

MECHANICS  
MEHĀNIKAGLASS AND CARBON FIBER CONCRETE MICROMECHANICAL AND  
MACROMECHANICAL PROPERTIESSTIKLA UN OGLEKĻA ŠĶIEDRU FIBROBETONA MIKROMEHĀNISKĀS UN  
MAKROMEHĀNISKĀS ĪPAŠĪBAS

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## 1. Introduction

During the last years is significantly increased compressive strength for concretes which are used in construction industry. Concrete with compressive strength 50-60 MPa, traditionally appreciated like 'high' strength concrete now is changing to 120-150 MPa for skyscrapers and other heavily loaded construction members. Unfortunately, increasing the strength concrete is becoming more brittle. To overcome this situation one effective solution is to use short small fibers for concrete reinforcement. While situation of unstable cracks propagation are acquired soon in loaded unreinforced concrete matrix, cracks can be bridged by fibers, in

the case of fiber reinforced concrete, and the material can carry loads far beyond the plain concrete matrix cracking. Such fibers may be metallic – steel and non-metallic - glass, carbon and aramid. This paper is devoted to experimental investigation of glass and carbon fiber reinforced concrete (FRC) elaboration, casting and matured material strength properties investigation.

### ***Glass fibers***

Glass fibers are produced as E-glass and S-glass. Unfortunately, these fibers are not suitable for use as concrete reinforcement,

because its mechanical strength decrease very rapidly in concrete alkaline environment. The cement matrix is alkaline because the by product (or leftovers) of cement becoming stone again is lime, which is mainly calcium hydroxide, which is very alkaline or basic (see Figure 1). It has to be a special type of glass to put it into cement for reinforcement. This special glass is called AR Glass - Alkaline Resistant. For Cem-FIL AR Glass Fibres the chemical composition is the  $\text{Na}_2\text{O}$   $\text{CaO}$   $\text{ZrO}_2$   $\text{SiO}_2$  system. In our experiments were used such fibers with the properties as

follows: single filament tensile strength  $3.5 \text{ GN/m}^2$ , strand tensile strength  $1.7 \text{ GN/m}^2$ , strain at breaking point (strand) 2.4%,  $E=72 \text{ GPa}$ , filament diameters 14 microns, specific gravity  $2.68 \text{ g/cm}^3$ , length 12 mm, number of fibers 212 million per kg, fiber aspect ratio 857/1, specific surface area  $105 \text{ m}^2/\text{kg}$ .

### ***Carbon fibers***

Carbon fibers are made out of organic polymers such as polyacrylonitrile. To make carbon fibers, the polymer is stretched into alignment parallel with what will eventually be the axis of the fiber. Then, an oxidation treatment in air between 200 and 300 C transforms the polymer into a nonmeltable precursor fiber. This precursor fiber is then heated in a nitrogen environment. As the temperature is raised, volatile products are given off until the carbon fiber is composed of at least 92% carbon. The temperature used to treat the fibers varies between 1000 C and 2500 C depending on the desired properties of the carbon fiber [1]. Carbon fibers are chemically resistant to concrete alkaline environment. On the market carbon fibers are available as strings, ribbons and fabrics (see Figure 2.).

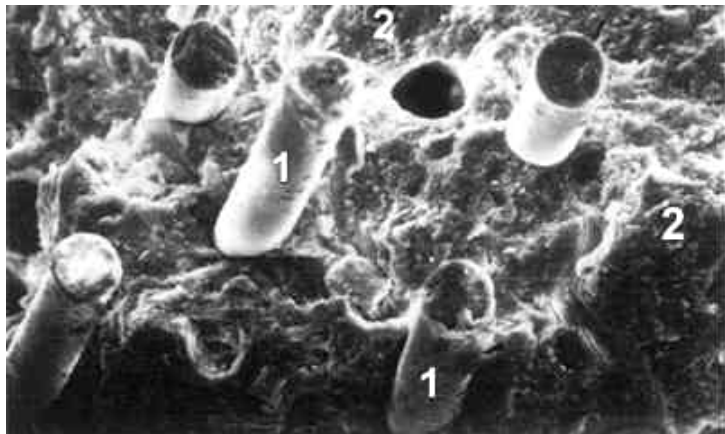


Fig. 1. Dense lime deposits around filaments of conventional glass FRC after 1 year under water; 1- AR glass fiber; 2- Lime crystals (Picture is property of Cem-FIL Corporation)

