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MECHANICAL PROPERTIES IMPROVEMENT OF FIBER REINFORCED CONCRETE

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Abstract. Fiber reinforced concrete mechanical properties are limited due to low adhesion between polymer fibers and cement matrix. To ensure a strong interaction between the two materials, polypropylene fibers ($d = 0.305$ mm) were modified by an oxygen plasma treatment. The interface interaction was moreover activated using finely ground concrete recyclate, whose individual grains (1–64 µm) ensure an adhesion improvement in interfacial zones. The adhesion enhancement was verified by pull-out tests, when reference and modified fibers were pulled-out from cement matrix specimens. Such obtained results were used as a crucial parameter to numerical simulations of bending tests of specimens ($550 \times 150 \times 150$ mm) with properties following fiber reinforced concrete. It was shown that samples reinforced with modified fibers and contained activating recyclate reached on higher residual bending strength then those with reference fibers.

Keywords: Fiber reinforced concrete, macro fibers, polymer fibers, interfacial shear stress.

1. Introduction

Fiber reinforced concrete (FRC) has became popular at production of prefabricated concrete materials, shotcretes, and industrial high-loaded floors. Such material is composed from polymeric macro-fibers (amount ca. up to 1 % vol. of whole mixture), cement, and aggregate [1, 2].

Technical standards EN 14845-1 and EN 14845-2 describe FRC as structural concrete reinforced with fibers having static effect and fulfilling requirements of EN 14889-2. During three-point bending test of notched specimens $550 \times 150 \times 150$ mm, such FRC has to exhibit, besides, residual strength at least 1.5 MPa at crack mouth opening displacement (CMOD) of 0.5 mm (corresponding deflection 0.47 mm). It is clear that such behavior differentiates the FRCs from strain hardening or engineered composites, where strain-hardening response is required after reaching the elastic limit [1].

D. J. Kim et al. explained that strength limit of a fibrous composite material (including FRC) is a function of fibers volume, fibers length to diameter ratio, and the interfacial interaction between fiber surfaces and matrix. In the field of FRCs, it means that increasing fibers amount weakens the cement matrix mechanical properties in the stage of elastics response during loading. It is therefore clear that fibers amount should be as small as possible. On the other side, once matrix limit of proportionality is reached and the matrix is damaged by the crack, fibers transfer the acting stress across the crack (crack bridging) and thus ensure macroscopic integrity of whole material. Amount of stress transfered via fibers depends especially on their number and on adhesion between fiber surfaces and the cement matrix [3].

However, such adhesion is mostly too poor, especially between polymeric fibers and the cement matrix due to fibers smooth and chemically inert surfaces (related to cement matrix) [4, 5]. Mechanical potential of fibers – tensile strength – is therefore unused.

To avoid issues connected with the poor adhesion between the two materials, some researches have applied additional treatment of fibers in order to decrease their surface free energy and to increase their morphology, both ensuring improvement of bond to the matrix. For these purposes, several types of treatment may be employed, e.g. chemical (use of high alkali solutions) and physical (mechanical roughening) [6–8]. Plasma modification has shown to be a promising technology, combining both the chemical (etching) and physical (roughening caused by a ion bombardment) treatment, as proven by Li et al. from the early 1990s [9, 10] and many other researches later, e.g. [11–14]. It is also worth noting that such treatment has been extended through many industrial fields over the past few years, especially for the surface treatment (roughening, activating, cleaning) of polymeric materials [15]. Therefore, there is no obstacle to apply such technology during surface treatment of the fibers.

Although a benefit of fiber surface treatment was proven from the perspective of "surface science" many times, this was not achieved from the practical point of view, including the field of FRCs. To connect theoretical findings with praxis of civil engineering, we studied an influence of plasma modified fibers on mechanical properties of FRC samples using numerical simulations, following EN 14845-1.

