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INFLUENCE OF FIBER ORIENTATION ON THE CYCLIC BEHAVIOR OF STRAIN-HARDENING CEMENT-BASED COMPOSITES (SHCC)

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Abstract: Today, the building industry makes a major contribution to global warming and increasing scarcity of resources. Hence, it is urgent to foster application of new construction materials in modern infrastructures. Such materials have a great potential to reduce the use of resources, while offering a high performance under various exposures. In this context, strain-hardening cement-based composites (SHCC) may play a prominent role since they exhibit ductile behavior under different types of mechanical loads, plus they are considered to be very durable due to the reduced ingress of deleterious materials. The last feature can be traced back to small crack widths characteristic for this type of materials.

For a safe use of SHCC in the practice of construction, it is necessary to have an extensive knowledge about their mechanical performance and damage mechanisms under cyclic loading conditions. Since the fiber deterioration is strongly influenced by the fiber orientation, this parameter deserves to be closely investigated. The article at hand presents first results on the cyclic behavior of SHCC specimens with different fiber inclination angles of 0°, 30° and 60° related to the direction of tensile force. To estimate the effect of the fiber orientation, cyclic tension-swelling tests were performed. The results of monotonic, quasi-static tensile tests served as a reference. Subsequently, the crack surfaces were investigated by means of electron microscopy in order to evaluate the degradation of the polymer fibers and the surrounding cementitious matrix.

1 INTRODUCTION

Climate change and the increasing shortage of resources are forcing the construction industry to search for alternatives to conventional reinforced concrete aiming to minimize materials usage while increasing durability for prolonged service life.

A promising substitute is known as strain-hardening cement-based composite (SHCC), also referred to as Engineered Cementitious Composite (ECC). SHCC is a micro-mechanically designed high-performance fiber-reinforced material exhibiting significant load-bearing and strain capacities of several percent [1]. These unique deformation properties result from multiple crack formations facilitated by crack-bridging and stress transfer mechanisms over the crack by the fibers into weaker areas of the specimen’s cross-section leading to subsequent crack initiation. On account of the multiple crack development, SHCC has an remarkable energy absorption capacity making it an ideal material structures exposed to dynamic loads such as explosions or impact [2]. Additionally, cyclic loading scenarios caused by rolling traffic, wind, and earthquakes impose significant stress on structural components. This type of loading has attracted extensive research attention from various perspectives, ranging from the micro to the mesoscopic level [3–5]. Tension-swelling and reversed cyclic loading tests have revealed different types of deterioration phenomena, including fiber pull-out, fiber fatigue, and complete fiber degradation due to repetitive crushing between crack faces.

However, a comprehensive understanding of cyclic performance and its influencing factors is still lacking. One of the little investigated parameters is the orientation of the fibers that is known to affect the mechanical response under quasi-static loading conditions. Several of these studies investigated the influence of the fiber inclination angle at single fiber level [6, 7]. It was found that increasing the inclination angle results in an elevated crack-bridging stress, along with a stress concentration at the fiber exit point, leading to the fracture of the brittle matrix, known as matrix spalling. The increase in pull-out force can be attributed to the additional deformation processes of the fibers occurring near the exit point coupled with increased friction between the fiber and the matrix. However, this inclination angle also significantly affects the tensile strength of the fiber, as the surface damage becomes more severe.

Moreover, several authors conducted quasi-static tests on SHCC specimens at the mesoscopic level [8–10]. These experiments showed that an increase in the fiber inclination angle leads to a reduction in the tensile strength, attributable to the diminishing crack-bridging capacity of the fibers. This phenomenon arises due to a greater fiber deterioration and a higher number of ruptured fibers caused by deflection of the fiber over the sharp edges of the matrix. Furthermore, the authors stated that inclined fibers are to be regarded as flaws that reduce the strength of the composite [10].

To investigate the influence of the inclination angle on the crack-bridging capacity of PVA fibers under cyclic loading condition, Ranjbarian and Mechtcherine [11] conducted cyclic single fiber pull-out tests with inclination angles of 0°, 30° and 60°. Their findings revealed that the fiber inclination causes the ruptured section to relocate from inside the fiber channel to the fiber’s exit point. This occurs due to the abrasion of the fiber surface resulting in the weakening of the cross-section.

