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Naučni rad

FIBER REINFORCED CEMENT COMPOSITES-IMPROVEMENT OF MECHANICAL AND DEFORMATION PROPERTIES

CEMENTNI KOMPOZITI-UNAPREĐENJE MEHANIČKIH I DEFORMACIONIH OSOBINA

D.Lj. Jevtić [1], D.M.Zakić[2], A.R.Savić[2]

[1]Faculty of Civil Engineering, University of Belgrade and guest professor, AG Faculty, Banja Luka, RS, BiH

[2] Faculty of Civil Engineering, University of Belgrade, Serbia

Izvod

U ovom radu su prikazani rezultati sopstvenih laboratorijskih ispitivanja u kojima se istražuje uticaj čeličnih vlakana kao mikroarmature na promenu svojstava cementnih kompozita tipa maltera i betona. Ispitivane su mešavine – kompoziti tipa maltera koji su imali konstantan (identičan) sadržaj cementa, peska i silikatne prašine. Druga vrsta maltera – kompozita sadržala je 60 kg/m^3 čeličnih vlakana kao i jedan superplastifikator. Ispitivane su fizičko-mehaničke karakteristike kako mikroarmiranih maltera, tako i etalona (zapreminska masa, čvrstoća pri savijanju, čvrstoća pri pritisku). Ispitivanja na kompozitima tipa betona uključila su određivanje zapreminske mase, mehaničke čvrstoće i deformaciona svojstva. Rezultati ispitivanja ukazuju na poboljšanje svojstava mikroarmiranih kompozita.

Ključne reči: *Kompozit, malter, beton, superplastifikator, čelična vlakna.*

Abstract

This paper presents the results of authors' laboratory testing of the influence of steel fibers as fiber reinforcement on the change of properties of cement composite mortar and concrete type materials.Mixtures adopted - compositions of mortars had identical amounts of components: cement, sand and silica fume. The second type of mortar contained 60 kg/m^3 of fiber reinforcement, as well as the addition of the latest generation of superplasticizer. Physical and mechanical properties of fiber reinforced mortars and etalon mixtures (density, flexural strength, compressive strength) were compared. Tests on concrete type cement composites included: density, mechanical strengths and deformation properties. The results showed improvement in the properties of fiber reinforced composites.

Key words: *Composite, Mortar, Concrete, Superplasticizer, Steel Fibers, Silica Fume.*

1. INTRODUCTION

Contemporary Civil engineering is permanently setting new conditions concerning the quality of engineering materials. These conditions have to be completely fulfilled in order to increase the durability, serviceability and cost-effectiveness of modern buildings. The composite materials, which will be the main subject of this paper, are offering great possibilities in the field of research and combination of more advanced solutions in order to keep up with contemporary trends.

Fiber reinforced cement (FRC) composite materials are basically mortar and concrete composites made with addition of different types of fibers which represent a special micro-reinforcement. Uniformly dispersed fibers are strengthening the cement matrix, thus improving the whole set of properties of the basic material. The cement matrix, as the base, can be reinforced using metalic (steel), synthetic (polymeric), ceramic (glass), or natural (organic) fibers.

Table 1. Significant properties of different fiber types [1]

Fiber Type	**Specific gravity γ_s [g/cm^3]**	**Tensile strength f_t [MPa]**	**Elastic modulus E [GPa]**	**Ultimate elongation ε_{ul} [%]**	**Max. temp. T [°C]**	**Resistivity in alkali environment**
Steel	7,8	500-2600	200	0,5-3,5	—	Resistant
Glass (AR)	2,5-2,7	1500-3700	75	1,5-3,5	—	Resistant
Asbestos	3,2-3,4	550-3500	200	0,6-3,0	—	Resistant
Polypropylene	0,9	300-750	3,5-12,0	6,0-25,0	~160	Resistant
Polyester	1,4	800-1100	10,0-19,0	≤ 5,0	~240	Neutral
Polyethylene	0,9	20-30	0,12-0,40	300-700	~100	Neutral
Polyvynilalc.	1,3	800-900	26,0-30,0	5,0-7,5	~240	Resistant
Acrylic	1,1-1,2	600-900	15,0-20,0	6,0-9,0	~150	Resistant
Nylon	1,1-1,4	700-800	7,0-13,0	16,0-20,0	~400	Neutral
Artificial silk	1,5	400-600	6,0-7,0	10,0-25,0	—	—
Carbon	1,6-1,9	550-2600	30-230	1,0-2,0	3000	Resistant
Cellulose	1,2-1,5	200-500	5,0-40,0	≤ 3,0	—	Not resistant
Cotton	1,5	400-700	4,0-5,0	3,0-10,0	—	Not resistant

