Energy-Efficient Reinforced Heating System Implemented as a Carbon Concrete Formwork

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Abstract. This paper reports the development of an energy-efficient reinforced heating system implemented as a carbon concrete formwork. At present, nearly 70% of the provided heating energy for private households is based on fossil resources. The aim of research and development is to exclusively use renewable energy, to avoid power stations und combustion plants. Therefore, innovative technologies are needed that enable the generation of heat from electric energy. To achieve this goal, carbon concrete heating elements (CCE) were developed by Chemnitz University of Technology (TUC). These elements consist of thin-walled textile reinforced concrete and can be used for curved forms and rational functionalities, combined with durability and economic efficiency. A carbon roving, meander structured and not impregnated, creates the heating energy. A roving, often used in composites, consists of endless parallel fibre filaments. For structural and mechanical reasons, the basis is a reinforcing glass fibre grid (GFG). The carbon fibre has a high electric conductivity and a negative temperature coefficient (NTC element), which enables fast heating up to the target temperature. Therefore, power consumption increases with the temperature. The practical implementation of the CCE involves with many challenges: The properties of the concrete have to be adjusted, options for wall fastening as well as energy input, steering, and performance of the system have to be developed. During production, the exact positioning of the integrated elements and the use of resource-friendly casting and forming technology must be ensured.

Keywords: Carbon concrete heating · Renewable resources · Energy-efficiency

1 Introduction

A promising opportunity to use renewable energies for thermal power generation are electric heating systems, like mobile electric radiators, night storage heating, electric floor heating, infrared heating, or natural stone heating systems.

Especially natural stone heating systems have a high potential for energy efficient building, because of their high performance of up to 400 W (≙ 2000 W/m^2) [1]. The temperature of a marble stone heating plate, with the dimensions 40 × 50 × 2 cm^3, can rise up to 90 °C after one hour, starting at 23 °C (Fig. 1). Over a long period, the maximum surface temperature is 94 °C under full performance.

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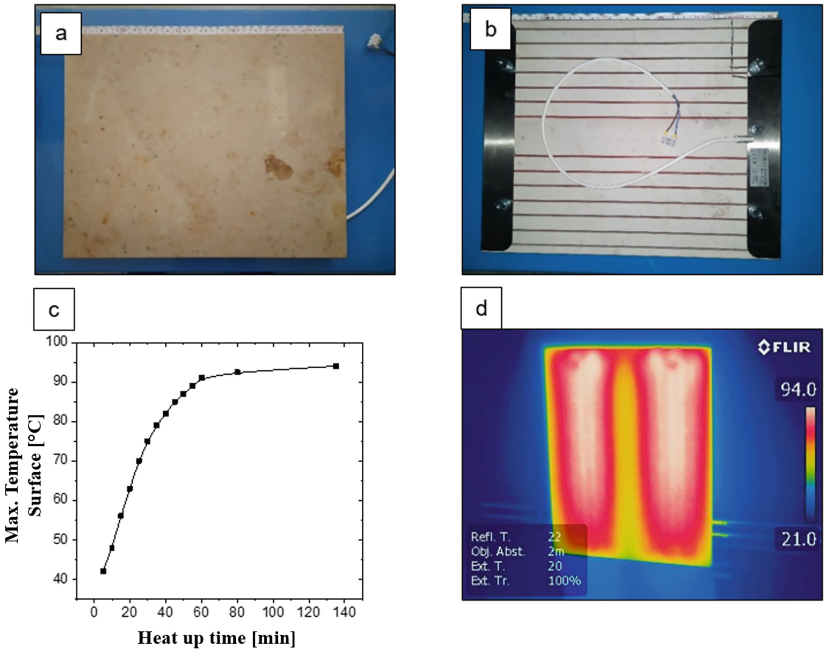

Fig. 1. Natural stone heating by the company Granotech: a) front view, b) back view, c) heat-up curve, d) infrared picture during full power.

