Improvement of the load-bearing capacity and durability of textile-reinforced concrete due to the use of polymers

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Abstract

Textile-reinforced concrete (TRC) allows the production of thin-walled high load-bearing structural elements. As well as the maximum load-bearing capacity, the durability under various conditions is one major issue for future applications. This paper deals with the technical requirements needed to investigate aspects of bond quality between concrete matrix and reinforcement as well as the durability of TRC. In general, the results show that a polymeric impregnation of the reinforcement and also a polymeric modification of the concrete can lead to a significant improvement in durability – that is, the loss of tensile strength due to the alkalinity is reduced – and in the load-bearing capacity of TRC.

Keywords: Textile-reinforced concrete, impregnated reinforcement, load-bearing capacity, constant loading, durability

1. Introduction

Textile reinforced concrete (TRC) represents an interesting new construction material, offering several additional advantages compared to steel- or fibre-reinforced concrete. These advantages dominate in those fields of applications where thin-walled structural elements with a high load-carrying capacity are required.

In textile-reinforced concrete, textiles made of alkali-resistant (AR-) glass fibres are applied in order to carry the forces arising from tensile load. Previous investigations have shown that the mechanical properties of the glass reinforcement have not been fully exploited. The reasons for this are shown in Figure 1, which was produced by a scanning electron microscope of a roving embedded in concrete with fine-grained aggregates. Only the outer filaments of the roving are in direct contact with the concrete (fill-in zone), the inner filaments having no contact with the concrete. Therefore these filaments can not be activated for any load transmission. To improve the bond properties of TRC, polymers are used for roving impregnation and concrete modification.

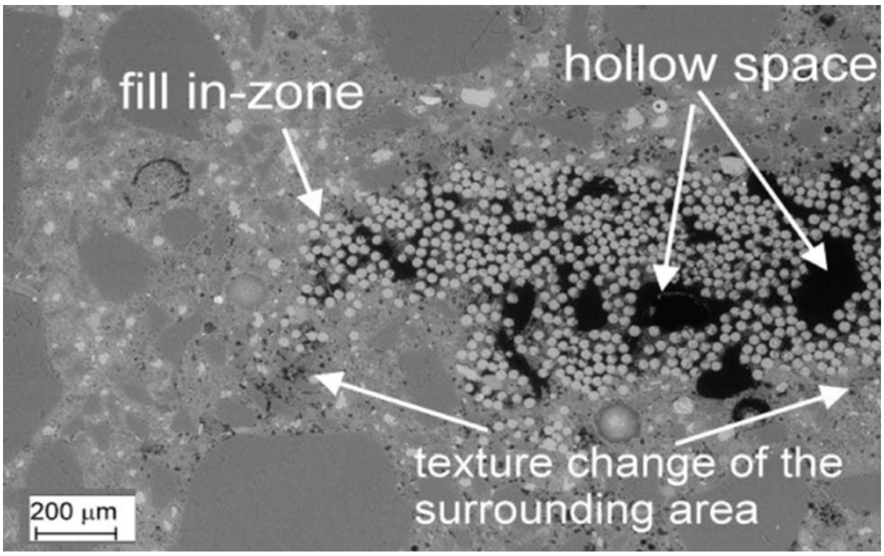

Figure 1: Cross-section of a 2400 tex roving embedded in concrete

Even if the reinforcement is AR-glass, there is a strength loss due to the alkalinity of the concrete[3]. Therefore the aim of this work is to present the impact of polymers used for modification of the reinforcement as well as the concrete on the load-bearing behaviour and on the durability.

2. Materials

2.1. Rovings and textiles

Due to its low price, AR-glass reinforcement is mainly used for TRC. The structure of AR-glass rovings, carbon rovings and aramid rovings is similar. They all consist of some hundreds to some thousands of filaments with diameters of a few µm. These rovings (yarns) are processed usually into two- or three-dimensional textiles similar to the one depicted in Figure 2.

