardized methodology. The mobility of the mixtures was determined according to [22]. The compressive strength of concretes and fiber concretes (at the age of 3 and 28 days) was determined according to [23], the tensile strength at bending (at the age of 28 days) was determined according to [24]. The abrasion resistance was determined according to [25].

The use of experimental design methods and experimental statistical modeling makes it possible to assess the influence of the entire set of variable factors and determine the rational amount of dispersed reinforcement and plasticizer for concretes with different strength requirements.

5. Results of investigating the properties of concrete mixtures and concretes

5. 1. The influence of concrete composition on the water-cement ratio of mixtures

The values of W/C of concrete mixtures, compressive strength at the age of 3 and 28 days, tensile strength at the age of 28 days, and wear resistance of concretes and fiber-reinforced concretes at 15 points of the plan of the implemented 3-factor experiment determined in experimental studies are given in Table 2.

Table 2

W/C of the tested concrete mixtures. Bond strength, flexural tensile strength, and wear resistance of the tested concretes and fiber-reinforced concretes

No.	W/C	Compressive strength 3 days ($f_{cm.3}$), MPa	Compressive strength 28 days (f_{cm}), MPa	Flexural strength 28 days ($f_{c.tf}$), MPa	Abrasion (G), g/cm^2
1	0.440	28.6	47.5	4.61	0.441
2	0.393	31.2	51.8	4.92	0.437
3	0.410	30.3	51.9	5.05	0.394
4	0.460	30.0	52.1	5.02	0.386
5	0.420	30.8	53.5	5.22	0.359
6	0.406	33.3	58.3	5.40	0.423
7	0.418	32.6	57.9	5.57	0.367
8	0.400	35.6	60.2	5.93	0.359
9	0.388	34.6	61.2	6.01	0.348
10	0.400	34.9	59.1	6.12	0.336
11	0.392	36.1	56.7	5.82	0.415
12	0.374	36.8	63.1	6.00	0.404
13	0.384	36.8	65.9	6.32	0.343
14	0.403	36.3	61.1	6.23	0.339
15	0.387	37.4	66.7	6.57	0.332

As noted above, all mixtures had equal mobility, respectively, their W/C depended on the composition of the concrete. According to the data given in Table 2, an experimental-statistical (ES) model was calculated with all significant coefficients [20, 21], which describes the influence of varied factors on the W/C of the concrete mixture (the excluded insignificant coefficients in the model were recorded as ±0):

$$\begin{aligned} W/C = {} & 0.398 - 0.018x_1 \pm 0x_1^2 - 0.003x_1x_2 + \\ & +0.007x_1x_3 + 0.006x_2 + 0.005x_2^2 \pm 0x_2x_3 - \\ & -0.015x_3 + 0.005x_3^2. \end{aligned} \quad (1)$$

For the convenience of analysis, a cube-shaped diagram was constructed for this EC model [21], shown in Fig. 2.

As shown in the diagram in Fig. 2, with an increase in the amount of cement in the concrete composition, the W/C ratio of the equal mobility mixture is expected to decrease. The introduction of polypropylene fiber in an amount of up to 1.5 kg/m^3 has almost no effect on the water consumption and, accordingly, the W/C ratio of the concrete mixture. When the amount of fiber is increased to 3 kg/m^3, the W/C ratio of the equal mobility mixture increases by only 4–6 %. This effect is explained by the rather easy distribution of fibers with a length of 39 mm in the concrete mixture. Increasing the amount of plasticizer Sika® Plastiment®-1230 from 0.6 to 0.8 % of the cement mass significantly (by 7–9 %) reduces the W/C ratio. With a further increase in the amount of plasticizer (up to 1 %) the W/C ratio of the equal mobility mixture is further reduced, but to a lesser extent. In total, due to an increase in the amount of plasticizer from 0.6 to 1 %, the W/C ratio of the mixture is reduced by 12–15 %.

