XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Durable Textile-reinforced Concrete Made of Fast-setting, Mineral-impregnated Carbon-fibers (MCF) Reinforcements and Alkaline-activated Matrix

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Abstract. *Textile Reinforced Concrete (TRC) is a class of material with massive potential to strengthen existing or build entirely new thin-walled structures. However, state-of-the-art polymer-based textile reinforcements commonly suffer under weak compatibility with concrete and insufficient reinforcing efficiency at elevated temperatures. Mineral-impregnated carbon-fiber (MCF) composites represent instead a promising alternative reinforcement with a wide-ranging innovation potential regarding digital and automated processability, freedom design, chemical compatibility and ecological and environmental footprints. Among the existing variants of mineral impregnation, geopolymer (GP) impregnation for carbon fiber (CF) enables stable early-age rheological properties and fast-setting by moderate-temperature activation.*

The paper at hand presents a methodology to automatically manufacture textile reinforcements made of MCF composites via a continuous pultrusion and robotic–assisted structuring process to meet future market demands. After an advanced geopolymerisation process by thermal curing, the resulting grid-like reinforcements were implemented in a fine-grained, alkali-activated material (AAM) based concrete matrix and characterized with respect to their uniaxial tensile performance. By further applying AAM as cement-free binder, sustainable and fireproof reinforced concrete can be designed with an evident reduction in CO_2 emission as compared to conventional cementitious systems. The improved chemical affinity facilitated by GP impregnation governs the cracking phase, resulting in a finer and more diffuse pattern, whereas the higher unidirectional strength of epoxy (EP)-impregnated yarns is responsible for the higher ultimate strength of the composite.

Keywords: *Textile-reinforced Concrete; Mineral Impregnation; Alkali-activated Materials; Automated processing; Geopolymer*

1 Introduction

Reinforcing cementitious materials with textiles to enhance their toughness and tensile performance has been of growing interest in recent decades, in particular with the rising demand for a more sustainable building sector (Mechtcherine, 2013). So-called textile-reinforced concrete (TRC) enables thin-walled structural elements with outstanding strength and reduced carbon footprint in the whole production chain for strengthening existing structures or new construction (Fürst et al., 2022). In comparison with other fiber reinforcements, carbon fiber (CF) possesses excellent specific strength and durable properties, being extremely favorable for high-performance cementitious composites (Chand, 2000). The manufacturing of available textile reinforcements required the impregnating of a large number of filaments with polymeric matrices, yielding an even stress distribution, high shape integrity and load-bearing function in concrete (Dvorkin et al., 2013). However, these polymeric matrices are very sensitive to the elevated temperatures, resulting in the loss of their reinforcing ability (Tlaiji et al., 2018). To overcome such limitations associated with organic impregnation matrices inorganic coatings were designed, e.g. based on lime (Ferrara et al., 2021), pozzolanic silica (Nadiv et al., 2017; Signorini et al., 2018), cement (Mechtcherine et al., 2020; Peled et al., 2006; Zhao et al., 2020)), aluminosilicate precursors (Hung et al., 2011; Lyon et al., 1997; Zhao et al., 2021a, 2023) or calcium silicate cement (Rambo et al., 2016). As a consequence, the so-called mineral impregnated carbon fiber (MCF) reinforcements have been developed at the TU Dresden in combination with high automatization for cementitious composites (Mechtcherine et al., 2020). Comparable mechanical properties to organic-based textiles, improved bond quality at elevated temperatures, effective chemical compatibility between the MCF and cementitious substrates, low-cost and high environmental sustainability and excellent geometrical flexibility in manufacturing and design are regarded as primary features for MCF (Mechtcherine et al., 2020).

As compared to cementitious impregnation, geopolymer (GP) - as an innovative, low carbon, sustainable and fireproof binder material – can provide long-lasting processing windows at the initial stage and a rapid setting on demand within several hours by low thermal activation, being great significance of industrial production (Zhao et al., 2021a). By far the studies on MCF reinforcement elements are mainly unidirectional rods, while the systematic investigation on automated technology of manufacturing of two or three-dimensional mesh structures from MCFs and herewith the load-bearing behavior of their reinforced cement composites are still lacking. The current study developed the methodology of manufacturing textile reinforcements based on MCF made with GP and investigated their performance after implementation in a concrete matrix made of alkali-activated material (AAM). The load-bearing capacity of the resulting TRC specimens with biaxial MCF textiles was characterized under direct tensile loading and compared with a commercial textile impregnated with epoxy resin with similar features. The failure mode and cracking behavior of the TRC composites were then correlated to their mechanical properties.

