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EFFECTS OF TEMPERATURE AND STRAIN RATE ON THE BEHAVIOR OF STRAIN-HARDENING CEMENT-BASED COMPOSITES (SHCC) SUBJECTED TO TENSILE LOADING

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Abstract: This paper reports the experimental findings on the tensile behaviour of strain-hardening cement-based composites (SHCC) subjected to elevated temperatures and different strain rates and to combinations of these parameters. Uniaxial tension tests with in-situ temperature control were performed at 22 °C, 60 °C, 100 °C and 150 °C. In addition, the effect of loading rate was investigated using the strain rates of 10^{-5} s^{-1}, $3 \cdot 10^{-4}$ s^{-1} and 10^{-2} s^{-1} at all four temperatures considered. It was shown that tensile strength decreases both with an increase in temperature and with a decrease in the strain rate. The strain capacity increases with decreasing strain rate at temperatures of 22°C and 60°C, but for the temperature of 100°C this material property increases when the strain rate increases. At 150°C the investigated SHCC loses its ductility and no noticeable strain rate effect can be observed. These results and possible mechanisms leading to changes in mechanical performance are discussed on the basis of the observed crack patterns on the specimens' surfaces as well as the microscopic investigations of the condition of fibres on fracture surfaces.

1 INTRODUCTION

Strain-hardening cement-based composites (SHCC) constitute a group of fibre-reinforced, fine-grained concretes which display high strain capacity when subjected to tensile loading. This quasi-ductile behaviour results from progressive multiple cracking achieved by the optimized crack-bridging action of short, thin, well distributed, polymeric fibres. The SHCC family of materials can be used in specific engineering applications as shown in [1-3].

The characteristic behaviour of SHCC subjected to tension under monotonic, quasi-static loading has been intensively studied during the last years by several authors and is relatively well known. In addition to these investigations, the behaviour of SHCC under cyclic tensile loading [4], alternating tension-compression, and tensile creep has also been investigated.

Several authors [6, 7] found strain rate dependents of materials behavior. Tension tests performed up to 10^{-2} s^{-1} exhibited, with increasing strain rate, an increase in tensile strength and a decrease in strain capacity.

Single fibre pullout test results have been used to explain the respective findings, with rate-dependent chemical bond reported to dominate in [7] and slip-hardening in [5]. In both cases PVA fibres were used.

With a further increase in strain rate up to 10 to 50 s^{-1}, SHCC showed an increase in both tensile strength and strain capacity, but, other than when tested under quasi-static loading, with no distinctive multiple cracking [6]. This specific behaviour was related to a more pronounced fibre pullout from the matrix and to marked plastic deformation of the fibres [6] as well as to internal damage of specimens.

The knowledge and understanding of the material behaviour and damage mechanisms at additional exposures, like higher temperature, is of great importance for the correct design of structures. Low-melting-point fibres such as polypropylene are mostly used to mitigate concrete spalling in case of fire. Nevertheless, the effect of such fibres on the bending post-cracking strength after exposure to temperatures up to 800 °C was investigated [8] and up to 400 °C a decrease in the stiffness and an improvement in the post-peak response were observed. Magalhães et al. [9] performed residual tensile tests on SHCC containing 2% of PVA fibres pre-treated at temperatures ranging from 90 °C to 250 °C. For the case of 250 °C, it was shown that strain capacity decreased around 92% while the tensile strength decreased around 68%.

This work deals with the combined effect of temperature and strain rate on the mechanical behaviour of SHCC subjected to tensile loading. The in-situ uniaxial tension tests were performed at temperatures of 22, 60, 100 and 150 °C at strain rates of 10^{-5}, $3 \cdot 10^{-4}$ and 10^{-2} s^{-1}.

Additionally, crack patterns on the specimens' surfaces as well as the fracture surfaces were investigated by using Enviromental Scanning Electron Microscope (ESEM) to identify specific failure mechanisms of SHCC under various loading rates and temperature regimes. The chosen temperatures cover a range from hot weather (60 °C) up to specific operation regimes as, e.g., in power plants (100-150 °C).

Table 1: Mix proportions of SHCC

Component	[kg/m³]
Cement	505.0
Fly ash	613.5
Water	359.3
Quartz sand	534.2
Superplasticizer	19.3
Viscosity agent	3.2
Superabsorbent polymers (SAP)	2.0
PVA fibres	29.0

2 MATERIALS AND PROCESSING

The material composition used in this investigation (Table 1) was first developed by Brüdern and Mechtcherine [10]. Binder was a combination of Portland cement type 42.5R-HS and fly ash. The mixture contained only very fine aggregates – equally graded quartz sand with particle sizes ranging from 0.06mm to 0.20 mm, important for the uniform distribution of fibres. A superplasticizer and a viscosity agent were added to the mixture in order to attain the desired workability. Furthermore, superabsorbent polymers were added to the mixture in order to improve the frost resistance, to mitigate shrinkage, and to induce micro-defects favourable to the formation of multiple cracks, cf. [10]. The SHCC used in the present work had a PVA fibre volume content of 2.2% (d = 40 µm, l = 12 mm). Detailed information on mix design may be found in [4, 10].

