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Research paper

Influence of Carbon Fibre Reinforced Polymer and Recycled Carbon Fibres on the compressive behaviour of self-compacting high-performance fibre-reinforced concrete

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Abstract: In recent years, carbon fibres have been extensively used to strengthen concrete structures. In most cases, the lamination process is carried out using epoxy resin as matrix. In some cases, especially when strengthen structural elements made of weak concrete, it is possible to replace the epoxy resin with an inorganic, cement matrix, while at the same time maintaining a sufficient efficiency of strengthen understood as the percentage increase in the compressive strength of concrete samples due to the applied reinforcement in relation to the reference concrete. In these studies, elements of carbon fibres mats that are reinforced with a cement matrix were used as the starting product for fibre recovery. The laminate, which was used to reinforce concrete elements, was detached from the concrete surface and subjected to processing in order to obtain clean carbon fibre scraps without cement matrix. Then, the obtained carbon material, in shaped form, was used to strengthen self-compacting, high performance, fibre reinforced concrete (SCHPFRC). For comparative purposes, this concrete was also strengthened by carbon fibre mats (with one and three layers of CFRP). Each samples were tested in uniaxial compression test. The compressive strength of concrete reinforced with 1 and 3 layers of CFRP was higher by 37.9 and 96.3%, respectively, compared to the reference concrete. On the other hand, the compressive strength of concrete reinforced with 1 and 3 layers of carbon fibre scraps was higher by 11.8 and 40.1%, respectively. Regardless of the reinforcement technique used, the composite elements showed a higher deformability limit in comparison plain concrete. The obtained results showed that it is possible to reuse carbon fibre to strengthen structural elements made of SCHPFRC effectively, using simple processing methods.

Keywords: external reinforcement, fibre-reinforced concrete, high-performance concrete, recycled carbon fibres, self-compacting concrete, waste processing

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1. Introduction

Self-compacting concrete (SCC) technology is undoubtedly an important achievement of the last decades. It was possible thanks to the intensive development of admixtures and additives for concrete mixtures. This contributed to design structures with complicated geometry without the need for mechanical compaction of the concrete mixture. High segregation resistance and flowability are two most important features of SCC [1]. According to [2] low water to powder ratio, limited aggregate content and usage of superplasticizer are major principles to prepare SCC. It has been proven that due to adequate rheological properties water to binder ratio and cement paste content are the most meaningful factors [3].

High-performance self-compacting concrete (HPSCC) combines the features of appropriate fluidity of concrete mix and high-strength concrete. High-class cements are most often used in the production of this concrete, but waste materials are also used more and more simultaneously. It is possible to produce HPSCC with the use of by-products as: ferronickel slag [4], eggshell powder and blast furnace [5], nano-metakaolin [6] and granite waste [7] as a partial replacement of cement and/or aggregate in traditional SCC.

Self-compacting high-performance fibre-reinforced concrete (SCHPFRC) combines many advantages of technology, durability and quasi-elasticity behaviour. This composite material has opened up new possibilities for designing and shaping concrete structures susceptible in particular to the action of dynamic forces, explosions and fatigue loads [8]. It has been analysed many times that incorporation of steel fibres into concrete mix increase mechanical properties of concrete [9, 10].

Despite the excellent mechanical properties of SCHPFRC, sometimes it is necessary to improve some of them. The use of composite materials allows to increase the load-bearing capacity and stability of structural elements when required. Fibre-reinforced polymer (FRP) materials are polymers which are reinforced with fibres. Among the fibre most commonly used in engineering are carbon, glass, aramid and basalt. High strength to weight ratio, excellent fatigue properties, resistance to aggressive environments, low thermal conductivity and relatively low lifecycle costs are key essential benefits of FRP materials [11].

Currently, an intensive search is being made for the possibility of processing and reusing various materials; including carbon fibres, which is in line with the principles of sustainable construction. For instance, processing glass fibre reinforced polymer (GFRP) waste into fibres was performed by [12] using new mechanical recycling method. It has been proven that using thermally activated semiconductors, it is possible to recover fibres from FRP composites [13].

