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ORIGINAL ARTICLE

Investigation of pull-out and mechanical performance of fibre reinforced concrete with recycled carbon fibres

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Abstract This paper presents the pull-out bonding behaviour and mechanical performance of recycled carbon fibre (rCF) reinforced concrete based on the recent investigation of fibre reinforced concrete (FRC) with rCF recovered from pyrolysis. Single fibre pull-out tests have been carried out to identify the apparent interfacial shear strength of different types of rCF and virgin carbon fibre (vCF) to identify the fibre matrix connection. Furthermore, a series of tests have been carried out to identify the workability, compressive strength and tensile strength of FRC. Besides rCF, also vCF and steel fibre were used for fabrication of FRC test specimens. rCF have shown the same adhesion behaviour and strength like vCF. Furthermore, the use of unsized or acrylate-based sized rCF creates an adhesion between fibre and matrix material. During the pull-out tests, the failure does not occur as an adhesive crack between fibre and cement matrix, but as a cohesive crack in the cement matrix. The mechanical performance of FRC with rCF was compared with mortar and FRC with vCF and steel fibres. The results of compressive test conducted for FRC with vCF and rCF indicated that the influence of vCF and rCF on the compressive strength of FRC was insignificant. On the other hand, the results of tensile test conducted for FRC with vCF and rCF indicated that the tensile strength of FRC with rCF was at least 14.9% greater than that of FRC with vCF.

Keywords Recycled carbon fibre · Fibre reinforced concrete · Pull-out · Fibre matrix bonding

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1 Introduction

Although concrete is the most widely used construction material in the world due to its economical and durability merits, major shortcoming of concrete is low tensile strength compared to its compressive strength. Therefore, steel reinforced concrete is commonly used in construction to overcome the shortcoming of plain concrete. Steel reinforced concrete always requires a concrete cover thickness to avoid corrosion of embedded steel. Significant research efforts have been made to develop concrete with non-corrosive fibre and textile reinforcement, to reduce the concrete cover thickness of concrete elements [1–3]. Fibre reinforced concrete (FRC) has been introduced to improve tensile and flexural performance of plain concrete [4, 5]. FRC is a composite material that consists of mixture of concrete and discontinuous, discrete, uniformly dispersed fibres. FRC enhances tensile strength and crack resistance by incorporating fibres into concrete. The fibres used include steel fibres, glass fibres, and synthetic fibres. Ultra-High-Performance Concrete (UHPC) is a type of FRC that typically uses straight steel fibres, significantly improving mechanical properties such as high compressive strength and tensile behaviour, thereby enhancing bending and deformation resistance and crack resistance. The enhancement in mechanical behaviour improves with increased use of steel fibres. However, the production cost of UHPC is considerably high, with steel fibres, which constitute 1–2% of the total volume, accounting for over 50% of the production cost. Minimizing fibre usage to ensure economic feasibility is critical and urgent for the practical application of UHPC in structures. Consequently, extensive research is being conducted domestically and internationally on using various fibres in UHPC. FRC is the main research topic of this paper.

Along with the need for non-corrosive concrete reinforcement comes the increasing supply of rCF from fibre reinforced polymers (FRP) composites. FRP are used in the aviation, automotive, shipbuilding, wind energy, and construction sector. Carbon and glass fibres are commonly used to fabricate the FRP composites. The current CF demand is increasing by 10% annually. According to this forecast, demand in 2024 will be 122 kilo tons of vCF [6]. Statutory recycling rates, e.g. 95% in the automotive industry and 70% for construction and demolition waste, raise urgent questions about recycling and the environmental impact of the fibres used [7]. Especially for high valued vCF, a high-quality recycling concept is of economic and ecological importance. With the currently foreseeable state of the art, it is not possible to recycle CF without loss of length [8]. In contrast, recycled carbon fibres (rCF) retain 80–90% of the mechanical properties of virgin fibres [9, 10] and are significantly less expensive. Studies have been performed on the reinforcement behaviour of recovered carbon textiles for concrete, instead of recycling the textiles on fibre level [11]. But, flexural performance of concrete reinforced with recovered textiles showed a pronounced decrease of 30–40% in flexural strength with high variance compared to new carbon textile reinforcement. This shows that recycling on textile level in not a suitable way. So far research for using rCF in different sectors is ongoing. Furthermore, fibre shortening compared to endless rovings is less of a problem for use in FRC than in other applications where a flat textile is required. Due to the lower costs compared to vCF with comparable mechanical properties, the fibres are suitable for the construction industry.

Steel fibres are the most commonly used fibres in FRC. Recently, however, CF, basalt-, or mixed fibres are also used [12, 13]. Many researchers reported that the material properties of concrete can be improved by reinforcing with steel fibres and CF. Mastali et al. [14] and Kimm et al. [15] reported that the volume fraction and length of vCF and rCF induced a remarkable increase on the mechanical properties and impact resistance of FRC. However, according to the experimental results for FRC exposed to high temperature by Zhan et al. [16], the volume fraction of CF affects the material properties. Furthermore, the length of fibres has less influence on the material properties than the volume fraction [16]. In addition, a large number of studies have been conducted on fatigue, vibration characteristics, and high temperature resistance of concrete mixed with CF [16–18]. The aim of this study is to evaluate the mechanical performance of UHPC using CF and steel fibres, both of which have excellent mechanical properties.

As a collaborative research work between two research groups at ITA of RWTH Aachen University (Germany) and KICT (Korea), a series of tests was conducted to investigate the mechanical performance of rCF reinforced concrete. The pull-out bonding performance of different types of rCF was investigated by ITA. Based on the test results at ITA, one rCF type for further tests at the KICT were selected. KICT investigated the workability, compressive strength and tensile strength of rCF reinforced concrete. Aim of this study was to improve the knowledge of different rCF types and sizing agents on mechanical performance of FRC to design a specific rCF type which is suitable for its use in concrete in the future. For this purpose, single fibre pull-out tests and tests on FRC were performed. This paper highlights the results.

