Journal of Theoretical and Applied Mechanics, Sofia, 2013, vol. 43, No. 3, pp. 77–86

STRENGTH-DEFORMATION PROPERTIES OF FINE-GRAINED FIBRE-REINFORCED CONCRETES*

M. Mironova, V. Naidenov
Institute of Mechanics, Bulgarian Academy of Sciences, Acad. G. Bonchev St., Bl. 4, 1113 Sofia, Bulgaria,
e-mails: mirona@imbm.bas.bg, naidenov@imbm.bas.bg

[Received 19 November 2012. Accepted 03 June 2013]

Abstract. The main strength-deformation properties of fine-grained fiber-reinforced concretes with different type and quantity of fibres, used as repair overlays, are discussed. The results of mechanical properties of experimental compositions are obtained and generalized for two basis ages and standard laboratory environment. The experimental results are mathematical processed using MATLAB procedure. The basic characteristics – residual strength, toughness indexes and residual strength factors are obtained as a function of type as well as quantity of the hybrid fibre-reinforcement.
Key words: fibre – reinforced concrete, deformation, residual strength, first crack, toughness index.

1. Introduction

Fibre structural reinforcement turns the hardened brittle concrete into a more flexible composite system, and with identical characteristics of its entire cross section. The material is capable of absorbing energy and carrying larger tension stresses under cyclic loading and crack development. Thus, a number of concrete mechanical characteristics are improved, i.e. resistance to brittle fracture, residual strength after the first crack opening (i.e. the "first crack" strength), fatigue strength under long term loading and fracture toughness. As a result, concrete remains intact even after the exhaustion of its carrying capacity, while fibres hamper crack widening and extension.

These properties explain why cement containing composites is widely used as a repair overlay of existing and damaged concrete and asphalt internal and external pavements, roads, bridge slabs, parking lots, sidewalks etc.

*Corresponding author e-mail: mirona@imbm.bas.bg

The accumulated research experience, adopted regulations and the world-wide practice prove its capabilities [1, 2, 3].

There is practically no experience in Bulgaria on the use of fibre-reinforced concrete (FRC) as an overlay of existing infrastructure facilities. A limited practice of in-door casting of concrete overlays on previously built massive conventionally reinforced foundations and slabs exists. Note, that the overlays are relatively thin (7–10 cm), power floated and finished FRC [4].

Hence, the necessity of studying and disclosing the strength-deformation behaviour of such composites is especially actual due to the accumulated serious national problems urgently requiring regulation of the methods and practice of repair of infrastructural facilities subjected to long-term exploitation.

2. Experimental program

The above arguments motivate the execution of this experimental program. Its task is to find the characteristic values of parameters which are of crucial importance for the calculation of thin (5–7 mm) overlays of fine-grained FRC (with different fibres and fibre combinations). The decision to perform the study following basically the American standard [5] is motivated by the possibilities of using samples whose dimensions of the cross section are commensurable with the thickness of the studied repair overlays. Thus, the interpretation of results becomes simpler. Additional possibility of a more detailed characterization of the ductile behaviour of FRC, considering three deformation intervals, is also available. Such a set up better suits the specificity of an external loading of variable intensity applied.

The samples (cubes 7.07 $\times$ 7.07 $\times$ 7,07 cm) were prepared from pure clinker cement CEM I 52.5 (HOLCIM Bulgaria), fine aggregate (river sand-fraction 0–4 mm, the Negovan quarry, Sofia), coarse aggregate crashed stone (fraction 4–8 mm, the Studena quarry, Sofia) and a carboxylate super plasticizer DYNAMON SX, MAPEI, Italy. Concrete mix design is given in Table 1.

