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Electrical Joule Heating and Early Strength of Mineral-impregnated Carbon Fibre Reinforcement (MCF)

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Abstract: *Mineral-impregnated carbon fibre reinforcement (MCF) has attracted increasing attention due to its low-cost, easy manufacturing, high temperature and chloride resistance, when it replaces traditional steel reinforcement for concrete construction. Considering its excellent electrical conductivity, this paper investigates the effect of electrical Joule heating on the temperature increase, mechanical and microstructural characteristics of MCF. Different duration of electrical heating ranging from 0.5h, 1h, 2h, 4h to 8h had been explored. In addition, the effect of water spray treatment on the electrically heated MCF will be conducted. For the MCF reference without electrical heating, it is not hardened and the early flexural strength can't be obtained. The temperature of MCF under the voltage of 15 V gradually increases to 100.5 °C and then keeps stable. The highest early flexural strength of MCF immediately tested after heating reached 290.8 MPa when the electrical heating time is 8h, and with the water spray treatment. Interestingly, the water spray treatment seems to benefit the strength development, with the less generated micro pores around the interfaces of carbon fibres to cement matrix. The results indicate that the rapid hardening MCF subjected to electrical heating can work as self-heating elements or rapid production and transportation of MCF for concrete structures.*

Keywords: *Electric heating, MCF, mineral-impregnated carbón fibre reinforcement, flexural strength, wáter spray, electrical resistivity.*

1 Introduction

Concrete is a widely used material in the construction of various infrastructure facilities such as buildings, roads, bridges, dams, and foundations, owing to its excellent mechanical and durability properties. However, due to its brittleness, steel bars are usually added to concrete to enhance its tensile and bending strengths. Although the alkaline environment formed by the hydration products in concrete can prevent steel bars from corrosion, their long-term service, exposure to aggressive environments, and accumulation of corrosive media significantly reduce their service life, leading to cracking and affecting the normal use of structures (Dong et al., 2019). Therefore, a new reinforcement material called mineral-impregnated carbon fiber (MCF) has been developed as an alternative to traditional steel fiber reinforcement. MCF reinforcement not only has better environmental corrosion resistance but is also more cost-effective than steel bars.

The idea of using mineral-impregnated carbon fibre as a reinforcement in construction was first proposed by the team led by Prof. Mechtcherine. They believed that mineral impregnation, rather than using thermoplastic or thermosetting polymer impregnation, can improve high-temperature resistance, bond to the cementitious matrix, and facilitate large-scale industrial production. MCF also offers flexibility in shaping and dimensions during the production process, allowing for the creation of one-dimensional rods, two-dimensional mesh structures, and three-dimensional shell structures (Mechtcherine et al., 2020). 3D printing concrete technology involves creating a 3D model of a building and then printing the structure layer by layer using building material through layered processing and overlay molding. The successful integration of MCF as reinforcement in 3D printing concrete was achieved, demonstrating the high feasibility and adaptability of MCF in digital construction (Mechtcherine et al., 2020).

This study investigates the possibility of cement paste as impregnation for the production of MCF. The early flexural strength development of MCF by electric Joule heating are proposed with different cement replacement rates by metakaolin. The temperature increase, flexural strength and microstructural morphology of the electric heated MCF with/without water spray are comprehensively compared and analyzed. To enhance the early strength of MCF, it is expected that this study can partially solve some problems of MCF's practical applications, especially be beneficial for the procedures of prefabrication and transportation.

2 Experimental preparation

2.1 Raw materials and mix design

The study made use of SIGRAFIL® C T50–4.4/255-E100 (SGL Group, Germany) carbon fiber comprising 50,000 filaments, each with a diameter of approximately 7 μm. The specific resistance of each filament, which was a crucial factor affecting the electric heating effect, was determined to be 17 μΩm. For additional detailed characteristics such as fineness, diameter, and mechanical properties, can refer to Table 1 furnished by the manufacturer.

Table 1. Properties of carbon fibre yarns.

