

Electrically heated carbon textile reinforced concrete – perspectives for multifaceted building concepts

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Abstract. Carbon textile reinforced concrete (CTRC) is currently used as a high-performance composite material in the construction industry, comprising concrete and a non-metallic reinforcement. In addition to remarkable material properties such as tensile load-bearing behaviour, durability and density, this innovative material features high electrical conductivity, offering the potential for electrical heat generation within building components. In this context, the electrical conductivity of carbon fibres, as well as their high thermal conductivity along the fibre direction can be utilized for accelerating processes such as the hydration of concrete in the composite material or the development of electrically heated carbon textile reinforced concrete. For this purpose, investigations have been carried out on material combinations with textile reinforcement (CTR) and ultra-high-performance concrete, with a specific focus on the electrically heated carbon textile reinforcements at temperatures up to 80 °C. The impact of electrical heating of CTR was evaluated by analyzing the specific resistance on selected non-metallic reinforcement materials. For the composite material (CTRC) tensile strength tests and heating tests were performed. To facilitate the evaluation of the CTRC, an automated crack evaluation software was developed and validated for the results from laboratory tests utilizing digital image correlation. This software automatically determines the crack behaviour such as crack widths and stress-strain behaviour for the users in the form of a graphical user interface. This interdisciplinary approach connects materials science with thermal management in concrete construction, providing valuable insights into the practical use of CTR in multifaceted building concepts.

1 Introduction

Carbon textile reinforced concrete (CTRC) is an innovative construction material that integrates high-performance carbon textile reinforcement (CTR) within a concrete matrix. This composite enables the creation of lightweight, durable, and resource-efficient structures, exhibiting exceptional material properties such as tensile strengths reaching up to 4200 N/mm² [1-3]. Beyond its mechanical benefits, carbon fibres also possess electrical conductivity [1]. By leveraging the electrical and high thermal conductivity of carbon fibres along their fibre direction, the development of electrically heated CTRC is possible. An example of heated CTRC is illustrated in Figure 1. This multifunctional material functions as a heating element within structural components by utilizing Joule's heating principle [1,4,5]. When an electric voltage is applied to the conductive fibres, heat is generated, causing an increase in temperature.

Research on construction materials has explored various applications of electrical heating technology within the built environment, investigating its integration into different systems [6-8]. Electrical heating systems have been studied in several concrete applications, particularly for pavement heating [8].

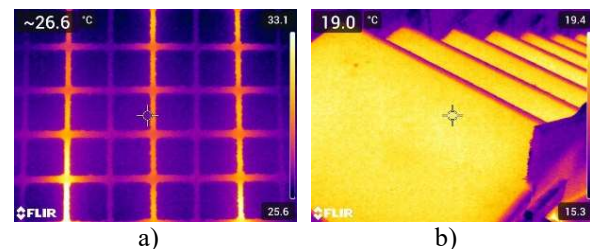


Fig. 1. Electrically heated CTRC: a) Acrylate-impregnated CTR; b) CTRC stairs.

Since the 1960s, methods such as embedding electrical cables or heated fluid-containing pipes in bridge decks and ramps have been utilized to prevent ice formation [8]. In 1981, a bridge deck heating system incorporating gravity-driven heat pipes alongside a geothermal heat exchanger was introduced, further advancing the field [8]. Subsequent studies aimed to improve the efficiency of electrical heating systems by employing electrically conductive concrete, where electrical conduction within the concrete matrix occurs through ionic movement [8]. To enhance conductivity, metallic or other conductive fibres and particles can be incorporated into the concrete matrix [8,9]. Chung et al. examined the self-heating performance of different conductive additives, assessing their effectiveness from an initial temperature of 19 °C [10]. Their research demonstrated that uncoated fibres

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and steel fibres were among the most effective materials for self-heating, alongside flexible graphite [10].

