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ORIGINAL ARTICLE

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Fibre reinforced ultra-high performance concrete – Rheology, fibre bond strength and flexural strength

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Abstract

Ultra-high performance concrete (UHPC) is characterised by a high compressive strength, high durability, and a dense microstructure. The latter causes UHPC to fail in a brittle and sometimes explosive manner. For this reason, UHPC is reinforced with microfibre reinforcement. On the one hand, these lead to increased tensile and bending loads being able to be absorbed, but above all to ductile post-fracture behaviour. The fibres used are mostly steel fibres.

An essential aspect of the fibre reinforcement is the bond strength between UHPC and metallic fibre. The bond is divided into chemical-adhesive bond, form bond and friction bond. Depending on the shape, material and surface condition of the fibre, the individual types of bond have different effects on the concrete. To quantify these effects, fibre pull-out tests are often carried out. These provide information about the bond strength between the fibre and the concrete. However, results of various studies show that the bond strength does not automatically correlate with the actual influence on the resulting tensile and flexural strengths of concrete components.

Keywords

Ultra-high performance concrete, fibre reinforced concrete, bond strength

1 Introduction

Ultra-high performance concrete (UHPC) is known for its high compressive strength above 150 MPa and its very dense microstructure [1]. These properties are based on a high binder content, a low w/b value of 0.20 - 0.25 and a matrix optimised for packing density. The dense microstructure of the material leads to a good resistance against frost and chloride attack as well as against carbonisation [2]. Despite the high amounts of binder, the good mechanical characteristics of UHPC allow constructions with very thin elements that have the same load capacity of regular concrete elements with much higher volumes. Furthermore, the requirement of less material but with enhanced mechanical properties has positive impacts on capital and running costs like transportation and restoration [3]. Thus, in terms of durability and requirements of raw materials, UHPC can be assigned as a promising building material.

Compared to the high compressive strength, the flexural and tensile strength of UHPC is much lower and requires a reinforcement in form of rebars and/or fibres [4]. A rebar reinforcement mainly increases the flexural and tensile strength of the material, while a fibre reinforcement introduces a more ductile failure behaviour compared to the brittle to explosive failure behaviour of non reinforced UHPC [4]. In contrast to the mechanical properties of the hardened concrete, the workability of the fresh concrete is reduced by the fibre reinforcement. This is more significant with increasing fibre volume content. Thus, in UHPC a fibre content of 1 – 3 vol.% is mainly used [5]. This work will connect and discuss the results of several investigations at the Department of Structural Materials and Construction Chemistry at the University of Kassel. These were carried out to get a better understanding of various aspects of fibre reinforced concrete [6–15]. This includes investigations regarding the bond behaviour of different fibre materials, fibre modifications and concrete mixtures as well as functionalization of the fibre reinforcement to improve concrete properties. The latter is introduced into the concrete by using fibre reinforcement made of shape memory alloys (SMA). The SMA have the ability to "remember" an imprinted shape that can be regained after mechanical deformation. That shape transformation can be achieved by thermal or mechanical activation depending on the chemical composition of the SMA.

https://doi.org/10.1002/cepa.2859

2 State of the art

To ensure a positive effect of the reinforcement a sufficient bond between reinforcement material and cementitious concrete matrix has to be assured. The bond between fibre and UHPC matrix can be subdivided into three different parts: the adhesive bond, the shear bond due to anchorage of e.g., hook-shaped fibres, as well as the frictional bond (Figure 1) [6; 10].

The adhesive bond results from physical and chemical interactions between the UHPC matrix and fibre material [16]. The physical interaction is mainly based on micro-interlocking of the fibres that is given due to surface topography of the fibre. The chemical interaction is influenced by the degree of hydration, cementitious phases on the fibre surface as well as the abundance of aggregates and air voids in the contact zone between fibre and UHPC matrix [17]. This zone is also called interfacial transition zone (ITZ). In case of standard concrete, the ITZ has a lower strength then the surrounding cementitious matrix. This is mainly due to a slightly higher water concrete and the abundance of a calcium hydroxide layer in the ITZ [18; 19]. Thus, micro-cracking occurs inside the ITZ and not directly on the fibre surface. However, in UHPC, the ITZ is strengthened due to the secondary reaction of silica fume inside the system. The abundant calcium hydroxide is replaced by C-S-H phases and the ITZ is reduced in thickness.

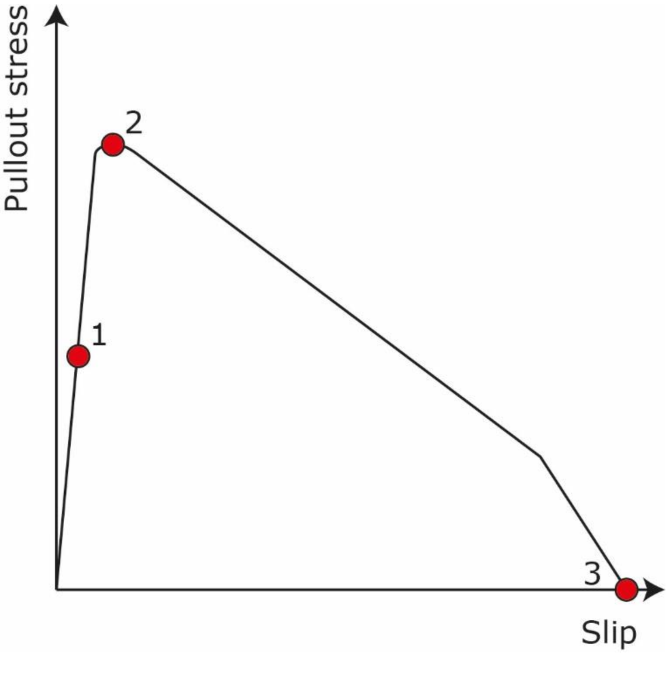

Figure 1 Sketch of a typical fibre pullout stress/slip-diagram of a straight fibre.