The marble heating consists of a metal heating element, which transforms electric energy into heat as a result of elastic bounces of electrons with other electrons, atoms, and photons. Thus, the resistance increases with the temperature and the performance falls. The complex production, like cutting from blocks, milling of slits, gluing the heating element, and the limited design of form and surface are disadvantageous.

The new carbon concrete heating element (CCE) will follow up here. The mineral construction material concrete behaves similarly like marble, while an electro conductive carbon roving provides the heating power. These carbon roving is directly integrated during production and increase the effectivity of heating.

The heating system of the future is free from fossil resources and only uses renewable energies. The aim is to achieve a significant contribution to the energy revolution by developing and realising an energy efficient integrated reinforced concrete heating system. A functional textile serves the reinforcement of concrete and creates the infrared emission. In addition, the development allows for the efficient production of a carbon heating. It is implemented in lightweight construction with high heating power ($>$1000 W/m^2), low weight, and individual design.

2 Materials and Methods

2.1 Components for Carbon Concrete Heating Elements

The energy efficient reinforced carbon concrete heating systems consist of a textile reinforcement (alkali-resistant glass fibres) for higher strength, a carbon roving for creating the thermal power through an resistance heating, and a mineral matrix (fine-grained concrete).

Textiles

There are heating textiles on the market, e.g. by the company Gustav Gerster GmbH & Co. KG. They were developed for tempering polymer composites (Fig. 2) but are not useful for concrete matrix.

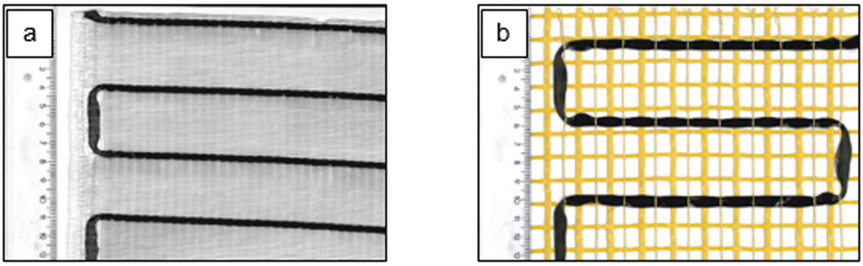

Fig. 2. Commercial carbon heating textiles on glass fibre textile from Gustav Gerster GmbH & Co. KG.

The carrier textile of product (Fig. 2a) is not useful for the combination with the concrete, because it has to be manually cut out of the textile structure before using. For that reason, the flexible semi-finished product cannot be freely positioned without tension and fixing.

Furthermore, the mesh size of the other heating textile with yellow grid (Fig. 2b) is not big enough for concrete to flow through it smoothly. Hence, a carbon roving, fixed on a glass fibre grid (GFG), is not available on the marked now. So, an in-house development was needed, which has to ensure the reinforcement and the heating function. The reinforcement was implemented by glass fibre textiles and the heating function by carbon fibre roving.

The company solidian GmbH has a GFG for plane elements: a rigid GRID Q87/87-AAE-21 and for curved elements SITGrid200. Possible alternatives are GFG AR 184, AR 777 and AR 780 from Dr. Günther Kast GmbH & Co. Technische Gewebe, Spezial Fasererzeugnisse KG.

Carbon Fibre Rovings

A variety of carbon rovings were tested for the application of the heating wire. These are characterized by their high electrical conductivity and negative temperature coefficient (NTC). Therefore, a fast heating up to the target temperature is possible, because in contrast to conventional metallic heating wires, the resistance decreases with increasing temperature and the power consumption increases (Fig. 3).

