Energy storing carbon concrete heating element with phase change material for integration into smart home systems

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Abstract. Securing and storing energy is one of the most important issues for the future of the global construction industry. Numerous technological innovations are being developed to meet this challenge. Every person has an individual consumption for private or commercial use. For example, a lot of energy is needed to build and operate a building. For this, it is necessary to develop technologies to secure and store energy in some way. This paper reports on the path to a new energy-storing carbon concrete heating element, the required flowable concrete mixture and the influence of the Phase Change Material (PCM) on energy storage, strength and producibility. The manufacturing process is semi-automated and virtual controlled by an online order generator. For example, a special mechanism for contacting the tailored meander-structured carbon roving and the automated messenger for several production steps have been created. All components used in this formation are suitable for Smart Home applications in modern houses, which can be implemented completely or as an isolated application with appropriate digital interface. Combined with presence recognition and artificial intelligence for lifestyle habits, these houses will be able to efficiently distribute rare and precious energy to where it is needed.

1 Introduction

In private households, over 90 % of final energy is used for heating applications, predominantly natural gas as the energy source [1]. Due to the current transition to the exclusive use of renewable energies, fewer and fewer power plants and combustion plants will be available in the future. The development of innovative technologies for heat generation and heat storage from electrical energy is therefore absolutely essential.

This paper provides the basis for this challenge. The energy-efficient reinforcement-integrated concrete heating systems consist of a textile fiber reinforcement to increase strength, a carbon fiber roving to generate thermal power through electrical resistance heating and a mineral matrix. The glass fiber grid (GFG) defined as the preferred variant can be used in both flat and curved formwork. In the case of a single curvature, the GFG follows the specified contour without any problems. For double-curved and/or 3D surfaces, a modification of the GFG is necessary. Cuts or segmentations must be made at certain points. The GFG can then only be used for these adapted contours.

The energy requirement of these infrared heaters or partial storage heaters made of concrete with carbon fibers is significantly lower than that of the electric natural stone heaters established on the market [2]. In addition, unlike natural stone heaters, the use of low-polymer concrete matrix materials also allows curved versions of the heating elements. In this way, they can be designed according to customer requirements.

The primary application is energy refurbishment with wall/ceiling heating elements and home storage systems that are fed from self-sufficient, renewable energy sources. In such systems, the modules can either be operated directly or store energy as a buffer in the event of a temporary energy surplus. The storage effect is to be investigated and increased using integrated phase change materials (PCM, latent heat storage). This means that renewable energy can be stored efficiently (smartly) according to demand and then used for heating.

The paper reports on the digitalization of the design and manufacturing technology as well as the automated installation and insulation of the heating carbon roving, resulting in an economical process chain for individually manufactured concrete heating elements. In addition, several sensor signals must be integrated into a wireless control system to regulate the heating elements so that the modules can be used in modern building technology concepts (smart homes). Surplus photovoltaic output can be used to heat the modules. This paper also presents a calculation for the energy storage system.

2 Materials and Methods

2.1 Components for Carbon Heating Elements

2.1.1 Concrete Variations

An elementary component of the heating plates is the concrete (special definition mortar), which ensures

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dimensional stability, transfers the heat and encases and insulates the heating roving. There are basically two shades of color, each determined by the cement used. The first mixture is a light gray, based on the gray "CEM II/A-LL 42.5 N", while the second mixture is almost white, due to the white cement "CEM II/A-LL 42.5 R".

On this basis, a wide variety of color shades can now be applied in powder form according to individual customer requirements. The concretes with white cement reproduce the colors directly, the gray cement darkens the shade slightly (see Fig. 1).

Fig. 1. Variety of colors in concrete plates

Both the gray and the white concrete mix were developed as self-compacting concrete. X0 was specified as the exposure class. Table 1 contains the qualitative and quantitative compositions of gray and white concrete. Both mixtures contain a water/cement ratio of 0.60.