Number of filaments	Second column
Fineness (tex)	50 k
Diameter (μm)	6.9
Tensile strength (GPa)	4.4
Elasticity modulus (GPa)	255
Sizing type	Epoxy

To fully saturate the carbon fibers, the cement-based suspension employed commercially available Mikrodur R-X® and Mikrodur P-U® micro-cement (Dyckerhoff®, Wiesbaden, Germany). In order to achieve a fine particle-size distribution, a micro-silica suspension of EMSAC 500E (MBCC Group, Mannheim, Germany) with approximately 50% solid content was added as the source of silica. The Superplasticizer (SP) MSH FLÜSSIG (FM)® (GCP®, Georgia, USA) based on naphthalene-sulfonate was incorporated at a dosage of 2% by mass of the suspension to achieve the desired workability for the impregnation process. The primary composition principle focused on utilizing particle sizes smaller than the diameter of the filaments to ensure optimal fiber distribution within the matrix, thereby achieving good penetration behavior and a stable impregnation process. Consequently, the small particle size

Metakaolin (MK), MetaMax® (BASF, Trostberg, Germany) was selected for use. In this study, three suspension mixes were examined and compared to assess the impact of Metakaolin on the mechanical and microstructural performances of impregnated carbon fibers yarns. Table 2 presents the respective compositions and weights of suspensions for impregnation.

Table 2. Mix proportion of 1L cement-based impregnation suspension with/without metakaolin.

Mixture constituent	Cement mix [g/L]	25% Metakaolin mix [g/L]	50% Metakaolin mix [g/L]
Micro-cement R-X	345.4	172.7	-
Micro-cement P-U	345.4	345.4	345.4
Metakaolin	-	172.7	345.4
Micro-silica	345.4	345.4	345.4
Superplasticizer (start)	13	13	13
Superplasticizer (end)	18.1	18.1	18.1
Water	493.3	493.3	493.3

2.2 Fabrication of MCF yarns

The impregnated carbon fibers are automatically fabricated using the continuous pultrusion machine developed by the Institute of Construction Materials at the Technical University of Dresden, elaborated upon in detail in (Zhao et al., 2021; Junger et al., 2022).

2.3 Electric heating and curing regimes

After cutting the impregnated yarn into 1.2 m sections, both ends of each piece are washed and dried with tap water and paper towels to remove any isolating suspension and surface moisture, which could hinder the heating treatment performance by increasing contact resistance. Next, the vertically hanging specimen's two ends are attached to electrodes using alligator clamps and connected to the laboratory power supply Voltcraft LPS1305. During the heat treatment at 15 V, the current was measured, and the temperature was recorded using a temperature sensor and thermal camera. To prevent excessive water loss during the electric Joule heating process in the experimental group, the surface of the yarn was sprayed with a mist mode water bottle every 10 minutes, avoiding water stream formation and disturbances.

2.4 Flexural strength measurement

To assess the flexural strength obtained by utilizing electrical heating and spraying as a post-treatment method, three-point bending tests are conducted on the yarn specimens immediately after the corresponding post-treatment and after a 28-day curing period. The tests are performed using the ZwickiLine Z2.5 machine manufactured by ZwickRoell in Germany, with a support span of 100 mm, a load cell capacity of 1.0 kN, and a displacement rate of 5 mm/min. For each variation, six samples are tested. To determine the flexural strength, the height (h) and width (b) of the yarn cross-sections are measured individually, assuming an elliptical shape for the cross-section. The maximum flexural stress is calculated using the following equation (1):

$$\sigma_{\max} = \frac{8FL}{\pi b h^2} \tag{1}$$

where F is the maximum force and L is the support span.

2.5 Microstructural analysis

The microstructural observation of MCF was conducted using the environmental scanning electron microscope (ESEM) Quanta 250 FEG from FEI, Eindhoven, Netherlands. The cross-section of the MCF was observed.

