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MULTI-LEVEL INVESTIGATIONS ON BEHAVIOUR OF TEXTILE REINFORCED CONCRETE WITH SHORT FIBRES UNDER TENSILE LOADING

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Abstract: The mechanical performance of textile-reinforced concrete (TRC) in tension can be considerably improved by adding short fibre to its matrix. The goal of the study is to understand the mechanisms of the interactions between continuous and short fibres in cement-based matrix and to develop a multi-scale model for the mechanical behaviour of cement-based composites with such hybrid reinforcement.

Uniaxial tension tests on TRC specimens as well as multifilament-yarn and single-fibre pullout tests were performed to study the fracture behaviour of the composite material and its components and gain better understanding of the crack bridging mechanisms. Furthermore, visual inspection and microscopic investigation provided deeper insight into the specific phenomena relevant to the characteristic material properties.

This article presents experimental findings for some chosen parameter combinations including the type of short fibres and the water-to-binder ratio. Furthermore, failure mechanisms are discussed providing a basis for a multi-scale model, which will be published elsewhere.

1 INTRODUCTION

Textile-reinforced concrete (TRC) is a composite material consisting of a finely grained cement-based matrix and high-performance, continuous multifilament yarns made of alkali-resistant (AR) glass, carbon, or polymer. The major advantages of TRC are its high load carrying capacity, i.e. tensile strength, and pseudo-ductile behaviour, which is characterised by large deformations due to its tolerance of multiple cracking [1]. Such large deformations prior to material failure are crucial in respect of both structural safety and energy dissipation in the case of impact loading [2]. However, that high strength levels can be only reached at high deformations means that for the service state, where only small deformations are acceptable, the design load-bearing capacity of TRC must be much lower than its tensile strength. Moreover, relatively wide cracks observed at high deformations are undesirable. In recent years researchers have performed several test series to investigate the influence of short fibres on various properties of TRC [3-4]. However, the mechanisms in the joint action of short fibre and textile reinforcement are still not fully understood. In order to gain more and better insight into the specific material behaviour of the finely grained concrete with such hybrid reinforcement, a new multi-scale investigative program has been initiated at the TU Dresden.

This paper presents some of the results on the effect of adding different types of short fibres on the fracture behaviour of TRC.

At macro-level of observation, uniaxial tension tests on thin, narrow plates made of TRC with and without the addition of short fibres were performed. These series constitute the core of the experimental program. Special attention was directed at the course of the stress-strain relationship, crack pattern development, and fibre failure behaviour. Furthermore, tests at meso- and micro-level of observation, i.e. multifilament-yarn and single-fibre pullout tests, respectively, were performed to provide detailed insights into the various failure mechanisms observed in the experiments, the bond behaviour between short fibres and the finely grained concrete as well as between the yarn surface and the matrix. Moreover, visual inspections of the specimens' surfaces and microscopic investigation of the fracture surfaces were performed and evaluated to clarify the fracture criteria and the various failure mechanisms observed in the tests.

Based on the experimental results at the micro-scale a physically based, rheological model consisting of simple rheological elements will be developed. Then, as a next step, an adequate description of the material behaviour at the meso and macro scales will be developed using statistical approaches and according to the results of fracture mechanical and phenomenological investigations.

2 MATERIALS

2.1 Concrete

Matrices with slag furnace cement (CEM III) and the addition of pozzolans show favourable properties regarding the durability of glass fibre as well as the bond between fibre and cementitious matrix [5-6]. To match the small diameter of both the continuous filaments and the short fibres, the maximum aggregate diameter had to be small as well (typically < 1 mm). One such fine-grained, cement-based concrete was chosen. Two designated mixtures M030 and M045, having water-to-binder ratios of 0.30 and 0.45, respectively, were used in this investigation. Finally, a super-plasticizer was added to achieve sufficient flowability. Table 1 gives the compositions of the two finely grained concretes under investigation.

Table 1: Concrete composition [kg/m^3]

Matrix	M030	M045
w/b	0.30	0.45
Cement CEM III B 32.5	632	554
Fly ash	265	233
Micro-silica suspension*	101	89
Quartzite sand 0-1 mm	947	832
Water	234	330
Super-plasticizer	11	2

* solid:water = 1:1

2.2 Textile reinforcement

One type of polymer-coated, biaxial fabric made of alkali-resistant glass was used as textile reinforcement for TRC specimens as well as for the multifilament-yarn pullout tests. The weft and warp threads had a fineness of 2*640 tex (mass in g of 1 km yarn; tex = g/km), the spacing between yarns was 7.2 mm, cf. Figure 1.