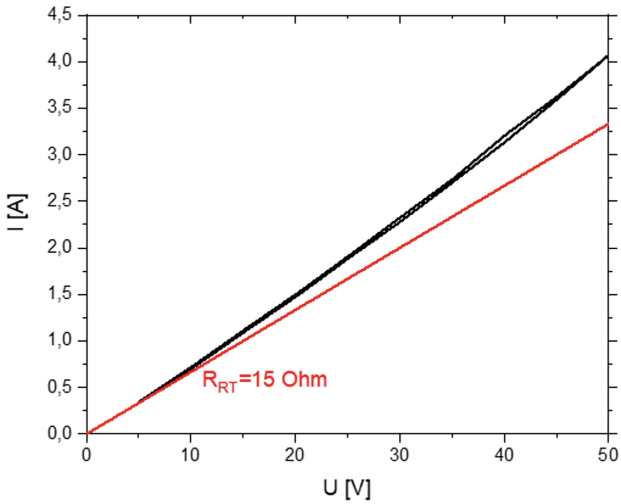

Fig. 3. U-I characteristic of a carbon roving (black) compared to constant ohmic resistance behaviour (red).

The carbon rovings investigated in the project are listed in Table 1, including their characteristic resistance (R_c). The resistance values were determined by using a multimeter.

Table 1. Selected roving types and measurements.

Roving type	Linear density [tex]	Spec. Resistance R_c [Ohm/m]
Toho Tenax HTA40 E13	400	72.1
Tenax	800	34
R + G Sigrafil C30 50k 3300 tex	3300	9.2
Zoltek 50K PX35 Charge 2	3710	9.1
Zoltek 50K PX35 Charge 1	3710	8.7
Bacuplast	3500	8

A carbon heater must be designed to provide the desired surface heating. Factors include the operating voltage, the maximum power of the elements, the heating surface, and the roving length. This results in the required specific resistance of the roving, which can be selected for production according to Table 1.

Concrete

For this study, Steinbeis Research Centre BetoTex developed a special concrete mixture for casting, as a self-compacting mixture matched to specific heating systems (Table 2). A special mixing procedure was processed, using an Eirich RO5T.

Table 2. List of components for used concrete.

Component
CEM I 52,5 N grey
Silica sand 0–2 mm
Silica sand 0–4 mm
Rock flour
Defoamer
Stabilizer
PCE-Fluxing agent
Water

Formwork

The formwork is an essential part for the production of concrete elements. There are various possibilities to fill a formwork for concrete casting. Gravity is used the most. For a plain CCE, a standing formwork made of wood, acrylic as well as PU was used (Fig. 4).

The surface design of the concrete elements correlates primarily with the structure or quality of the formwork, whereby the component surface corresponds exactly to the formwork surface. In addition to smooth element surfaces, structured component surfaces are also possible with structured PU moulded mats.

Methods for Integration of the GFG with Heating Carbon Roving

The GFG, which has been defined as the preferred variant, can be used in both plane and curved formwork. In the case of single curve, the GFG adapts to the given contour without any problems. For double-curved or 3D surfaces, a modification of the GFG is necessary [3]. For example, cuts or segmentations have to be made at certain points. The GFG can then only be used for these adapted contours.

The integration depth of the GFG is decisive for the position of the heating structure. Various solutions were investigated, one GFG-layer was used. Besides fixing to the formwork by means of adhesives, screws and hold-downs to prevent floating, FriPOX spacers (HPF GmbH & Co. KG) were used (Fig. 5 [2]). These have been adapted to the specific requirements of the GFG and can be stacked on top of each other to enable the depth of integration at any point. The number of spacers depends on the integration depth, size, and stiffness of the GFG.

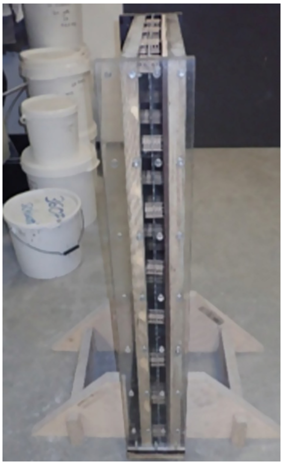

Fig. 4. Formwork variant for plane carbon concrete elements: self-construction of an upright formwork made of wood with transparent side made of acrylic.