3 Results and discussion

3.1 Temperature development within MCF

Figure 1 shows the final temperature and average current of MCF with different mixtures after subjected to 15 V power input. The generated current fluctuates around 1.3A, and with the increase in metakaolin content, there is a slight increase in the current value. This indicates that the overall effect of metakaolin on the electrical conductivity of MCF is limited. As for the generated temperature, it varies within the range of 90 to 110 degrees. The MCF specimens without metakaolin produce the highest average temperature reaching approximately 100.5 °C. With the increased content of metakaolin, the final temperature slightly decreases to 95.8 °C.

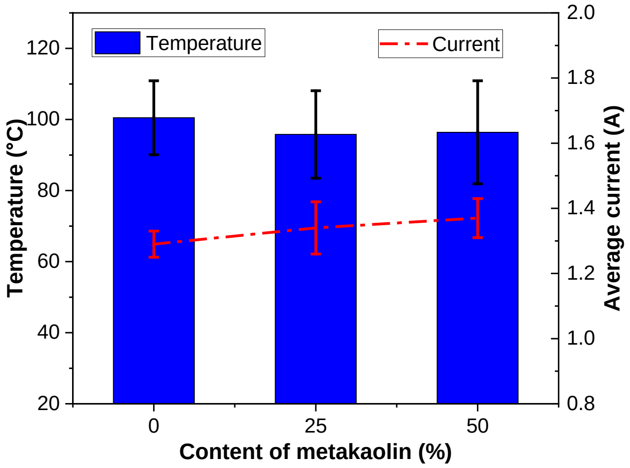

Figure 1. Average current and final temperature for the MCF with different contents of metakaolin under voltage of 15V.

3.2 Early flexural strength of MCF

Taking 100% cement MCF as an example, figure 2 presents the early flexural strength results of MCF yarns impregnated with 100% cement paste and tested immediately after 0.5, 1.0, 2.0, 4.0, and 8.0 hours of electric heating. For the samples without any heating treatment, they had not yet hardened, and their strengths were zero, indicating the need to accelerate the hardening process and increase the early strength of MCF yarns. For MCF yarns without water spray, the flexural strength increased from 39.7 to 78.8 MPa as the electric heating time increased from 0.5 to 4 hours and then decreased to 63.8 MPa when the heating time doubled to 8 hours. There are two primary reasons for the enhanced flexural strength during electric heating: the rapid setting and the changed viscosity of the cement matrix, and the increased cement hydration and formation of more hard hydration products. Additionally, the increasing trend of flexural strength before 4 hours of electric heating suggests that the water evaporation during this process does not significantly affect the curing and cement hydration process, indicating that the remaining water content is sufficient to partially achieve the bonding role of cement clinkers. Conversely, the strength decrease after 8 hours of electric heating indicates that excessive water evaporated after long-term heating, and the remaining water was inadequate for the curing and hydration process of the cement matrix. Moreover, the strength reduction may be due to the dramatic drying shrinkage, which generates defects and cracks inside the cement matrix, given the massive loss of water in a short period of time. MCF yarns with intermittent water spray during electric heating were observed to have continuous flexural strength increase with heating time, reaching a maximum of around 291 MPa at 8 hours. This was due to the fact that the evaporated water could be fully replenished, providing sufficient water for complete cement hydration. It should be noted that the water spray had little effect on strength enhancement for heating times of less than 2 hours, and the flexural strengths were almost identical, especially when the heating time was only half an hour or 1 hour. This is because, in the early stages, there is not much loss of water content, and the remaining excessive water hardly affects cement hydration and strength development, which explains the minimal effect on flexural strength enhancement.

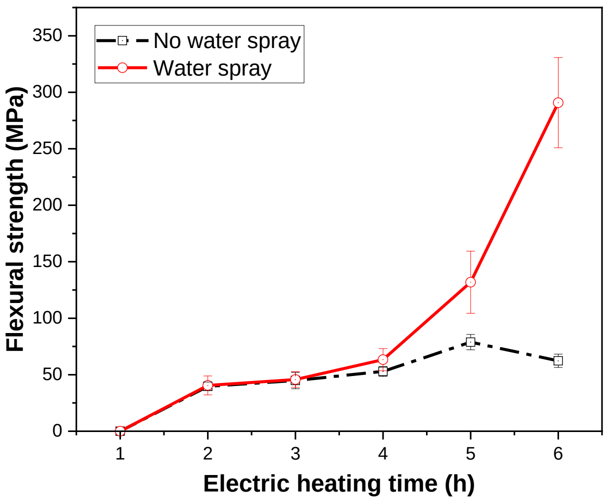

Figure 2. Flexural strength of mineral-impregnated carbon fibre yarns without metakaolin tested immediately after electric heating.

