Steel fibrous concrete with high-early strength for rigid pavements repair

S Kroviakov 1, V Kryzhanovskyi 1, M Zavoloka 1

1 Odessa State Academy of Civil Engineering and Architecture, 65029, Didrikhsona st., 4, 65029, Ukraine

E-mail: vitolloscience@gmail.com

Abstract. Experimental results, including the selection of repair concrete and steel-fiber-concrete mixtures for rigid pavement repair are presented. The complex effect of the superplasticizer, hardening accelerating agent and steel anchor fiber on the concrete mixture properties has been studied. Compressive and flexural strength characteristics of the repair material were determined in the early and design ages of hardening. Using the method of experimental statistical modeling, the optimal dosages of dispersed reinforcement in combination with accelerating agent and workability modifier have been determined.

1. Introduction
In world practice, roads with rigid pavement are actively used [1]. Ukraine is also increasing the pace of highways construction using rigid road pavements [2]. For maintenance, permanent and major repairs, as well as reconstruction of this pavement types, it is necessary to provide for special technological methods using high-early strength concrete compositions. The repair technology with asphalt concrete, generally accepted in Ukraine, does not justify itself in view of the material pliability under dynamic loads, especially at high temperature drops. Traffic density and axle load increase and exceed the limit values during the overhaul period, for this reason, asphalt concrete becomes an ineffective repair material.

2. Analysis of recent researches and problem statement
In many countries of the CIS and the former USSR, most roads were designed for load group B (60 kN per axle) and group A (100 kN per axle). However, at present, regulatory documents already provide for loads up to 115-130 kN per axle, which is actively used by cargo carriers. [3].

Cement-concrete pavements are the most promising in terms of increasing load-bearing capacity, performance and durability of roads. Under present day heavy traffic conditions, rigid pavements are more economical, even if the capital cost of their construction is significantly higher than asphalt concrete [4]. That is, with the growing of road sections with rigid pavements, the task of repairing these pavement types is becoming increasingly important.

It should be noted that the pavement works like a slab on elastic ground, so the pavement is designed for flexural strength. Therefore, use of high-strength concretes for repair cannot be a complete solution to the problem due to their high brittleness to dynamic loads. High performance concretes also cannot use their full potential due to low W/C ratio (no more than 0,3) and, as a consequence, increase in shrinkage deformation, shrinkage cracks may appear, especially in the early stages of hardening [5].
Concrete with dispersed reinforcement is widely used in road construction, which is used as different types of fiber: steel, basalt, polypropylene, glass [6,7]. The use of fiber makes it possible to increase abrasion resistance, crack resistance and the most important indicator for rigid pavements – flexural strength.

Steel-fiber concrete was first used as a repair material for rigid road pavements in the USA. [8]. Strength indicators of steel-fiber reinforced concrete in flexural strength reach high values > 12 MPa [9]. In turn, use of steel-fiber allows to reduce shrinkage deformations and increase frost resistance of concrete. The above-described advantages of this material make it possible to use it as a repair material for rigid road pavements.

To achieve the greatest structural and technological efficiency of repair compositions, to increase the early strength of concrete is crucial task. Its solution makes it possible to open traffic on the road section after repairs in a shorter time.

3. Research objective
Determination of the steel anchor fiber, hardening accelerator and superplasticizer amount on the compressive and flexural strength of modified repair concrete at the age of 2 and 28 days.

4. Materials and research methods
To increase workability, all concrete mixtures were modified with BASF MasterGlenium SKY 608 plasticizer in the amount of 1,2% by cement mass. This amount was considered rational based on the results of previous studies [10].

Cement CEM II/A-S 42,5 "Dyckerhoff Cement Ukraine" was used as a binding material. Crushed breakstone (grade 5-20 mm) and quartz sand were used as coarse and fine aggregates. The aggregates grain size is shown in table 1 and meets the requirements of the following standards: DSTU B V.2.7-75-98, DSTU B V.2.7-32-95, BS EN 12620:2013, ASTM C 33/C33M-18.