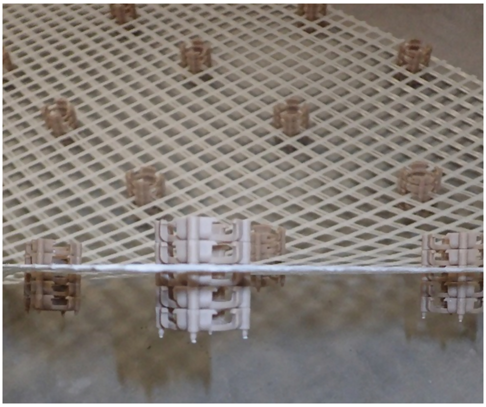

Fig. 5. Spacer FriPOX and GFG.

2.2 Sample Preparation

The manufacturing process of the carbon heating elements is divided into the following work steps:

1) preparation of the functional textiles,
2) preparation of formwork,
3) integration of functional textile in formwork,
4) casting technology,
5) curing time,
6) dry heating.

An essential work step is the preparation of the functional textiles [5]. First, the GFG is cut to size and the carbon roving is applied to the reinforcement textile in a meandering pattern and fixed in place using hot glue. When laying the roving, a minimum distance of approx. 2 cm from each other and from the edge must be ensured in order to avoid voltage bridges and, thus, hotspots. Then the roving ends are contacted by means of crimping and the sensor is positioned in the middle of the GFG. The result is shown in Fig. 6.

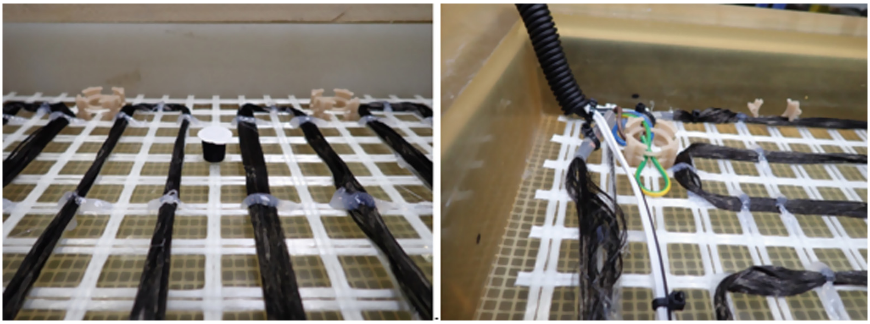

Fig. 6. Prepared functional textile: GFG and carbon roving.

Furthermore, the integration elements (GFG, carbon roving, force introduction elements “FIE” [2–4], positioning aids, sensors, contacting and wire routing) are prepared accordingly and positioned in the formwork (Fig. 7). Depending on the design, the elements are produced lying or standing with the self-compacting concrete mix in the concrete casting process [8].

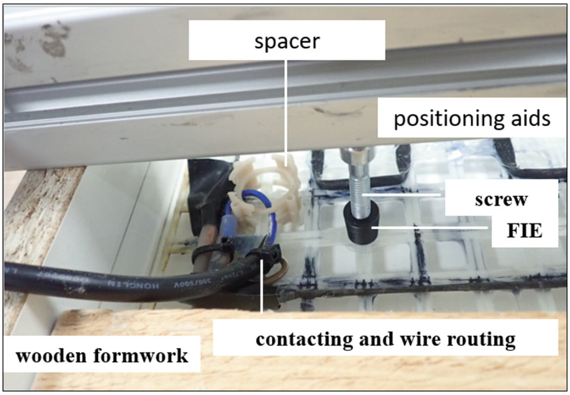

Fig. 7. Positioning of the components in the horizontal formwork.

