BOND BEHAVIOUR OF TEXTILE REINFORCEMENT IN REINFORCED AND PRESTRESSED CONCRETE

VERBUNDVERHALTEN VORGESPANNTER UND NICHT VORGESPANNTER TEXTILER BEWEHRUNG IN BETON

COMPORTEMENT ADHESIF D'ARMATURES TEXTILES PASSIVES ET PRECONTRAINTES

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SUMMARY

Textile reinforcement is used nowadays in many applications. Fibre reinforced concrete is also well understood. The use of textiles as reinforcement for cementitious composites, however, is a relatively new field for which some detailed research is needed. Moreover, if textiles will be used as a prestressing element further, knowledge is required.

This paper discusses the bond behaviour of textiles used for reinforcement or prestressing in cementitious materials under different conditions. The presented results are based on experiments with textiles made out of carbon and aramid, which are mostly chemically compatible with the cement matrix. Some of these textiles were uncoated, others were impregnated with an epoxy resin or coated with SBR (Butadien-Styrol). Pullout tests and tensile tests show that resins and coatings strongly influence bond behaviour and tensile strength of the textile and therefore the load bearing capacity of the composite element. The different temperature coefficients of the textiles used compared with the cement in the concrete test specimens were accounted for by storing the specimens in different environments before testing.

On the basis of the preliminary results reported in this paper the efficiency of the different textile reinforcements will be discussed.

ZUSAMMENFASSUNG

Textile Bewehrungsmaterialien werden seit längerer Zeit beispielsweise im Bereich der faserverstärkten Kunststoffe eingesetzt. Auch in zementgebundenen Systemen finden Kurzfasern bereits ihre Verwendung. Dagegen ist die Verwendung von textilen Materialien als Verstärkung in zementgebundenen Werkstoffen eine relativ neue Anwendung, die noch Forschungsbedarf aufweist. Dies gilt insbesondere dann, wenn diese textile Bewehrung auch als Vorspannelement eingesetzt werden soll.

Eine der Grundlagen ist die Charakterisierung des Verbundverhaltens von textiler Bewehrung und Beton. Der vorliegende Beitrag zeigt die Ergebnisse von Pullout-Versuchen mit in Beton schlaff oder auch vorgespannt eingelegten Textilien (Carbon und Aramid). Einige dieser Textilien werden unbeschichtet eingesetzt, andere wiederum sind mit Butadien-Styrol beschichtet bzw. mit Epoxydharz imprägniert. Die Ergebnisse zeigen, dass solche Beschichtungen bzw. Imprägnierungen einen großen Einfluss auf die Zugfestigkeit und den Verbund haben können und daher auch die Tragfähigkeit des Gesamtbauteil wesentlich beeinflussen. Aufgrund der Tatsache, dass die untersuchten textilen Materialien einen gegenüber Beton verschiedenen Temperaturdehnmodul aufweisen, werden auch Ergebnisse von unterschiedlich gelagerten Probekörpern gezeigt und miteinander verglichen.

RESUME

Les armatures textiles sont utilisées depuis longtemps, par exemple pour renforcer des matières plastiques. Des fibres courtes sont également utilisées dans les matériaux cimentaires. Le renforcement des matériaux cimentaires avec des textiles est toutefois une application encore relativement nouvelle qui montre un besoin de recherche, surtout si les armatures textiles doivent être utilisées comme éléments de précontrainte.

La caractérisation de l'adhérence entre l'armature textile et le béton est un objectif primordial. L'article présent montre les résultats d'essais d'arrachement de textiles (carbone et aramide) utilisés comme armature passive ou précontrainte. Certains textiles étaient sans enduit, d'autres étaient enduits de butadiène-styrène ou imprégnés de résine époxy. Les résultats montrent que de tels enduits ou imprégnations peuvent avoir une grande influence sur la résistance à la traction et l'adhérence, et par conséquent influencer également la capacité portante de la structure. Les résultats obtenus pour des éprouvettes ayant suivi différent traitements de cure sont comparés, tenant compte des différents coefficients de dilatation thermiques du béton et des textiles.

KEYWORDS: uncoated textiles, impregnated textiles, concrete, Carbon, Aramid, bond, anchorage, frictional resistance, pull-out, prestress

INTRODUCTION

Bond behaviour of textile reinforcement in concrete is expected to vary from that of FRP bars or conventional steels bars. Most textile rovings used as concrete reinforcement consist of thousands of single filaments and therefore can not be defined as a single rod. If such a roving is embedded in concrete the shape of the cross section determines the bonded area and it must be clarified how many filaments were in direct contact with concrete. A great deal of research has been done in this area to characterize bond behaviour of such multi-filament elements in concrete but quite new innovations necessitate further research /BRAMESHUBER/, /NAMMUR/, /OHNO/.

One parameter that may strongly influence the bond performance is the difference in the coefficient of thermal expansion from that of steel or concrete. It is also known that transverse pressure improves bond. This effect is not present in embedded multi-filament rovings which have not been fully infiltrated with cement due to voids between the inner filaments. The Poisson's effect, however, will become significant and will influence the transverse stress field if the roving is impregnated and/or prestressed.

An often used test to analyse anchorage of reinforcing bars is the pull-out test. If one wants to do such a test with textile reinforcement one has to consider that an uncoated roving has a high capillary action that greatly influences the w/c ratio during the hydration process. It is therefore not feasible to prepare a pull-out specimen where the roving is not fully saturated in concrete. Another point is that if the textile roving is impregnated or coated with a resin, the roving itself is a composite and shear stiffness and shear strength vary over the cross section. Hence, the length between where the load is applied to the roving and where the roving is embedded in the concrete is not negligible.

EXPERIMENTAL DETAILS

Concrete mix

The concrete mixture proportions are shown in table 1. For textile reinforced concrete, criteria such as low shrinkage, high early strength, good workability (self compacting and self levelling) and high adhesion and compatibility to the fibre were considered. The key properties of the hardened concrete are listed in table 2. For further details see FRECH /1/.