The use of electrically conductive concrete has been further investigated in various projects, such as the implementation of a conductive concrete de-icing system on the Roca Spur Bridge in 2001 by Tuan [8,11]. This system effectively removed snow up to a depth of 257 mm with a power density reaching 431 W/m² [8,11,12]. Yehia et al. [13-15] conducted additional studies by adjusting the ratio of steel fibres in conductive concrete. Through small-scale heating experiments, they demonstrated that an average power density of 48 W/m² could elevate the slab temperature from -1.1 °C to 15.6 °C within 30 minutes [12,13,15]. Building upon this, Zhao et al. [16] explored the use of carbon fibre wires as heating elements in concrete, utilizing both finite element modelling and laboratory experiments. Their findings indicated that a power density of 1134 W/m² could raise the concrete temperature from -25 °C to 0 °C within 2.5 hours [16].

Karalis et al. [5] performed experimental and numerical studies on mineral-impregnated carbon fibre-reinforced grids for efficient and low-power de-icing of geopolymer concrete surfaces. Their research demonstrated that a surface temperature of 45 °C could be attained by applying a voltage of 2.2 V, requiring only 95.6 W/m² over a 30-minute period [5].

Further investigations have examined the potential of electrically heated concrete for accelerating curing, enabling in-situ curing of concrete structures in cold climates, and assessing the effects of different additives [17,18]. He et al. [17] analyzed the impact of incorporating nano-carbon black into conventional concrete, while Salim et al. [18] evaluated the influence of varying dosages of multi-walled carbon nanotubes and carbon fibres, ranging from 0 to 1% by cement weight. Additionally, Gomis et al. [19] investigated conductive cement pastes containing carbonaceous materials through experimental and modelling approaches, establishing correlations between laboratory results and mathematical predictions. Furthermore, Rao et al. [20] conducted experimental analyses on the material properties, such as density and thermal conductivity, of electrically heated concrete incorporating steel fibres and graphite.

Moreover, CTRC can function as an electrical resistance heating element, allowing applications such as radiant heating or thermal energy storage within concrete components, while also offering condensation protection [21-23]. This capability has been demonstrated in studies where electrically heated CTRC was used for radiant heating in walls and staircases [24]. Additionally, the heat generated by electrically heated CTRC has been found to enhance the hydration process of concrete and can be applied for de-icing purposes in outdoor environments such as parking lots, airport runways, and bridges [6,25]. To analyze the properties of electrically heated textile-reinforced concrete, Xu et al. [26] performed both finite element analysis and experimental investigations on the electrothermal characteristics of carbon/glass fibre hybrid textile-reinforced concrete. Their findings confirmed its efficiency for de-icing applications via heat generation.

In their numerical model, Xu et al. assumed a uniform temperature distribution along the carbon rovings, justified by their length exceeding the spacing, the periodic symmetry of the rovings in the cross-section, the consistent physical properties of all materials, and the neglect of contact thermal resistance effects. Moreover, Dahlhoff et al. [23] examined the effects of electrical heating on carbon textile reinforced concrete subjected to freeze-thaw conditions. Their findings revealed that electrical heating effectively inhibits the freezing of CTRC at sub-zero temperatures while maintaining its tensile strength and crack integrity [23].

This paper presents various aspects of electrically heated CTRC, aiming to enable multifaceted building concepts. These aspects are implemented in the research project, which focuses on developing a resource-efficient, material-minimized, multifunctional, and modular lightweight bridge using ultra-high-performance concrete (UHPC) reinforced with carbon textiles. The MultiTexBridge concept is based on prestressed UHPC combined with multifunctional carbon reinforcement, offering enhanced load-bearing capacity, crack distribution, and self-healing properties for durable, material-saving lightweight structures.

The electrical conductivity of the carbon reinforcement allows for an integrated heating function to prevent roadway icing, eliminating the need for de-icing salts. Additionally, heating the carbon reinforcement during production can accelerate strength development. Due to the high density of UHPC and its self-healing properties, this construction method eliminates the need for waterproofing and surface coatings.