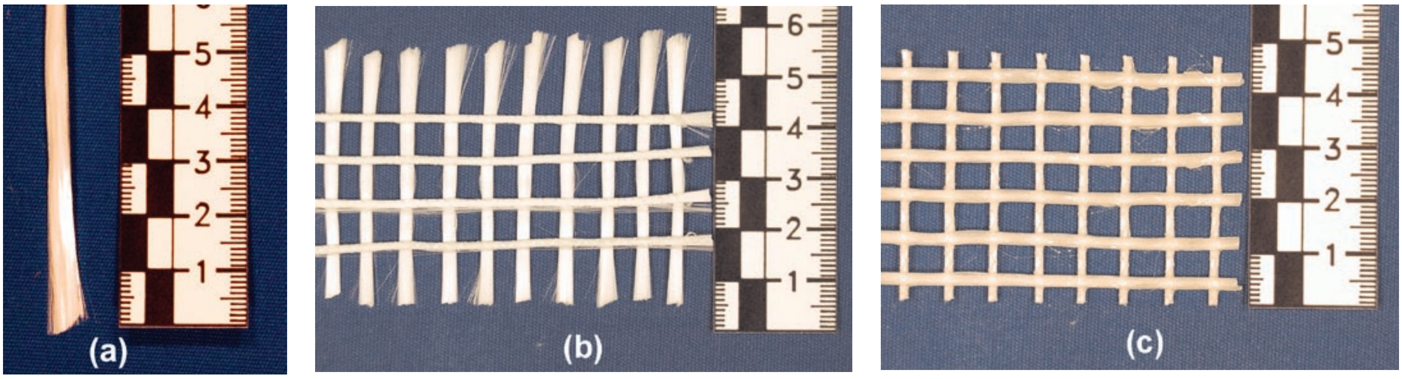

Figure 2: (a) AR-glass roving 2400 tex, (b) glass-fibre textile MAG 07-03, (c) glass-fibre textile MAG 07-03 impregnated with an epoxy

The rovings used in this paper consist of approximately 1560 filaments with an average diameter of 27 µm, corresponding to a linear density of 2400 tex (1 tex = 1 g/km). Table 1 gives an overview of the reinforcement materials mainly used for the current research.

		Filament	**Roving**				**Textile**
Name	-	VET-**F**-ARG-2400-1-03	VET-**RO**-ARG-2400-1-03	Roving – EP 3.1.2 Impregn.	Roving – EPL Impregn.	Roving – PRE 1 Impregn.	MAG-07-03
Density	g/cm^3	2.68	--	--	--	--	--
Titer	tex	1.55	2400	2400	2400	2400	--
Tensile strength	N/mm^2	1691 ± 275	695 ± 67	1541 ± 64	1885 ± 72	1700 ± 96	968 ± 105*
E-Modulus	N/mm^2	53340	53000	n. d.	63200	56200	51330*

*: in 0° direction (direction of the applied load)
n. d.: Not determined

Table 1: Characteristics of the reinforcement including standard deviation[3, 4]

2.2. Polymers for concrete modification and roving impregnation

As previously mentioned, the main aim of concrete modification and roving impregnation with polymers is the improvement of the load-bearing capacity of textile-reinforced concrete; however, another consideration is durability. Therefore different types of polymers, primarily polymer dispersions and epoxies, were used for roving impregnation in previous investigations. These investigations showed that the best results can be achieved by using epoxies for roving impregnation[8], hence the current research into epoxies. The results obtained with three different epoxies will be presented: EPL is a cold hardening epoxy system; EP 3.1.2 is also a cold hardening but waterborne system; PRE1 is a Prepreg (used for PREimPREGnated textile structures) system which was cured at 120°C for 2 hours. The epoxy resins were hardened by addition of an amine hardener according to the stoichiometric ratio. The detailed mechanical and chemical properties of these epoxy resins can be found in References [1] and [7].

2.3. Concrete

Within the scope of the SFB 532 (Collaborative Research Center 532 at Aachen University) a special fine-grained concrete denominated as PZ 0899-01 has been developed, which serves complex requirements for application in textile concrete[2]. The epoxy-modified fine-grained concrete mixture (called EP 3.1.2-10%) is based on mixture PZ 0899-01. The epoxy content of the concrete mixture was set to 10mass% with regard to total binder content. The volume, which is filled by the added polymer, is taken into account as proportionate to the total masses of the other components; the ratios of the other materials are kept constant.

In order to achieve a constant water/binder ratio of 0.4 in the concrete mixture, the water content of the waterborne epoxy is taken into account for the required water content. The compositions of PZ 0899-01 and the epoxy-modified concrete are shown in Table 2. The pH value of both concretes is about 13.5.

Name	Cement (CEM I 52.5 R)	Fly ash (fa)	Silica fume (sf)	Eporxy 3.1.2	Sand < 0.6 mm	Quartz flour	Super-plastiziser
	kg/m^3						$\%_{\Sigma c+fa+sf}$
PZ 0899-01	490	175	35	-	714	499	1.5
EP-3.1.2-10 %	458	164	33	65	667	467	1.5

Table 2: Composition of fine-grained concrete with and without polymer modification[7]

3. Experimental programme

The influence of polymer-impregnated rovings and polymer-modified concrete mixtures on the bond quality and the load-bearing capacity was investigated with a tensile test (see section 3.3). Within the scope of the paper several series of TRC composite specimens were prepared. The first reference series comprised glass-fibre rovings embedded in the concrete matrix. Further series included roving impregnation, concrete modification and different production methods. Table 3 shows the experimental programme.

No.	Concrete	Reinforcement	Impregnation material	Application method
1	PZ 0899-01	8 Rovings VET-**RO**-ARG-2400-1-03	--	--
2			EP 3.1.2	Fresh on hard
3				Fresh on fresh
4	EP-3.1.2-10 %			Fresh on hard
5				Fresh on fresh

Table 3: Experimental programme

By use of the 'fresh on hard' (F/H) method, the impregnated reinforcement was embedded into the concrete or polymer-modified concrete matrix after the curing process of the epoxy. In contrast to the F/H method, the impregnated reinforcement used for the 'fresh-on-fresh' (F/F) method was cured during the hydration process of the concrete.

In the following sections, possible investigational methods for judging the durability of TRC will be presented.

