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Effect of short fibres on fracture behaviour of textile reinforced concrete

R. Barhum & V.Mechtcherine
Institute of Construction Materials, TU Dresden, Dresden, Germany

ABSTRACT: Textile reinforced concrete (TRC) exhibits very favourable stress-strain behaviour with high load-carrying capacity, achieved only after relatively high deformations accompanied by formation of a considerable number of fine cracks. This article addresses the effects of using short fibres (glass and carbon) on the fracture behaviour of this material as additional reinforcement in TRC. A series of uniaxial, deformation-controlled tensile tests were performed. Dispersed and integral short glass fibres as well as dispersed short carbon fibres were used in the investigations. On one hand, TRC plates with high degree of reinforcement, both separate and in combination with a low degree of short fibres were tested. On the other hand, experiments on TRC plates with a relatively low degree of textile reinforcement, separate and in combination with a high degree of short fibres were performed. Very pronounced effects due to the different types of short fibre on the stress-strain behaviour and cracking of TRC could be observed. In particular, a pronounced increase in the first-crack stress was observed in all cases when short fibres had been added. Still further, the influences of dispersed and integral short glass fibres on the course of stress-strain curve of TRC were compared. Finally the observed phenomena were discussed and classified as to their underlying causes with the support of microscopic investigation and visual inspections on the specimens' surfaces.

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 glass, carbon, or polymer. The chief advantages of TRC are its high tensile strength and pseudo-ductile behaviour, characterised by large deformations due to its tolerance of multiple cracking. This interesting material with its excellent mechanical properties can be highly appropriate to many applications both for new structures and for the strengthening or repair of old structural elements made of reinforced concrete or other traditional materials (Brameshuber 2006, Curbach & Jesse 2009).

Previous investigations showed that textile reinforced concrete has a high tensile strength, which is typically reached at relatively large deformations (Jesse 2004). Such large deformations prior to material failure are very important with regard to structural safety as well as the energy dissipation in case of impact loading. However, that high strength levels can be only reached at high deformations means that for the service state, where only small deformations can be accepted, the design load-bearing capacity of TRC must be lower than its tensile strength. Moreover, relatively wide cracks observed at high deformations are undesirable.

In recent years, several test series have been performed to investigate the influence of short fibres on different properties of textile reinforced concrete (Butler et al. 2006, Hinzen & Brameshuber 2007). However, the mechanisms of the joint action of short fibre and textile reinforcement are still not fully understood. In order to gain better insight into the specific material behaviour of the fine-grained concrete with such hybrid reinforcement, a new investigative programme was started at the TU Dresden. In this study the effect of using different types of short fibres on the fracture behaviour in textile reinforced concrete are investigated using uniaxial tension tests on thin, narrow plates made of TRC. Special attention is directed to the course of the stress-strain relationship and crack development. Furthermore, visual inspections of specimens' surfaces and microscopic investigation of fracture surfaces have been evaluated. On the basis of these data, the mechanisms of the interaction between continuous fibres and short fibres in cement-based composites are discussed.

2 TYPICAL BEHAVIOUR OF TRC

Jesse (2004) showed that the behaviour of TRC under tensile stress can be subdivided into three states, as presented schematically in Figure 1. The first state is the free-crack state, I. In this state, TRC shows linear-elastic behaviour until the stress increase leads to the formation of the first crack. The second state IIa represents the state of crack-formation, where more and more relatively fine cracks form due to the increase in the tensile stress. The crack-widening state, IIb, is the last state in the stress-strain relation. In this state no or only a few new cracks appear, but the existing cracks grow and become wider until the ultimate stress is reached and the material fails.

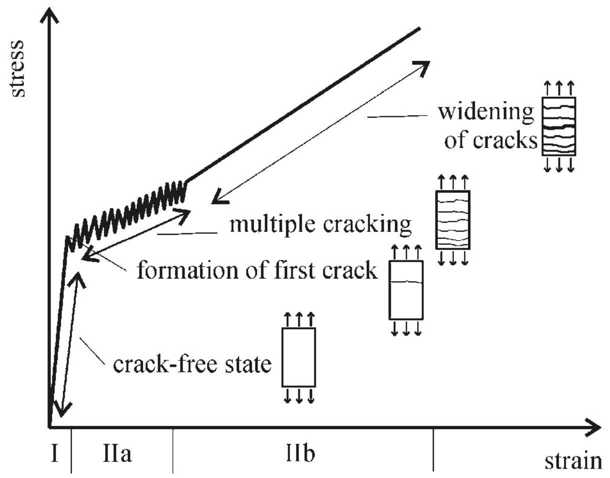

Figure 1. Schematic representation of a typical stress-strain curve for TRC with indication of cracking states.