Besides the properties shown in Table 1, relevant fiber parameters are also: aspect ratio (length/diameter ratio), fiber adhesion capabillity and fiber content (volume fraction). Essentialy, the fiber-reinforcement concept is about the increment of quality of a complex composite material (mortar and concrete) achieved by improving certain properties of fresh and hardened material which are crucial for its practical application. The best effects are achieved in the field of strength improvement (especially in flexure, tension and shear) as well as in ductility increment of the above mentioned composites. Also, good results are obtained concerning the reduction of shrinkage, as well as the improvement of fatigue and impact resistance behavior.

The use of silica fume as a pozzolanic admixture in mortar and concrete types of composites makes possible the modelling and optimization of their properties. This refers to both physical effects of silica fume usage – filling the cavities between the cement grains, and chemical effects, i.e. reactions between SiO_2 from the pozzolanic powder and $Ca(OH)_2$ from the cement (eg. 1).

$$SiO_2 + Ca(OH)_2 + nH_2O \rightarrow CaO \cdot SiO_2 \cdot (n+1)H_2O \qquad (1)$$

Using superplasticizers as chemical admixtures, improvements can be achieved either by increment of consistancy (workability) or, on the other hand, by decrement of water quantity required for the same consistency. The main advantage of the new generation of chemical admixtures lays in the slump preservation for more than 90 minutes, even at increased ambient temperature. This is possible because of the synergetic action between organic compounds (polymers) and inorganic compounds (cement) which are present in the carboxylic ether polymers (polycarboxilate) type of admixtures. These admixtures have long side chains connected to the polymer structure, thus providing the preservation of consistency in time by keeping the cement particles at certain distance.

As it can be observed in Fig. 1 (the Corradi's hypothesis of reaction mechanism), new functional monomer groups serve as so called "parashoots", decreasing the speed of adsorption and thus preserving the initial slump value [2].

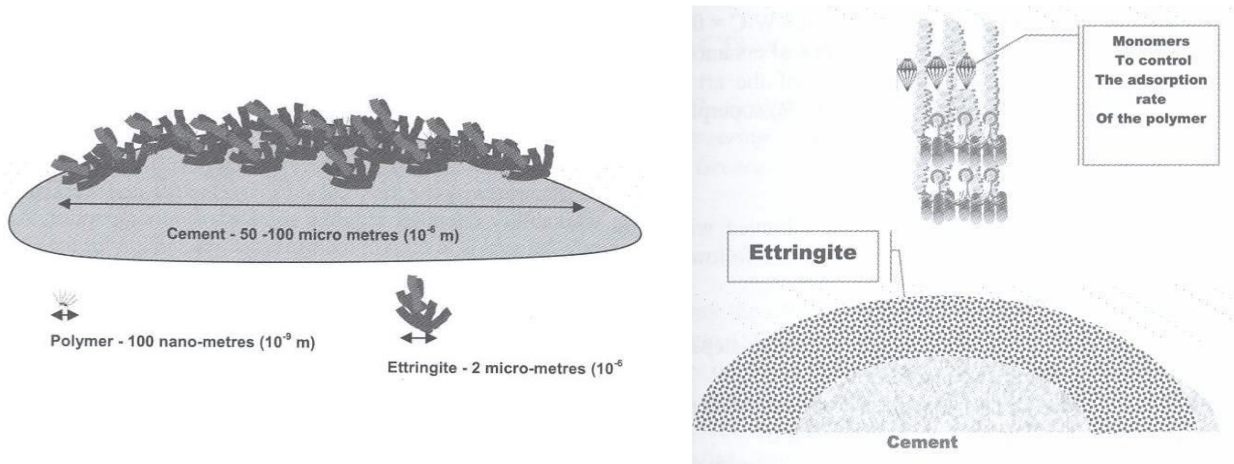

Figure 1. a) Mechanism of action of superplasticizer and b) The "parashoot" effect of monomeric superplasticizer