Table 1: Concrete mixture proportions

Materials	kg/m³
CEM I 42,5 R	480
Fly ash	154
SF-Suspension (50% water)	82
Sand 0 – 0.6 mm	460
Sand 0.6 – 1.2 mm	920
Water	170
Superplasticizer	17
Total	2283

Table 2: Concrete properties (stored at 20°C, 65% RH)

Concrete Properties		1 d	7 d	28 d
Compressive strength	N/mm²	25	62	75
Flexural strength	N/mm²	5	9	11,5
Shrinkage	mm/m	-	0,5	0,6
Young's Modulus	N/mm²	-	-	37.300

Textile reinforcement

The textile reinforcement consisted of carbon with a warp knitted structure and Aramid in the form of woven fabric. Tests with AR glass (Alkali resistant glass) were performed but are not presented in this paper. In table 3 the main characteristics of the textiles used are listed.

The tensile strength reached in the uniaxial tensile test was about 1300 MPa for carbon and 2600 MPa for epoxy impregnated Carbon (Fig. 2). This rather low strength is due to a low static fatigue limit, imperfections in the material, stiffness of the clamping devices and also the damage caused by the textile production and is not the true strength of the material itself. The structure of the fabric is the most straight forward, i.e. a warp knitted structure with two perpendicular rovings. The rovings are connected to each other by a binder thread. This means that the initial strain is limited. The pronounced weft effect does not occur.

Table 3: Textile structures

Type	C	CE	Aramid I	Aramid II
Material	Carbon	Carbon, impregnated with epoxy	Aramid, SBR coated	Aramid, SBR coated
Construction	Biaxial layer, warp knitted 0°/90°	Biaxial layer, warp knitted 0°/90°	Biaxial woven fabric 0°/90°	Biaxial woven fabric 0°/90°
Weight, reinforcement per m²	320 g	135 g	0° 81 g 90° 104 g	0° 81 g 90° 52 g
Roving	1700 tex	1700 tex	0° 4x336 tex	0° 2x2x336 tex
Theoretical area of one roving	~ 0,95 mm²	~ 0,95 mm²	~ 4x0,25 mm²	~ 2x2x0,25 mm²
Mesh size	10 mm	25 mm	0° 16,7 mm 90° 6,5 mm	0° 16,7 mm 90° 13 mm
Measured tensile strength per roving	~ 1.350 N	~ 2.700 N	~ 2.500 N	~ 2.500 N

Opposite to this the two Aramid fabrics were woven fabrics. Both Aramid fabrics were coated on the surface with a SBR resin, however, the inner filaments were not fully saturated with resin. This leaves the textile very flexible and easy to handle in contrast to the epoxy impregnated carbon layer, which acted as a stiff sheet.

Both Aramid fabrics had the same reinforcement ratio and mesh size in the warp direction, but with a different disposition. For Aramid layer I, each single roving (á 336 tex) is equal to one warp. Four of these warps were then bundled to a kind of thread to obtain a minimum mesh size which is needed to get concrete in. For Aramid layer II, two single rovings (á 336 tex) were bundled to one warp and afterwards two warps were arranged nearby during the weaving process. The diverse disposition of the roving can be seen in figure 1.

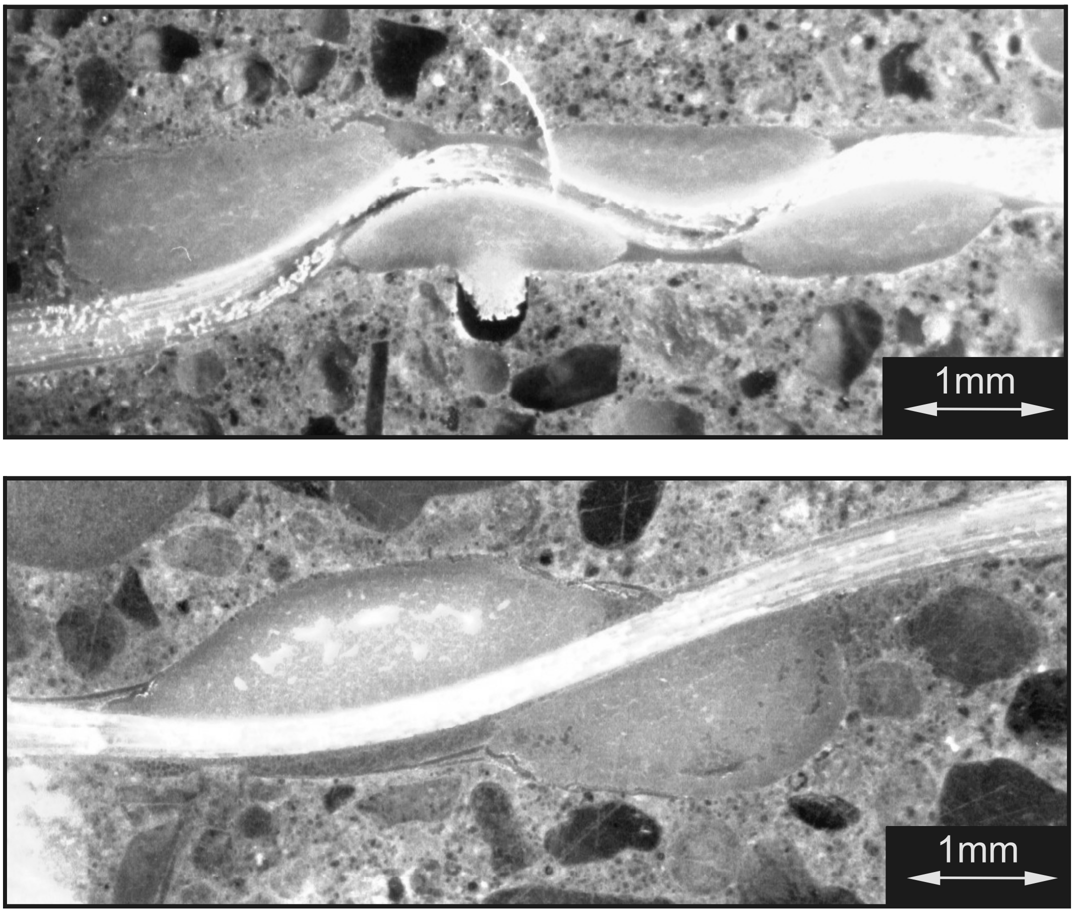

Figure 1: Cross section of one thread of Aramid woven fabric (top: Aramid I, bottom: Aramid II)

It should be noted that the tensile and pull-out tests were carried out with some warp rovings that were directly cut out of the textile fabric and therefore the perpendicular weft rovings were included. Consequently the results of the tensile tests shown in figure 2 are more representative for further research because the weft effect is integrated.

