

The possibility of producing fiber-reinforced concrete with high deformation properties by regulating the microstructure and using it in the design of transport structures was considered. It was found that to create high-performance transport structures, it is necessary to modify fiber mixtures with complex additives, i. e. increase the strength of fiber-reinforced concrete at the micro-level. To obtain a denser structure of the concrete matrix, complex additives were used – ultrafine additive (silica fume) and Master Air 200 B air-entraining additive. It was experimentally proved that using such additives reduces the water-cement ratio and further strengthens the concrete matrix structure.

The design of the unloading structure on the railway line constructed from the Karadag station (Republic of Azerbaijan) to the SOCAR oil and gas processing and petrochemical complex using fiber-reinforced concrete modified with complex additives was made. The results of designing the fiber-reinforced concrete unloading structure were analyzed and the results of designing the fiber-reinforced concrete unloading structure and the regular concrete unloading structure were compared. As a result of the comparison, it was found that using fiber-reinforced concrete decreases the cross-section diameter of the effective reinforcement of the slab – the cross-section diameter of the effective reinforcement of the pavement slab decreases from $\varnothing 2 \times 32$ mm to $\varnothing 32$ mm in the upper and $\varnothing 25$ mm in the lower row, respectively. Crack resistance is also increased compared to regular concrete.

Thus, in order to create structures with high transport and operational parameters, it is necessary to modify fiber-reinforced concrete mixtures with complex additives

Keywords: fiber-reinforced concrete, silica fume, concrete microstructure, crack resistance, deformation properties, durability, unloading structure

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DEVELOPMENT OF EFFECTIVE FIBER-REINFORCED CONCRETE COMPOSITIONS USED IN TRANSPORTATION STRUCTURES

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1. Introduction

Very difficult and harsh operating conditions of road structures provide for special requirements for the materials. Cement-concrete pavements operate in complex stress under repeated dynamic loads from vehicles. At the same time, such artificial conglomerates as concrete are characterized by an internal stress state. On the other hand, they are exposed to aggressive environmental effects [1]. As in other areas of the construction industry, the requirements for the properties of concrete used in transport structures have been tightened.

Concretes with high compressive strength are known to have rather low bending tensile strength and crack resistance. However, with an increase in compressive strength, the tensile strength of high-strength concretes increases slightly, which reduces concrete capabilities and effectiveness. To increase one of the main disadvantages of concrete, which affects the service life of a structure – crack resistance, the efficiency of using high-modulus fibers was theoretically substantiated and experimentally confirmed [1–3]. Thus, there is a need to increase the crack resistance of concrete and one of

the most effective solutions of this problem is using dispersive fibers in concrete. At the same time, the mechanical properties of concrete are fundamentally changed (strength, crack resistance and impact resistance). This increases the durability of the structure, resistance to aggressive environmental effects, and, consequently, operational reliability. Dispersive fibers in a concrete matrix prevent cracking [1, 2].

Increasing the performance of fiber-reinforced concrete due to the modification of fiber-reinforced concrete mixtures with complex additives is relevant, since using such concretes ensures the durability of the structure, which, in turn, affects the technical and economic parameters.

2. Literature review and problem statement

Using metal and reinforced concrete in construction allows designing and constructing buildings and structures of almost any shape and size. Recently, new composites with more unique properties have been used more often. It was found that using fiber-reinforced concrete in construction is

based on its crack resistance, fire resistance, and high frost resistance [4]. The authors [1] found that using metal fiber in the composition of concrete changes its characteristics: tensile strength increases up to 30 %, crack resistance and impact resistance increase significantly. The authors [1] found that small particles of silica fume (SiO_2) react with $\text{Ca}(\text{OH})_2$ to form calcium silicate hydrate. The formed crystals of calcium silicate hydrate further strengthen the structure of the cement stone, prevent the penetration of moisture and other aggressive substances into the cement stone composition. At the same time, Master Air 200B additives have a positive effect on the formation of a dense cement stone structure. These additives, reducing the water-cement ratio, further compact the concrete structure and also increase the cement and aggregate adhesion in the contact area [1]. However, the theoretical results require practical confirmation, which is not shown in [1].