3.3 Microstructural analysis

In this study, the microstructures of MCF composites after 30 min and 2 h electric heating with/without water spray were analyzed by using ESEM, to provide a microcosmic perspective on the mechanical properties of the composites. Figure 3 shows that in the densely structured composites, the fibers were embedded thoroughly and uniformly distributed within the surrounding cement-based matrix without exhibiting any conspicuous gaps. This adequate infiltration led to substantially enhanced interaction between cement matrix and carbon fibers, thereby explaining the exceptional mechanical properties of the MCF as evidenced during the three-point bending test.

In Figure 3a, evident cracks manifest, whose formation may be attributed to the elevated temperature and rapid evaporation of water induced by electric heating for a duration of 30 minutes. In contrast, Figure 3b illustrates that the incidence of microcracks and their dimensions can be ameliorated through the application of a moderate water spray.

In comparison to the specimens that underwent electric heating for a relatively brief duration, those that were subjected to heat treatment that persisted for 2 hours exhibited more obvious cracks, as depicted in Figure 3c. This may be related to the microstructure interference resulting from the accelerated hydration and excessive water evaporation that is caused by electric heating.

Based on the microstructure analysis presented in Figure 3d, it can be observed that the MCF composites subjected to water spraying exhibited a notable reduction in the occurrence of cracks in comparison to the no-sprayed counterpart. Therefore, the application of spray water can be considered as a contributing factor in the inhibition of the initiation and propagation of cracks in the MCF composite material.

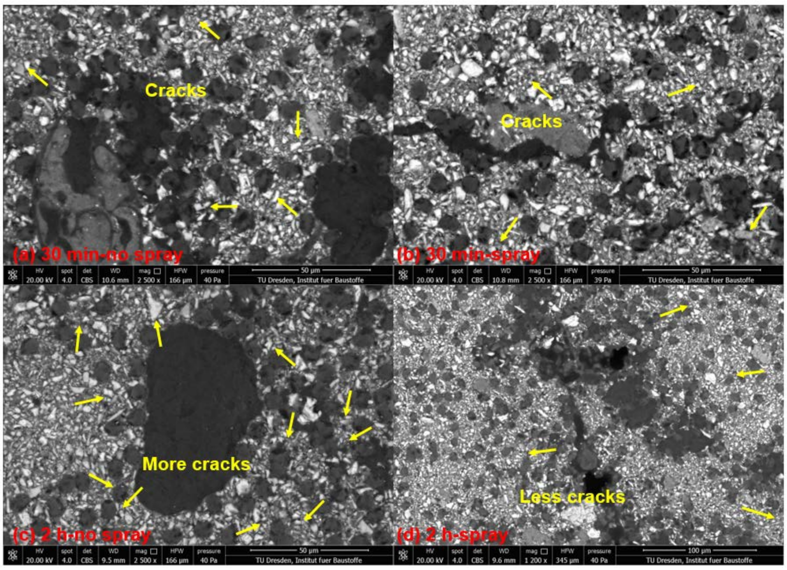

Figure 3. Cross section morphology of MCF composites after 30 min and 2 h electric heating with/without water spray.

4 Conclusions

- The early flexural strength of MCF composites can be significantly enhanced using electric Joule heating, particularly under the external voltage of 15 V.
- The MCF composites manufactured without metakaolin shows a higher temperature, but lower current compared to the MCF with metakaolin.
- Fast curing by electric Joule heating on MCF induce micro pores inside MCF, especially the interfaces between carbon fibres and cement matrix. The water spray treatment helps to alleviate the formation of cracks.

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