INFLUENCE OF CONCRETE MOISTURE ON THE FLEXURAL STRENGTH OF CARBON FIBRE REINFORCED CONCRETE

EINFLUSS DER BETONFEUCHTIGKEIT AUF DIE BIEGE-ZUGFESTIGKEIT VON KOHLESTOFFFASER-VERSTÄRKEM BETON

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SUMMARY

Carbon fibres are frequently used as reinforcing fibres in composite materials. The application in concrete composites is therefore also possible. Since there are hardly any results on embedded fibres, the influence of carbon fibres on compressive and flexural strength was shown. For this purpose, a high-strength concrete (HPC) with two different moisture contents was examined. It was found that with the addition of carbon fibres to the concrete, an increase in flexural strength could be achieved. The drying of the concrete also led to an increase in the flexural strength. However, both effects overlap only to a limited extent. When determining the compressive strength, exactly the opposite was shown: the drying of the concrete and the addition of carbon fibres both had a negative effect on the compressive strength.

ZUSAMMENFASSUNG

Carbonfasern werden meistens als Verstärkungsfasern in Verbundwerkstoffen verwendet. Auch der Einsatz im Betonverbund ist daher möglich. Da kaum Ergebnisse zu einbetonierten Fasern vorliegen, wurde der Einfluss von Carbonfasern auf Druck- und Biegezugfestigkeit gezeigt. Dazu wurde ein hochfester Beton (HPC) mit zwei unterschiedlichen Feuchtigkeiten untersucht. Es zeigte sich, dass mit der Zugabe von Kohlenstofffasern in den Beton eine Steigerung der Biegezugfestigkeit erreicht werden konnte. Die Trocknung des Betons führte ebenfalls zu einer Steigerung der Biegezugfestigkeit. Beide Effekte überlagern sich jedoch

nur bedingt. Bei der Bestimmung der Druckfestigkeit zeigte sich genau das Gegenteil. Die Trocknung des Betons sowie die Zugabe von Kohlestofffasern hatten beide einen negativen Effekt auf die Druckfestigkeit.

1. INTRODUCTION

The building industry is considered one of the main emitters of CO_2. A change is currently taking place in the construction industry. With the increasing awareness of environmental protection, the focus in the construction sector is moving away from environmentally harmful materials towards sustainable or more efficient building materials. With each new material come opportunities and problems. One of the most promising material is carbon. This material has already proven itself in other areas such as the aerospace industry. Due to its high strength and lightness, it makes sense to use it in the building sector. Despite its energy-intensive production, its high performance makes it possible to build with it in a way that saves resources in the long term. Currently, it is already being used in maintenance or in the development of corrosion-resistant reinforcement. So far, carbon fibres have mostly been used in combination with a synthetic resin. These resins are criticised for being dangerous to humans and the environment. With carbon fibre concrete, it would be possible to do without the resins. Therefore, tests were carried out with carbon fibres at different concrete moisture levels and the flexural strength and compressive strength were determined.

2. CARBON FIBRES

Carbon fibres are mostly used as reinforcing fibres in composite materials [1]. The high-strength carbon fibre takes over the load transfer along the fibre and the matrix fixes and supports it. Compared to other materials such as steel or aluminium, the resulting material has many advantages [1] & [2]. Despite their comparatively low density, the fibres have very high strength and stiffness values. Compared to their solid form, the material in fibre form even delivers significantly higher strength and elastic modulus values [2]. Due to their fibre form, carbon fibres exhibit strongly anisotropic behaviour in terms of their strength, Young's modulus and thermal expansion coefficients. Another advantage is that the fibres are largely corrosion-resistant and have a high fatigue strength. Due to the high-performance of the fibres, material can be saved and maintenance work can be reduced, which leads to a favourable energy balance over the service life [2].

Until now, expensive carbon has mainly been used in aviation because of the powerful and at the same time light material. With the higher material requirements and decreasing production costs, the material is increasingly used in other areas such as the automotive sector, in boat construction, for sports and leisure equipment and in the wind power sector. So far, the material has only been used to a limited extent in the construction sector. The high planning effort together with the high price have so far prevented its widespread use. One of the few areas of application in the construction industry is the maintenance of buildings. High mechanical performance and good durability are exploited to increase or ensure the stability of structures. Reinforced concrete structures can be subsequently reinforced with carbon strips bonded from the outside. The Technical University of Dresden went one step further and produced with the "cube" the world's first carbon house [3]. The house, which consists almost entirely of carbon concrete and has a carbon reinforcement. This allows the amount of concrete to be significantly minimized, since the reinforcement does not need to be protected against corrosion and thus requires a smaller concrete cover. At the University of Munich, carbon fibres in concrete are being tested as an alternative to steel fibres [4]. The fibres can be aligned with a 3D printer. Carbon also offers a promising application in bridge construction. In May 2020, for example, the first German net arch bridge was built in Stuttgart with hangers made of carbon. The lightweight hangers in combination with the high resistance to fatigue, made this subway bridge an economical alternative to net arch bridges with steel hangers [5].