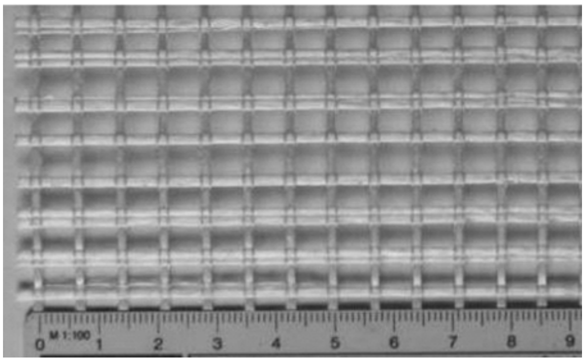

Figure 1: Textile reinforcement (AR-glass).

2.3 Short fibres

Three types of short fibre were chosen and combined with textile reinforcement layers as additional reinforcement for this investigation: short dispersed glass, short integral glass and carbon fibres. All fibres had a length of 6 mm.

Integral fibre consisted on average of approximately 100 filaments. While the dispersed glass fibre had a diameter of 20 µm, the individual filaments of integral fibre measured 13 µm in diameter. The carbon fibre had a diameter of 7 µm. During mixing of fine-grained concrete, short dispersed fibres are distributed within the fresh matrix as thousands and millions of predominantly single filaments. Integral short fibres remain stuck together and act as short pieces of multifilament yarn in the mixture, cf. Figure 2. A fibre content of 1.0 % by volume of concrete was chosen for this study. While both types of glass fibre had the same tensile strength of 1,700 MPa and a Young's modulus of 72 GPa, the short carbon fibre had a tensile strength of 3,950 MPa and a Young's modulus of 283 GPa.

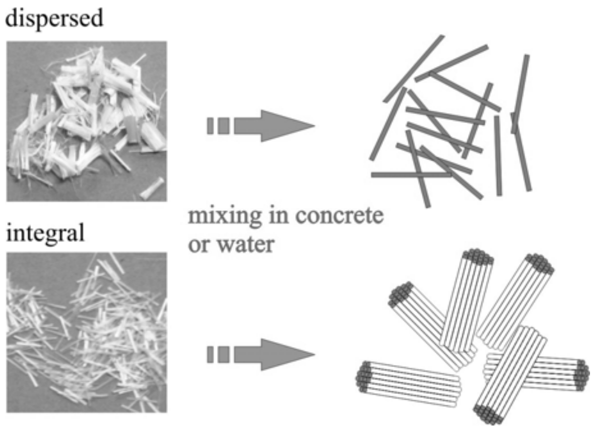

Figure 2: Graphic presentation of the condition of fibres used in this investigation when mixed with water or concrete.

3 SPECIMENS' PREPARATION AND TEST SETUP

Tests at macro-level of observation by means of uniaxial tensile tests were performed on rectangular plates (500 mm x 100 mm x 12 mm) reinforced by 2 layers of textile. The specimens were produced using the lamination technique explained in [7]. All plates were demoulded at a concrete age of 2 days and then stored in water until reaching an age of 7 days. Subsequently, the plates were stored in a climate-controlled room at 20 °C and 65 % RH up to a testing age of 28 days. The force was introduced to the specimens via non-rotatable steel plates glued to the TRC plates, see Figure 3.

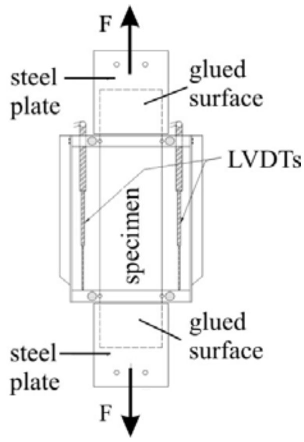

Figure 3: Schematic view of the test setup used in uniaxial tension tests.

For multifilament yarn pullout tests, i.e. tests at meso-level of observation, rectangular specimens (200 mm x 70 mm x 12 mm) were cut from larger plates produced and cured in the same manner as those for uniaxial tensile tests. However, here only one layer of textile was used as reinforcement. The anchorage length was determined by specific arrangement of a "must"-crack position visible as a saw cut on both sides, cf. Figure 4. In the notched cross-section only one multifilament yarn still intact and connect the two parts of the plates to each other. More details concerning this test setup may be found in [8].