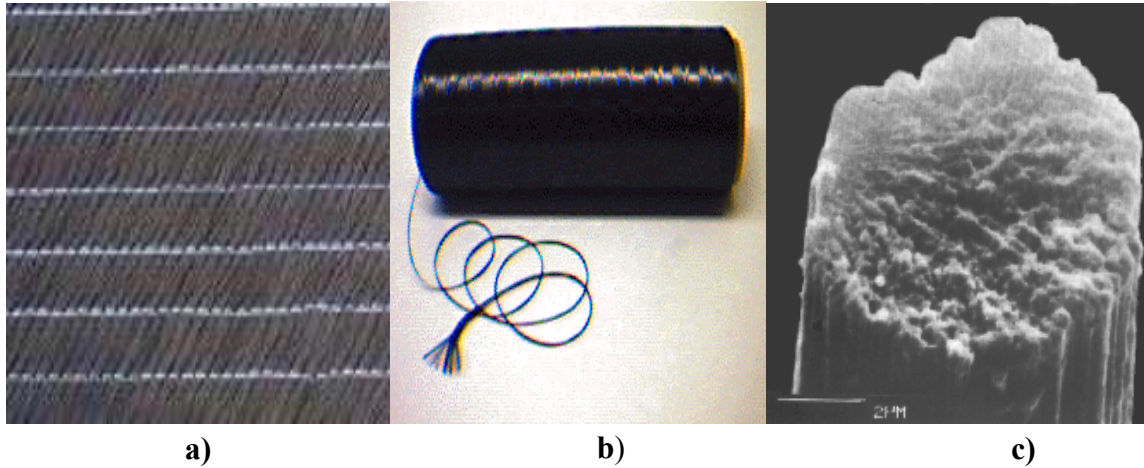


Fig. 2. a, b) Commercially available carbon fiber products; c) single carbon fiber [1]

## 2. Fiberconcrete preparation

### 2.1. Mix design

Basic principles for fiberconcrete still the same like for conventional concrete. Fibers are observed as aggregates with specific elongated form. The main common principles are: Low water/cement ratio; aggregate packing based on "ideal" grading curves; water content determination on the principle of absolute volumes [3]. Specific in FRC mix design is the following:

- Fibers can be observed as aggregate with determined specific surface and very unfavorable shape, what requires more paste content to provide normal workability. It may be achieved by correction of aggregate "ideal curve" to provide good workability "lifting up" small size tail on the grading curve.
- It is important to provide good contact zone between fibers and cement paste, so water/cement ratio must be as low as possible.
- To achieve good workability and strength characteristics, superplasticizer and mineral micro fillers must be used.
- Aggregate cross-section maximum linear size must be not larger then the length of fibre (if fibers of one size are used).

For the total mix volume corresponding formulae can be used [4]:

$$1 = \frac{M_c}{\rho_c} + \frac{M_{Ag}}{\rho_{Ag}} + M_w + M_a + \frac{M_f}{\rho_f}, \quad (1)$$

where  $M_c$  is cement content [kg];  $\rho_c$  is specific weight of cement [ $kg/m^3$ ];  $M_{Ag}$  is weight of aggregates [kg];  $\rho_{Ag}$  is specific weight of aggregates [ $kg/m^3$ ];  $M_w$  is water content [ $m^3$ ];  $M_a$  is air volume in concrete [ $m^3$ ];  $M_f$  is fiber content [kg];  $\rho_f$  is specific weight of fibers [ $kg/m^3$ ].