The frictional bond is mainly based on the micro-interlocking between fibre and UHPC matrix [20]. Thus, a rough fibre surface, a strong ITZ and, in general, longer fibres enhance the frictional bond [10; 21]. The frictional bond is activated in the moment when the adhesive bond reached its maximum stress (Point 1 in Figure 1). The fibre starts to "debond" from the matrix and is slowly pulled out of the matrix upon complete fibre pullout. However, the adhesive bond is still partly active and, therefore, both bonding mechanisms contribute to the maximum bond strength (Point 2 in Figure 1). After complete debonding and failure of the adhesive bond, the frictional bond is mainly responsible for the post failure behaviour upon complete fibre pullout (Point 3 in Figure 1) and is, therefore, important for the post cracking behaviour of UHPC components.

The bond strength can be strengthened even further by a shear bond due to an anchorage [22; 23]. This can be applied by physically deforming of the fibres. The most common types for this are end-hooked or twisted fibres. However, a too strong bond is also not favourable as in that case, the fibre would not be pulled out of the matrix. This would lead to an abrupt failure of the concrete component, which is the opposite to what is desirable for fibre reinforced concrete.

The bonding of the fibre reinforcement described above is dependent on different aspects of the used fibres and concrete. The fibre material as well as its mechanical and microstructural properties has a significant influence on the fibres' performance [10; 24]. Furthermore, the chemical and physical properties of the used concrete contribute to the resulting properties of the reinforced concrete. In general, a higher strength of the concrete leads to a stronger bond between fibre and matrix [24]. However, the bonding of the fibre reinforcement can be modified and optimised in different ways. This can be supported by adding different admixtures to the concrete [25; 26]. Vice versa a modification of the fibres can also be exploited to enhance the bond. This can be done by physical or chemical treatment [10; 27] or by coating of the fibres [28] to enhance the fibres surface roughness.

In contrast to the positive influence on the mechanical properties of the hardened concrete, a fibre reinforcement is leading to a reduction of the workability of the fresh concrete [19; 29; 30]. Workability of fresh concrete is mostly described by rheological properties. These can be measured by quantitative measurements of slump flow, plastic viscosity, and yield stress. While slump flow can be gathered relatively simple and is a decent method at the building site, the measuring of plastic viscosity and yield stress requires a rheometer or viscometer. These testing devices measure the shear stress and the shear rate of a testing gauge that moves through the fresh concrete (Figure 2). The gathered data can be interpreted in several ways using model systems. In general, fresh concrete is mostly described as a *Bingham fluid*. In contrast to a *Newtonian fluid*, these fluids reveal a specific yield stress, i.e., a specific stress is required before the fluid starts to flow. However, due to numerous studies, these models were modified and specified for different cementitious systems [13; 30–32]. Using the fitted models, fresh concrete can be described more detailed and more realistic.

The investigations have shown that fibre reinforcement significantly influences the rheological properties of fresh UHPC. Hence, the volume fraction of the fibres in UHPC are mostly limited to approx. 3 vol% [5]. This is further influenced by different parameters, such as fibre aspect ratio (ratio if fibres length to diameter), fibre geometry and also concrete matrix rheology [29; 33].

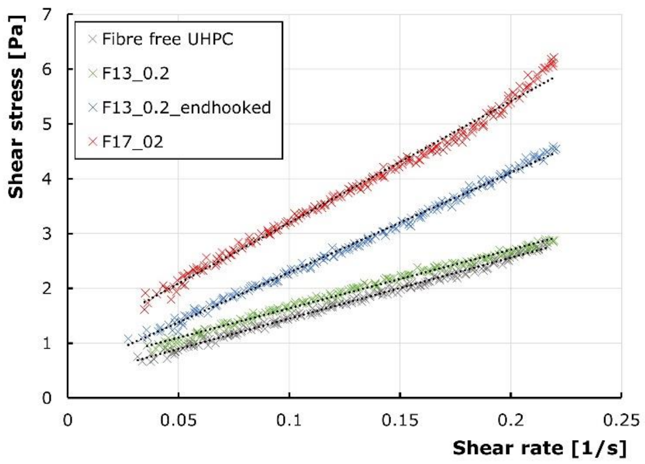

Figure 2 Influence of fibre reinforcement (1. vol.%) on the rheology of fresh UHPC. Rheometer measurements of the shear stress and shear rate reveal that fibres with a length of 13 mm and a diameter of 0.2 mm increase the measured shear stress. This influence is enhanced by endhooked fibres and fibres with a greater fibre aspect ratio.

To improve the properties of fresh and hardened UHPC a functionalisation of the fibre reinforcement was investigated in several studies. For this, fibres made of shape memory alloys were used. These shape memory alloys have the ability to "remember" an imprinted shape. This ability is based on a fully reversible phase transformation from the low temperature phase martensite to the high temperature phase austenite. The phase transformation can be triggered due to thermal or mechanical activation. Thus, when a SMA element is mechanically deformed and the phase transformation occurs, a SMA element will change its form into the imprinted shape [34]. Depending on the chemical composition of the SMA, two different shape memory effects can be exploited. The "one-way shape memory effect" (also known as pseuoplasticity) and the superelasticity (Figure 3).

The most used shape memory alloy is the Ni-Ti SMA, also known as Nitinol [34; 35]. However, this alloy is mostly used in medicine, aeronautics, and robotics and not for applications in constructions due to its enormous costs. In civil and mechanical engineering SMA based on iron or copper are used as they are cheaper than Nitinol and are, therefore, affordable for large scale applications [36; 37]. The use of SMA in civil engineering is quite novel, as first investigations were carried out in the 1970s while first applications were used in the 1990s and early 2000s [37–40]. Several publications proposed different iron-based shape memory alloys for the use in applications [36; 37; 39] as these are affordable and reveal a decent shape memory effect. This is also the case for the quite novel SMA based on a Fe-Mn-Al-Ni alloy [41; 42].

