Utilization of waste carbon fibre reinforced polymers in the production of cementitious composites with electrical conductivity function

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Introduction. CFRP (carbon fibre reinforced polymer) composites are widely used in many industrial sectors, such as automotive, aircraft, gas storage vessels and renewable energy industries, mainly due to their excellent strength/weight ratio and good corrosion resistance (Asmatulu et al, 2014). The demand for CF and CFRP was increased to 194 kt by the end of 2022, which represents an annual growth rate of 11.98% concerning 2010 (Danish, 2022). Being so spread, these materials generate significant amounts of waste at the end of their life cycle. Today, there are available solutions for FRP composite materials recycling, covering mechanical recycling, thermal processes (pyrolysis, fluidised bed pyrolysis, micro-waves pyrolysis), solvolysis, chemical recycling or degradation of the matrix by microorganisms; some of the methods more commercially advanced than others, but mainly their economic viability is limited. Additionally, industrial applications using recycled fibres or resins are still rare, although some studies on the practical applications of FRP recyclate already exist. E.g., the influence of partial replacement of sand aggregates by FRP recyclate on the properties of polyester-based mortars was investigated by Castro et al. Results showed the positive effect on mechanical properties of the polymer mortars modified with the FRP recyclate – the authors concluded, that the partial replacement of sand aggregate with FRP waste materials, up to 8% of the total weight content, has an incremental effect on the flexural and compressive strength of the polymer mortars, regardless of the size class of the FRP waste (Castro 2013). Another promising utilization of CFRP recyclate may be in cementitious composites, where the incorporation of the CFRP recyclate can provide added value in the form of increased flexural tensile strength, impact resistance or electrical conductivity. The limited literature available on CFRP waste-modified cementitious composites suggests that CFRP waste can be incorporated into cementitious composites as cement/aggregate replacement or as reinforcing material. E.g. Mastali et al. (2016) reported that the flexural strength of cementitious composite reinforced with 0.25%, 0.75%, and 1.25% waste CFRP pieces increased by 31.20%, 50.94%, and 66.94%, respectively. CFRP recyclate presence in the cementitious composite can also affect its electric conductivity, which can be utilized in many specific applications such as structural health monitoring or heating/deicing concretes. However, the comprehensive literature about the electrical conductivity of CFRP recyclate-reinforced cementitious composites is scarce and results often contradicting. The presented research aims to broaden the knowledge in the field by evaluating the effect of the character and concentration of CFRP recyclate on the mechanical parameters and electrical conductivity of cementitious composites.

Materials and methods. The source material for the preparation of CFRP recyclate was discarded carbon fibre pressure vessels for gas storage, i.e., vessels at the end of the life cycle and those that did not pass the output inspection in production. The vessel composition was about 79% of the carbon fibres and 21% of thermoset epoxy resin. The waste containers were cut into pieces and further disintegrated using a double shaft shredder (DR120/350) and shear mill CM 2500. Fractions 2-6 mm and 0-1 mm were further separated from the resulting material by sieving, part of the materials was also thermally treated (550°C). The input CFRP recyclate materials were as follows:
-CFRP chips fraction 2-6 mm, without thermal treatment (designated 2-6 NTT) (Fig. 1)
-CFRP chips fraction 2-6 mm, thermally treated (designated 2-6 TT)
-CFRP dust fraction 0-1 mm, without thermal treatment
The raw materials for cement-based composite were as follows: Cement 42.5, fine aggregates 0-1 mm, silica fume, water and water reducing agent. The proportion of mentioned components was identical in all samples, the variable was the proportion and type of conductive component. The mix proportions are summarized in Table 1. During the casting process, copper plate electrodes were inserted into the samples. After demolding, the samples were treated in water for 28 days. The electrical impedance of the samples was measured by an LCR meter at two different frequencies. The values were determined for samples in the dry state and also for samples fully saturated with water. Mechanical parameters (compressive and flexural strength) and the bulk density of the samples were also determined.

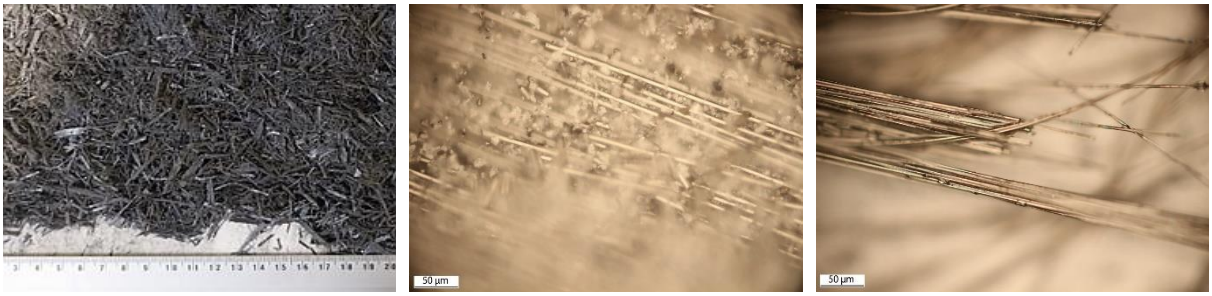

Fig. 1 CFRP waste after processing in shear mill (left), optical microscope image of thermally untreated (middle) and thermally treated (right) fibres