3. INFLUENCE OF CONCRETE MOISTURE

The concrete moisture has an influence on the static compressive strength of concrete. For this purpose, it can be seen in Fig. 1 that the compressive strength of moist concrete decreases much more as a function of temperature than that of dry concrete without moisture [6]. The effect of concrete moisture on the pull-out resistance of steel fibres was investigated in [7]. Corrugated steel fibres were pulled out of the concrete with two different concrete moisture contents. In the dried concrete, a significantly higher pull-out resistance of the fibres was determined than in wet concrete, as shown in Fig. 2. The failure mode fibre rupture only occurred in dried concrete. In addition to these two influences, moisture has an effect on many other points, for example, the fatigue resistance of HPC also decreases with increased moisture [8].

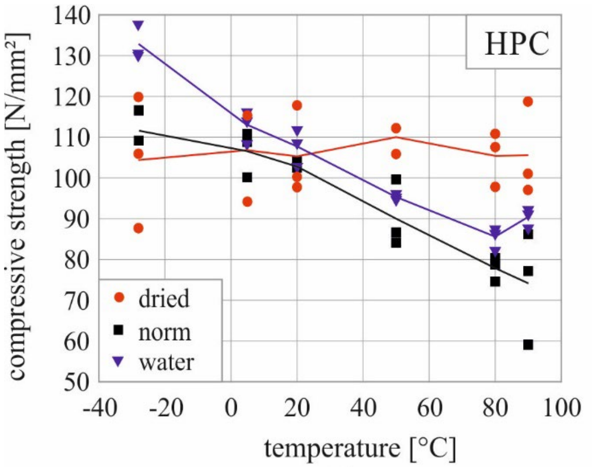

Fig. 1: *Compressive strength under temperature influence – HPC [6]*

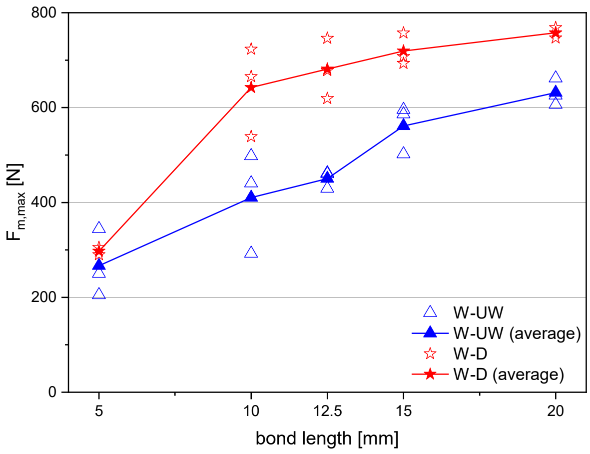

Fig. 2: *Pull-out resistance of fibre type W [7]*

4. MATERIALS AND METHODS

4.1 Material and Geometry

For the investigations with carbon fibres in this paper, an HPC with a maximum grain size of 2 mm (HPC2) was used. This mixture is based on the HPC of the Priority Programme SPP2020 [9]. The water-cement ratio (w/c) was 0.35. The exact components and quantities are listed in Table 1. Carbon fibres "SFC EPB F" from the company "Schwarzwälder Textil-Werke Heinrich Kautzmann GmbH" with a length of 6 mm were used. A picture of the fibres used can be seen in Fig. 3.

Table 1: Composition of HPC with w/c = 0.35

COMPONENT [-]	HPC2	HPC2-C
	Amount (kg/m³)	Amount (kg/m³)
CEM I 52,5 R-SR3 (na)	500	500
Quartz Sand H33 (0/0.5 mm)	75	75
Sand 0/2	850	850
Polycarboxylatether (PCE) Superplasticizer	6	6
Water	176	176
Carbon fibres: SFC EPB F – 6 mm (2 vol.-%)		23

Fig. 3: Close-up of carbon fibre bundle

4.2 Storage condition and experimental programme

Two different storage conditions were used to investigate the influence of concrete moisture. All samples were stored under water for 28 days. After 28 days, half of the samples were tested, while the other half were dried in the oven at 105°C for at least 14 days. In this way, concrete with two different moisture contents (see Table 2) could be examined. Furthermore, HPC2 without fibres and with 2 vol.-% carbon fibres were tested. Table 2 summarises the storage conditions and the experimental programme.