2 Experimental methods

In this chapter, the experimental methods employed to analyse the various aspects that enable multifaceted building concepts are described. The methods are presented with a focus on the materials and equipment utilized, the number of trials conducted, and the procedural steps followed. Additionally, the data analysis approach is explained, focusing on how the results were evaluated to draw meaningful conclusions.

2.1 Specific resistance of the investigated CTR

To characterize the material properties of the CTR, fibre strands (FS) in the warp direction (K) were prepared from the samples, ferrules were crimped, and connections were made using terminal blocks. The clamping voltage was gradually increased on the power supply, and the current for the entire system was read from the power unit. The specific resistance was calculated as the ratio of voltage to current, using the carbon FS length as a reference value.

Building on this, the heat development of the carbon reinforcements was analyzed by examining their surface power in W/m². The reinforcements were connected as fabric layers using ferrules and terminal blocks. The desired clamping voltage was applied via the power supply, and fibre strands were switched in using a

control box, as shown in Figure 2. Heat distribution was then captured and analyzed through thermographic imaging.



Fig. 2. Experimental Setup for investigating surface power of CTR.

In the experimental investigations on the specific resistance of CTR, three carbon reinforcements were used, as shown in Figure 3. The reinforcements differ in terms of the impregnation material and, in particular, the geometry, specifically the fibre cross-sectional area, yarn fineness, and reinforcement cross-sectional area, as summarized in Table 1.

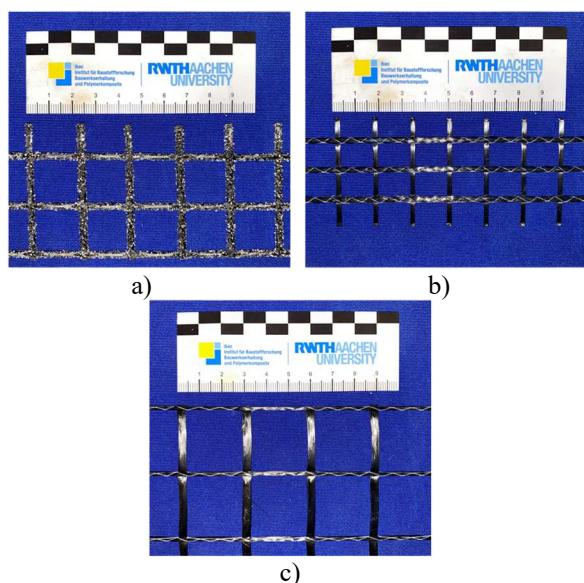


Fig. 3. Investigated CTR: a) CTR-EP-Sand; b) CTR-P-1015; c) CTR-A-2525.

Table 1. Material parameters of the investigated CTR based on the manufacturer's specification [27,28].

| | Textile Reinforcement | | |
|--|---|-------------------------|------------|
| | CTR-EP-Sand | CTR-P-1015 | CTR-A-2525 |
| Impregnation [-] | Epoxy-Resin with additional quartz sand | Poly-styrene | Acrylate |
| Roving Axis Distance [mm] | 21/21 | 12/16 | 27/27 |
| Roving Cross-Section [mm²] | 0.91/0.91 | 1.81/0.45 | 0.91/0.91 |
| Textile Cross-Section [mm²/m] | 43/43 | 142/25 | 31/31.5 |
| Titer [tex] | 1600/1600 | 3220/800 | 1600/1600 |
| Average Tensile Strength (Warp Direction) [MPa] | 4200 ± 215 ¹⁾ | 2920 ± 95 ¹⁾ | 2712 |

¹⁾ Measurements performed at the Institute of Building Materials Research (ibac), RWTH Aachen University.