3.1. Single filament test

In order to investigate the chemical attack on AR-glass in alkaline solutions, tensile tests on single filaments have been performed (see Figure 3(a)). Before testing, the filaments were stored in an alkaline solution in order to accelerate the ageing prosess of the specimen. The configuration of this alkaline solution was chosen according to the aforementioned fine-grained concrete.

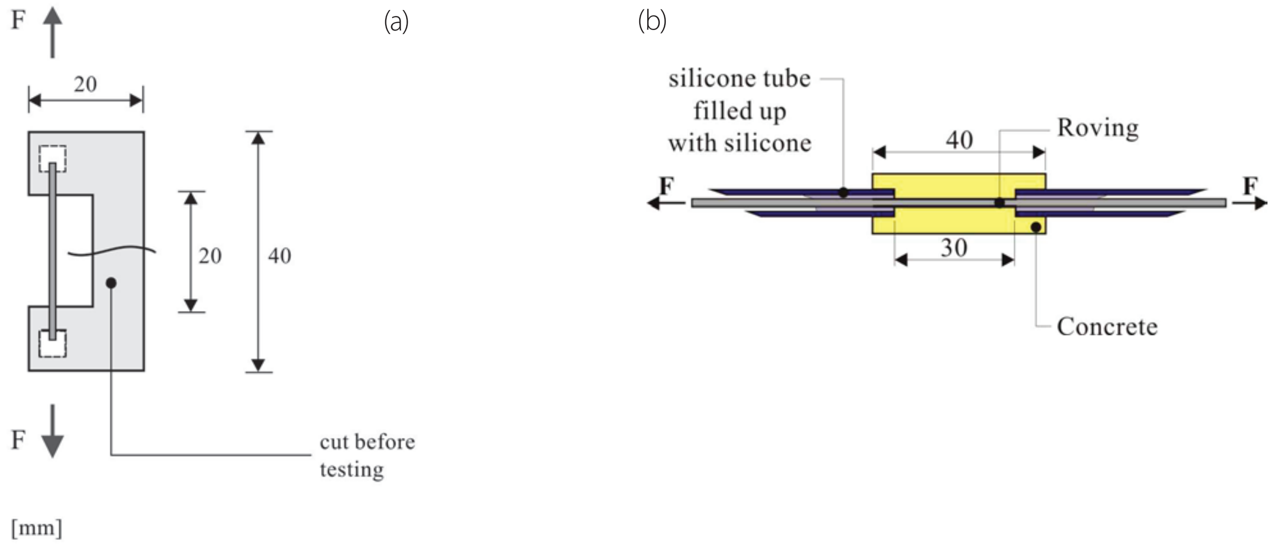

Figure 3: (a) Dimensions of a filament specimen; (b) dimensions of an SIC specimen

Figure 3(a) shows the tensile test specimen. Each single filament was glued between two U-shaped papers before testing. In order to test these specimens a special testing machine was developed at the ibac. The tensile load is applied on the filament with a rate of 0.546 mm/min. A load cell measures the applied load and two LVDTs are used to determine the displacement. The preparation of the test specimens requires a high degree of accuracy and caution because the tested filaments have a diameter of about 27 µm. The filament diameter has a standard deviation of 1 µm, which results in a rather high scatter of the filament tensile strength. Nevertheless it is possible to calculate the area of the effective filament cross-section (since filament diameters are measured using a microscope and camera). This is a definite advantage compared to tensile tests on rovings (multifilament yarns), since not all filaments in a roving contribute equally to load bearing, making interpretation of results extremely complex.

3.2. SIC test (strands in cement)

The change of tensile strength of a roving embedded in concrete after climatic stress (for example hot water) can be measured with the SIC test. For the SIC test a roving is concentrically cast into fine-grained concrete. The test specimens are 40 mm long, 10 mm high and 10 mm wide and stored after a hardening period of 28 days at 23°C and 95% relative humidity (RH) several times in water at different temperatures. Silicone tubes are used to protect the roving outside the concrete from water ingress (Figure 3(b)). Filling the silicone tubes with silicone prevents the concrete from entering the tubes. Furthermore this measure permits a precise definition of the embedded length of the roving in the specimen.

A tensile force can be applied to the roving ends outside the concrete for measuring the loss in tensile strength of the embedded rovings after climatic stress. The SIC tests are carried out at a displacement rate of 1 mm/min.

3.3. TSP test

For this tensile test dog-bone-shaped specimens (also called TSP specimens) have been produced. The geometry of the TSP specimens can be seen in Figure 4. In order to achieve a roving failure the amount of reinforcement depends on the used rovings – for example, using 2400 tex roving, eight rovings are required. The rovings are clamped centrically in a steel mould ($500 \times 100 \times 6$ mm^3) and filled with the fine-grained concrete mixture PZ 0899-01 and the polymer modified mixture. The waistline is milled in the samples by means of a steel template. In the central area, the specimen width is constantly 60 mm over a length of 250 mm. This leads to a homogeneous stress distribution in the mid-part of the specimen. The specimens are produced and tested in a displacement-controlled testing devise (0.5 mm/min). The tensile load is applied via rounded-off steel elements, as shown in Figure 4. During testing the change of length is measured on two sides over 250 mm using electrical gauges.