Table 2: Storage conditions and experimental programme

	HPC2-UW	**HPC2-D**	**HPC2-C-UW**	**HPC2-C-D**
FIBRE TYPE	**-**	**-**	**CARBON**	**CARBON**
Fibre content	-	-	2 vol.-%	2 vol.-%
Number of prisms	3	3	3	3
28 d under water	X	X	X	X
Minimum 14 d at 105°C	-	X	-	X
Moisture content	7.8 M-%	~0.1 M-%.		

4.3 Test setup

A testing machine of the company "Zwick Roell" of the type Z010 for the three-point bending flexural test was used. For the static compression tests a testing machine of the company "Testing" of the type 500/20 kN was used. A distance of 10 cm between supports was chosen for the three-point bending tensile test. The load was applied centrally between these supports at a loading rate of 1.2 mm/min. The static compressive strength was tested after determining the flexural tensile strength on an area of 4 x 4 cm² and a loading speed of 0.6 N/(mm²·s).

5. RESULTS

5.1 Flexural Strength

A characteristic force-displacement diagram for HPC2 and HPC2-C in the three-point bending flexural test is shown in Fig. 4. It can be clearly seen that up to the maximum force, both types of concrete have a similar curve. In the case of HPC2, the specimen is fractured after reaching the breaking load and can therefore no longer absorb any further forces. With HPC2-C, the fibre effect sets in after the maximum load is reached and a residual load-bearing capacity can still be achieved. Fig. 5 shows the results of the flexural strengths. It can be seen that for both HPC2 without carbon fibres and HPC2-C with fibres, the concrete moisture had a negative influence on the flexural strength. Thus, the flexural strength of HPC2 increased by 23.1% from 11.7 MPa to 14.4 MPa due to drying. For HPC2-C, drying caused an increase of 13.1% from 13.0 MPa to 14.7 MPa. The increase in flexural strength due to the carbon fibres can be seen especially in the concrete of the underwater storage. The flexural strength increased from 11.7 MPa to 13.0 MPa due to the addition of the carbon fibres. This clear difference of 11.1 % is no longer visible in the dried concretes HPC2-D and HPC2-C-D, where the difference was only 0.3 MPa. It was shown that the flexural strength of the concrete can be increased by using carbon fibres. The fibres can absorb relevant tensile forces under load and positively influence the flexural strength. The effect seems to be smaller with dried concrete. In [10] it is mentioned that carbon fibres contract and become thicker under thermal stress. This could contribute to the fact that the composite behaviour is weakened after drying, thus reducing the positive effect of drying.