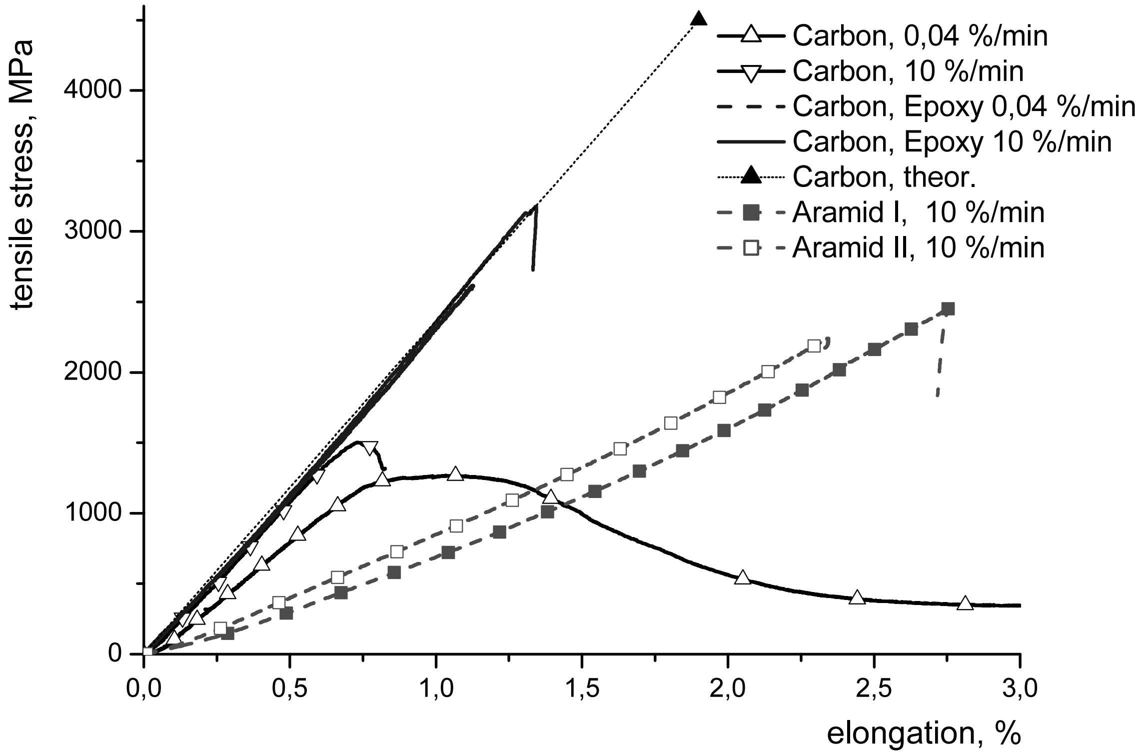

Figure 2: Tensile stress-strain relations of carbon and Aramid rovings at different displacement rates

Specimen preparation

It is a difficult to test the bond performance of textile reinforcement with ordinary pull-out tests intended for steel reinforcing bars. This is due to the various parameters discussed previously.

To get a representative specimen, thin test specimens were sawn from a plate (1000 mm x 1000 mm x 10 mm) where the textile fabric was orientated in the middle. The unprestressed plates were manufactured by placing a 5 mm thick layer of concrete in a mould and putting the textile layer on top of it. Another layer of 5 mm was than cast and slightly vibrated by a special vibrator which was developed for this purpose. The prestressed plates were cast in one pour and slightly vibrated, which was necessary to make sure that the entire fabric was embedded in concrete. For details see /KRÜGER/, /REINHARDT/.

The thin plates were demoulded after 24 h and wet cured for 27 days. Thereafter the pull-out specimens were cut using a saw. Depending on the experiment, some specimens were stored another 10 days in standard climate at 20°C and 65% RH or for 4 to 10 days in water at a temperature of 80°C. This test procedure is based on the strand-in-cement test (SIC test), which is used to test the alkali resistance of glass fibres in concrete /GRCA/. Due to the difference in temperature coefficients of the textiles used compared to concrete this method may also be useful to characterize the durability of the fibers especially the influence on the bond strength. Prior to testing all of the specimens were stored 2 days at standard climate. This time is required to prepare the specimen for the pull-out tests.

Pull-out test

The specimens were glued with an epoxy resin into saw-tooth shaped steel plates that were then fixed with two bolts to the test apparatus (Fig. 3). An electro-mechanical test apparatus was used to perform the tests. Load and displacement at the height of the saw cut was measured at a constant displacement rate of 1.0 mm/min.

The test set-up shown allowed us measure displacement over the total debonding length not just over the embedded length of 20mm. Moreover this is analogous to a double side pull-out test until maximum load.

