POLYMER IMPREGNATED TEXTILE REINFORCEMENT CURED IN CONCRETE BY MEANS OF ELECTRIC HEATING

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ABSTRACT

Conventional polymer impregnated textile reinforcements possess only limited drapability due to the completed curing of the polymer impregnation. This limits the design flexibility of textile reinforced concrete (TRC) and complicated the integration of TRC into digital production processes (e.g. additive manufacturing). To enable flexible textile reinforcements with high mechanical performance, the authors investigate so called prepregs (uncured polymer impregnated textiles). These prepregs are highly drapeable and are cured after placement within the concrete matrix. The prepreg curing is facilitated by direct electric heating of the carbon textile. In this initial study, the feasibility of this approach is demonstrated and evaluated.

KEYWORDS

Prepregs; electric heating; flexible reinforcement

INTRODUCTION

Textile reinforced concrete (TRC) is an alternative construction material in which the traditional steel reinforcement of concrete is replaced with a reinforcement made of high-performance technical textiles, for example made from alkaline resistant glass or carbon fibres (Peled et al., 2017). TRC offers several advantages over traditional steel reinforced concrete, such as high corrosion resistance enabling a stark decrease of the concrete cover required (J. Hegger & Voss, 2008). Additionally, textiles are highly drapeable, enabling high freedom in design of slender TRC elements and structures (Josef Hegger et al., 2018). In addition, the high-performance technical textiles offer significantly higher mechanical performance than steel, with a breaking stress of up to 4000 MPa in case of carbon (compared to about 500 MPa for steel) (Peled et al., 2017). TRC has been researched for more than 20 years and is still a highly topical research area, which is currently entering the market (Beckmann et al., 2021).

To enable a successful load induction into the reinforcement textiles, which are not a monolithic material but consist of thousands of individual filaments, an impregnation is necessary (Friese et al., 2022). The most common impregnations are based on polymer materials such as epoxy resin or aqueous polymer dispersions, but mineral impregnations are also being researched (Neef & Mechtcherine, 2022). While these impregnations drastically increase the load induced into the textiles and therefore the yield strength of TRC elements, current impregnations are comparatively stiff and limit the design freedom of the TRC reinforcement. Complex shapes can only be realized prior to impregnation and curing of the textiles, and the cured reinforcement cages need to be transported to their destination.

Challenges regarding impregnation and shaping of fibre reinforced plastics (FRP) have also been encountered in other industries. In the automotive and aerospace industries, a common approach enabling a high quality impregnation while retaining drapability/shaping flexibility are so called prepregs (K. Bajpai & Singh, 2019). In FRP processes, prepregs are usually cured using externally provided thermal energy, e.g. using hot surfaces or an oven. Directly transferring this approach to concrete manufacturing would require a lot of energy, since the whole concrete element would need to be heated. Therefore, the authors propose a different approach. By utilizing the electric conductivity of the carbon fibres and ohmic heating, the carbon reinforcement can be heated directly within the concrete matrix, allowing for a quick and efficient curing of the prepreg reinforcement textile. A simple physical model of the resulting circuit is shown in Figure 1 below.