2.2 Electrical heating of CTRC

Based on the results from the experiments in section 2.1, a specimen was manufactured with CTR-A-2525 and an ultra-high-strength concrete (UHPC) from matrices engineering GmbH. The specimens measured 1000 x 100 x 20 mm³ (L x W x H), with a constant mortar cover on both sides and a single layer of CTR-A-2525. For this, CTR grids consisting of four fibre strands in the warp direction were cut from larger textile reinforcement grids. The specimens were demoulded after one day, stored in water until the 7th day after production, and then stored at a temperature of 21 ± 4 °C and a relative humidity of 52 ± 11 % until testing after production.

Before testing, the fibre strand ends were contacted using ferrules and terminal strips. After 10 days, 17 days, and 31 days, the testing was conducted. Therefore, each time the clamping voltage was increased in two steps, and the temperature of the specimen was monitored over time using a thermographic camera. At defined time points, the surface temperature was measured and compared. The test was repeated twice on the selected testing days. The experimental setup is depicted in Figure 4.

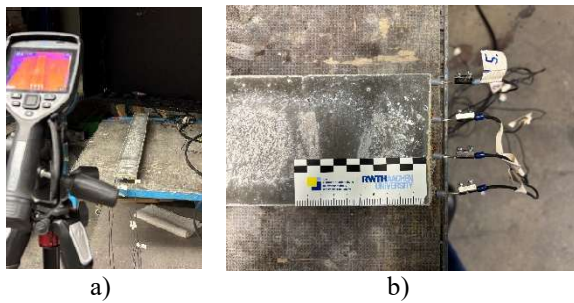


Fig. 4. Experimental Setup for electrically heated CTRC: a) Overview; b) Connection detail.

To further investigate the bonding properties of the material combination of UHPC and CTR-A-2525, two-layer specimens were produced, as shown in Figure 5 and Figure 6. The specimen dimensions were $1000 \times 100 \times 30$ mm (L \times W \times T), produced with two layers of CTR, which were cut from large CTR plates in the warp direction. Testing was performed concurrently with the optical measurement system Aramis[®]. For optical deformation measurement, a stochastic pattern was applied to the specimens.

For testing, the specimens were clamped in steel plates at the upper and lower load introduction areas over a length of 250 mm. A torque of 100 Nm was applied to the RM specimens, given their 30 mm thickness. Tensile strength tests were carried out using a 150 kN universal testing machine (Zwick Z150 TL), with a displacement control rate of 2 mm/min until failure occurred. The load and crosshead displacement were recorded in the TestXpert[®] software and then transferred to the DIC software.

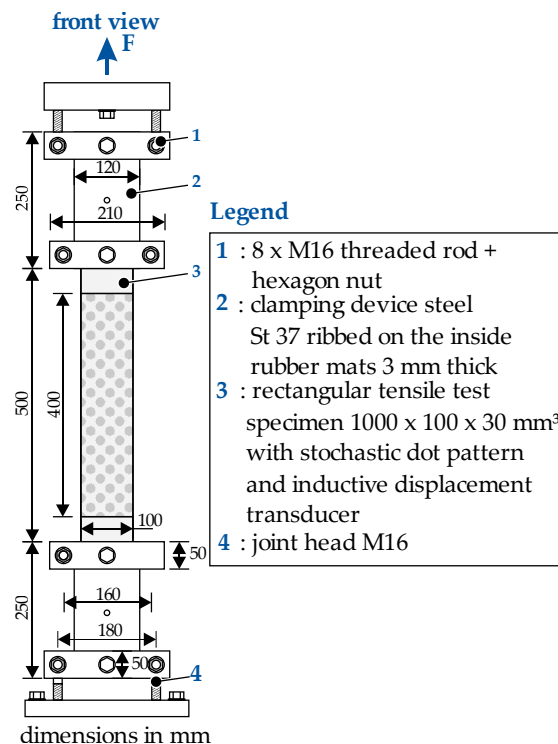


Fig. 5. Test setup for the tensile strength tests on rectangular CTRC specimen – Schematic drawing.