2. EXPERIMENTAL RESULTS

2.1. Research on mortar composites

This paper presents the results of own experimental research, conducted in the Laboratory for Materials, Institute for Materials and Structures, Faculty of Civil Engineering, University of Belgrade, on two types of mortar – cementitious composites. In fact, the paper compares the reference mortar mixture (marked as “E”) made without the addition of fibers and fiber-reinforced mortar (marked as “V”) with steel fibers added. Experimental studies of mechanical strength (flexural strength and compressive strength), which are the subject of this paper, were conducted on these mortar composites. Adopted mixture compositions, i.e. contents of mortar "E" (reference mixture) and mortar "V" (fiber-reinforced mortar) were identical with regard to the amounts of basic components: cement, sand and silica fume. Fiber-reinforcement (60 kg/m^3) and superplasticizer were present in the second type of mortar (marked as "V"). The presence of the superplasticizer was needed to achieve the same consistency of this composite and reference mortar mixture. The amount of water in both mortars was adopted to achieve the mortar slump flow of 180 ± 20 mm. Cement used in this experimental study was pure Portland cement CEM I 42.5 R produced in Cement Works "Lafarge" Beočin. Standard three-fractional (quartz) sand has been chosen as aggregate for mortars studied in both series. Its fractions (I – 0/0.5 mm, II – 0.50/1.00 mm and III – 1.00/2.00 mm) were used in mass ratio 1:1:1. Therefore, nominally largest aggregate grain in mixture was D=2 mm. Silica fume was present in both series in the amount of 10 % of the cement mass. Chemical composition of silica fume is given in Table 2. Specific surface area by the BET method amounted to 6120 cm^2/g, and density of silica fume was 2.23 g/cm^3.

Table 2. The results of chemical analysis of silica fume

LOI	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**TiO_2**	**Na_2O**	**K_2O**
2.76%	94.62%	0.23%	0.10%	0.35%	0.11%	0.03%	0.45%	1.32%

LOI – Loss on ignition

Admixture type superplasticizer named "Glenium 51", produced by M.A.C. s.p.a., Treviso, Italy, was added in amount of 1% of the cement mass. This admixture of newer generation is based on carboxylate ethyl polymers with long side chains, which provide sustained consistency for a longer period of time (see Fig. 1). Steel fibers used as fiber-reinforcement were locally produced. The manufacturer of the fibers was "Spajić" company, Kobišnica, Serbia. Adopted fibers were bent on ends (hooked), dimensions 30x0.6 mm, with aspect ratio l/d =50, in quantity of 60 kg/m^3 (0.45% of volume). Basic properties of these fibers are presented in Table 3, and Figure 2 shows the shape of fibers.

Table 3. Basic properties of fibers declared by the manufacturer "Spajić"

Parameters	Declared Properties
Type and shape	Steel fibers bent on both ends (hooked)
Cross section	Circle
Tensile strength	min. 1100 MPa
Melting point	app. 1500°C
Angle of bending	min. 45°
Total length (A)	30±2 mm
Thickness (E)	0.6±0.1 mm
Length of unbent part (B)	20±1 mm
Length of bent part (C)	4.5±1 mm

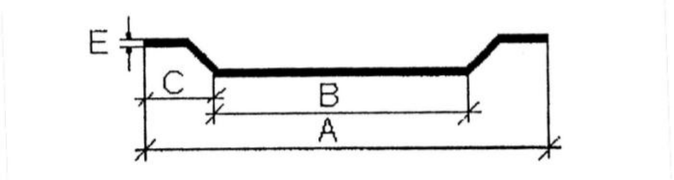

Figure 2. The shape of fibers used as fiber-reinforcement

In order to examine the mortar properties, 15 prismatic (4x4x16 cm) specimens were made of each composite type. Specimens were cured in a mold and in humid environment for the first 24 hours, and afterward, until the day of examination, constantly in water. Comparative examinations were conducted on fresh mortar (density measurement) and on hardened mortar (measurement of flexural and compressive strength) after 2, 4, 7, 28 and 90 days. The average values of the three measurements for each type of mortar have been represented in Table 4. as well as on Fig. 3, 4 and 5.