In recent years, we have observed a significant increase in the use of carbon fibres to strengthen concrete structures, which results from the many advantages of this material [14]. Xiong et al [15] used recycled carbon fibre reinforced polymer materials (CFRP) in fibres reinforced rubberized concrete. It has been demonstrated, that incorporation of these material in concrete mixture improved flexural toughness, ductility, energy absorption capacity and impact resistance were meaningly increased. Kimm et al [16] used short pyrolyzed recycled carbon fibres to improve mechanical properties of fibre reinforced concrete. It has also been shown in [17] that it is possible to produce more durable pervious concrete using mechanically processed carbon fibre composites (in form of scraps) from the aerospace industry. According to [18] mechanical recycling, thermal recycling (pyrolysis, fluidised bed thermal processing) and chemical recycling (solvolysis, low temperature chemical recycling methods) are the most comonly methods used to retreive fibres from composites and dry carbon fibre wastes.

Based on the above observations, it can be concluded that it is possible to recycle composite materials and re-use them in broadly understood engineering. As has been shown, until now, recycled composite materials have been used mainly as an additive to concrete, which improved its properties. Their use as external reinforcement has not been considered by scientists, especially in the aspect of reinforcing special concretes. Hence a research proposal to fill this gap. In the authors' opinion, the impact of recycled carbon fibres and CFRP on the effectiveness of the reinforcement of self-compacting high-performance fibre-reinforced concrete has not been sufficiently understood. Based on the number of scientific papers related to the analysed materia, which is shown in Figure 1, it can be conducted that considered special concrete reinforced with CFRP scraps has not yet been analyzed.

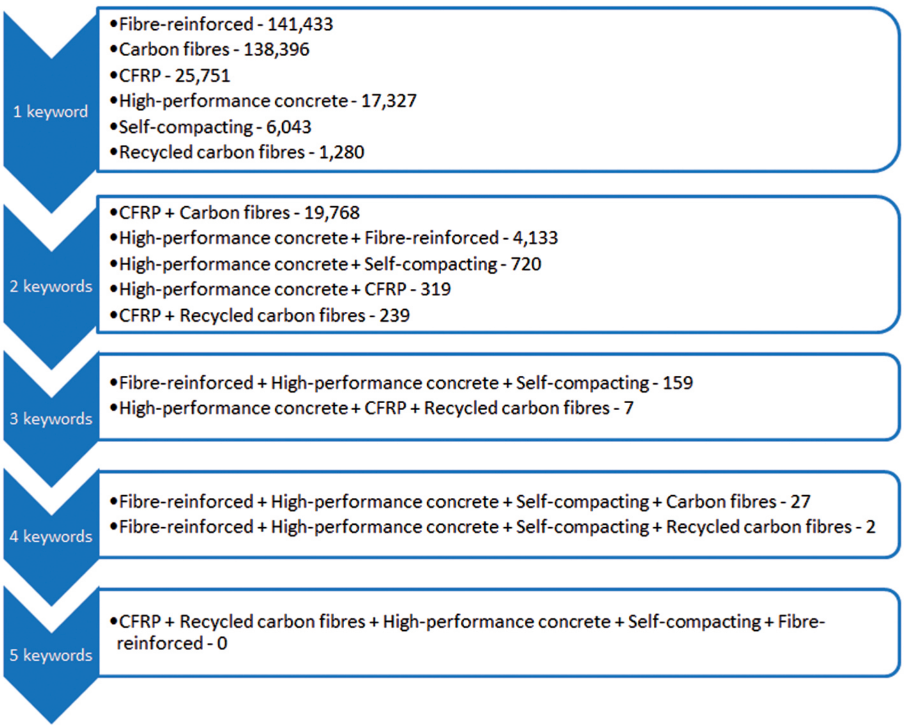


Fig. 1. Number of papers associated with "Influence of recycled carbon fibres on the effectiveness of the reinforcement of self-compacting high-performance fibre-reinforced concrete" searched in abstract, article title, and keywords in the Scopus database on 26.03.2022 [19]