The investigation at hand intends to analyze the effect of the fiber orientation on the cyclic performance on a mesoscopic level. For this purpose, cyclic tension-swelling tests are carried out on small prisms with fiber inclination angles of 0°, 30° and 60° related to the direction of loading. Digital image correlation (DIC) techniques are employed to examine the cracking behavior of the composite during the cyclic loading. Subsequently, the crack faces are analyzed using an environmental scanning microscope (ESEM) to evaluate the degradation of the polymer fibers.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

The investigation was carried out on a high-strength Strain-Hardening Cement-based Composite (SHCC) developed at the Institute of Construction Materials, TU Dresden [12]. The detailed composition is given in

Table 1.

Table 1. Composition of the high-strength PE-SHCC under investigation

Component	**[kg/m³]**
Cement CEM 52.5R-SR3/NA	1460
Micro silica ELKEM 971	292
Quartz sand 0.06 – 0.2 mm	145
Superplasticizer Glenium ACE460	35
Water	315
PE fibers 2 % by volume	20

The SHCC consisted of ultra-high molecular weight polyethylene (UHMWPE) fibers, namely the commercially available PE fiber SK78 manufactured by DSM Dyneema, The Netherlands. The fibers had a length of 12 mm and a diameter of 20 µm. They were chosen for their exceptional mechanical properties. To achieve a favorable ductility by multiple crack formation, the fiber volume fraction was set to 2.0 %. To ensure proper fiber distribution, the aggregate size of the fine quartz sand was limited to 0.2 mm. The bonding between the hydrophilic fibers and the surrounding cementitious matrix was enhanced by using Portland cement and silica fume as the binder materials. Because of the low water-to-binder ratio superplasticizer was used to enable a suitable workability.

The SHCC preparation involved homogenizing all dry components, except the fibers, in a mixer. The premixed liquid ingredients were added, and the mixture was blended until agglomeration occurred. Prior to incorporating the fibers, they were separated from each other by blowing them in a specialized bucket using compressed air, thus improving their distribution. Subsequently, the fibers were slowly added into the mixture until a plastic consistency was achieved. For specimen production, an extrusion-like approach was employed. The fresh SHCC was filled into a specially designed mold measuring 20 cm x 20 cm, equipped with a lid. The lid was gradually closed, and the material was extruded through an opening on the opposite side, as depicted in Figure 1.

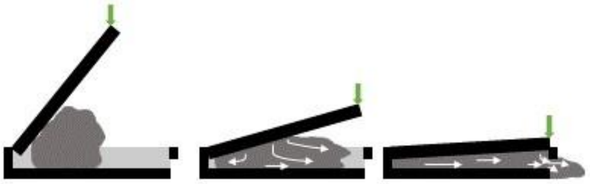

Figure 1. Production of the specimens

24 hours after production, the plates were demolded and stored for an additional 55 days at a temperature of 20 °C and a relative humidity of 65%. Prior to testing, specimens measuring 2 cm x 10 cm were cut out of the plates, oriented with respect to the direction of extrusion. The samples were then notched to a depth of 3 mm, and a black and white speckle pattern was applied to the surface for Digital Image Correlation (DIC) analysis.

2.2 Test Setup

Figure 2 depicts a schematic representation of the setup for the mechanical tests on specimens with different fiber inclination angles. The samples were notched in order to reduce the number of cracks and concentrate damage to just a few crack planes. Furthermore, crack localization should be predictable and not take place outside the measuring range. Hence, the calculated stress was related to the remaining net cross-section of the notched area.

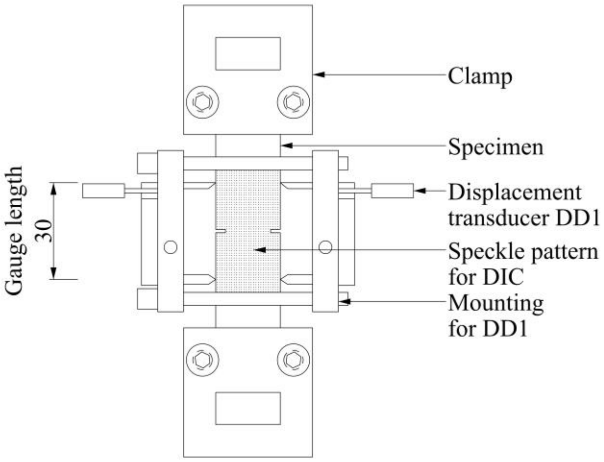

Figure 2. Test configuration

The tests were performed using a universal testing machine Zwick 1445 RetroLine equipped with a 10 kN load cell. The specimens were attached to the machine by a special clamp with a clamping area of 2 cm x 2 cm. The deformation was measured by two HBM displacement transducers DD1 with a range of ± 2.5 mm within a gauge length of 30 mm.