### 2.2. Mixing sequence

Fibers were used in our investigation had a form of strands (bundles) (see Figure 3.a). Static electrical forces haven't allowed separate fibers in the mix during dry mixing. Therefore in



a)



b)

Fig. 3. a) AR glass fibers before adding into concrete; b) glass fibers with concrete ingredients (mixed dry)



a)



b)

Fig. 4. a) AR glass fiberconcrete mix; b) the same mix after applied external vibration

this case is not possible to obtain fibers homogeneous distribution in the mix with other fiberconcrete ingredients (see Figure 3.b). Fiberconcrete concrete was obtained mixing ingredients in wet way adding fibers in small portions during mixing. Were investigated mixes with volume amount of fibers  $V_f$  from 0.4% to 4% (12 different mixes were prepared). Different strand length were investigated. All mixes were stiff and not workable (see Fig. 4.a). Using the vibrations mixes were mixed and casted into the mould (see Fig. 4.b). Situation was very similar for glass and carbon fiber concretes.

### 3. Tensile strength investigation

Fiberconcrete prismatic samples with the size 10x10x40 cm were elaborated. With the goal to control the location of macro-crack formation place, samples were cutted by dimant saw at the middle of the bottom surface of the prism (at the depth of 1 cm, thickness of the saw was 2 mm) and were tested under 4 point bending conditions (distances between supports were: 30 cm between bottom and 10 cm between upper). 5 cm were the distance from the each edge to the nearest bottom support. Fully computer driven testing mashine Zwick -150 (with ultimate force 150 kN) were used.



Fig. 5. a) Macro-crack is crossing glass fiber bundle which is laying in crack's plane. Bundle is poorly penetrated by concrete paste (fibers are free of cement paste) and was worked as initial micro-crack in material; b) pulled-out fibers in bundles are crossing crack's plane

On both sides of the middle of the prism were mounted displacement transducers. Electrical signal from displacement transducers were synchronized with applied load signal (from Zwick 150 computer) through data collecting station Spider 8 (see Figure 6). Averaged value from both sides transducers was established as beam midpoint deflection value. Fiberconcrete samples were tested under displacement control loading conditions with the pass rate 0.1 mm/min [5]. Stress- prism midpoint deflection diagrams for glass fiber and carbon fiber concrete samples are shown in Figure 7 and 9. Plots in Figure 7 corresponds to short 12 mm AR-glass fiber strands fiberconcrete tensile strength evaluation. In all cases concrete matrix with the same compressive strength were used. In all cases all curves have approximately the same initial elastic behaviour region (linear part on each curve at loading beginning). In this region stretched material is staying solid, all load is carrying concrete matrix while fibers in the material are not fully stretched. Next part of the curve corresponds to concrete matrix disperse cracking with one or few macrocracks formation in more heavily stretched part of a bended prism.

Tensile load bearing function in the prism crosssection is transforming from concrete matrix to fibers bridging macrocracks flanks. This region is slightly non-linear and is extending to each curve peak value. From the peak value, intensive fibers and strands pulling-out from the



