

Recycled fibres in textile-reinforced concrete combined with building component activation

Vanessa Overhage¹ and Thomas Gries²

¹Research Assistant of Institute for Textile Engineering, RWTH Aachen University Germany

²Professor of Institute for Textile Engineering, RWTH Aachen University Germany

Abstract: The construction industry is the most resource-intensive sector. Concrete is, with an annually demand of 4.4 billion tonnes, the most widely used material in the world. An increase in demand of a further 25% is already forecast for the year 2050. The main components of concrete are resources limited materials. By using textile-reinforced concrete, resources can be saved in concrete production compared to steel-reinforced concrete. Furthermore, the production of the new carbon fibres requires a high energy input, it is desirable to use these already existing fibre materials for as long as possible. Studies show that recycled carbon fibres from carbon fibre reinforced plastic waste still have 80% of the original mechanical properties. The construction industry is a possible field of application for the fibre reuse. Moreover, it is also possible to use the conductivity of carbon fibres for simultaneous use as reinforcing material. The conductivity can be used as a sensor or, due to the thermal conductivity, as a heating element. A possible field of application for this could be, the thermal activation of building components. The use of recycled carbon fibre yarn as a reinforcement material and for thermal component activation is being evaluated.

Keywords: recycled carbon fibre, textile reinforced concrete, Building component activation

1 Introduction

Since the invention of reinforced concrete in 1854, this composite material made of concrete and reinforcing steel has become the most important material in the construction sector (1). The required quantities of both basic materials are correspondingly high. In 2013, the global production volume of concrete was between 7 and 10 billion cubic metres (2). The production of concrete requires cement as a binding agent, the production of which causes high CO₂ emissions. The production of one tonne of cement in Germany, for example, produces around 600 kg of CO₂ emissions. Overall, cement production accounts for about 6% to 7% of global man-made CO₂ emissions (3). The production of one tonne of steel requires about 19 GJ of energy and causes about 2.3 t of CO₂ emissions. Furthermore, sand is needed for concrete production, which is also only available in limited quantities (4). Therefore, it makes sense to reduce the amount of concrete used. One way to reduce the amount of concrete needed for a building component is to use textile concrete, in which the steel reinforcements are replaced by reinforcements made of technical textiles. The amount of energy required and the CO₂ emissions for the production of the reinforcement materials are also lower in relation to the component (5).

Carbon fibres (CF) are particularly suitable as a material for textile reinforcements due to their high tensile strength and corrosion resistance (5). However, the production of CF is also very energy-intensive and causes greenhouse gas emissions. In addition, CF production is cost-intensive. (6) For this reason, the recycling of CF is interesting from an ecological and economic point of view.

Studies show that recycled CF (rCF) from CF reinforced plastic waste still have 80% of the original mechanical properties. The construction industry is a possible field of application for the fibre reuse. Furthermore, it is also possible to use the conductivity of CF for simultaneous use as reinforcing material. The conductivity can be used as a sensor or, due to the thermal conductivity, as a heating element. A possible field of application for this could be, the thermal activation of building components.

The present work investigates the usability of such staple fibre yarns made from (rCF) as reinforcement material for concrete as reinforcement and as heat conductors for thermal component activation in concrete.

2 State of the Art

In the following the state of the art of textile reinforced concrete, recycled carbon fibres, building component activation and Conductivity is presented.

2.1 Textile Reinforced Concrete

Concrete as an artificial rock is very well suited to bear compressive forces due to its internal structure. One disadvantage of concrete, however, is its tensile strength, which for normal concrete is only about 10 % of its compressive strength (7). Structural elements that are subjected to tensile loads must therefore be

provided with reinforcement in order to be able to absorb the tensile forces (1). For this purpose, ribbed steel is usually used, which ensures optimal load transfer from concrete to steel. Furthermore, the thermal expansion of steel and concrete is the same. Therefore, this material combination has proven itself (1).

A major disadvantage of reinforced concrete is the steel's susceptibility to corrosion. If it begins to corrode, the rust displaces the concrete. This leads to stresses and ultimately cracks (1). Furthermore, the mechanical properties of the steel are negatively affected by corrosion (5). Therefore, minimum thicknesses of protective concrete must be provided between steel and the environment. This makes components more voluminous than they structurally need to be (1).