The authors [2] theoretically found the technical and economic efficiency of the field of rational use of fiber-reinforced concrete, but it was not proved experimentally. Generalization of the study of physical and mechanical characteristics by the authors [1, 2] allows using fiber-reinforced concrete in road pavement, tunnel lining, construction of runways, tanks, coastal structures, floors of industrial enterprises and other structures.

In recent years, using fiber-reinforced concrete in transport structures has led to significant progress in solving many problems. However, it should be noted that fiber materials increase concrete properties such as strength, crack resistance only at the macro-level. To create transport structures with high technical and operational performance, it is necessary to modify fiber-reinforced concrete mixtures with complex additives, i. e. increase the strength of fiber-reinforced concrete at the micro-level. In other words, the production of high-strength fiber-reinforced concrete by regulating its microstructure and using such concrete in the development of methods for designing rigid road surfaces and other structures is one of the urgent problems. In this direction, the work of the author, who used nanoparticles to strengthen the concrete matrix, is of interest [3]. However, using silicon oxide nanoparticles for matrix strengthening makes the material economically unprofitable. And in the work of other authors [4], ultrafine waste from a thermal power plant (fly ash) was used to improve the strength of composite materials at the micro-level, but the effect of improving physical and mechanical properties is much lower.

All this suggests it expedient to conduct a study on the development of a high-strength matrix composition for fiber-reinforced concrete using silica fume (metallurgy waste) and an air-entraining additive. Considering the peculiarities of the design area of the unloading structure (availability of strong mineral materials, increase in traffic intensity, and, consequently, traffic load, increase in construction rate), fiber-reinforced concrete structures may be of great interest in the future. Especially if these transport structures are exposed to aggressive environmental effects. Below is an example of designing an unloading structure under a railway located on the Absheron Peninsula. A characteristic feature of this design area is the proximity of the Caspian Sea, which negatively affects structural elements.

3. The aim and objectives of the study

The aim of the study is to create a high-strength matrix for fiber-reinforced concrete, which allows designing transport structures exposed to dynamic loads.

To achieve the aim, the following objectives were set:

- to develop a composition of fiber-reinforced concrete that provides high crack resistance;
- to investigate the microstructure of fiber-reinforced concrete;
- to investigate the deformation properties of fiber-reinforced concrete;
- to design the fiber-reinforced concrete unloading structure and examine the operation under load.

4. Materials and methods of the study

In the study, we used samples made of KCLASS A CEM II/A-P 42,5R Portland cement of the «NORM» company with the following additives:

- Master Air 200B (BASF),
- silica fume oxide – waste of ferrosilicon production containing over 90 % of spherical amorphous SiO_2 ,
- crushed stone obtained by crushing river stone,
- river sand with a fineness modulus $\text{IM}=2$.

To determine the mechanical properties of modified fiber-reinforced concrete, standard methods were used [5–7]. To study the chemical-mineralogical composition and microstructure of fiber-reinforced concrete, X-ray analysis, microscopy and IR spectroscopy methods were used [8]. X-ray analysis was performed on an X-RAY diffractometer (Jiangsu, China), microscopy on an FE-SEM Qyanta 400 F scanning electron microscope (Filips, Netherlands).

The design was carried out under the current standards for transport structures [9, 10].

5. Results of the study on using modified fiber-reinforced concrete in the design of unloading structure

5.1. Study and development of fiber-reinforced concrete composition

To obtain durable and strong fiber-reinforced concrete with high technical and operational properties, it is necessary to achieve a more reliable interconnection of the cement matrix with metal fiber, as well as to provide anti-corrosion protection of fiber materials in the matrix. For this purpose, ultrafine additives can be used, which play a very important role in obtaining a denser structure of the concrete matrix at the micro-level. One of these additives is silica fume. Silica fume is a waste of ferrosilicon production and contains over 90 % of spherical amorphous SiO_2 [2, 3]. Using silica fume as an additive is due to the fact that the additive particles fill the voids in the cement stone and thereby form new hydrate compounds. The particle size of silica fume is 50 times smaller than that of cement. These fine SiO_2 particles react with $\text{Ca}(\text{OH})_2$ to form low-basicity calcium silicate hydrate. These crystals of calcium silicate hydrate additionally compact the cement stone structure. The stronger the cement stone structure, the less moisture and other aggressive substances enter it. It should be noted that silica fume has high dispersion, so the need for water increases with its amount. For this, silica fume is used together with plasticizers and air-entraining additives, which reduce water consumption.