2 Materials and methods used in the present study

To evaluate the adhesion behaviour, three different rCF types from a manufacturer in Germany and three vCF Types, two from Germany and one from South Korea were used in this research. The material properties of the different CFs according to the measurements carried out are listed in Table 1. Additional information has been taken from the respective product data sheets.

Locally available material was used for vCF, therefore different vCF were used. The used vCF at ITA for the pull-out test had different preparation materials. EP-vCF is a roving for epoxy-based matrix materials and PU-vCF is suitable for polyurethane-based matrix materials. Both fibres were obtained from Teijin Carbon Europe GmbH, Wuppertal, Germany. KICT used a locally available vCF from Ace C & Tech Co., South Korea, which is referred to as K-vCF in this paper.

The rCF were obtained from CarboNXT, Mitsubishi Chemical Advanced Materials GmbH, Wischhafen, Germany. The rCF types can be differentiated according to the form of the recycling process and their preparation content. Pure-rCF is from prepreg or end-of life waste and has no sizing after pyrolysis. In comparison resized-rCF are also from prepreg or end-of-life waste and got an acrylate base sizing after pyrolysis. The cut-off-rCF fibres originate from cut-off waste, which is why no pyrolysis was carried out and the standard sizing of the vCF remains on the fibre surface. In this case, the sizing type was unknown.

2.1 Single fibre pull-out test

To conduct the pull-out test, the test apparatus of Fimabond and Favimat + of TexTechno–Herbert Stein GmbH & Co. KG, Mönchengladbach, Germany, are used. The CF is embedded in the mortar matrix (see Table 2) with the Fimabond.

A higher water to binder ratio than usual is necessary for the single fibre pull-out tests due to the embedding process. Otherwise the surface of the concrete matrix will dry too quickly and the fibres can no longer be embedded properly. The fine

Table 1 Properties of fibre material

Name	vCF			rCF		
	EP-vCF	PU-vCF	K-vCF	Pure-rCF	Resized-rCF	Cut-off-rCF
Manufacturer	Teijin Carbon Europe GmbH, Wuppertal, Germany		Ace C&Tech Co, South Korea	CarboNXT, Mitsubishi Chemical Advanced Materials GmbH, Wischhafen, Germany		
Type of waste	–	–		Prepreg/End-of-Life	Prepreg/End-of-Life	Cut-off waste/non-pyrolysed
Tensile strength (MPa)	2.940	3.120	4.900	1.570	1.880	3.460
Tensile modulus (GPa)	204	201	230	208	202	210
Elongation at break (%)	1.4	1.52	2.1	0.77	0.94	1.58
Filament diameter (µm)	7.11	7.03	7	6.96	7.32	6.92
Density (g/cm^3)	1.774	1.783	1.80	1.816	1.767	1.782
Preparation material	Epoxy*	Polyurethane*	–	–	Acrylate based	Unknown/mixed
Preparation content (%)	1.3*	1.0*	–	0	2.5–3.0	< 5.0*

*From data sheet

Table 2 Mixture composition of mortar for single fibre pull-out test (weight ratio)

W/B	Cement	Fly ash	Silica fume	Quartz powder	Sand	Superplasticizer
0.18	1	0.36	0.07	1.02	1.45	0.018

aggregates had a particle size of max. 0.6 mm. After the embedding process the Favimat + is used to carry out the pull-out test. A total of 10 test specimens with each vCF and 18 test specimens with each rCF were prepared and tested. The embedding and pull-out process is shown in Fig. 1.

To produce a test specimen, a single fibre is inserted into the cannula and then shortened so that it protrudes approximately 2–3 mm from the end of the cannula. A drop of the matrix material is then placed on the top of the stainless-steel crucible. The embedding process of the sample takes place semi-automatically in the Fimabond. The fibre is embedded to a total depth of 1000 µm at a speed of 6000 µm/min. The curing time for the mortar matrix in the Fimabond is 20 min. A temperature of 30 °C prevails in the device. The test specimens are stored in a specially designed box at constant climatic conditions of 23 °C room temperature and a relative humidity of 65%.

The pull-out tests are carried out on the Favimat +. For testing, the specimens are inserted into the tester with the fibre pointing downwards. The specimen is then moved down to the clamp and aligned manually so that the fibre lies straight on the right clamp jaw and the free distance between the specimen and the clamp is as small as possible. After closing the left clamp, the crucible is automatically moved away from the clamp at a speed of 100 µm/min, to pull-out the fibre.

The apparent interfacial shear strength between the fibre and matrix material can be calculated as [19].

$$\tau_{\text{app}} = \frac{F_{\max}}{\pi * d_f * l_e}$$

where $\tau_{app} =$ apparent interfacial shear strength, $F_{max} =$ maximum force, $d_f =$ fibre diameter, $l_e =$ Embedding length.

Afterwards, the extracted fibres are examined under a scanning electron microscope (SEM) to check for residual attachments. This enables conclusions to be drawn about the type of failure between the fibre and the matrix or within the matrix.

2.2 FRC test specimen preparation

A standard UHPC mixture was used to produce the test specimens at KICT. Portland cement and silica fume were used for the fabrication as reactive powder. The fine aggregates had a particle size of max. 0.5 mm and silica powder an average particle diameter of about 10 µm (98% of SiO_2 and a density of 2.60 g/cm^3). Also, a high-performance water reducing agent was used. The following table provides the mixture composition of the mortar and FRC used (Table 3).