An alternative to reinforced concrete is the reinforcement by textile fibres with high tensile strength. These do not corrode, which minimises the thickness of the concrete cover layer and increases the service life of the component. A prerequisite is the alkali resistance of the materials (8). Possible materials for the fibres are glass, carbon, basalt or aramid (5).

The fibres can be added to the concrete unordered in the form of short fibres, but then they do not support tensile force transmission. Alternatively, the concrete can be reinforced with yarns, fabrics or scrims specific to expected loads (1). This is similar to the principle of reinforced concrete. Reinforcement with textile fibres can also be one, two or three dimensional. However, due to the drapability of textile fibres in their original state, there are significantly more design possibilities than with steel reinforced concrete. Fibre structures can form complex, three-dimensional geometries and multiple curved surfaces (5).

The forces acting on a component are transmitted to the reinforcement via mechanical bond, adhesive bond or friction bond. When using ribbed strands as steel reinforcement, the forces are mainly transmitted via the mechanical bond, while the adhesive bond and friction bond are negligible. Since the textile fibres used for reinforcement have a smooth surface, adhesive and frictional bonds are activated here for load transmission (9). Since the concrete matrix only penetrates the edge zones of the yarns, a distinction is made between outer and inner filaments. Without the impregnation of the yarns, the inner filaments would only be insignificantly involved in the load transfer. Therefore, the use of unimpregnated yarns would be ineffective (9).

2.2 Recycled Carbon Fibre

Global demand for CF has increased from 33,000 tonnes in 2010 to an estimated 120,000 tonnes in 2022 (10). As production increases, so does the amount of waste from CF, which is why its recycling is becoming increasingly important (10). In terms of the circular economy, the recycling of material for components that can no longer be used should be strived for (11). Since many components containing CF are designed for mechanical strength and chemical resistance, the recycling process is complex. However, due to the high cost of virgin CF (vCF), recycling can also be economically viable (19).

Dry offcuts produced during the manufacture of composite fibre components can be shredded and used as fillers or non-directional reinforcing fibres in construction, injection moulding or compression moulding. Once impregnated, fibres must first be freed from the matrix. This can be solved for cured as well as for not yet cured matrices by means of pyrolysis (thermal) or solvolysis (chemical). Short fibres, medium-length fibres or long fibres can be obtained from this. Short fibres can be used in a similar way as the particles from the recycling of dry waste. Medium-length and long fibres, on the other hand, can be processed into materials and semi-finished products that exploit the directionality of the mechanical properties of CF (12). In the context of this work, the further processing of rCF into yarns is relevant, as they are used and investigated as reinforcements in concrete specimens. In order to be able to produce a yarn from the rCF, they are mixed with carrier fibres made of plastics such as polyamide 6 (PA6). From this mixture, a carded fleece can first be obtained, which is then stretched and spun into a so called hybrid-yarn (10).

2.3 Building Component Activation

Thermal component activation describes a climate system that uses the building masses to regulate the temperature. Building component activation is often also called concrete or building core activation. Building component activation describes constructions of ceiling, floor or wall systems for changing the indoor climate. Most commonly, these are building component-integrated, water-guided pipe systems (13).

Due to their massive construction and the associated storage capacity, concrete structures can be used for space heating or cooling. The concrete acts as a storage and heat transfer medium. Concrete is suitable for energy storage because the material's uniform thermal conductivity ensures rapid heat transfer (13). This creates an even distribution of heat or cold throughout the day. Temperature peaks are thus avoided (14). Building component activation with water as the medium is defined in DIN-EN 1264-1 as a heating or cooling system that is embedded in the room enclosure surfaces of the room to be heated/cooled consisting of heating circuit pipes.

A basic distinction is made between two different types of building component activation, the thermal building component activation located on the surface, also called thermoactive building component systems or the concrete core activation used in the middle of the building component. The variants are distinguished by their position in the building component, pipe diameter and pipe spacing (15).