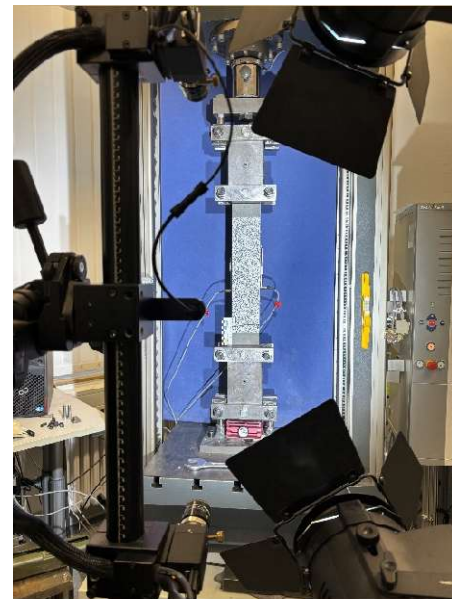


Fig. 6. Test setup for the tensile strength tests on rectangular CTRC specimens: a) Schematic drawing; b) Overview.

In the analysis, the x-axis was defined along the tensile direction, with the y-axis oriented perpendicular to it. For the evaluation of the CTRC specimens, an automated crack evaluation tool (ACE) based on [29] was used. This tool automates the determination of crack width, crack number, and crack distribution. Additionally, virtual extensometers can be added for strain analysis.

3 Results

3.1 Specific electrical resistance - CTR

In the experimental tests, the specific carbon resistances and carbon temperatures were determined, as shown in Figure 7. Three test specimens were measured for each material. A clear difference in specific resistance was observed across the materials studied. The CTR-A-2525 exhibited the highest values for specific resistance, corresponding to a lower CTR temperature. In contrast, CTR-EP-Sand showed, on average, 13 % lower values, while CTR-P-1015 showed 14 % lower values compared to CTR-A-2525. The authors suspect that the fluctuations in the specific resistance of CTR-EP-Sand are due to the connection quality. Therefore, the connection temperature was examined. The experiments also revealed significant variation in the connection temperature of the reinforcement, as seen in Figure 8. Furthermore, it is essential to maintain a low connection temperature in practical applications to ensure the long-term quality of the connections in structural components.

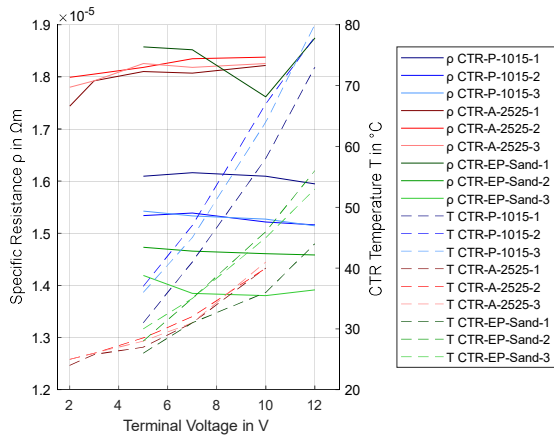


Fig. 7. Specific carbon resistance compared to CTR temperature as the clamping voltage increases.

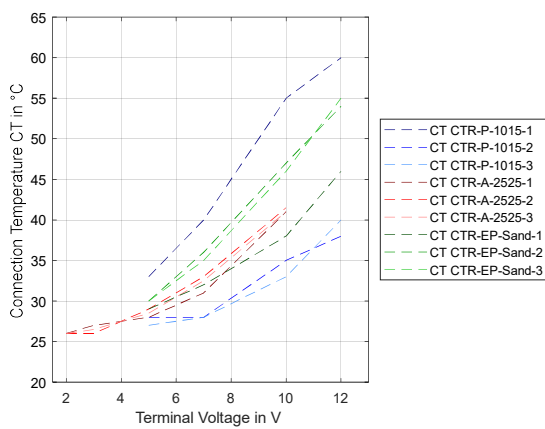


Fig. 8. Connection temperature for increasing clamping voltage

To enable applicability in building concepts, the quality of the connections is of great importance. On average, CTR-EP-Sand exhibits the highest connection temperatures, while CTR-A-2525 shows consistent results without any outliers.