To examine the influence of the fiber orientation on the cyclic performance of SHCC, a three-part experimental procedure was implemented as illustrated in Figure 3.

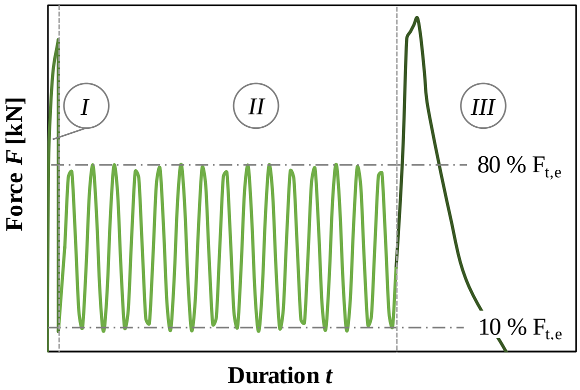

Figure 3. Schematic test procedure

The routine consisted of: I) pre-damage with a defined deformation of 0.25 mm, II) cyclic loading stage with 20,000 cycles, and III) quasi-static pull-out. For the quasi-static loading phases, a displacement rate of 0.05 mm/s was chosen. During the cyclic loading stage, a sinusoidal load with a frequency of 1 Hz was applied on the samples with upper and lower load limits set at 80 % and 10 % of the first-crack stress ($f_{t,e}$), respectively.

Accompanying the mechanical examinations, images were captured after defined numbers of loading cycles with a SLR camera Nikon Z6 II in order to analyze the crack development, including crack initiation and opening via digital image correlation (DIC) using the image analysis software GOM Correlate.

3 TEST RESULTS

3.1 Quasi-static loading

Prior to investigating the influence of the fiber inclination on the cyclic performance of SHCC, preliminary quasi-static tests were conducted on notched miniature specimens in order to provide a reference and to define load limits for the tension-swelling tests. The inclination-dependent characteristic mechanical properties, including first-crack stress ($f_{t,e}$), tensile strength (f_t) and maximum deformation (u_{max}) are given in Figure 4. Here, maximum deformation is defined as the displacement when reaching the tensile strength f_t.

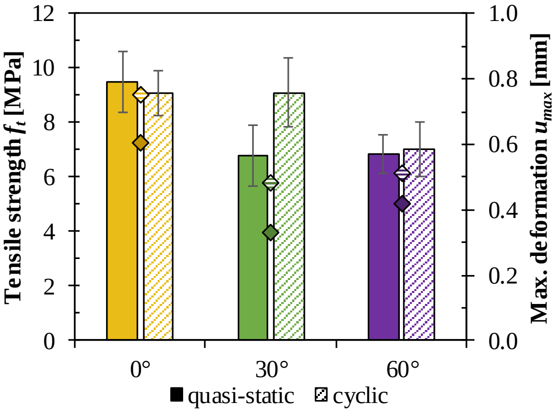

Figure 4. Tensile strength values and maximum deformation depending on the fiber orientation

The results show that an increase in fiber inclination angle leads to a decrease in the first-crack stress, consistent with previous research findings. The figure suggests that the ultimate tensile strength and corresponding deformation initially decrease from 0° to 30° and then exhibit an increasing trend. However, the analysis of pristine, unnotched samples revealed that both tensile strength and deformation capacity decrease with increasing fiber inclination angle, as obtained from previous investigations. The observed difference in the mechanical characteristics between notched and unnotched may be attributed to a more significant impact of structural defects in the notched samples that result in a deviation in the decreasing trend with increasing fiber inclination.

Moreover, the cracking behavior, i.e. number of cracks and average crack width during the quasi-static tests was assessed using DIC; see Table 2.

Table 2. Number of cracks and average crack width under quasi-static loading depending on the fiber orientation (standard deviation is given in brackets)

Angle	**Crack count N_R [-]**	**Max. crack width w_c [µm]**
0°	20.3 (6.9)	42.6 (12.3)
30°	12.8 (1.9)	61.6 (19.1)
60°	12.0 (4.2)	70.4 (23.8)

In addition to the observed decrease in maximum deformation with increasing fiber inclination, the reduction in ductility is also evident from the decrease in the total number of cracks within the gauge length and the simultaneous increase in the maximum average crack width, as can be seen in the table. Notably, the discrepancy in the number of cracks and crack opening between inclination angles of 0° and 30° is more pronounced compared to that between 30° and 60°.