2. Interaction between fiber and matrix

Post-cracking response of FRC is influenced by behavior of one fiber that is pulled out from the matrix. This phenomenon was described by Ch. Li et al. and C. Redon et al. [16, 17]. The behavior is divided into two stages, the first describes chemical interaction between the two materials (P_{deb}), while the second mechanical interaction activated by fiber movement out of the matrix (P_{pull}), concretely:

$$P_{deb} = \sqrt{\frac{\pi^2 E_f d_f^3}{2} (\tau_0 u + G_d)} \tag{1}$$

and

$$P_{pull} = \pi d_f \tau_0 \left[1 + \frac{\beta \left(u - \left(\frac{2\tau_0 L_e^2}{E_f d_f} + \sqrt{\frac{8G_d L_e^2}{E_f d_f}} \right) \right)}{d_f} \right] \times \left[L_e - u + \left(\frac{2\tau_0 L_e^2}{E_f d_f} + \sqrt{\frac{8G_d L_e^2}{E_f d_f}} \right) \right], \tag{2}$$

and τ_0, as a frictional stress after sudden drop following the peak pull-out load, by:

$$\tau_0 = \frac{P_{pull}}{\pi d_f L_e} \tag{3}$$

where E_f is Young's modulus of elasticity of fibers; d_f, fibers diameter; τ_0, interfacial shears tress between fiber surface and matrix; u, fiber free-end displacement; G_d, interfacial bond strength; β, a shear retention factor, parameter describing slip softening / hardening behavior; L_e, fiber embedded length.

3. Fibers and their treatment

3.1. Polymeric fibers

Polymeric macro-fibers were used for all experiments described below. Their geometrical and mechanical properties were as follows: material, polypropylene (PP); morphology, smooth; length, 60 mm; diameter, 305 µm; density, 900 kg/m^3; Young's modulus of elasticity, 6.1 GPa; tensile strength, 440 MPa; elongation, 8 %. Mechanical properties have been determined experimentally, as reported in [18].

3.2. Fiber Treatment

Two fiber types were used: reference (further marked as R) and plasma treated (P30 and P120 according to treatment duration). Plasma treatment was executed using Tesla VT214 device. Treatment parameters were: plasma, cold; gas, oxygen; power of RF source, 100 W; gas pressure, 20 Pa; treatment duration, 30 and 120 seconds.

Name	Cement [wt. %]	Recyclate [wt. %]	W/C [-]
Ref	100	0	0.40
Rec	70	30	0.41

Table 1. Weight proportions of cement matrices.

4. Pull-out tests

Two matrices were used to carry out pull-out tests. The reference matrix (Ref) was made from Portland cement CEM I 42.5R and the modified matrix (Rec) contained 30 wt. % concrete recyclate as a substitution for cement at the form of finely ground powder. The recyclate was used to fill interfacial zones between fiber surfaces and surrounding matrix and thus to ensure the adhesion between the two materials with individual grains. Grain size differed between 1–64 µm, as measured by Blain's method. Matrices compositions are summarized in Table 1. Specimens made from such matrices had dimensions equal to $25 \times 20 \times 30$ mm, contained a single fiber in their centerline (fiber embedded length was equal to samples height – 30 mm). Results of this experiment were used as basic input values for numerical modeling of FRC bending tests.

The whole experiment was carried out using loading frame Veb Tiw Rauenstein FP100. The specimen was anchored by its matrix body to a static part of the frame, while the single fiber, protruded from the specimen body, was caught by a moving frame part. The experiment was displacement controlled at the constant rate of 3 mm/min, finished after reaching to 4.5 mm of fiber-free end displacement (only R and P30 were further used).

Results from pull-out tests – dependence between fiber free-end displacement and force resisting to that – are summarized in Figure 1. It is clear from these results that the maximal force recorded during pull-out reference fiber (R) from the reference matrix (Ref) slightly overcame 10 N, while in the case of 30 seconds plasma modified fibers (P30) and matrix containing concrete recyclate (Rec), the force reached on more than 14 N. Despite of the assumptions, fibers exposed to plasma for 120 seconds (P120) exhibited adhesion to the matrix worse than these modified for 30 seconds. This could be caused by their diameter reduction due to too long treatment. Therefore, such fibers were not used for numerical simulations described below. According to equation (4), shear stresses were calculated from thus obtained results. It was calculated that $\tau_{0,R} = 3.24 \cdot 10^5$ Pa and$\tau_{0,P30} = 4.56 \cdot 10^5$ Pa in the case of reference and 30 seconds modified fibers, respectively.