Due to the large heat dissipation surfaces, the surface temperature of a TCA can be kept very low. The flow temperature is between 25 and 30 °C, which is controlled by the outdoor temperature. With such a heating system, the heating medium temperatures are only a few degrees above the desired room temperature (13).

Low heating temperatures are necessary for optimum system utilisation and effective use of renewable energies. A future-oriented system is the combination with solar collectors. Another possibility is the use of the regenerative provided heat through geothermal energy (13).

2.4 Conductivity

Conductivity is the ability of a conductive substance to conduct or transfer energy, other substances or particles in space. In the following, a distinction is made between thermal conductivity and electrical conductivity.

Thermal conductivity is a property of a material. It determines the flow of heat through a material based on thermal conduction. It is a molecular process that describes the exchange of kinematic energy from one molecule to another (16). The corresponding formula symbol is λ and the unit is watts per metre and kelvin ($W/(m \cdot K)$). This indicates how well a material conducts heat. Therefore, the lower the thermal conductivity λ , the more suitable the material is for thermal insulation (17). The thermal properties of CF are direction-dependent due to the high anisotropy of the fibre structure. This fibre structure depends on the manufacturing process of the CF. The characteristic values of the thermal conductivity of concrete, steel reinforced concrete and CF are in the following Table 1.

Table 1. Characteristic values of the conductivity of selected materials (18, 19).

	Modulus of elasticity E [kN/mm ²]	Thermal conductivity λ [W/(m·K)]	Thermal expansion coefficient α [K ⁻¹]
Concrete	27	1,35	5 * 10 ⁻⁶
Steel reinforced concrete	31 kN/mm ²	50 W/(m·K)	11 * 10 ⁻⁶
Carbon fibre	700 kN/mm ²	5,4 W/(m·K)	-1,0* 10 ⁻⁶

Electrical conductivity, is a material property and physical quantity that indicates how well an electric current is conducted. The formula symbol is either σ or k , the corresponding unit is Siemens per metre [S/m]. The reciprocal of electrical conductivity is resistivity with ohms' times metres ($(\Omega \cdot m)^{-1}$) (20).

The specific resistance ρ describes the resistance of a material related to the length and the cross-section. If the resistance is increased, the conductivity decreases and vice versa. Resistance and conductivity are therefore inversely proportional to each other (21).

In the case of electrical conductivity, current conduction occurs proportionally and in the same direction as the electric field caused by the current density. In this case, Ohm's law applies. Ohm's law states that the resistance, formula symbol R , of a conductor remains constant regardless of the voltage applied (21).

When considering heat generated by electrical energy, one comes across the term heating resistor. A heating resistor describes the conversion of electricity into thermal energy. In the process, the energy of the electrodes, which was supplied by the current source, repels from the atomic trunks. The resulting vibrations heat the conductor (21).

The electrical properties of CF are characterised by a low specific electrical resistance ρ . This depends on the type of fibre and reaches values in the range of 10^{-3} - 10^{-5} Ω per cm. A low resistance in turn indicates good electrical conductivity. To achieve this conductivity, CFs must first be coated with an electrically conductive layer (17). Due to this, the yarns provided are equipped with an impregnation in the course of the test preparation.

3 Design of Experiments

Four-point bending test and thermal conductivity tests were carried out on reinforced concrete specimens as part of this work. The following table shows the experimental design. The series of flexural tests were designated with letters A-E and the series of thermal conductivity with numbers 1-6.

Table 2. Design of Experiments.

	Testing method	Reinforcement	Impregnation	Number of Yarns
A	Four-point bending test	Wrapped Yarn rCF 1	Epoxy	4
B			Epoxy	9
C		Wrapped Yarn rCF 2	Epoxy	4
D		Wrapped Yarn vCF	Epoxy	4 x 3
E		-	Epoxy	-
1	Thermal conductivity test	Wrapped Yarn	Conductivity increasing	1
2				2
3			-	1
4		Friction Yarn	Conductivity increasing	1
5				2
6			-	1

3.1 Concrete Sample Production

The yarns used as reinforcement are impregnated with an epoxy resin or a conductive increasing impregnation before being placed in the concrete. This ensures force transmission between the fibres and improves recyclability or increases the conductivity in case of the thermal conductivity testing. The epoxy matrix enables force transfer between the individual fibres and thus ensures that the inner fibres of a yarn also bear loads and stretch under load, otherwise the smooth fibres would slide off each other (22). The concrete is too coarse-grained to penetrate between the fine fibres, so the concrete alone would only transfer the loads to the outermost fibres (5). Another advantage is that impregnated yarns or scrims are much easier to detach from the concrete later, which improves recyclability (23).