2. Research significance

Nowadays, we attach more and more importance to responsible waste management. Initiated several years ago, the global trend of recycling most materials (not only construction materials) contributes to cleaner production, which is in demand. In the case of the material which is concrete, waste materials are used more and more often in its production. The composition of the concrete mix is modified by using waste materials with binding properties, as well as by using various (fine and coarse) waste aggregates. For almost several decades, civil engineering has been using composite materials in various forms (mainly tapes, mats, nets) to strengthen engineering structures. During this process, organic and inorganic matrices are commonly used. Considering the rapidly changing world, including the intensive development of construction, we should now consider the recycling options of reinforced structures. Therefore, this paper proposes a method of processing reinforced concrete elements (with the use of composite materials) in which carbon fibres were recovered. As a result, a material in the form of shreds of carbon fibres was obtained, which was reused to strengthen SCHPFRC in a significant way, which is in line with the trend of responsible waste management. Sometimes there is a need for additional reinforcement of axially compressed concrete elements (e.g. bridge pillars, columns etc.) made of high-strength concrete. Therefore, this analysis covered small cylindrical samples, constituting a section of the column structure as shown in Figure 2.

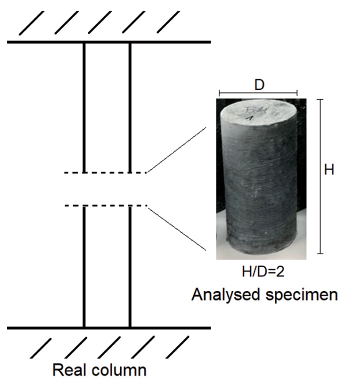


Fig. 2. Cylindrical specimen as a fragment of column

3. Materials and methods

3.1. Concrete mixture and speciemens

In this studies self-compacting high-performance fibre-reinforced concrete (SCHPFRC) was used. Table 1 shows the composition of the concrete mixture. As a binder Portland cement CEM I 52,5R and Sika Fume additive in fine-powder form have been used. River sand (fraction 0–4 mm) was used as fine aggregate while diabase (fraction 4–8 mm) was

Table 1. Content of the concrete mixture

Cement [kg/m^3]	Sika Fume [kg/m^3]	Fine aggregate [kg/m^3]	Coarse aggregate [kg/m^3]	Water [kg/m^3]	Super-plasticiser [kg/m^3]	W/C [–]	Steel fibres [kg/m^3]
500	60	650	1000	160	17.5	0.32	78

used as coarse aggregate. Steel fibres had a form of hooked–end fibres with length to diameter ratio equal to 40 (length = 20 mm and diameter = 0.5 mm). When analyzing the behavior of fresh concrete mixture, it was determined that the slump flow was 660 mm and plastic viscosity was 13 s. These features were examined in accordance with European Standards [20]. In this studies 20 cylindrical specimens with dimensions of height/diameter equal to 200/100 mm were made. In this group, 5 series of samples were made and tested (4 samples in each series) as has been noted in Figure 3.