Table 1. Composition of gray and white concrete

Component	White	Gray
CEM II/A-LL 42.5 N	-	500 kg/m³
CEM II/A-LL 42.5 R	500 kg/m³	-
Limestone powder	150 kg/m³	
Quartz sand 0-4 mm	1300 kg/m³	
Superplasticizer	2.2 kg/m³	
w/c	0.6	

2.1.2 Fiber Reinforcement

The purpose of the fiber reinforcement is to hold the carbon roving in the correct position and to stabilize the concrete in the event of thermal stresses. A large selection of fibers are available. Ultimately, practicality and price are the deciding factors. Vertex G 120 is utilized in the application, a glass fiber thermoset with a grid spacing of approx. 40 mm and a basis weight of 145 g/m².

2.1.3 Carbon Heating

As in previous publications with carbon heating [2, 3], the roving from TENAX was used. This can be formed without any problems and does not lose any strength during processing. The exact designation is TENAX-E STS40 and the properties are 48 K and 3200 tex.

2.1.4 Phase Change Material (PCM)

It is already established that phase change materials can be used. The combination of carbon heating with concrete is innovative and under research. PCMs are regarded as latent heat accumulators. This property occurs when they change phase from solid to liquid, in which case heat continues to be stored without the temperature of the material changing. Once capacity is reached, the temperature of the material continues to rise. A schematic is shown in Fig. 2 [4]. This process takes place in reverse in the same way when the stored energy is released. The temperature is maintained at the set plateau until the phase change is complete.

The used material is "Advanced PCM-Granulat" with a melting point 28 °C (core plateau temperature). It consists of a rubber carrier material and the PCM itself. It is supplied as loose granules and can thus be applied to the concrete structure.

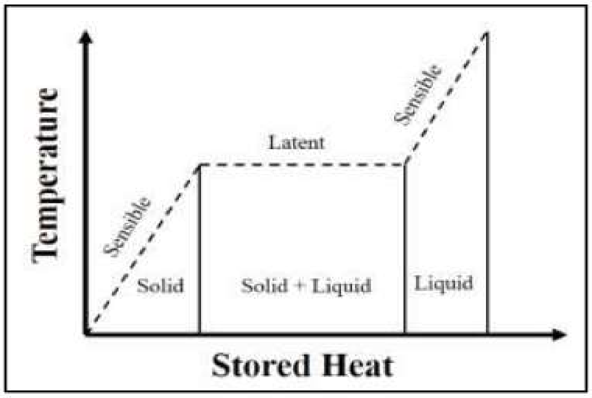

Fig. 2. Properties of latent behavior of PCM energy storage [4]

2.1.5 Force Application

Force application elements are available in various shapes and materials. They are usually adapted to the surrounding material. Thermal conductivity was a high priority for this application, as thermal energy was not to be transferred via the fixings into the wall. The second requirement is the short installation height due to the thin structure of the concrete plate. Therefore, instead of metal, a plastic insert was used, the "K in K Typ 173 M8x14" by the Böllhoff company. It consists of a glass-filled polyamide, with an M8 internal thread and a coarse external thread (hub diameter is 13.5 mm). The total length is 14 mm and is closed at the bottom (see **Fig. *3***).

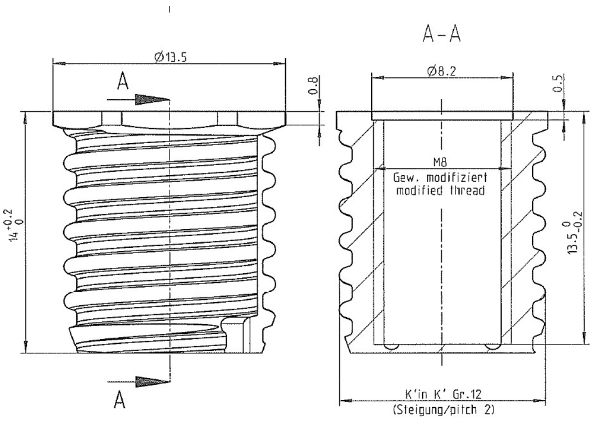

Fig. 3. Extract of the drawing from the Böllhoff data sheet "K in K Typ 173 M8x14"

2.2 Sample Preparation

2.2.1 Preparation of Test Specimens Concrete Strength

All the necessary components were combined in an "Eirich R05T" mixer. To assess the flow properties and workability, the mixtures were tested according to "Hägermann" [2, 5].

