PULL-OUT MECHANISM DETAILED MICROMECHANICAL INVESTIGATION IN SITUATION WHEN OUT OF CONCRETE IS PULLING STRAIGHT STEEL FIBRE

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Abstract. Concrete matrix samples with steel fibres embedded into concrete under different angles were fabricated and tested for pull-out test, pull-out force versus pull-out fibre length diagrams were obtained. Microscopic investigations of the samples after rupture were carried out and fibre canal geometrical parameters were measured. On the basis of microscopic investigations and pull-out diagrams mechanical behaviour of straight steel fibre with different inclination angles was thoroughly analysed. Average energy of the pull-out test for each fibre inclination angle was obtained.

Keywords: steel fibres, fibre pull-out, concrete matrix.

Introduction

Use of fibreconcrete as a structural material is becoming more popular in recent years thanks to its durability, as well as the particularity of its internal structure (on the macro and micro level) and that is why fibreconcrete is more and more often used in load bearing constructions. Fibreconcrete is a composite material with short fibres chaotically distributed in concrete matrix. Durability of any composite material directly depends on the features of the components contained in it, reaching mechanical properties synergy, if the material structure is close to optimal. In structural applications different types of fibres may be used in fibre concrete as the reinforcing components (steel, polymeric, glass and other), which grants the structure various types of features. Mechanical resistance to deflection under bending loading is one of the most important structural properties of fibreconcrete. During fracture fibres, which are bridging macro crack, are pulling out. Performing single fibre pull-out tests it is possible to investigate loaded structure failure micro mechanics. Broad experimental program was realized and the results are presented below.

Materials and methods

The fabricated samples contained straight steel fibre symmetrically embedded by ends into two pieces of concrete. Fibre was 26 mm long with the diameter in a range 0.45 ÷ 0.5 mm. One sample is shown in Fig. 1, 2. The samples were tested for fibre pull-out [1] and the pulled out parts were studied using a scanning measuring microscope KEYENCE VHX 2000 [2] with a digital computed video camera and image processing software, shown in Fig. 1. This microscope allows to receive 2D and quasi 3D images.

Fig. 1. **Surface scanning at 40 °**

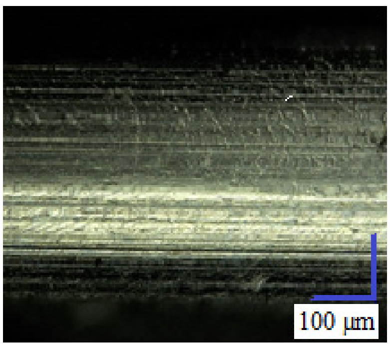

Fig. 2. **SF surface before pull-out**

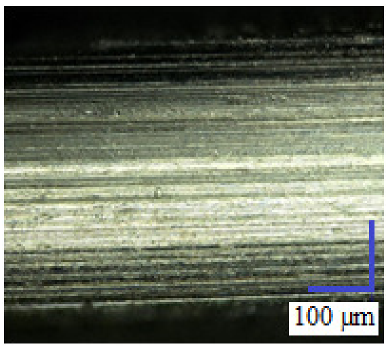

Fig. 3. **SF surface after pull-out**

Analysis of the fibre surface showed that for steel fibre (SF) before pull-out (see Fig. 2) on the fibre surface along the whole length clear deepened strips (roughness) are presented, as well as relief crackling in a form of small cracks. The surface after SF pull-out (shown in Fig.3) is more worn and the strips are already polished by the surface of the concrete. The fibre surface was exposed to friction.

Let us look at the matrix surface that has been left in the fibre channel after pull-out testing under a microscope. Fig.4 shows the hollow left by the fibre after pull-out and we see traces of steel (glossy spots) along the channel's internal surface, where the fibre was exposed to friction, as well as incisedstrips along the length of all hollow [3]. In the pull-out experiments [1] each sample both concrete pieces were clamped in the testing machine grips. Than tensile load was applied measuring the values of the applied load and increasing the distance between the concrete pieces (that corresponds to pull out fibre length). The diagrams show the applied force – pulled out fibre length was obtained (Fig. 5).