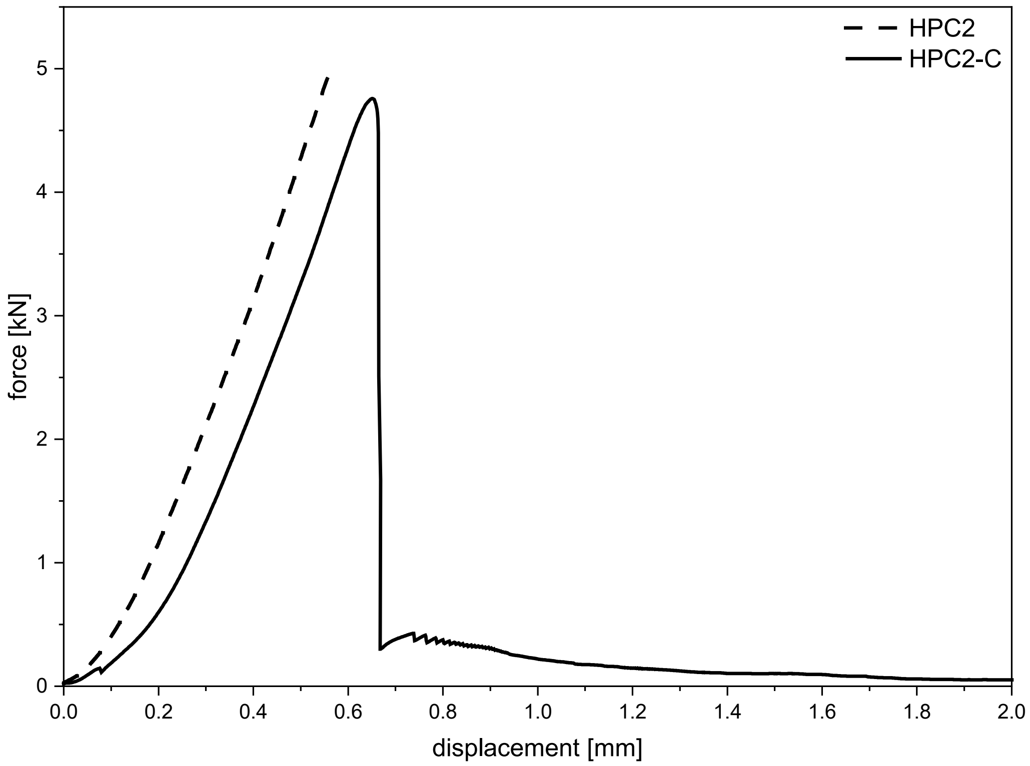

Fig. 4: Typical force-displacement of HPC2 and HPC2-C

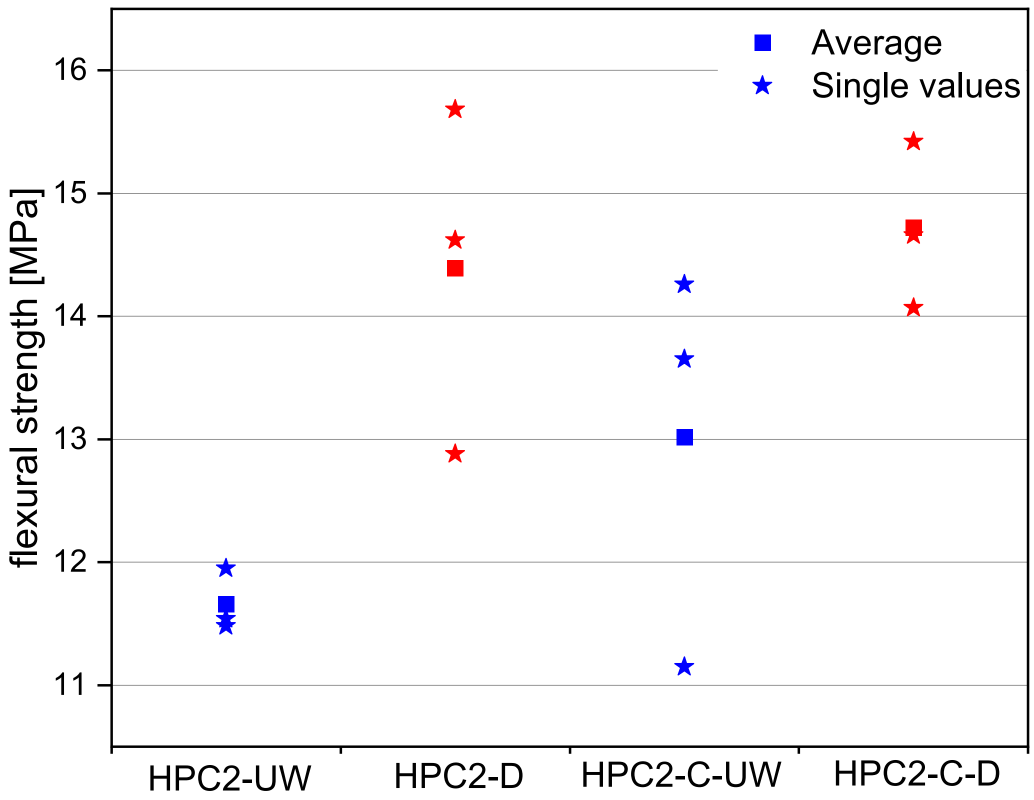

Fig. 5: Results of the flexural strengths

5.2 Compressive Strength

The influence of the carbon fibres and the moisture content on the compressive strength is shown in Fig. 6. It can be seen that regardless of the concrete moisture, drying at 105 °C had a negative influence on the compressive strength. Thus, the compressive strength of the concrete without fibres decreased by 27.3% from 87.2 MPa to 63.4 MPa. For the concrete with included carbon fibres, the compressive strength decreased from 76.8 MPa to 62.3 MPa due to drying, which corresponds to a percentage decrease of 18.9%. Besides the influence of drying, the addition of carbon fibres also seems to have a negative effect on the compressive strength. While the fibre addition has no effect on dried concrete, it is clearly visible in wet concrete. Thus, the compressive strength decreases by 11.9% from 87.2 MPa to 76.8 MPa due to the carbon fibres. Due to the fact that carbon fibres cannot absorb compressive forces, they do not contribute to load transfer but are to be regarded as a defect in the concrete matrix under compressive stress.

