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STUDY OF FINE-GRAINED FIBER CONCRETE CRACKING RESISTANCE FROM THE POINT OF VIEW OF DESTRUCTION MECHANICS

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Fiber reinforced concrete began to appear in the market in the 60s of the last century, and since then the interest in this type of reinforcement has been steadily growing. The article presents the results of studies on the crack resistance of concrete reinforced with polypropylene fibers of various lengths and volume concentrations in fine-grained concrete. Waste from the wet magnetic separation of the Poltava mining and concentration plant was used as an aggregate in the concrete. Polypropylene fibers with the various lengths diameter of 0.2 mm were used for reinforcement. The influence of the length and volume concentration of fibers on the crack resistance of the same strength concrete of was studied. The study results indicate that the increase in the length and volume concentration of fibers, within the limits of the experiment, significantly affects the crack resistance of fine-grained concrete.

Key words: fine-grained concrete, waste of mining and processing plant, polypropylene fibers, volume concentration, crack resistance, stress intensity factor.

Introduction

The extraction of minerals from the earth is associated with the formation of waste as associated rocks or they are formed after their use. In most cases, the waste is a mineral raw material suitable for further use in human activities, for example, ash and slag of thermal power plants, waste from the enrichment of ferrous and non-ferrous metals. At the Poltava Mining and Processing Plant (**FERREXPO POLTAVA MINING)**, the outputs of dry magnetic separation are realized in the form of crushed stone, and the outputs of wet magnetic separation in the form of fine sand are stored in special storages. They have a rock surface, which combines enhanced adhesive properties with cement stone. Unaffected by an unstable grain composition, they can be used as a fine aggregate in concrete. Fiber concrete, which has improved strength and deformability characteristics, is increasingly being used in construction. At the same time, fibers of different composition and origin, geometric characteristics, physical and mechanical properties are used as dispersed reinforcement. Each type of fiber has its advantages and disadvantages.

This year in Poltava, fine-grained concrete reinforced with polypropylene fibers was used during the repair of floors in warehouses with an area of more than 7,500 m^2. Before the war, in 2021, using the same concrete, a floor covering an area of more than 1,000 m^2 was laid in the city of Dnipro.

As it is known, fiber concrete is fiber-reinforced concrete. At the same time, fibers do not replace the main reinforcement. The introduction of fibers with different strength and deformability characteristics into the cement-concrete matrix permit to purposefully adjust the properties of composite materials (Akhmednabiev, R et al.2022). Fibers can be polymer, metal, mineral or of other origin.

Thus, for example, the introduction of fibers with a high modulus of elasticity – steel, glass, carbon – into the cement-concrete matrix, it is possible to obtain composite materials, which physical and mechanical properties are several times higher than those of the matrix (Perfilov, V. 2023 ,Hunyak; O.2020). In addition, such fibers permit to reduce the cost of traditional reinforcement in reinforced concrete structures.

On this basis, high-strength fortification structures were developed with the use of fiber reinforcement of steel fibers (Doroshenko O. et al. 2014, Momber, A. W. 2004)

Concretes reinforced with fibers that have a low modulus of elasticity – synthetic, copper, etc. – are characterized by a low modulus of elasticity, increased deformability, crack resistance, and resistance to dynamic loads. (Fatahi B. 2012, Novytskyi O 2021).

The fibers contribute to greater resistance to cracking during shrinkage and service. However, they are intended for primary reinforcement. They are added during the production of concrete as a component of the concrete mix. The disadvantages of fiber concrete are reduced convenience when laying the mixture and the possibility of corrosion spots on the surface of the concrete if the steel fibers come out to the surface. (Fatahi B. 2012. Mohammad. H 2019).

Other methods for achieving high strength of concrete and methods for studying their properties are also known (Miarka, P et al.2018, Seitl S. 2018). Fiber reinforcement is most commonly used to provide higher tensile and flexural strength, greater energy absorption capacity, and improved deformability characteristics. In addition, the uniform distribution of short fibers in the concrete mixture increases isotropic properties, which are not characteristic of ordinary concrete and reinforced concrete. (Sadek S. 2013. Malíková, L. et al. 2016).