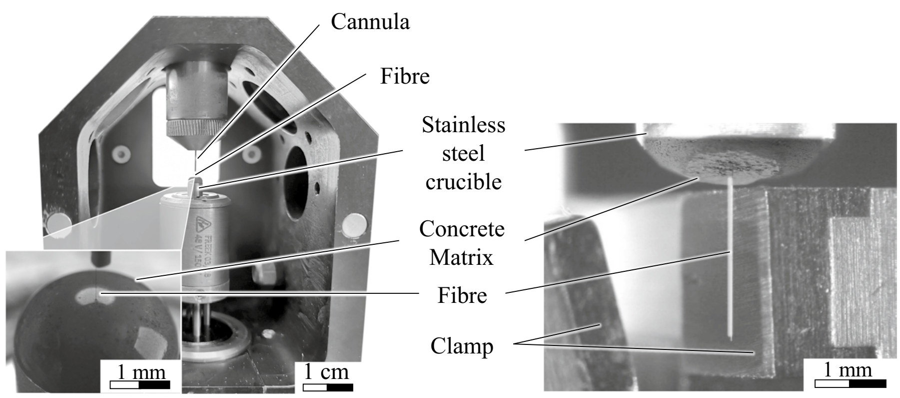


Fig. 1 Preparation of the sample in the Fimabond for the fibre embedding (left) and in the Favimat before pull-out (right)

Table 3 Mixture composition of mortar for FRC based on UHPC (weight ratio)

W/B	Cement	Silica fume	Silica powder	Expansion agent	Sand	Superplasticizer	Steel fibre	K-vCF	rCF
0.2	1	0.2	0.25	0.05	1.1	0.018	1%	0 ~ 1%	0 ~ 1%

A standard local UHPC mixture was used for the tests at KICT. FRC enhances tensile strength and crack resistance by incorporating fibres into the concrete. These fibres include steel fibres and synthetic fibres such as PVA and PP. However, using high-performance fibres, as CF in FRC is inefficient and uneconomical because the performance of the CF exceeds that of the matrix. Although steel fibres are the most commonly used fibres for FRC, vCF and rCF are also mixed with steel fibres during the test specimens' preparation. Therefore, to maximize the performance of CF, they were applied in UHPC. One objective of this study is to identify the influence of vCF and rCF on the mechanical performance as well as workability of FRC with CF and steel fibres.

Two different types of CF (K-vCF and resized-rCF, see Table 1) and one steel fibre were used for the compressive- and direct tensile strength test. Figure 2 shows the shape of vCF, rCF and steel fibres used in the test.

The used K-vCF has a length of 6 mm. The copper coated steel fibre shown in Fig. 2c has a diameter of 0.2 mm, a length of 20 mm, and an elastic modulus of 200 GPa. For the mixing process dry materials were poured into a vertical mixer of 60 L for dry mix for 10 min with 40 rpm. Afterwards water and superplasticizer were added and mixed for 10 min with 70 rpm. Before manufacturing, the liquid mortar was mixed with fibrous materials for 5 min with 40 rpm. Different fibre volume ratio was considered for the mortar mix, i.e. vCF and rCF: 0.5 ~ 1.0%, Steel fibre 1.0% + vCF, and rCF (0%, 0.5%, and 1.0%).

After mixing the materials, mortar and FRC were placed in moulds for each test specimen, and the test specimens were covered with a plastic sheet and cured at room temperature for 48 h and then demoulded. The demoulded specimens were cured by a high-temperature steam of 90 °C for 48 h and then left in a dry state at 20 °C until the compressive and tensile tests were carried out.

2.3 Slump flow test

Workability of FRC was evaluated in accordance with ASTM C109/C109M-21 [20] and the dispersibility of fibre was evaluated by visual observation after the flow test. As shown in Fig. 3, the dispersibility of fibres was classified as Grade 1 (excellent), Grade 2 (normal), and Grade 3 (defective) according to the state of fibre clumping [21].

Grade 1 is in a good condition because the fibres are evenly dispersed, Grade 2 has some fibre clumping and material separation, but there is no significant impact on the placing, and Grade 3 has severe fibre clumping and material separation with poor workability.

2.4 Compressive strength test

For the compressive test three $50 \times 50 \times 50$ mm^3 cubic specimens were prepared. The compression test for the specimens was performed in accordance with the ASTMC39/C39M-1 [22] using a universal testing machine with a capacity of 3000 kN (Fig. 4b). The

Fig. 2 Shape of fibres used in the test: **a** K-vCF; **b** resized-rCF; and **c** steel fibres

Fig. 3 Dispersibility of fibres within FRC: **a** Grade 1, **b** Grade 2, and **c** Grade 3

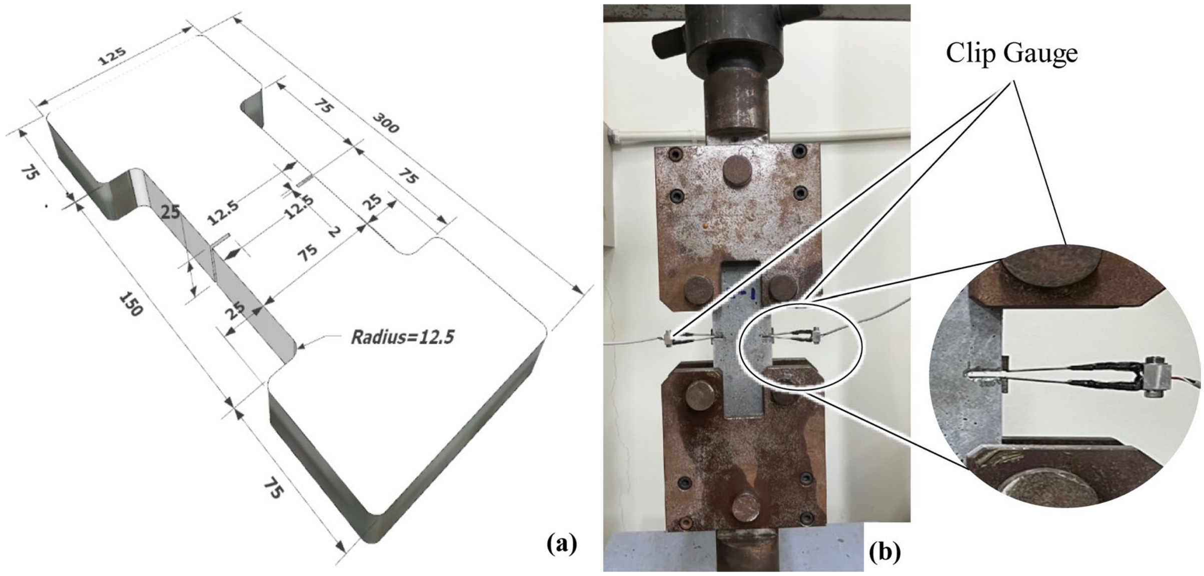


Fig. 4 Direct tensile test: **a** dimensions of specimen (unit: mm).; and **b** set-up and strain gauges

load was applied to the specimen until the specimen was failed at a loading rate of 0.1 mm/s using a displacement control method, and the average value of three tests was used to calculate compressive strength.