Table 1. Comparing of fine and coarse aggregates sieve analysis according to different building codes

| Sieve size, mm | % Passing by weight | DSTU B V.2.7-75-98 | DSTU B V.2.7-32-95 | EN 12620:2013 | ASTM C 33/C33M-18 |
|---------------|---------------------|---------------------|---------------------|-----------------|---------------------|
|               | Crushed breakstone  | Sand                | Crushed breakstone  | Sand            | Crushed breakstone  | Sand                |
| 20            | 100                 | 100                 | ≥ 90                | -               | 90-99               | -                   |
| 10            | 54,7                | 100                 | 20-70               | -               | -                   | -                   |
| 5             | 5,0                 | 100                 | 0-10                | -               | 0-15                | 100                 |
| 2,5           | 0,8                 | 97,0                | -                   | 80-100          | 0-5                 | 85-99               |
| 1,25          | 0                   | 84,5                | -                   | 55-95           | -                   | -                   |
| 0,63          | 0                   | 32,6                | -                   | 30-80           | -                   | -                   |
| 0,315         | 0                   | 35,3                | -                   | 20-50           | -                   | -                   |
| 0,16          | 0                   | 10,5                | -                   | 0-15            | -                   | -                   |
| < 0,16        | 0                   | 1,5                 | -                   | -               | -                   | -                   |

According to the optimal symmetrical 9-point plan, 2-factors experiment [11] was carried out, the following compositional factors were varied:

$X_1$ – the amount of admixture Sika Rapid 3 hardening accelerator, from 0 to 2,4% by cement content (from 0 to 9,6 kg/m$^3$);

$X_2$ – the amount of steel anchor fiber with Ø 1 mm and length 50 mm, from 0 to 100 kg/m$^3$. 


The concrete mixture was adjusted depending on the amount of dispersed reinforcement and modifiers. Mathematical planning of the experiment made it possible to minimize labor costs to determine the optimal concrete compositions and fiber-reinforced concrete mixtures with the best strength characteristics. Table 2 shows the matrix of a two-factor experiment with the investigated repair concrete compositions. The varied factor levels of experimental-statistical (ES) models were normalized in the range from -1 to +1.

Table 2. Concrete and fiber-concrete mixtures. Physical and mechanical properties of concretes

| № of mixture | Cement, kg/m³ | Sand, kg/m³ | Crushed stone, l/m³ | SKY 608, % | Steel fiber, kg/m³ (X₁) | f₀ck.cube.2 (MPa) | f₀ck.cube.28 (MPa) | f₀ctk.2 (MPa) | f₀ctk.28 (MPa) | W/C ratio | Average density, kg/m³ |
|--------------|---------------|-------------|---------------------|------------|------------------------|------------------|------------------|--------------|-----------------|----------|------------------------|
| 1            | 830           | 1190        | 0                   | 0          | 46,5                   | 85,5             | 5,6              | 9,0          | 0,288           | 2530     |
| 2            | 830           | 1190        | 1,2                 | 0          | 51,8                   | 76,2             | 5,8              | 7,2          | 0,316           | 2540     |
| 3            | 830           | 1190        | 2,4                 | 0          | 56,4                   | 72,8             | 6,0              | 6,9          | 0,307           | 2530     |
| 4            | 788           | 1180        | 0                   | 50         | 49,2                   | 90,7             | 8,2              | 16,1         | 0,332           | 2530     |
| 5            | 400           | 1180        | 1,2                 | 50         | 53,7                   | 85,3             | 8,4              | 15,5         | 0,328           | 2550     |
| 6            | 782           | 1180        | 2,4                 | 50         | 59,1                   | 83,1             | 8,7              | 14,9         | 0,325           | 2540     |
| 7            | 752           | 1170        | 0                   | 100        | 52,6                   | 92,5             | 8,6              | 16,8         | 0,344           | 2550     |
| 8            | 750           | 1170        | 1,2                 | 100        | 55,9                   | 87,1             | 8,9              | 15,7         | 0,337           | 2590     |
| 9            | 745           | 1170        | 2,4                 | 100        | 61,5                   | 84,7             | 9,2              | 15,2         | 0,331           | 2550     |