3 Experimental

Different investigations were carried out to characterise several aspects of fibre and rebar reinforced UHPC. This includes mechanical and physical properties of hardened concrete [6; 8; 10; 15; 43] as well as fresh concrete [7; 8; 11; 13]. In case of the hardened concrete, the bonding strength between different fibre types and cementitious UHPC matrix was investigated and various methods for bond modification and enhancement were shown [6; 10].

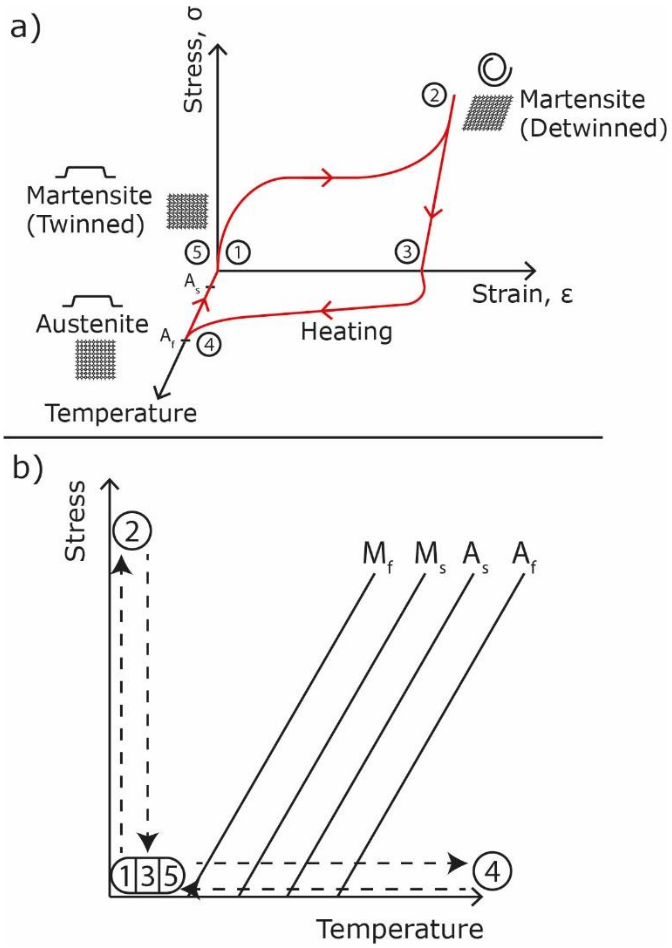

Figure 3 Sketch of the one-way shape memory effect exemplary shown for an endhooked SMA fibre. a) Visualization in the stress/strain/temperature-diagram. b) corresponding stress-strain-temperature path. Point 1 shows the endhooked fibre (imprinted shape), point 2 shows mechanical deformation of the fibre. This deformation is permanent (Point 3). Thermal activation of the SMA fibre above a specific temperature (A_f) activates the shape memory effect and the fibre returns into its imprinted shape (Point 4). This fibre stays in this shape after cooling (Point 5). Based on [35].

This is done using fibre pullout tests that allow to quantify the bond strength between fibre and UHPC. Stainless steel and brass coated steel fibres as well as SMA fibres made of Ni-Ti were tested regarding their bond strength. To modify the bond stress of these fibres roughening of the fibres and coating of the fibres with plastics was investigated and compared with resulting concrete strengths of fibre reinforced UHPC samples. Additionally, investigations in regard to bond stress of fibres in $C0_2$-reduced UHPC based on alkali activated materials (AAM) were investigated [15].

For investigations of fresh concrete, the influence of fibre volume fraction and fibre shape on the rheological properties were measured using slump flow as well as measurements using concrete rheometers and viscometers. These methods allow a quantification of the fibres influence on the fresh concrete properties. Fibres made of shape memory alloys was used to optimise the rheological properties of fresh concrete. For this purpose, endhooked fibres (imprinted geometry) were formed into a circular shape. These fibres were added into the concrete in the mixing process. This will counteract agglomeration of the fibres. After filling of the moulds, the still flowable concrete was heated inside an oven to activate the fibres. This led to a transformation in the imprinted shape and, therefore, to enhanced mechanical properties after hardening.

Detailed information on the experimental procedures can be found in the referred publications.

4 Results and discussion

4.1 Bond between different fibres and UHPC

It was found that different fibre materials reveal a varying bond strength with UHPC [8; 10]. This was shown for different steel fibres as well as SMA fibres made of Ni-Ti (Figure 4). The tests have shown that stainless steel fibres have a much stronger bond than brass coated steel fibres. This difference is even more prominent when comparing stainless steel fibres to Ni-Ti SMA fibres [8; 10].

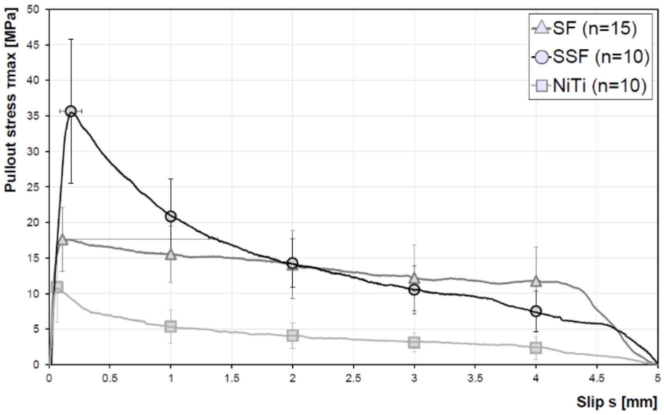

Figure 1 Bond stress of stainless steel (SSF), brass coated steel (SF) and Ni-Ti SMA (Ni-Ti) fibres embedded in UHPC [10].