Besides, the decrease in tensile strength and deformation capacity can be also traced back to the total number of fibers contributing to crack bridging since there is a clear decrease when considering a same-sized cross-section.

3.2 Cyclic loading

Based on the findings of the quasi-static experiments, different load levels were assigned to the respective fiber orientations each corresponding to the average first-crack stress of the respective testing series; see Table 3.

Table 3. Upper and lower force limits for each fiber orientation (values given in N)

Angle	Lower force level 10 % $F_{t,e}$	Upper force level 80 % $F_{t,e}$
0°	82.1	656.5
30°	66.9	534.9
60°	61.3	490.4

Figure 5 depicts the stress-deformation relationships for representative samples with various fiber inclination angles subjected to cyclic tension-swelling loading conditions. For better clarity, the data acquired during the cyclic loading phase were filtered resulting in the display of only every 1,000th load cycle.

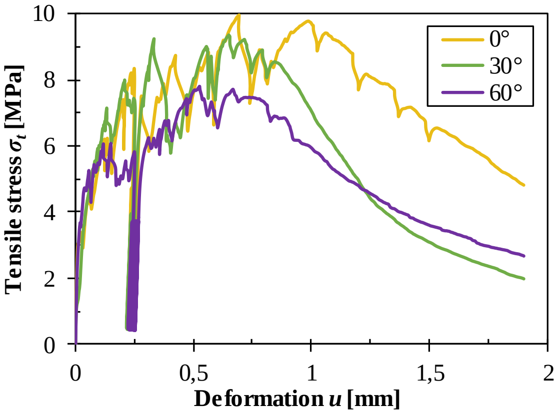

Figure 5. Stress-deformation-curves for representative samples of each testing series

According to the diagram the material shows an initial strain-hardening behavior before the cyclic load is applied. Subsequent tension-swelling loading causes further deformation within the measuring range, which varies based on the fiber orientation. The development of the maximum deformations during the cyclic loading stage is depicted in Figure 6.

Regardless of the fiber orientation, an initial rapid increase in deformation occurs during the first few hundred cycles, after which it becomes more gradual. This pattern is consistent with the findings from quasi-static tests. Among the testing series conducted with different fiber angles, the 0° series exhibits the highest deformation, followed by 60° and then 30°.

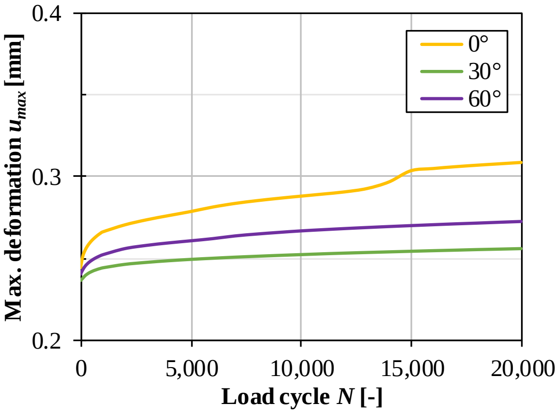

Figure 6. Development of the maximum deformation during the cyclic loading stage

The subsequent determination of the residual load bearing capacity under quasi-static loading conditions should clarify the influence of the fiber orientation on the material's performance. While the 0°-samples exhibit a pronounced strain-hardening behavior with an increase in maximum deformation when reaching the ultimate tensile strength, lower deformations could be observed in case of the oriented specimens which corresponds to the quasi-static test results; see Table 4.

Table 4. Overview of ultimate tensile strengths and corresponding maximum deformations under cyclic loading conditions (standard deviations are given in brackets)

Angle	Tensile strength f_t [MPa]	Max. deformation u_{max} [mm]
0°	9.06 (± 0.83)	0.75 (± 0.34)
30°	9.09 (± 1.25)	0.48 (± 0.18)
60°	7.03 (± 1.00)	0.51 (± 0.12)

Regarding the load-bearing capacity, a change in the original trend can be observed, i.e. a decrease in tensile strength cannot be attributed to a specific fiber inclination. While a slight decrease is noted for the 0° fiber orientation, the tension-swelling load results in an increase in tensile strength for samples with inclined fibers, especially in case of 30° inclination angle; cf. Figure 7.