5. Research results

For each concrete mixture, compressive strength test of samples at the age of 2 and 28 days were carried out (cubes 10x10x10 cm) and flexural strength test (prisms 10x10x40 cm) according to DSTU B V.2.7-214:2009.

Strength characteristics of mixture № 1 (f₀ck.cube.2 = 46,5 MPa, f₀ctk.2 = 5,6 MPa, f₀ck.cube.28 = 46,5 MPa, f₀ctk.28 = 9,0 MPa) made it possible to use it as a starting point for further improvement of concrete repair mixtures based on the research carried out [10,12]. Workability of the investigated concrete and steel-fiber concrete mixtures satisfied the requirements for full-depth repair compositions [13,14], slump was 6-9 cm.

Based on experimental data, ES-model was obtained (1), which describes the effect of the accelerator amount (x₁) and fiber (x₂) on the mixtures W/C ratio with equal workability. According to the model (1), a diagram was drawn in (figure 1) to analyze the combined effect of varied composition factors on the W/C ratio of repair concrete and steel-fiber concrete mixtures.

\[
W/C = 0,328 - 0,005x_1 \pm 0x_1^2 \pm 0x_1x_2 + 0,012x_2 - 0,003x_2^2
\]
Analysis of the diagram in figure 1 shows that dispersed reinforcement with steel fiber has a nonlinear effect on the water demand of the mixture, with fiber amount of 50 kg/m$^3$, W/C ratio increases more noticeably than with increase in the fiber dosage from 50 to 100 kg/m$^3$. However, even at the maximum dosage of fiber (100 kg/m$^3$), W/C ratio of mixtures are in the range of 0,332-0,344, which ensures quality of the repair composite. It is also necessary to note the effect of reducing the W/C ratio with an increase in the amount of the hardening accelerator agent. This is due to the accelerator is a liquid that can perform a function similar to water.

According to the data given in table 2, ES-models were drawn, reflecting the influence of various factors on the compressive strength at the age of 2 (2) and 28 (3) days of hardening.

\[
f_{ck,cube2} (\text{MPa}) = 53.80 + 4.78x_1 + 0.42x_1^2 - 0.25x_1x_2 + 2.55x_2 \pm 0x_2^2
\]

(2)

\[
f_{ck,cube28} (\text{MPa}) = 85,0 - 4.68x_1 + 2.02x_1^2 + 1.23x_1x_2 + 4.97x_2 - 3.23x_2^2
\]

(3)

The combined effect of variable composition factors on the compressive strength of concrete and fiber-reinforced concrete is reflected in the diagrams drew using ES models (2), (3): at the age of 2 days (figure 2, a), at the age of 28 days (figure 2, b).
Figure 2. Influence of the hardening accelerator and steel fiber amount on the compressive strength at the age of 2 days (a) and 28 days (b)

Diagram on figure 2 (a) shows that, using the maximum amount of the hardening accelerator, regardless of the fiber amount, after 2 days of hardening, concrete has strength at least 55 MPa. That is, already at early age, the concrete strength actually corresponds to the C 32/40 grade. At the same time, fiber-reinforced concretes with the fiber amount in the composition of 50 kg/m$^3$ and higher have strength 55 MPa and more already with the amount of hardening accelerator from 1.4%. Using the maximum amount of dispersed reinforcement and Sika Rapid 3 admixture, early strength of fiber-reinforced concrete is at least 60 MPa, that is, already at the age of 2 days, strength is achieved, which provides concrete grade C 35/45.