This relationship does not transfer to CO_2-reduced UHPC based on AAMs. In AAM-based UHPC, the bond stress between steel fibres and matrix is generally higher compared to cement-based UHPC. Furthermore, in contrast to the cement-based system, the brass coated fibres reveal a stronger bond than stainless steel fibres. The difference between the two fibre types, however, is smaller compared to the cementitious UHPC [15].

This difference does not transfer to actual flexural bending tests of UHPC prisms, reinforced with the same fibres. The flexural strength of the samples with SF fibres is significantly higher than for the SSF fibres (Figure 5). Ni-Ti fibres could not be tested due to availability of the materials.

The bond strength between fibre an UHPC can be modified by different method. In own studies a modification by surface roughening using a laser and coating of fibres with TPE were investigated (Figure 6). Roughening of the fibres increased in maximum bond stress for all investigated fibres by approx. 2 to 3 times. In case of stainless-steel fibres, the bond was partially too strong as several fibres are torn during testing [10]. This is not favourable as it would counteract the wanted ductile post failure behaviour of the reinforced concrete. Coating of the fibres also led to an increase in maximum bond stress between fibre and cementitious UHPC matrix [6]. However, the increase was not that significant compared to roughening of the fibres.

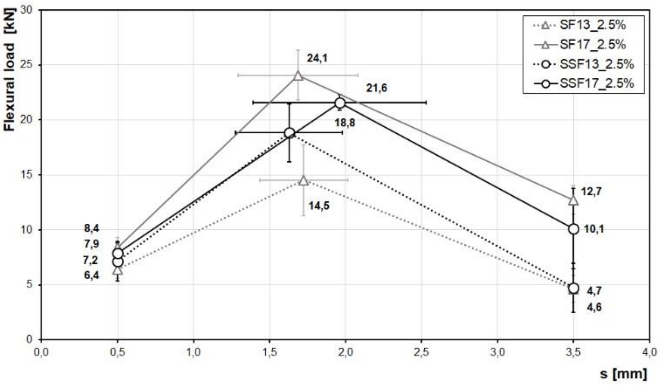

Figure 5 Influence of fibre material and length on flexural strength of fibre reinforced UHPC. Fibre volume fraction is 2.5 %. The flexural load at a displacement of 0.5 mm, 3.5 mm and at maximum load with standard deviations is shown [10].

Furthermore, it was found out that the results regular fibre pullout tests that are carried out in a linear way without any fibre inclination do not fit to the corresponding flexural strengths of fibre reinforced UHPC prisms [6]. Therefore, the pullout setup was adapted to inclined fibre pullout tests with inclinations of 15°, 30° and 45°. The tests revealed a less significant influence of the TPE-coating on the bond strength. It was revealed that the improvement due to the coating is limited on the adhesive bond between fibre and matrix. The frictional bond is weakened for coated fibres. This could be due to peeling of the TPE-coating. The negative influence on the frictional bond is also seen in bending tests of UHPC reinforced with TPE-coated fibres. These revealed a lower maximum flexural strength compared to samples reinforced with regular steel fibres [6]. In reinforced concrete, the fibres are randomly distributed and orientated. Thus, after initial cracking, the fibres inside the cracking area are activated and pulled out. This pullout will

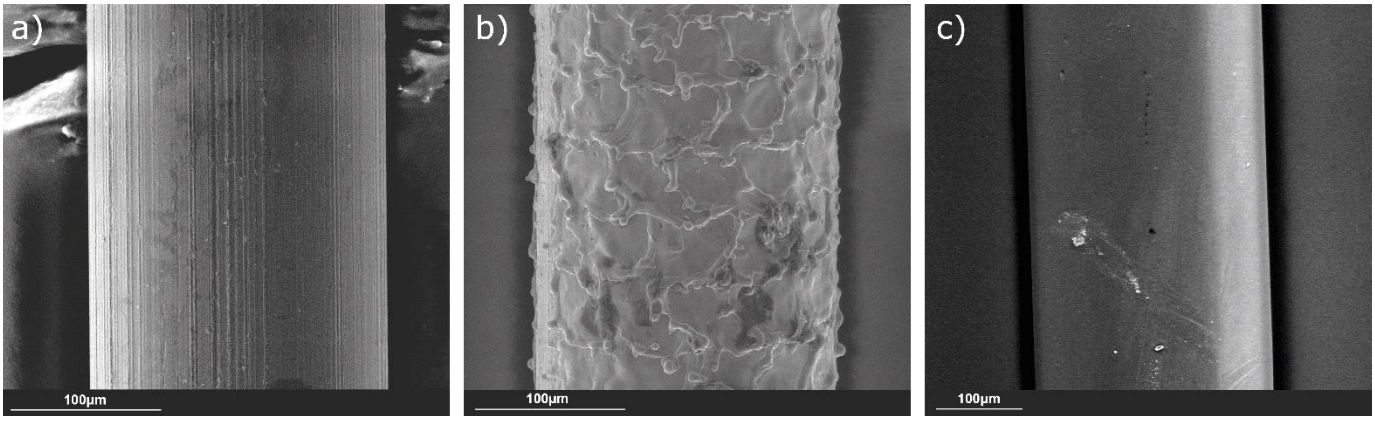

Figure 6 SEM images of surfaces of different fibres. a) Surface of a regular brass coated steel fibre [10]. b) Surface of a roughened fibre due to laser treatment [10]. c) Surface of a TPE-coated fibre. Images in secondary electron mode.

occur in random orientation. Therefore, the fibres that are pulled out with an inclination lead to a deteriorated post cracking behaviour of the UHPC.

Both fibre modifications revealed a significant influence on the bonding strength between fibre und UHPC matrix. Roughening of the fibres increased the bond strength significantly, while coating of the fibres improved the adhesive bond of the fibres. The frictional bond, however, was decreased. This was seen in fibre pullout tests as well as in flexural bending tests [6; 10].