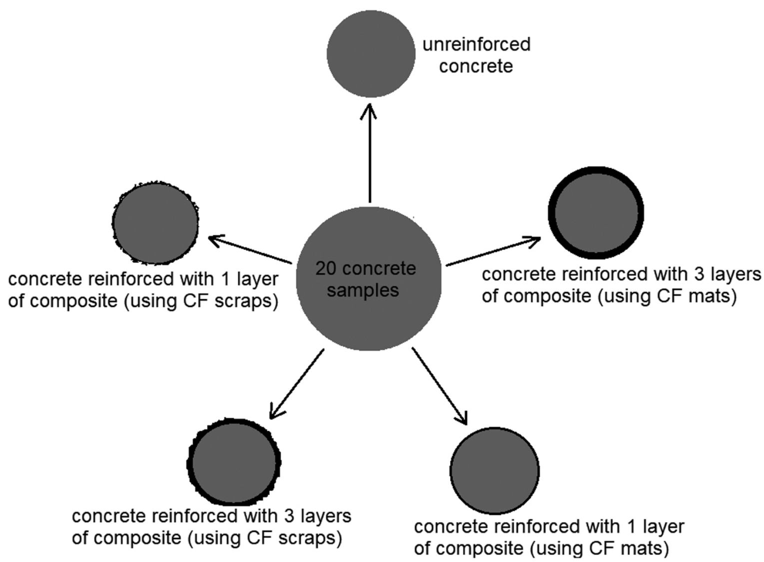


Fig. 3. Type of analysed group of specimens

3.2. Carbon fibres mats and shreds

Retrofitting of SCHPFRC was prepared using carbon fibres and epoxy resin. In these studies two forms of carbon fibres were used. The first form was carbon fibre mats SikaWrap 300 C (Table 2). The second form was recycled and cutted carbon fibre mats. These recycled carbon fibre mats were obtained from reinforced concrete elements using SikaWrap 300 C mats with a cement matrix. Elements of the reinforced concrete were crushed in a jaw crusher (Figure 4a), thanks to which the carbon mats and concrete were sep-

Table 2. Properties of SikaWrap 300 C carbon fibres

Dry fibre density [g/cm^3]	Effective thickness [mm]	Ultimate elongation at the break [%]	Tension strength [MPa]	Young modulus [GPa]
1.82	0.167	1.7	4000	230

arated (Figure 4b). The carbon mats were then cut into irregularly shaped pieces with a shredder. The dimensions of the resulting shreds of carbon fibre mats did not exceed 5×30 mm.

(a)

(b)

Fig. 4. Jaw crusher (a) and material after crushing process (b)

3.3. Epoxy resin

The lamination of carbon fibre mats and shreds of carbon fibre mats was carried out with the use of epoxy resin. The parameters of this material, according to the manufacturer's information, are given in Table 3.

Table 3. Properties of Sikadur 300 epoxy resin

Density [kg/dm^3]	Viscosity in +23°C [mPas]	Elongation at the break after 7 days at +23°C [%]	Tension strength after 7 days at +23°C [MPa]	Young modulus during bending after 7 days at +23°C [GPa]	Young modulus during tensile after 7 days at +23°C [GPa]	Glass transition temperature [°C]
1.16	700	1.5	45	3.5	2.8	53

3.4. Lamination process

Before starting the lamination process, the concrete surface was properly prepared to ensure the highest adhesion of the external reinforcement to the concrete. For this purpose, the concrete surface was grinded with bituminous grinding discs, which contributed to the removal of the cement laitance from the reinforced surface of the samples. This treatment contributed to the improvement of the morphology of concrete surfaces through its appropriate shaping. Then the samples were washed with tap water and dried. All dust was removed from the concrete surface immediately prior to sample amplification. Importantly, the humidity of the concrete surface did not exceed 4% during lamination.

In both cases, the dry lay up method was used in the lamination process. Regardless of the fibre form used, concrete samples were covered with a CFRP along their whole height (200 mm). In the case of SikaWrap 300 C carbon fibre mats, 50 mm overlap was provided. In this case, the major fibres were arranged perpendicular to the specimen axis (0° orientation). In this way, 1 and 3 layers of CFRP reinforcement were made. When using carbon fibre shreds, the principal fibres (shreds) were oriented randomly, but evenly. The amount of the recycled CFRP per 1 or 3 layers corresponded to the amount of fibres needed to reinforce the sample in the classic way using the carbon fibre sheet (in mass, including material for overlap). The lamination process was executed at a room temperature of 22°C ± 1°C, and a humidity of 58% ± 1%. Due to the curing time of resin, samples were tested in compression tests 7 days after lamination. Part of specimens prepared for compression tests were shown in Figure 5.

Fig. 5. Part of cylindrical specimens before tests

4. Instrumentation and testing

The uniaxial compression tests of the concrete specimens were performed using a servo-controlled machine (Figure 6). The testing system, equipped with a high-capacity and high-stiffness load frame coupled with servo-hydraulics and digital control technology. The research was carried out with the constant axial force being approximately 7.5 kN/s.

Fig. 6. Testing machine used in compression tests

The measurement of the axial force was carried out by means of a force transducer, while the displacements were measured by extensometer. Radial and axial displacements were determined through the measurement of all of the specimens' dimension changes, where the extensometer was mounted directly between the compression plates.