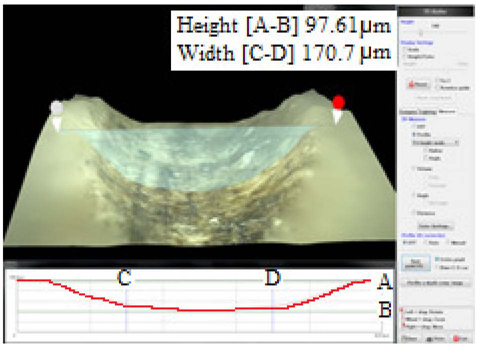

Fig. 4. **Surface of the channel left by the fibre**

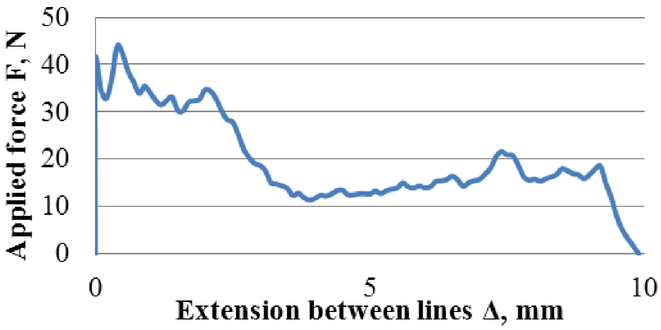

Fig. 5. **Pull-out diagram for SF oriented under the angle 90 °**

With the help of a microscope, the internal canal surface in the concrete matrix was obtained and it is shown in Fig.6.

Fig. 6. **Surface of channelleft by the fibre orientated under 90 °**

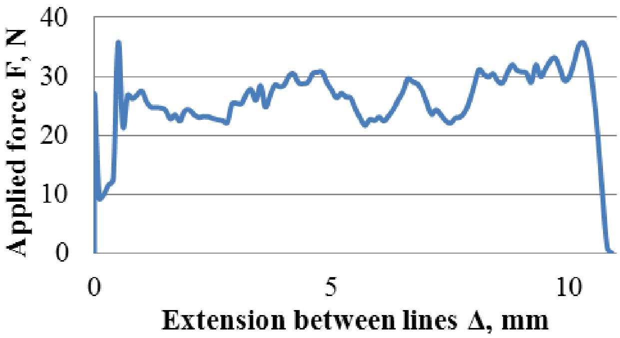

Fig. 7. **Pull-out diagram for straight steel fibre orientated at an inclination of 80 °**

To reach the maximum deepening, we need the side lighting. We see particles (crumbles) of concrete and uneven surface on the canal surface, where the fibres were intensively pull-out. In the area of fibre moving, intense deterioration of the concrete matrix surface takes place. The diagram (Fig.5) shows the boost of force with the pull-out length of the fibre approximately equal to 7.3 mm, this is caused by the fact that small particles have accumulated between the fibre and matrix forming a "plug". The fibre, having an inclination angle of 90 °,is pulling out from one part of the concrete at the length of approximately 10 mm.The diagram of pull-out of straight steel fibre oriented under the angle of 80 ° is presented in Fig. 7. It is seen that the value of the applied force along the whole pull-out length changes within ≈ 22÷32 N. During the microscopic study of the sample surface (see Fig. 8), we see a trace of pull-out fibre of the concrete matrix. The trace looks like undamaged surface, which means that the fibre, during the initial loading, destroys the concrete surface in the area of fibre output (in Fig. 9) and there is no fibre friction (this is proved by broken-off particles during the experiment). Thanks to the inclination angle it is possible to define the length of the trace (canal) after concrete destruction. The Fig.8 shows a section, in which the vertical projection of the trace (canal) is represented (AB = 566.3 µm) and the horizontal projection of the trace (canal) (CD = 342.4 µm) (see Fig. 9). To calculate the length of the trace, the sinus function was applied (1) for the inclination angle (see Fig.10).