It is known that fiber-reinforced concrete demonstrates increased strength and deformability under dynamic loads, which was confirmed during tests of elements made of fiber-reinforced concrete under explosive loads. (Sanytskyi M. A.,2021). The increased resistance of fiber-reinforced concrete to the influence of water pressure during repair work of industrial floors and hydraulic structures is also noted. (Fowler D.W,2009).

Dispersed reinforcement with synthetic fibers having a low modulus of elasticity does not lead to a noticeable increase in strength under static loads, but the resistance of such a composite under impact loads is greater compared to bulk concrete. (Fowler D.W.,2009).

One of the fiber concrete disadvantages is the problem of ensuring a uniform distribution of fibers in the volume of the matrix, which deteriorates with increasing fiber length, which was investigated in previous works. (Hossein M., 2020). The difficulty of mixing fibers with the matrix haunts even with dispersed reinforcement of soil-cement concrete during the erection of bored piles (Lei Yang et al., 2022).

Purpose of the study: To evaluate the effect of polypropylene fibers on the crack resistance of fine-grained concrete using waste from a mining and processing plant as a filler.

Materials and methods

Portland cement PC 42.5 of the Ivano-Frankivsk cement plant was used as a binder in the work. As a fine aggregate – waste from wet magnetic separation of the Poltava mining and processing plant with a particle size modulus of 1.1. Propylene fibers' diameter was 0.2 mm. Polycarboxylates were used as a plasticizer.

In this work, the crack resistance of concrete is evaluated by the critical stress intensity factor (SIF) at the crack tip. This coefficient was called "fracture toughness" SIF (Panasyuk V.V et al.1981) Thanks to the intensive development of linear fracture mechanics, other criteria have been developed that are accepted as characteristics of the material's resistance to crack propagation. For example, the critical opening of a crack at its top, the specific energy of the formation of surfaces, the energy released during crack growth, etc. There are certain dependencies that allow these values to be converted to SIF.

The ratio of the released energy to the increase in the area of the crack, denoted as G, can also be used by analogy with the SIF (stress intensity factor) as a parameter that determines the conditions of destruction. These parameters are related to ratios (Irvin, 1958)

$$\boldsymbol{GE}=K_{ic}^2 \quad \text{in flat stressed state;} \tag{1}$$

$$\boldsymbol{GE}= K_{ic}^2\,(1-\nu) \text{in flat deformation.} \tag{2}$$

It is noted that **G**, by definition, corresponds to the generalized force and has the term "crack propagation force". Generalized force can be determined by analogy with ordinary forces, there are formulas for its calculation related to materials testing methods (Korten H 1976).

$$\boldsymbol{G}=\frac{P^2}{2}\left(\frac{dc}{dA'}\right) \quad (3)$$

where ***P*** is breaking load; ***C*** is compliance of the sample with a crack; ***A*** is the area of a crack that formed again.

It can be seen from equation three that **G** does not depend on the stiffness of the structures or the testing machine, but only depends on the change in compliance of the cracked specimen as the crack length changes.

In this work to determine the force of crack propagation, samples were tested as plates with dimensions of 100x80x4 cm, filled with different amounts and lengths of fibers. The slabs were produced in specially made forms in a horizontal position and compacted with laboratory-type vibrators with standard characteristics. During the forming process, steel traverses measuring 40 x 1000 mm were laid in the directions of the long sides of the plate, into which profiled steel anchors with a diameter of 10 and a length of 100 mm were screwed so that they were molded into the concrete mixture. Thus, the rigidity of the plates during the tests was ensured. At the stage of formation, an initial crack measuring 52 x 2 mm was formed by the geometric center of the plates (Fig. 1).