Fig. 6. Fiberconcrete prism under 4-point bending test

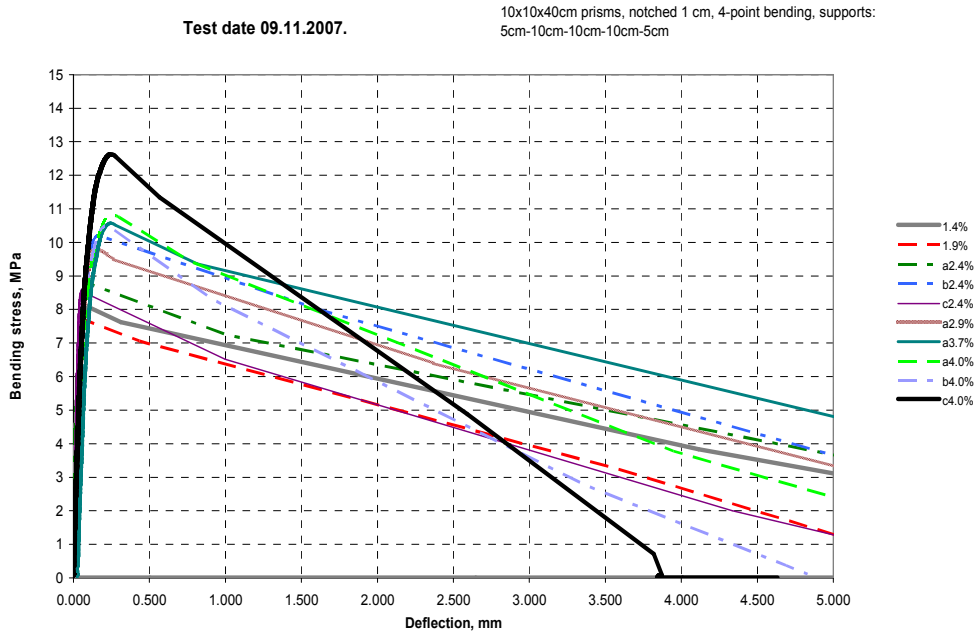


Fig. 7. Stress-midpoint deflection diagrams for glass fiberconcrete (subjected to 4-point loading) with fiber content  $V_f$  from 1.4% to 4%, and fiber strand length equal to 12 mm matrix is latched simultaneously with partial fiber breakage in the most loaded strands, bridging the main macrocrack. Consequently, fibers amount increase in concrete leads to increase of the maximal bearing stress (peak value on the curve). The fibers amount started with 1.4 % at the beginning leads to bending stress peak value equal to 8 MPa and correspondingly last ratio was used 4.0 % which gave peak value higher than 12 MPa. For high fibers volume fraction values we have the saturation (in our case  $V_f = 4\%$ ). This saturation can be explained by lower rate of concrete paste penetration into bundles, for high values of  $V_f$  (in this case fresh fiberconcrete is very stiff and unworkable). In this case, each bundle pull-out force is decreasing.

Post cracking behaviour (curve part after the peak value on Figures 7 and 9) is quit different for fiberconcretes with short (12 mm glass fibers at Fig. 7) and long ( 40 mm long carbon fibers at Fig. 9) fibers. Performed observations shown, that fibers pull-out and partial rupture micro-mechanism is the main mechanism that is governing fiberconcrete tensile strenght at post cracking stage.

#### 4. Tensile fracture micro-mechanics

Macro-crack one flank surface view is shown on the Figure 8. Microscopical investigation shown, that during fiberconcrete mixing, glass fiber bundles are working like small pumps, absorbing water from concrete (by capillary forces) at the beginning stage of mixing fiberconcrete ingredients. If bundles in concrete are not splitting (or splitting partially), only fibers on the bundle outside surface are in contact with cement paste. In this case only small part of fiber amount is participating in increase of concrete tensile strength; simultaneously bundles are staying filled by water and are empty out of cement paste.



Fig. 8. Crack surface of broken AR-Glass fiber concrete prism

During fiberconcrete hardening, this water (from inside the bundles) partially is participating in concrete matrix hydration and partially is vapouring. Empty bundles are increasing air content and are working as initial cracks, decreasing mechanical fiberconcrete properties (see Fig. 5.a). Microscopical macro-crack's surface investigation shown two different scenario of fiber bundle participation in tensile load bearing, bridging crack flanks after concrete matrix cracking: a) bundle is fully or partially laying on crack surface (bundle or bundle major part, for longer bundles) angle to crack surface plane  $\sim 0^\circ \div 15^\circ$ . In this case, depending on the rate of concrete paste penetrating the bundle, bundle is playing the role of initial micro-crack in material, weakening material cohesive strength (in our investigation we haven't observed fully penetrated by concrete paste bundles). Situation is shown in Figure 5.a and can be recognized at Figure 8; b) bundle is crossing crack plane under angle  $>15^\circ$ . In this case bundle is currying tensile load bridging crack flanks, and is broking by two mechanisms: partially pulling out fibers from the concrete and partially breaking through fibers in the bundle (see Figure 5.b).