Table 1. Mix design

Components	Amount, kg/m^3
Cement CEM I 52,5 (HOLCIM Bulgaria)	360
Fine aggregate (river sand) 0–4 mm	780
Coarse aggregate (crashed stone) 4–8 mm	1140
Carboxylate admixture DYNAMON SX	3.60
Water	152

Six different compositions of a fine-grain concrete were studied. One of them was taken as a basis, i.e. it was not reinforced. The remaining five concretes were fibre-reinforced by means of fibres of different type and fraction – see Table 2. The fibres used in the study were provided by the Bulgarian branch of PROPEX CONCRETE SYSTEMS, USA.

Table 2. Compositions

Fiber type	Fiber quantity (kg/m^3) in a composition No					
	1	2	3	4	5	6
Fibermesh F300	–	0.900	0.900	0.900	0.900	0.900
Enduro 600	–	–	4.00	–	–	–
Novocon XR 1035	–	–	–	25.00	–	–
Novocon HE 0630	–	–	–	–	25.00	40.00

Fibermesh F300 are anti-shrinkage polypropylene micro-fibres with graded length from 6 to 24 mm (fibrillated for secondary reinforcement with a potential for residual strength performance).

Enduro 600 are polypropylene corrugated fibres for structural reinforcement, 45 mm length.

Novocon XR 1035 are continuously deformed circular segmented steel macro-fibres for structural reinforcement, 35 mm length.

Novocon HE 0630 are steel macro-fibres with hooked end for structural reinforcement, 35 mm long.

3. Experimental results

The samples were kept in standard laboratory environment and tested on the 28-th and the 180-th day, respectively, following the standard requirements [5]. Initially, bending tests were performed and "load-deflection" curves were recorded. Then, samples were subjected to compression tests.

The experimental "load-deflection" curves were mathematically smoothed, enabling one to automatically calculate the characteristic values of bending strength and strain. These quantities were needed to calculate the equivalent strengths and toughness indices.

A special procedure within MATLAB environment, using part of the built-in functions and algorithms, was developed to process the experimental results. It reads and interpolates the specific data, using a built-in interpolation procedure which covers all experimental points. Then, the algorithm arranges data into "elastic" and "plastic" areas.

Both "elastic" and "plastic" data are separately processed, looking for the best polynomial approximation and (if allowable) for a generalized polynomial over the whole interval of deformation variation. An interpolation polynomial is used with a degree chosen such as to cover all experimental points and provide an approximation curve of minimal mean quadratic deviation. Considering both areas and the generalized polynomial (if any), the degree of the interpolation polynomial can be varied in accordance with the actual experimental data.

Using the relation "loading-deflection, an "equivalent loading" is specified in the plastic area as a mean integral quantity. Since the number of points in the plasticity area is small, and the points are registered considering different intervals of deformation variation, one needs to interpolate them using a very small interval. For that purpose, a procedure where the interpolation curve should pass through all points is used, and the curve slope between two neighbouring experimental points should be considered. The plasticity area is divided into equal intervals and filled with a sufficient number of points with coordinates "deformation-load". Thus, the integral of the equivalent load can be numerically found with sufficient accuracy:

$$F_{\text{equiv}} = \frac{1}{d_0 - d_1} \int_{d_0}^{d_1} F(x)dx, \tag{1}$$

where:

d_0 – initial value of the first crack limit;

d_1 – final value of the plasticity limit;

k_d – proportionality coefficient with variable value – $k_d = 3$; 5.5; 10.5.

The first value of d_1 is automatically found, and it corresponds to the maximal load, while the second one is found as a product of the coefficient k_d and the value of d_0. Note, that those data can vary in each specific case:

$$d_1 = k_d d_0.$$

The results of each mathematical procedure are graphically visualized. They are generalized in Table 3. The relations "bending strength-deflection" for the studied composition and for 28 and 180 days of age, are shown in Figs 1–7.