2 Experimental program

2.1 Materials and fabrication of MCF textile

A commercially available carbon fabric with grid size of 20 x 20 mm² impregnated with an epoxy (EP) resin, GRID Q85/85 – CCE – 21, from Solidian, Germany, was used as reference material. In both the warp and weft directions it has 3200 tex with an average tensile strength of 3300 MPa per single yarn. For the MCF production, a continuous heavy carbon tow SIGRAFIL® C T50-4.4/255-E100 from SGL Group, Germany, was applied with 50,000 filaments having a diameter each of 6.9 µm, epoxy sizing and filament tensile strength of 4,400 MPa.

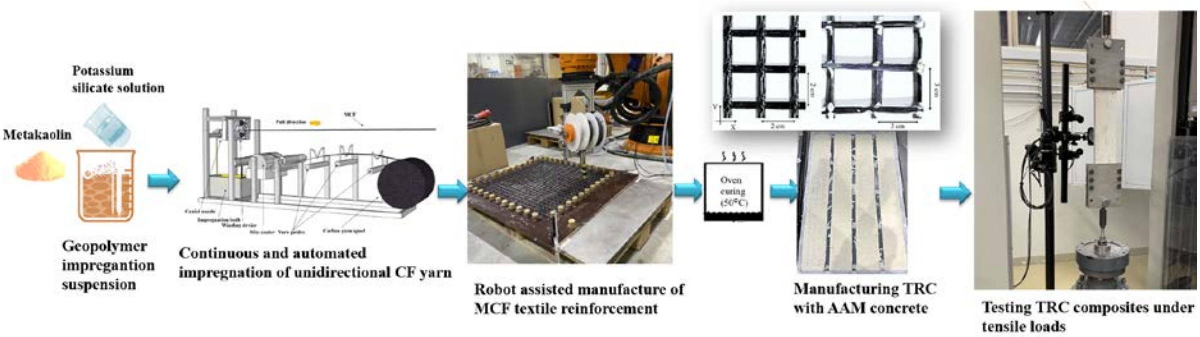

Figure 1. Schematic description of the production and the testing of MCF-made textiles.

The GP impregnating suspension used and the related mixing procedure were specifically designed to attain sufficient impregnation quality, described in (Zhao et al., 2021a, 2021b). Intensive mixing was conducted via a T 50 digital ULTRA-TURRAX® at 7000 rpm for 7 min. The suspension was prepared by mixing metakaolin (MK) ($Al_2O_3 \cdot 2SiO_2$) from BASF, Germany, a superplasticizer Sapetin D27 from Woellner, Germany and a potassium silicate solution Geosil® 14517 from Woellner, Germany. Flexural strength of 8 MPa and compressive strength of 37 MPa were obtained from the test on specimens with dimensions of 10×10×60 mm^3 for the impregnation matrix after curing by 50 °C for 16 hours and additional storage under 20 °C and 65% RH for 28 days. The fabrication of unidirectional MCF yarn was achieved via an automated, continuous pultrusion process, as described in (Liebscher et al., 2022). The carbon yarns were drawn at a 6 m/min velocity under constant tension and guided via a kiss-coater for pre-wetting and an impregnation bath including a five-roller-foulard and shaped by a conical nozzle with an inner opening diameter of 4.1 mm. The resulting uniaxial MCF yarn element features a fiber volume fraction of 16 vol.-% and a mean tensile strength and Young's modulus of 2103 MPa and 246 GPa, respectively, following the ISO 10406-1. Following the initial impregnation, the fresh axial MCFs were wrapped onto a spool mounted on a robotic arm and then deposited into a desired mesh structure in a continuous stretched, highly aligned way through a square plate with a side length of 750 mm and a grid size of 30 mm between the axes of neighboring yarns; see Figure 1. The movement of the robotic arm was controlled by a 3D model script based on the KUKA prc plugin for Grasphopper. To ensure the necessary robustness and high compatibility of the joining between each yarn element for transport and field use, the same impregnating suspension was further used as gluing approach. The fresh MCF textiles and conjunction positions were sealed and solidified in an electric oven at 50 °C for 16 hours.