3 MATERIALS, TEST METHOD, TEST PARAMETERS

3.1 *Material composition*

In previous investigations it was found that matrices with slag furnace cement (CEM III) and the addition of pozzolans show favourable properties regarding durability of the glass fibre as well as of the bond between fibre and matrix (Butler et al. 2005). One of these fine-grained, cement-based concretes was chosen for this investigation. The binder was composed of cement, fly ash and micro silica. Two mixtures, each with differing water-to-binder ratios (0.3 and 0.45, respectively), were calibrated. Fine sand with a maximum grain size of 1mm was used as aggregate. Table 1 sets out the matrices' compositions. Finally, a superplasticizer with a basis of naphthalene-sulphonate was added in order to achieve sufficient flowability. The average slump flow value obtained with a small cone was 200 mm.

Coated, biaxial fabric made of alkali-resistant glass (AR-glass) was used as textile reinforcement. Two different degrees of reinforcement were achieved by varying the number of textile layers. The degree of reinforcement was calculated for one layer of fabric in volume as 66.33mm^2/m. Figure 2 shows the type of textile used in this investigation. The fineness of the weft and warp threads as well as the spacing between the yarns are given in Table 2. The fineness is given in tex, which is equal to the weight of one kilometre of yarn in grams.

Table 1. Matrix composition [kg/m³].

Water-to-binder ratio	0.30	0.45
CEM III B 32.5 NW-HS-NA	632	554
Fly ash	265	233
Micro silica suspension*	101	89
Fine sand 0/1	947	832
Water	234	330
Superplasticizer	11	2

* solid:water = 50:50

Table 2. Textile used as reinforcement.

NWM3-013-07-p2 (30%)			
Warp		Weft	
Fineness [tex]	Spacing [mm]	Fineness [tex]	Spacing [mm]
2*640	7.2	2*640	7.2

Table 3. Types of fibre used and properties.

Type	Material	Diameter [µm]	Density [g/cm^3]	Tensile Strength [MPa]	Young Modulus [MPa]
Dispersed	AR-glass	20	2.68	1700	72,000
Integral	AR-glass	13	2.68	1700	72,000
Dispersed	Carbon	7	1.70	3950	238,000

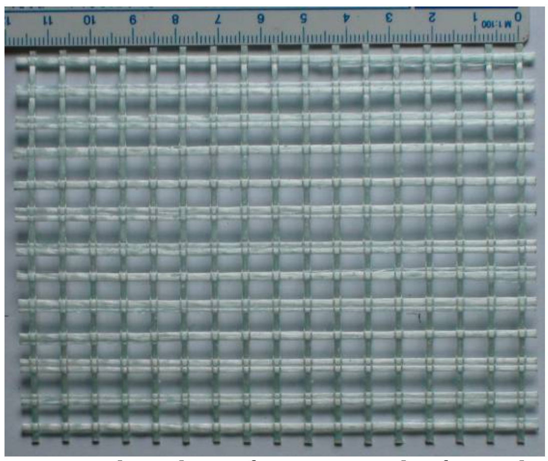

Figure 2. Biaxial textile reinforcement made of AR-Glass.

Dispersed and integral AR-glass short fibres (SGF) as well as dispersed short carbon fibres (SCF) were chosen for testing the TRC in combination with textile layers. Where dispersed short fibres are dispersible in water and they distribute and spread in mixture to thousands of single mono-filaments, the integral short fibres remain stuck together and stay in strands in the mixture. All types of fibre had a length of 6 mm. Table 3 gives other properties of the short fibres.

3.2 *Preparation of the specimens and test setup*

Rectangular plates 500mm long and 100mm wide were cut out of bigger plates 525mm long and 425mm wide, which were produced using a lamination technique. The laminating process started with the spreading of a thin concrete layer on the bottom of the mould. The first sheet of textile reinforcement was laid upon this fresh concrete layer and then, gently, partially pressed in and smoothed. The complete imbedding of first textile layer took place during the insertion of the second concrete layer; the thicknesses of the concrete layers depended on the desired thickness of the plate and the desired number of textile layers. Subsequently, these production steps were repeated until all reinforcing layers were placed and incorporated into fine-grained concrete. The thickness of the plates was 12mm.