The following notations are used:

f_c – compression strength, MPa;

f_b – bending strength, MPa;

d_0 – deflection at the moment of the first crack occurrence, μm (the "first crack" displacement);

d_1, d_2, d_3 – deflection which are 3, 5.5 and 10.5 times larger than the first crack one, μm;

σ_1, σ_2, σ_3 – residual strength under deflection d_1, d_2, d_3, MPa;

σ_{1eq}, σ_{2eq}, σ_{3eq} – equivalent bending strength under deflection which is 3, 5.5 and 10.5 times larger than the first crack strength, MPa;

I_5 – toughness index as a ratio between: (i) – the "curve" area (i.e. the area bounded by the curve) regarding deflection which is 3 times larger than that registered at the occurrence of the first crack (the "first crack" deflection), and (ii) – the curve area prior to the occurrence of the first crack;

I_{10} –toughness index found as a ratio between: (i) – the curve area corresponding to a deflection which is 5.5 times larger than the first crack one, and (ii) – the curve area prior to the occurrence of the first crack;

I_{20} – toughness index found as a ratio between: (i) – the curve area corresponding to a deflection which is 10.5 larger than the first crack one, and (ii) – the curve area prior to the occurrence of the first crack;

Residual strength factor $R_{5,10} = 20(I_{10} - I_5)$;

Residual strength factor $R_{10,20} = 10(I_{20} - I_{10})$.

The physical meaning of those characteristics determines the upper limits of the toughness indices I_5, I_{10} and I_{20} – 5, 10 and 20, respectively. They correspond to an ideal-plastic behaviour of the composite prior to the occurrence of the first crack, and to a pure plastic behaviour of the material next to the first crack occurrence. Practically, such a material behaviour is hard to attain since an ideal optimization of the concrete composition, type and quantity of the fibre-reinforcement is needed.

As residual strength factors $R_{5,10}$ and $R_{10,20}$ are derived from the toughness indices, they provide data on the residual strength level next to the occurrence of the first crack in different deformation intervals.

3. Result analysis

The variation of the compression strength found, considering the two ages, follows the normal logic of FRC performed using the specified fibres and fibre fractions. Those fibres do not significantly affect material compression strength whose logical increase at the age of 180 days is established for all studied concrete compositions. Hence, it follows that the material strength has not been significantly affected by the type and quantity of the fibre reinforcement. However, it seems useful to asses the material characteristics under bending. First of all, note that bending of samples fabricated from material with composition 2 (Fig. 2 – FIBERMESH F300 reinforcement) essentially differs from bending of samples of the basic non-reinforcement concrete (composition 1, Fig. 1), and values of all strength-deformation parameters can be measured. Hence, the ductile behaviour of the composites, thus reinforced, becomes more expressed, outlining the capabilities of those fibres to participate in the composition of thin concrete repair layers.

Reinforcement by means of different quantities of macro-fibres (compositions 3, 4, 5, 6) results in measurable increase of the material carrying capacity next to the occurrence of the first crack, and the values of the strength-