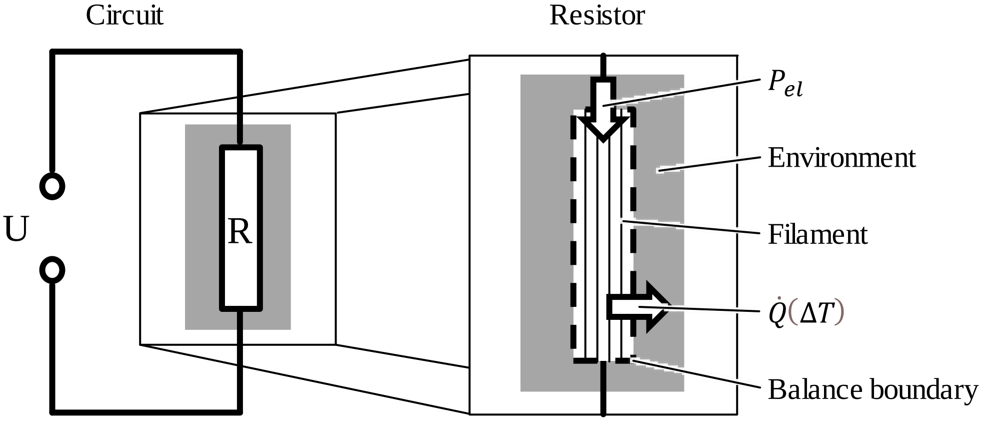


Figure 1: Simple physical model of an electrically heated roving

Within this paper, initial investigations into the heating of carbon reinforcement for and in concrete are presented.

MATERIALS AND METHODS

Two commercially available carbon fibre rovings were used in this work, which only differ in their linear density (titre). The properties of these fibres are given in Table 1. In addition, a commercially available bisphenol A/F based epoxy resin system consisting of resin and hardener was used for impregnation of the fibres.

Table 1: Properties of the used carbon fibres according to the manufacturer

Fibre designation	Designation and type of sizing	Titre [tex]	Tensile strength [MPa]	Tensile Young's modulus [GPa]	Elongation at break [%]
Tenax^{TM}-E STS 40	E23 (Epoxy type)	1600	4300	250	1,7
Tenax^{TM}-E STS 40	E23 (Epoxy type)	3200	4300	250	1,7

To analyse the curing process within concrete, a concrete mixture as described in Table 2 was used. The fine concrete mix is based on the design PZ-0899-01 described by Brockmann and designed for TRC (Brockmann, 2006).

Table 2: Concrete mixture used in this paper

Substance	CEM I 52.5 N	Fly ash	Silica fume	Siliceous fines 0 - 0.25 mm	Siliceous sand 0.2 - 0.6 mm	Water	Superplasticizer
Amount [g/L]	490	175	35	500	713	280	7

The carbon fibre rovings were impregnated with the epoxy resin using a setup based on DIN EN ISO 10618 and shown in Figure 2. The fibre is unwound from a bobbin and guided through a bath filled with resin and hardener. After immersion in the epoxy, the fibre is guided through a nozzle to ensure full penetration of the carbon fibre roving and to squeeze off any excess material. The impregnated roving is then placed on a winding frame. For an initial pre-curing of the roving, the impregnated roving is stored at room temperature for six hours. Afterwards, the roving is processed in the tests or stored for later testing at -19 °C, which stops the curing reaction.

