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Effects of elevated temperatures on the interface properties of carbon textile-reinforced concrete

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ABSTRACT

This work reports on an experimental investigation of the influence of elevated temperatures on the interface between carbon yarns and a Portland cement based matrix. Polymer-coated and uncoated carbon yarns were tested at temperatures of 20 °C under a double-sided pullout test configuration after being subjected to a heating regime at temperatures of 100, 150, 200, 400 and 600 °C. The degradation mechanisms of the cementitious matrix were investigated by X-ray diffraction and thermal analysis. Using an environmental scanning electron microscope, micro-structural analysis was performed to evaluate the degradation of the carbon yarn and of its interface with the matrix. After preheating up to 150 °C, samples with coated fibres showed significant increases in maximum pullout load and, correspondingly, work to pullout. On a micro-scale this is related to a polymer interlocking mechanism in the yarn–matrix interface, which is generated during the heating and cooling of the polymer yarn coating. Above 400 °C no further typical fibre pullout behaviour was observed; the reinforcing yarn failed suddenly after the cracking of the matrix. For uncoated yarn preheating up to 200 °C had no significant impact on the maximum pullout load. At 600 °C the matrix and fibres showed major signs of deterioration; no further typical fibre pullout behaviour other than failure of the reinforcing yarn could be observed.

1. Introduction

The correct understanding of the bonding behaviour of textiles with cement-based matrices is an important step in comprehending the degrading mechanisms which a composite can suffer when subjected to elevated temperatures. Different to conventional reinforcement systems, the textiles are composed of yarns fabricated using a large number of filaments. In the yarns themselves the outer filaments in direct contact with the matrix show better bond performance, while neighbouring inner yarns are activated by friction [1]. When a coating is used, the filaments are stressed more equally, resulting in more filaments taking part in the load-bearing function [2].

To characterise fibre–matrix interface pullout, experimental tests on yarns and filaments were performed in single [3–5] and two-sided [6–8] configurations. Although two-sided pullout tests are more complicated and time-consuming in their designing and carrying out, they can predict material behaviour in a more realistic way since the fibres bridge cracks during the test. Two-dimensional fabrics can also be tested under a pullout-loading configuration [9,10]. Such tests take into account the fabric geometry and also the intersection of warp and weft yarns; which give rise to a further mechanical bond component.

Bonding properties of carbon-fibres at room temperatures have already been investigated in the past. Katz et al. [11] performed single-sided pullout tests in carbon filaments with two different diameters: 10 and 46 μm. For the smaller fibre the bond strength varied from 0.52 MPa, for a water-to-binder ratio of 0.50, to 1.29 MPa for a matrix with silica fume addition and w/b ratio of 0.35. Badanouiu and Holmgren [12] performed tests using carbon yarns. The authors tried to improve bond by treating the surface of the yarn with silane and also designing a matrix with polymer and silica fume additions. The results showed an improvement of the bonding properties of carbon fibres in matrices containing silica fume and high amounts of polymer. The silane treatment of the fibres led to an increase in the average bond strength of 368% for samples cured in air and by 140% for samples cured first in a fog room. Scheffler et al. [13] showed that tailoring sizings and compatible coatings provide a basis to achieve highest carbon roving performance in the concrete composite. In addition, a modification of coatings by nanoclay enables to tailor the morphology of the

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interfase and contributes to reduce crack widths at maximum force by development of hydration products and thus enhancing the interface stiffness of the composite.

The effect of high temperature on the ultimate tensile strength (UTS) of pitch-based carbon fibres under a nitrogen atmosphere seems not to be affected up to 1300 °C. Tanabe et al. [14] showed that in a nitrogen atmosphere the carbon fibre UTS even increases slightly from 1000 to 1300 °C. Sauder et al. [15] showed that for PAN and rayon-based carbon fibres UTS increases slightly when the temperature increases to 1600 °C. This phenomenon was related to a possible reduction in flaw severity associated with internal stress relaxation. When exposed to oxygen atmosphere the carbon undergoes an oxidisation process and burning which starts from 300 to 400 °C for uncoated carbon yarns and from 200 to 250 °C for polymer-coated yarns [16].

When exposed to high temperatures Portland-cement-based concrete materials exhibit a loss in strength. Chen et al. [17] showed that the residual compressive strength of high strength concrete starts to decrease above 200 °C, yielding only 10% of its original strength at 800 °C. This can be traced back to the calcium hydroxide decomposition, which takes place between 370 and 470 °C, and of calcium carbonate and of other carbonates, occurring between 600 and 730 °C. Drchalová et al. [18] performed mechanical tests in PAN-carbon fibre reinforced cement based composites after preheating the samples to temperatures up to 1000 °C. For the material with Portland-cement matrix a drop in tensile strength from 4.86 to 3 MPa at 600 °C was noticed, which was governed by the carbon fibre pullout from the cement matrix. At higher temperatures this behaviour is dominated by the matrix. Çavdar [19] demonstrated that carbon fibres as well as PP, glass, and PVA are active in cement-based matrices under bending and compressive loads only up to 450 °C.

