COMPOSITE FIBER PULL-OUT IN CONCRETES WITH VARIOUS STRENGTHS

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Abstract. Micromechanics of novel types of fibers –composite fibers is under investigation. Fiber manufacturing technologies were analysed. Macrofibers were manufactured using monofilament microfibers: carbon fibers and glass fibers. During manufacturing four types of macrofibers were fabricated: epoxy matrix/carbon fibers with smooth surface (CF1), epoxy matrix/glass fibers with naturally uneven geometry and surface (GF1), epoxy matrix/glass fibers with smooth surface (GF2) and epoxy matrix/glass fibers with rough surface (GF3).Possibiliy of composite fiber to withstand to mechanical pulling out of concrete matrix was investigated experimentally. Single fiber pull-out sampleswere prepared. Three different concrete matrices were designed and used – low (M3), average (M2) and high strength (M1) concretes ranging from 40 to 120 MPa. Experimental results were analysed.

Keywords: composite fibers, fiber reinforced concrete, high strength concrete, fiber pull-out.

Introduction

Fiber reinforced concrete (FRC) is becoming more popular material for structural applications during the last decades. Fibers are adding straight into a concrete mix. FRC is a composite material. Concrete is a matrix and short fibers are working as a reinforcement. Fibers are reinforcing concrete matrix increasing durability, impact resistance and mitigating the initiation and growth of cracks. Steel [1; 2] and polypropylene (polymer) [3] fibers are more popular in building practice. Three factors are important for fibers successful work in concrete of the structural element [2]: high strength, high elastic modulus, and high resistance to pulling out of concrete. Concrete is cracking during hardening because of shrinkage. External load application to the structural element is leading to shrinkage crack growth and additional crack formation. Fibers are bridging cracks. Future crack growth happensdepending on how much submissive fibers are, how easy it is to pull each fiber out of a concrete matrix. Single fiber pull-out test is highly appropriable for these mechanical phenomena investigation [2; 4]. Novel types of fibers –composite fibers look very promising for structural applications. Fibers are comparably light, stiff and strong. It is important to investigate how easy it is to pull single fiber out of a concrete matrix, depending on the matrix compressive strength. This is the subject of the current report.

Materials and methods

Composite macrofibers were manufactured in the RTUConcrete Mechanics Scientific Laboratory. 3 types of fine grainedconcrete were designed and pull-out specimenswere prepared. Simultaneously samples were prepared (cubes) for compressive strength testing. Pull-out specimenswere matured and then tested using the testing machine Zwick Z150.

1. Fiber manufacturing technologies

Fibers were manufactured in three different technologies: fibers were fixed in both ends, fibers were fixed and slightly stretched, fibers were covered by additional rough interlayer giving surface roughness. Fibers were cut in pieces having the length equal to 50 mm. Four different fibers were obtained with diameters ranging in 1.52-2.2 mm (see Fig. 1).

Manufacturing of CF1 and GF1macrofibers. Thread of microfibers was fixed by an upper tail end and fibers were hangedunder the dead weight. The otherend was just fixed to line up the fibers thread. Each individual microfiber filamentwas not specially aligned to the thread longitudinal direction, so some of microfibers in the thread were slightly deviated from a straight direction. Fibers were impregnated by epoxy resin (with curing agent)using a brush. It was necessary to drag the brush over the tow several times until the required amount of epoxy resin was applied.

Fig. 1. **Composite macrofiber manufacturing**: Epoxy matrix/Carbon fiber 1 (CF1), Epoxy matrix/Glass fiber 1 (GF1), Epoxy matrix/Glass fiber 2 (GF2) and Epoxy matrix/Glass fiber 3 (GF3)

Macrofibers GF2 manufacturing: The thread pretension was introduced to get more straight microfibers orientation in the composite macrofiber to ease the fiber manufacturing and laying epoxy. The thread of glass microfibers was tied in the frame, and then it wasstrained by a spring. Individual fiberfilamentsinside the tow were aligned. Glass fibers were impregnated by epoxy resin having smooth surface. Epoxy application was done with a brush or sponge. The sponge was soaked in epoxy resin and it was required several times to drag it over the thread until the required amount of epoxy resin was applied. Then, after epoxy resinwas hardened macrofibers were released from pre-stress and the quality was inspected. Macrofiberswere slightly bent and inspected for tow delamination under microscope.