For mechanical characterization of strength, the various mixtures were placed in flat wood molds, 300 x 300 mm². The plates produced were 20 mm high and were stored and cured in a climatic chamber for 28 days.

2.2.2 Preparation of Test Specimens Concrete Compressive Strength

The same procedure as for the production of the flexural strength (2.2.1) was used here. For mechanical characterization of compressive strength, the different mixtures were placed in plastic cubes of 150 mm edge length, stored and cured in a climatic chamber for 28 days.

2.2.3 Preparation of Test Specimens Force Application

Square plates with an edge length of 375 mm and a height of 50 mm were cast to produce the test specimens. To prevent the Böllhoff inserts (chapter 2.1.5) from sliding directly on the surface, they were fixed to the bottom of the mold with a screw. They were then cast with the gray concrete mix (chapter 2.1.1) (see Fig. 4), stored and cured in a climatic chamber for 28 days.

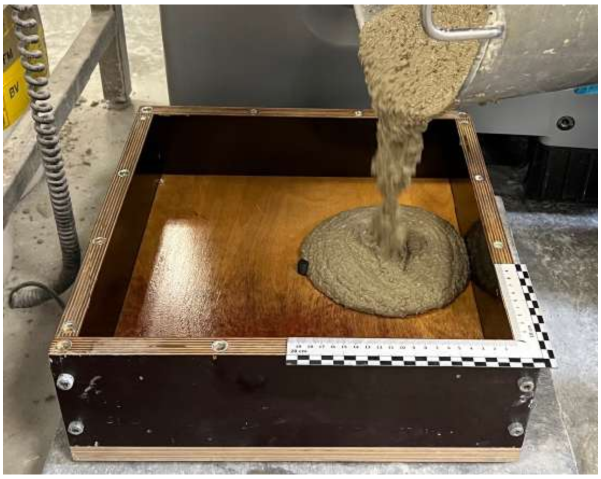

Fig. 4. Casting the Force Application Elements

2.2.4 Digital Configuration/Production Planning

An online order generator (for research purposes only at the moment) has been developed that allows potential customers to select and order their desired heating plate. In addition to the dimensions and power, the color and a possible curvature can also be selected. After a successful order, the online order generator sends a confirmation to the company and three production data sheets in PDF format to the embroidery company, the contact specialist and the concrete manufacturer. This means that each department knows exactly what needs to be done.

2.2.5 Carbon Heating Manufacturing

Tailored Fiber Placement (TFP) is used to place the carbon roving onto a thin thermoplastic fleece. Carbon fleece and fiber reinforcement are bonded together by a hot air melting process (see Fig. 5).

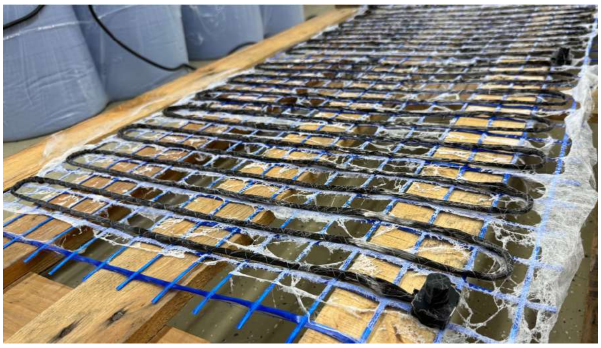

Fig. 5. Carbon roving molten onto fiber reinforcement

The next step is semi-automated contacting (robot-assisted screwing of contacts with a vacuum gripper) of the carbon roving, sensor application, and wiring of all necessary fixings.