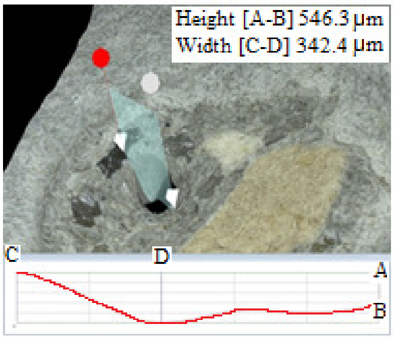

Fig. 8. **Analysis of the channel surface in the sample N38 (3D)**

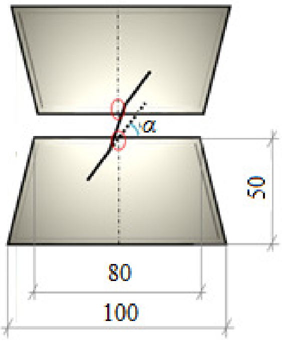

Fig. 9. **Areas of concrete spalling**

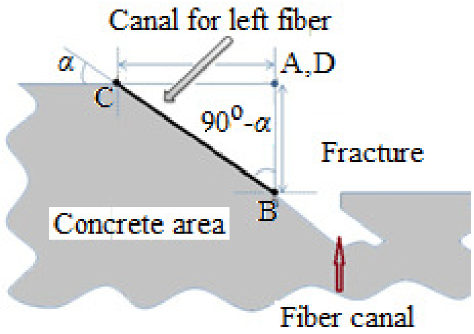

Fig. 10. **Canal surface when spalling the concrete and turning the fibre**

$$\sin\left(90^{\circ}-\alpha\right)=\frac{CD}{CB}\,, \qquad (1)$$

where α – fibre inclination angle, º;
CD – horizontal projection of the trace obtained during the experiments, µm;
CB – canal length when the matrix is broken, µm.

Hence a formula (2) arises:

$$CB=\frac{CD}{\sin\left(90^{\circ}-\alpha\right)}. \qquad (2)$$

The point C in Fig. 8 is located higher than the studied length of the trace ≈ by 40 % (diagram of Fig. 8). Hence, CD = 342.4 · (100-40 %) = 342.4 · 0.6 = 205.44 µm or 0.205 mm. We find CB by the formula (2): CB = 0.205 / sin (90-80 º) = 0.205 / sin (10 º) = 0.205 / 0.1736 = 1.18 mm. As the point D has been taken from the very beginning of the channel, the found distance 1.18 mm includes the diameter of the pull-out fibre. Thereby, 1.18 - (0.45 ÷ 0.5) - 0.1 = 0.58 ÷ 0.63 mm – is the true length of the fibre canal after destruction of the matrix (0.1 mm – distance between the fibre and the length of the trace, when the concrete matrix is damaged). The Part 2 (see Fig.12) of sample N38 has not formation of channel length (the trace that has been left is seen because the steel fibre was bent manually to get the picture of the surface under a microscope). So, at rather large inclination angle fibre was pulled out only from one part of concrete. The graph (see Fig. 7) shows an intense decrease of the applied force to ≈ 0.5 ÷ 0.6 mm, which matches the found distance CB = 0.58 ÷ 0.63 mm. Conclusion: the initial decrease is explained by destruction of the matrix of the sample tested by fibre. After matrix destruction the fibre has intense debonding and pull-out of fibre out of the concrete matrix with friction.