In addition, the surface power density was assessed for varying connection counts of the carbon fabrics, and its correlation with the CTR temperature was analyzed, as illustrated in Figure 9. The results indicate that, despite the previously discussed deficiencies in connection quality, the CTR-EP-Sand consistently exhibits high surface power densities alongside elevated carbon temperatures in the tested configurations. In contrast, the CTR-P-1015 demonstrates the lowest surface power densities among the materials investigated.

Based on the conducted investigations, a CTR was selected for the electrical heating experiments with UHPC. Electrical property analysis predominantly supports the selection of CTR-P-1015.

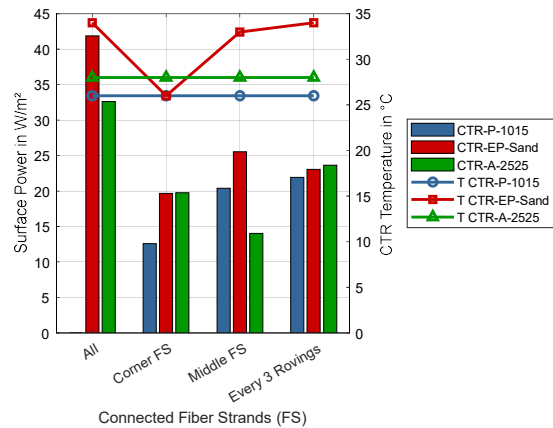


Fig. 9. Surface Power of CTR with varying number of connections and CTR temperature.

However, considering the need for an optimal trade-off between connection quality, surface power, and specific carbon resistance, CTR-A-2525 was ultimately chosen. Furthermore, due to the coarse grain size of the UHPC, a larger roving axis distance was selected.

3.2 CTRC

For the composite material CTRC, terminal voltage was applied to the test specimens at three different time points (10 days, 17 days, 24 days) relative to the manufacturing date, and surface temperature was measured using a thermographic camera. With the applied voltage, surface power of 465 W/m² and 190 W/m² was examined. As shown in Figure 10, the surface temperature decreases with increasing testing duration. At 10 days after manufacturing, the temperature is approximately 1 °C higher than at 17 and 24 days under a voltage of 19 V. The authors suggest that this behaviour can be attributed to the drying process, which results in a reduction in conductive water within the specimen. No significant difference is observed between the 17-day and 24-day measurements.

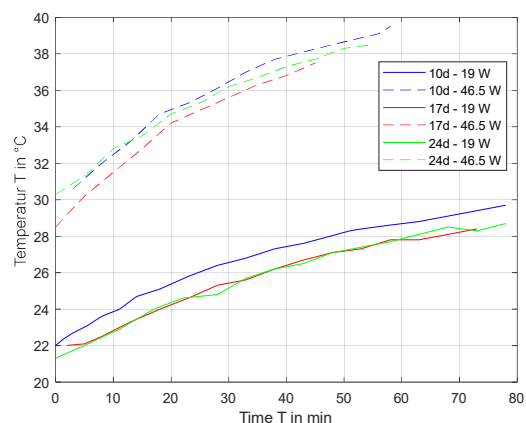


Fig. 10. Surface Temperature of the CTRC.

Further investigation of the composite behaviour was conducted through tensile strength tests. The results are summarized in Table 2.

The tensile strength was determined to be 4176 ± 168 N/mm², indicating a high load-bearing capacity. This tensile strength of the reinforcement is

significantly higher than the average tensile strength specified in the manufacturer's specifications, cf. Table 1. The initial crack strength, relative to the UHPC cross-section ($100 \times 30 \text{ mm}^2$), was measured at $7.63 \pm 1.88 \text{ N/mm}^2$, highlighting the material's resistance to crack initiation. At failure, an average of 14 ± 2 cracks were observed, with an average crack width of $0.13 \pm 0.02 \text{ mm}$, suggesting a well-distributed cracking pattern. Based on the number of weft rovings in the tensile specimen, it can be observed that one crack forms per weft roving, resulting in a number of cracks to weft roving ratio of 1.