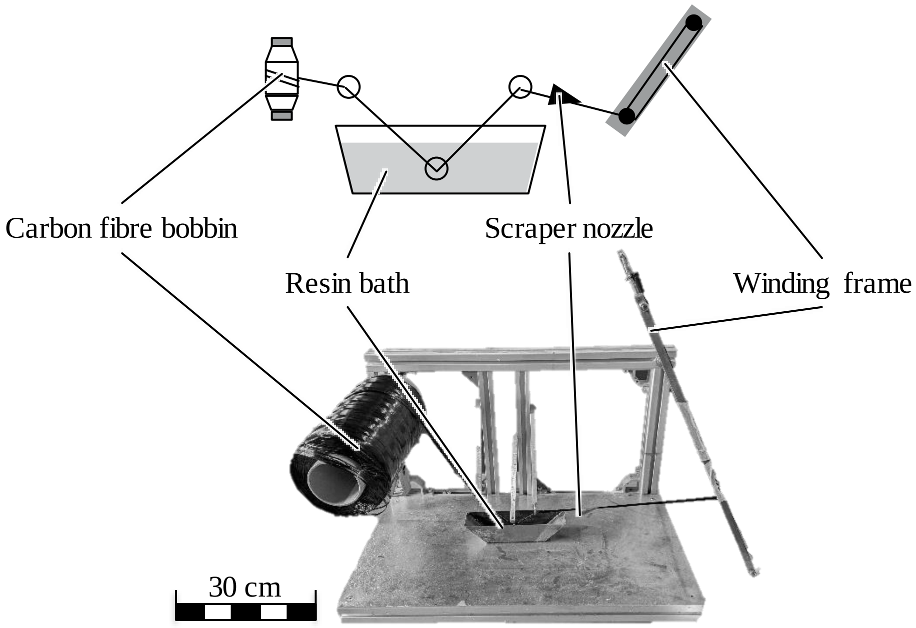


Figure 2: Impregnation process for rovings used in this paper

Prior to electrical contacting, all rovings are cut to a uniform length of 35 cm. For all electrical tests, the rovings are fitted with wire ferrules to facilitate the electrical contact. In some specimens, a small amount of conductive paste based on silver is applied to the wire ferrule areas to reduce the contact resistance.

The tests were performed in three stages. Initially, non-impregnated rovings were contacted without a concrete matrix to determine the range of the voltage required to reach temperatures of roughly 100 °C in the roving. Building on this, freshly impregnated rovings were contacted with the same voltage to determine whether the impregnation has a significant influence on the roving resistance and temperature. The set-up for both these tests is shown in Figure 3 below. The roving temperature was measured using an IR camera.

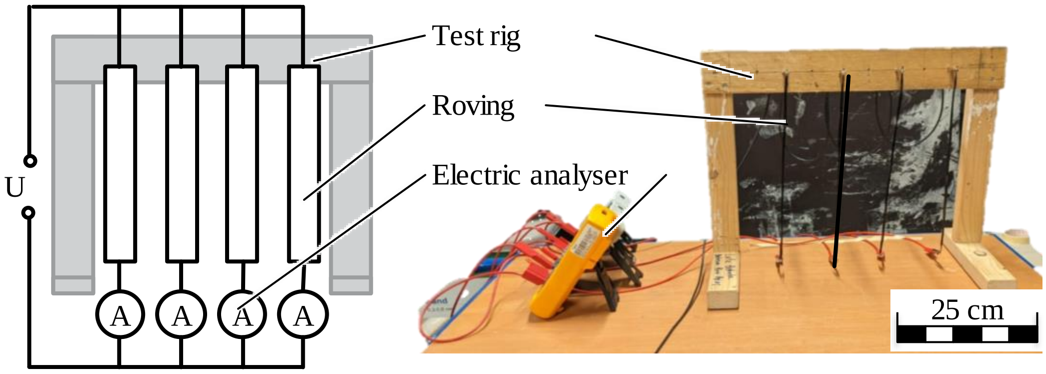


Figure 3: Set-up for roving tests

In the final test stage, the impregnated and contacted rovings were placed in a concrete matrix prior to turning on the electric current, as shown in Figure 4. To evaluate the bond performance of the rovings, test specimens based on Lorenz were produced (Lorenz et al., 2013). Since the rovings are placed within the concrete matrix, measurements of the roving temperature by IR-camera were not possible.

Instead, an electric temperature probe (Type K) was embedded in each roving. The rovings were heated for 1 h and 5 h and compared to a reference specimen which was cured outside of the concrete matrix, as done in the state of the art. After 24 hours of curing in the formwork, the specimens were cured in a water bath for an additional 27 days and subsequently tested.