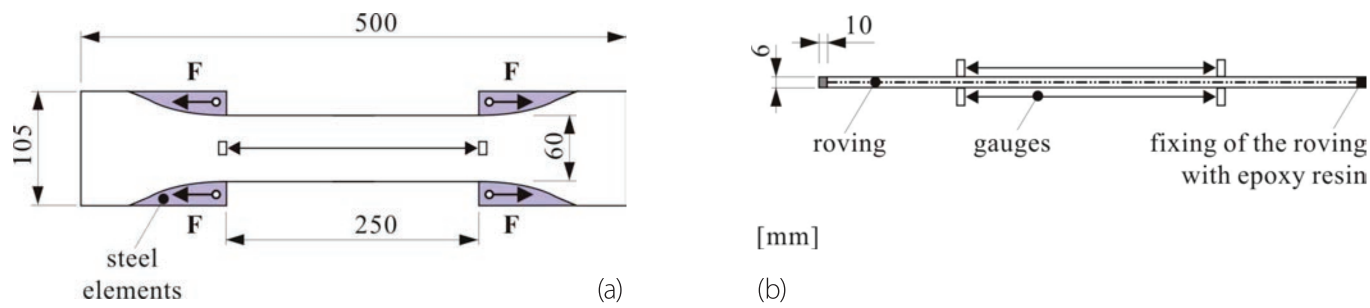

Figure 4: Testing of a TSP specimen: (a) top view of the specimen; (b) cross-section

In order to investigate the loss of maximum roving tensile strength due to the alkalinity of the concrete matrix, the rovings, which are sticking out of the sample body, are glued with epoxy at the ends of the specimen. So the individual filaments are fixed at each end of the sample. During the loading process, filaments are unable to slip towards the centre of the sample from the sample edges. Therefore the rovings can reach their maximum tensile strength. Due to this sample preparation the TSP test allows conclusions concerning the changes in the stress–elongation behaviour, the cracking image and the maximum roving tensile strength after climatic stress. In order to investigate the influence of a polymer modification on the load-bearing capacity and bond quality of TRC, the rovings are not fixed at their ends.

4. Results

4.1. Load-bearing behaviour of polymer-modified textile-reinforced concrete

The tensile test samples (TSP specimens) were stored for 28 days at 23°C and 95% RH and then for seven days at 23°C and 50% RH after concreting. From experimental load–displacement curves, nominal fibre stress–elongation curves have been determined. Typical stress–elongation curves of the TSP tests are given in Figure 5 and the results are shown in Table 4. The nominal fibre stress has been simply calculated by dividing the applied force through the total filament cross-section. With these curves the typical material behaviour of the composite textile-reinforced concrete can be explained. In the first elongation area the force is mainly carried by the concrete. The *E*-modulus of the concrete determines the slope of the curve. After the concrete breaks at the weakest point of the cross-section, the reinforcement has to bear the full load in this cracked zone. In the neighbourhood of this crack the elongation increased more rapidly.

As shown in Figure 5, multiple parallel cracks are developed in the matrix without consequent failure of the composite. After the crack formation is completed, the reinforcement has to take up the load completely. This part of the stress–elongation curve depends on the material properties of the reinforcement and the bond quality between concrete and reinforcement.

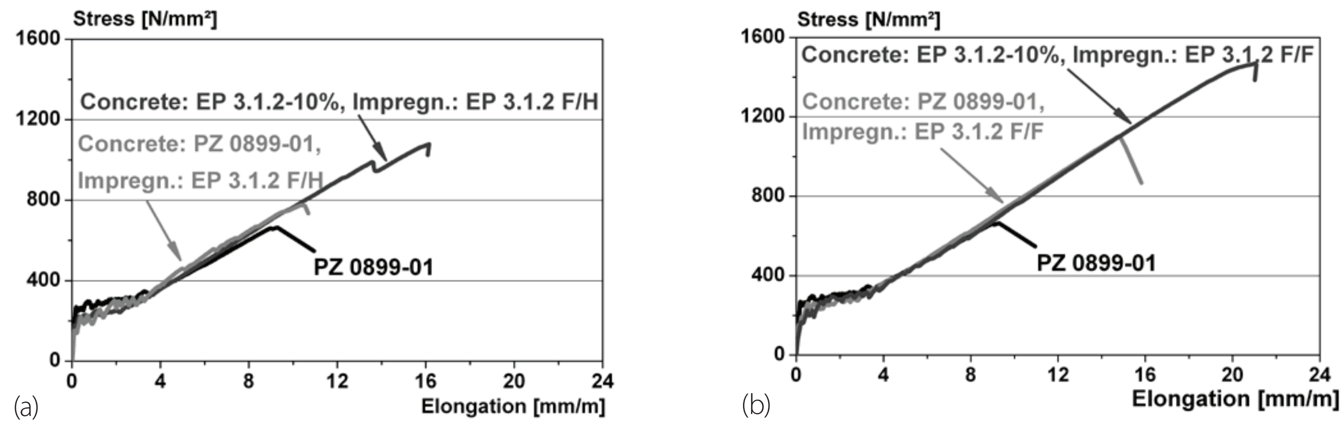

Figure 5: Nominal fibre stress–elongation curves of TSP, influence of roving impregnation, concrete modification and different application methods: (a) F/H; and (b) F/F