After a curing time of 1 to max. 3 days, the elements are demoulded and stored at 20 °C and at approx. 40% humidity for 14 days from the day of production. The CCE are then gently dried for at least another 14 days. For this purpose, the temperature is increased daily by 3 to 5 K in order to achieve gentle drying of the concrete matrix. If heating takes place too early or too quickly, water vapour bubbles form inside, which can lead to cracks or other damage of the components.

2.3 Test Set-Up

Strength

The 4-point bending tensile strength based on DIN EN 12390-5 was determined on the manufactured samples. The test is carried out on the Zwick/Roell Z250 with a load frame of 10 kN and samples measuring 500 × 106 × 20 mm^3 (length × width × height). The support width (L) is 450 mm and the support distance (L/3) 150 mm (Fig. 8).

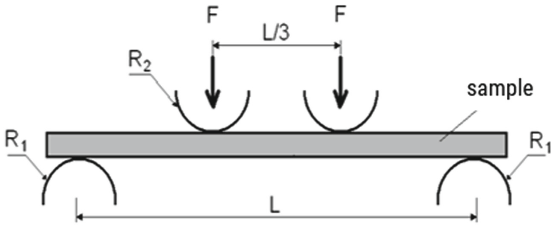

Fig. 8. Schematic representation of the 4-point bending test (force F, support width L, support radius R_1, impactor radius R_2).

Heat-Up Process

The CCEs are set up vertically at room temperature and heated up slowly with a gradual increase in power in order to avoid concrete damage [6] due to thermal stresses and a sudden escape of residual moisture (Fig. 9).

A standard heat-up procedure is developed as a template for the control programme of the heating elements to avoid damage of the concrete [7]. The increase in temperature depends on the plate thickness (Fig. 9) and amounts to 3–5 K/d. The maximum plate temperature is 90 °C.

In addition, this provided insights into the power design for the desired target temperatures and heating times.

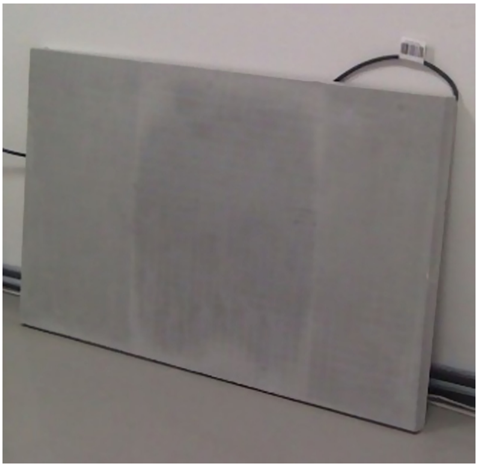

Fig. 9. CCE with grey concrete mix 100 cm × 60 cm × 3 cm.

3 Results and Discussion

3.1 Influence of the Fibre-reinforcement on Concrete Strength

Figure 10 shows the distribution scheme of 4-point bending (DIN EN 12390-5) of differently orientated reinforced concrete samples.

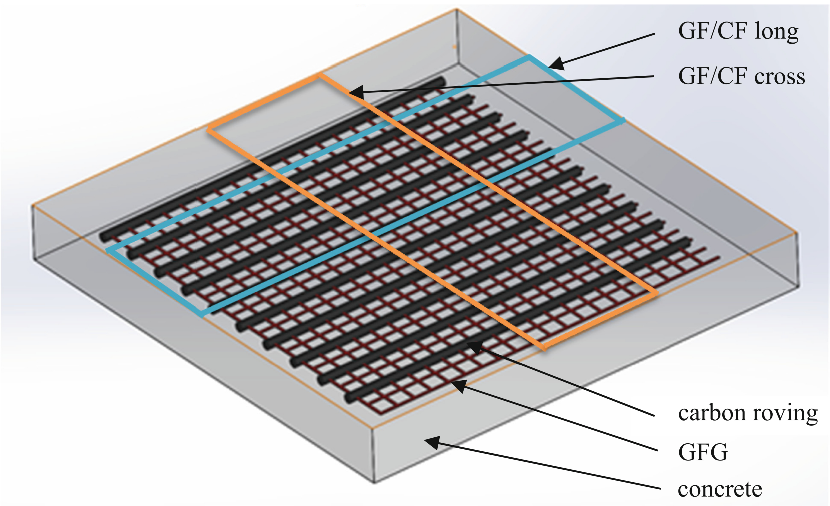

Fig. 10. Fibre distribution scheme of the 4-point bending test samples.