2.5 Direct tensile strength test

The direct tensile strength of test specimens was evaluated in accordance with the KCI-M-19-006 [23]. Figure 4a and b respectively shows the dimensions of a dumbbell-type coupon specimen for the direct tensile test and the test set-up. Two clip-type strain gauges were mounted at 12.5 mm-deep notches of the specimens to measure the crack width during the test (Fig. 4b). An average value of three tests per group of specimens was used to calculate tensile strength.

3 Results

3.1 Single fibre pull-out test

In this section, the results of the pull-out tests are presented and supplemented by findings from a microscopic examination. An overview of all measured apparent interfacial shear strengths is shown in Fig. 5. The data set is checked in advance for outliers due to fibre breakage or other sources of error. Due to the influence of the actual embedment depth on the absolute forces, outliers with a deviation of the embedment depth of +/−20% are usually excluded from the evaluation to avoid distortions. Due to the inhomogeneity of the mineral matrix, such restrictions are not applied. The planned embedding depth of 1000 µm was not achieved due to shrinkage of the matrix material during curing. The actual embedding depth averaged 531 µm and varied between 97 µm and 837 µm. In the following, only specimens with an embedding depth of at least 200 µm are considered.

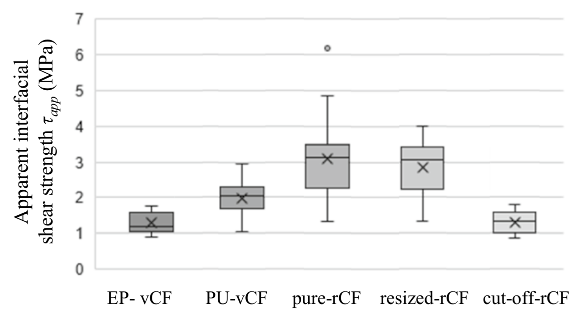


Fig. 5 Evaluation of the apparent interfacial shear strength

The mean apparent interfacial shear strength of the EP-vCF is based on 8 out of 10 samples, after consideration of the embedding depth. Overall, the EP-vCF test series achieves the lowest measured strengths with an average of 1.29 MPa. However, this test series also shows a low scatter of results and thus achieved homogeneous results at an overall low level.

The test series of the PU-vCF is based on 10 samples. With a mean apparent interfacial shear strength of 1.98 MPa, the results show higher average strengths than the EP-vCF. Around the mean value, the results scatter in a range of $+/-1$ MPa.

The evaluation of the pure-rCF test series is based on 15 out of 18 samples. The mean apparent interfacial shear strength of this test series is 3.11 MPa., which is about 60% above the average strength of the PU-vCF. The standard deviation is 1.27 MPa. Accordingly, strongly scattering results are found for the pure-rCF type. In particular, the only outlier is recorded in this test series according to the rule of 1.5 times the quartile spacing. This represents the highest measured value with a strength of 6.17 MPa.

The test series of resized-rCF with an acrylate-based sizing is based on 14 out of 18 samples. The mean strength of 2.85 MPa was tested. So, the results are very similar to the pure-rCF test series. The lower three quartiles agree almost exactly with each other. However, with a standard deviation of 0.85 MPa, the results of the resized-rCF series are less scattered.

In the cut-off-rCF test series, 18 samples of rCF are examined with an unknown standard sizing. For the cut-off-rCF, a mean interfacial shear strength of 1.3 MPa with a standard deviation of 0.32 MPa is determined. Thus, this cut-off-rCF shows almost identical results to the EP-vCF. With a value of 0.86 MPa, the lowest result of all test designs was recorded for the cut-off-rCF.

Following the pull-out tests, the surfaces of the fibres are examined under the SEM. For this purpose, both the fibres from the test specimens and a sample of the respective fibre type before embedding are compared. All in all, most of the fibres show flat residues of the mineral matrix. The respective conditions of the fibres are described below according to the different fibre types. Figure 6 shows exemplary the images of the EP-vCF, the pure-rCF and the resized-rCF before embedding and after the pull-out test.

After the pull-out test of EP-vCF has been carried out, the fibre surface is covered by bound mortar residues over a large area or in places. The fibre surface, which was embedded in the mortar and not further covered by residues after pull-out (see Fig. 6d), does not show any visible damage.

The surface condition of the pure-rCF before testing resembles both vCF and the resized-rCF. Within the sample, no defects could be visually detected that indicate damage to the fibre structure during the recycling process. The condition of the fibre surface is shown in Fig. 6b. Parallels can be seen between the pure-rCF and EP-vCF types also after testing. In addition to larger bound mortar fractions, individual grain residues are also visible on the exposed fibre surface. Furthermore, a partly irregular cross-sectional shape of the pure-rCF was observed during the investigation (see Fig. 6e, part highlighted with an asterisk). The axial indentation of the fibre is presumably caused by the manufacturing process. This does not signal any