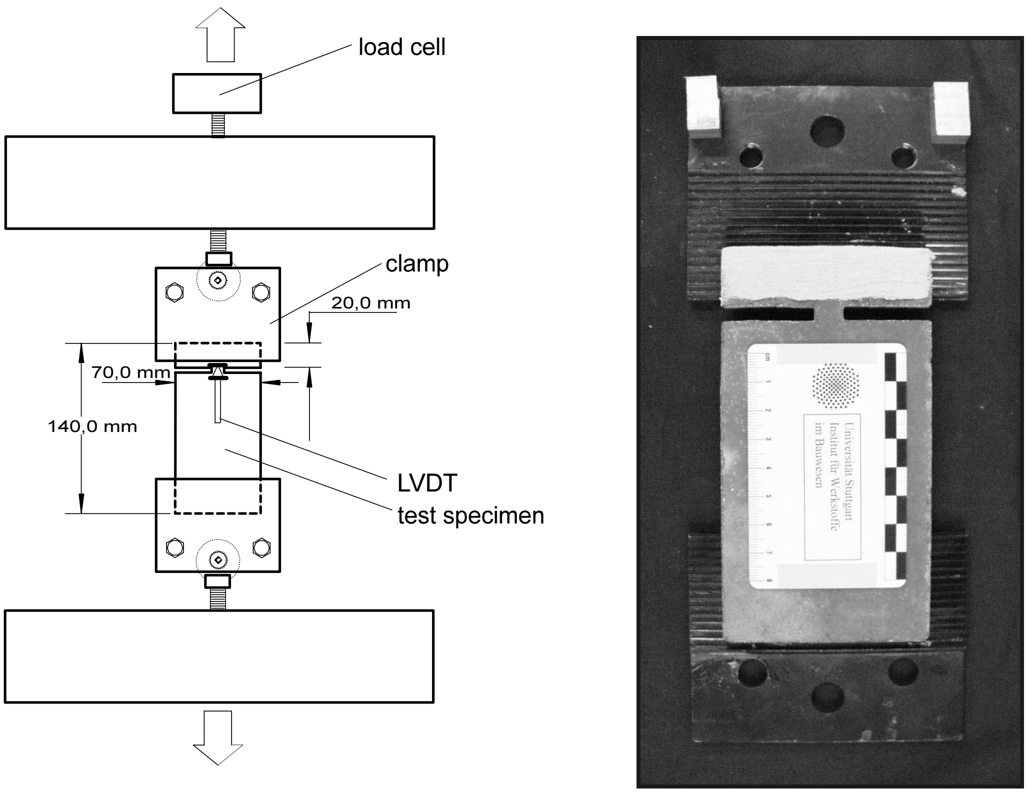

Figure 3: Schematic test set-up for pull-out test

RESULTS

The following figures show average curves of some test results. One problem that occurs during pull-out tests of multi-filament rovings in concrete is that the bond surface of such a roving varies over a large range. Hence, it is impracticable to characterize the real bonding area. The slip is therefore plotted versus the pull-out force, which is divided by the remaining bending length to compensate the change of the bending length during the test. The curves show a double sided pull-out until maximum load. It is obvious that the bond between roving and concrete, especially for the prestressed specimen, is damaged at the point where the specimen was saw cut. Figure 4 shows an idealised schematic model for the pull-out tests conducted and stress distribution of the roving.

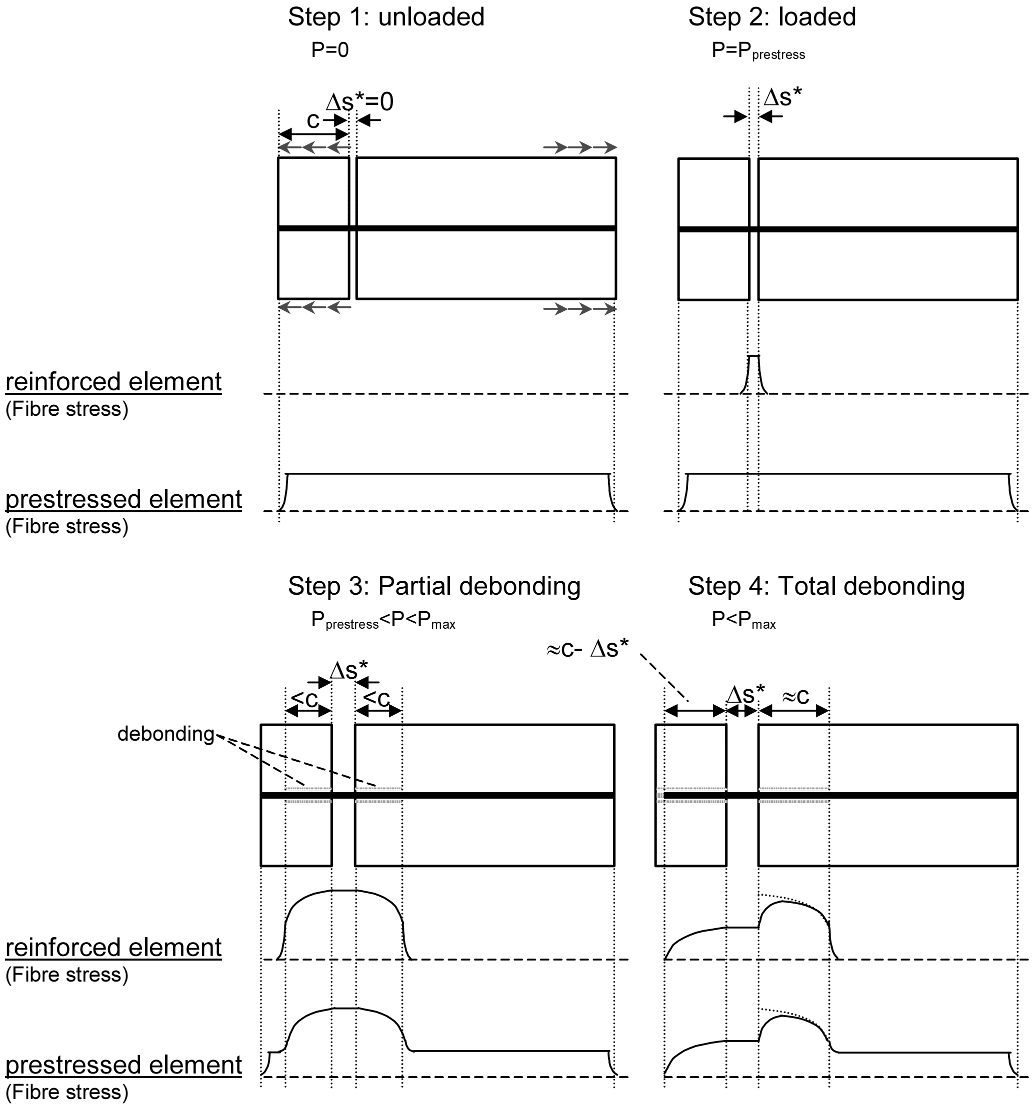

Figure 4: Schematic model for the pull-out of a textile roving

Carbon reinforced elements

In figure 5 the test results of carbon reinforced and prestressed specimen stored at standard climate at 20°C, 65% RH are illustrated.