For concreting, the standard mixing ratio of the ITA concrete laboratory (see Table 3) is used, which was determined in the past by means of the special research area "Textile-reinforced concrete" in subproject C1.

Table 3. Fine Concrete Mixture.

Components	Volume [%]	Quantity [g/dm ³]
Cement CEM I 42,5 R	22,3	490
Fly ash	8	175
Silica fume	1,6	35
Quartz powder	22,7	500
Sand aggregate size 0,2-0,6mm	32,4	713
Water	12,7	280
Superplasticizer	0,3	7

The drying process is carried out according to DIN EN 12390-2, 3. 24 hours after concreting, the specimens are stripped and placed in a water bath for 6 days. After the water bath, the individual specimens dry for 21 days.

3.2 Test setup

The test specimens are tested for bending tensile strength in a four-point bending test in accordance with the DIN EN 1170-5 standard as shown below in the figure 1.

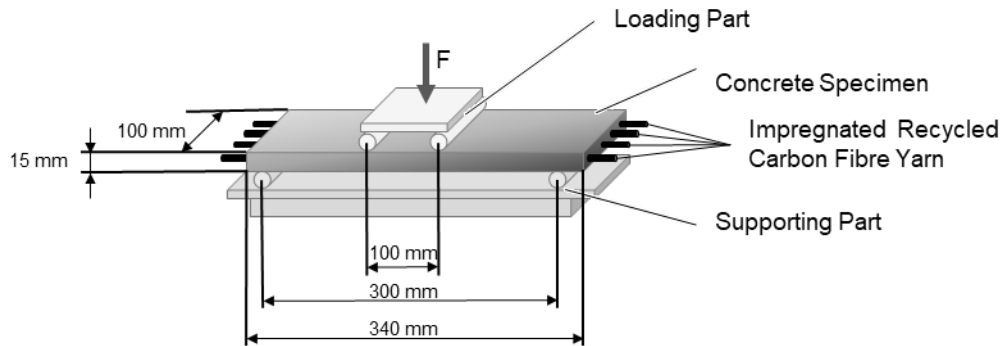


Figure 1. Schematic representation of four-point bending test setup.

The main components of the test setup are the force transducer, the supporting and the loading part, the and the force measuring sensor. The supporting parts are spaced 300 mm apart for the tests and the loading parts are spaced 100 mm apart. The contact surfaces of the supporting and the loading parts are rotatable mounted rollers with a radius of 10 mm. Figure 2 schematically shows the test setup for measuring the thermal conductivity.

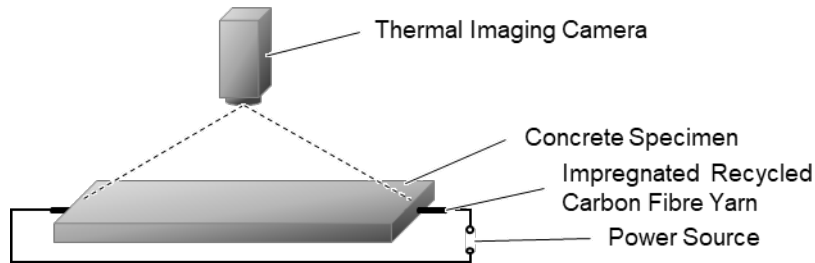


Figure 2. Schematic representation of the thermal conductivity test setup.