2.2 Direct tensile tests on TRC composites

Direct tensile tests were conducted on rectangular plates with a dimension of 600 x 100 x 20 mm^3 to assess the mechanical behavior of textile reinforced concretes (TRC). The composite features 4 wrap yarns in the loading direction with an effective reinforcement ratio of 0.38% by cross-section, calculated with the effective cross-sectional area of a single yarn of 1.87 mm^2. A servo-hydraulic testing machine, Zwick Z1200Y, was applied to perform the uniaxial tension tests at a controlled displacement rate of 0.05 mm/s with a unique metal clamping system containing two steel plates towards each other. The 140 mm long region at each specimen edge served as the anchorage region, strengthened with two extra pieces of EP-textile of 98 x 130 mm². The deformation of the gauge length of 300 mm in the centre of the specimen was monitored by two high-resolution cameras constructed on each side from GOM GmbH at a frequency of 2 Hz, coupled with a light source, to capture crack development and fracture processes for digital image correlation (DIC) analysis. Four identical specimens were investigated for each parameter. Fine-grained, AAM concrete containing the same MK powder and ground-granulated blast-furnace slag (GGBS) powder, supplied by Dyckerhoff, Niederorschel, Germany, as binder materials with a water-to-binder ratio of 0.55. the chemical composition of the binder materials used are shown in **Table 1**. Coarse sand 0/2 from Ottendorf, Germany, and quartz sand BCS 413 from Strobel, Germany, were selected as aggregate, while the quartz sand BCS 413 from Strobel, Germany, was selected as macro-fillers. The same commercial potassium silicate solution, Geosil® 14517, was applied as alkali activator. The mixing was performed using a 5L-planetary mixer HSM20 from Hobart, Leipzig, Germany, for 10 min. Compressive strength of 67 MPa of concrete matrix was determined at the age of 28 days, tested on a mortar prism (40*40*160 mm³) according to DIN EN 196-1. Table 2 gives the composition of AAM concrete. The fresh concrete mixture was cast into the mold by the lamination technique to achieve high homogeneity and eliminate entrapped air bubbles. Demolding after 24 hours, the TRC specimens were stored under seal for 28 days at 20 °C and relative humidity of 65%.

Table 1. Chemical composition of binder materials used of concrete matrices.

Element compositions	SiO_2	Al_2O_3	CaO	Fe_2O_3	TiO_2	K_2O	Others
Metakaolin	53.0	43.8	0.02	0.4	1.7	0.2	S, Mg, Na
GGBS	33.6	8.4	47.5	-	1.4	-	S, Mg

Table 2. Mix design and properties of AAM concrete under investigation.

Components	Amount
Metakaolin	519
Ground-granulated blast-furnace slag	156
Quartz sand BCS 413	264
Sand 0-2 mm (Ottendorf)	759
Alkali activator	613

3 Results and discussion

3.1 Tensile mechanical behavior of TRC

Figure 2 plotted the strength curves obtained from tensile tests of prismatic plates including EP and MCF textiles. Stress values on the y-axis were normalized to the net cross-section of the warp yarn merely, while the strain at the peak load was regarded as the ultimate strain capacity. Their tensile responses primarily followed a tri-linear characteristic trend for TRC composite (Butler et al., 2010), implying the formation of multiple cracking with a strain-hardening behavior. Figure 3 summarizes the ultimate tensile strength σ_t, strain at failure, tensile stress at the first matrix crack, and the cracked modulus E_c obtained from the direct tensile tests. TRC specimens including the EP-textiles presented higher tensile strength and strain values and cracked modulus, which can be traced back to its superior inherent tensile strength of the single yarn itself addressed by the manufacturer. Nevertheless, the tensile properties of the resulting MCF are still lying in a high range of the classical polymer-bound textiles. However, textiles were not capable of withstanding stresses exceeding the ultimate strength of their single bar elements, showing reductions of 13.3% and 7.96% for EP and MCF counterparts, respectively, highlighted as the blue dash lines in Figure 3a. This feature implied more degradation and coercive force from the weft yarn and concrete matrix during loading on TRC. The first crack strengths of the composites of all yarn types were close to each other due to the marginal contribution of the textile and the dominant role of tensile strength of the plain matrix at this mild loading stage.