Table 4. Overview of physical and mechanical properties of tested mortars

Age (days)	Density (kg/m^3)		Flex.strength (MPa)		Increment (compared to refer.) (%)	Comp.strength (MPa)		Increment (compared to refer.) (%)
	Series ''V''	Series ''E''	Series ''V''	Series ''E''		Series ''V''	Series ''E''	
2	2290	2143	4,5	3,4	32,35	24,5	21	16,66
4	2278	2135	7,9	5,0	58,00	38,2	29	31,17
7	2265	2130	8,9	6,0	48,33	46,3	34	36,17
28	2251	2090	9,5	6,65	42,86	68,5	53	29,25
90	2244	2082	9,8	7,3	34,25	85,3	66	29,24

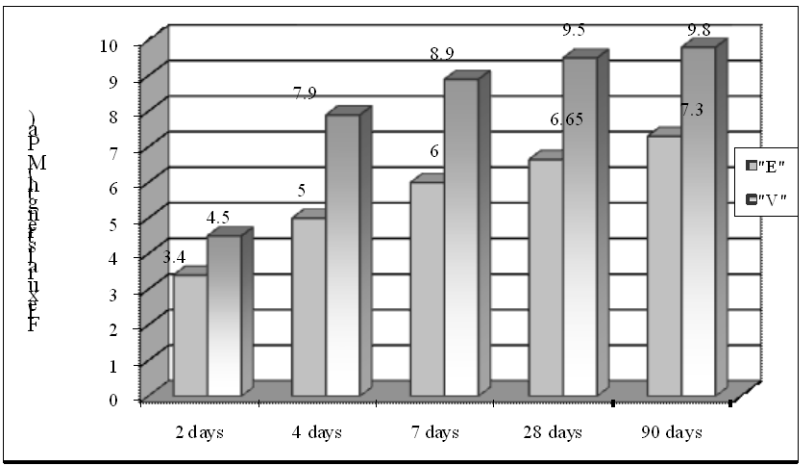

Figure 3. Comparative review of flexural strength on both series ''E'' and ''V''