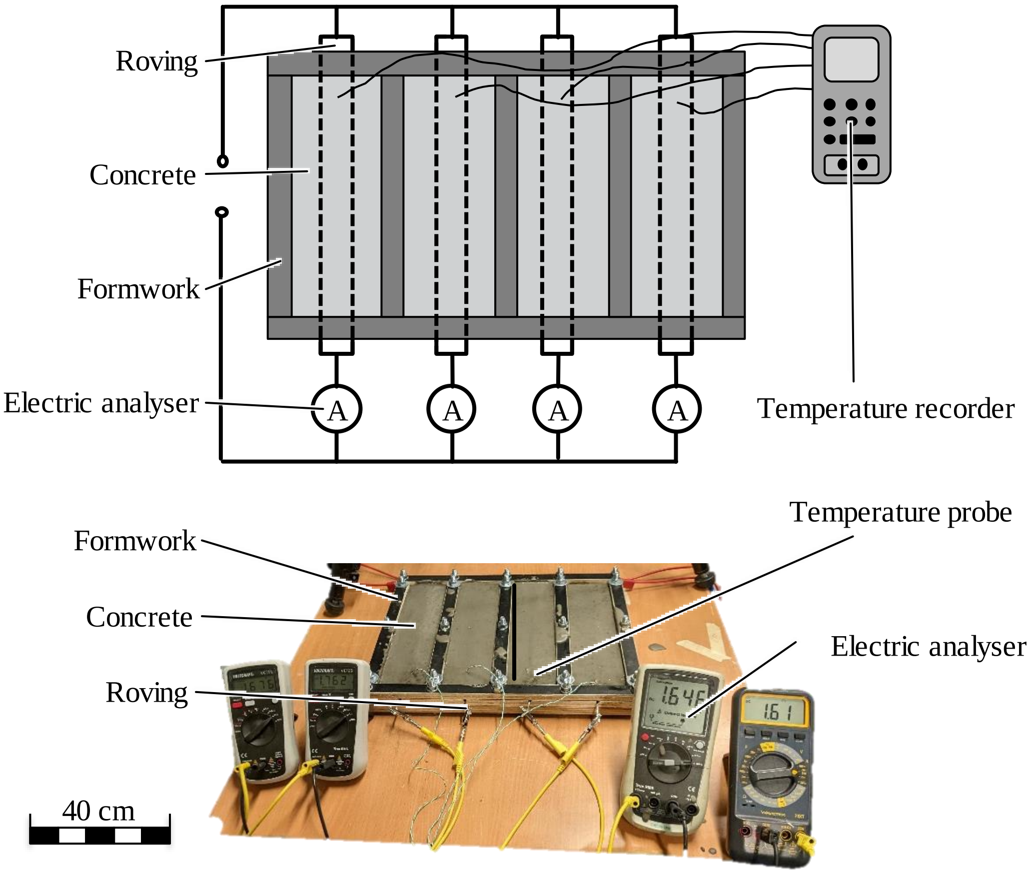
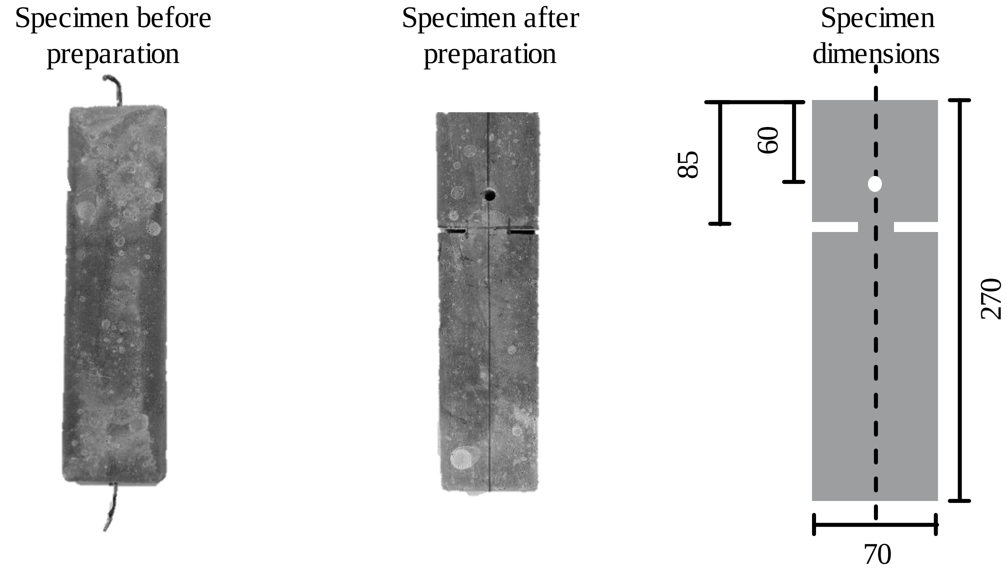