Table 2. Mean Values with standard deviation of Tensile Strength Tests.

| | |
|--|---------------|
| Tensile Strength [N/mm ²] | 4176.47 ± 168 |
| Initial Crack Strength relative to UHPC cross-section (100 x 30 mm ²) [N/mm ²] | 7.63 ± 1.88 |
| Crack Number at Failure [-] | 14 ± 2 |
| Average Crack Width at Failure [mm] | 0.13 ± 0.02 |
| Ultimate Strain at Failure [%] | 3.73 ± 0-56 |

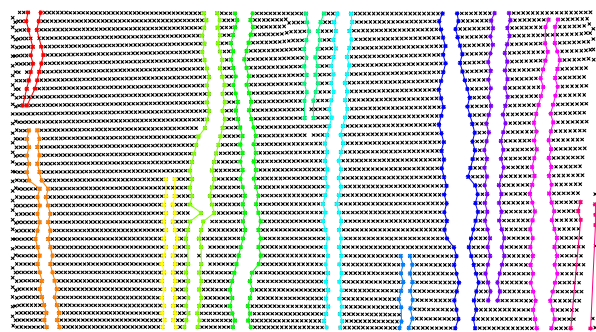


Fig. 11. Example crack pattern of a test specimen at failure.

With the results of the tensile strength tests and the electrical heating experiments, the feasibility of the material combination as CTCR has been demonstrated. Several aspects have been analyzed for the implementation of a MultiTexBridge, which can be utilized for its planning.

4 Conclusion and Outlook

Within the framework of this investigation, the potential of using CTCR as a composite material for electrical heating applications in construction was investigated. A thorough evaluation of the material's performance was carried out by combining electrical property tests, tensile strength measurements, electrical heating experiments, and thermal analysis. The findings provide a basis for assessing the suitability of CTCR in advanced structural concrete systems and offer valuable insights for future material selection and design optimization. The key findings can be summarized as follows:

- The specific carbon resistance and carbon temperature were measured for different materials, revealing significant differences in their performance. The results indicated that

the lowest specific resistance was correlated with the highest heat generation in the carbon material. Significant variation in connection temperature was observed, underscoring the importance of maintaining low connection temperatures for long-term connection quality in practical applications.

- The tensile strength and electrical heating experiments demonstrate the feasibility of using CTCR as a viable material for electrical heating applications. Surface power densities of 465 W/m^2 and 190 W/m^2 were achieved with the applied voltage, correlating with variations in surface temperature up to $40 \text{ }^\circ\text{C}$ over time. Furthermore, the drying process appears to influence the material's thermal behaviour, as observed by a temperature difference between 10, 17, and 24 days.
- The tensile strength tests demonstrated tensile strength values up to 4150 N/mm^2 and a strong bond behaviour, evidenced by the small crack widths and a high number of cracks, ensuring effective stress distribution. The high tensile strength, effective bond, and favourable crack distribution form a solid basis for the use of electrically heated multifunctional CTCR, ensuring durability and reliable performance.
- The analysis of connection quality, surface power, and specific carbon resistance were key factors in selecting the optimal material for the application.

Further research will focus on the practical applications of the electrically heated carbon textiles in de-icing systems, for example MultiTexBridge, specifically characterizing their performance at various temperatures. Long-term cyclic testing will be conducted to evaluate the durability of the system under continuous use, particularly regarding its efficiency in preventing ice. Additionally, further material characterization is essential to refine the design and ensure the durability and reliability of the system under in-situ conditions. These studies will provide crucial insights for the optimization of electrically heated CTCR for broader applications in construction projects.

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