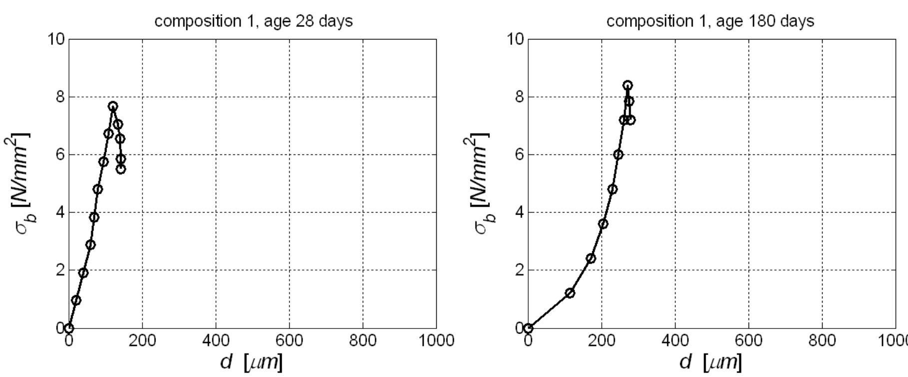

Fig. 1. Composition 1, age 28 and 180 days

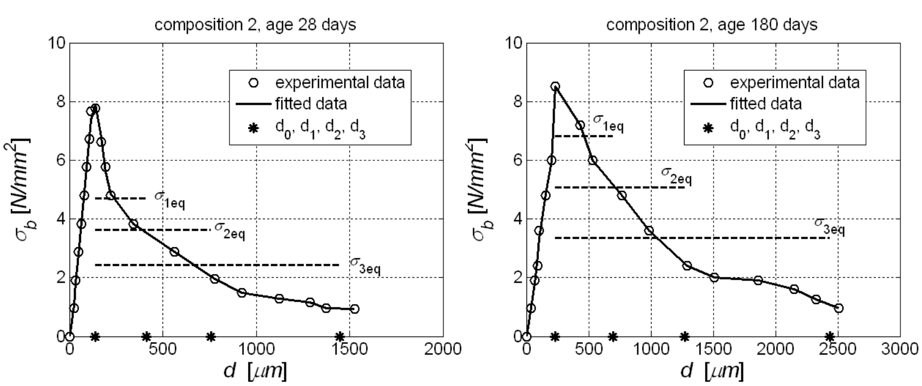

Fig. 2. Composition 2, age 28 and 180 days

Table 3. Generalized strength-deformation characteristics

composition	1		2		3		4		5		6	
age, days	28	180	28	180	28	180	28	180	28	180	28	180
f_c, MPa	39.62	40.65	40.18	40.51	36.64	39.57	36.83	40.44	41.46	47.75	36.93	43.68
f_b, MPa	8.33	8.64	7.78	8.52	8.45	8.90	8.24	8.66	8.63	10.30	8.87	9.72
σ_{1eq}, MPa			4.70	6.82	5.71	6.97	6.09	6.50	5.98	7.53	7.06	8.33
σ_{2eq}, MPa			3.63	5.07	4.64	5.26	5.20	.69	5.12	6.06	6.55	7.57
σ_{3eq}, MPa			2.42	3.35	3.50	4.21	4.25	4.40	4.37	4.38	5.81	6.17
σ_1, MPa			3.23	5.29	4.53	5.26	4.85	5.67	4.81	5.69	6.56	7.97
σ_2, MPa			2.05	2.61	3.42	2.94	4.34	4.45	4.13	4.00	5.85	6.16
σ_3, MPa			0.92	1.03	1.37	1.08	1.33	2.19	3.26	2.04	4.09	3.68
d_0, μm	120	221	138	232	152	248	169	256	183	287	194	305
d_1, μm			414	696	456	744	507	768	549	861	582	915
d_2, μm			759	1276	836	1364	929.5	1408	1006.5	1578.5	1067	1677.5
d_3, μm			1449	2436	1596	2604	1774.5	2688	1921.5	3013.5	2037	3202.5
I_5			2.27	3.76	2.54	3.63	2.78	2.85	3.25	2.95	2.73	3.48
I_{10}			3.95	6.29	4.65	6.16	5.35	5.62	6.26	5.35	5.70	7.12
I_{20}			5.57	8.78	7.41	8.59	9.23	9.18	11.29	8.15	10.65	12.25
$R_{5,10}$			33.54	50.58	42.19	50.71	51.27	55.30	60.21	47.94	59.42	72.75
$R_{10,20}$			16.16	24.92	27.60	24.25	38.80	35.64	50.29	29.03	49.56	51.25