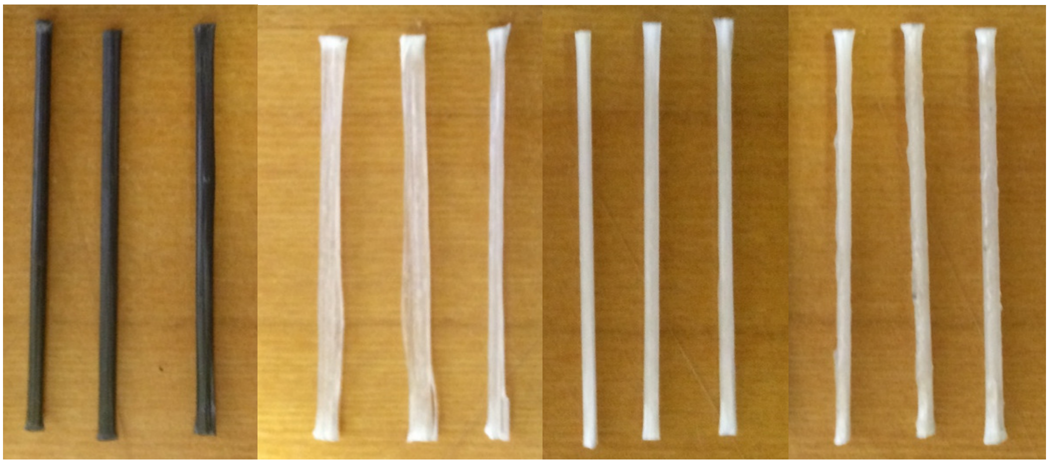


Fig. 2. **Four composite fiber types:** CF1, GF1, GF2 and GF3

Manufacturingof GF3 macrofibers is very similar to GF2. Additionally, the external surface of slightly pre-stressed matured GF2 macrofibers was covered by a thin layer of epoxy resin with blended fine sand (fraction 0-0.5 mm). In such way fibers with rough surface were obtained (see Fig. 2).

Table 1

Macrofibers physical and mechanical properties

Property	**Glass fiber 1 (GF1)**	**Glass fiber 2 (GF2)**	**Glass fiber 3 (GF3)**	**Carbon fiber 1 (CF1)**
Length, mm	50	50	50	50
Diameter, mm	2.18	1.97	2.2	1.52
Aspect ratio, *l/d*	22.9	25.4	22.7	32.9
Number of microfibers	800	800	800	24000
Specific gravity, $kg \cdot m^{-3}$	1850	1200	-	970

Single fiber pull-out tests were carried out using the testing machine Zwick Z150. Pull-out displacement was measured using the non-contact measuring device – video extensometer Messphysik. The measuring principle of this device is the ability to measure displacement between two reference straight lines drawn on the sample. These lines have to be in good contrast with the testing specimen surface. Loading rate – 5 mm·min^{-1} was used for all specimen pull-out tests.

2. Concrete matrix

Portland cement (Aalborg White CEM I 52.5 R) was used as a binder in the experimental mixes, naturally fractioned and washed quartz sand (SaulkalneS 0-1mm) as the main aggregate. Milled quartz sand (Anyksciai Quartz powder 0-120µm) and silica fume (Elkem Microsilica 920 Densified) were used as a micro filler, having micro and nano-size particles. Polycarboxilate based high range water reducing admixture (SIKA D400) was used to control the mix workability.

Tree types of concrete mixtures were designed. The first type concrete mixture is high strength concrete (M1) with the cement content 800 kg·m^{-3}, silica fume, water to cement w/c ratio 0.25. The second type concrete mixture is normal strength concrete (M2) with the cement content 550 kg·m^{-3}, having silica fume and with *w/c* ratio equal to 0.55. The third type concrete matrix was low strength (M3) with the cement content 400 kg·m^{-3}, without silica fume, and w/c ratio equal to 0.75. The amount of the micro-filler was adjusted in order to achieve the paste content 550l ±7 % in all cases.

3. Pull-out specimens

The test specimens were made with pre-defined crack and only fiber bridge forces between two concrete parts (see Fig. 3). Fiber in the sample was symmetrically embedded by the ends in two pieces of concrete separated by a plastic film, perpendicularly to the film plane. The concrete specimens – pull-out and concrete compressive strength specimens were cured in normal conditions 20 ºC, RH > 95 %.

a) b)