No.	Concrete	Roving impregnation	Production method	σ_{yarn}	$\Delta\sigma_{yarn}$	x_{crack}
-	-	-	-	N/mm²	%	mm
	PZ 0899-01	-	-	665 ± 54	0	5.8 ± 2.3
	PZ 0899-01	EP 3.1.2	-	812 ± 123	22	33.0 ± 19.0
	PZ 0899-01	EP 3.1.2	fresh on hard	1125 ± 110	70	13.1 ± 6.2
	EP 3.1.2-10%	EP 3.1.2	fresh on fresh	989 ± 109	49	26.6 ± 9.9
	EP 3.1.2-10%	EP 3.1.2	fresh on hard	1355 ± 94	104	12,6 ± 1,9

σ_{yarn} Maximum yarn stress
$\Delta\sigma_{yarn}$ Improvement of the load-bearing capacity compared to PZ 0899-01
x_{crack} Average crack distances at state of failure

Table 4: Results of the TSP test

Due to the application of epoxy-impregnated rovings (with EP 3.1.2) into the concrete mixture (PZ 0899-01) the load-bearing capacity can be increased significantly (Table 4) both for the application methods F/H and F/F. By a high degree of impregnation a larger load-bearing cross-section can be activated in the roving. The impregnation leads to an improved efficiency of the mechanical properties of the reinforcement[8, 9].

By use of the F/F method the increase of load-bearing capacity is enhanced compared to use of the F/H method (see Table 4). Figure 6, which was produced by a scanning electron microscope, shows the different interfaces of an impregnated roving caused by these two application methods. With the F/H application method a clear-cut interface between concrete and reinforcement is formed. In contrast to this application method an extended, homogenised interfacial zone can be achieved with the F/F method. This leads to improved properties of the outer bond between impregnated reinforcement and concrete matrix because the unhardened epoxy is able to admix and interact with the fresh concrete at the interface.

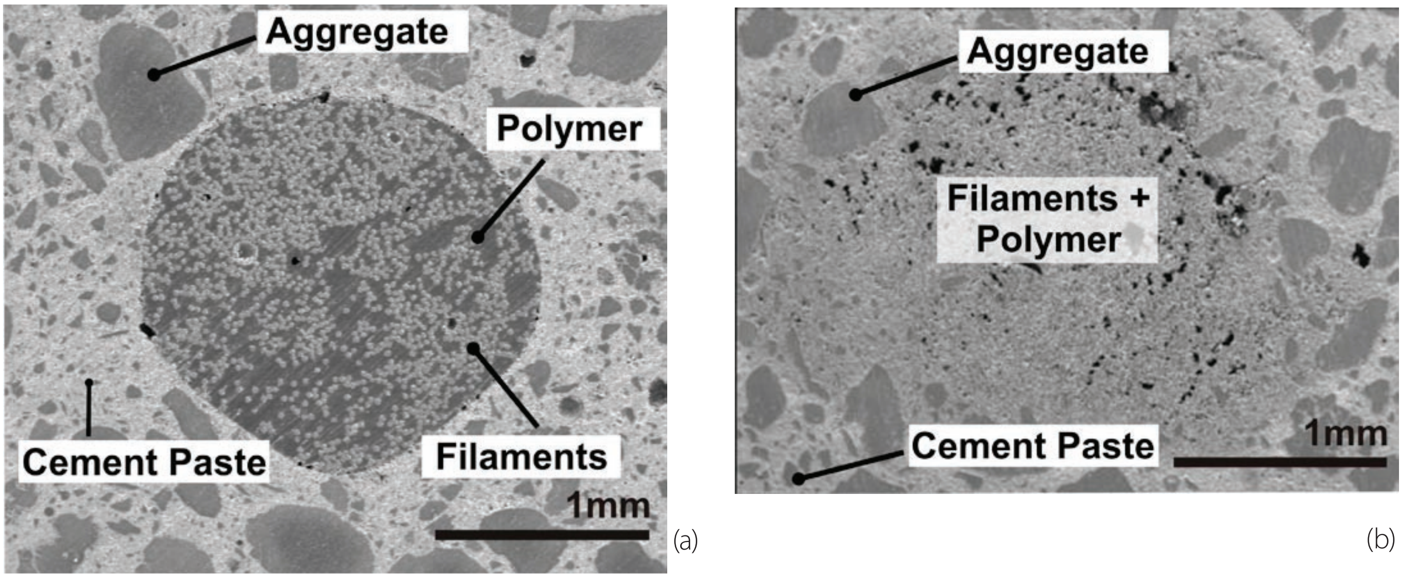

Figure 6: Roving impregnated with epoxy – influence of different application methods (a) F/H and (b) F/F on the interface[10]

The effects of a roving impregnation on the bond qualities are also reflected in the values of the average crack distances at state of failure. Due to an impregnation of the reinforcement the values of the average crack distances are greater than the values for the reference (PZ 0899-01), because of a reduced contact surface between concrete and reinforcement. This is an indication that the impregnated roving almost acts as a single FRP reinforcement rod in a concrete matrix. Due to the F/F application method the average crack distances are less than the values for the F/H application method because the use of an F/F method leads to better global stress transfer between the impregnated fibre bundle and the surrounding matrix. While the F/F method leads to a finer crack pattern, fewer but wider cracks are formed in the specimens with the F/H method. The crack opening might even become too large for real applications.