Finally, the mold is prepared with release agent, force application, spacer and the carbon heating. The PCM's are apportioned during the casting of the concrete (see **Fig. *6***).

Fig. 6. Casting process with mold, carbon roving, textile, PCM, sensor and concrete

2.3 Test Set-Up

2.3.1 Flexural Strength

The 4-point flexural tensile strength based on DIN EN 12390-5 [6] was determined on 30 manufactured samples, cut from the plates, see chapter 2.2.1. As described in [3], the 4-point flexural test was selected to determine loading characteristics because, unlike the 3-point flexural test, there is a constant bending moment between the upper force application points. The support width (L) is 135 mm and the support distance (L/3) 45 mm (Fig. 7).

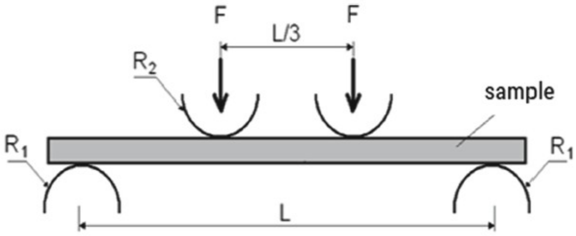

Fig. 7. Schematic representation of the 4-point flexural test (force F, support width L, support radius R1, impactor radius R2). [3]

In this way, the material parameters are determined more realistically, especially for plate-shaped samples, and these are less influenced by possible inhomogeneities in the sample [7, 8, 9, 10].

The test is carried out on the Toni Technik TONINORM SERIE 2000 with a load frame of 20 kN and samples measuring 160 × 45 × 20 mm³ (length × width × height)(see Fig. 8).

Fig. 8. Sample during 4-point flexural test

2.3.2 Compressive Strength

Compressive strength is one of the most important parameters for characterizing the mechanical properties of concrete [3]. Three specimens were tested (see 2.2.2). The compressive strength was determined in accordance with DIN EN 12390-3 [11] on the Toni Technik ToniPACT II (see **Fig. *9***).

Fig. 9. Sample during compressive test

2.3.3 Force Application

To quantify the process of force application, a classical concrete test according to DIN EN 1992-4 [12] was applied. This pull-out test used a Zwick/Roell Z250 testing device with five samples. A circular hold-down device is mounted by two flat bars and an adapter is fitted between the load cell and the threaded insert in the concrete plate (see Fig. 10). The force is then applied and measured with displacement at a constant test speed of 5 mm/min.

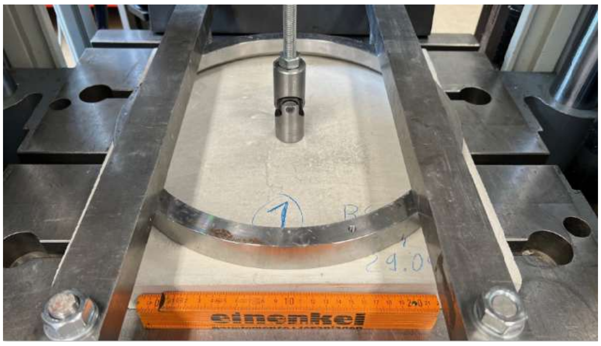

Fig. 10. Sample during pull-out test

2.3.4 Calculation of Heat Energy Storage by PCM

The theoretical assumption that an electrical storage system achieves a storage capacity Cs of 0.9 kWh/m² is the basis of the calculation for the thermal energy storage system made of concrete and PCM. To vary the capacity, the plate thickness (from 20 to 60 mm) and the PCM content are changed. The constants for the calculation are shown in Table 2.
Here are the formulas used:

Volumetric heat capacity of concrete:

$$v = c * \rho \ [Wh/(m^3 \times K)] \quad (1)$$

Specific energy storage concrete plate (thickness d [m]):

$$Es = v * d \ [Wh/(m^2 \times K)] \quad (2)$$

Weight per unit area PCM, ms [g/m²].