4.2 Optimisation of fresh concrete rheology

The workability of fresh concrete is also strongly influenced by the addition of fibres. In contrast to the positive influence on the mechanical properties of the hardened concrete, the workability of fresh concrete is degraded due to fibre reinforcement (Figure 7). This is further promoted by higher aspect ratio (length/diameter ratio) of the fibre as well as by "complex" fibre shapes, e.g., endhooked and twisted fibres.

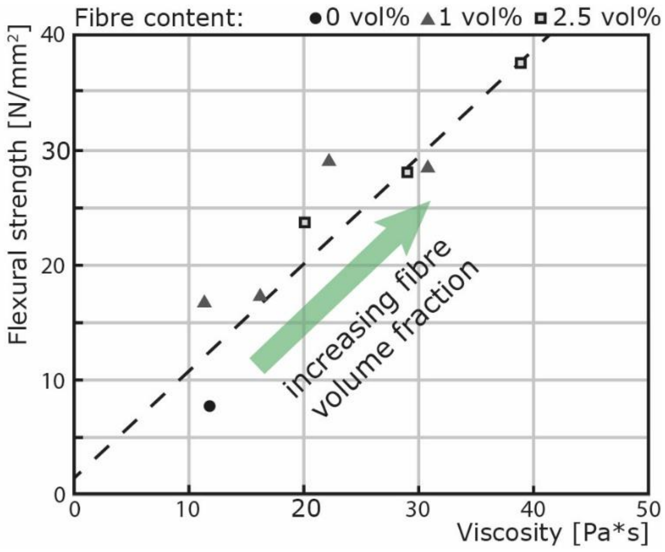

Figure 7 Influence of fibre reinforcement on the plastic viscosity of fresh concrete and the flexural strength of hardened concrete depending on fibre volume fraction. Image modified from [8].

The use of fibres made of shape memory alloys (SMA) allow to use fibres with an optimised shape for the rheological properties of fresh concrete. The circular shape of fibres leads to a decrease of about 30% in plastic viscosity as well as in yield stress compared to regular straight fibres (Figure 8) [8; 13]. Furthermore, it was shown that the transformation of the fibres inside the fresh UHPC is possible without damaging the internal microstructure of the material [8; 14]. For this proof, five single endhooked fibres (imprinted shape) made of Ni-Ti were formed in a circular geometry. After addition to the fresh concrete, the sample was heated inside an oven to 60 °C. This temperature is above the specific transformation temperature A_f of the alloy, thus, the fibres transformed into their imprinted shape. A nearly complete retransformation of all fibres was found. Furthermore, no damaging or grooves inside the microstructure were found in the hardened concrete using μ-CT imaging [8; 14].

For future research the activation of the fibres using induction heating will be focused. This method would be more suitable as the concrete itself would be excluded from heating. Due to the induction effect, only the fibres (and small areas of concrete around the fibres) would be heated directly. This would be beneficial for the fresh concrete properties as deterioration of fresh concrete properties due to heating would be minimised.

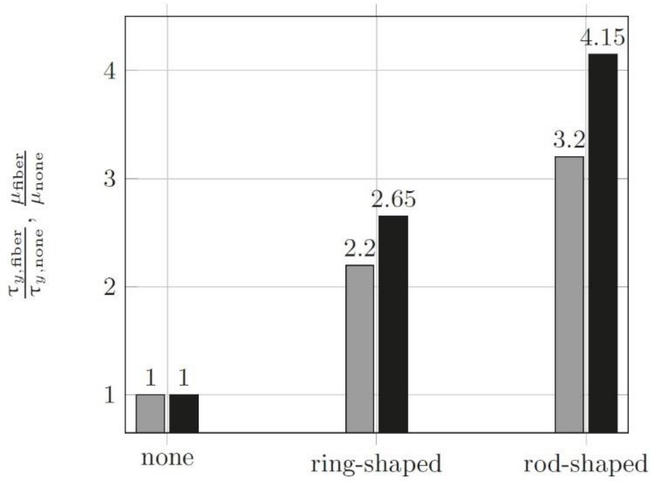

Figure 8 Influence of ring-shaped fibres onto the plastic viscosity μ and yield stress τ_γ of fresh UHPC compared to regular rod-shaped fibres as well as a reference without fibres. (Black: $\frac{\mu_{fibre}}{\mu_{reference}}$; Grey: $\frac{\tau_{\gamma,fibre}}{\tau_{\gamma,reference}}$). Image from [13].

4.3 Internal prestressing of UHPC using SMA rebar and fibre reinforcement

Another use of SMA as reinforcement in UHPC is the prestressing capability of the material. In this application, the one-way shape memory effect is exploited. In contrast to the use as a rheology optimising tool (see chapter 4.2), the material is prevented to deform due to the activation of the material by anchoring inside the UHPC. Thus, a stress is applied on the concrete that can be used as a prestress application.

In [42] it was shown that the quite novel Fe-Mn-Al-Ni SMA has a huge potential for such applications. The material is affordable and reveals significant benefit compared to other SMA. The material allows to combine the different shape effects. However, this still has to be investigated and will be part of future work. The actual implementation of the proposed Fe-Mn-Al-Ni SMA in form of a rebar reinforcement revealed an increase in maximum flexural strength due to the activation of the shape memory effect. Prestrained rebars were fixed inside the moulds and after hardening of the concrete, the specimens were heated inside an oven. This increase was significantly higher compared to non activated rebars [43]. Furthermore, a sample with non-prestrained rebars was heated to exclude that the improvement is only because of the thermal treatment of the samples (Figure 9). However, investigations of the metallic microstructure revealed an unfavourable texture of the rebars. Thus, the shape memory effect was not that distinct compared to other SMA [44; 45] as well as to the same alloy that was used in [42]. Further research will be focused on the use of the Fe-Mn-Al-Ni alloy in forms of fibres and the implementation of a prestress by the fibre reinforcement. This would be quite effective, as no extra rebar reinforcement is possible, and the prestress elements are added directly in the mixing process. However, many single fibres will behave completely different than some single rebars in regard to applying the prestress onto the concrete.