Figure 4: Test set-up for rovings in concrete

To evaluate the bond performance of the rovings in concrete, tests according to Lorenz were performed (Lorenz et al., 2013). The specimens were prepared as shown in Figure 5 below and tested on a universal tensile testing machine at a constant speed of 1 mm/min. After a displacement of 4 mm is reached, the pull-out is completed at an increased speed of 10 mm/min. During the pulling the applied force is measured. After the experiment, the measured force is divided by the protruding length to analyse the displacement-bond flow relationship. The bond flow as defined by Lorenz et al. is the measured pull-out force divided by the pull-out length, which is useful to normalize measurements with (slightly) different pull-out lengths.


Specimen before preparation

Specimen after preparation

Specimen dimensions

Figure 5: Specimens for concrete pull-out tests

RESULTS AND DISCUSSION

Evaluation of the measured resistance of the rovings shows that the resistance of the rovings is independent of temperature and voltage for the measured ranges (up to about 150 °C and 8 V). However, the resistance is highly dependent on the linear density/titre of the rovings and the contacting method (with or without silver paste) (see Figure 6 below). In addition, impregnation of the rovings also increases the resistance, as is to be expected for an insulating impregnation material like epoxy resin.

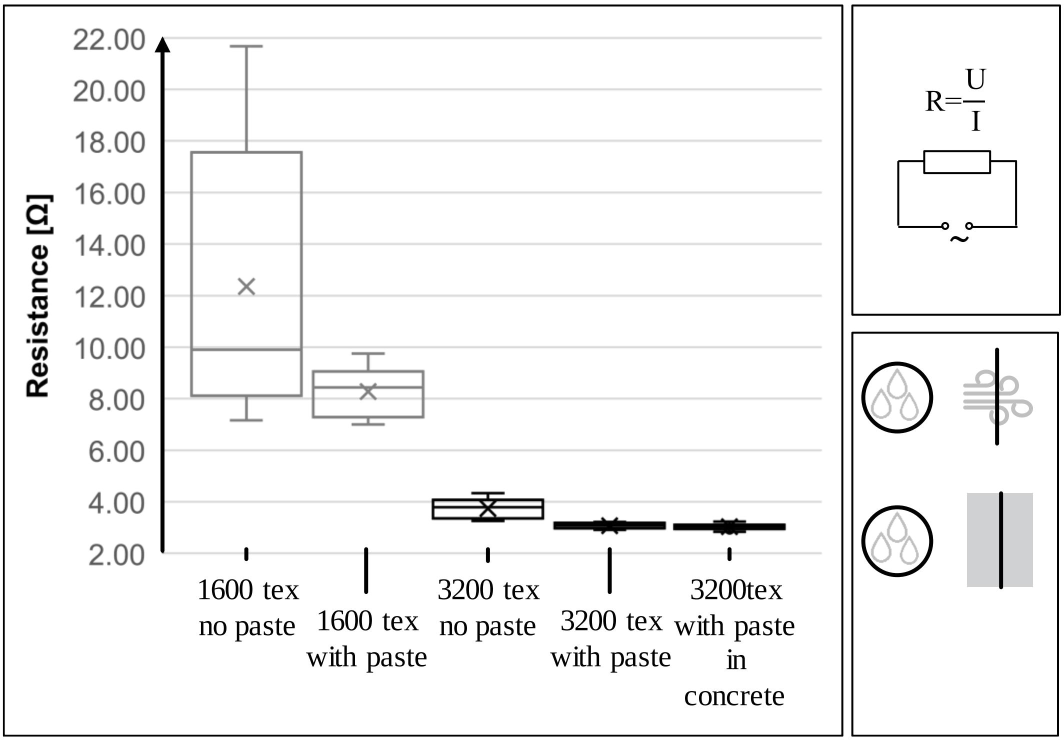


Figure 6: Resistance of impregnated rovings