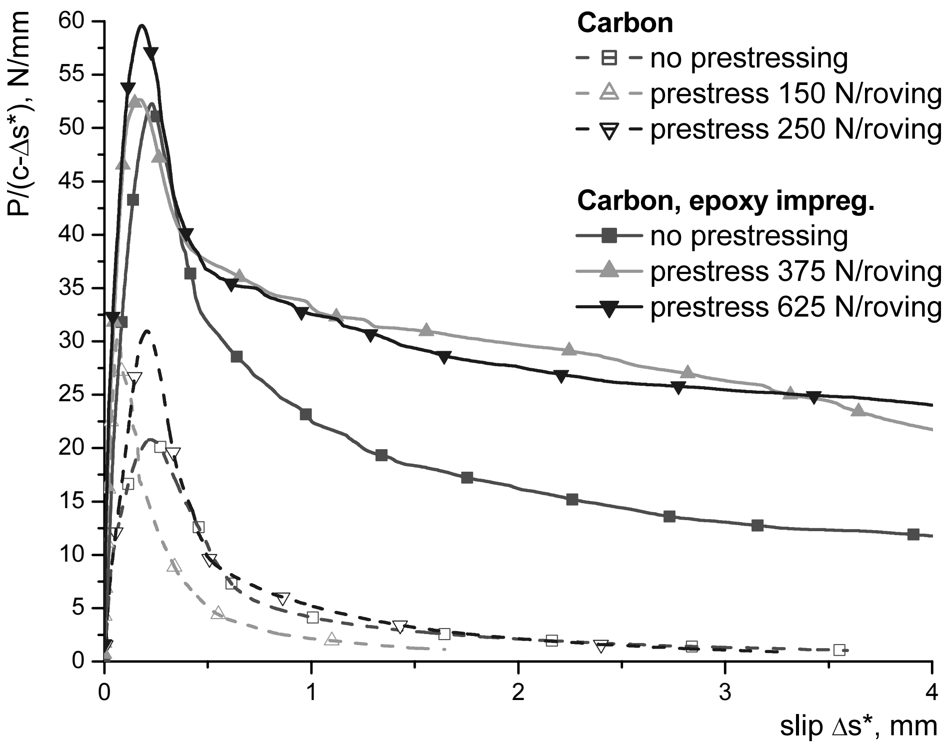

Figure 5: Bond stress per unit length versus slip based on 20mm double sided pull-out (stored at 20°C, 65% RH for 40 days)

It can be seen that in this case impregnation of a carbon roving with an epoxy resin generally results in a better bond. It is assumed that the main reason for this is the ribbed surface formed by the binder threads and the change of the roving diameter over its length especially at the crossing points where the perpendicular woof roving is fixed. The binder threads are caused by the warp knitting process (Fig. 6) and were fixed by the epoxy resin.

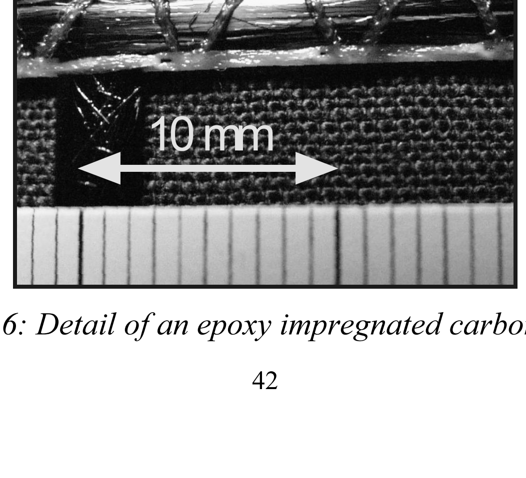

Figure 6: Detail of an epoxy impregnated carbon fabric

In practice the main design criteria to characterise the fibre-matrix interface are the values for the bond stress of adhesion and frictional resistance. Both values require knowledge of the exact dimensions of the reinforcement. Figure 7 shows the cross section of some textile reinforcement embedded in concrete. It is obvious that the cross section of the textile rovings varies on a large scale. Additionally, the impregnated roving has cavities caused by the impregnation process. These cavities are fully surrounded by epoxy resin and consequently no concrete could get in. In figure 8 one can see an unimpregnated carbon roving cast in concrete where only a few fibres were completely surrounded by concrete. Moreover most of the fibers have no direct contact to the surrounding concrete or to a neighbour fibre. As a result it seems to be very complex and not practicable to characterise the contact area whether the roving is impregnated or not.