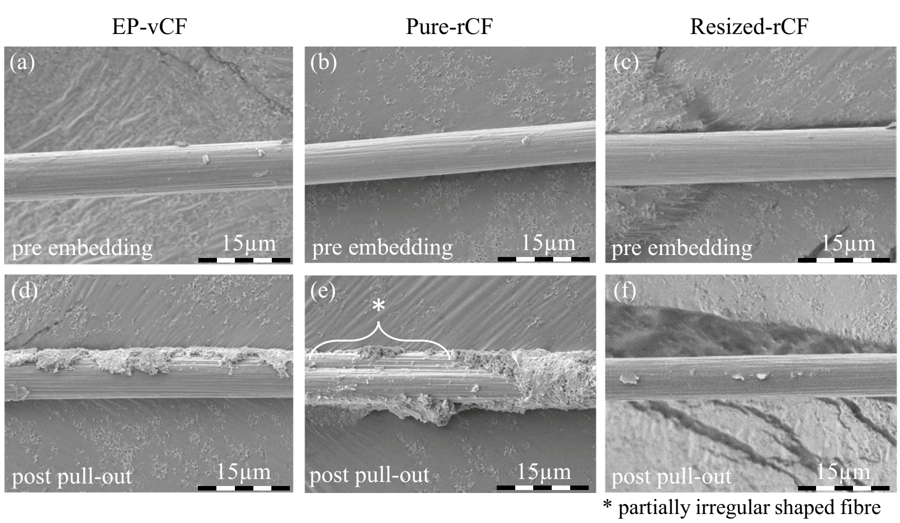


Fig. 6 Surface characteristics of fibres **a**–**c** pre-embedding before pull-out and **d**–**f** post pull-out

deterioration of the fibre quality due to recycling or embedding in mortar.

The surface structure of the resized-rCF is also visually comparable to the structure of the EP-vCF before embedding. No residues of mortar can be identified on the surface of the resized-rCF even after performing the pull-out test. Overall, the highest absolute strengths were also measured in the pull-out test for the resized-rCF type.

Overall, the following findings were obtained from the Single fibre pull-out test:

- The visual surface condition of the rCF is similar to the condition of the vCF before testing. Accordingly, the fibre surface does not appear to be profoundly damaged by the recycling process.
- In the format of the pull-out tests of EP-vCF and pure-rCF, the failure of the adhesive bond (mainly) does not occur at the interface between fibre and matrix, but in the matrix. Accordingly, the presumed bond strength is higher at the interface than the bond strength in the matrix for both vCF and rCF. In the case of the resized-rCF and adhesive failure occurs. But, the measured strength is comparable.
- Due to the greater distribution of the shear strength of pure-rCF compared to resized rCF the sizing seems to have a positive influence. But, the difference is rather low. In order to gain more precise insights, further test series would be required to investigate sizing materials for the resizing adapted to concrete matrix.
- The apparent interfacial shear strength is greater with non-pyrolysed fibres. Therefore, the rCF do not have a negative influence on the bonding behaviour.

Further conclusions, in comparison with the other test results are summarized in the discussion chapter.

3.2 Slump flow test

Base on the outcomes at ITA, the resized rCF were used at KICT for the following tests. The results of slump test conducted for UHPC and FRC are provided in Table 4.

FRC mixed with resized-rCF showed a greater decrease in slump flow than plain UHPC or FRC mixed with K-vCF. The slump flow of FRC mixed with 1% of resized-rCF (rCF1.0%) was at most 50.0% of plain UHPC. On the other hand, FRC mixed with K-vCF showed at most 14.3% decrease in slump flow than that of plain UHPC. FRC mixed with 1% of steel fibre showed no significant change in the slump flow.

Table 4 Slump flow of mortar and FRC

FRC ID	No fibre	K-vCF 0.5%	K-vCF 1.0%	Resized-rCF 0.5%	Resized-rCF 1.0%
Slump flow (mm)	210	190	180	140	105

3.3 Compressive strength test

The results of compressive test conducted for UHPC and FRC are provided in Fig. 7. The influence of K-vCF on compressive strength of FRC was insignificant. Figure 7a shows the results of compressive test conducted for FRC mixed with carbon.

The compressive strength of FRC mixed with 1% of resized-rCF was 32% greater than that of plain UHPC. On the other hand, the compressive strength of FRC mixed with 0.5% of resized-rCF was 8.2% smaller than that of plain UHPC.

Figure 7b shows the results of compressive test conducted for FRC mixed with carbon and steel fibres. The compressive strength of FRC mixed with CF (K-vCF and resized-rCF: 0.5 ~ 1.0%) and steel fibres (1.0%) was at least 40% greater than that of FRC mixed with CF (K-vCF and resized-rCF: 0.5 ~ 1.0%) only. Note that the compressive strength of FRC mixed with steel fibres (Steel 1.0%) was 125% of that of mortar. Therefore, the increase in the compressive strength of FRC mixed with CF and steel fibres was due to the steel fibres.

3.4 Direct tensile strength test

The tensile strength of FRC mixed with rCF was at least 33% greater than that of plain UHPC. For the same volume fraction of CF, the tensile strength of FRC with rCF was at least 14.9% greater than that of FRC with vCF. As shown in Fig. 8b, matrix cracked in the initial loading phase and after the crack stress increased linearly until a rupture of fibres. Because the bond strength between ultra-high strength mortar