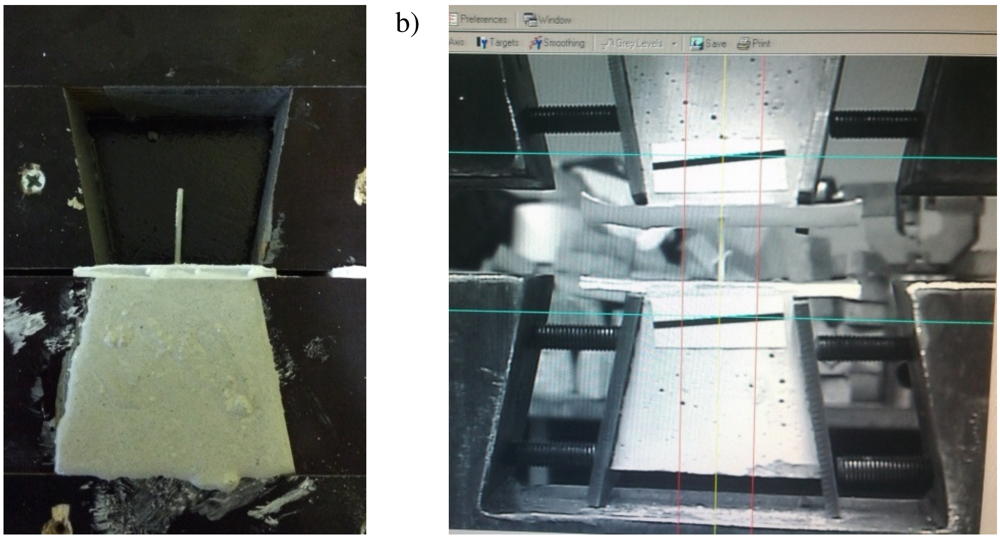


Fig. 3. **Fiber pull-out sample manufacturing (a) and testing (b)**

Results and discussion

1. Concrete compressive strength

Average compressive strength results for concrete matrix types M1, M2 and M3 are presented inTable 2. Matrix M1 has the highest strength, M2 has medium and M3 has the lowest average strength. Matrix type M3 was slightly modified with adding less and more water in the mixture, it resulted in M3A slightly higher and M3B with even lower strength. Concrete compressive strength for M2 and M1 is roughly about 2 times and 3 times higher than M3.

Table 2

Concrete compressive strength at 28 days age

Mixture	Number of samples	Density, kg m^{-3}	Compressive strength, MPa	Standard deviation, MPa
M1	14	2295	122.3	5.31
M2	15	2166	74.86	4.48
M3	12	2120	41.84	4.03
M3A	2	2124	48.90	-
M3B	2	2115	31.33	-

2. Pull-out behaviour

Only averaged curves (over all particular set samples data) for each configuration (fiber type and concrete matrix type) are presented. Averaging was done over the force values for particular samples corresponding to the current value of pulled out displacement. To make the graphical pull-out behaviour representation more readable, pull-out energy was used. Pull-out energy U_{sum} shows the amount of work necessary to pull-out specific fiber.

Photographs of four fiber types are presented in Table 3: table rows correspond to the fiber type, table columns correspond to concrete matrix type.

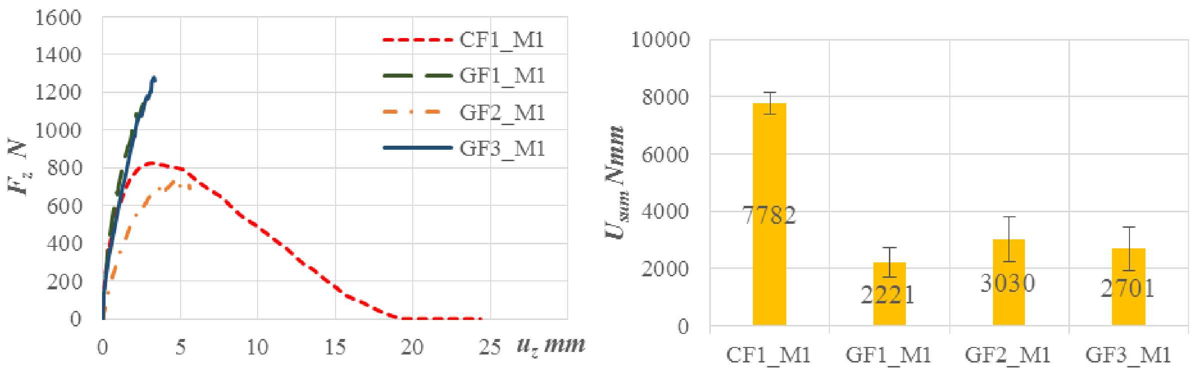


Fig. 4. **Four fiber types in concrete matrix M1. On the left - averaged pull-out curves, on the right - pull-out energy:** CF1; GF1; GF2; GF3