An external power source is connected to generate heat in the specimens using electricity. The thermal images are recorded with an infrared thermal imaging camera over 4 hours at intervals of 7.5 minutes. Infrared images are generated based on the temperature differences detected. In order to improve the conductive properties and the contacting, a metallic ferrule is attached to the ends of the yarn and pressed tight with a crimping tool. This procedure is intended to distribute the subsequent current flow from the source to the yarn more evenly. Since the yarns used are hybrid yarns, this bundling can also ensure that the yarn is more stable and a transfer to the conductive CF is guaranteed.

4 Results

The results of the tests carried out are presented below. First the four-point bending tensile tests and then the results of the thermal conductivity tests are evaluated.

4.1 Four-point Bending Test

The results of the four-point bending tests are shown and described in a stress-strain diagram. As listed in Table 2, five series are tested. The series include two different rCF yarns with 2 cm spacing A, C, a variant with reinforcing yarns at half spacing B, and as a reference a virgin staple fibre yarn D and an unreinforced concrete sample E. The reinforcement mass of the carbon fibres is comparable for A, C and D. As the yarns of sample D are finer, 3 yarns were concreted in each case bundled at a distance of 2 cm. Figure 3

illustrates the results as flexural stress-strain curves. For the overview, a typical curve of each of the samples was selected and are shown below.

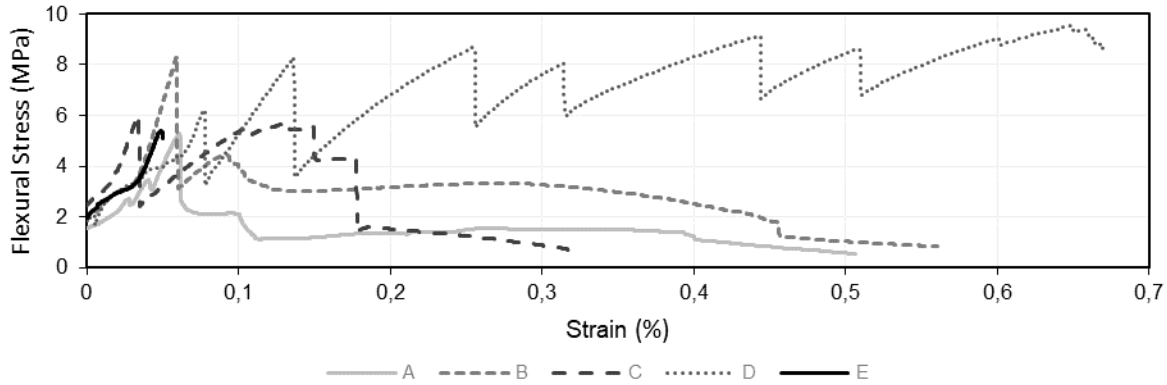


Figure 3. Flexural stress-strain curves.

It can be recognised that series B and D depict a gradual failure. Especially in D, the fractures of the individual yarns are visible, whereby it can be detected that here several finer yarns are present as reinforcement. The first and second high point of series C reach a similar flexural stress. Compared to the unreinforced specimen of series E, series A achieves only a minimally higher flexural stress, but the strain is much more distinctive and no immediate failure occurs after the first break. During the visual inspection of the specimens, it was noticeable that significantly more entrapped air formed in the reinforced specimens, especially in the area of the reinforcement. If these air voids are avoided, more significant differences are expected in the future. In comparison of series A and B, it can be seen that the higher percentage of reinforcement represents a significant difference, which shows that the reinforcement made of rCF yarn has an influence

4.2 Thermal Conductivity Test

In addition to testing the bending tensile strength, tests of the thermal conductivity were carried out as listed in the design of experiments (Table 3) in order to evaluate the use of the rCF yarns for component activation in concrete. The yarns were impregnated with a conductivity improving coating. Before the actual test, the resistance of the specimens is measured using a multimeter.

Table 4. Specimen details and test strength.