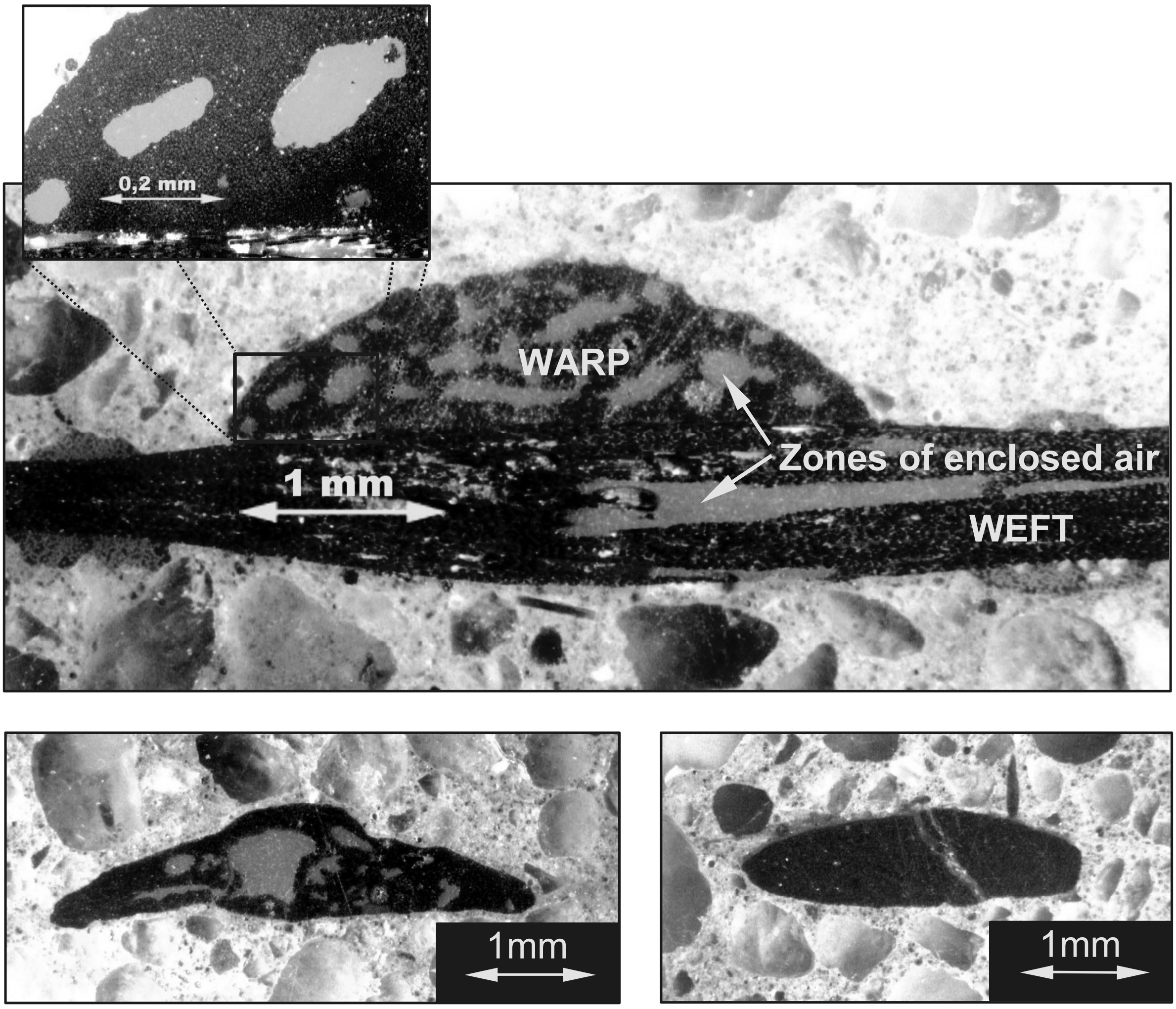

Figure 7: Exemplary cross sections of epoxy impregnated carbon rovings

In Figure 5 one can see that the friction of the epoxy impregnated prestressed elements is higher compared to the reinforced elements. This may be due to the transverse pressure applied through the prestressing so the Poisson's effect becomes significant. It is also visible that the frictional resistance will decrease at higher slip due to the impairment of the roving surface. It was observed during the testing that the binder threads, which formed the ribs, failed by shear.

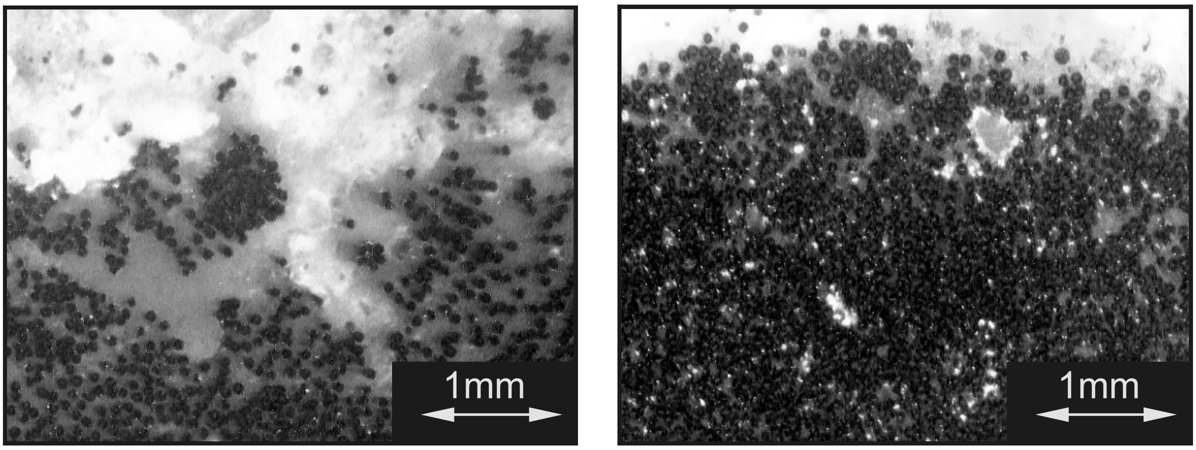

Figure 8: Detail of reinforced (left) and prestressed (right) carbon roving in concrete

As can be seen in figure 5 the roving that was not impregnated shows a low maximum bond stress and after bond failure a very low frictional resistance. Consequently the critical roving length becomes very large. It is obvious that the prestress results in a higher maximum bond stress. There is a significant difference, however, between the curves. The roving that was prestressed to a load of 150N shows a higher stiffness until peak load compared to the unprestressed or to the other prestressed (250N prestressing) rovings. This can be explained when one knows that the prestress of 250N per roving could not be applied to the concrete at the time of casting was applied to the concrete one day after concrete placing. The prestress of 150N could, however, be applied to the concrete at the time of casting, which results in the stiffer behaviour. Hence, both prestressed rovings show nearly the same maximum bond strength. It is assumed that the bond strength is therefore greatly influenced by the Poisson's effect. This may be due to the prestress, which results in an increase of the contact zones of the inner filaments. In figure 8 and 9 the bundling effect of prestressing is shown.

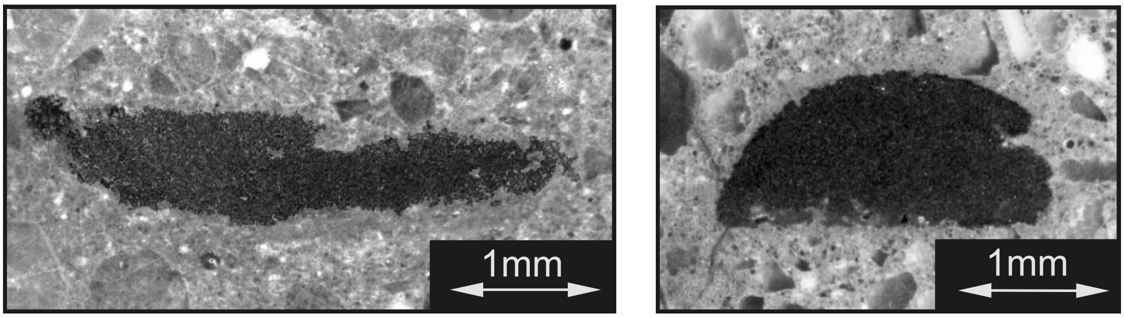

Figure 9: Cross section of reinforced (left) and prestressed (right) carbon roving in concrete

In figure 10 test results from the pull-out tests where the test specimens were stored for 10 days in 80°C water are illustrated. It can be seen that the different storing conditions do not result in a dramatic change of bond strength. It is obvious, however, that the frictional resistance of the reinforced epoxy impregnated roving increased. The reason for this may be the continued hydration, but this has not been verified. On the other hand maximum bond stress decreases, which may be negligible if the deviation of the test results is taken into consideration. Further tests with freezing and thawing will be undertaken.