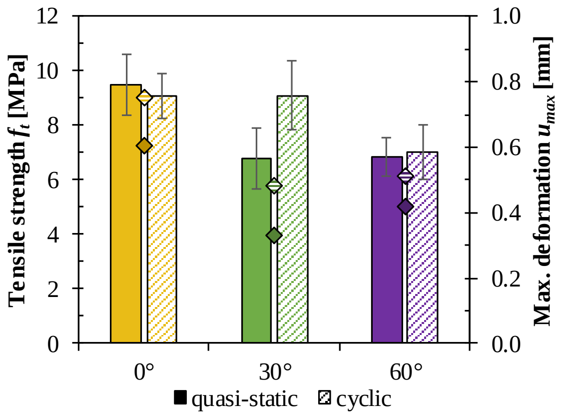

Figure 7. Comparison of tensile strengths and corresponding maximum deformations under quasi-static and cyclic loading conditions with respect to fiber orientation

These observations can be attributed to various mechanisms, including interlocking effects and matrix spalling. A schematic representation of the mechanism causing the observed mechanical behavior is depicted in Figure 8.

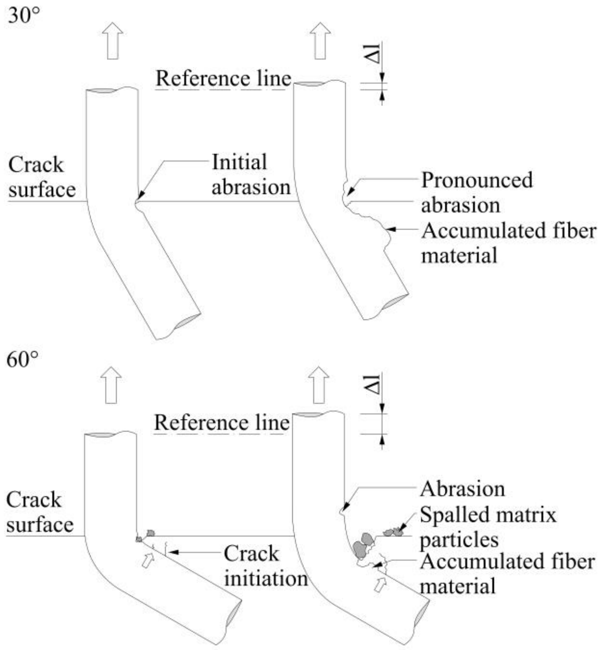

Figure 8. Schematic illustration of the degradation mechanisms on inclined fibers under cyclic loading

Matrix spalling primarily affects the deformation characteristics of the material. The high strength of the cementitious matrix necessitates a greater force to initiate matrix spalling. In case of the 30° inclination, the deflection force at the exit point resulting from the inclined fiber pull-out is insufficient to induce this type of concrete failure. However, at a 60° angle, the pull-out resistance is high enough to trigger matrix spalling due to increased friction between the fiber and matrix at the exit point during repeated loading. Once matrix spalling occured, longer fiber lengths can be released, leading to greater deformation. Moreover, the reduced matrix spalling of the 30° series compared to 60° fiber orientation may result in increased abrasion of the fiber's surface as the fiber is repeatedly pulled over the sharp edge of the matrix. The peeled-off material accumulates behind the affected area creating an interlocking effect that enhances the increase in tensile strength in case of the 30°-series by increasing the pull-out resistance.

In order to explain the relation between the crack development and the presented mechanisms Figure 9 gives an overview of the relation between the mean crack width (w_c), the normalized crack count (N_R) and the fiber orientation during the respective test stages, including pre-damage, cyclic load, residual load bearing capacity and pull-out.