The plates were demoulded at a concrete age of two days and then stored in water until an age of 7 days. Subsequently, the plates were stored in a climate-controlled room at 20°C and 65%RH until an age of 28 days.

The uniaxial tensile tests on the narrow TRC plates were performed with a deformation rate of 0.5mm/min. The loading was increased continuously until failure occurred. The force was transferred to the plates via non-rotatable steel plates glued to the TRC plates. Deformation was measured by two linear variable differential transformers (LVDT). Figure 3 shows the test setup.

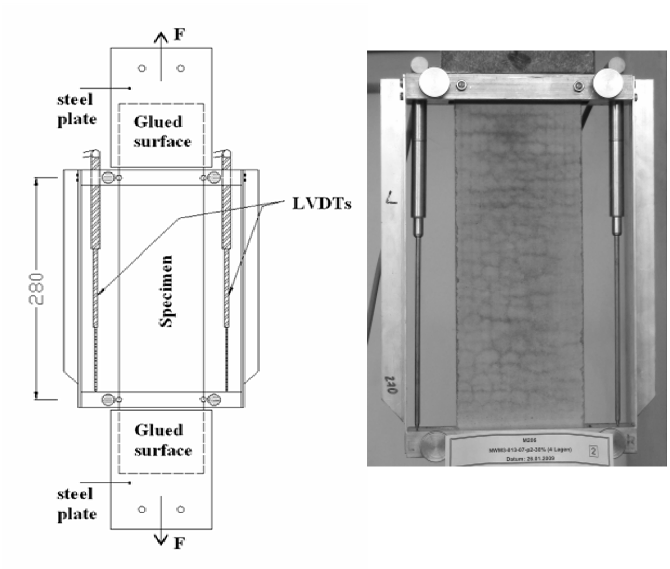

Figure 3. Schematic view of the test setup (left) and a TRC plate during a tensile test (right).

In order to investigate the influence of the selected types of short fibres on the fracture behaviour of textile reinforced concrete, combinations of parameters were tested as given in Table 4. For each parameter combination, at least three specimens with both types of fine-grained concrete (cf. Table 1) were produced and tested.

Table 4. Parameter combinations.

Textile	Short fibres				
	0.0 %	0.5 vol.-%		1.0 vol.-%	
		Glass (dispers)	Carbon (dispers)	Glass (dispers)	Glass (integral)
2 layers	X			X	X
4 layers	X	X	X		

4 RESULTS AND DISCUSSION

In the following, the stress-strain curves obtained from the uniaxial tensile tests are presented and evaluated. The interpretation of the results is supported by visual inspection of the tested specimens' surfaces and to some extent by the results of microscopic investigation.

4.1 *General effects of short fibres*

Influence on first-crack stress

An obvious increase in first-crack stress was clearly observed in all experiments with the addition of short fibres when compared to the results obtained for the TRC without short fibres. This effect was most pronounced in the tests with a relatively low degree of textile reinforcement (two textile layers only) when a relatively high amount of short fibre was added.

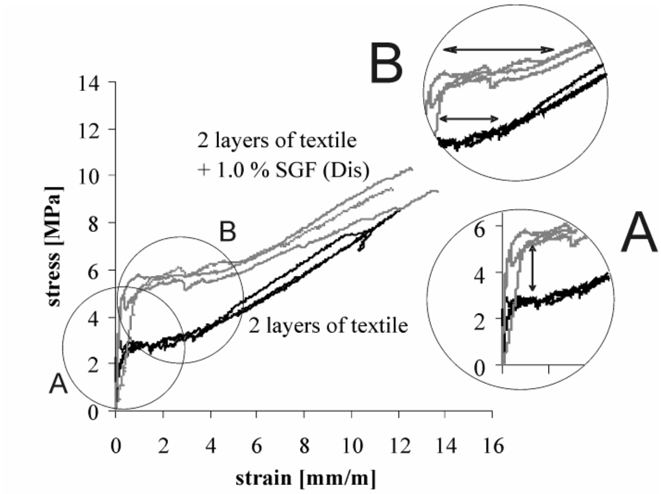

Figure 4. Effect of the addition of dispersed short glass fibres on the mechanical behaviour of TRC plates in tension.