5. Results

5.1. Compressive behaviour

The average compressive strength of the self-compacting, high-performance fibre-reinforced concrete was equal to 83.03 MPa. Maximum axial strain of the SCHPFRC during the maximum compressive stresses was 0.006. Usually, the maximum destructive deformation for HPC concrete without micro reinforcement is about to 0.0035. Nevertheless it should be noted that incorporating a relatively big amount of steel-fibre reinforcement to the concrete increases this value, what was observed. During compression, behavior of SCHPFRC is linear-elastic with a quasi-plastic range of work near the peak of stresses.

In the case of concrete samples reinforced with the carbon fibre mats and recycled carbon scraps, a relevant increase in compressive strength was achieved in relation to the reference concrete. The compressive strength and deformability of samples reinforced using Sikawrap 300 C was significantly higher than of concrete reinforced using recycled carbon scraps. Results form this survey has been presented in Table 4.

In the case of samples reinforced with one and three layers of CFRP, an increase in compressive strength was obtained in comparison to the reference concrete by 38% and 96%, respectively. The longitudinal deformation of concrete reinforced with one and three

Table 4. The results of the research

Type of specimen	Form of reinforcement	Average compressive strength [MPa]	Standard deviation [MPa]	Average axial strain during fracture [–]	Efficiency of reinforcement related to reference [%]
FRC	–	83.03	0.63	0.006	–
FRC/1/CFRP	CFRP	114.5	5.2	0.0122	37.9
FRC/3/CFRP		163	9.9	0.0191	96.3
FRC/1/rCF	Recycled carbon fibres in form of scraps	92.8	3.0	0.0081	11.8
FRC/3/rCF		116.3	4.4	0.0095	40.1

Note: CFRP – Carbon Fibre Reinforced Polymer, rCF – recycled Carbon Fibres, number 1 or 3 means number of layers of external reinforcement.

layers was 0.0122 and 0.019 respectively, which translates into a 103% and 218% increase compared to unreinforced concrete.

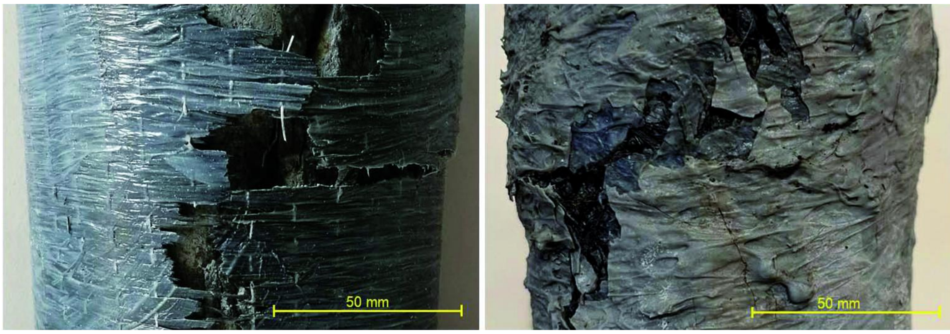
By using concrete reinforcement in the form of recycled carbon fibre scraps, a 12% and 40% increase in compressive strength was achieved for one and three layers of reinforcement compared to the reference concrete. On the other hand, the longitudinal deformation of the samples was higher by 35% and 58% for the specimens reinforced with one and three layers, compared to unreinforced concrete.

It is worth noting that the standard deviation of the compressive strength was significanlty lower for concrete reinforced with waste carbon fibre scraps than for reinforced with carbon fibre mats. This shows that the stress-strain characteristics of samples reinforced with recycled carbon fibre scrap can be more predictable than with traditional reinforcement.

5.2. The course of failure

Figure 7 presents the course of destruction, which is representative for most of the analyzed types of samples. Regardless of the number of reinforcement layers, the course of destruction was essentially similar. In the case of concrete samples strengthened by CFRP, cracks in the CFRP mats were observed after exceeding the maximum stresses, most often located in the central (middle) part of the sample (Figure 7a). It was accompanied by a characteristic bang. In the case of samples reinforced with one layer of CFRP, there was a greater area of failure (torn mat) than in the case of concrete reinforced with three layers of CFRP.