Energy per square meter PCM:

$$Em = e * ms \ [Wh/m^2] \quad (3)$$

Temperature range required for energy storage:

$$\Delta T = (Cs - Em) / Es \ [K] \quad (4)$$

Table 2. *Constants for the Calculation*

Name	Value	Unit
Specific heat capacity of concrete **c**	1	kJ/(kg×K)
Density of Concrete ***ρ***	2100	kg/m³
Storage Capacity (Specific Energy) PCM **e**	240	kJ/kg

2.3.5 Heat-Up and Cool-Down Process

In order to clearly demonstrate the effect of the PCM in the concrete during the cool-down process, two concrete plates with the same size and weight were produced. One plate consists only of concrete, the other plate has an additional PCM surface weight of 2222 g/m² (200 g on 300 x 300 x 25 mm³). Both plates were stored and dried in a climatic chamber for 28 days.

Both plates were stored overnight at 40 °C and then placed next to each other in the climatic chamber at 17 °C (see **Fig. *11***).

Fig. 11. Both plates in the climatic chamber

An infrared camera records the surface temperatures of both panels during the cool-down process (see Fig. 12).

Fig. 12. Experimental setup climatic chamber

2.3.6 Smart Home Integration

The Smart Home System applied in this case consists of an energy source, energy storage and an intelligent interface that distributes the energy flow. Two solar panels (balcony power station), the carbon heating plate and the energy controllers from Shelly (“1PM Pro” and “Plus 1PM”) were used here (see **Fig. *13*** for example).

Fig. 13. Connection of the Shelly Pro 1PM to Solar Panels

3 Results and Discussion

3.1 Characterization of concrete

The 4-point flexural tests and compression tests were carried out on gray and white concrete. The result of the 4-point flexural tensile strength is shown in Fig. 14 and the compressive strength values are presented in Fig. 15.

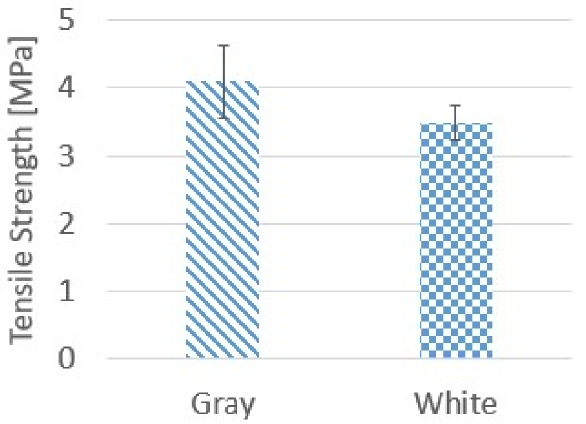

Fig. 14. 4-point flexural tensile strength results for concrete mixes

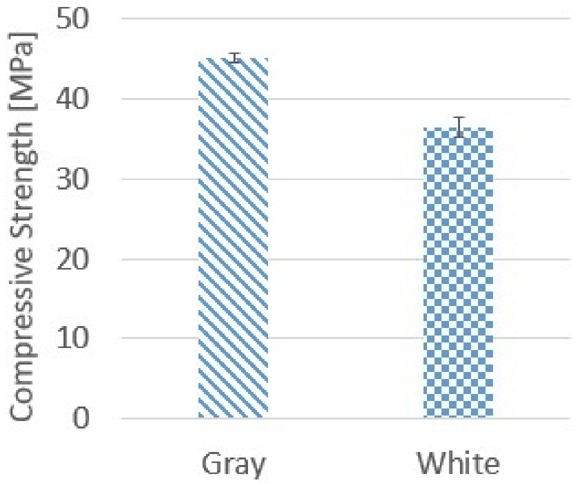

Fig. 15. Compressive strength results for concrete mixes

As shown in the two diagrams, the gray concrete mixture is characterized by significantly higher strengths (flexural tensile strength 4.1 MPa (~15 %) and compressive strength 45 MPa (~20 %) than the white mixture. The gray mixture was used as the basis for further investigations.