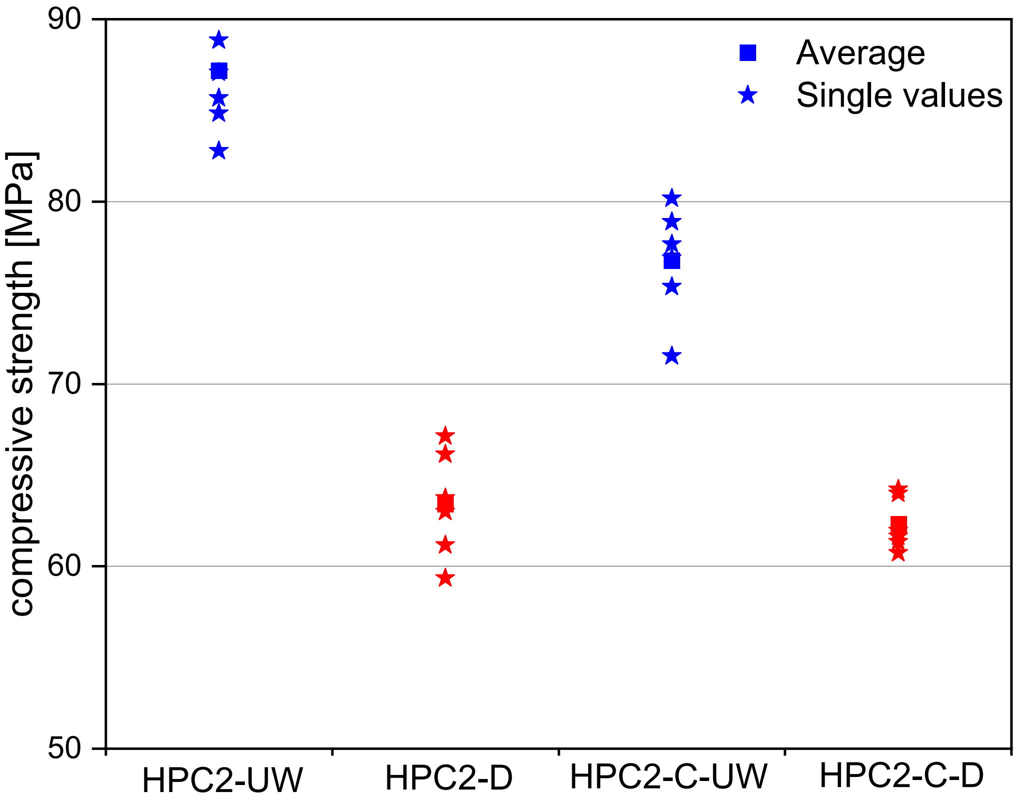

Fig. 6: Results of the compressive strengths

6. CONCLUSIONS AND OUTLOOK

Carbon fibres as a new material in concrete was used in the investigations described here. An HPC with a maximum grain size of 2 mm and two different storage conditions were investigated. It was shown that the flexural strength increased significantly when the concrete was dried. Drying resulted in a 23.1 % higher flexural strength compared to the wet concrete. With the addition of 2 vol.-% carbon fibres, an increase in flexural strength of 11.1 % was achieved. Both effects did not overlap, so that there was nearly no difference between dried specimens with and without fibres. A reason for this behaviour may be the influence of the temperature during drying at 105°C. Carbon fibres behave differently at higher temperatures than concrete. This influence on the bond behaviour must be determined more precisely in further researches. For this purpose, the concrete can be dried at a lower temperature in a vacuum. The effect of the carbon fibres on the compressive strength must also be examined more closely in further tests. Another approach to study is the behaviour of carbon fibres on the fatigue behaviour of concrete. The fatigue behaviour under compressive load as well as under tensile load should be investigated. Currently, carbon fibres are criticised mainly because of their eco-balance. In the future, lignin derived from wood could replace petroleum-based raw materials. To make the manufacturing process more environmentally friendly, mainly renewable energy should be used in the future. Another challenge is to research and develop suitable processes for a circular economy as already exists in the steel industry.

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