5. Numerical simulations

Numerical simulations followed procedure of three-point bending test described in technical standard

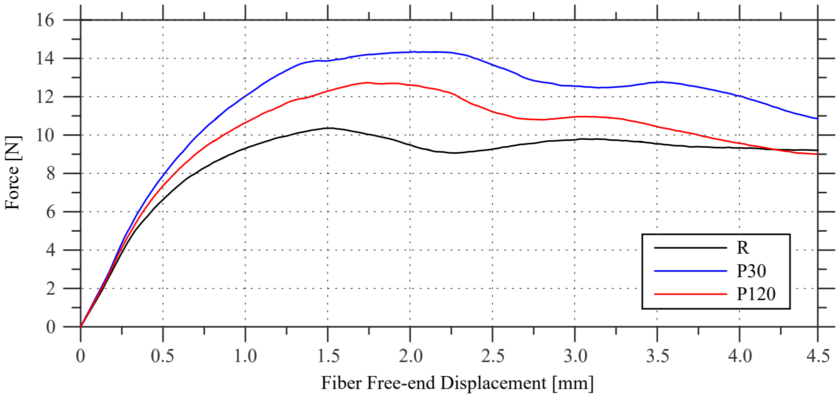

Figure 1. Pull-out behavior of reference and modified fibers.

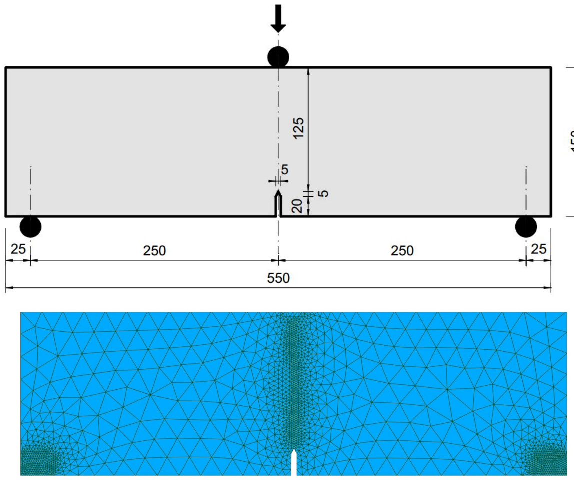

Figure 2. Geometry of FRC specimen (top) and mesh of computational model (bottom).

EN 14845-2. As already mentioned in Introduction, notched FRC specimen 550 × 150 × 150 mm, containing 0.5 vol.% of fibers, has to exhibit at least 1.5 MPa of bending strength in post-cracking phase during midspan deflection of 0.47 mm. To avoid lengthy experimental testing, numerical simulation was employed. SHCC material model [19, 20], suitable also for FRCs, was applied. Mash of the 2D model, counting 3080 of predominantly triangle linear elements, was created in Salome software [21]. Non-linear numerical analysis was conducted using OOFEM software [22], proceeded in 800 steps. Numerical experiment was controlled by displacement. Solution was searched by Newton-Raphson's method. The stiffness matrix was compiled in 2D plain-stress preposition. Geometry of the specimen and mesh of finite elements are shown in Figure 2.

Two calculations were done; the first contained reference, while the second one 30 seconds plasma modified fibers. Mechanical properties of matrix was set to correspond common concrete. All parameters set to numerical model were as follows (reference / modified fibers): E Young's modulus of elasticity of matrix, 20 / 20 GPa; ν Poisson's ratio of matrix, 0.2 / 0.2; G_f fracture energy of matrix, 5.0 / 5.0 N/m; f_t tensile strength of matrix, 2.5 / 2.5 MPa; *softType* a parameter describing post-peak behavior, 3 / 3: Hordijk's softening; *shearType* a parameter describing shear stiffness of cracked material, 1 / 1: constant shear retention; *shearStrengthType* a parameter limiting the magnitude of resulting shear stress acting on crack plane; 1 / 1: the threshold is set to the value of the tensile strength; V_f fiber volume ratio, 0.005 / 0.005; D_f fiber diameter, 0.305 / 0.305 mm; D_f fiber length, 60.0 / 60.0 mm; E_f Young's modulus of elasticity of fibers, 6.1 / 6.1 GPa; G_f shear modulus of fibers, 1.0 / 1.0 GPa; τ_0 frictional shear stress between the fiber and the matrix during debonding, 0.324 / 0.456 MPa; f snubbing coefficient; 0.5 / 0.5; k_f fiber cross-section shape correction factor, 0.9 / 0.9; *FSStype* a class describing type of fiber bond shear strength, 0 / 0: constant shear strength; *fiberType* class of reinforcing fibers, 2 / 2: short randomly oriented fibers; *nCracks* maximal number of cracks, 2 / 2; M exponent related to fiber unloading, 1 / 1; *fibreActivationOpening*, 10^{-6} / 10^{-6}; d_{w0} lower bond allowing to smoothen the traction-separation law for fibers, 10^{-7} / 10^{-7}; d_{w1} upper bond allowing to smoothen the traction-separation law for fibers, 10^{-7} / 10^{-7}.