Fibers GF1 and GF3 withstood maximum 1250 N load at 3,1 mm displacement and ultimately failed in concrete matrix M1 (see 4). Fiber delamination from the concrete matrix occurred during tensile loading and failed before fiber pull-out started. Fiber and concrete matrix good adhesion was built up with fiber rough and uneven surface, this did not allow the pull-out process to occur (see Table 3). It can be seen from the photos that the outer par of composite fiber is delaminated and probably it was the reason of rapid failure. Fiber GF2 has a diverse failure mode. Due to fiber even and smooth surface, not only fiber and concrete matrix delamination occurred, but also minor pull-out processtook place inside the macrofiber. Fiber slip changed failure mode: composite fiber filaments started to fail initially at the outside surface. Since there was minor fiber pull-out, GF2 ultimate force was lower than GF1 and GF3. Maximum load capacity for GF1 and GF3 is 1.8 times higher than GF2.

CF1 fibers pulled-out from concrete matrix completely. The CF1 curve is similar to the GF2 curve where minor pull-out process occurred, but carbon fiber CF1 has significantly higher strength, this ensured complete pull-out from the concrete matrix. It can be seen from Fig. 4 4, fiber CF1 delamination from the concrete matrix occurred until the tensile force reached approximately 800 N, after that fiber pull-out took place. The pull-out process takes place at high load rates, with gradual force decrement.

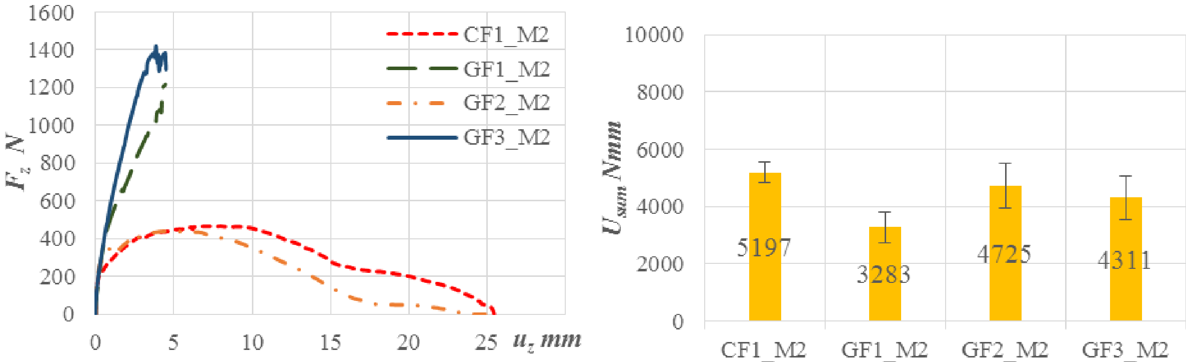


Fig. 5. **Four fiber types in concrete matrix M2, on the left – average pull-out curves, on the right – pull-out energy:** CF1; GF1; GF2; GF3

Fibers with smooth surface CF1 and GF2 pull-out out from the concrete matrix M2 was complete (see Fig. 55). Fibers with uneven and rough surface GF1 and GF3 failed at approximately 1200 N and 1400 N. Failure occurred at 4.2 mm. It can be seen in Table, 3 fiber GF1 and GF3 failure mode is similar in the concrete matrix M2 and M1. Fibers with uneven and rough surface are subjected to rapid failure (all fiber filaments are breaking at the same length) at high load rates. Both fibers CF1 and GF2 are pulling-out from the concrete matrix, up to 5 mm fiber pull-out behaviour is very similar, but even insignificant difference in fiber diameter (see Table 1) allows CF1 to continue load increase during pull-out up to 10 mm. This gives 10 % increase in fiber pull-out energy.