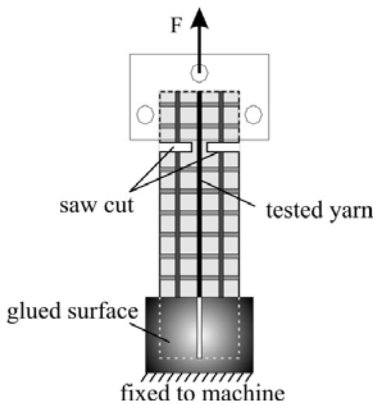

Figure 4: Schematic view of test setup used for multifilament-yarn pullout tests.

For the tests at micro-level of observation, a series of single-fibre pullout tests was performed on specimens prepared according to [9, 10]. These tests were performed only on short glass fibres. The specimen was fixed to the clamps, and the fibre was glued to the upper mounting plate of a testing machine as shown in Figure 5.

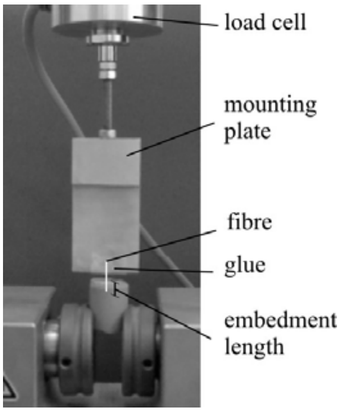

Figure 5: Testing device for single-fibre pullout tests.

4 EXPERIMENTAL RESULTS

4.1 Uniaxial tensile tests

Figure 6 shows representative stress-strain curves obtained from the tests on TRC specimens with and without the addition of 1.0 % by volume of short dispersed glass, integral glass, and carbon fibres. A pronounced increase in first-crack stress could be observed in all experiments with the addition of short fibres in comparison to results obtained with reference TRC plates. The first-crack stress value increased approximately by a factor of 2.5 when short dispersed glass fibres or carbon fibres were added. The most pronounced increased, approximately by factor 4, was recorded due to the addition of short carbon fibres when matrix M045 (w/b = 0.45) was used. Table 2 summarizes the corresponding values.

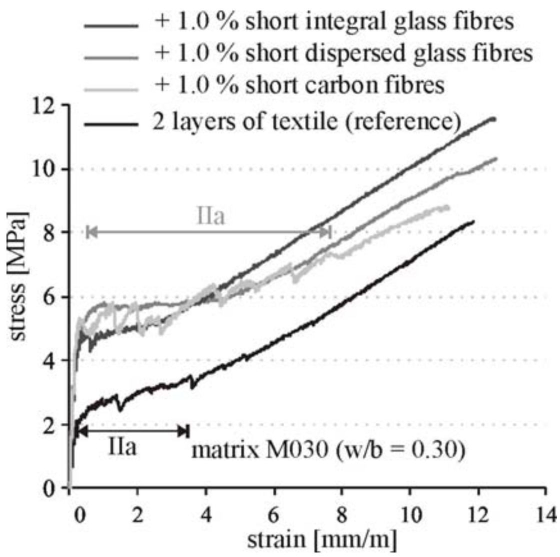

Figure 6: Effect of addition of short dispersed glass, integral glass and carbon fibres on the characteristic stress-strain behaviour of TRC plates subjected to tensile loading.

The addition of short fibres led, on the other hand, to the expansion of the region IIa, where multiple cracks form. This expansion was particularly pronounced in the case of the TRC with short carbon fibres: The corresponding stains had more than doubled, cf. Figure 6.

The observation of the specimens' surfaces showed that this widening resulted from the formation of greater numbers of cracks. To emphasize, for the same strain level the TRC specimens with short fibre always exhibited a higher number of cracks in comparison to the TRC specimens without short fibre as shown in Figure 7 for specimens with the addition of short dispersed glass fibres. This holds true for both types of matrices M030 and M045.

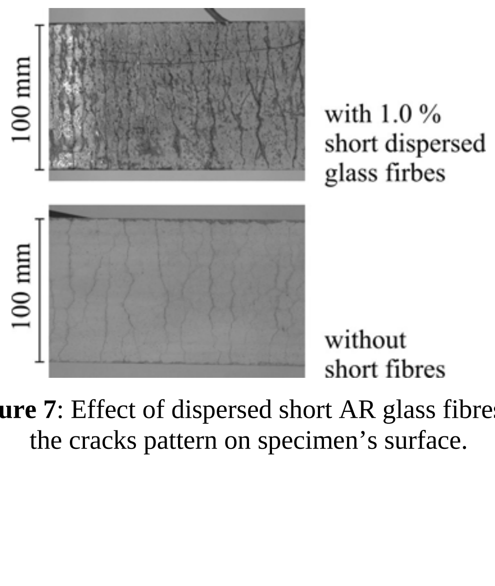

Figure 7: Effect of dispersed short AR glass fibres on the cracks pattern on specimen's surface.