Master Air 200B air-entraining additive has a positive effect on the formation of dense cement stone structure. Using such additives reduces the water-cement ratio and additionally strengthens the cement stone structure. At the

same time, they increase the adhesion between the cement and aggregate particles in the contact area. The compressive strength of the original concrete modified with complex additives was 50 MPa. Concrete porosity is known to be one of the main factors affecting the corrosion of cement stone and concrete. Therefore, reducing porosity is the most effective way to prevent corrosion. As a result, the deformation properties of concrete, and therefore of the entire structure, are significantly increased. Thus, using fiber material increases the tensile strength of the modified concrete up to 65 MPa. The construction and technical properties of fiber-reinforced concrete are given in Table 1.

Table 1

Construction and technical properties of concrete, modified fiber-reinforced concrete

No.	Parameter	Test result
1	Slump, cm	9
2	Concrete mix density, kg/m ³	2.500
3	Compressive strength after 7 days of concrete hardening, MPa	39
4	Compressive strength after 28 days of concrete hardening, MPa	60
5	Tensile strength after 28 days of concrete hardening, MPa	20

The microstructure of the concrete matrix modified with the above additives is shown in Fig. 1.

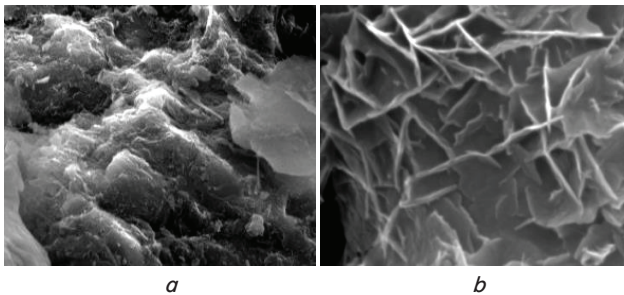


Fig. 1. Microstructure of concrete matrix for fiber-reinforced concrete: *a* – regular concrete (5.000 times magnification); *b* – modified concrete (60.000 times magnification)

Compaction of the concrete structure when modified with complex additives was also confirmed by IR spectroscopy. The results are shown in Fig. 2.

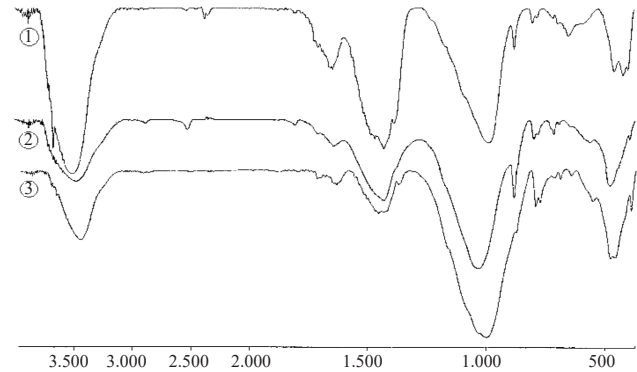


Fig. 2. IR spectroscopy of concrete samples: 1 – without additive; 2 – with silica fume; 3 – with complex additives

5. 2. Design of fiber-reinforced concrete unloading structure

Using fiber-reinforced concrete with high deformation properties and crack resistance in the design of transport structures increases the strength, durability of the structure and overhaul periods. Taking into account the increased deformation properties and high crack resistance of fiber-reinforced concrete compared to regular concrete, the unloading structure was designed. The purpose of the design is to create a theoretical basis for using fiber-reinforced concrete in transport structures operating under aggressive conditions and dynamic loads. Such an unfavorable combination of loads often causes cracking, which, in turn, reduces the operational reliability of the structure. For this purpose, the unloading structure was designed using the example of the forecast construction of a railway from the Karadag station (Azerbaijan Republic) to the SOCAR oil and gas processing and petrochemical complex (Fig. 3, 4) using fiber-reinforced concrete modified with complex additives. Under the current standards, before the start of design work, the geotechnical conditions of the design area were studied at the exploration stage, a geodetic and hydrogeological survey was carried out.