As can be seen in Figure 6, application of the silver paste significantly reduces the resistance of the system. This reduction is also visible in the IT-images, where the contact resistance leads to a local temperature maximum at the contact point, which is much less pronounced for specimens with silver paste. This resistance reduction is much more pronounced for the lower titre. A likely explanation is that the wire ferrules which are crimped onto the roving work better with a thicker roving, which has a higher tire. As can also be seen in Figure 6, placing the rovings in concrete has no influence on the roving resistance.

The temperature that is reached depends mainly on the power applied to the circuit, as is to be expected. As can be seen in Figure 7, the temperature reached is largely independent of the titre of the rovings. This is the same for impregnated and non-impregnated rovings.

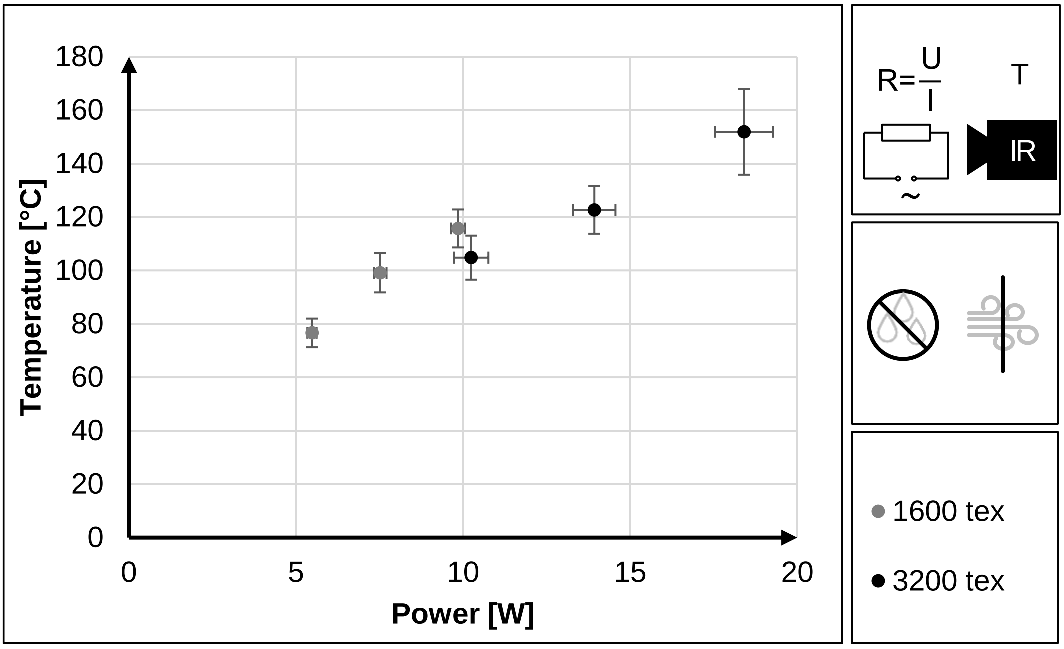


Figure 7: Relationship between applied power and temperature of the roving (depicted are results for unimpregnated rovings)

For the impregnated and unimpregnated rovings not placed in concrete, the steady temperature is reached after a few minutes. Within concrete, this steady state is reached much later (after about 30-40 minutes) and at much lower temperatures for the same power applied. This is of course due to the much higher thermal conductivity of wet concrete compared to air. With the same power that results in temperatures of about 120 °C in air, temperatures of about 50 °C are reached in the roving in the concrete matrix.