Table 2: Mechanical performance of TRC plates with and without the addition of 1.0 % by volume of short dispersed glass, integral glass and carbon fibres

Specimens with 2 layers of textile		First-crack stress [MPa]	Tensile strength [MPa]	Work-to-fracture [kN·mm]
		Average value (standard deviation)		
M030	Without short fibres	1.92 (0.37)	8.34 (0.33)	20.14 (0.91)
	+ 1.0 % short dispersed glass fibres	4.65 (0.21)	9.69 (0.35)	28.88 (1.90)
	+ 1.0 % short integral glass fibres	4.20 (0.06)	10.77 (0.73)	27.45 (2.12)
	+ 1.0 % short carbon fibres	5.04 (0.37)	8.81 (0.34)	27.03 (1.41)
M045	Without short fibres	1.17 (0.14)	7.25 (0.21)	18.48 (3.37)
	+ 1.0 % short dispersed glass fibres	3.46 (0.06)	7.46 (0.22)	20.50 (4.59)
	+ 1.0 % short integral glass fibres	2.39 (0.69)	9.49 (1.01)	21.16 (1.36)
	+ 1.0 % short carbon fibres	4.48 (0.27)	8.09 (0.11)	23.26 (3.37)

Since the stress-strain curves for TRC with short fibre are always above the corresponding curves for TRC without short fibre, see Figure 6, it can be concluded that the energy dissipated (area under the stress-strain curve) increased noticeably due to the addition of short fibres. The work-to-fracture due to the addition of (all types of) short fibres increased by approximately 40 % for the TRC specimens made of the matrix M030 and by approximately 15 % for the M045-TRC, cf. Table 2.

Moreover, the tensile strength of the composite was significantly enhanced by the addition of short integral fibres. An average increase in the tensile strength values by more than 2.4 and 2.2 MPa was achieved due to the addition of short integral glass fibres to TRC plates made with matrices M030 and M045, respectively. The addition of short dispersed fibres (glass or carbon) led to only a very moderate increase in the tensile strength of the composite: 1.35 MPa for the TRC specimens made of the matrix M030 with short dispersed glass fibres and less than 1 MPa for those made of the matrix M045 with the addition short carbon fibres, cf. Table 2.

4.2 Multifilament-yarn pullout tests

These tests, considered as meso-level of observation, were performed to investigate the effect of the short fibre on the bond between yarns and the surrounding matrix. Figure 8 shows force-displacement curves obtained for the specimens made with matrix M045 and 1.0 % of short dispersed glass fibre. Obviously, the addition of short fibre led to a higher ultimate pullout force, which indicates a better bond between the yarn and the matrix. Increase in the average pullout force by 45 % was achieved. The increase was less pronounced (just 11.6 %) when matrix M030 was used, cf. Table 3. Furthermore, it is clear from Table 3 that higher pullout-force was needed when matrix M030 was used in comparison to that observed for the TRC made of the matrix M045, see Table 3.

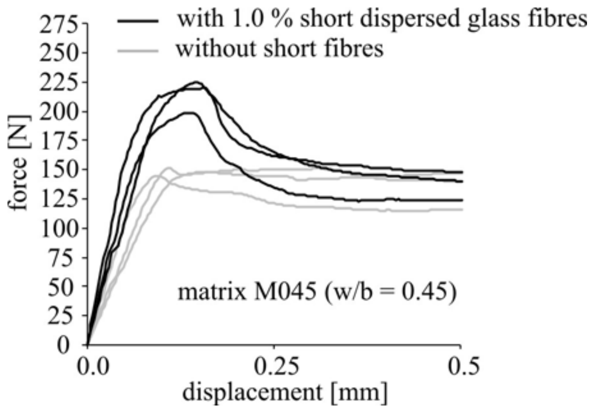

Figure 8: Results of multifilament-yarn pullout tests with the matrix M045 with and without the addition of 1.0 % short dispersed glass fibres.