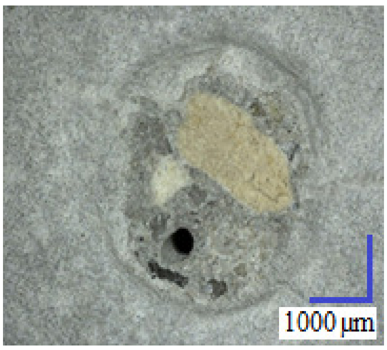

Fig.11.**Studied surface of the first part of sample N38**

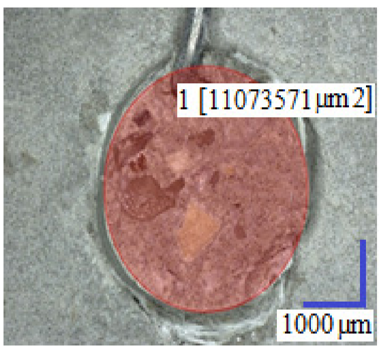

Fig.12.**Studied surface of the second part of sample N38**

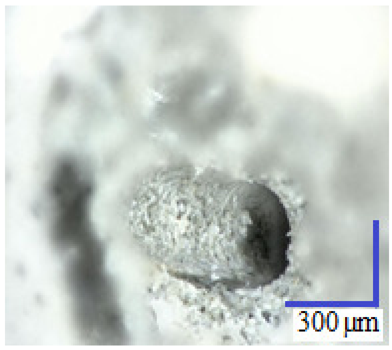

Fig.13.**Channel surface left by the oriented fibre at an angle of 80 º**

Fig.13 shows the studied surface, where the fibre takes the maximum, intense surface deterioration, when pulling the fibre out of the concrete matrix. It should be noted: a) the surface is rugged with cavern formation; b) the surface has visible particles, which leads to friction and plugs formation. In the diagram in Fig. 7 – with the length of 5.7 mm and 7.3 mm of the pull-out fibre we see decline of the force caused by congestions.

Let us consider the straight steel fibre at the angle – 10 °. The diagram in Fig.17 shows at the initial stage decline of the applied force. This decline is explained by intense concrete spalling and fibre plastic rotation (see Fig.9) without pulling out both ends of fibre. To explain the force decline, we find the channel surface left by the orientated fibre during the concrete matrix fracture.

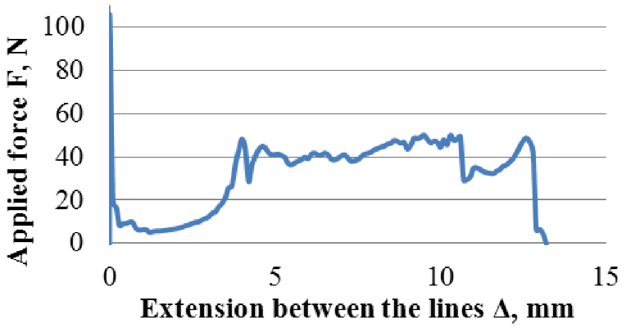

Fig.14.**Pull-out of SF at an angle of 10º**

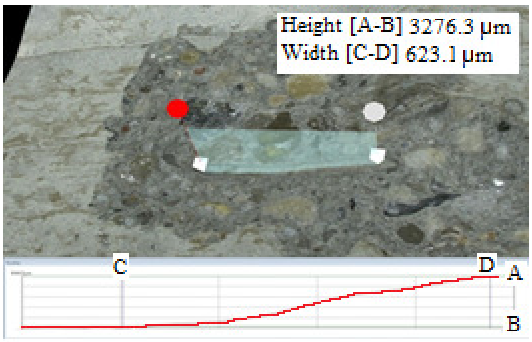

Fig.15. **Analysis of channel surface in sample N55 (3D) – 1 part**

To find the channel length left by the fibre breaking the matrix of the first part (see Fig. 15) Fig. 10 and formulas (1-2) are used. It is given that CD = 3276.3 µm and the angle α = 10 °. We find sin(90 ° - α) = sin (90-10 °) = sin(80 °) = 0.985; CB = CD / sin (80 °) = 3276.3 / 0.985 = 3326.2 µm = 3.3262 mm. Fig.15 shows – we make sure that the true length of the canal broken by the fibre is correct. The point C is taken further from the beginning of the channel aperture – it means that the fibre diameter is not taken into account at this distance, and the point D is located at the beginning of channel formation (see Fig.16).

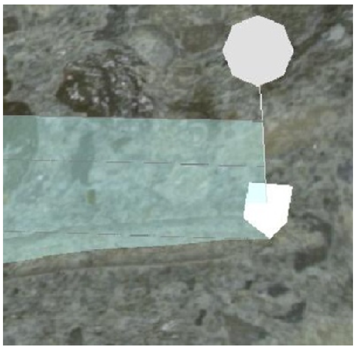

Fig.16.**Location of point D in sample N55**

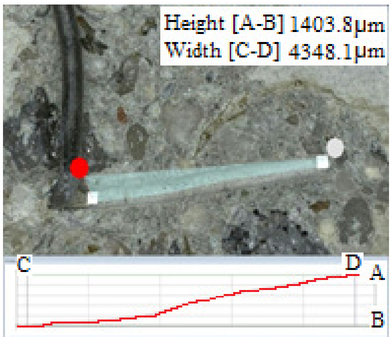

Fig.17.**Analysis of channel surface in sample N55 (3D) – 2 part**

Fig.18.**Channel surface left by the oriented fibre at an angle of 10 º in sample N55**

The obtained distance CB = 3.3262 mm – is the true length of the canal broken by the fibre when the concrete is broken.