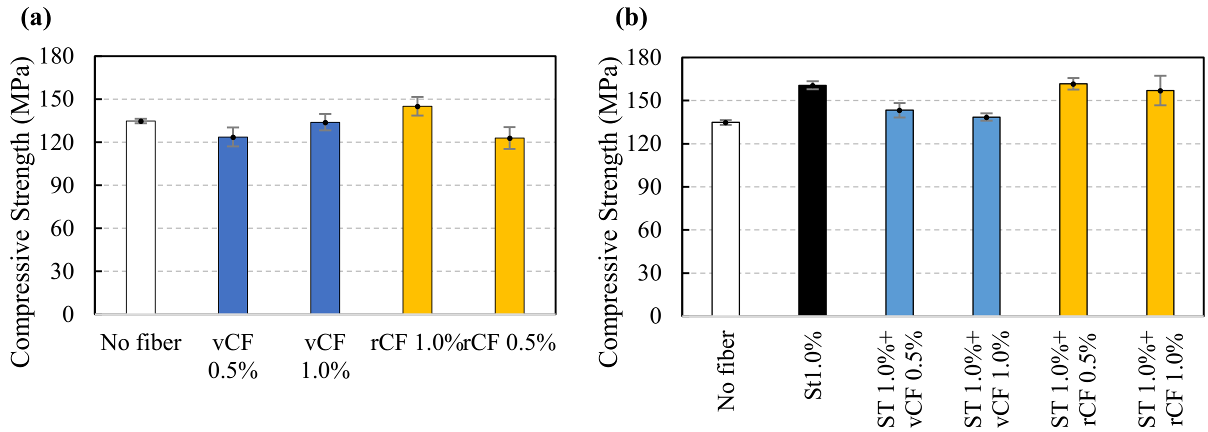


Fig. 7 Results of compressive strength test for plain UHPC and FRC: **a** mortar and FRC mixed with vCF and rCF, and **b** mortar and FRC with mixed fibres

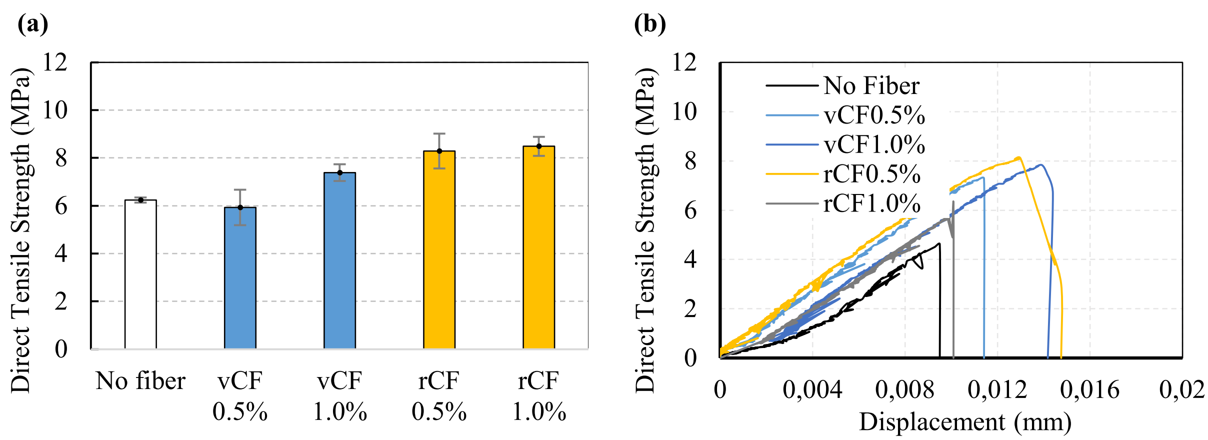


Fig. 8 Results of tensile strength test for FRC with carbon fibres: **a** direct tensile strength and **b** tensile stress versus displacement

and CF was very high, all fibres were ruptured without being pulled out.

With the addition of 1% CF, the direct tensile strength was decreased compared to vCF 0.5% and rCF 0.5%. Comparing the breaking line after failure, fibres were observed in the vCF specimen, while no fibres were visible in the rCF specimen. This means that vCF were pulled out from the matrix, but rCF were fully bonded and ruptured within the matrix. The use of only CF leads to direct failure. Figure 9 shows the results of tensile test conducted for FRC mixed with CF and steel fibres.

The tensile strength of FRC mixed with CF and steel fibres was at least 8.2% greater than that of FRC mixed with CF only. The combination of steel and rCF leads to a higher tensile strength. The addition of 0.5% rCF in combination with steel fibres shows the highest values. The maximum proportion of fibres is presumably reached at a total of 1.5%, which is why the samples with 1.0% steel and 1.0% vCF or rCF have slightly lower strength values. In contrast to the direct failure of FRC with CF steel and steel and CF combined FRC show a longer displacement and extraction of the fibres. The combination of fibres increases the displacement by more than 200% compared to using steel fibre alone.

When the fractured cross-sections were compared after the failure, rCF was ruptured but steel

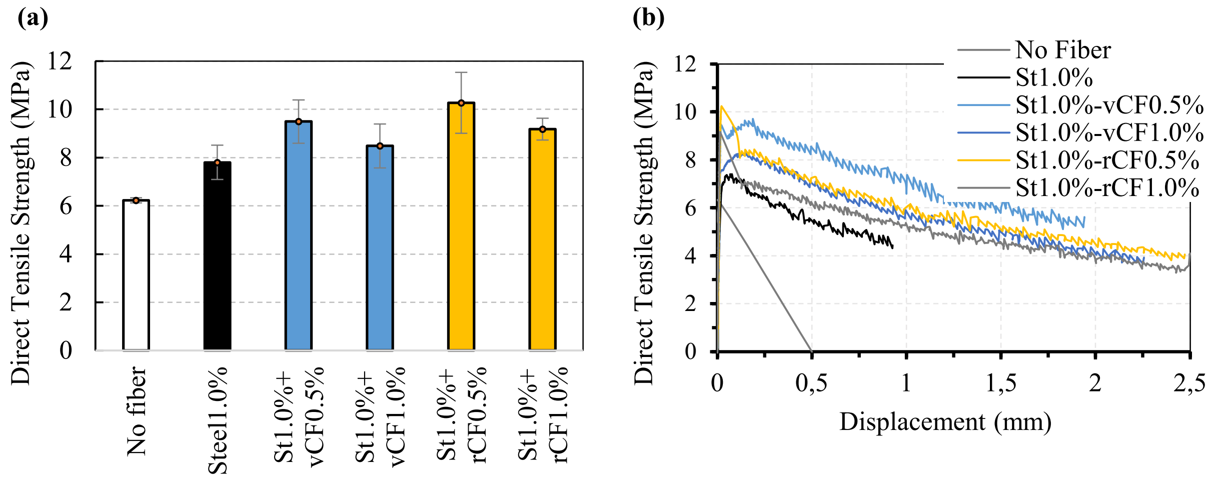


Fig. 9 Results of tensile strength test for FRC with steel fibres and carbon fibres: **a** direct tensile strength and **b** tensile stress versus displacement