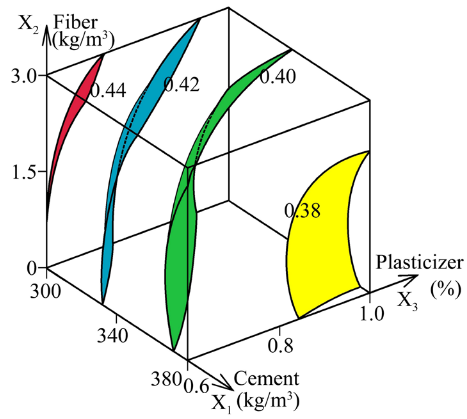

Fig. 2. The effect of varying composition factors on the W/C of equal mobility concrete mixtures

5. 2. The influence of variable composition factors of concretes on their strength

EC models, which are built according to the data given in Table 2 and reflect the influence of variable composition factors on the compressive strength of concretes and fiber-reinforced concretes at the age of 3 and 28 days, respectively, take the form:

$$\begin{aligned} f_{cm.3}(\text{[illegible]}) \text{[illegible]} & + \quad x_1 \quad x_1^2 \pm \\ & \pm 0x_1x_2 \pm 0x_1x_3 + 0.35x_2 \pm 0x_2^2 \pm \\ & \pm 0x_2x_3 + 0.72x_3 - 0.48x_3^2, \end{aligned} \quad (2)$$

$$\begin{aligned} f_{cm}(\mathrm{MPa}) = {} & 60.24 + 5.67x_1 - 1.38x_1^2 \pm 0x_1x_2 + \\ & +0.77x_1x_3 + 1.50x_2 - 1.57x_2^2 - 0.46x_2x_3 + \\ & +2.10x_3 - 0.74x_3^2. \end{aligned} \quad (3)$$

According to the EC models (2) and (3), the diagrams shown in Fig. 3, *a*, *b*, respectively, were constructed.

Early strength is an important indicator for rigid pavement concretes from the point of view of the possibility of performing subsequent technological operations and the required duration of concrete care procedures. As revealed by analysis of the diagrams and data in Table 2, the strength of the tested concretes at the age of 3 days was approximately 58 % of their design strength at the age of 28 days. With an increase in the amount of cement, the compressive strength of rigid pavement concretes naturally increases. At the same time, both at the age of 3 days and at the age of 28 days, this increase is nonlinear and an increase in the amount of binder from 300 to 340 kg/m^3 causes a more significant change in strength than an increase in the amount of binder from 340 to 380 kg/m^3.

The introduction of fiber has practically no effect on the value of the compressive strength of concrete at an early age – due to dispersed reinforcement, the $f_{cm.3}$ value increases by no more than 0.7 MPa. At the design age, due to the introduction of polypropylene fiber in an amount of 2–2.5 kg/m^3, the compressive strength of concrete increases by approximately 3.5 MPa. This increase also cannot be considered significant, but the main purpose of using dispersed reinforcement, as mentioned above, is to increase the tensile strength of concrete at bending and wear resistance.

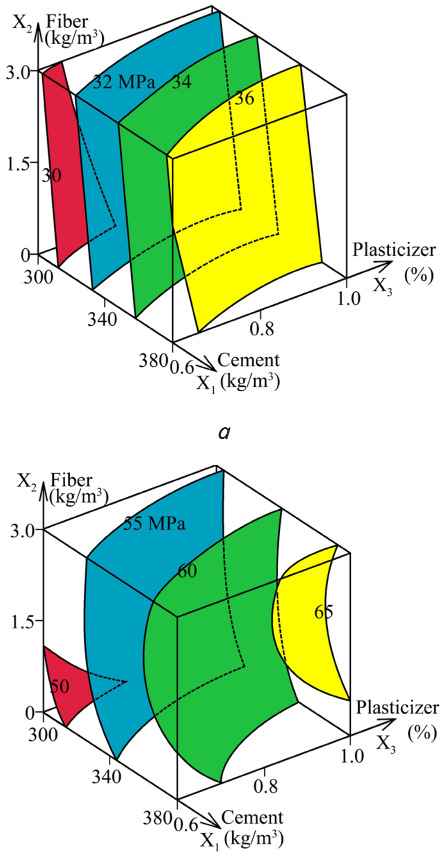

Fig. 3. The influence of varied composition factors on the compressive strength of concretes and fiber-reinforced concretes: *a* — at the age of 3 days; *b* — at the age of 28 days

By reducing the W/C of equal mobility mixtures when increasing the amount of plasticizer Sika® Plastiment®-1230 from 0.6 to 0.9 % of the cement mass, the early compressive strength of concrete and fiber concrete increases by approximately 2 MPa. The design strength of concrete with such a change in the amount of plasticizer increases by approximately 5 MPa. An increase in the amount of Sika® Plastiment®-1230 above 0.9 % no longer affects the strength of concrete.