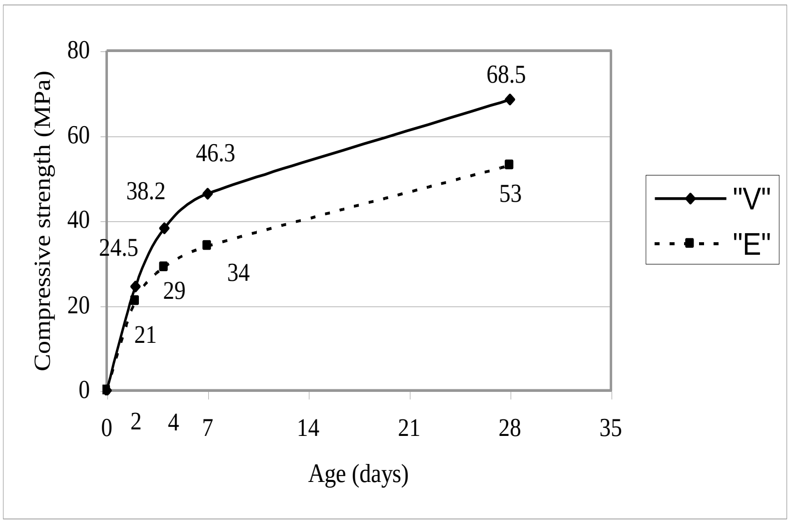

Figure 4. Compressive strength growth in time

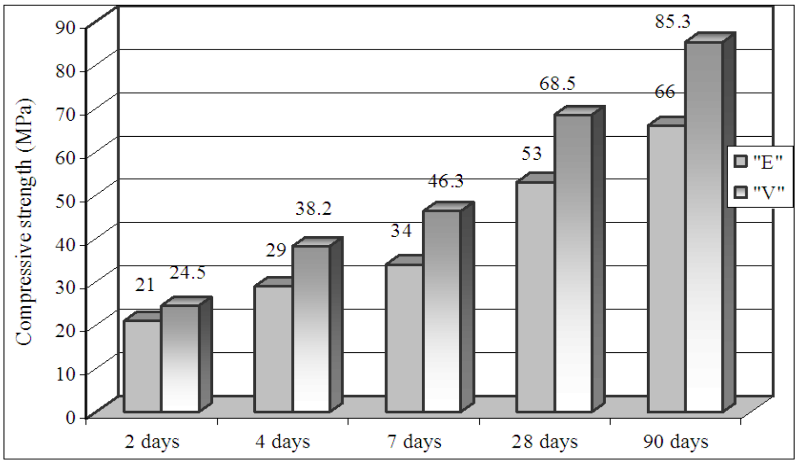

Figure 5. Comparative review of compressive strength on both series ''E'' and ''V''

2.2. Research on concrete composites

Research on concrete included mix design and proportion based on cement, silica fume and river aggregate separated in three fractions, steel fibers, as well as admixture type superplasticizer. Steel fibers bent on ends, dimensions 50x1.0 mm (aspect ratio l/d = 50), produced by "Spajić", were used in these analyses, too. Silica fume was specified as "SikaFume HR/-TU", produced by "Sika", Switzerland. Admixture named "Viscocrete 5-800 Multimix" from the same producer was applied. Cement marked as PC 20M (V-L) 42.5 R "Lafarge" Beočin was used in this research. Two concrete mixes (series marked as 1 and 2) with different quantities of cement (320 and 350 kg/m^3) were made. Quantity of silica fume amounted to less then 10% of cement mass and can be considered as constant (in mix 1-9.4% and in mix 2-8.6%). Quantities of aggregate were constant (1900 kg/m^3) as well as quantities of steel fibers (25 kg/m^3). Both mixes had fluid consistency, and the quantity of water was varied in order to obtain the same starting consistency according to the slump test (12-13 cm). Measured density of fresh concrete amounted to 2385 kg/m^3 (for mix 1) and 2450 kg/m^3 (for mix 2) – see Table 5.

Table 5. Properties of fresh concrete

Type of concrete	m_c [kg/m^3]	m_{SiO_2} [kg/m^3]	m_a [kg/m^3]	γ [kg/m^3]	m_v/m_c	*Initial slump Δh [cm]*	*Slump after 45 min Δh [cm]*
1	*320*	*30*	*1900*	*2385*	*0.5*	*13*	*8.5*
2	*350*	*30*	*1900*	*2450*	*0.425*	*12*	*8.0*

Compressive strength tests were performed on cube shaped (20x20x20 cm) specimens, at the age of 3, 7 and 28 days, while the splitting tensile strength was measured only at 28 days old specimens (cylinder shaped specimens, 30 cm high and 15 cm in diameter). The results of the research, (represented as the average of three measurements) are shown in Table 6. The photograph given as Figure 6 shows the specimen after the splitting tensile test. The photograph shows that steel fibers continue to bridge the crack after the break [3], [4].

Table 6. Overview of physical and mechanical properties of studied concrete

Age (days)	Compressive strength $f_{p,\,sr}$ (MPa)		Splitting tensile strength $f_{zc,\,sr}$ (MPa)	
	Series ’’1’’	Series ’’2’’	Series ’’1’’	Series ’’2’’
3	23,8	26,0	–	–
7	34,9	36,7	–	–
28	49,2	51,8	3,6	3,8

Figure 6 . Spliting tensile test - Steel fibers continue to bridge the crack after the breakage of the specimen

Figure 7. Shear strength test

Testing of shear stress properties showed that in the case of fiber reinforced concrete great increase (app. 61%) of this property appeared (Fig 7), [5]. As it can be seen from Figure 8, the fiber reinforcement of a cement-based matrix by using steel fibers contributes to the substantial improvement of toughness and ductility of concrete. As both of the two stress-strain diagrams are shown at the same coordinate system, it is obvious that the ductility of the composite - which could be defined as the surface between the σ-ε line and x-axis, in the case of fiber reinforced concrete (series 2) greatly exceeds the ductility of the reference concrete (series 1). The testing was conducted using the equipment for monitoring and acquisition of stress-strain data which was connected to the computer [6].

