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Carbon fibre reinforced cement-based composites as smart floor heating materials

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ABSTRACT

A systematic development of an electrically heatable cement-based composite, prepared by admixing a few volume percent of chopped carbon fibres without a need of adding further heating elements, is reported. The optimal volume content of carbon fibres is determined to range from 1 to 2 volume percent, if 3 mm long and 7 μm thick carbon fibres are being used. By applying an electrical current to the composite material, a temperature rise suitable for heating rooms and walls can be induced. Mechanical tests show that the flexural strength of carbon fibre reinforced composite is not decreasing during electrical heating at 60 °C for 4 weeks. For electrical heating purposes, graphite or silver is found to be the best electrode material.

1. Introduction

Screed is an indispensable part of the modern interior design for height adjustment and has to withstand different static and dynamic loads. Common floor screeds are cement-based composites consisting of Portland cement, sand and aggregates, and in most cases they are fabricated as a free floating structure. Heating elements are placed in floor heating screeds between the screed plate and the underlying insulation. To be able to withstand shrinkage and temperature stresses, fibre reinforcement is often added to the composite mixture. If fibre reinforcement would be included as admixture of electrically conductive fibres, in-situ electrical heating of the screed would be feasible without installing heating elements below the floor plate, assuming that the admixed conductive fibres can provide good conductivity of the composite on the one hand and provide high flexural strength on the other hand. Previous research on carbon fibre reinforced mortar and concrete has shown that adding 0.5 to 3.0 percent by volume of chopped carbon fibres can increase strength [1–5] and decrease electrical resistance significantly [6–9]. Thus, electrical conductivity increases by several orders of magnitude upon adding a few volume percent of carbon fibres into the concrete or mortar [7–9]. Further studies have shown that it is possible to use carbon fibre reinforced concrete to deice roads [10] or to heat buildings [11,12] by applying a low voltage generated electrical current (e.g. up to 12 V). Electrical conductivity is provided by carbon fibre contact bridges granting high electrical conductivity over distances exceeding the length of single fibres [8], in comparison to concrete without carbon fibre reinforcement. It has been shown, that carbon fibre admixture does not influence thermal conductivity, which would have negative effects on thermal insulation of floor constructions [13].

The aim of this work is to investigate the electrical properties of a chopped carbon fibre reinforced cement-based composite in order to determine the optimal carbon fibre aspect ratio and volume content, and to report on influences of the electrical resistance heating on mechanical properties of the composite. Furthermore different embedded electrode materials are tested in order to report on electrode corrosion during electrical resistance heating. Since electrical heating is more expensive than conventional heating with gas or fuel oil, developing smart heating systems for saving energy is essential to reduce costs. This concept is implemented, for instance, in heating only selected areas of the floor heating screed in order to save energy for those areas where heating is typically not required (e.g. areas where pieces of furniture like cabinets or shelves are placed). Accordingly, a

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prototypic modular floor heating plate is presented, which allows individual heating of different areas by using a grid of embedded electrodes.

2. Material and methods

2.1. Materials and specimen preparation

The properties of the carbon fibres used in the studies and the material suppliers are summarized in Table 1. Portland cement (Type I 52.5 R) was used throughout with sand (d_{50} = 0.2 mm), silica fume (Elkem Microsil) and water reducing agent (BASF Glenium ACE 430). The composition of the cement mixture is shown in Table 2. The admixture of silica fume (d_{50} = 0.4 μm) and finely ground cement (d_{50} = 8 μm) is added to improve the fibre dispersion in the cement paste [14]. Water cement ratio was 0.35 (including water reducing agent).

Mixing all solid components, apart from carbon fibres, was carried out in a solid state. Water and water reducing agent were added and mixed in a rotary mixer at 400 RPM until a homogeneous mixture was achieved. Finally, the carbon fibres were added and the mixture was stirred again at 50 RPM until the fibres became uniformly dispersed. A batch size was 40 g (three specimens) for conductivity measurements, 80 g (six specimens) for 3-point-bending tests and 200 g for the plate heating test. The cement mixture was poured into Teflon molds with dimensions of 60 × 13 × 6 mm for each specimen for conductivity and flexural strength measurements and 100 × 100 × 8 mm for plate heating tests. Subsequent to preparation, the specimens were stored at 100% humidity for 24 h, then transferred for 6 days into a water bath and then kept another 3 weeks at 60% humidity prior to testing or further treatment.