## 5. Fiber pull-out experiments

While fiber bundle pullout mechanism was recognized as the main micro-mechanical mechanism of post-cracking fiberconcrete behavior few fibers pull-out experiments were realized with the goal to understand and appreciate fiber bridging effect in fiberconcrete post cracking behaviour. Two glass fiber were embedded into concrete orthogonally to concrete sample surface on the depth of 1 cm. After that it was pull-out by external stretching force. Force – fiber clamping point displacement diagram for two fibers is shown on the Figure 10, similar diagram for fiber bundle is shown on the Figure 11. For two fibers first fiber break very rapidly leads to the break of second fiber and its pull-out (both fibers are breaking at the distance lower than full embedded length -1 cm). For fibers bundle nature is similar- at first stage are breaking fibers embedded into the concrete matrix (fibers forming outer circle of the

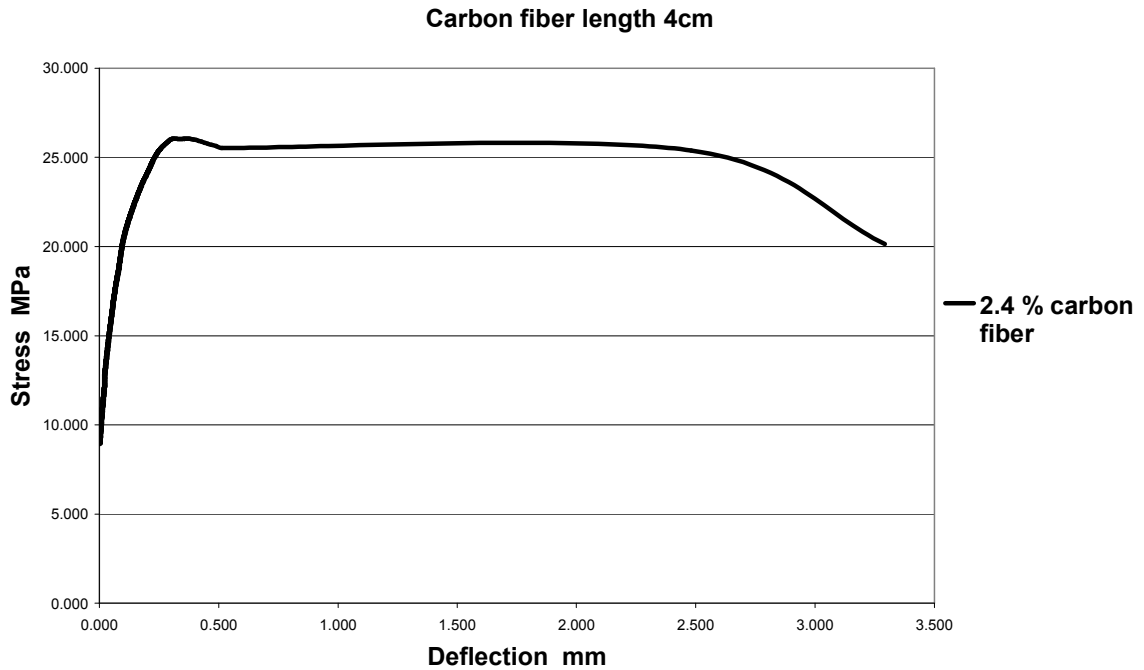


Fig. 9. Stress-midpoint deflection diagrams for carbon fiberconcretes (subjected to 4-point loading) with fiber content  $V_f = 2.4\%$ , and fibers strand length equal to 40 mm