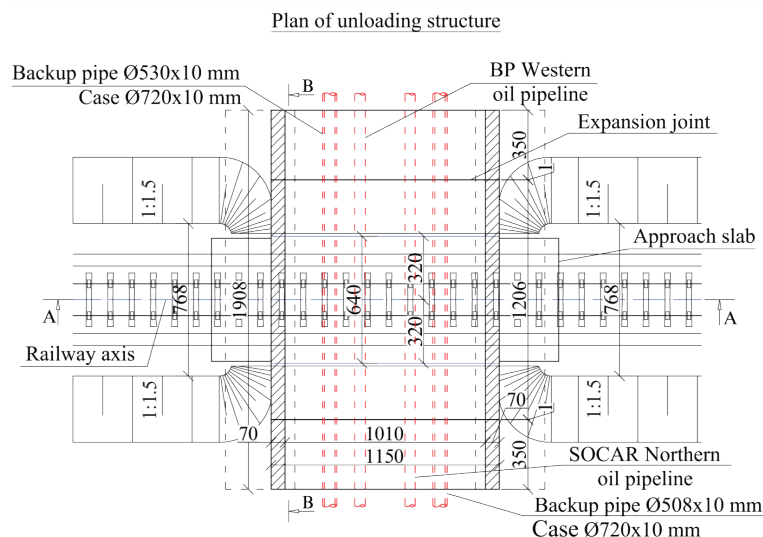


Fig. 3. Plan of the unloading structure under the railway

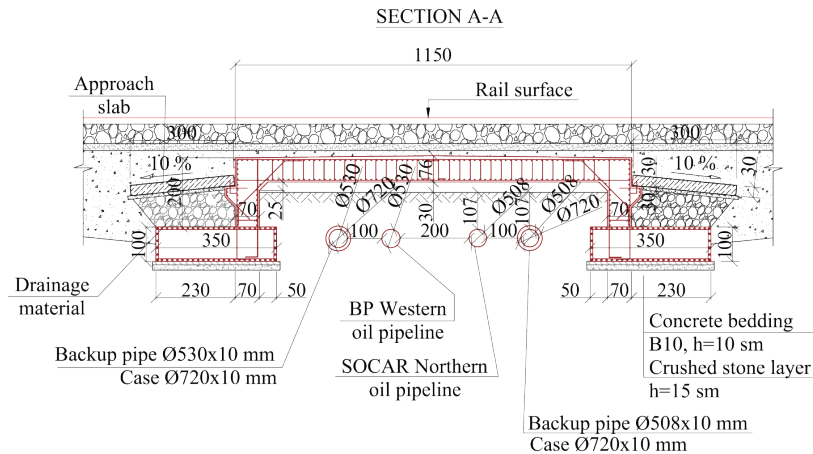


Fig. 4. Cross-section diagram of the unloading structure under the railway

The forecast railway crosses two oil pipelines, Northern (SOCAR) (with the diameter $d=508$ mm) and Western (BP) (with the diameter $d=530$ mm). To protect the pipelines from damage, deformation, as well as taking into account changing operating conditions, a reinforced concrete unloading structure is constructed above these pipelines. One of the reasons that complicate this problem is the location of backup pipes next to the existing pipelines, which in turn increases the size of the unloading structure. The total length of the reinforced concrete unloading structure above the pipelines is $L=19.08$ m, dimension $Q=10.1$ m (Fig. 3, 4).

The design of the unloading structure was carried out using SAP2000 V14 (USA). The results were also verified by CSIBridge V.21.2.0 (USA). As a result of comparing the fiber-reinforced concrete unloading structure with the regular concrete unloading structure, the main advantages and disadvantages of fiber-reinforced concrete were identified. Considering these advantages and disadvantages allows using it in other transport structures, such as roads, bridges, overpasses, tunnels, pipes.

The standard vertical live load from rolling stock (CK) is taken as the maximum equivalent load v , kN/m, obtained from a concentrated load of $24.5 K$, kN and a uniformly distributed load of $9.81 K$, kN/m of the track. Here $K=14$ is the class of live load. As the design showed, the best result of using fiber-reinforced concrete in the unloading structure is achieved in the road slab. The unloading structure with a dimension of 10.1 m and a total length of 19.08 m under the railway is subjected to dynamic loads and aggressive environmental effects. According to the design (SAP2000 V14, CSIBridge V.21.2.0), using fiber-reinforced concrete will reduce the cross-sectional diameter of the effective reinforcement of the slab and increase its crack resistance compared to regular concrete (Fig. 5, 6).