In the case of the samples reinforced with shredded carbon fibre mats, the failure was not rapid, unlike the samples reinforced with CFRP. Cracks (fracture net) were observed on the surface of the samples, the propagation of which was limited by randomly distributed recycled carbon fibres reinforcement (Figure 7b). Minor areas of loss of adhesion between



(a) (b)

Fig. 7. The course of destruction of samples strengthened by CFRP (a) and carbon fibre scraps (b)

carbon fibre scraps and epoxy resin were observed. It should be emphasized that there was no delamination of the composite material from the concrete surface.

6. Final conclusions

The study showed that self-compacting high-performance fibre-reinforced concrete can be effectively strengthened by the use of carbon materials both in form of fibre mats and shreds. It should be clearly emphasized that the article refers to the comparison of Sikawrap 300 C carbon fibre mats and carbon fibre shreds, which can be used in the strengthen of concrete structures. The results presented in this paper are limited only to the determination of the maximum stresses and deformations of SCHPFRC strengthened by composite materials. Despite the fact that greater level of reinforcement of concrete was obtained for samples strengthened by carbon fibre mats, in the authors' opinion, the increase in compressive strength for concrete strengthened by shreds of carbon fibres – derived from recycling – is significant. It has been proven that both the longitudinal deformability and the compressive strength of the samples increases with the increase of the amount of external reinforcement.

Thanks to the use of recycled carbon fibres in strengthen of concrete elements, carbon footprint is reduced, which is in line with the current trend in civil and materials engineering. In order to more thoroughly assessment the influence of carbon fibre scraps on the behavior of concrete, it is necessary to examine effectiveness of reinforcement of various concretes strengths, which will be made and analyzed in future tests.

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Wpływ mat z włókien węglowych i włókien węglowych z recyklingu na efektywność wzmocnienia samozagęszczalnego fibrobetonu wysokowytrzymałościowego

Słowa kluczowe: zbrojenie zewnętrzne, fibrobeton, beton wysokowytrzymałościowy, włókna węglowe z recyklingu, beton samozagęszczalny, przeróbka odpadów

Streszczenie:

W ostatnich latach włókna węglowe są szeroko stosowane do wzmacniania konstrukcji betonowych. W większości przypadków proces laminowania odbywa się z użyciem żywicy epoksydowej jako matrycy. Czasami, zwłaszcza przy wzmacnianiu elementów konstrukcyjnych wykonanych z betonu o stosunkowo niskiej wytrzymałości na ściskanie, możliwe jest zastąpienie żywicy epoksydowej matrycą nieorganiczną; cementową, przy jednoczesnym zachowaniu dostatecznej efektywności wzmocnienia – rozumianej jako procentowy wzrost wytrzymałości betonu na ściskanie wskutek zastosowania materiału kompozytowego, w odniesieniu do betonu referencyjnego. W procesie kruszenia jako nadawę zastosowano elementy betonowe wzmocnione matami z włókien węglowych przy zastosowaniu matrycy cementowej. Laminat został oderwany od powierzchni betonu i poddany dalszej obróbce w celu uzyskania czystych, niezawierających matrycy cementowej skrawków mat z włókna węglowego. Następnie otrzymany materiał został wykorzystany do wzmocnienia samozagęszczalnego, wysokowytrzymałościowego fibrobetonu (SCHPFRC). Dla celów porównawczych beton ten został także wzmocniony z użyciem mat z włókien węglowych (1 i 3 warstwy wzmocnienia). Próbki cylindryczne przebadano w teście jednoosiowego ściskania. Wytrzymałość na ściskanie betonu wzmocnionego 1 i 3 warstwami CFRP była wyższa odpowiednio o 37,9 i 96,3% w porównaniu z betonem referencyjnym. Natomiast wytrzymałość betonu wzmocnionego 1 i 3 warstwami strzępów z włókna węglowego była wyższa odpowiednio o 11,8 i 40,1%. Niezależnie od zastosowanej techniki wzmocnienia, próbki kompozytowe cechowały się wyższą odkształcalnością graniczną w odniesieniu do betonu referencyjnego. Uzyskane wyniki wykazały, że możliwe jest wykorzystanie włókien węglowych z recyklingu do efektywnego wzmocnienia elementów konstrukcyjnych wykonanych z SCHPFRC, przy użyciu nieskomplikowanej metody przeróbki odpadu.

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