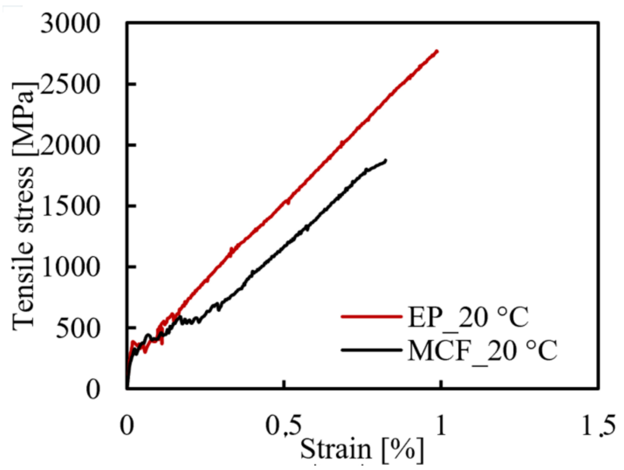

Figure 2. Representative tensile stress-strain curves of carbon textiles made with GP and EP impregnation.

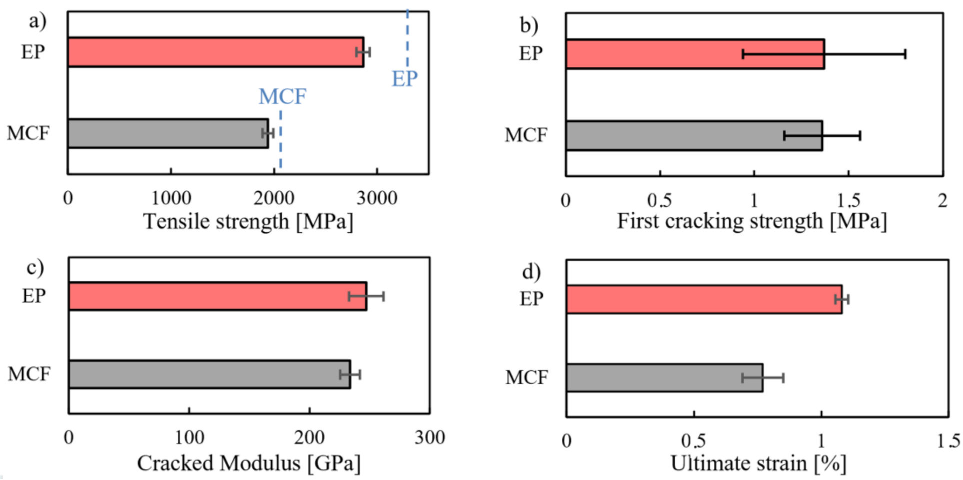

Figure 3. Mean values of a) tensile strength, b) first cracking strength, c) cracked modulus and d) ultimate strain for different TRC groups. Tensile strength is normalized to the actual dry fiber cross-section. In blue color, the mean tensile strength of the single yarns is plotted.

Table 2 provides average crack widths (crack control) and the number of cracks for different textile types at different loading stages. Their corresponding appearances of the crack patterns

at three test stages are described in Figure 6, which are mapped on the surface of the composite plate by the DIC analysis. The multiple-cracking phase of TRC happens in general at the early stages of the loading history, which is less sensitive to the strength capacity of the textile but is governed by the chemical affinity between the textile and the matrix. In this regard, the MCF samples show 37.3% smaller average crack widths than the EP counterparts, associated with an increase of the crack number of 33.3%. A previous study on the single yarn pull-out behavior (Zhao et al., 2023) confirmed weaker chemical adhesion of the single EP yarn towards surrounding GP concrete substrates than the MCF bar.
Interestingly, the evolution of crack width and spacing along with the stress-strain relationships indicated a rapid propagation of the average width in the case of the MCF upon 0.05% strain. Beyond this strain level, the opening of cracks developed slowly up to the final localization. However, no clear correlation between the extent of the load-bearing capacity increase and crack control can be observed, despite a higher bridging capacity arising from the higher tensile properties of the EP textile is expected. Direct tensile tests on all TRC composites revealed a similar crack pattern, which contained transversal, uniformly distanced cracks at low strains and was less prone to bifurcation and interconnection usually. As compared to the EP TRC, the MCF counterpart disclosed a finer and more diffused pattern with less opening and simultaneous closing of existing cracks at almost every stage of the loading history (see Figure 3).