Figure 4 shows the corresponding results obtained for TRC with and without the addition of 1% by volume of dispersed short glass fibres. The water-binder ratio of the matrix was 0.3. As can be seen in Figure 4 the first-crack stress value was doubled due to the addition of short fibres. This improvement in material response can be ascribed to three probable reasons:

1) The bridging of micro-cracks by fine, well distributed short fibres mitigates crack growth and consequently the formation of the first macro-crack. Thus a higher stress is needed to induce macro-cracking.

2) The addition of short fibre leads to a decrease in deformation of the matrix due to shrinkage (Barhum 2007) and therefore reduces internal damage to the fine-grained concrete therefrom. Furthermore, short fibres bridge micro-cracks which develop due to shrinkage (cf. also reason 1).

3) Due to the addition of short fibre the overall reinforcement degree increases. Since the strength and stiffness of AR-glass fibre is considerably higher than the corresponding material parameters of the matrix, the strength of the crack-free composite materials (i.e. the first-crack stress) must increase with increasing degree of fibre reinforcement.

Effects on the formation of multiple cracks and the shape of the stress-strain curve

After the first crack appears, the formation of multiple cracks begins, (cf. Fig. 1), which is one of the key features of TRC, since it tolerates high deformations, and thus contributes favourably to the ductile behaviour of the composite. Detail B in Figure 4 clearly demonstrates the effect of short fibre addition at this stage: The strain region where multiple cracks form expands by more than double due to the presence of short fibre. This expansion can be traced back to a higher number of cracks, as was observed by the visual inspection of the specimens' surfaces. Figure 5 shows that the surface of the TRC specimens containing short fibre has more and finer cracks in comparison to the TRC-specimens without the addition of short fibres.

Three possible mechanisms responsible for such behaviour can be named at this stage of investigation:

1) Higher stress levels in the tests on the specimens with the addition of short fibre lead even prior to the development of the first macro-crack to formation of a greater number of micro-cracks over the entire specimen volume or length, respectively. Beginning with the first-crack stress the macro-cracks develop from these micro-cracks. A greater number of finely distributed micro-cracks offer more nuclei for macro-crack formation, leading to more pronounced multiple cracking.

2) The formation of a macro-crack results in a decrease of matrix stress in the vicinity of the crack. The next crack may not form at a distance below a threshold value depending on the kind of the reinforcement used. Adding short fibre causes additional stress transfer over the macro-cracks, which results in a less pronounced relaxation of the matrix in their vicinity. A new crack can form at a smaller distance from an existing crack, thus more pronounced multiple cracking can be observed.

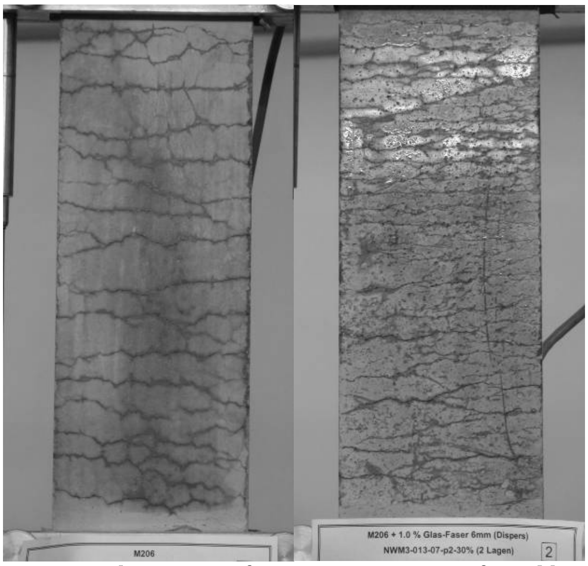

Figure 5. Crack patterns of TRC specimens reinforced by two layers of textile: without short fibres (left) and with 1.0% short glass fibres (right) tested in uniaxial tension mod.

3) Microscopic investigation of fracture surfaces (ESEM) showed that short fibres can be linked to multifilament yarns. This might improve the bond between textile and matrix, thereby leading to smaller crack widths and higher cracking density. Figure 6 shows the "implantation" of glass short fibres in multifilament yarns in a TRC plate reinforced by 4 layers of textile and 0.5% (by volume content) short glass fibres.