3.2 Force Application Results

A primary focus of the development was the attachment of the heating elements to buildings. In addition to the high-force transmission construction, the focus is on the thermal insulation effect on the structure. According to the test specifications of DIN EN 1992-4, in addition to the values, the fractional elements are also included in the classification and evaluation. For the gray mixture with the Böllhoff M8 inserts, five samples were tested.

Corresponding break-out concrete blocks (see **Fig.** ***18***) are the result of the pull-out test (see **Fig.** ***16***). The shape and size can vary, but the entire insert must be embedded in the surrounding material as a cone-shaped concrete body (see **Fig.** ***17***).

The average pull-out force of the M8 threaded inserts is 2545 N (with a standard deviation of 175.4). The insert always remained intact, no damage to the thread was visible.

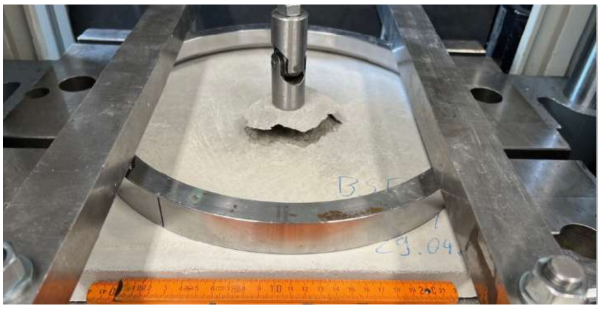

Fig. 16. Completed Pull-out test

Fig. 17. Cone-shaped concrete body with thread adapter

Fig. 18. Overview results pull-out test

According to the curve shape of the individual samples and the fracture pattern, the scatter is low and therefore the reproducibility is high.

3.3 Functional analysis

3.3.1 Calculation of Heat Energy Storage by PCM

Three scenarios were calculated to achieve the required energy storage of 0.9 kWh/m². Firstly, the process without the addition of PCM, secondly, all panels have the same PCM content and thirdly, the PCM content increases with the panel thickness. There are two graphs for each calculation: the resulting weight per unit area of the plate and the temperature increase required to achieve the energy storage (see **Fig.** ***19***).

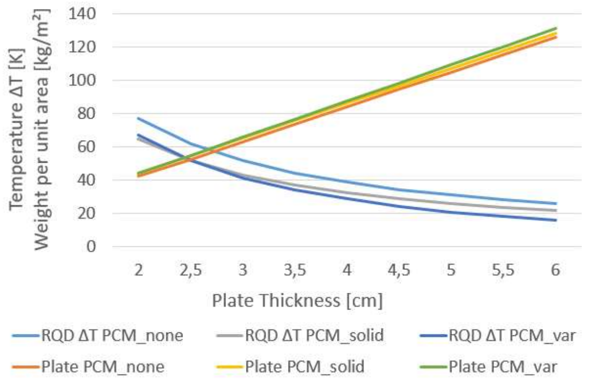

Fig. 19. Required temperature increase for storage capacity and weight per unit area of the plates

Based on the curves, it can be determined that as the plate thickness increases, the resulting weight per unit area increases linearly.

The required temperature difference decreases with increasing plate thickness. It decreases even more as the PCM content increases. This function decreases proportionally and saturates as it progresses. The variable proportion of PCM causes a jump downwards compared to the curve without PCM. It can be seen that the amount of PCM significantly reduces the required temperature difference.