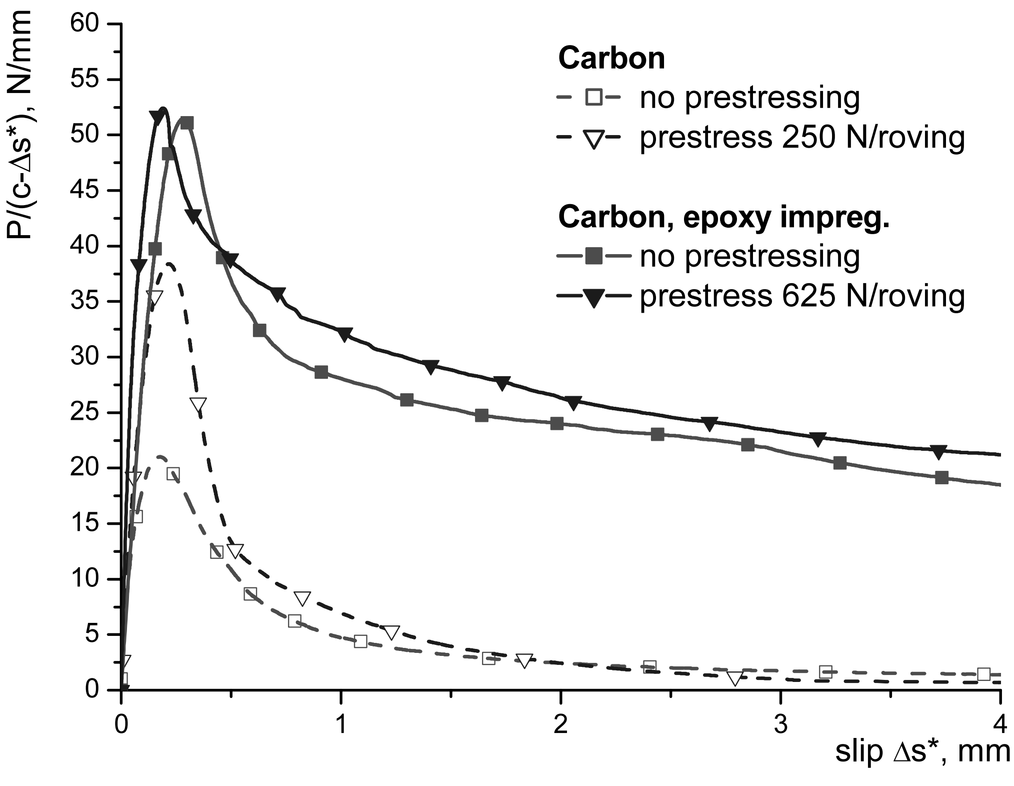

Figure 10: Bond stress per unit length versus slip based on 20mm double sided pull-out (stored at 20°C, 65% RH for 30 days and at 80°C in water for 10 days)

Aramid reinforced elements

In this paper only SBR coated Aramid woven fabrics are reported. The results of the pull-out tests are shown in figure 11 and 13. Comparison of specimens with the same reinforcement ratio, but the different weavings, one can notice that the bond behaviour behaves differently.

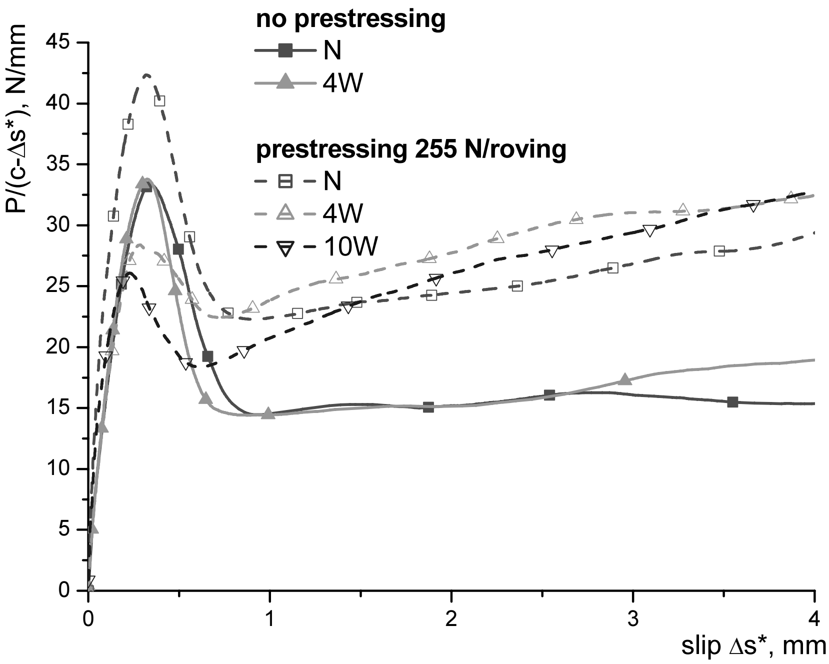

Figure 11: Bond stress per unit length versus slip of Aramid I (20mm double sided pull-out)
N = stored at 20°C, 65% RH for 40 days,
4W = stored at 20°C, 65% RH for 36 days and at 80°C in water for 4 days
10W = stored at 20°C, 65% RH for 30 days and at 80°C in water for 10 days

The specimens stored in water at 80°C show a large decrease in maximum bond stress. It is assumed that the change in bond behaviour is caused mainly by the SBR coating. At high temperatures SBR shows a larger creep. If one considers the negative modulus of thermal expansion of Aramid and the prestress, this may explain the deterioration of bond and therefore the reduction of prestress. On the other hand the prestressed elements show a higher frictional resistance compared to the unprestressed elements, regardless of how the elements were stored. It can also be seen that the frictional resistance remains nearly constant or increases at higher slip depending on prestressing. It is assumed that this is due to bundling and Poisson's effect caused by prestressing. During the test it was observed that the SBR coating was abraded and small particles that remained between the roving and the concrete resulted in a kind of barricade, which lead to higher frictional resistance. This stiffening effect may also be intensified by the weft effect. The influence of the weft effect can be observed if one compares the test results of the two different Aramid fabrics (Fig. 11 and 13). In addition, if one surveys the reinforced and the prestressed elements (Fig. 12), the straighten orientation of prestressed rovings is noticeable and the weft effect becomes minor with regard to prestress only in warp direction.