With the use of polymer-modified concrete an improved bond between impregnated reinforcement and concrete matrix can be reached, therefore higher bond forces can be transmitted. This leads to a better performance in the TSP test, which is expressed in an increased rupture stress compared to the curves with unmodified concrete and impregnated reinforcement (Figure 5).

As shown in Figure 5, the maximum increase of the fracture load can be achieved with the use of epoxy-modified concrete and epoxy-impregnated reinforcement in combination with the F/F application method. In this case both epoxies for impregnation and concrete modification are able to admix and interact at the interface. This results in a further improvement of the interfacial stress transfer between reinforcement and concrete.

4.2. Durability of polymer-modified textile-reinforced concrete

4.2.1. Durability model for AR-glass reinforcement in TRC

The loss of strength of AR-glass in a highly alkaline environment is due to the growth of small flaws in the glass filaments. It is assumed that these flaws originally (after production of the AR-glass rovings) measure approximately 40 nm. The growth of theses flaws is due to the attack of the alkaline pore solution of the concrete. In order to allow a prediction of the AR-glass strength loss over time, a durability model has been developed. The detailed functionality is described in References [3] and [11]. The model should allow an accurate calculation of the loss of strength due to the outdoor weather conditions in which the TRC element is erected.

As indication for the loss of performance, the loss of strength is calculated as follows:

$$\Delta f_{1,t} = 1 - \frac{f_t}{f_{t=0}} \qquad (1)$$

where $\Delta f_{l,t}$ degree of strength loss at time *t*

f_t tensile strength of the specimen at time *t*.

In order to predict the long-term loss of strength of AR-glass in concrete a two-step process currently has to be used. First the loss of strength of accelerated-aged tensile specimens (TSP specimens) is determined as a function of the storage temperature and the storage time. In order to accelerate the ageing process the samples are stored under water or at a high relative humidity (> 95% RH). With the achieved loss of strength over time values, model curves are calculated, by use of the model parameters. These model parameters then allow a step-wise calculation of the loss of strength over time with regard to dependency on climate – represented by the temperature, relative humidity and rainfall of the desired location. These values have to be present for a representative time and can then be used to extrapolate the climate over a longer time period. The basic idea behind this approach to calculating loss of strength is that the pore system of the concrete is only filled with water during rainy periods and the drying stages afterwards. At all other times the pore system is fairly dry and the corrosion of the AR-glass is slowed down significantly. This also means that the assumption of a water-saturated pore system might overestimate the loss of strength of the AR-glass reinforcement.

In order to calibrate the model and to check the aforementioned assumptions, large outdoor weathering tests were performed and remain ongoing. Figure 7 shows a comparison between the predicted losses of strength due to a water-saturated pore system (AR-glass corrosion at all the times – the temperature was set to 13.6°C, which is the average yearly temperature in Aachen) and the humidity-sensitive approach. It also shows the results of outdoor-weathered specimens after a maximum time of 4.5 years. As concrete the PZ-0899-01 and as reinforcement the VET-RO-ARG 2400 rovings were used.

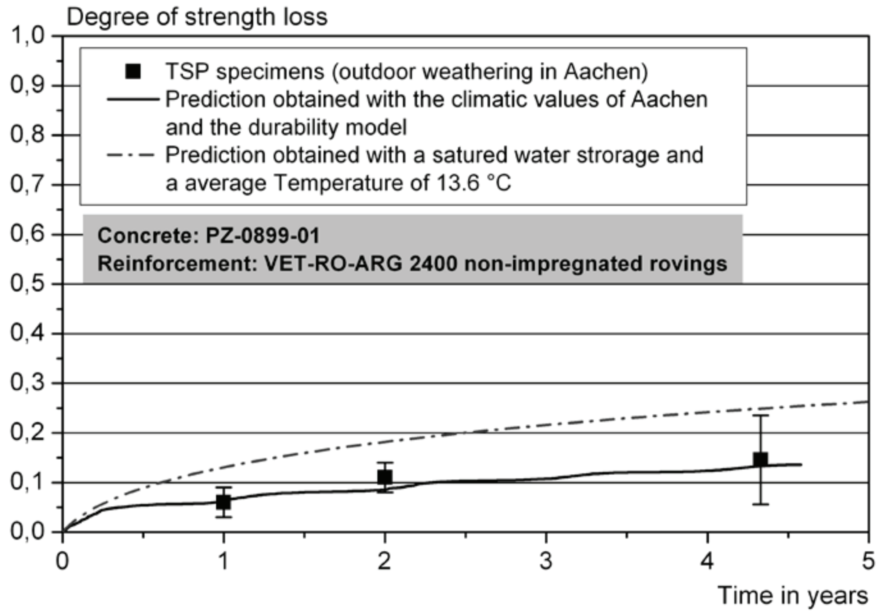

Figure 7: Comparison of the predicted loss of strength due to a water-saturated environment, the climate in Aachen (Germany) and the results of the outdoor-weathered TSP specimens tested after the indicated time (the standard deviation of the tests is also indicated)