3.3.2 Heat-Up and Cool-Down Process

This test compares the cooling of two concrete plates with and without PCM next to each other. The result can be seen in the cool-down curve (see **Fig. *20***).

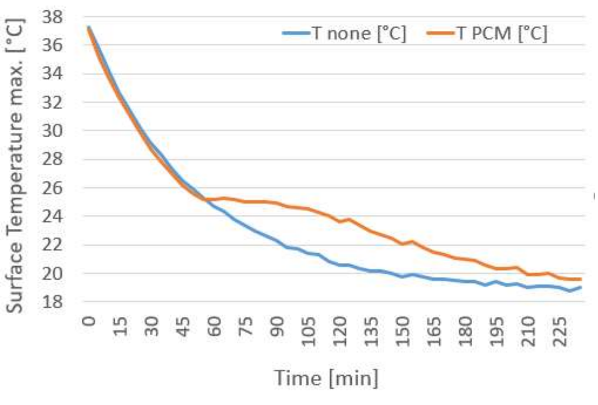

Fig. 20. Cool-down curve

Both plates initially cool down together at the same rate. When the phase transition of the PCM is reached (approx. at 25 °C after 50 minutes), the temperature of the PCM plate remains on a plateau for almost 60 minutes before it sinks. The concrete plate without PCM continues to cool down during this time. After four hours, both plates have cooled down similarly.

3.3.3 Smart Home Application

As soon as energy is provided by the solar panel, the Shelly controllers query the demand of the carbon heating plate. This is fully charged to the desired capacity (query via the set core temperature). If there is still energy left over, it is fed into the domestic power grid to the electrical consumers.

The entire energy flow is recorded and can be monitored and downloaded online (see Fig. 21).

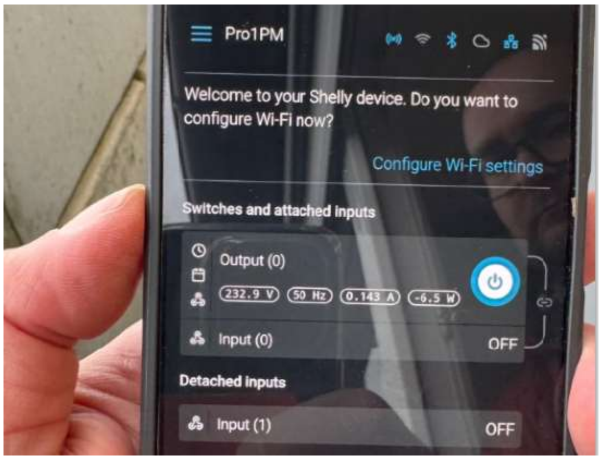

Fig. 21. Online Status of the Solar Panels with Shelly

This system can run independently (isolated application) or be integrated into an existing Smart Home System (Google, Apple, Amazon, Bosch…).

4 Conclusion

In summary, basic scientific questions about the function of heating elements with carbon fibers in concrete module construction are clarified. Based on the results of the extensive tests, the enormous potential of carbon concrete heating plates as thermal energy storage for private and commercial buildings in the modern construction industry has been demonstrated. PCM has been proven to increase storage capacity. The integration of the plates into smart home systems by means of intelligent interfaces or as a stand-alone solution was shown. Semi-automated production further reduces the production effort, time and costs. This paper therefore represents a significant contribution to the energy transition, as (self-generated) electrical energy can be stored as heat. The dependence on fossil resources is lowered and the emission of climate-damaging CO_2 is reduced.

Acknowledgements

The authors would like to thank the following sponsors for their financial support «BMBF - Bundesministerium für Bildung und Forschung» (Federal Ministry of Education and Research) within the initiative «WIR! Wandel durch Innovation in der Region - SmartERZ» for the project „CoCoHeat", funding indicator 03WIR1414A. Many thanks also to our industry partners predEVOLUTION technologies GmbH and Betonstein Flöha GmbH.

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