Tensile strength of carbon rovings impregnated with different materials under anodic polarization

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Abstract. Carbon textiles are used more and more as reinforcement in concrete structures. Due to their high durability the concrete covers can be extremely thin compared to traditional steel reinforced concrete, resulting in the possibility to build very thin elements with excellent performance. To improve the properties of the carbon textiles, the rovings are normally impregnated with different types of polymers. Additionally to the use as reinforcement, carbon textiles can also be used as anodes for cathodic protection. However, while first tests have shown, that impregnated carbon rovings are suitable to be used as CP-anodes, it is still not clear under which conditions the new types of anodes are stable or when they start to dissolve. This paper describes investigations on the influence of an anodic polarisation on the tensile strength of different types of impregnated carbon rovings.

1 State of the art

Due to the excellent mechanical properties and the electrical conductivity of carbon fibers, carbon textiles are of particular interest as an anode material. By using carbon reinforcements higher tensile strengths can be achieved compared to steel for a given composite concrete element. Furthermore, it is possible to create thin and slender components, since the use of textile reinforced concrete doesn't require a quite thick concrete cover like steel rebars. [1, 2] Attention must be paid to the ability of an electrical power distribution of textiles in order to make efficient use of carbon as an anode within textile reinforced concrete. In addition, the bonding behavior with mortar, which should be as high as possible, plays a decisive role. The properties mentioned are largely responsible for the functionality of the CP, since the current densities on the surface should be distributed as even as possible. [2]

Excellent mechanical properties, durability and electrochemical stability of carbon fibers have been thoroughly proven, which justifies its increasing use as a structural strengthening material. [3,4] In order to investigate the suitability of carbon rovings with different impregnation materials for cathodic protection, a possible reduction in tensile strength under anodic polarization is of interest. Tensile tests with impregnated rovings at room temperature were carried out by Kulas. [5] A significant difference was determined between epoxy resin and styrene-butadiene rubber as impregnation material. Tension and elongation of epoxy impregnated textiles were considerably higher.

Examinations related to the mechanical properties of carbon fiber fabrics under temperature stress were carried out by Younes et. al. and Raupach et. al. [6,7]

Both studies implemented stationary tensile tests with impregnated carbon fiber fabrics. For both, epoxy resin impregnated carbon [7] as well as styrene-butadiene rubber impregnated carbon [6] an extreme decrease of the tensile strength is observed after heating up to 200 °C due to dissolution of the impregnation material.

Mechanical performance of carbon fiber-reinforced polymer plates in simulated ICCP systems was investigated by Zhu et. al.. [8] The influence of different storage solutions and current densities on the mechanical properties of carbon fiber reinforced plates (CFRP) was tested. The examined CFRP plates were composed of multi-layer carbon fibers bounded by laminating epoxy. Anodic polarization was implemented with current densities of 0.2, 2, 20 and 40 A/m² in 3.5 % NaCl solution, a mixture of saturated Ca(OH)₂ solution with 1 % NaCl and in saturated Ca(OH)₂ solution. After completion of the impressed current tests, uniaxial tensile tests with a universal testing machine (tensile loading rate of 0.2 mm/min) were conducted. It was determined that an increasing applied current density leads to a decreasing tensile strength and elastic modulus in saturated Ca(OH)₂ solution and in mix solution. [8]

Similar experiments were conducted by Sun et. al.. [9] Uniaxial tensile tests on CFRP after polarization in simulated impressed current cathodic protection system with 3 % NaCl solution were carried out. A linear relationship between applied load and displacement was observed. An increase of the current density leads to a significant reduction of the tensile strength. Comparable experiments in simulated pore solution obtained similar results. [10]

Nevertheless, a necessity for further research is apparent. The aim of this paper is to check, whether an anodic polarization has an influence on the tensile strength of carbon rovings. The carbon reinforcements

used were impregnated with two different materials, which are epoxy resin and styrene-butadiene. The tensile strength of rovings and rovings embedded in mortar have been investigated.

In the first step of the experimental investigations, the maximum loads of the individual carbon fiber bundles were determined. In the following step, the rovings were anodically polarized before the determination of the maximum load. For rovings embedded in mortar, a similar procedure has been applied.

Furthermore, current density-potential curves of the carbon materials were prepared in order to be able to make a statement about the electrochemical properties of these materials.