The conclusions drawn from the presented figure are as follows:

- The loss of strength predicted with a complete and constant water saturation and the average yearly temperature of Aachen overestimates the loss of strength obtained with the outdoor-weathered samples.
- The prediction with the durability model based on the climatic conditions of Aachen shows good agreement with the outdoor-weathered specimens.
- The increase of the scatter after 4.5 years can be due to a non-homogeneous corrosion process.
- One very important fact is that the curves were calibrated for the climate in Aachen and are not therefore valid for other climates.

In order to calculate the loss of strength over time for other combinations of reinforcement and concrete, the aforementioned tests have to be conducted. To give an idea how different polymeric modifications affect the durability of TRC, the following section will give selected results from different test series.

4.2.2. Selected results of the durability investigations on various reinforcement materials

Single filament tensile tests were performed initially to gain an insight into the influence of the alkalinity of the concrete matrix. Figure 8(a) shows the degree of strength loss of AR-glass filaments with and without impregnation with epoxy prior to their storage in alkaline solution at 50°C. The pH of the solution is 13.5 and matches the pore solution of the used concrete. The film thickness of the epoxy layer on a single filament is below 1 μm. The tensile tests were performed with ten single filaments after 7, 14 and 28 days of storage in alkaline solution at 50°C. As shown in Figure 8(a) the impregnation shows no influence on the degree of strength loss of the AR-glass reinforcement. After a period of 7 days, the degree of strength loss is approx. 40%. This value increases during the next 14 days up to 60%. These results have to be considered in light of the following two aspects: the impregnation with epoxy on a single filament has a very low thickness; and the attack area of the alkaline solution is equal to the whole filament area. Rovings which are used as reinforcement in concrete show a greater impregnation layer thickness and a much smaller attack area because the alkaline solution only accesses the roving in the pores of the concrete. The increased thickness is due to the impregnation process because single filaments are very sensitive to mechanical treatments. Therefore the results have to be interpreted very carefully.

This influence of the attack area can also be seen in Figure 8(b) which displays the results of the TSP tests (dog-boned-shaped specimen) stored in water. One test series for each point in time contains three single specimens.

The impregnated textiles reveal a significant lower degree of strength loss than the non- impregnated textiles. This reduction in the degree of strength loss is probably a result of the noticeably smaller attack area of the alkaline solution in the pore system and the increased thickness of the epoxy resin compared to the filament tests. The influence of the thickness of the epoxy will be investigated in further test series.

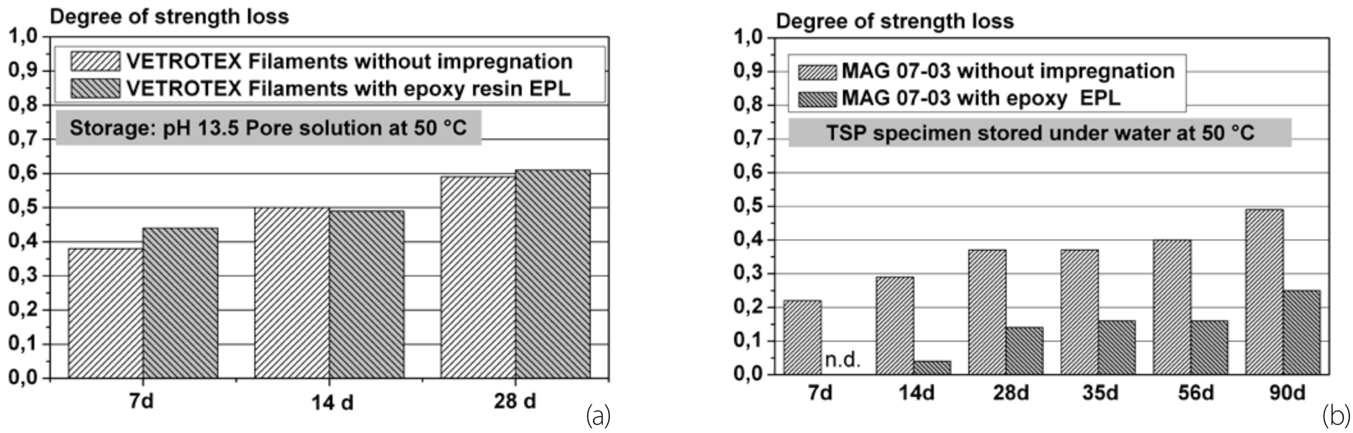

Figure 8: (a) Degree of strength loss of filaments after storage in alkaline solution at 50°C; (b) degree of strength loss of TSP specimens after storage in accelerated ageing (50°C/water); both with and without epoxy resin EPL (n.d. = not determined)