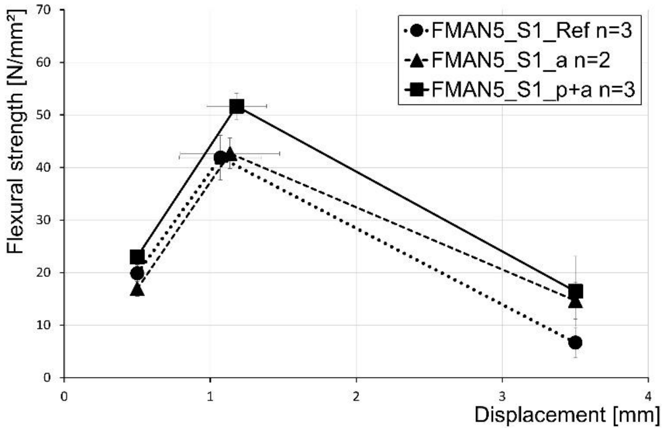

Figure 9 Influence of thermal activation of the shape memory effect on the maximum flexural strength of rebar reinforced UHPC. Shown are a reference (FMAN5_S1_Ref; non-prestrained and non heated), non prestrained but heated (FMAN5_S1_a) and prestrained and heated samples (FMAN_S1_p+a). Image from [43].

5 Conclusion and outlook

The results of the different studies have shown that the bond strength of fibres is dependent on several factors, e.g, fibre material, fibre surface topography and fibre shape. Steel fibres reveal a better bond strength compared to fibres made of a Ni-Ti alloy. The performance of the fibres can be modified and improved by surface roughening or fibre coating with plastics. Roughening of the fibres leads to a significantly improved bonding due to microinterlocking, while coating of fibres enhances the adhesive bond between fibre and cementitious matrix. This allows the use of microfibres that would have a significantly worse bond strength than the regular used steel fibres. Combined with the use of shape memory alloy fibres a huge potential for applications in civil engineering is given. Due to the use of reinforcement made of shape memory alloys, the workability of fresh concrete can be improved. This was shown for the plastic viscosity and the yield stress of UHPC. Furthermore, shape memory alloys can be used for prestress UHPC. This was shown for a Fe-Mn-Al-Ni alloy. In general, shape memory alloys combined with UHPC reveal a huge potential for civil engineering and applications in the building industry. This was shown for concrete technology and applies to fresh concrete properties as well as to the properties of hardened concrete.

However, there are still several open questions regarding fibre reinforced concrete, especially for fibre reinforcement made of SMA, as well as fibre modification. These questions will be addressed in future research.

1. Is it possible to use the elastic characteristics of plastics that are used for fibre coating? This is especially interesting for the sustainability of UHPC.
2. How does the coating behave on the microstructural scale? This could be investigated using *in situ* µ-CT measurements during fibre pullout tests.
3. Do other fibre shapes have a more dominant impact on the rheology of fresh concrete?
4. How will inductive activation affect the fibre reinforced fresh concrete?
5. Is it possible to use fibres made of SMA for prestress applications in UHPC?
6. How will the combination of different shape memory effects influence the properties of UHPC?

References

[1] Bornemann, R.; Schmidt, M.; Fehling, E.; Middendorf, B. (2001) *Ultra-Hochleistungsbeton UHPC - Herstellung, Eigenschaften und Anwendungsmglichkeiten* in: Beton- und Stahlbetonbau 96, H. 7, S. 458–467. https://doi.org/10.1002/best.200100550

[2] Wang, D.; Shi, C.; Wu, Z.; Xiao, J.; Huang, Z.; Fang, Z. (2015) *A review on ultra high performance concrete: Part II. Hydration, microstructure and properties* in: Construction and Building Materials 96, S. 368–377.
https://doi.org/10.1016/j.conbuildmat.2015.08.095;

[3] Racky, P. (2003) *Wirtschaftlichkeit und Nachhaltigkeit von UHPC* in: Schmidt, M.; Fehling, E. [Hrsg.] *Ultra-hochfester Beton: Planung und Bau der ersten Brücke mit UHPC in Europa; Tagungsbeiträge zu den 3. Kasseler Baustoff- und Massivbautagen*. Kassel: Kassel Univ. Press, S. 49–57.

[4] Fehling, E.; Schmidt, M.; Walraven, J.; Leutbecher, T.; Fröhlich, S. (2014) *Ultra-High Performance Concrete UHPC – Fundamentals, Design, Examples*. s.l.: Ernst & Sohn.

[5] Wu, Z.; Shi, C.; Khayat, K. H. (2019) *Investigation of mechanical properties and shrinkage of ultra-high performance concrete: Influence of steel fiber content and shape* in: Composites Part B: Engineering 174, S. 107021. https://doi.org/10.1016/j.compositesb.2019.107021

[6] Schleiting, M.; Klier, K.; Wiemer, N.; Wetzel, A.; Zarges, J.-C.; Heim, H.-P.; Middendorf, B. (2023) Fibre pullout behaviour of fibre-reinforced UHPC with TPE-coated fibres in: Construction and Building Materials 376, S. 131043.
https://doi.org/10.1016/j.conbuildmat.2023.131043

[7] Schleiting, M.; Wetzel, A.; Gerland, F.; Niendorf, T.; Wünsch, O.; Middendorf, B. (2020) *Improvement of UHPFRC-Rheology by Using Circular Shape Memory Alloy Fibres* in: Mechtcherine, V.; Khayat, K.; Secrieru, E. [Hrsg.] *Rheology and Processing of Construction Materials*. Cham: Springer International Publishing, S. 142–148.