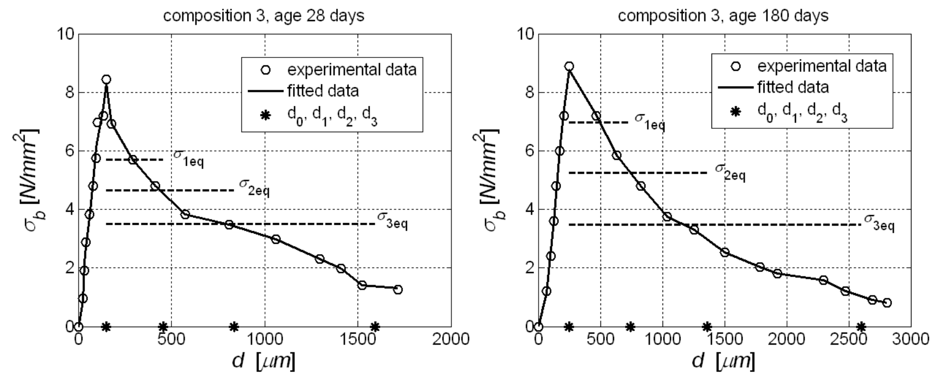

Fig. 3. Composition 3, age 28 and 180 days

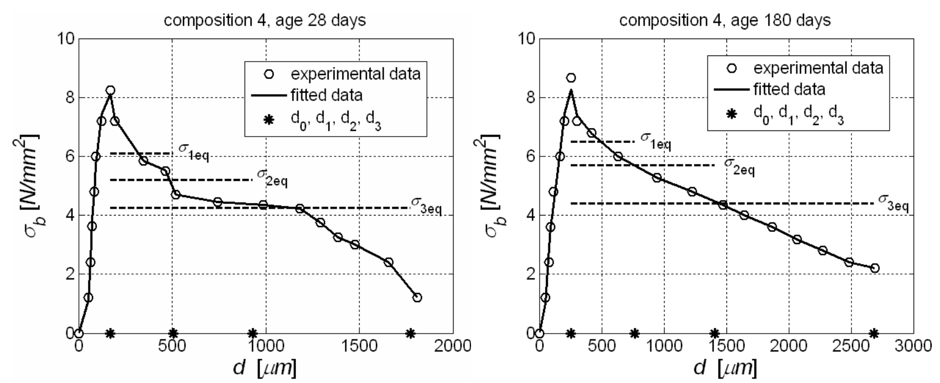

Fig. 4. Composition 4, age 28 and 180 days

deformation characteristics increase at the age of 180 days (Fig. 3, 4, 5, 6).

Note, the relative similarity between the behaviour of compositions 3, 4 and 5, reinforced by means of fibres of different types. This determines a certain equivalence between a reinforcement performed by using 4 kg/m^3 of polypropylene macro-fibres (composition 3) and that performed using 25 kg/m^3 of steel fibres (compositions 4 and 5). Some significant differences are also observed. They are mostly related to the net deflections, residual strength within the increasing interval of deflection and toughness indices, i.e. to the residual strength factors, where the outline of the advantages of the steel fibre reinforcement is relatively better.