2 Experiments

In the following, the experimental set-up used in this work is presented and explained. For this purpose, both, the materials used and the preparation of the test specimen are discussed.

2.1 Materials

Four different carbon reinforcements were used for this study. More details about these materials are given in table 1.

Table 1. Carbon reinforcement characteristics.

Name	Impregnation	Mesh width	Cross-sectional area
	-	[cm]	[mm ²]
Roving without impregnation	-	-	1.80
Q 142/142-CCE-38 (E)	Epoxy	3.8	5.42
Q 142/142-CCS-38 (S)	SBR	3.8	5.42
Carbon with mesh size 38 mm (SDK)	„Smart Deck“ epoxy [12]	3.8	5.42

The three reinforcements with impregnation were delivered as a two-dimensional layer, with rovings perpendicular to each other in the warp and weft directions. One carbon mesh with impregnation is shown in figure 1 (top). The carbon roving shown in figure 1 (below) is cut out from the carbon mesh. Figure 2 shows an un-impregnated carbon roving. These were unwinded and cut out from rolls.

“Smart Deck” [12] is a current joint research project on the development of a multi-functional textile reinforced concrete layer for bridges.

Fig. 1. Impregnated carbon fabrics. Top: Carbon mesh; Below: Carbon roving

Fig. 2. Un-impregnated carbon roving

2.2 Preparation of the specimens

For the tensile tests to be carried out, the carbon reinforcement was cut in the warp direction into strands of 53 cm in length. Consequently, steel sleeves, each 11.5 cm in length and 2.5 cm in inner diameter were cut and deburred. The cut rovings were set by means of plastic frames provided in the sleeves and shielded with a special polymer and thereby anchored. This frame is shown in figure 3.

The special polymer offers special properties such as high compressive strength even under extreme conditions, and it can be precisely filled into the sleeve. The finished test specimen is shown in figure 4.

Fig. 3. Specimen Preparation.

Fig. 4. Completed test specimen.

For the 3 textiles 10 samples each, 5 for polarisation and 5 as reference, were produced. Thus, 30 specimens were prepared with the above-mentioned anchoring polymer.

The un-impregnated rovings were tested directly on the tensile testing machine without embedding.

2.3 Anodic polarisation

For the preparation of the polarized test specimens, identical boundary conditions, such as a length of the roving of 53 cm, were chosen in order to compare the two states, polarized and unpolarized, under the same conditions.

The rovings were potentiostatically polarized against a titanium mixed oxide counter electrode in a saturated calcium hydroxide solution for one week. Based on previous work [2], the potential in these experiments was kept at 450 mV against manganese dioxide (ERE 20) [11].

2.4 Test set up

For the tests of the 53 cm long rovings a testing machine capable of pulling with a maximum load of 100 kN was used. The adjustment device with inserted roving is shown in figure 5.

Fig. 5. Test set-up with adjusted roving.

The testing machine, which was used for tensile tests of the un-impregnated rovings can be seen in figure 6.

Fig. 6. Test set-up for unimpregnated carbon

The rovings were tested at a speed of 2 mm/min and a preload of 20 kN.

3 Results

3.1 Tensile tests

Figure 7 shows the results for the series of un-impregnated rovings. In total, 6 unpolarized specimens and 6 polarized specimens were tested.

Fig. 7. Relation between force and elongation for un-impregnated rovings.

Un-impregnated rovings had a cross-sectional area of 1.80 mm^2 . The mean value of the maximum stresses is $741 \pm 68 \text{ N/mm}^2$ for unpolarized specimens and $591 \pm 96 \text{ N/mm}^2$ for polarized specimens. Polarized samples show approximately 150 N/mm^2 lower tensile strength as unpolarized samples. The elongation is longer for the polarized samples and it has been suggested, that the filaments of polarized samples may show more elongation by water absorption. Further tests are required to clear this point.

All tested impregnated rovings had a cross-sectional area of 5.42 mm^2 . The EP and SBR impregnated rovings had a free test length of about 20 cm. Figure 8 shows the relation between force and elongation for epoxy impregnated rovings. Figure 9 shows an EP-impregnated roving after completion of the experiment. The centric cracks can be clearly recognized.

Fig. 8. Relation between force and elongation for epoxy-impregnated rovings.

Fig. 9. Broken EP-impregnated roving after completion of the tensile test.