The measured average maximal bond flows for the two series cured in concrete for 1 h and 5 h respectively as well as the reference cured outside concrete are given in Figure 8 and were also reported in (Scheurer et al., 2023). Differences in the number of tested specimens are the result of damages during the production and testing procedure.

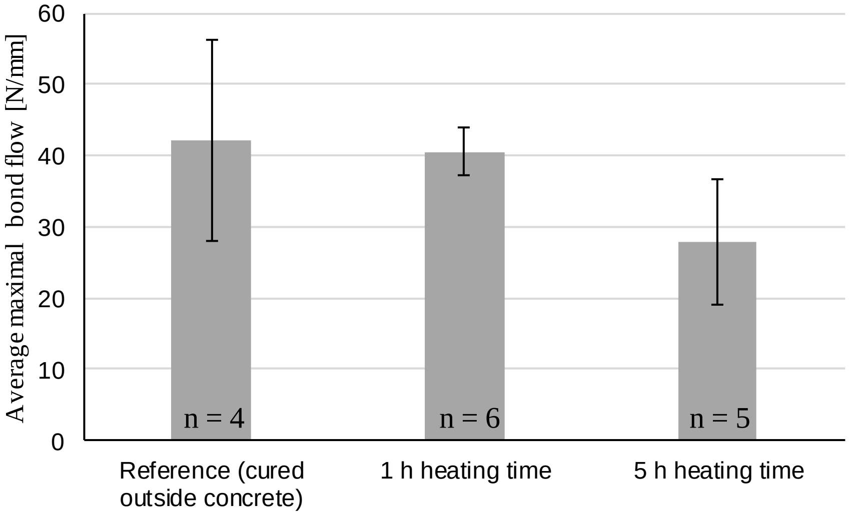


Figure 8: Average maximal bond flow of the specimens

These bond low results indicate that curing of the polymer impregnation within the concrete matrix is feasible and results in similar bond strength compared to the reference cured outside concrete. However, increasing the curing time does seem to weaken the bond, most likely due to damages introduced in the bond area. While the measured temperature within the roving is about 50 °C and therefore below temperatures suggested to influence ettringite formation (more than 60-70 °C, according to (Divet & Randriambololona, 1998)), local temperature spikes might go above this temperature. Further investigations into this effect and the ideal curing conditions are necessary.

SUMMARY AND OUTLOOK

In this paper, first investigations into the adaptation of the so called prepreg process, which is well established in FRP manufacturing, to the production of textile reinforced concrete are presented. Prepregs are pre-impregnated textiles in which the polymeric impregnation is only cured after the final shape of the component is formed. In FRP, this is usually achieved by external heat induction using heated surfaces or an oven/autoclave. In the approach investigated in this paper, the electric conductivity of a carbon reinforcement is used to use resistance heating for curing of the preimpregnated reinforcement textile. The main results are the following:

- Curing of carbon reinforcements by means of electric heating is possible. While the polymer impregnation does increase the resistance of the roving, heating of an impregnated roving is still possible by using suitable contacting methods, such as wire ferrules with silver paste.
- Due to the high thermal conductivity and thermal capacity of wet concrete, temperatures reached in concrete are significantly lower than in air, leading to a roving temperature of about 50 °C in concrete for the same power that leads to 120 °C in air
- Heating of the rovings in concrete is a sensitive process that needs to be analysed closely. While comparative bond performance is reached when the roving is heated for 1 hour, longer heating times seem to damage the bond, reducing bond performance.

Further research into the sensitive process is necessary to understand the mechanisms leading to the reduced bond performance after longer heating times and to identify the ideal process parameters (time and temperature combination) for the curing of prepregs in concrete. In addition, in the initial trials presented in this paper, only rovings were investigated. The transfer of the results to the grid like textiles usually employed in TRC needs to be investigated and contact methods for such textiles need to be developed. Additionally, a method for the integration of the prepreg approach in the manufacturing methods for TRC needs to be developed.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.