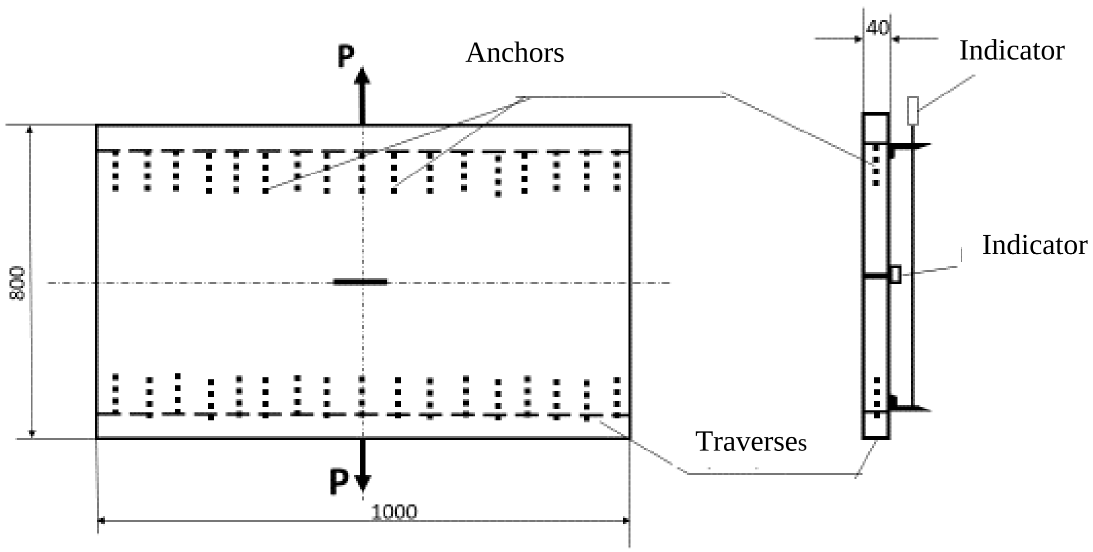

Fig. 1 Diagram of a slab for testing crack resistance

The tests were carried out after 28 days of concrete hardening with a testing machine with a maximum load of 10 tons. The loading speed was assumed to be 600-700 N/min and constant at all loading stages. Tensile forces from the grips of the testing machine were transmitted to the specimens through a hinged device. Thus, the opening of the crack was caused by normal stresses, and the tangential stresses remained equal to zero until the complete destruction of the samples.

Before testing, the plates were bleached and graduated to fix the crack length at different stages of the test. Along the vertical axis of the plates, supports were glued for fixing the indicators.

During the tests, the following were monitored every 30 seconds:

Time ***t***, load ***P***, length of crack 2a, displacement of supports, width of opening crack.

According to the data of these tests, crack resistance was also determined by the equation (Evans A.1979).

$$K_{ic} = K_m + \tau_i \sqrt{\pi L(l)}\ (\text{l-ú})/(1+\text{d}/D_e)^2 D_e \quad (4)$$

where K_m is the crack resistance of the matrix; τ_i – shear stress on the fiber-matrix interface; L is the size of the fiber pull-out zone; ***ú́*** – critical displacement before destruction; d – distance between fibers; D_e is the fiber diameter.

Fracture toughness was also determined by testing samples 70x70x280 without cuts

According to, the destructive stress during bending calculated in a section with a notch, but without taking into account the stress concentration, is found in a number of cases to be lower than the stress in smooth samples. In some cases, the strength of the material in the cut is almost halved, and if the material is heterogeneous enough, this difference practically disappears. Considering the studied material as a heterogeneous material, samples without cuts were tested for the determination of SIF. Fracture toughness was calculated using the equation (Brown J.H 1972).

$$K_{ic} = (3Plc^{\frac{1}{2}})/Bd^2[1.99 - 2.47\ \frac{c}{d}\ + 12.97(c/d)^2 - 23.17(\frac{c}{d)^3} + 28.8(c/d)^4 \quad (5)$$

where – P is destructive load; B is sample width; l is the distance between supports; d is sample height; c is depth of cut.

The specified porosity of the sample was taken as the depth of the cut.

Results and discussions

Crack resistance is one of the most important characteristics that determine the durability of products and structures. The crack resistance of concrete operating in complicated conditions plays an important role in ensuring the reliability of structures.

We calculated the stress intensity factor (SIF) using three methods. In order to determine the SIF according to Brown's method, beam samples measuring 7x7x28 cm per bend were tested. According to this technique, the SIF is directly dependent on the bending strength limit and varies slightly depending on the depth of the cut. Calculations were carried out according to equation (5).