For comparison, using this program, an analysis of the reinforced concrete slab of the regular concrete unloading structure, as well as the fiber-reinforced concrete slab was made, internal forces, short-term elastic deformations, graphs of the required reinforcement area were studied.

Based on the analysis of the reinforced concrete slab of the unloading structure, it was found that the combination of fiber and bar reinforcement can reduce the crack width, decrease reinforcement consumption and reduce the complexity of work and construction time.

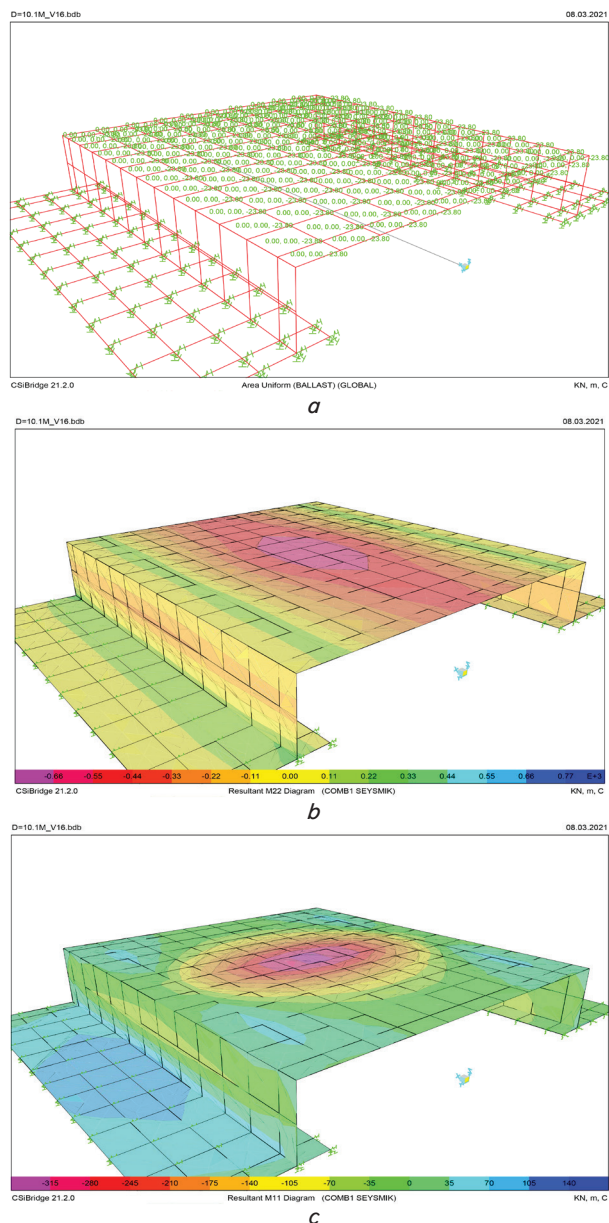


Fig. 5. Design model of the unloading structure: *a* – loading diagram of the unloading structure; *b* – diagrams of the maximum moment curve in the x -axis direction; *c* – diagrams of the maximum moment curve in the y -axis direction

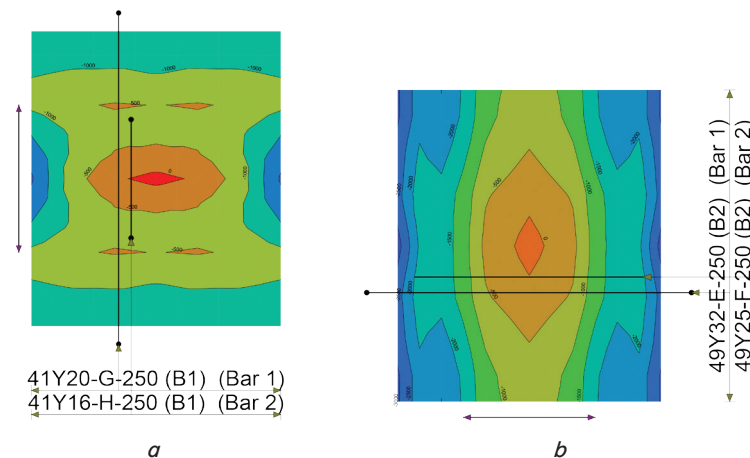


Fig. 6. Reinforcement of the unloading structure according to SAP2000 V14:
a – recommended longitudinal slab reinforcement; *b* – recommended effective slab reinforcement

6. Discussion of the results of using modified fiber-reinforced concrete in the design of unloading structure

The microstructure of the concrete matrix modified with additives shows the presence of densely spaced needle-like crystals (Fig. 1, *b*). As a result of Portland cement reaction with active silicon oxide, needle-like crystals of low-basicity calcium silicate hydrate are formed in the system. As a result, the strength is increased by 30 %.