In the present work the bond of polymer-coated and uncoated PAN-based carbon yarns with a Portland-cement matrix was investigated for temperatures ranging from 20 to 600 °C. Double-sided pullout tests were performed on the pre-heated and reference specimens at room temperature (20 °C). Micro-structural analysis using an environmental scanning electron microscope was carried out to evaluate the degradation of the carbon fibre and of its interface with the matrix. X-ray diffraction and thermal analysis were used to quantify the degradation of the matrix when exposed to the different temperatures.

2. Materials and processing

2.1. Carbon fibres

The carbon fibre was obtained from TohoTenax Europe GmbH. The fibre used in the present study is the TohoTenax HTA (High Tenacity Fibre) with a nominal fineness of 800 tex and density of 1.79 g/cm^3. Table 1 presents the properties of coated and uncoated carbon yarn and filament. The basic material used in the production of the carbon fibre was Acrylonitrile. In a first step, using a catalytic process together with co-monomers and solvents, a Polyacrylonitrile (PAN) fibre is spun to obtain the so-called chemical precursor. In the second step the precursor is oxidised at temperatures ranging from 250 °C to 300 °C in air, and subsequently carbonated in nitrogen atmosphere at temperatures ranging from 1000 °C to 1500 °C to drive off non-carbon atoms. During this thermal treatment the fibres are stretched in order to align the polymer molecules, thus enhancing the mechanical parameters, i.e., tensile strength and Young's modulus. Before winding onto bobbins several surface treatments are performed to improve the handling quality and the chemical properties of the fibre surface. Because the carbon fibre under investigation was not produced for use in cementitious matrices, a subsequent polymer coating was applied.

This coating is an aqueous dispersion based on self-crosslinking polymers. The polymer coating was applied as a suspension with a polymer content of 30% by weight by means of two counter-rotating rollers with a contact pressure of 1.7 bar between the rollers. The fresh polymer was dried and cross-linked by infra-red heating at 160 °C for 1 min. The polymer film remained stable at temperatures up to 200 °C. At temperatures in excess of this, the polymer was decomposed stepwise up to 500 °C. The carbon fibre resisted oxidation up to temperatures in the range of 550–600 °C.

Table 1
Fibre filament and yarn: physical and mechanical properties.

Properties	Uncoated		Coated
	Filament	Yarn	Yarn
Fineness (tex*)	0.067	803	903
Diameter (μm)	6.96	–	–
Number of filaments	–	12,000	12,000
Tensile strength (MPa)	3245	1032	2723
Strain to failure (%)	1.46	0.58	1.51
Young's modulus (GPa)	213.5	222.9	204.4

* Mass in g of 1 km yarn or filament, respectively; (tex = g/km).

2.2. Matrix and specimen preparation

In mixing the specimens for the pullout tests, a finely grained matrix was used, which consisted of cement, fly ash, microsilica, and quartz sand [20]. Table 2 summarises the matrix composition. A superplasticizer with a basis of naphthalene-sulphonate was added in order to achieve sufficient flowability. The average slump flow value measured with a small cone (bottom diameter 100 mm, top diameter 60 mm, height 70 mm) was 200 mm.

Doubly symmetrical, narrowed prisms with a notch depth of 1 mm were used as specimens (cf. Fig. 1). In the vicinity of the notch each specimen was 5 mm thick, and at the ends the thickness increased to 10 mm. The width of the samples was 50 mm. Each specimen was reinforced with one multi-filament yarn extended over the entire length of the sample. Prior to concreting, the reinforcing yarn was fixed on a stretching frame in order to imbed it properly into the fine-grained concrete. After casting the samples were demoulded at an age of two days and stored in water (20 °C) until one day before testing. Afterwards the samples dried for one day at a controlled lab temperature (20 °C). Steel plates were then glued to the loading areas of the specimens and fixed between the clamping jaws of the testing machine. In this way a nearly unconstrained mounting of the specimens was possible.

3. Experimental testing procedure

The double-sided pullout tests were performed using coated and uncoated multifilament yarns embedded in the fine-grained matrix. Before testing, the specimens were heated up to 100, 150, 200, 400, and 600 °C and subsequently cooled to room temperature (20 °C). Additional experiments on specimens stored at

Table 2
Matrix composition [19].

Mix ingredients	(kg/m^3)
CEM I 32.5 R	557
Fly ash	251
Microsilica suspension (50% powder by mass, 50% water by mass)	56
Sand 0–1 mm	1114
Water	251