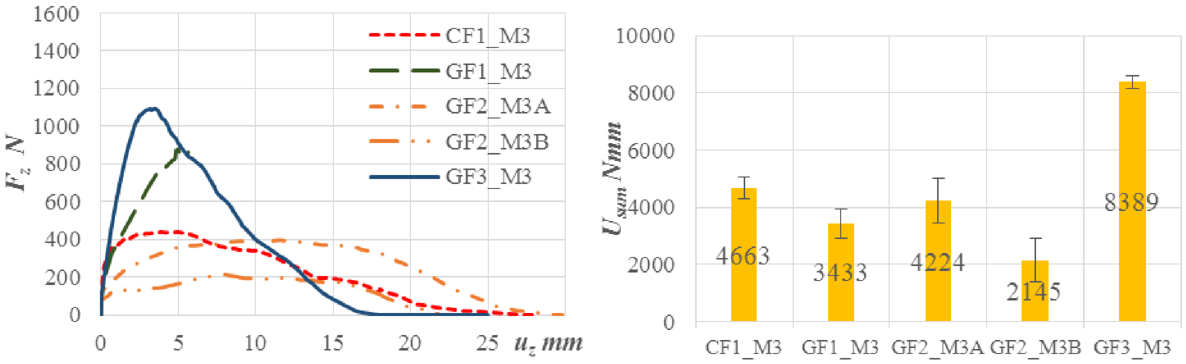


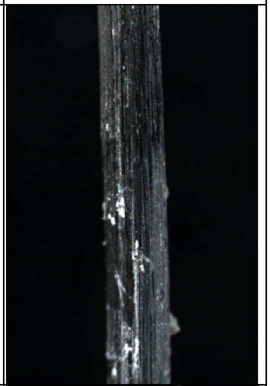
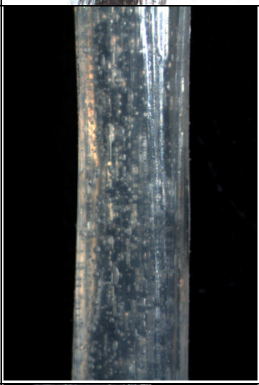
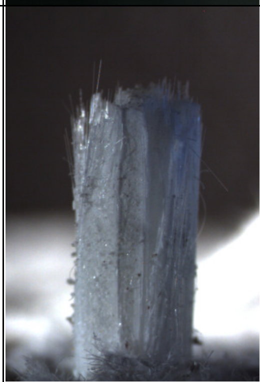
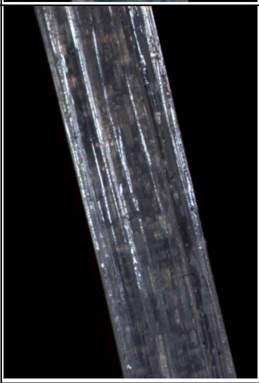
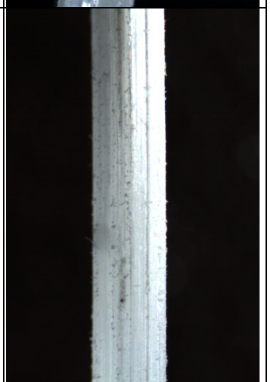
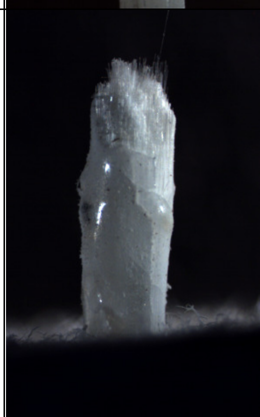
Fig. 6. **Four fiber types in concrete matrix M3, on the left – average pull-out curves, on the right – pull-out energy:** CF1; GF1; GF2; GF3

The fiber pull-out from concrete matrix M3 curves can be seen in Fig. 6. All fibers have pulled-out completely, except GF1, which had uneven geometry. GF1 failed at approximately 940 N load. From GF1 behaviour in three concrete matrices M1, M2 and M3 it can be seen that fiber and concrete matrix delamination increases with concrete strength reduction.In concrete matrix with higher strength less delamination occurs. In concrete matrix with lower strength longer delamination occurs. The curves become less steep with reduction in concrete matrix strength and failure load becomes smaller. Fiber GF3 has the highest load throughout the pull-out process and has the highest pull-out energy 8400Nmm. Fiber load bearing capacity built up with fiber rough surface and perfect balance between the fiber strength and friction forces. During the pull-out process almost all fiber surface layer with rough particles was peeled off (see Table 3).

Fiber CF1 pulled-out completely from all concrete matrices M1, M2 and M3. With concrete matrix strength increase, fiber load bearing capacity also increased. No evident surface defects were observed after fibers were completely pulled-out.

Table 3

Four composite fibers before and after pull-out in three concrete matrixes

Fiber type	Fiber before pull-out	Fiber after pull-out in concrete matrix:		
		M1	M2	M3
CF1				
GF1				
GF2				
GF3				

Conclusions

Three different types of composite macrofibers were fabricated. Fiber micromechanics were investigated pulling them out of three different compressive strength concrete matrixes. Macrofibers made of strong carbon fibers have not realised theor potential and were pulled out from all matrices completely with comparably low resistance. Fibers will work better with stronger concrete than M1 matrix. Among macrofibers based on glass fibers, the fibers GF1had the lowest tensile strength be cause of microfibers orientation deviations inside the macrofiber and accordingly lower fiber volume fraction. Fibers effective work is expected in concretes with lower compressive strength than M3. Fibers GF3 are effective with matrix M3 arresting cracks with opening till 3-5 mm. Fibers GF3 with increased surface roughness showed good results.

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