Table 3: Ultimate force of multifilament-yarn pullout tests for both matrices with and without the addition of dispersed short glass fibres

Type of specimen		Ultimate pullout-force [N]
		Average value (standard deviation)
M030	Without short fibres	215.4 (22.1)
	+ 1.0 % short dispersed glass fibres	240.5 (26.1)
M045	Without short fibres	147.6 (3.20)
	+ 1.0 % short dispersed glass fibres	214.0 (14.0)

4.3 Single-fibre pullout tests

4.3.1 Fibre pullout parallel to its axis

The single-fibre pullout tests, regarded as tests at micro-level of observation, showed that brittle failure of fibres dominated when matrix M030 was used. Typically, a vertical drop in the force-displacement curves due to fibre breakage was observed after the relatively high ultimate force was reached, see Figure 9. This relatively high ultimate force at fibre failure indicated the good matrix-fibre bond when matrix M030 was used. In contrast, the ultimate pullout force of the fibres embedded into matrix M045 was much lower. Here, most of the tests provided force-displacement relationships with a pronounced softening branch, which indicated fibre pullout, cf. Figure 9.

4.3.2 Pullout of inclined fibres

As short fibres are oriented nearly randomly within the matrix, only very few fibres are aligned parallel to the direction of the applied tensile load. The great majority of the fibres are oriented at different angles to the crack surface and, therefore, to the direction of the pullout. The angle of inclination of a fibre in a cementitious matrix can have a pronounced influence on its pullout resistance, as has been shown experimentally by several researchers, e.g., [12].

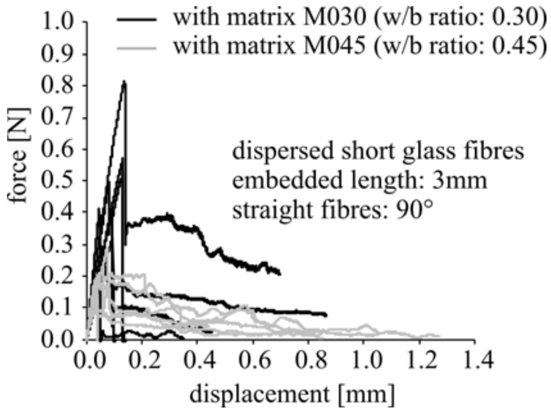

Figure 9: Force-displacement curves obtained from the single dispersed glass fibre pullout tests with matrix M030 and matrix M045.

In this investigation three representative angles are considered from among all possible cases, as shown in Figure 10:

• Plane fibres, 0°, i.e., fibres are oriented parallel to the crack surface; it is assumed that this type represents all fibres oriented to the crack surface at angles between 0° and 30°. These fibres are considered as non-bridging fibres; i.e., the contribution of these fibres to the stress bearing capacity of the matrix is neglected.

• Straight fibres, 90°, i.e. fibres are oriented parallel to the load direction; this type represents all fibres oriented to the crack surface at angles between 60° and 90°. The results of pullout tests on these fibres are shown in the previous Section. 4.3.1.

• Inclined fibres, 45°; this type represents all fibres oriented to the crack surface at angles between 30° and 60°.

Figure 11 shows the large scattering in the results obtained from fibre pullout tests with the angle of 45° for both matrices M030 and M045. In some cases barely measurable pullout behaviour was recorded, in other cases the maximum load cell capacity was reached before the fibre failed. The reasons for such behaviour are discussed in the next section in conjunction with microscopic investigations. It should be mentioned here that these test were limited to the short integral fibre.

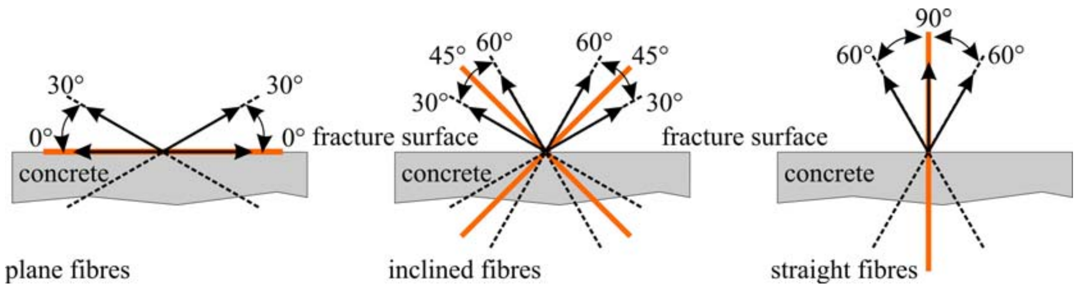

Figure 10: Classification of the fibre orientations in respect of the fracture surface.