With regard to the 4-point bending strength f_{ct} of the panels, the GFG results in a strength increase of 57% compared to the unreinforced concrete. In the case of carbon

Table 3. Results of the 4-point bending test DIN EN 12390–5.

Sample	f_{ct} [MPa]	Standard deviation
Concrete	7,57	0,45
Concrete + GF	11,87	1,19
Concrete + GF/CF cross	8,14	1,34
Concrete + GF/CF long	10,97	0,70

roving, only a very slight increase in the maximum strength in the cross direction could be demonstrated compared to samples without GFG and carbon roving. The unimpregnated roving cannot absorb forces transverse to the fibre and acts as a failure point.

However, the strength in the long direction of the carbon roving showed nearly the same compared to the GFG reinforcement. This can be attributed to the lack of impregnation of the roving and the resulting lack of bonding between fibre and matrix (see Figure 10 and Table 3). Thus, the carbon heating roving reduces the effectiveness of the GFG, which must be taken into account when designing the panels in terms of strength.

Nevertheless, since the carbon heating plates are not exposed to large forces during use, the strengths achieved when using the carbon roving are still sufficient for practical use.

3.2 Heat-Up Properties

The heating process of a CCE is shown as a thermographic image in Fig. 11. The heat signature of the individual heating roving is clearly visible on the surface.

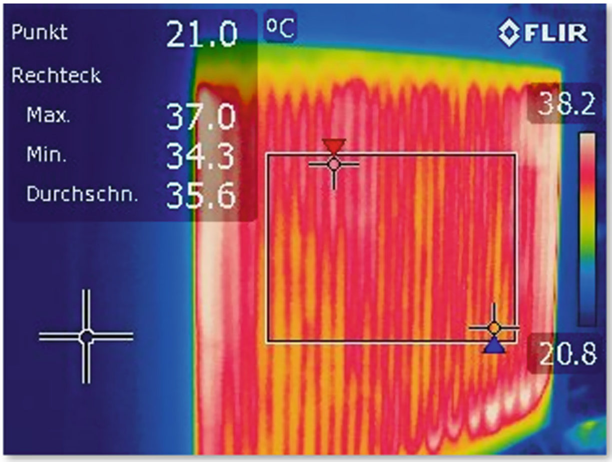

Fig. 11. Thermographic image of the heating process of a CCE.

Due to the low resistance of the carbon and the good heat transfer inside the component, surface temperatures of over 100 °C can be achieved within one hour with a power density of about 1 kW/m^2 with the CCE.

Figure 12 shows the temperature performance of the carbon heater in comparison to the marble heater, in each case at maximum power.

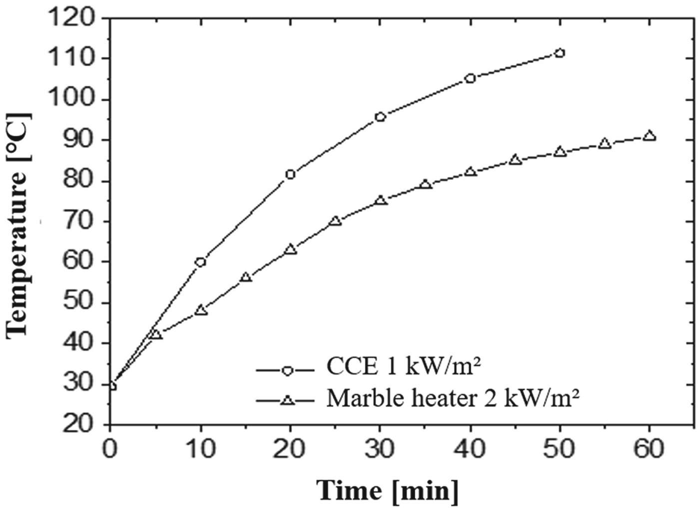

Fig. 12. Temperature curve of the surface of carbon heater at maximum output compared to the natural stone heater.