[8] Schleiting, M.; Wetzel, A.; Krooß, P.; Thiemicke, J.; Niendorf, T.; Middendorf, B.; Fehling, E. (2020) *Functional microfibre reinforced ultra-high performance concrete (FMF-UHPC)* in: Cement and Concrete Research 130, S. 105993.
https://doi.org/10.1016/j.cemconres.2020.105993;

[9] Schleiting, M.; Wetzel, A.; Wiemer, N.; Middendorf, B. (2020) *Shape memory alloy microfibres in UHPC – possibilities and challenges* in: Middendorf, B.; Fehling, E.; Wetzel, A. [Eds.] *HiPerMat 2020 5th International Symposium on Ultra-High Performance Concrete and High Performance Construction Materials*. Kassel. Kassel: Kassel University Press, pp. 69–70.

[10] Wiemer, N.; Wetzel, A.; Schleiting, M.; Krooß, P.; Vollmer, M.; Niendorf, T.; Böhm, S.; Middendorf, B. (2020) *Effect of Fibre Material and Fibre Roughness on the Pullout Behaviour of Metallic Micro Fibres Embedded in UHPC* in: Materials (Basel, Switzerland) 13, H. 14, S. 3128. https://doi.org/10.3390/ma13143128

[11] Gerland, F.; Schleiting, M.; Schomberg, T.; Wünsch, O.; Wetzel, A.; Middendorf, B. (2020) *The Effect of Fiber Geometry and Concentration on the Flow Properties of UHPC* in: Mechtcherine, V.; Khayat, K.; Secrieru, E. [Hrsg.] *Rheology and Processing of Construction Materials*. Cham: Springer International Publishing, S. 482–490.

[12] Schleiting, M.; Wetzel, A.; Göbel, D.; Krooß, P.; Frenck, J.-M.; Niendorf, T.; Middendorf, B. (2022) *Growth of C-S-H phases on different metallic surfaces* in: Journal of microscopy. https://doi.org/10.1111/jmi.13089

[13] Gerland, F.; Wetzel, A.; Schomberg, T.; Wünsch, O.; Middendorf, B. (2019) *A simulation-based approach to evaluate objective material parameters from concrete rheometer measurements* in: Applied Rheology 29, H. 1, S. 130–140. https://doi.org/10.1515/arh-2019-0012

[14] Middendorf, B.; Schleiting, M.; Fehling, E. (2022) *Potential of shape memory alloys in fiber reinforced high performance concrete* in: Zingoni, A. [Hrsg.] *Current Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems*. London: CRC Press, S. 1307–1312.

[15] Wetzel, A.; Göbel, D.; Schleiting, M.; Wiemer, N.; Middendorf, B. (2022) *Bonding Behaviour of Steel Fibres in UHPFRC Based on Alkali-Activated Slag* in: Materials (Basel, Switzerland) 15, Nr. 5. https://doi.org/10.3390/ma15051930

[16] Naaman, A. E.; Namur, G.; Alwan, J. M.; Najm, H. S. (1991) *Fiber Pullout and Bond Slip. I: Analytical Study* in: Journal of Structural Engineering, H. 117, S. 2769–2790.

[17] Ostrowski, K.; Sadowski, Ł.; Stefaniuk, D.; Wałach, D.; Gawenda, T.; Oleksik, K.; Usydus, I. (2018) The Effect of the Morphology of Coarse Aggregate on the Properties of Self-Compacting High-Performance Fibre-Reinforced Concrete in: Materials (Basel, Switzerland) 11, Nr. 8. https://doi.org/10.3390/ma11081372

[18] Holschemacher, K.; Klug, Y.; Dehn, F.; Wörner, J. D. (2006) *Faserbeton* in: Bergmeister, K.; Wörner, J. D. [Hrsg.] *Beton- Kalender 2006, Teil 1: Turmbauwerke, Industriebauten*. Berlin: Ernst & Sohn, S. 585–663.

[19] Wietek, B. (2020) *Faserbeton*. Wiesbaden: Springer Fachmedien Wiesbaden.

[20] Breitenbücher, R.; Song, F. (2014) *Experimentelle Untersuchungen zum Auszugsverhalten von Stahlfasern in höherfesten Betonen* in: Beton- und Stahlbetonbau 109, H. 1, S. 43–52. https://doi.org/10.1002/best.201300049

[21] Kim, B.-J.; Yi, C.; Ahn, Y. (2017) *Effect of embedment length on pullout behavior of amorphous steel fiber in Portland cement composites* in: Construction and Building Materials 143, S. 83–91. https://doi.org/10.1016/j.conbuildmat.2017.03.030;

[22] Leutbecher, T.; Fehling, E. (2012) *Tensile Behavior of Ultra-High-Performance Concrete Reinforced with Reinforcing Bars and Fibers: Minimizing Fiber Content* in: ACI Structural Journal 109, H. 2. https://doi.org/10.14359/51683636;

[23] Kim, D. J.; Kim, H. A.; Chung, Y.-S.; Choi, E. (2016) *Pullout resistance of deformed shape memory alloy fibers embedded in cement mortar* in: Journal of Intelligent Material Systems and Structures 27, H. 2, S. 249–260. https://doi.org/10.1177/1045389X14566524

[24] Kim, D. J.; Kim, H. A.; Chung, Y.-S.; Choi, E. (2014) *Pullout resistance of straight NiTi shape memory alloy fibers in cement mortar after cold drawing and heat treatment* in: Composites Part B: Engineering 67, S. 588–594. https://doi.org/10.1016/j.compositesb.2014.08.018

[25] Wu, Z.; Khayat, K. H.; Shi, C. (2017) Effect of nano-SiO2 particles and curing time on development of fiber-matrix bond properties and microstructure of ultra-high strength concrete in: Cement and Concrete Research 95, S. 247–256. https://doi.org/10.1016/j.cemconres.2017.02.031