The positive influence of short fibres on the stress-strain behaviour of TRC can be clearly noticed in the crack-widening state (IIb) as well. While the strain capacity of the composite was preserved, the tensile strength of the composite with short fibre is generally higher than for the material without adding short fibre. Since the stress-strain curves for TRC with short fibre were always above the corresponding curves for TRC without short fibre, it can be concluded that the energy absorption (area under the stress-strain curve) increases significantly due to the addition of short fibres.

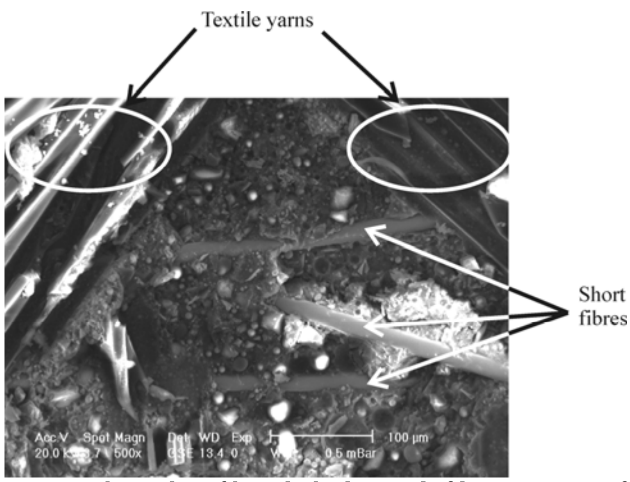

Figure 6. Short glass fibres linked to multifilament yarns of a textile layer (from a TRC plate reinforced with 4 layers of textile and 0.5% short glass fibres).

4.2 *The difference in effects of integral and dispersed short fibres*

Figure 7 shows the results of the uniaxial tension tests on TRC specimens with 2 textile layers, with and without short fibre. Two types of AR-glass fibre were used in this test series: dispersed and integral. The concentration of short fibre was 1% by volume. Water-to-binder ratio of the mixture in these tests was 0.45.

It can be recognised clearly from the graph that dispersed short fibre is more efficient in increasing the first-crack strength of TRC in comparison to the integral fibre. With increasing stress and strain levels the advantage of short fibres begins to fade; until TRC failure the stress-strain curves for the plates with and without the addition of dispersed short fibres approach each other closely. Obviously the failure probability of short dispersed fibres increases steadily with increased loading and crack opening. It is very likely that great majority, if not all of the dispersed fibre, fail before the tensile strength of the composite is reached.

The addition of the integral short fibre leads only to a moderate effect with regard to the increase in first-crack stress but improves the load-bearing capacity of TRC over the entire strain range. The integral fibres remain in strands during concrete mixing and consequently in the hardened TRC. The action of the integral fibre in TRC is similar to that of the multifilament yarns. Due to the “concentration” of the filaments the positive effect on first-crack stress is less pronounced, since the arrest and bridging of micro-cracks is less efficient and since only outer filaments of the filament bundle have a good bonding to the surrounding matrix. However, the integral fibres remain “active” also at high deformations.

As a result the short integral fibres exhibit a positive effect right up to TRC failure. It is seen in the nearly parallel course of the stress-strain curves for TRC with and without addition of the integral short fibres. It is worthy of mention that such shifting in the course of the curve indicates a considerable increase in the energy which can be dissipated when TRC with short fibre addition is subjected to tensile loading.

The influence of the type of short fibre on crack formation was investigated by visual inspection of the specimens’ surfaces. The specimens made of TRC with addition of dispersed short fibres showed more and finer cracks as well as more uniform distribution of the cracks over the length of the specimens when compared with the corresponding data for TRC with integral short fibre. This result accords with the assumptions concerning the active mechanisms of the fibre addition as discussed above.