Compared to conventional natural stone heating with 2 kW/m^2, higher temperatures can be achieved in fewer time and with the half of the area output by the CCE. This clearly underlines the great potential of carbon heating in terms of energy efficiency and heating conduction.

3.3 Energy Consumption

The results of the energy consumption measurement of the CCE are compared with those of a conventional marble heating panel (Fig. 13 and Fig. 14). The measurements show that the carbon heating plate reaches a higher maximum temperature about three times faster than the marble plate. This results in lower energy consumption during the heating phase. For heating up the CCE, the costs are 50% less compared to the marble plate. Due to the comparable heat storage capacity, the cooling and reheating times of the two heating plates are analogous at about 45 min each.

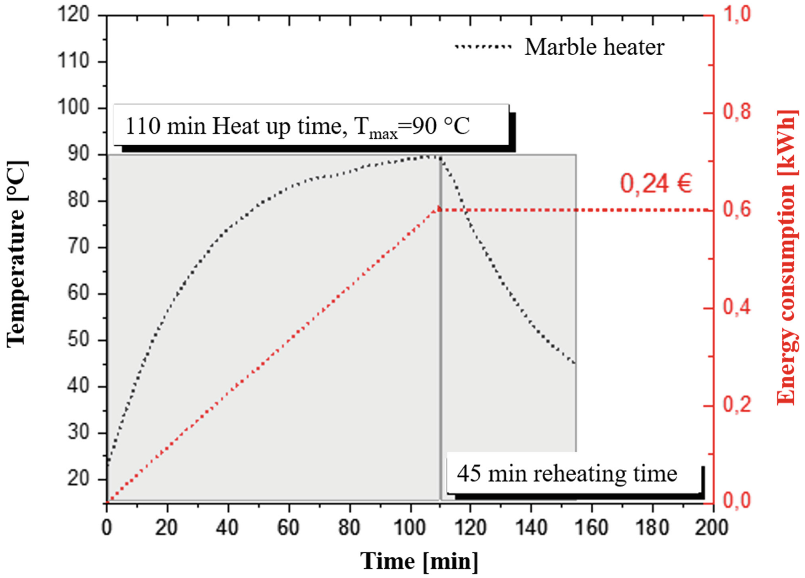

Fig. 13. Temperature curve and energy consumption of a 50 × 40 × 2 cm^3 conventional marble plate.