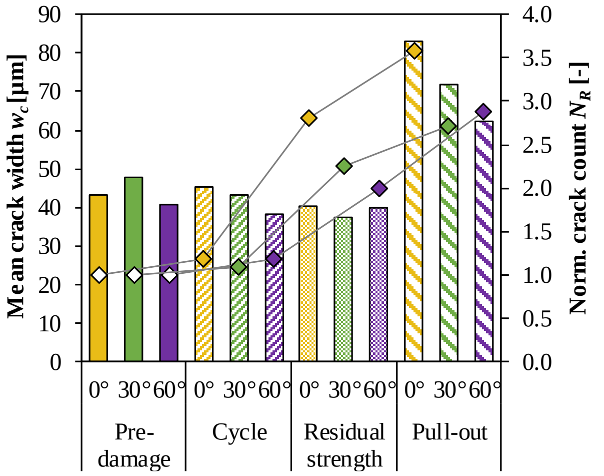

Figure 9. Relationship between mean crack widths and normalized number of cracks depending on the fiber orientation after the particular loading phase

It should be noted that in this context "pull-out" refers to the point at which the load drops below the initial crack strength during the slip-softening phase of quasi-static loading.

Mean crack width w_c and normalized crack count N_R are calculated according to Equations (1) and (2), respectively:

$$w_c = u_x / N_x \tag{1}$$

$$N_R = N_x / N_I \tag{2}$$

In these equations, u_x is the deformation at the end of the specific loading phase, N_x is the corresponding number of cracks and N_I is the number of cracks when reaching the defined pre-damage.

By analyzing the diagram, several observations can be made. While for the average crack opening no clear tendency could be identified, the number of cracks increases non-linearly during the test. Regarding the cyclic loading phase, 60°-oriented specimens exhibit the highest increase in number of cracks followed by 0° and 30°. This finding highlights the enhanced spalling of the matrix, which in turn leads to increased crack initiation due to a higher amount of micro cracks in these regions. The more pronounced crack development of these series also explains the higher increase in deformation during the cyclic loading stage. The differences in the normalized crack count in the third loading phase are similar to the preliminary tests under quasi-static loading conditions. Furthermore, the total number of cracks for each inclination angle is also on a comparable level.

Considering the mean crack width, it is observed that for the testing series with inclined fibers, the crack width decreases during the cyclic and final loading phase until the ultimate tensile strength is reached. This decrease is attributed to small deformations during the cyclic stage and a significant increase in the number of cracks during the quasi-static phase.

In summary, the mechanical behavior of SHCC with different fiber orientations is only slightly affected by low-cycle tension-swelling loads.

4 MICROSCOPIC INVESTIGATIONS

Microscopic examinations were conducted on representative samples to analyze the impact of the fiber orientation and loading type on the deterioration of the material, particularly the fibers using an environmental scanning electron microscope QUANTA FEG 250 (FEI). Additionally, microscopy was employed to validate the assumptions regarding the underlying mechnisms of the observed phenomena. The analysis was performed in high vacuum mode to minimize the charging of the polymer fibers. Figure 10 presents a pulled out fiber from the 30°-testing series under quasi-static loading conditions. Only minor differences could be observed with regard to the degradation state of the fibers at different inclination angles. The majority of the fibers were completely pulled out with only minor damage, such as peeled-off fibrils. Furthermore, ruptured fibers could be identified resulting from local abrasion of the fiber’s surface and a reduction of the cross-section as the fibers passed over the sharp crack edge at the fiber exit point; cf. Figure 11.

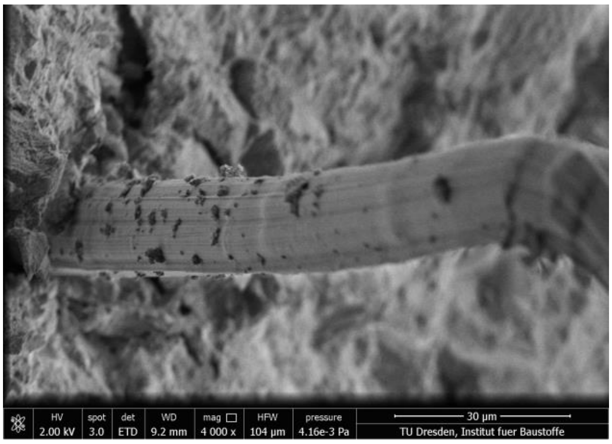

Figure 10. Pulled out fiber under quasi-static loading conditions (30° inclination)

Figure 11. Ruptured fiber with an inclination angle of 30° in quasi-static loading regime

The probability for fiber rupture under quasi-static loads appeared to increase with increasing inclination angle. As was shown in Figure 8 an inclination of 30° may result in higher abrasion leading to fiber interlocking within the channel, while 60° angle caused a higher rate of matrix spalling under cyclic tension-swelling loads. Microscopic investigations confirmed the significant abrasion on the fiber surface at a 30° angle, supporting the aforementioned assumptions; see Figure 12. Nevertheless, many fibers are pulled out with only slight deterioration signs, as observed in the quasi-static loading regime.