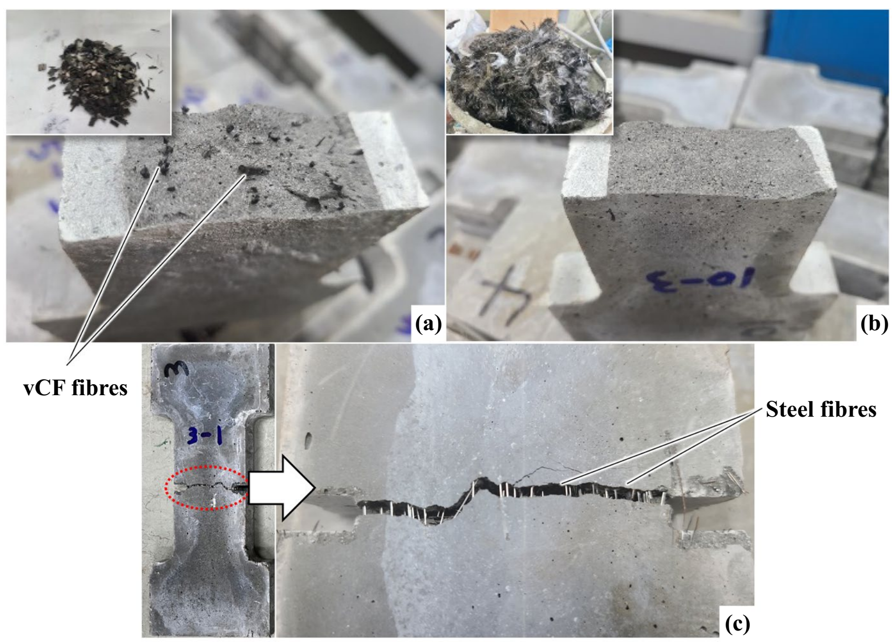
fibres were pulled out at failure. Furthermore, as shown in Fig. 10b, even after the matrix cracked, the specimens were able to resist to applied load. The test results indicated that the presence of steel fibres in the matrix provides crack bridging forces that resists crack formation (see Fig. 10c) and hence the tensile strength was increased.

4 Discussion

During the curing of the single fibre pull-out test specimens the matrix material shrinked due to the material properties. Therefore, not all prepared specimens could be used and evaluated due to a high variation of fibre insertion depth.

Non-pyrolysed cut-off-rCF and vCF have shown almost identical results. Cut-off rCF are a waste

Fig. 10 Fractured section after testing: **a** FRC with vCF, **b** FRC with rCF, and **c** FRC with steel fibres



product from the production of CF-textiles. Cut-off-rCF are non-pyrolysed rCF because these fibres were not used as reinforcing material in a matrix material and are resulting out of production cut-off waste. These fibres have therefore not yet been in contact with a polymer matrix material, which is why the fibres are non-pyrolysed compared to the two other rCF types. So, the surface properties of cut-off rCF and vCF remain comparable Due to the similarity of the results to EP-vCF, it can be assumed that the cut-off-rCF are also with an epoxy-based sizing. Before testing, the preparation of these fibres was unknown and seems due to the results to be similar to EP-vCF in this case. If required, this single-fibre pull out test could give besides the results about the fibre matrix adhesion, presumptions of the fibre types when comparing the results.

The increased adhesion of pyrolysed rCF can be explained on the basis of chemical or physical influencing factors. Physical adhesion could be in the form of roughening of the surface due to the pyrolysis process. This would cause an interlocking between the fibre and the concrete and thus increases the resistance to the pull-out of the fibre. It is uncertain whether this includes the irregular cross-section shown in Fig. 6. In addition, the irregularly shaped cross-section needs to be evaluated with a greater amount of fibres to analyse the reason for the irregularity. Since this only occurred with the pure and pulled-out fibres after testing, it is unclear whether this was coincidental and the damage was caused by the fibre production, the previous life-cycle, the pyrolysis process, in the specimen preparation or due to the adhesion in the pull-out process. In order to obtain a precise determination, a greater number of samples would have to be examined in a next study.

In the case of the resized fibre, which was coated with an acrylate-based sizing after pyrolysis, a micro-rough surface structure of the sizing material could also lead to a corresponding interlocking. However, a clear change in the surface structure could not be detected during the visual examination using SEM. No residues of mortar can be identified on the surface of the resized-rCF even after performing the single fibre pull-out test. This could be due to the acrylate-based sizing of the fibre.

The lack of adhesion of the EP-vCF samples might be due to the micro-smooth surface of the sized fibre and the low reactivity of epoxy-based sizing with concrete. Although this worsens the bond between the fibre and the matrix material, it can be useful in the context of recycling. Therefore, the resized rCF were used for the testing at KICT. The bonding behaviour was as good as for the pure rCF, but in terms of recycling, they might show better separation results. This assumption, as well as the influence of other sizing materials adapted to the matrix, would require detailed investigation in further tests.

The results of compressive test conducted for FRC with vCF and resized rCF indicated that the influence of vCF and resized rCF on the compressive strength of FRC was insignificant. Fibres are mainly suitable for absorbing tensile rather than compressive forces. It is therefore a positive result if the compressive strength does not change significantly due to the addition of fibres in the FRC. On the other hand, the results of tensile test conducted for FRC with vCF and resized rCF indicated that the tensile strength of FRC with resized rCF was at least 14.9% greater than that of FRC with vCF. An explanation therefore might be the change in adhesion due to the pyrolysis and a positive influence of the resizing material. Furthermore, when FRC was mixed with rCF and steel fibres, the tensile strength of FRC can be increased up to 66.1% compared to mortar.