According to Table 2, a similar (1) to (3) EC model was also constructed, which describes the influence of varied factors on the tensile strength of the studied concretes and fiber concretes during bending. The diagram shown in Fig. 4 was constructed according to this EC model.

Analysis of the diagram in Fig. 4 reveals that by increasing the amount of cement, the tensile strength of concrete and fiber-reinforced concrete increases as expected. In total, when changing the dosage of the binder from 300 to 380 kg/m^3, the $f_{c.tf}$ value increases from 4.5–5.5 MPa to 5.8–6.6 MPa.

By increasing the amount of plasticizer to 0.9–1.0 % of the cement mass, the $f_{c.tf}$ value increases by approximately 0.3 MPa, i.e., insignificantly. The rather low efficiency of the plasticizer in controlling the tensile strength compared to the influence of this modifier on the compressive strength of concrete is known in materials science and is described in particular in [11, 26].

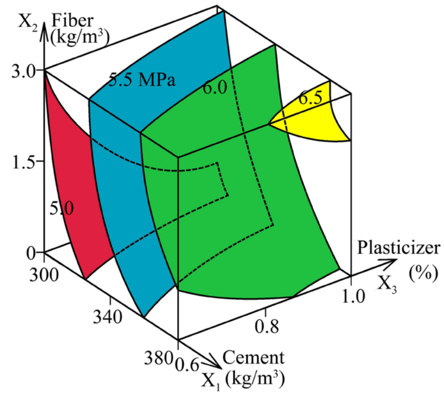

Fig. 4. The influence of varied composition factors on the tensile strength of concretes and fiber-reinforced concretes at bending

The use of dispersed reinforcement with polypropylene fiber increases the tensile strength of concrete by an average of 0.5–0.6 MPa. At the same time, the main increase in strength occurs when introducing fiber in an amount of about 2 kg/m^3. For compositions with a larger amount of cement, dispersed reinforcement has a slightly higher efficiency than for compositions with a smaller amount of fiber. This effect can also be explained by the better work of dispersed fibers in a stronger sand-cement matrix.

In general, the achieved level of tensile strength at bending allows the use of the studied concretes for road pavements from categories II and III (the minimum class of concrete for bending tensile strength according to DBN V.2.3-4:2015 should be B_{btb}4,0) to Ia (the minimum class of concrete for bending tensile strength according to standard [2] should be B_{btb}4,8).

5. 3. Influence of variable composition factors on the wear resistance of concrete

The EC model, built according to the data given in Table 2, reflecting the influence of variable composition factors on the wear resistance of concrete and fiber concrete, takes the form:

$$g\left(\mathrm{gr/cm^2}\right)=0.358-0.018x_1+0.010x_1^2\pm$$
$$\pm 0x_1x_2\pm 0x_1x_3-0.037x_2+0.021x_2^2-$$
$$-0.002x_2x_3-0.007x_3\pm 0x_3^2. \qquad (4)$$

A cube-shaped diagram was also constructed using this EC model, which is shown in Fig. 5.

Analysis of the EC model (4) and the diagram in Fig. 5 reveals that by increasing the amount of cement from 300 to 380 kg/m^3, the abrasion of the studied concretes decreases by 11–14 %, i. e., their wear resistance increases. With an increase in the amount of plasticizer in the composition, the abrasion of concretes and fiber concretes decreases insignificantly. This influence of these varied factors on the level of wear resistance of the material is generally similar to their influence on the tensile strength of concretes during bending, which is described above. Most significantly, by 0.07–0.08 g cm^2 (by 17–19 %), the abrasion of the studied concretes decreases due to the introduction of polypropylene fiber. At the same time, most of this influence (14–16 %) is manifested already when using dispersed reinforcement in an amount of 2–2.5 kg/m^3. As is known, the positive effect of dispersed reinforcement is explained by the ability of fiber fibers to hold individual structural blocks of concrete as a coarsely heterogeneous material [17], which contributes to better resistance to dynamic influences [3, 6, 26, 27].