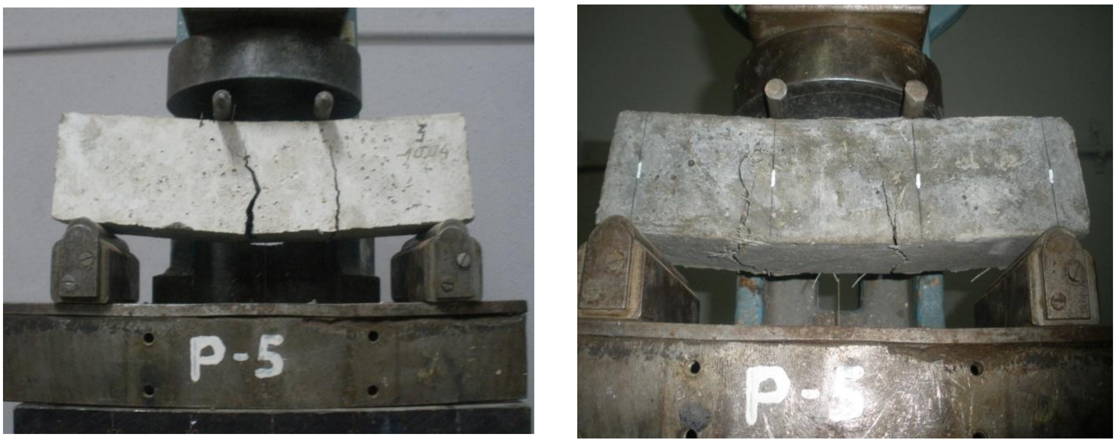

Fig. 2. Samples during bending tests

The stress intensity factor (SIF) was determined in the same way by equation (4) for multiple failure of fiber composites with fiber pullout.

In addition, to assess the crack resistance, the crack propagation force **G** was determined using the method described above. Calculations were carried out according to equation (3).

According to the results of the plates' tests, compliance curves were constructed for the width of the crack opening, and the compliance of the sample was plotted along the ordinate axis, and the half-length of the crack along the abscissa axis (Fig. 4). The ***dc/dA*** parameter was determined by the slope of the tangent to the abscissa axis. Then, knowing the modulus the compositions elasticity determined in advance, the stress intensity factor was calculated. The SIF determined by this method is 10-15% higher than that calculated by equation (4). As the crack opening length increases, fracture toughness increases, which can be seen in the graph (Fig. 5).