Table 1. Mix proportions and physico-mechanical properties of the samples

Designation	Amount of dust (% wt).	Amount of fraction 2-6 NTT (% wt.)	Amount of fraction 2-6 TT (% wt.)	Bulk density (kg/m^3)	Flexural strength (MPa)	Compressive strength (MPa)
VB-REF	0	0	0	2158	10.6	97.5
VB-U1-AR	0	1	0	2091	12.5	95.4
VB-U2-AR	0	2	0	2141	16.4	99.2
VB-U3-AR	0	3	0	2166	20.8	94.1
VB-U4-AR	0	4	0	2050	21.5	100.1
VB-U1-AR_V	0	0	1	2125	14.4	95.4
VB-U2-AR_V	0	0	2	2083	15.5	92.4
VB-U3-AR_V	0	0	3	2025	20.8	89.1
VB-GU1-AR	0.5	0.5	0	2058	11.2	102.4
VB-GU2-AR	1	1	0	2050	12.1	95.4
VB-GU3-AR	1.5	1.5	0	2050	16.9	93.1

Results and discussion. Table 1 shows that the addition of CFRP recyclate does not have a significant negative effect on the concrete mechanical parameters. Although the compressive strength of the concrete slightly decreased with increasing percentage of recyclate, the decrease compared to the reference sample was up to 10% only. On the other hand, an increase in flexural tensile strength was observed with an increasing proportion of CFRP. Measured values of impedance (Z) are summarized in Table 2. Considering that impedance is the resistance imposed on the alternating current, the lower the impedance value, the higher the conductivity of the material. The results show, that the impedance is to a high extent influenced by the state of the material (wet/dry), the frequency and the type and fraction of the FRP recyclate. The impedance was reduced by the addition of CFRP recyclate in all cases. The decrease compared to the reference sample is less noticeable in the dried state at a lower frequency. At a frequency of 100 kHz, a decrease in impedance of 2 orders of magnitude was observed. The lowest impedance (and thus the highest conductivity) was achieved by incorporating 2 and 3% of thermally treated chips (samples VB-U2-AR_V, VB-U3-AR_V), where the achieved values allow the composite to be used in heated floors/surfaces. The use of thermally untreated CFRP chips also brings a significant reduction in impedance, but the values achieved do not reach the values required for the intended applications even when incorporating 4 wt% recyclate. This is due to the relatively large residual proportion of resin covering the crushed chips, which can only be partially removed by mechanical processing. Further improvements in conductivity can then be achieved by combining the different grades (fractions) of CFRP recyclate - for example, a sample combining thermally untreated chips and powder, both additives at 1.5% concentration, showed very low impedance comparable to a sample with 2% of thermally treated fibres. This could be because the conductive network formed by each additive type will overlap with one another and significantly improve conductivity (Wu, 2015). This effect can be magnified if the used additives are of different sizes and shapes such that each filler will improve the conductivity network at a different level which will result in producing a continuous conductive path. (El-Dieb, 2018). The recipes will be further optimized to achieve higher conductivity within follow-up research. The main focus will be on the possibility of using mechanically only treated CFRP.

Table 2. Summarization of the impedance characteristics of the samples

Designation	Z (k Ω) Dry state, 1kHz	Z (k Ω) Dry state, 100 kHz	Z (k Ω) Wet state, 1kHz	Z (k Ω) Wet state, 100 kHz	Water absorption (%)
VB-REF	2250	521	505	56	10,6
VB-U1-AR	1848	4.9	5.1	3.9	11.6
VB-U2-AR	1507	12.5	3.6	2.6	8.5
VB-U3-AR	1606	5.8	2.7	1.7	11.0
VB-U4-AR	1622	6.3	1.8	1.1	10.7
VB-U1-AR_V	1068	2.6	0.3	0.2	10.7
VB-U2-AR_V	158	1.6	0.2	0.1	14.4
VB-U3-AR_V	0.9	0.9	0.09	0.06	11.5
VB-GU1-AR	2023	3.2	1.1	0.8	12.8
VB-GU2-AR	2201	4.3	0.5	0.3	12.5
VB-GU3-AR	453	2.2	0.3	0.2	11.5

Conclusions. The main objective of the presented research was to evaluate the effect of the character and concentration of CFRP recyclate on the mechanical parameters and electrical conductivity of cementitious composites. The following can be drawn:

- The incorporation of waste CFRP could significantly improve the electrical conductivity of the concrete without sacrificing the mechanical properties and characteristics of the mixture. On the contrary, the flexural strength is positively affected.

-Even the presence of non-thermally treated CFRP chips can influence the conductivity of cementitious composites. With a suitable combination of CFRP waste fractions and shape parameters, conductivity comparable to samples with heat-treated CFRP waste can be achieved. This is significant in terms of potential energy savings for the recycling process and the economic viability of the recycling method.

-It was found that by appropriate treatment and composition of CFRP, conductivity values suitable for industrial applications can be achieved. Further research will be focused on optimising the composition of CFRP and adjusting the dispersion of recyclate in the material to achieve maximum conductivity and low sensitivity to moisture content changes while minimising the cost of CFRP waste treatment.

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