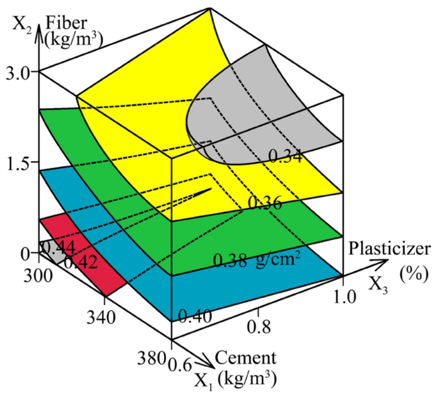

Fig. 5. The influence of varied composition factors on the abrasion resistance of concretes and fiber-reinforced concretes

6. Discussion of the influence of polypropylene fiber and lignosulfonate-type plasticizer on concrete properties

As a result of the comprehensive analysis of the influence of the amount of polypropylene fiber and plasticizer Sika® Plastiment®-1230 on the properties of concrete for rigid pavements, the following can be said. From the point of view of ensuring the highest tensile strength at bending and wear resistance (lowest abrasion), it is possible to recommend the introduction of the maximum amount of polypropylene fiber X Mesh with a fiber length of 39 mm – 3 kg/m^3 into the concrete composition. In particular, this is indicated by the coordinates of the zone of minimum values in the EC model (4). However, the most noticeable changes in the mechanical properties important for concrete road surfaces occur already with the introduction of dispersed reinforcement in the amount of 2–2.5 kg/m^3 (Fig. 4, 5). Also, with the amount of polypropylene fiber of about 2–2.5 kg/m^3, the highest compressive strength of concrete is achieved at the design age (Fig. 3, *b*). The amount of fiber in the concrete composition has practically no effect on the early compressive strength of concrete (Fig. 3, *a*).

A more significant positive effect of the introduction of fiber at the design age can be explained by the better work of fibers in a stronger sand-cement matrix due to better adhesion to the matrix. That is, with increasing age, the fibers were better held by the matrix than at an early age [6, 17, 26]. The achieved level of positive influence of fiber on the tensile strength of concrete during bending is approximately equal to the results described in [6, 19, 27].

Thus, taking into account economic feasibility (the retail price of X Mesh fiber is USD 8–9 per kg), the amount of this dispersed reinforcement of about 2.2–2.3 kg/m^3 can be considered rational for use in road surface concrete. In this range of the varied factor X_2 (the amount of fiber), the maximum values of the fields of the EC models (2) and (3), which describe the compressive strength at the early and design age, are achieved. Also, with this amount of fiber, the values of the tensile strength of concrete at bending and abrasion almost do not differ from the maximum and, accordingly, the minimum for model (4).

The effectiveness of the use of polypropylene fiber from the point of view of achieving a comprehensive improvement in the properties of rigid pavement concrete in the data studied was close to the results reported in [11, 19]. As noted above, this effect is primarily due to the ability of fibers to better bind individual structural blocks of concrete as a coarsely heterogeneous material. Thanks to the use of the proposed technical solution, the most important mechanical indicators for road surfaces were increased. This improvement was noticeable, although relatively limited in scale. However, the technological simplicity and low cost of achieving this complex effect allow us to recommend the use of dispersed reinforcement of concrete road surfaces with polypropylene fiber X Mesh. It is also important to note that in concretes with a larger amount of cement in the composition, i.e., higher classes that are used mainly for the construction of roads of categories Ia and Ib [2], the effectiveness of the use of dispersed reinforcement was higher.