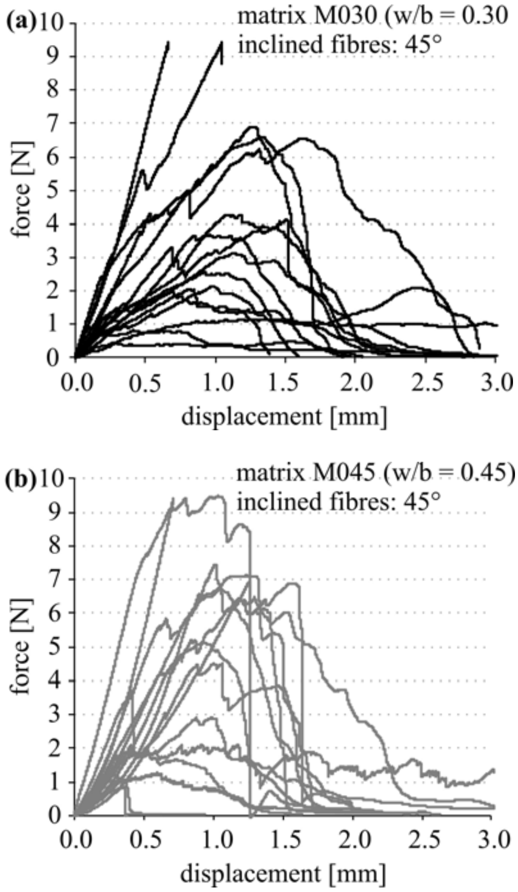

Figure 11: Force-displacement curves obtained from the single inclined integral glass fibre pullout tests with the matrix a) M030 and b) M045.

More details on the obtained results at all levels of observations may be found in [7, 11].

5 DISCUSSIONS

In comparison to short integral fibres, short dispersed fibres have proven themselves to be significantly more efficient in improving the behaviour of TRC at low strain levels, especially with regard to the increase in first-crack stress, cf. Figure 6 and Table 2. The explanation seems quite straightforward: since dispersed fibres are much more numerous and much more finely distributed in the matrix, they are better able to bridge both micro cracks and very fine cracks.

The higher number of cracks observed on TRC specimens' surfaces with short fibres can be traced back to the additional stress transfer (by short fibres) over fine macro-cracks. This resulted in a less relaxation of the matrix in the cracks' vicinity. The next crack may form at a smaller distance from the existing crack; more pronounced multiple cracking can develop.

Due to their small diameter and marked slenderness, the failure probability of short dispersed fibres increases steadily with increased loading and crack opening. It appears that the great majority, if not all, of the dispersed fibres fail long before the tensile strength of the composite is reached. In contrast, integral fibres remain ‘‘active’’ at high deformations also, which explains the increase in the tensile strength of the composite when short integral glass fibres are added to TRC, cf. Figure 6 and Table 2.

Microscopic investigation showed, moreover, that short fibres can improve the bond between multifilament yarns and surrounding matrix by means of new, additional cross-links, which lead to a better yarn-matrix bonding. By their random dispersion in the matrix and their positioning on the yarn surface, short fibres provide extra “connecting points” to the surrounding matrix. Figure 12 illustrates experimental evidence that such cross-links in connection with short fibre indeed exist. This finding, among others, can give a straight explanation of the mechanisms leading to the improvement of bond strength, due to the addition of short fibres, obtained from multifilament-yarn pullout tests, cf. Figure 8. Having more adhesive cross-links between matrix and filaments leads to better bonding, and thus a higher pullout force is needed.

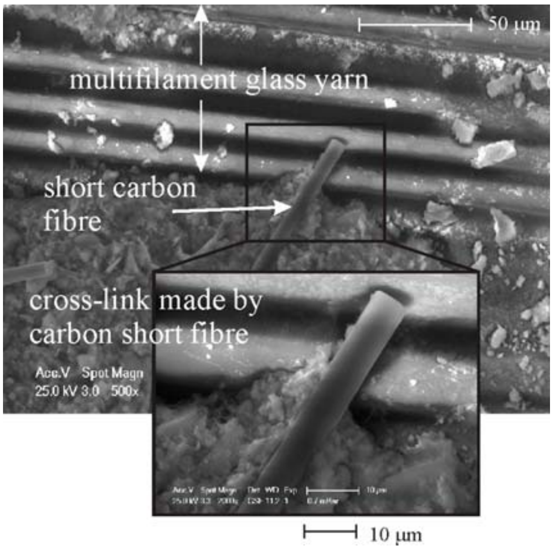

Figure 12: "Cross-link" between multifilament-yarn and matrix caused by a short carbon fibre.

Results presented in Figure 9 show that the water-to-binder ratio influences the bond between the matrix and single short fibres. In order to explain this, the specimens of single-fibre pullout tests were carefully split in the middle and investigated using ESEM (Environmental Scanning Electron Microscope). In most of the specimens made with the matrix M030, a part of the fibre was found, i.e., the part remained in the specimen after fibre breakage, cf. Figure 13a. In contrast, the empty fibre canal in the cases when matrix M045 was used indicated a complete fibre pullout, cf. Figure 13b.