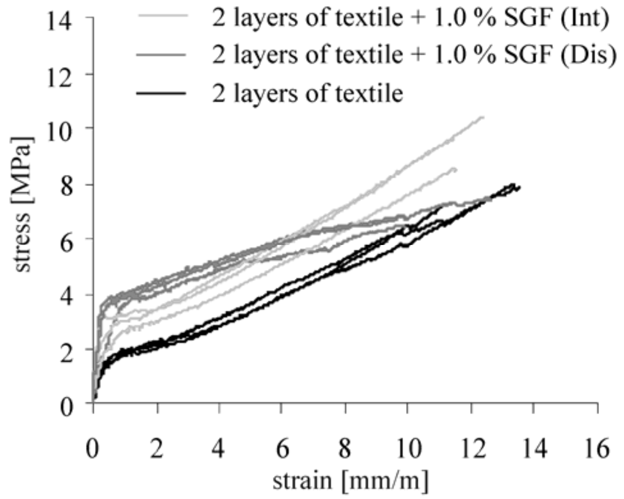

Figure 7. Effect of dispersed and integral short glass fibres on behaviour of TRC plates under tension.

4.3 *Influence of short carbon fibres*

The results of the uniaxial tensile tests on TRC reinforced plates made with addition of dispersed short carbon fibres (SCF) are presented in this section. The significant influence of this type of short fibre on the workability of the mixture is not discussed here.

Plates with a relatively high degree of textile reinforcement (4 layers) and a relatively low degree of dispersed glass and dispersed carbon short fibre (0.5 % by volume) were produced and tested. Figure 8 presents the stress-strain relations observed. According to these results a more pronounced enhancement in the behaviour of TRC was achieved by the addition of the carbon fibre. The effect was particularly evident at low strain levels. The explanation of these findings is actually quite straightforward since carbon fibre has both a higher tensile strength and higher stiffness in comparison to AR-glass fibre.

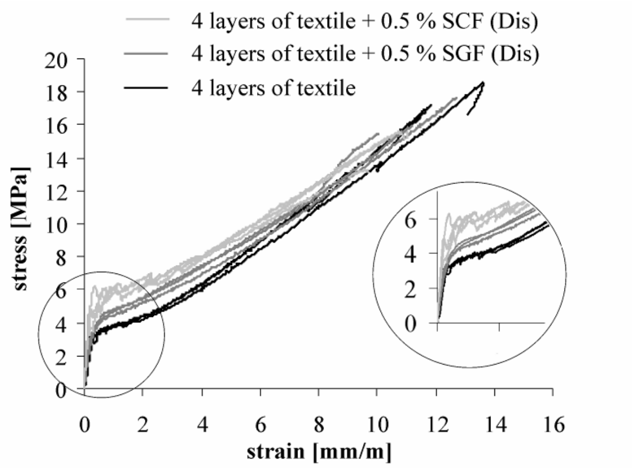

Figure 8. Effect of dispersed short glass fibres (SGF) and short carbon fibres (SCF) on the behaviour of TRC plates in uniaxial tension tests.

5 SUMMARY AND OUTLOOK

This article presents the preliminary results of a study of the effects of adding different types of short fibres on the fracture behaviour of textile reinforced concrete subjected to tensile loading.

Uniaxial tension tests were performed on TRC specimens with and without the addition of short fibres. The stress-strain curves demonstrate clearly the positive influence of the short fibre on their behaviour under tension. For example, the first-crack stress value was doubled due to the addition of 1.0% by volume dispersed short glass fibres to a TRC plate reinforced by two layers of textile. Furthermore, the energy absorption, identified by the area under the stress-strain curve, increased significantly due to the addition of all the types of short fibre chosen for this investigation. However, the influence of short fibre on the curve shape depends on the particular fibre type. While the addition of dispersed AR-glass fibre on the first-crack stress was very pronounced, the use of the same percentage of integral AR-glass fibre caused only moderate increase of this value. On the other hand, the addition of integral short glass fibre considerably improved the tensile strength of TRC, while the effect of dispersed fibre on this parameter was less pronounced.

First very promising results were obtained for TRC with the addition of carbon short fibres. A remarkable increase in the first-crack stress value was measured even for a relatively low concentration of dispersed short carbon fibres.

Research is still in progress and considerable experimental and theoretical efforts are needed in order to comprehend the effects of different types and amounts of short fibres in textile-reinforced concrete. A number of parameter combinations must still be investigated. The testing program will be extended to polymeric fibres, which are very efficiently used in Strain-Hardening Cement-based Composites (Mechtcherine 2005). Furthermore, investigations of material microstructure will be considerably intensified.

6 ACKNOWLEDGEMENTS

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