As can be seen from Fig. 2, IR spectroscopy of the samples from regular concrete (without additives) and concrete with chemical additives (air-entraining additives) (line 2 and 3, Fig. 2), the absorption band ($1.000\text{--}1.250\text{ cm}^{-1}$) covers a fairly large area. However, when analyzing the concrete samples modified with complex additives, the absorption band (line 1, Fig. 2) covers a much smaller area. This shows the presence of low-basicity calcium silicate hydrate with a regular crystal structure in the samples with silica fume. IR spectra with wide absorption bands are characteristic of the samples with an amorphous structure. At the same time, a decrease in the absorption intensity band in the samples with silica fume ($3.000\text{--}3.500\text{ cm}^{-1}$) shows a decrease in the number of water ions with weak molecular bonds compared to other samples. This proves that using silica fume enhances the formation of silicate hydrates with high intermolecular energy. It is known that in these types of calcium silicate hydrate, water enters the crystal lattice and even when it is heated to $800\text{ }^{\circ}\text{C}$, water ions cannot be separated from them.

It was experimentally proved that concrete modified with fine particles and chemical additives can be the most reliable and durable matrix for fiber-reinforced concrete.

From the results (Table 1), it can be seen that optimizing fiber-reinforced concrete at the macro- and micro-levels significantly increases its bending compression strength. Thus, using microdispersed reinforcement (steel fiber) for concreting structures exposed to dynamic loads is advisable, since this increases the crack resistance and frost resistance of the structure.

An analysis of the results of designing the fiber-reinforced concrete unloading structure was made. In addition, the results of designing the fiber-reinforced concrete unloading structure and the regular concrete unloading structure were compared. As a result of the comparison, the main advantages and disadvantages of fiber-reinforced concrete were identified, taking into account the main advantages, the

possibility of using it in other transport structures (roads, bridges, overpasses, tunnels, pipes) was considered. The best result of using fiber-reinforced concrete in the unloading structure is achieved in the road slab. The unloading structure with a dimension of 10.1 m and a total length of 19.08 m under the railway is subjected to dynamic loads. As shown by the design (CSIBridge V.21.2.0), using fiber-reinforced concrete decreases the cross-section diameter of the effective reinforcement of the slab and, compared to regular concrete, increases its crack resistance.

The prospect of this study in terms of further development lies in the possibility of using fiber-reinforced concrete in transport structures exposed to dynamic loads. It is known that transport structures (cement-concrete pavements, slabs of road tunnels, bridges, culverts, etc.) under dynamic loads function under bending tension, which leads to cracking during long-term operation. Fiber-reinforced concrete increases the crack resistance of structures, which increases the overhaul period.

7. Conclusions

1. The composition of fiber-reinforced concrete modified with complex additives was developed. It was found that with a 12–13 % content of metal fibers (of the concrete volume), the compressive strength of the modified concrete increases by 30 %.
2. The study shows that ultrafine additives play a very important role in obtaining a denser concrete matrix structure. Small SiO_2 particles react with $\text{Ca}(\text{OH})_2$ to form calcium silicate hydrate, additionally compacting the cement stone structure and preventing cracking.
3. The dependence of the deformation properties of fiber-reinforced concrete on the amount of fiber material in the concrete mixture was found. The greatest bending tensile strength is achieved with the fiber content of 12–13 % of the concrete volume. At the same time, the compressive strength increases by 21 %, while the tensile strength increases by 46 %.
4. When designing the unloading structure made of fiber-reinforced concrete modified with complex additives, the best result is achieved in the road slab. The design showed that using fiber-reinforced concrete decreases the cross-section diameter of the effective reinforcement of the slab and, compared to regular concrete, increases its crack resistance.

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