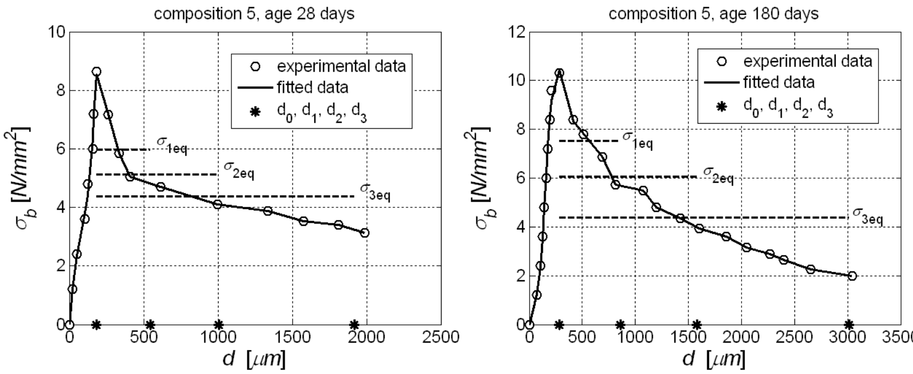

Fig. 5. Composition 5, age 28 and 180 days

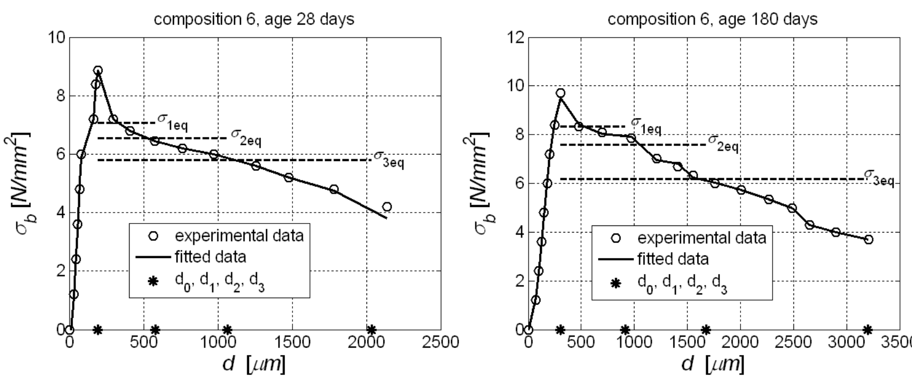

Fig. 6. Composition 6, age 28 and 180 days

As a whole, such a performance of composites reinforced by means of structural fibres of the outlined fraction can be expected, considering the calculated toughness indexes and the residual strength factors. Index I_5 is not larger than 3.5, I_{10} is within the limits 4 and 7 , and I_{20} – within the interval 5-12. Such a conclusion is based on the calculated factors of residual strength which do not exceeds a value of 60.

The effect of the different percentage of reinforcement using identical steel macro-fibres (compositions 5, 6) is of special interest. It is seen that an increase of the reinforcement fraction markedly yields increase of the composite ductility (Figs 5 and 6). Besides, a certain increase of the bending strength is also observed next to the first crack occurrence and for the highest reinforcement fraction (composition 6).

4. Conclusions

The study provides a possibility to use effectively the fibre-reinforcement in fractions as it is outlined above. This yields increase of the ductility of regular FRC concretes used for the fabrication of thin overlays. Hence, the level of material performance for such reinforcement fraction is considered to be comparatively high, but further optimization of its composition is obviously possible.

The complex effect of different fibres and reinforcement percentage on concrete deformation under loading of different type is disclosed. Material mix design should consider the type of the expected exploitation loading of a specific structure, on one hand, and the efficiency of the fibre-reinforcement percentages, on the other hand.

Besides the degree of ductility, a number of other factors are also important for the practical use of such composites. These are for instance environmental resistance, frost resistance, wear, type of the finished surface etc., whose effect is planned to be further studied.

REFERENCES

[1] ACI 325.13R-06 Concrete Overlays for Pavement Rehabilitation, Reported by ACI Committee 325.

[2] Bissonnette, B., L. Courard, D. W. Fower, J. L. Granju. Bonded Cement-Based Materials Overlays for the Repair, the Lining or the Strengthening of Slabs or Pavements, RILEM State of the Art Reports, Committee 193-RLS, 2011.

[3] Li, V. C. Driving Infrastructure Sustainability with Strain Hardening Cementitious Composites (SHCC), Advances in Cement-Based Materials, London, Taylor & Francis Group, 2010, 181–191.

[4] Naidenov, V., St. Draganov. High Performance Concrete Flooring Systems, Proceedings of 9^{th} Int. Conf. on Mechanics and Technology of Composite Materials, Sofia, September 2000, 110–120.

[5] C 1018 – 97 Standard Test Method for Flexural Toughness and First-Crack Strength of Fibre-Reinforced Concrete (Using Beam with Third-Point Loading).