The single-fibre pullout tests performed on inclined integral fibres yielded a very large scattering of their results; cf. Figure 11. This scattering can be at least partly explained by different arrangements of the solid particles in the vicinity of the fibre.

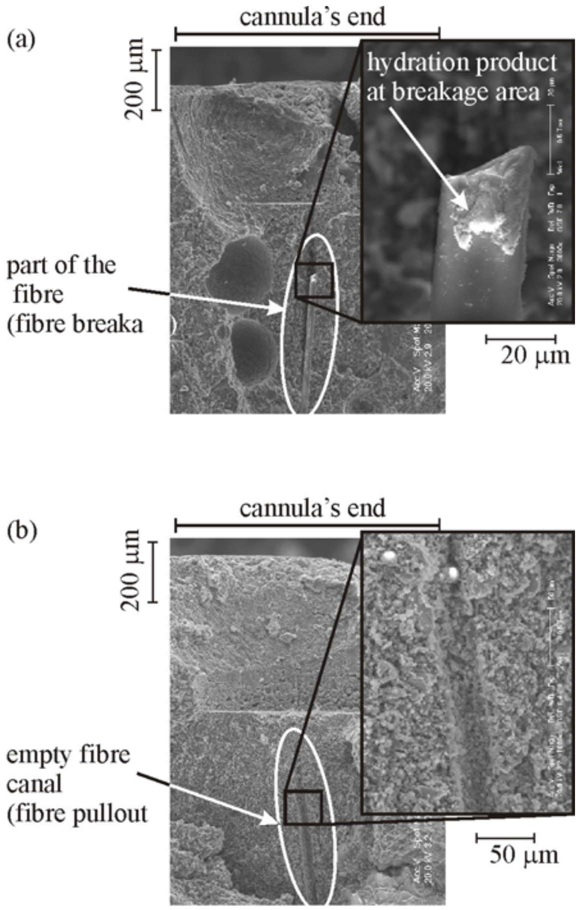

Figure 13: ESEM images on single-fibre pullout specimen with matrix a) M030 and b) M045.

Figure 14 shows three characteristic curves representing three different modes of failure as well as the corresponding microphotographs of the specimens. Figure 14a shows a tightly fixed fibre; there is no space in the vicinity of the fibre. Two particles clamp the fibre between them. The loading cell capacity was not high enough to finish the tests, which means that neither breakage nor pullout of the fibre could be achieved. In contrast, a relatively large void adjacent to fibre edge is presented in Figure 14b; much space in the fibre's vicinity allowed the fibre to be pulled out with very little resistance (maximum force). Finally, the case shown in Figure 14c represents the typical case of a uniform particle arrangement around the fibre. This arrangement led to the breakage of some outer filaments and the pullout of the majority of inner filaments. This mode of fracture is the preferred one.