Figure 13 reveals the presence of spalled matrix particles on the crack surface of the 60°-specimen, resulting in increased deformation and less severe fiber deterioration during the cyclic loading stage compared to the 30°-series.

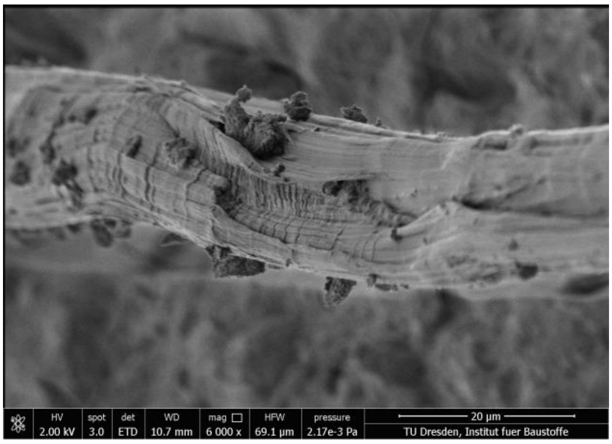

Figure 12. Local abrasion of an 30° inclined fiber under tension-swelling loads

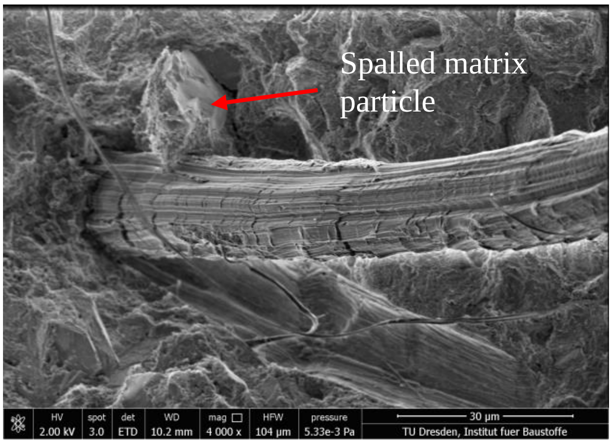

Figure 13. Pulled-out fiber (60°) with spalled matrix particle

Additionally, a significant number of fibers exhibit noticeable superficial damage, as depicted in the figure.

However, the observed degradation phenomena are less prominent than anticipated. A substantial amount of fibers is pulled out of the cementitious matrix, exhibiting only slight damages such as peeled-off fibrils. These observations indicate the existence of fiber orientation scatter, leading to the simultaneous occurrence of multiple deterioration mechanisms.

5 CONCLUSIONS

The study at hand focussed on the impact of the fiber orientation on the mechanical performance of a high-strength strain-hardening cement-based composite reinforced with polyethylene (PE) fibers under quasi-static and cyclic tension-swelling loading conditions. The specimens were manufactured using an extrusion-based method, aiming to align the fibers parallel to the direction of extrusion. Subsequently, the specimens were cut with specific fiber orientations of 0°, 30° and 60°, respectively.

Under quasi-static loading conditions it was observed, that the tensile strength decreased as the fiber inclination angle increased, resulting in a reduction in deformation capacity as well.

In contrast, cyclic tension-swelling loads caused a change in the material response with regard to the ultimate tensile strength. Here, the fiber inclination caused an increase in tensile strength after 20,000 load cycles, especially in case of 30° fiber orientation. This increase may be attributed to interlocking mechanisms resulting from pronounced surface abrasion. However, the increase in strength was almost negligible for the 60° fiber orientation. Higher deformations were measured during the cyclic loading for this testing series, possibly due to increased matrix spalling leading to an increase in the free length of the polymer fibers. Furthermore, matrix spalling was found to increase crack initiation during the cyclic phase. However, the material exhibited only minor influences under this number of load cycles.

Nevertheless, the abrasion of the fibers can lead to the premature fiber rupture thereby reducing the composite's performance also with regard to prolonged cyclic loading.

Due to non-uniform fiber orientations several degradation mechanisms are likely to superimpose, making it difficult to determine the influence of fiber orientation conclusively. For a comprehensive understanding of the impact of the fiber orientation single fiber pull-out tests should be conducted to isolate the effects of different inclination angles without overlapping influences.

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