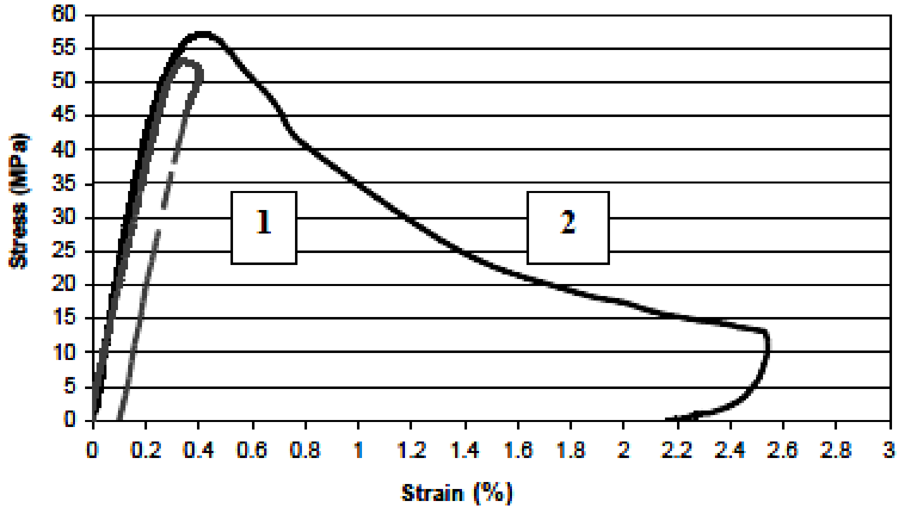

Figure 8. Stress-strain diagrams of both series of concrete, 1- reference and 2 – FRC

3. CONCLUSIONS

The presented results undoubtedly exhibit great improvement in mechanical properties for fiber reinforced mortar (FRC) made with the addition of steel fibers (“V”) in comparison to the reference mixture series (“E”). The addition of steel fibers in the amount of 60 kg/m^3 (0.45% of volume), combined with admixture type superplasticizer, gave higher strength, both flexural and compressive, at all ages. Better effects were observed in flexural strength tests (increase of 32-58%), but the compressive strengths were significantly increased (increase of 17-36%) as well. Table 4 gives a detailed overview of the results. According to these investigations on mortar type composites, the obtained results show very high values of compressive strength (app. 90 MPa).

Based on the results of fiber reinforced concrete (FRC) research, it can be concluded that the compressive strengths measured on specimens of series 1 and series 2 (28 days old) is approximately 50 MPa, which is achieved with relatively low quantities of cement (320 and 350 kg/m^3) and with the minimum addition of silica fume (app. 10%). Given the pozzolanic effect of silica fume in concrete, further growth of strenght can be expected even after 28 days.

Splitting tensile strenght was measured after 28 days, and it amounted to 3.6 MPa (for concrete 1) and 3.8 MPa (for concrete 2). This shows that with a relatively low percentage of steel fiber-reinforcement (25 kg/m^3) significant tensile strenght increment can be achieved; amounting to between 25-30% increase compared to the reference mixture specimens (without fiber reinforcement).

Toughness and ductility of steel fiber reinforced concrete are improved in comparison to normal concrete. It is obvious from the stress-strain diagrams that ductility of the composite made with steel fibers is approximately 12 times greater then the one of the reference concrete.

Testing of shear stress properties showed that in the case of fiber reinforced concrete great increase (app. 61%) of this property appeared.

Due to high mechanical strengths and presence of silica fume, these composites can be successfully used, both in new construction and in repairs and reconstruction of already existing structures. Especially they can be used for industrial pavements, as silica fume and fiber reinforcement represent a guaranty for chemical resistance. The use of steel fibre reinforced composites is recommended in particular for buildings where not only good physical and mechanical properties are required, but also high durability of materials used.

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