It is assumed that impregnation with epoxy resin instead of SBR coating will result in stronger anchorage and higher frictional resistance and therefore higher efficiency of the Aramid reinforcement.

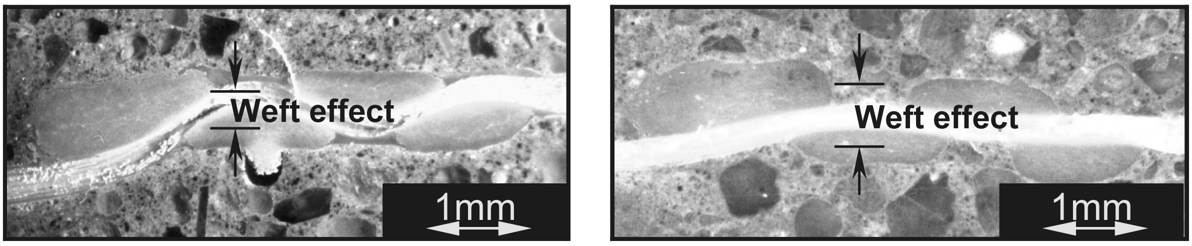

Figure 12: Cross section of prestressed (left) and reinforced (right) Aramid I roving in concrete

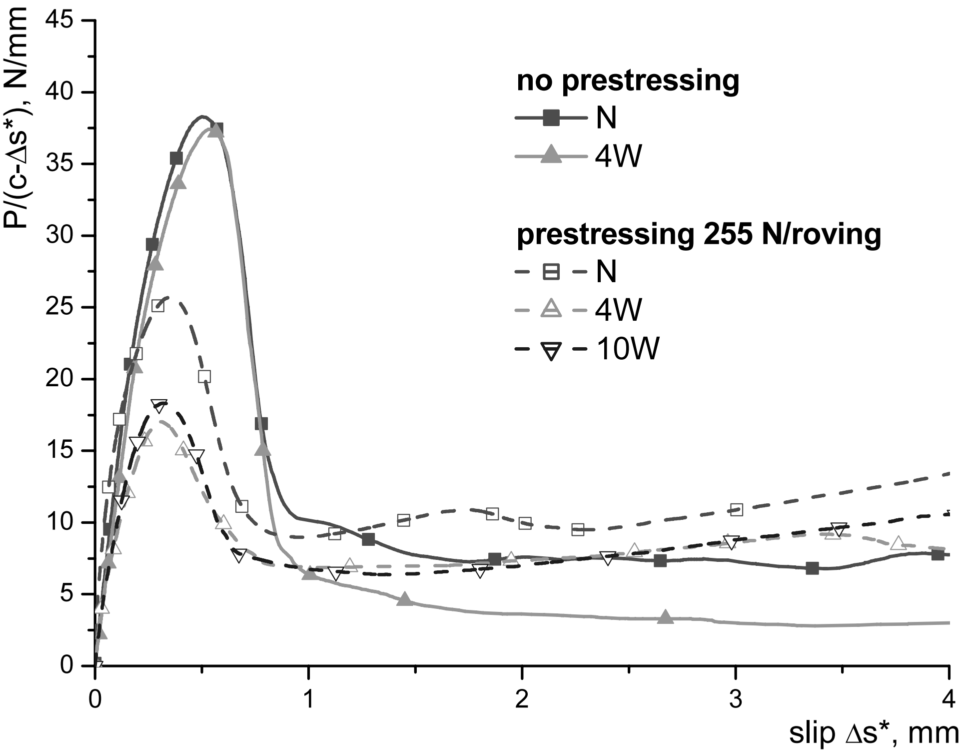

Figure 13: bond stress per unit length versus slip of Aramid II (20mm double sided pull-out)
N = stored at 20°C, 65% RH for 40 days,
4W = stored at 20°C, 65% RH for 36 days and at 80°C in water for 4 days
10W = stored at 20°C, 65% RH for 30 days and at 80°C in water for 10 days

CONCLUSIONS AND OUTLOOK

The experiments discussed in this paper were performed with reinforced and prestressed textiles and an special test set-up that was optimised for that purpose. Especially it was looked for the use of textiles as prestressing elements. The specifications for such textile prestressing elements are in some ways dissimilar from those of a non-prestressed textile element. For example the use of AR glass textiles as a prestressing element is not practical due to creep and a low static fatigue limit. Hence, the low durability is a problem for uncoated or unimpregnated roving.

Some concluding remarks:

- Impregnation is advantageous because the roving shows a large increase of tensile strength. Additionally if a crack occurs, the stress distribution over the cross section of the roving is more uniform resulting in higher stiffness. The high modulus of elasticity and shear modulus of a epoxy resin will be more effective than a coating with SBR or another similar product.
- Multiple cracking of the roving has to be avoided to obtain the full activation of the roving and full load bearing capacity.
- Adequate bond strength and friction resistance is essential to obtain sufficient energy dissipation. Due to the small elongation at failure of some materials like carbon, it is also necessary to tolerate debonding to allow for ductility of the composite element.
- The pronounced weft effect of a textile woven fabric may change from disadvantage to advantage if it is prestressed.
- It is believed that an analytic model for interfacial behaviour based on a bond-slip relationship using the shear strength and frictional resistance as parameters, is very complex and unfortunately not feasible. It seems to be more practicable to use an average bond and shear strength per unit length.

Further research is necessary to enhance anchorage and friction resistance of carbon and Aramid textiles. The textile structure and its combination with a compatible resin has to be optimised. For prestressing it is believed that woven fabrics can be gainfully applied. Finally tests with freezing and thawing must be conducted to prove durability.

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