6. Results

It was found from numerical simulations that residual strength of FRC specimen reinforced with plasma modified fibers (P30) at amount of 0.5 vol.% tightly exceeded 1.5 MPa at CMOD of 0.47 mm. In the same stage, the samples containing reference fibers exhibited only ca. 1.3 MPa. Results from both simulations are imagined in Figure 3, where the green line highlights the minimal bending strength required by EN 14845-2. It is obvious from these results that only FRC containing modified fibers fulfilled these requirements, so this can be considered as structural.

These simulations also revealed that the behavior of both specimens was practically identical in phases

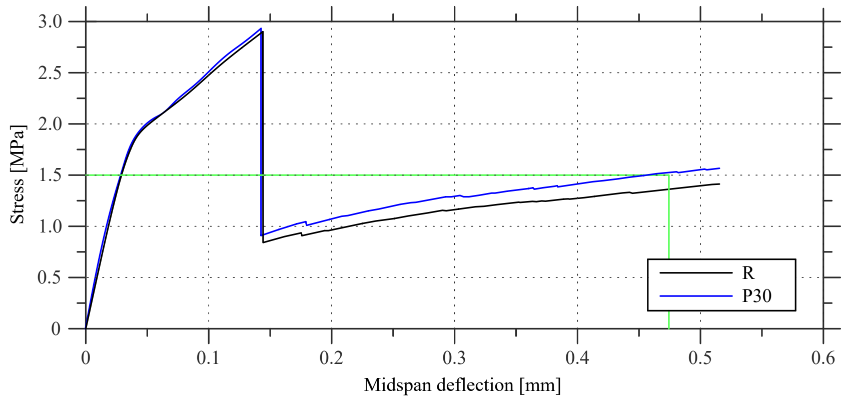

FIGURE 3. Normal tension as a function of midspan displacement.

until the fibers have not been activated yet. After, fibers bridged the opening crack, transfered acting stress and thus ensured macroscopic integrity of specimens. Based on the specimens post-cracking behavior, it is clear that the adhesion between modified fibers and the matrix was increased than in case of reference fibers. This finding proves that interfacial shear stress between the two materials plays an important role from the mechanical response point of view.

7. CONCLUSIONS

This work deals with searching of mechanical behavior of fiber reinforced concrete using numerical simulations of three-point bending tests. Reference and plasma modified polypropylene fibers (d=0.305) were used as reinforcement. Adhesion between these fibers and two types of the cement matrix was examined employing pull-out test. The purpose of the simulation was to find residual bending strength of specimens, following relevant technical standards. Finding were as follows:

- Adhesion between 30 seconds oxygen plasma treated fibers and the cement matrix containing concrete recyclate was higher by approx. 15 % then in the case of reference fibers and reference cement matrix.
- 120 seconds lasting plasma treatment did not bring any benefits in terms of adhesion improvement. Conversely, such treated fibers showed worse adhesion to the matrix than those 30 seconds exposed to plasma. This was probably caused by their diameter reduction as a consequence of too intensive ion bombardment.
- Numerical simulations revealed that residual strength of reference FRC at the midspsan deflection of 0.47 mm was less than 1.5 MPa, so this material did not meet requirements of technical standard EN 14845-2. On the other side, if plasma treated fibers and the cement matrix containing 30 wt.% of concrete recyclate were used, residual strength overcame minimal 1.5 MPa.

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