Table 2. Crack numbers and widths for different TRC groups.

Textile	Strain [%]	Average crack width [μm]	Crack number
Epoxy	0.05	50.5	5
	0.50	215.9	9
	1.00	363.0	9
MCF	0.05	110.2	1
	0.50	151.8	12
	0.83	227.8	12

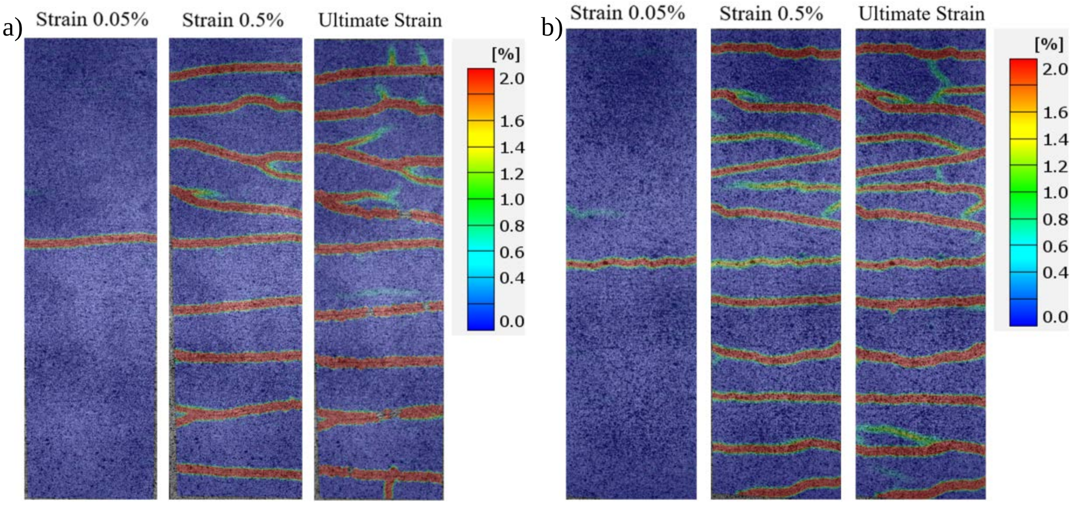

Figure 4. Axial strain colour map documenting the crack patterns for TRC representative specimens with a) EP yarn and b) MCF at different strain levels.

4 Summary and conclusions

Mineral-impregnated carbon fiber (MCF) is proposed as a viable substitute for steel reinforcement or conventional polymer-bound fiber systems. The paper at hand presents the automated process of the fabrication of GP-made MCF textile systems in conjunction with the continuous pultrusion of unidirectional yarn and fast-solidification process at 50 °C. The effect of GP impregnation in the AAM concrete matrix was compared with the EP resin agent.

The load-bearing capacity of TRC including the EP textile outperformed due to the inherent tensile characteristic of the single yarn, but was still in the same range as the MCF textile. The MCF counterparts failed consistently by yarns' rupture within the gauge length of the prismatic coupons and can eliminate the splitting risk in the case of the EP textile. DIC analysis demonstrated more diffused multiple cracking and crack control as a result of better chemical affinity towards the concrete matrix in the high-stress stage. The purposeful combination of cement-free concrete matrix, alternative reinforcement systems and high automation technology is a key milestone for reducing Portland clinker in the entire production chain, dealing with the global energy problem and achieving digital building.

Acknowledgements

This research is funded by the European Social Fund and co-financed by tax funds based on the budget approved by the members of the Saxon State Parliament under project LIP/KAKO 2019_TUD (No. 100380876). The authors would like to acknowledge as well the financial support granted by the Federal Ministry for Economic Affairs and Energy (BMWi) for funding the project "3DHyBeBe" with the project ID: 03LB3043C.

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