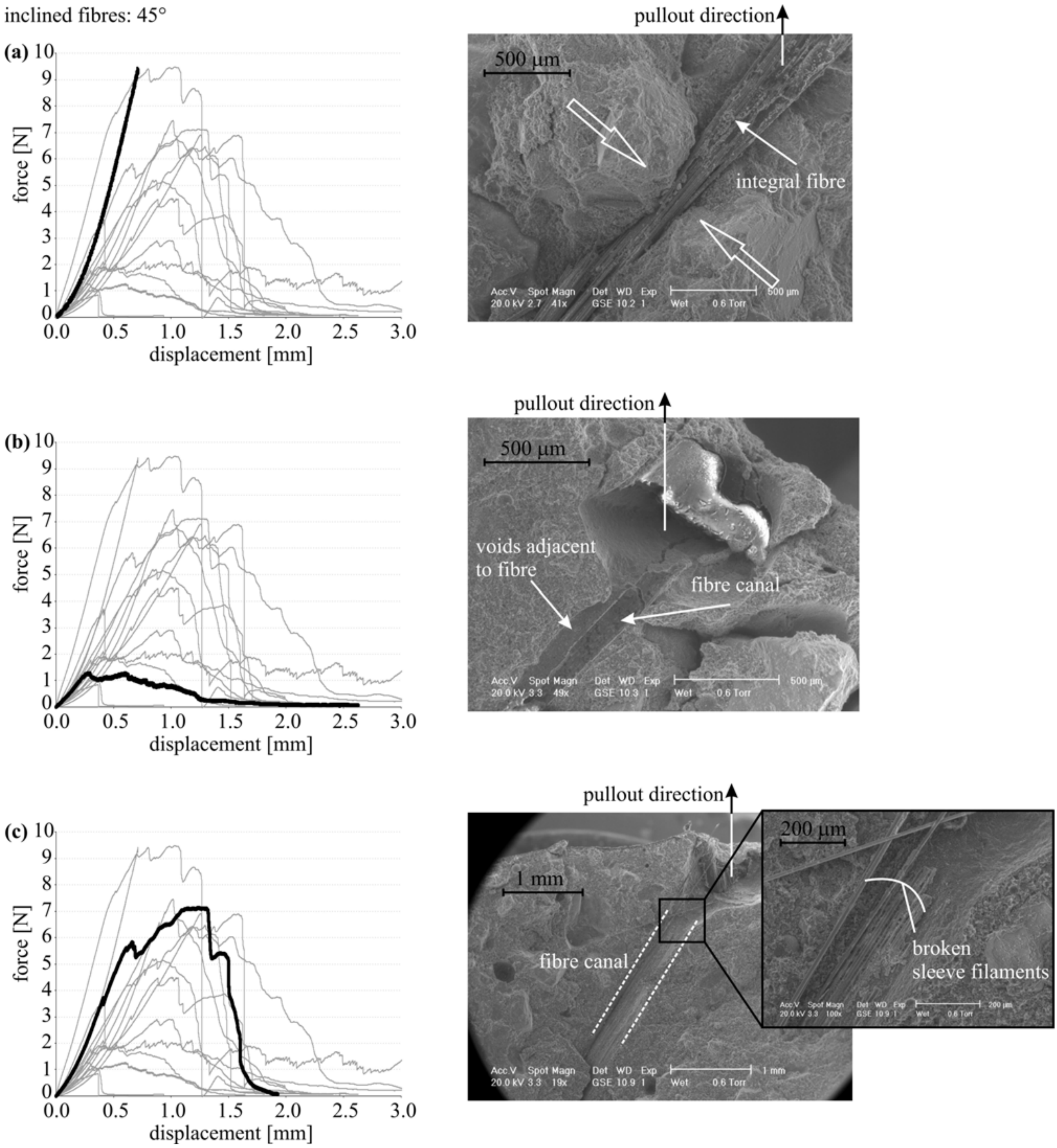

Figure 14: Three characteristic curves obtained from the single-fibre pullout tests performed on inclined integral fibres and the corresponding ESEM images: a) completely fixed fibre, b) easily pulled-out fibre, and c) typical fibre pullout response.

More details concerning bond and fracture mechanisms and deeper discussions are presented by the authors in [7-11].

6 CONCLUSIONS

In this research project the effects of adding different types of short fibres on the strength, deformation, and failure behaviour of textile-reinforced concrete subjected to tensile loading were investigated. The stress-strain curves obtained from uniaxial tension tests demonstrated clearly the positive influence of short fibre on the mechanical performance of TRC. Furthermore, depending on the water-to-binder ratio of the matrix various degrees of matrix-fibre bond were observed. To clarify the mechanisms leading to the enhancement of the mechanical performance of TRC, multifilament-yarn and single-fibre pullout tests were performed. The morphology of the matrix-fibre interface was studied using an electron microscope and provided some explanation of the phenomena observed. From the findings the following conclusions could be drawn:

- The first-crack stress value of TRC specimens increased pronouncedly due to the addition of short fibres. Increase by approximately four times was achieved due to the addition of 1.0 % by volume short carbon fibres when the matrix M045 (w/b = 0.45) was used.
- Expansion of the strain region, where multiple cracks form, was observed for the stress-strain curves due to the addition of short fibres. The visual inspection of the specimens´ surfaces showed that a higher number of cracks and finer cracks for given strain levels were formed when short fibres were added to TRC.
- The work-to-fracture of the composite was improved significantly by the addition of short fibre. Here the effect when matrix M030 (water-to-binder ratio of 0.30) was used was more pronounced.
- While the advantage of the addition of short dispersed fibre began to fade at relatively high strain levels, integral fibres improved the load bearing capacity of the TRC over the entire strain range, right up to failure.
- Short fibres improved the bond between multifilament-yarn and the surrounding matrix. By their random positioning on the yarn’s surface, short fibres built new “special” adhesive cross-links which provided extra connecting points to the surrounding matrix.
- The water-to-binder ratio of the matrix influenced the bond quality between fibre and matrix and, thus, the effect of short fibre on TRC behaviour.

ACKNOWLEDGEMENT

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