Analysis of the second part of the sample (see Fig.17). To find the length of the canal left by the fibre when breaking the matrix of the second part (see Fig.17) we use Fig. 10 and formulas (1) and (2). It is given that CD = 4348.1 µm and the angle α = 10 °. The received values: sin(90 ° - α) = sin (90- -10º) = sin(80 º) = 0.985; CB = CD / sin (80 º) = 4348.1 / 0.985 = 4414.3 µm = 4.4143 mm. The Fig. 17 – we make sure that the true length of the canal broken by the fibre is correct. The point C is taken further from the aperture – the diameter of fibre is not taken into account, and the point D is located at the beginning of canal formation. The received distance CB = 4.4143 mm – the true length of the canal broken by the fibre when breaking the concrete.

The sum of two channels is taken: 3.3262 + 4.4143 = 7.7405 mm. Fig.14 shows decline of the applied force along the length of fibre pulling out = ≈ 1.5 mm, and this value does not match the obtained length - 7.7405 mm. This phenomenon is explained by the fact that with smaller angles the mechanism of the concrete matrix breaking takes place at two stages.

Stage 1: rapid breaking of the concrete matrix takes place, as the volume of the concrete matrix at the output of fibre is very small. This breaking takes place in 2 parts of this sample.

Stage 2: a moment comes, when the fibre starts breaking the concrete slower and spends more energy – force boost takes place in the diagram of Fig. 14. The matrix fracture appears gradually – at first in the part 1, then in the part 2, creating the applied force's decline and increase. In the diagram sample N55 (see Fig.14) at a distance of ≈ 7.2 ÷ 7.6 mm, transfers into the condition of pull-out of fibre with easy friction inside (no sharp jumps). The obtained distance 7.7405 mm approximately equals to the distance 7.2 ÷ 7.6 mm. The following force decline in the diagram with the length of the pull-out fibre 10.7 mm is explained by the fact that the particles in the channel have created jam and stopped the fibre pull-out. And the first sharp decline of the force in the diagram for sample N55 matches the first considered stage. Fig.18 shows the particles, which play a direct role in pull-out of the tested fibre. The surface has caverns, which trouble accumulation of small particles inside the canal.

Results and discussion

The considered samples N38, N46 and N55 allow to make a conclusion that each obtained sample is unique in its own way and the obtained diagrams of dependence (the applied force from the length of the pull-out fibre) are explained in the micro environment individually. It is seen that with decrease of the inclination angle of the fibre the length of the trace of the broken concrete increases. When decreasing the inclination angle of fibre, the effect of fracture of the surface of two sample parts is increased. It is difficult to foresee if the diagram would be depending on the force application from the length of the pull-out fibre, because very many factors influence the pull-out of one studied fibre (particles, caverns on the sample surface, fracture of the concrete matrix depending on the strength of concrete, bulges, and cavities). This all impacts the sample testing with dimensions 10x10x40 cm at 4-point bending [3-4]. 52 samples were tested. Each inclination angle of fibre had 5 or 6 samples tested. The following diagrams were received: the data of averaged values of the samples with fibre

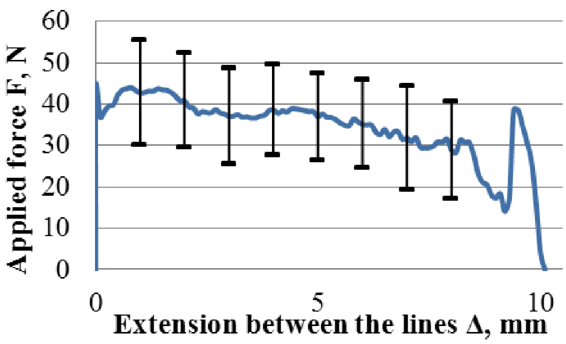

Fig. 19. **Average value for samples with fibre angle 70 °, where *F* – applied force [N] and Δ - extension between lines [mm]**