	Description	Number of yarns	Resistance R (Ω)	Voltage U (V)	Current I (A)	Temperature results ($^{\circ}\text{C}$)		
						Mean value	Maximum	Minimum
1	Impregnated Wrapped Yarn	1	42	10	0,24	25,7	26,5	22,5
2	Impregnated Wrapped Yarn	2	22	10	0,46	28,5	29,7	22,6
3	Wrapped Yarn	1	157	10	0,06	23,9	24,4	22,6
4	Impregnated Friction Yarn	1	89	10	0,11	24,8	25,5	22,1
5	Impregnated Friction Yarn	2	43	10	0,23	24,7	26,2	22,1
6	Friction Yarn	1	627	10	0,01	22,8	23,2	21,6

It is clearly visible that the resistances of the coated yarns are significantly lower compared to the uncoated yarns. Therefore, the significance of the coating is proven. As expected, the resistance was halved when using two yarns. The voltage was left constant at 10 V in all tests to ensure comparability.

On the right side of the table 4, the temperatures reached during the following temperature measurements are listed. Similar to the results of the resistance measurements, the samples with lower resistance reached higher temperatures faster during the measurements. The temperature curves over the measurement period of 240 minutes are shown below in Figure 4.

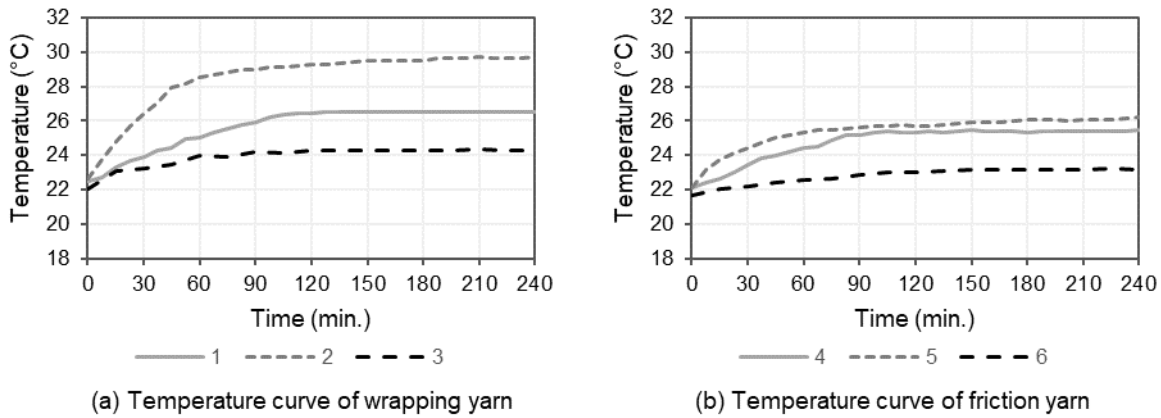


Figure 4. Temperature curves of wrapping yarn and friction yarn over time.

The specimens with wrapping yarn achieve a higher temperature curve than the specimens with the friction yarn. For both variations, the specimens with two yarns achieve higher temperatures, but the difference is clearly more distinctive with the wrapping yarn specimen compared to the friction yarn specimen. A wrapping yarn occurs therefore more suitable for thermal conductivity. The 90% mark of the respective maximum temperature of each series was reached after approx. 90 min for the wrapping yarns and at 75 min for the friction yarns in specimen 4 and at approx. 140 min for the friction yarn in series 5 and 6. A direct comparison clearly shows that the samples with the uncoated yarns 3 and 6 achieve significantly lower temperature differences.

5 Conclusion and Outlook

In summary, significant differences can be seen for both series of tests carried out. A positive influence of the flexural strength of rCF yarns as reinforcement in concrete can be identified. An accurate dimensioning and an improvement of the placement method to avoid air entrapment will be part of future research. An improvement of the test results is expected. The use of rCF yarns for component activation also seems possible. Here, a significant influence of the conductivity-increasing coating could be demonstrated. Based on this, further experiments are necessary in the area of coating materials as well as in the application and complete impregnation of the coating materials. Furthermore, an adaptation and variance of the specimen sizes as well as the electrical design to achieve the necessary temperatures depending on the area of application, indoor or outdoor, is intended. In order to try the feasibility of combining the thermal activation of building components and the use as reinforcement material, the investigation of the mechanical properties with the conductivity-increasing coating material is also planned. In the long term, the use of recycled carbon fibres is expected to have a positive impact on the construction industry.

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