Table 2 shows the exact values of forces and stresses for EP-impregnated rovings, whereby *up* indicates unpolarized and *p* indicates polarized specimens.

Table 1. Test results for epoxy-impregnated rovings.

Specimen	Force [kN]	Stress [N/mm ²]
E_up 1	14.2	2619
E_up 2	14.1	2604
E_up 3	14.6	2688
E_up 4	13.5	2492
E_up 5	14.1	2602
E_p 1	13.6	2509
E_p 2	10.1	1854
E_p 3	12.8	2364
E_p 4	12.3	2275
E_p 5	12.3	2273

The mean value of the maximum stresses is **2601** N/mm² with a standard deviation of 70 N/mm^2 for unpolarized specimens and **2255** N/mm² with a standard deviation of 243 N/mm^2 for polarized specimens. So, thus the polarized samples have a significantly lower tensile strength as compared to the unpolarized for the investigated materials and polarisations.

Tensile tests with SBR-impregnated rovings proved to be difficult, due to fixation problems. Figure 10 shows that the roving pulled out approximately 5 mm from the embedding material and thus did not allow a tensile test.

Fig. 10. SBR impregnated roving after tensile test.

Multiple preliminary trials have been conducted and many variations tested to determine the tensile strength of this type of reinforcement. As an example, the anchoring length was increased by using longer sleeves, sanding the ends before the sleeves were pasted at the ends, or using other resins for casting. However, unfortunately the determination of the tensile strength was not possible.

Figure 11 shows the relation between force and elongation for the “Smart Deck” [12] rovings which are impregnated with a special epoxy resin. For the “Smart Deck” [12] project, a special type of epoxy based impregnation has been developed, that makes the carbon particularly suitable for the use as a CP anode. The exact values of forces and stresses for these specimens are shown in Table 3. Here again, *up* indicates unpolarized and *p* indicates polarized specimens.

Fig. 11. Relation between force and elongation for “Smart Deck” [12] rovings.

Table 2. Test results for “Smart Deck” [12]-impregnated specimens.

Specimen	Force [kN]	Stress [N/mm ²]
SDK_up_1	11.9	2195
SDK_up_2	15.5	2863
SDK_up_3	14.0	2577
SDK_up_4	13.6	2500
SDK_up_5	18.8*	3475
SDK_p_1	16.3	3007
SDK_p_2	15.9	2924
SDK_p_3	14.2	2621
SDK_p_4	15.2	2796
SDK_p_5	14.9	2746

The mean value of the maximum stresses is **2534** N/mm² with a standard deviation of 274 N/mm² for unpolarized specimens and **2819** N/mm² with a standard deviation of 151 N/mm² for polarized specimens. The value marked with an asterisk (*) was recognized as an outlier and was not incorporated in the calculation.

In general, the individual curves of the polarized and unpolarized rovings show a similar curve progression. It can be assumed that no decreasing in tensile strength is provoked by anodic polarization up to 450 mV. However, it should be checked, whether there is a

reproducible increase of the tensile strength by anodic polarisation for this type of impregnated carbon anode.

4 Conclusions and Outlook

The aim of the work was to experimentally investigate and quantify the change in the tensile strength of carbon fiber bundles after an anodic polarization. For this purpose, rovings impregnated with epoxy resin, styrene-butadiene rubber, “Smart Deck” [12] carbon with special epoxy impregnation and carbon without impregnation were investigated

The following conclusion can be drawn from the experimental study:

1. Tensile tests with unimpregnated specimens show a decrease of tensile strength by ~20 % after polarization. Conversely, polarized specimens show an increased elongation compared to unpolarized specimens. Further study is needed to investigate if changes in tensile strength are solely caused by polarization or if water uptake influences the mechanical behaviour of carbon.
2. Tensile tests with epoxy-impregnated specimens show a decrease of tensile strength by ~13 % after polarization. Here, elongation reduces as well.
3. For the SBR-impregnated rovings it was not possible to carry out tensile tests, because due to the low adhesion the anchoring systems failed.
4. In addition, a special “Smart Deck” [12] carbon roving was analyzed for tensile strength before and after anodic polarization. After one week of potentiostatic polarization, an increase of tensile strength by ~11% has been observed. In order to determine the reason for this behavior, additional investigations are required.

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