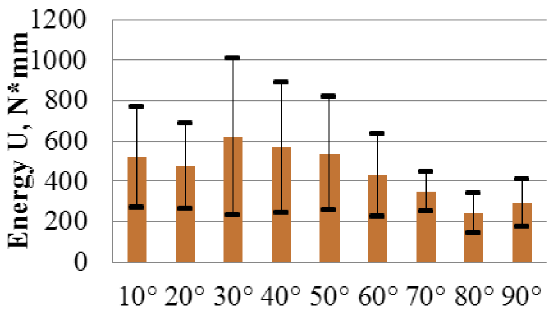

Fig. 20. **Average energy of pull-out of one *SF* at different angle inclination**

inclination angles equal to 70 °. The straight steel fibre pull-out procedure has a large dispersion of results. The confidence interval [5] is shown in Fig. 19.

The most energy was spent (see Fig. 20) for pull-out of the concrete at angles within this range 30-60 °. It is explained by the fact that the tested fibre bears the most friction power, as the angles are closer to 45 ° (when the fibre surmounts the maximum friction) and there is plastic deformation. At the angles of 70-90 °, the energy is minimal, because there is no plastic deformation of fibre. At these angles, there is the least surface deterioration (fibre surmounts pull-out easy, if comparing to other tested angles of the fibres). At the angles of 10-20 °, energy accumulation takes place at the expense of intense surmount of the concrete matrix breaking in the area of fibre pull-out. We shall note that none of the tested fibres was torn when pulled out.

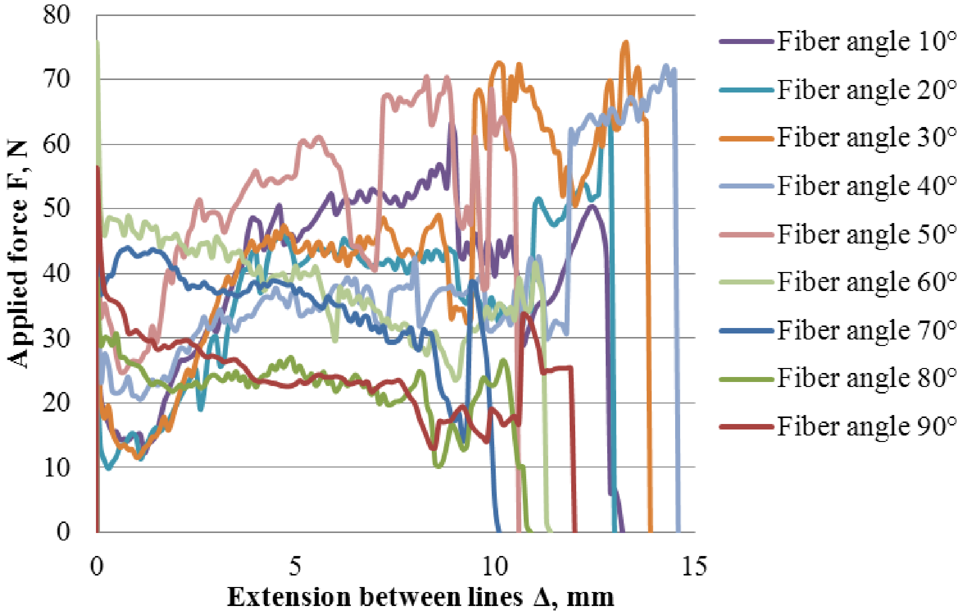

Fig. 21. **Average value of pull-out of one SF of the concrete matrix at different inclination angles**

Fig.21 shows the initial force decline for all samples. The length, at which the pull-out fibre bears the load at the angles of 50-90 ° is ≈ 10 ÷ 12 mm, and for the samples at the angles of 10-40 ° is: length ≈ 13-14.7 mm, and it is by 8 ÷ 32 % higher than at the angles of 50-90 °. The explanation of this phenomenon – presence of large areas of concrete spalling on the places of fibre output of the matrix in both parts of the concrete sample.

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