Analysis of the diagram on figure 2 (b) shows that use of the hardening accelerator makes it possible to significantly increase the early strength of concretes for the road pavements repair, but negatively effects on the composite strength at the standard (design) age of 28 days [15]. But it can be stated that the compressive strength of all concretes and fiber-reinforced concretes investigated in the framework of this experiment at the design age was higher than required by standard documents for rigid road pavement concretes [16]. It is important to note that some reduction in compressive strength at 28 days with Sika Rapid 3 is fully compensated by the dispersed steel fiber reinforcement. Fibrous concrete with the 2.4% of hardening accelerator and steel fiber of 100 kg/m$^3$ has strength 85 MPa, which is similar to the design concrete strength without hardening accelerator and fiber.

The pavement works like a slab on elastic ground, so it is especially important to take into account the flexural strength for selecting repair mixtures. Based on the data given in table 2, ES-models were drawn, reflecting the influence of variable composition factors on flexural strength at the age of 2 (4) and 28 (5) days of hardening.

\[
f_{ck,2} \text{ (MPa)} = 8,42 + 0,26x_1 + 0,02x_{12} + 0,05x_1x_2 + 1,55x_2 - 1,08x_{22}
\]

(4)

\[
f_{ck,28} \text{ (MPa)} = 15,27 - 0,81x_1 + 0,35x_{12} + 4,10x_2 - 3,70x_{22}
\]

(5)
On the basis of ES-models (4) and (5), diagrams were drawn showing the effect of the hardening accelerator admixture and steel fiber amount on the concrete flexural strength at early (figure 3 a) and standard (design) age (figure 3 b).

![Figure 3](image-url)

Figure 3. Influence of the hardening accelerator and steel fiber amount on the flexural strength of the studied concretes and fibrous concretes at the age of 2 days (a) and 28 days (b)

Analysis of the diagram (figure 3 a), shows that with the hardening accelerator Sika Rapid 3 in the fiber-reinforced concrete mixture from 1,2% and with steel fiber in the amount of 60 kg/m\(^3\) and higher, early flexural strength of the composite is not less 8.5 MPa. The highest values (8,7..9,3 MPa) value \(f_{t,2} \text{MPa}\) reaches at fiber dosage in the range of 85..90 kg/m\(^3\), further increase in the fibers dosage has small effect on the early flexural strength. Taking into account the compressive strength, which is described above, already after 2 days’ completion of repair work using modified fiber-reinforced concrete, in most cases, it is possible to open the road traffic.

Figure 3 (b) shows that with the hardening accelerator agent is added to the concrete mixture, its flexural strength at the design age decreases similarly to the compressive strength. However, the most important fact is that the use of anchor steel fiber in amount of more than 60 kg/m\(^3\), flexural strength of fiber-reinforced concretes not less than 16 MPa. Such high efficiency of the fiber at the design age is explained by the fact that the quality of the fibers work is largely due to their adhesion to the cement-sand matrix, and with age, the concrete and its matrix strength increases [17].

6. Conclusions and further researches

The study of the modified fiber-reinforced concrete strength (with the amount of MasterGlenium SKY 608 superplasticizer 1,2% by cement mass) showed that using a rational amount of the hardening accelerator Sika Rapid 3 (1,4-2,4% by cement mass) and steel anchor fiber (70..90 kg/m\(^3\)) the obtained composites are characterized by high compressive and flexural strength at early age and at the 28 days age. This allows to assert high efficiency of the developed modified fiber-reinforced concretes as a material for the rigid pavements repair, which allows starting the road pavement operation in the shortest possible time.
Further researches will be devoted to determining such important indicators as frost and wear resistance, which in turn effect on the concrete durability. It is also planned to conduct an experiment to determine and prevent shrinkage of high-early strength concretes and steel fiber reinforced concretes, especially in the early ages of hardening.

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