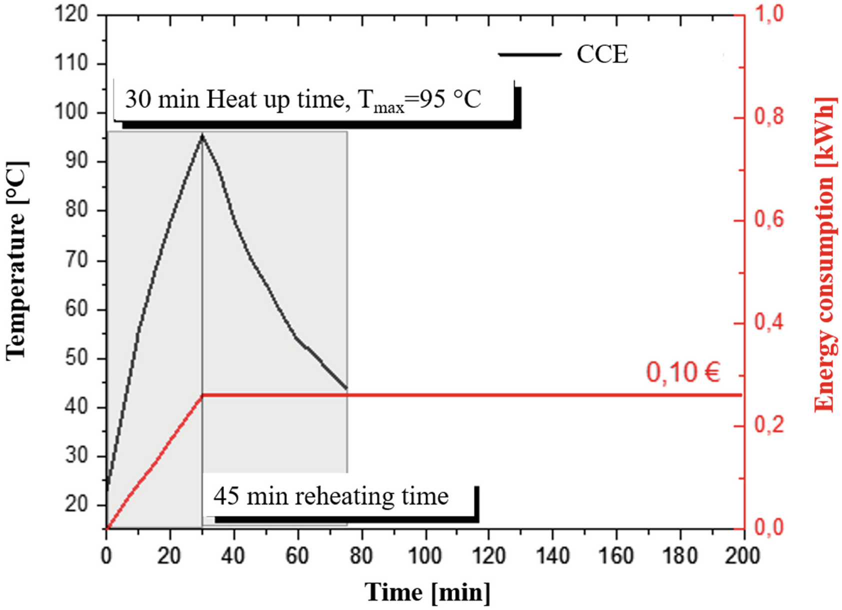

Fig. 14. Temperature curve and energy consumption of a 50 × 40 × 2 cm^3 CCE plate.

3.4 Reference Object

The reference object of the carbon heating elements is designed as a column to show the potential of carbon heating as a design element with integrated heating in indoor and outdoor areas. These curved elements are made using a cardboard formwork and a polystyrene core (Fig. 15). When demoulding the concrete column, the cardboard formwork is first destroyed, removed, and recycled. The formwork of the polystyrene core is then removed by pulling it out at prepared positions in order to ensure that the core could be reused.

Fig. 15. Formwork variant for curved CCE: Tubbox formwork tube from Max Frank GmbH with polystyrene core.

Over a period of two weeks, the heating process described above is used to slowly heat at 5 K/d to the target temperature of 60 °C (limited contact temperature). This is done comfortably via the temperature control of Appelt & Appelt GbR, enclosed in the water-blasted and welded cover plate (Fig. 16). Semi-circular cavities are provided in the lower part of the column so that the room air can circulate through the interior and the cover plate. This creates convection heat in the room in addition to radiation heat.

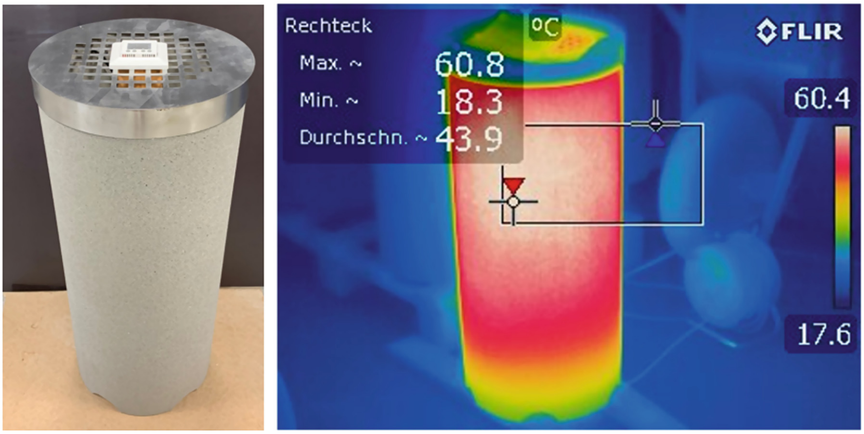

Fig. 16. Reference object "column" (left) and thermographic image of heated state (right).

4 Conclusions

This scientific work showed the technical implementation of an energy-efficient reinforcement-integrated carbon concrete heating system, which uses a functional textile made of glass and carbon fibres to generate the IR radiation. The textile also serves as reinforcement and, thus, strengthens the load-bearing behaviour. Lasting functionality was comprehensively investigated through, both, the material behaviour and the operating characteristics of the system as a function of the ambient conditions and the heating regime. With 50% of the applied power, compared to marble heating, a higher temperature (95 °C) can be achieved in a shorter time ($<$30%).

The two product variants, with plane and curved surfaces, were successfully implemented and a reference object was produced. They can be used for heating interiors as well as outdoor areas.

The production of the elements, in particular the preparation of the reinforcement textiles with the carbon heating roving, was done manually and was consequently very time-consuming. Further research is required to partially automate the process or at least increase the effectiveness. However, the great potential of carbon concrete heating elements could be clearly demonstrated.

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