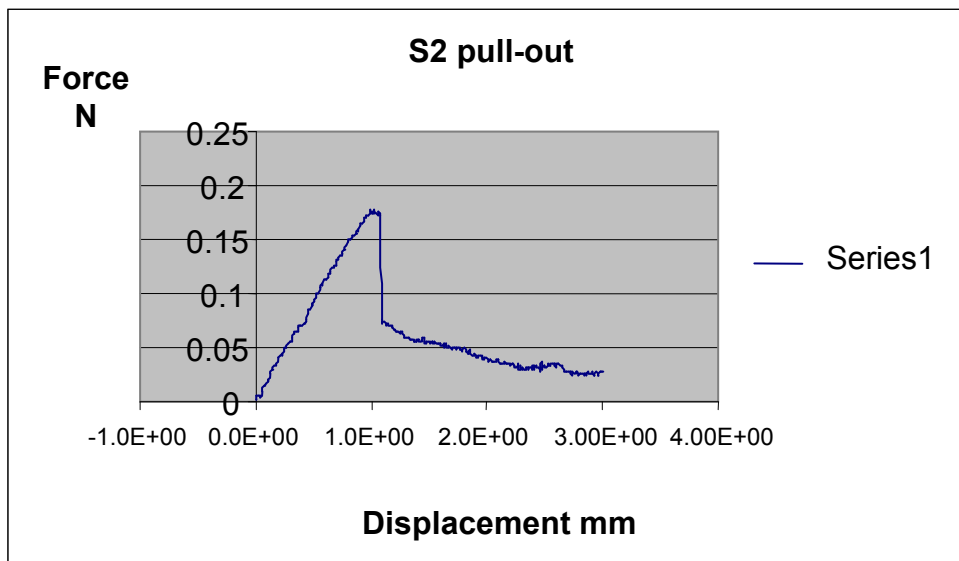


Fig. 10. Pull-out test result for two glass fibers

bundle), after that fibers which are forming internal bundle core (partially penetrated by concrete paste and free of concrete paste) are pulling out and rapturing (second peak on the Figure 11).

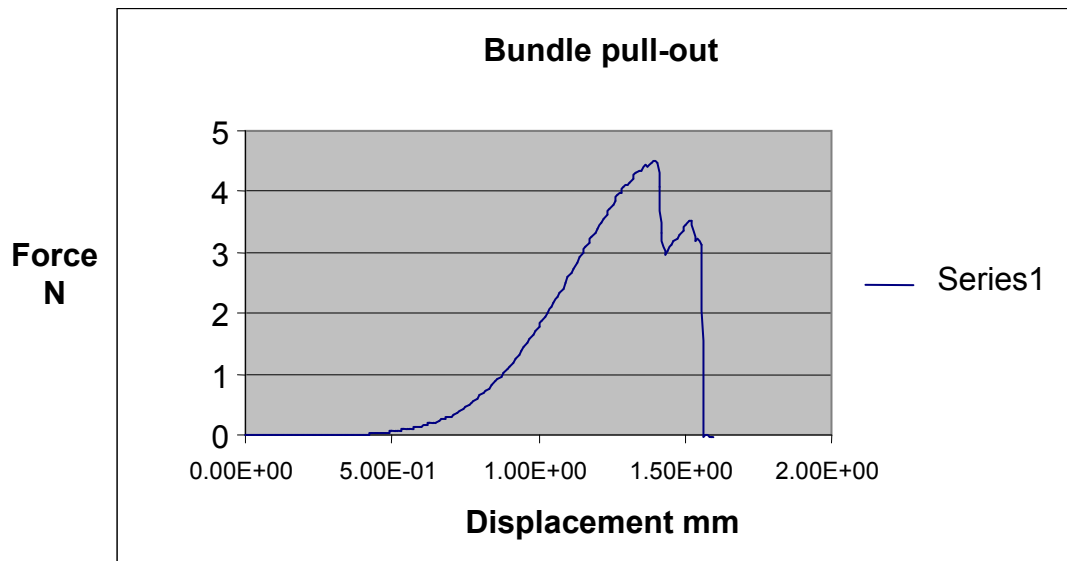


Fig. 11. Pull-out test result for a bundle (having approximately 1200 fibers)

## Conclusions

Were performed experimental investigations of the glass and carbon fiberconcrete tensile strength nature under 4-point bending loading conditions. Experiments show, that the main micromechanical mechanism of load bearing at post cracking stage, is the fibers pull-out from the concrete matrix with simultaneous partial fibers rupture in the bundles.