Changing the amount of plasticizer Sika® Plastiment®-1230 within the factor space of the experiment significantly affected, first of all, the level of compressive strength of the studied concretes. Increasing the amount of plasticizer also limitedly increased the tensile strength of concretes at bending and wear resistance. At the same time, taking into account the nonlinear nature of the influence of factor X_3 on strength (Fig. 3, 4) and the insignificant influence on abrasion (Fig. 5), the rational amount of Sika® Plastiment®-1230 additive for concretes of this type is 0.9 % of the cement mass.

An increase in the amount of cement in the composition is expected to increase the strength of concrete. However, due to dispersed reinforcement and the use of a rational amount of plasticizer, it is possible to obtain concretes with the strength required for a given category of road and increased wear resistance with a reduced consumption of binder.

It should be noted that the above dependences and recommendations are valid only for concretes with similar or similar composition with respect to the type of cement, plasticizer, and aggregates used. Changing the geometry and/or mechanical properties of dispersed reinforcement could significantly affect its operation in a cement-sand matrix, which must be taken into account under actual production conditions. However, this does not change the general specified trend of the influence of dispersed reinforcement on the properties of concrete. Therefore, the proposed technological solutions can be used in the practice of road construction.

In general, our results expand the understanding of the principles of obtaining effective concretes for use in road construction. The main practical effect of its application is to increase the operational characteristics and durability of coatings. In the future, it is planned to investigate the effectiveness of using polypropylene fiber of similar geometry to solve the problem of increasing the durability of road surface concretes operating under harsh operating conditions. Namely, under the action of freezing and thawing and the influence of an acidic environment, which are likely conditions for such road sections as approaches to bridges, tunnels, ports, etc.

7. Conclusions

1. Based on experimental data, a set of EC models was calculated, which made it possible to determine the influence of varied composition factors on the W/C of the concrete mixture and the mechanical properties of rigid pavement concretes. It was found that when the amount of lignosulfonate-type plasticizer is increased from 0.6 to 1 % of the cement mass, the W/C of the equal mobility mixture decreases by 12–15 %, and the introduction of polypropylene fiber insignificantly increases W/C. When the amount of cement in the concrete composition increases, the W/C of the mixture is expected to decrease.

2. Analysis of experimental data and calculated EC models revealed that with an increase in the amount of cement in the composition of concrete, their compressive and tensile strength at bending increases as expected. At the same time, a change in the amount of cement from 300 to 340 kg/m^3 causes a more significant increase in strength than a change in the amount of binder from 340 to 380 kg/m^3. Due to the introduction of fiber in an amount of 2 to 3 kg/m^3, the compressive strength of concrete at the design age of 28 days increases by approximately 3.5 MPa, the compressive strength at the age of 3 days practically does not change, and the tensile strength of concrete at bending, which is an important indicator for road surface concrete, increases by 0.5–0.6 MPa. The most noticeable increase in concrete strength occurs when dispersed reinforcement is introduced in an amount of 2–2.5 kg/m^3, while the effectiveness of dispersed reinforcement is higher for concretes with a higher amount of cement in the composition. When the amount of plasticizer Sika® Plastiment®-1230 is increased from 0.6 % to 0.9 %, the early compressive strength of the tested concretes increases by approximately 2 MPa, the design strength increases by approximately 5 MPa, and the tensile strength during bending increases insignificantly.

3. The wear resistance of concrete for rigid pavements increases most significantly due to the use of dispersed reinforcement. The introduction of polypropylene fiber X Mesh in the amount of 3 kg/m^3 reduces the abrasion of the studied concretes by 0.07–0.08 g/cm^2, i. e., by 17–19 %. At the same time, when using dispersed reinforcement in the amount of 2–2.5 kg/m^3, the abrasion decreases by 14–16 %. Increasing the amount of cement from 300 to 380 kg/m^3 reduces the abrasion of the studied concretes by 11–14 %; increasing the amount of plasticizer has an insignificant effect on this indicator. In general, our analysis revealed that, taking into account economic feasibility for the studied concretes of rigid pavements, the rational amount of Sika® Plastiment®-1230 additive is 0.9 % of the mass of cement, the rational amount of X Mesh fiber is 2.2–2.3 kg/m^3.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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