The influence of different polymeric modifications of the reinforcements can be seen in Figure 9(a), where the test results as well as the model curves are displayed. It can be seen that after 200 days of accelerated ageing (50°C and water storage) the loss of strength of the non-impregnated textile reinforcement in a non-modified concrete is approximately 60%. By use of a polymer-modified concrete this strength loss can be reduced by a nominal 10%. This is presumably due to the reduced water uptake of the modified concrete as is shown in Figure 9(b). It should be noted that the reduction of the strength loss in real weathering can be higher than the 10% shown because storage under water might be too harsh a test environment. Currently, various test series with different climatic storage conditions are being performed. Using an epoxy impregnation of the reinforcement, the strength loss can be further reduced. The reasons for the significantly different behaviour of the various epoxies are an ongoing research topic. One possibility is the diffusion properties of the epoxy resin against the alkali ions of the pore solution. The major difficulty in investigating the diffusion properties against the pore solution is the thinness of the impregnation around the reinforcement.

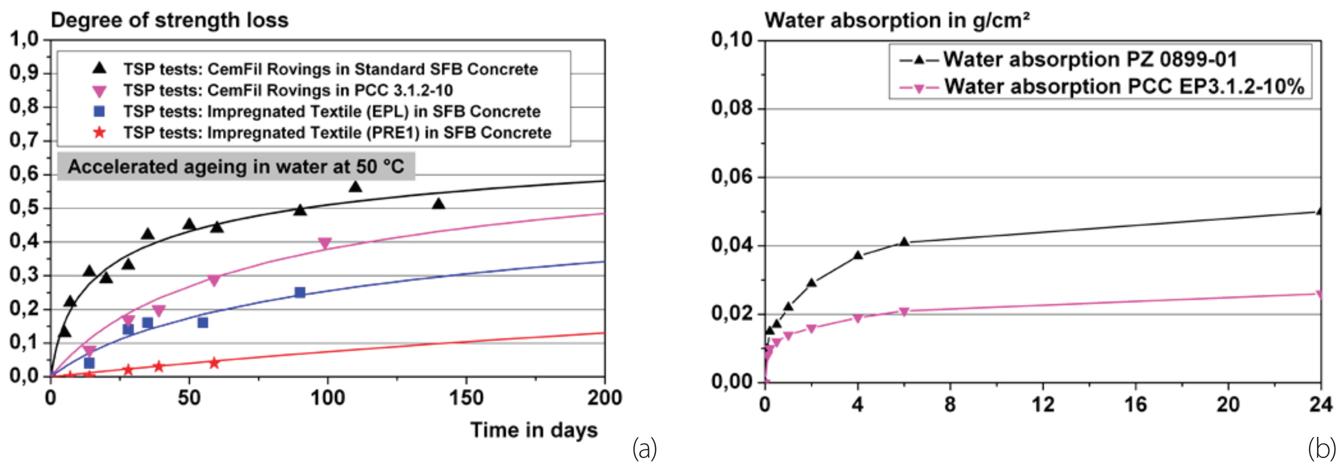

Figure 9: (a) Degree of strength loss of impregnated and non-impregnated reinforcement as a function of time – calculations undertaken in line with Reference [3]; (b) influence of a polymeric modification on the capillary water uptake of the concrete

It is also important to mention that the obtained values of the strength loss in accelerated ageing conditions can not be correlated with any strength loss due to outdoor weathering; in order to obtain a long-term strength loss, calculations with the durability model would have to be undertaken. The strength loss can be significantly reduced by the use of polymer modifications of the reinforcement and the concrete but a factor can not be derived from the actual results.

5. Conclusions

The influence of concrete modification as well as roving impregnation with epoxies and the use of different application methods on the load-bearing behaviour and the bond quality of textile-reinforced concrete were investigated. The results lead to the following conclusions:

- The load-bearing capacity of TRC can be increased significantly by the use of polymeric impregnations – here shown for various epoxy impregnations. The maximum increase of the fracture load can be achieved with the application method 'fresh-on-fresh' because both epoxies for impregnation and concrete modification are able to admix and interact at the interface.
- The bond properties between impregnated reinforcement and concrete can be improved by the use of polymers for concrete modification.
- The use of waterborne epoxies for impregnation of the reinforcement can lead to an extended, homogenised interfacial zone if the F/F method is used.

In this paper different test set-ups were presented to investigate the strength loss of AR-glass used as reinforcement in TRC. The test set-ups can cover all variations of the material TRC from the smallest element – i.e. single filament – up to a compound specimen. Also selected results which lead to a presented durability model were shown. The following conclusions can be drawn from this research:

- The predicted strength loss of AR-glass reinforcement in concrete – calculated with the presented durability model – shows good agreement with the results of the outdoor-weathered specimens.
- The durability of impregnated AR-glass textiles embedded in fine-grained concrete is improved compared to the non-impregnated AR-glass textiles. But also a polymeric modification of the matrix can reduce the loss of strength of the AR-glass reinforcement. Ongoing research deals with the reasons for the improvement of the durability caused by polymeric systems.

6. Acknowledgements

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