Fig. 3. General view of the plate during the tests

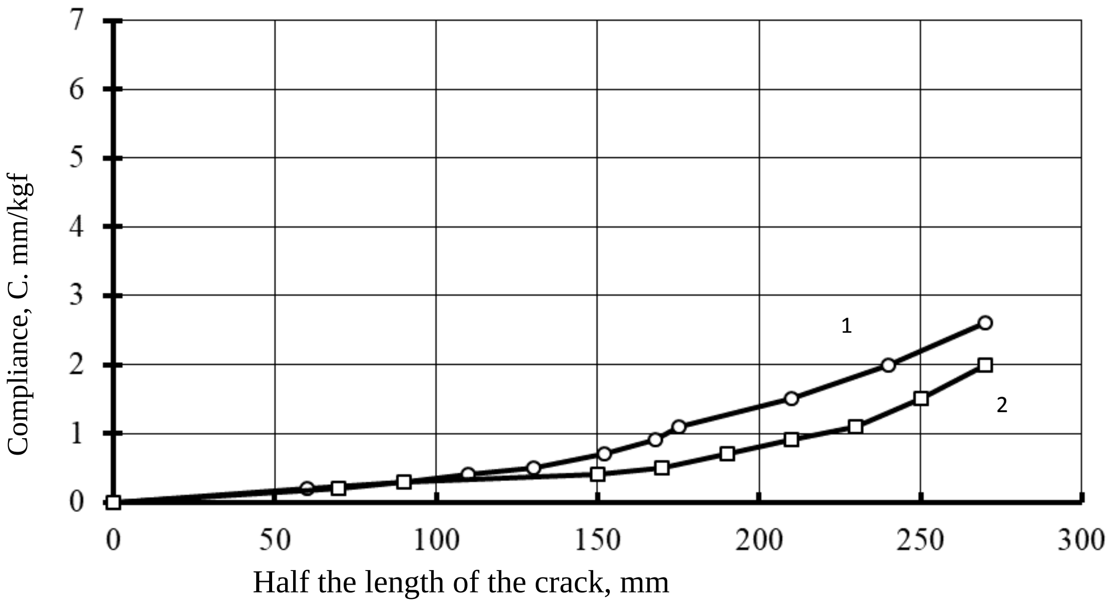

Fig. 4. Compliance curves. 1 composition 4-14; 2- composition 4-30.
(4 is the volume concentration, and 14 and 30 are the fiber length, respectively)

Obviously, as the length of the crack increases, the number of stringer fibers tightening the edges of the crack increases. Additional energy is spent to overcome the frictional stress on the interface, as it can be seen from the graphs in Figs. 5. These curves are characterized by one regularity – the initial straight section, which indicates the instantaneous release of elastic energy. The steep rise of the curve after the straight section is an indicator of the amount of load required to compensate for dissipative energy losses.

In the studied fiber concretes, the fiber length is 2–3 times shorter than the critical fiber length, calculated taking into account tangential stresses on the fiber-concrete surface. Therefore, during tests, the fibers cannot be torn, they will only be pulled out of the matrix. Since the fibers are hydrophobic, they do not have adhesion to the matrix, their contribution to the performance of the material under loads will be based only on overcoming tangential stresses at the fiber-matrix interface. It is obvious that when the width of the crack opening increases, the number of fibers entering the work increases. It is obvious that in order to overcome the frictional forces lying on the surface of separation, the number of fibers is increasing, additional work is required. This additional work corresponds to a rise in the graphs. As the width of the crack opening increases, the fibers that were included in the work at the very beginning already acquire inertia, some of them are pulled out, and some are deformed, decreasing in diameter, and due to the work of the system to overcome the pull-out forces, the pull-out decreases, as evidenced by the decline of the graphs.

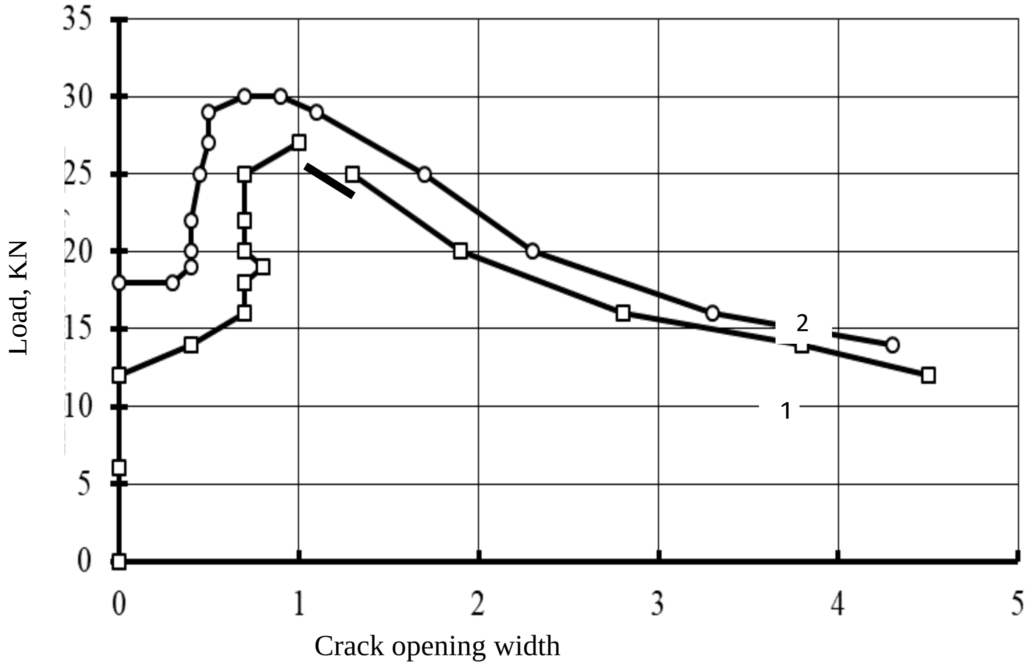

Fig. 5. Curves of the dependence of the crack opening width on the load:
1 is composition 4-14; 2 is composition 4 -30