[26] Naaman, A. E. (2000) *Fasern mit verbesserter Haftung* in: Beton- und Stahlbetonbau 95, H. 4, S. 232–238. https://doi.org/10.1002/best.200000400

[27] Chun, B.; Kim, S.; Yoo, D.-Y. (2021) *Benefits of chemically treated steel fibers on enhancing the interfacial bond strength from ultra-high-performance concrete* in: Construction and Building Materials 294, S. 123519. https://doi.org/10.1016/j.conbuildmat.2021.123519

[28] Casagrande, C. A.; Cavalaro, S. H. P.; Repette, W. L. (2018) Ultra-high performance fibre-reinforced cementitious composite with steel microfibres functionalized with silane in: Construction and Building Materials 178, S. 495–506. https://doi.org/10.1016/j.conbuildmat.2018.05.167;

[29] Biswas, R. K.; Bin Ahmed, F.; Haque, M. E.; Provasha, A. A.; Hasan, Z.; Hayat, F.; Sen, D. (2021) *Effects of Steel Fiber Percentage and Aspect Ratios on Fresh and Harden Properties of Ultra-High Performance Fiber Reinforced Concrete* in: Applied Mechanics 2, H. 3, S. 501–515. https://doi.org/10.3390/applmech2030028

[30] Khayat, K. H.; Meng, W.; Vallurupalli, K.; Le Teng (2019) *Rheological properties of ultra-high-perfor-*

mance concrete — An overview in: Cement and Concrete Research 124, S. 105828.
https://doi.org/10.1016/j.cemconres.2019.105828

[31] Martinie, L.; Roussel, N. (2011) *Simple tools for fiber orientation prediction in industrial practice* in: Cement and Concrete Research 41, H. 10, S. 993–1000.
https://doi.org/10.1016/j.cemconres.2011.05.008

[32] Mezger, T. G. (2019) *Das Rheologie Handbuch*. Vincentz Network.

[33] Martinie, L.; Rossi, P.; Roussel, N. (2010) *Rheology of fiber reinforced cementitious materials: classification and prediction* in: Cement and Concrete Research 40, H. 2, S. 226–234.
https://doi.org/10.1016/j.cemconres.2009.08.032

[34] Lagoudas, D. C. (2008) *Shape Memory Alloys*. Boston, MA: Springer US.

[35] Kaack, M. (2002) *Elastische Eigenschaften von NiTi-Formgedächtnis-Legierungen,* Dissertation. Ruhr-Universität Bochum.

[36] Janke, L. (2005) *Applications of shape memory alloys in civil engineering structures - Overview, limits and new ideas* in: Materials and Structures 38, H. 279, S. 578–592.
https://doi.org/10.1617/14323

[37] Abavisani, I.; Rezaifar, O.; Kheyroddin, A. (2021) *Multifunctional properties of shape memory materials in civil engineering applications: A state-of-the-art review* in: Journal of Building Engineering 44, S. 102657.
https://doi.org/10.1016/j.jobe.2021.102657

[38] Maji, A. K.; Negret, I. (1998) *Smart Prestressing with Shape-Memory Alloy* in: Journal of Engineering Mechanics, H. 124, S. 1121–1128.

[39] Cladera, A.; Weber, B.; Leinenbach, C.; Czaderski, C.; Shahverdi, M.; Motavalli, M. (2014) *Iron-based shape memory alloys for civil engineering structures: An overview* in: Construction and Building Materials 63, S. 281–293.
https://doi.org/10.1016/j.conbuildmat.2014.04.032

[40] Indirli, M.; Forni, M.; Martelli, A.; Spadoni, B.; Venturi, G.; Alessandri, C.; Bertocchi, A.; Cami, R.; Capelli, C.; Baratta, A.; Procaccio, A.; Clemente, P.; Canio, G. de; Carpani, B.; Bonacina, G.; Franchioni, G.; Viani, S.; Cesari, F.; Mucciarella, M.; Meucci, C. (2001) *Further New Projects in Italy for the Development of Innovative Techniques for the Seismic Protection of Cultural Heritage* in: Assisi, Italy.

[41] Tseng, L. W.; Ma, J.; Wang, S. J.; Karaman, I.; Kaya, M.; Luo, Z. P.; Chumlyakov, Y. I. (2015) *Superelastic response of a single crystalline FeMnAlNi shape memory alloy under tension and compression* in: Acta Materialia 89, S. 374–383.
https://doi.org/10.1016/j.actamat.2015.01.009

[42] Vollmer, M.; Bauer, A.; Frenck, J.-M.; Krooß, P.; Wetzel, A.; Middendorf, B.; Fehling, E.; Niendorf, T. (2021) *Novel prestressing applications in civil engineering structures enabled by Fe Mn Al Ni shape memory alloys* in: Engineering Structures 241, S. 112430.
https://doi.org/10.1016/j.engstruct.2021.112430

[43] Schleiting, M.; Wetzel, A.; Bauer, A.; Frenck, J.-M.; Niendorf, T.; Middendorf, B. (2023) *Potential of Fe-Mn-Al-Ni Shape Memory Alloys for internal Prestressing of Ultra-High Performance Concrete* in: Materials 16, 3816.
https://doi.org/10.3390/ma16103816

[44] Shahverdi, M.; Czaderski, C.; Motavalli, M. (2016) *Iron-based shape memory alloys for prestressed near-surface mounted* strengthening *of reinforced concrete beams* in: Construction and Building Materials 112, S. 28–38.
https://doi.org/10.1016/j.conbuildmat.2016.02.174;

[45] Sawaguchi, T.; Kikuchi, T.; Ogawa, K.; Kajiwara, S.; Ikeo, Y.; Kojima, M.; Ogawa, T. (2006) *Development of Prestressed Concrete Using Fe–Mn–Si-Based Shape Memory Alloys Containing NbC* in: MATERIALS TRANSACTIONS 47, H. 3, S. 580–583.
https://doi.org/10.2320/matertrans.47.580