When combining steel- and CF up to a total amount of 2.0% fibres, the test results are decreasing. As shown before, the amount of fibres in FRC is supposed to be not to high due to distribution problems which occur as shown in the slump test. The vCF have shown a minor influence in the slump test compared to rCF. As shown in Fig. 10, the vCF are distributed in agglomerations, as the sizing of the fibre before the cutting process causes the fibres to bond together. In this case, the majority of the fibre surfaces are in direct contact with each other. In comparison, the rCF are distributed with fewer agglomerations, as the rCF have less bonding with each other. The rCF were resized as short fibres after the pyrolysis process, when they did not stick together as much as vCF in an endless roving after the fibre production. Therefore, the rCF have a greater influence on the slump test, as a majority of the fibre surfaces are in direct contact to the concrete matrix. The resizing process of short fibres might have an influence as well.

Overall, in the tensile test, vCF were pulled out from the matrix, but rCF were fully bonded and ruptured within the matrix. In comparison for the single fibre pull-out the results seem to be different for the resized-rCF, because the adhesion between fibre and matrix is lower as no matrix residues are on the fibre surface after the pull-out test. The difference in the results is also due to the fibre distribution as mentioned before. The resized rCF are separated and evenly distributed Therefore the resized rCF are fully bonded to the concrete matrix and rupture due to the high forces during testing. In comparison, the vCF remain together due to the sizing and not every single fibre is fully bonded to the concrete matrix. The fibre–fibre bond differs from the fibre-matrix bonding and the bonded fibres pull apart while testing. This is why the vCF are visible at the fracture line and the resized rCF are not visible.

5 Summary and conclusion

Aim of this study was to improve the knowledge of different rCF types and sizing agents on mechanical performance of FRC to design a specific rCF type which is suitable for its use in concrete in the future. For this purpose, single fibre pull-out tests and tests on FRC were performed. In the pull-out tests, the aim was to evaluate the comparability of vCF and rCF in adhesion behaviour. In the slump-, compressive- and tensile strength test with FRC the aim was to identify the fibre matrix interaction and behaviour in the composite material.

The results presented show an improvement of the adhesion behaviour by using pyrolysed fibres. The resistance of the fibre pull-out results from the increased adhesion that occurs between the fibre material and the matrix until failure of the matrix is reached.

The results of slump flow test for FRC with vCF and resized rCF indicated that slump flow of FRC with rCF was at least 26.3% smaller than that of FRC with vCF. Therefore, FRC with rCF needs a high-performance water reducing agent to enhance workability. The tensile strength of FRC with resized-rCF was at least 14.9% greater than that of FRC with vCF. Therefore, resized-rCF can be used to improve tensile performance of FRC. The test results further indicated that if FRC was mixed with rCF and steel fibres, the tensile strength of FRC can further be increased.

The fibre distribute of rCF has less agglomerations caused by the resizing of the short fibres. If the vCF are cutted, the sizing has a bonding influence, even after insertion in the concrete matrix. Depending on the use case, the lack of adhesion between fibre and matrix of the resized-rCF might have a positive effect for the recycling. Further investigations are needed for the resizing with other materials for increasing properties. Therefore, besides the sizing material, also the order in the process, whether resizing takes place before or after the cutting process might have an influence and has to be further investigated. Additionally, the isotropic fibre distribution depending on different resizing materials for pyrolysed fibres as well as the influence on the recycling at the end of the lifecycle is ongoing and needs to be investigated in further studies.

When combining steel- and CF up to a total amount of 1.5% fibres, the test results are increasing. A greater amount of fibres decreases the test results slightly. As 1.0 rCF has a slightly higher tensile strength than 1.0 steel fibres it would be interested to test even greater amounts of just rCF fibres in FRC, to see if the point even seems to be with 1.5% fibres as well. But, the use of only CF leads to direct failure, in contrast to the longer displacement and extraction of steel and the combined fibres. An interesting fact is that the combination of fibres increases the displacement by more than 200% compared to using steel fibre alone.

In summary, the following findings can be noted for the adhesion of fibres in concrete:

- The use of pyrolysed unsized or acrylate-based sized fibres (named as pure-rCF and resized-rCF) creates an excellent adhesion between fibre and matrix material which is higher than for vCF
- Overall, the pyrolysed fibres achieve the highest absolute and average shear strengths. An increase of 150–250% in the apparent interfacial shear strength compared to the vCF could be observed. However, this finding comes with the highest scatter of absolute results.
- Non-pyrolysed cut-off rCF and vCF show almost identical results. It can therefore be assumed that the used cut-off rCF are the same fibre type with epoxy-based sizing as EP-vCF.
- The actual adhesive strength of pure, unsized rCF and concrete matrix is expected to be higher than the determined values because cohesive within the matrix can be observed.

- Sizing seems to have a positive influence on the homogeneity of the fibres, because the fibres with a sizing have shown a consistency of the apparent interfacial shear strength without outliers.
- The distribution of the fibres has an influence on the strength results. If fibre agglomeration occurs, the fibre–fibre bond ensures that the fibres are pulled out and therefore do not break directly at the fracture edge. If the fibres are distributed in cells, the fibre-matrix bond in the composite component is so strong that the fibres also break at the breaking edge.
- It was shown that the type of sizing but also the resulting fibre–fibre adhesion have an influence on the test results—when the fibres are resized after the pyrolysis, they adhere together less than vCF that are sized during fibre production and then cut into short fibres.

Although different matrices were used for the pull-out and FRC specimens in this study due to the local availability, the same matrix should be used for direct comparison of test results. It should be further noted that the number of test specimens for the compressive and tensile strength tests conducted in this study were limited to obtain reliable test results. This is an initial estimation; further test series will be required in subsequent studies for further in-depth results. Therefore, a test program with an increased number of specimens for the compressive and tensile strength of FRC, with the same matrix for pull-out and FRC specimens, should be conducted.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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