2.2. Conductivity and flexural strength measurement

After 4 weeks of curing time, both ends of the 60 × 13 × 6 mm specimens were sand-polished and electrically contacted by applying silver lacquer. To reduce border effects, 0.5 mm of the specimen surface area was removed by sand polishing. Subsequently the resistance between the most distant specimen ends was measured. For low impedance measurement, a M-4650 CR multimeter and for high impedance measurement, a Metriso 5000 ohmmeter were used. After measuring the overall dimension of the specimen at an accuracy of ±0.01 mm, the specific resistivity ρ can be calculated according to Equation (1):

$$\rho = R * \frac{A}{l} \quad (1)$$

where R is the electrical resistance, A is the cross-sectional area (13 mm width × 6 mm height) and l is the length of the object (60 mm). The specific resistance is determined for at least three specimens, whereupon the average and the standard deviation are calculated. The reciprocal value of the specific resistivity is defined as the electrical conductivity σ of a material. It can be calculated by the Equation (2):

$$\sigma = \frac{1}{\rho} \quad (2)$$

Flexural strength measurements were carried out with a total number of six specimens for each testing series. The testing machine is a Zwick/Roell Zwicki-Line Z0.5 with a 5 kN load cell being attached. The experimental setup is illustrated in Fig. 1. By measuring the maximum force F, the flexural strength fs can be calculated by the following Equation (3):

$$fs = \frac{3}{2} * \frac{F * l}{b * h^2} \quad (3)$$

in which l represents the distance between the supports (50 mm), b is the specimen's width (13 mm) and h is the specimen's height (6 mm). The specimen dimensions are determined employing a caliper gauge prior to the measurement at an accuracy of ±0.01 mm.

For electrical heating purposes and for corrosion experiments, an Elektro-Automatik EA-4036 laboratory power supply was used in a 50 Hz AC mode. Infrared images were recorded by a FLIR i50 thermal imaging system.

Table 1
Properties of carbon fibres used in the studies.

Fibre	Diameter [μm]	Density [g/cm³]	Tensile strength [MPa]	Young's modulus [GPa]	Fibre length [mm]	Supplier
HT C261	7	1.76	3950	230	3	Toho Tenax
HT C261	7	1.76	3950	230	6	Toho Tenax
CF-1 mm	7	1.7–2.0	3500	230	1	Procotex

Table 2
Composition of the cement mixture.

Material	Weight percent	Supplier
Cement Portland Type I	42.5	Schwenk Zement KG
Sand	34.5	–
Silica fume	8.0	Elkem AS
Water	14.0	–
Water reducing agent	1.0	BASF

3. Results and discussion

In conductive fibre reinforced cement-based composites, the properties and structure of non-conductive components, like sand or cement, do not affect the composites' conductivity [7]. The electrical conductivity of the composites depends merely on the volume fraction of carbon fibres, if uniform (in length and diameter) carbon fibres are being used [7]. Compared to concrete (having conductivity between 10^{-5} and 10^{-8} Ω^{-1} cm^{-1}, depending on the moisture content), carbon fibres possess by several orders of magnitude higher electrical conductivity (10^2 Ω^{-1} cm^{-1}) [15]. In the following sections the influence of fibre aspect ratio (defined as the ratio of fibre length to diameter) and volumetric fraction is studied in order to determine the optimal fibre dimensions and volume fraction for developing an in-situ heatable carbon fibre reinforced cement-based composite.

3.1. Fibre aspect ratio

It was shown that the fibre aspect ratio influences electrical conductivity of carbon fibre reinforced cement-based composites by using 1–15 mm long fibres [6]. Since shorter fibres (= lower aspect ratio) provide better workability of the cement paste it is reasonable to determine the optimal fibre length and subsequent

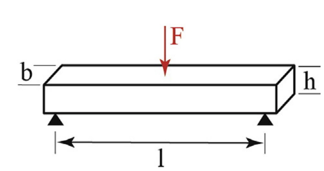

Fig. 1. Sketch of 3-point bending test for flexural strength measurement.