Performed fibers pull-out tests explained the particular work of each fiber and fibers strand in loaded cracked fiberconcrete.

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**Krasnikovs A., Habazs A., Šahmenko G., Lapsa V. Stikla un oglekļa šķiedru fibrobeta mikro-mehāniskās un makro-mehāniskās īpašības**

Pieliekot īsās stikla vai oglekļa šķiedras betonam, tiek iegūtas materiāla jaunās īpašības - materiāls kļūst kvazi plastisks. Kad šķiedru daudzums pārsniedz 0.5% no tilpuma, jūtami palielinās tā stiepes stiprība. Diemžēl palielinot šķiedru daudzumu, betonā ātri samazinās tā kustīgums un iestrādājamība. Rakstā ir apskatīti dažādi fibras iemaisīšanas paņēmieni, lai iegūtu šķiedras vienmērīgu sadalījumu gala produktā pie relatīvi augstas šķiedru koncentrācijas (1% - 4%). Raksts veltīts ar stikla un oglekļa šķiedrām armētā fibrobeta stiprības izpētei. Tika veikta salīdzinošā analīze fibrobeta prizmu (iepriekš iezāģēti prizmatiski paraugi ar izmēriem 10x10x40 cm) četru punktu lieces testu rezultātiem ar eksperimentiem, kuros dažāda skaita šķiedru kūļi tika rauti ārā no betona matricas („pull-out” eksperimenti). Tika konstatēts, ka galvenais plīsušā betona (betona ar makro-plaisām) slodzes nešanas mikromehānisms ir šķiedru izvilkšana un daļēja pārraušana kūļos, kas armē betonu.

**Krasnikovs A., Khabbaz A., Shahmenko G. and Lapsa V. Glass and carbon fiberconcrete micro-mechanical and macro-mechanical properties**

Adding short glass or carbon fibers to concrete new mechanical material behaviour is achieved- material starts to behave as plastic. When fiber volume fraction is more than 0.5% significantly increase the tensile strength. Performing experiments with relatively high fiber content (1% - 4%) different fiberconcrete mixing techniques are described in the paper, obtaining fiber homogeneous distribution in material. In present paper are shown the results of experimental tensile strength and post cracking behaviour investigations which were performed on glass and carbon fiberconcrete. Fiberconcrete prisms were subjected to 4-point bending. Experiments were shown, that the main load bearing micro-mechanical mechanism, on the post cracking stage, is the fibers pull-out from the concrete matrix with simultaneous partial fibers rupture in the bundles. With the goal to investigate this micro-mechanism were made few fibers and fibers bundle pull-out tests. Results of the performed tests were compared with observations obtained during 4-point prisms bending. Analysis explained the particular work of each fiber and fibers strand in loaded cracked fiberconcrete.

**Красников А., Хабаз А., Шахменко Г., Лапса В. Микромеханические и макромеханические свойства бетона армированного стеклянными и углеродными волокнами**

Добавление коротких стеклянных или углеродных волокон в бетон приводит к появлению у материала новых нетипичных свойств - материал становится квазипластичным. При превышении объемной долей волокон 0.5% значительно повышается прочность на растяжение. В работе описаны различные эксперименты и методы перемешивания фибробетона с целью получения однородного распределения волокон в материале с относительно высокими концентрациями волокон (1% - 4%). Приводятся результаты экспериментального исследования прочности на растяжение при изгибе. Призматические образцы испытывались на четырёхточечный изгиб. Экспериментально были установлены основные микромеханизмы прочности на критической стадии - выдергивание волокон из матрицы с одновременным разрывом части волокон в пучке. Результаты экспериментов сравнивались с проведенными микромеханическими тестами на выдергивание разного числа волокон из бетона. Проведенный анализ выявил роль отдельных волокон в пучке и объяснил поведение пучка в растрескивающемся фибробетоне.