For comparison, a concrete slab without reinforcement was tested using the same method. It should be noted that upon reaching a load of about 13 KN, the slab instantly split into two parts. It turned out to be possible to determine some parameters using this method. We can find a similar nature of destruction of composite materials in the literature (Guz, A.N. 1982).

The results of calculations of the stress intensity factor (SIF) for different compositions are shown in the table 1.

Table 1

The results of studying crack resistance of fiber-reinforced concrete

Compositions	SIF values determined: KN/м$^{3/2}$		
	By equation (1)	By equation (4)	By equation (5)
4-14	3011	2751	2082
4-22	3251	3022	2273
4-30	3317	3198	2570
Concrete matrix	-	-	1996

Note: The first number in the composition marks is the volume concentration of the fiber, the second is the length of the fiber.

The analysis of the data in the table shows that by introducing polypropylene fibers into the composition of fine-grained concrete, it is possible to obtain compositions in which the stress intensity factor is 4-30% higher than that of the matrix.

Conclusions

The conducted studies showed that all three methods of determining the stress intensity factor in fibrous compositions can be used, despite some differences in the results.

By introducing polypropylene fibers, fiber-reinforced construction compositions with increased deformability and crack resistance can be obtained, even if the length of the fiber is less than critical.

Such compositions can be recommended for use in road and bridge construction, as well as in the repair and restoration works of industrial and road structures.

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ДОСЛІДЖЕННЯ ТРІЩИНОСТІЙНОСТІ ДРІБНОЗЕРНИСТОГО ФІБРОБЕТОНУ З ТОЧКИ ЗОРУ МЕХАНІКИ РУЙНУВАННЯ

Фібробетон почав з'являтися на ринку в 60-х роках минулого століття, і з тих пір інтерес до цього виду армування неухильно зростає. Це пояснюється тим, що таке армування покращує ізотропні властивості бетону. У статті наведено результати дослідження тріщиностійкості бетону, армованого поліпропіленовими фібрами різної довжини та об’ємної концентрації в дрібнозернистому бетоні. Як заповнювач у бетоні використовували відходи мокрої магнітної сепарації Полтавського гірничо-збагачувального комбінату. Відходи сухої магнітної сепарації реалізується у вигляді щебню, тому не займає територію для зберігання, на відміну від відходів мокрого сепарування.

У другій половині минулого століття у світовій практиці була приділена увага армуванню бетону волокнами різного походження, і внаслідок цього в науковій сфері стали з’являтися теоретичні обґрунтування їх практичного застосування, з’явилися методи випробування армованих волокнами композитів з точки зору механіки руйнування.

Для армування використовувалися поліпропіленові волокна різної довжини діаметром 0,2 мм. Поліпропіленові волокна гідрофобні і не мають надійного зчеплення з цементним каменем, тому їх критична довжина досягає 6-7 см. Використання такої довжини волокон викликає труднощі у виробництві бетонної суміші. Тому в роботі використовувалися волокна довжиною від 14 до 30 мм. Було досліджено вплив довжини та об'ємної концентрації волокон на тріщиностійкість бетону В 25 міцності.

Зі збільшенням довжини волокна при однаковій концентрації однорідність суміші погіршується через утворення так званих «їжаків». Методика випробування дрібнозернистого фібробетону на тріщиностійкість розроблена на основі класичної теорії механіки руйнування матеріалів. Результати досліджень свідчать про те, що збільшення довжини та об’ємної концентрації волокон у межах експерименту істотно впливає на тріщиностійкість дрібнозернистого бетону.

Ключові слова: дрібнозернистий бетон, відходи ГЗК, поліпропіленові волокна, об’ємна концентрація, тріщиностійкість, коефіцієнт інтенсивності напружень.