In producing the SHCC, all dry components were homogenized in a mixer. The water and superplasticizer were added and mixed until a fluid consistency was achieved. Subsequently, the fibres were added during continuous mixing. Afterwards, the SHCC was mixed intensively until a good fibre distribution was achieved.

All specimens were cast horizontally in dumbbell shaped metal forms and vibrated. After casting the moulds were covered with plastic foil and stored for one day in a room under controlled temperature (T = 22 °C).

After de-moulding, the specimens were wrapped in plastic foil and stored at room temperature until testing. In order to produce flat surfaces, the superfluous material on the mould-filling side, was cut off with a saw after SHCC hardened. All specimens were tested at an age of 28 days.

3 EXPERIMENTAL TESTING PROCEDURE

For each combination of parameters four tests were performed on dumbbell-shaped specimens with dimensions of 330 mm x 30 mm x 30 mm (length x width x thickness). Figure 1 shows the test setup and specimen geometry used for the uniaxial tension tests.

Specimens are mounted in steel plates which were then fixed on the testing machine under rotatable boundaries. The position of the fixing plates was chosen approx. 10 mm to the narrow part of the specimen to minimize deformations and the effect of multi-axial stress distribution on the gauge length of the specimen.

All experiments were performed using a monotonic, displacement-controlled loading regime. Displacement was measured by two high temperature LVDT's at a gauge length of 80 mm.

Three different displacement rates were used: 0.0008 mm/s, 0.024 mm/s, and 0.8 mm/s, which corresponded to strain rates of 10^{-5}, $3 \cdot 10^{-4}$, and 10^{-2} s^{-1}, respectively. The tensile load and corresponding displacements were recorded continuously during the tests.

The uniaxial tension tests were performed at the reference room temperature of 22 °C as well at three different elevated temperatures of 60 °C, 100 °C, and 150 °C using an electric furnace operated simultaneously with the testing machine.

The heating rate was of 1 °C/minute. When the specific target peak temperatures were reached, the furnace temperature was maintained constant for one hour previous to the test and for the duration of the test as well. Table 2 gives an overview of the experimental program.

The Environmental Scanning Electron Microscope (ESEM) was used to investigate the condition of SHCC fracture surfaces for various testing conditions. The ESEM was operated under low vacuum of 0.6-0.7 mBar.

Additionally, high resolution photographs were made of the crack patterns on the specimens' surfaces following testing.

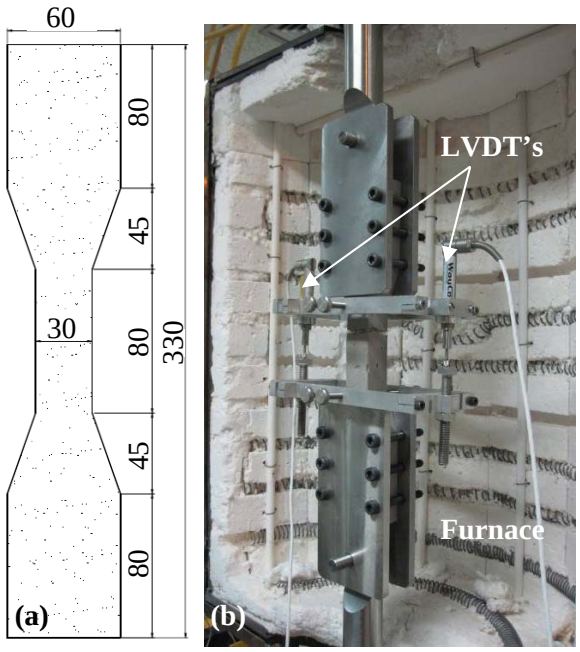


Figure 1: Uniaxial tension test setup: (a) specimen geometry (in mm) and (b) test setup showing the specimen attached to the testing machine by means of the metal plates, half of the electrical furnace, and instrumentation

4 RESULTS OF THE UNIAXIAL TENSION TESTS

Figure 2 shows one representative stress-strain curve obtained for each investigated strain rate at the temperatures of 22, 60, 100, and 150 °C. The results of the evaluation of all curves are given in Table 3. From these data it can be seen that the SHCC behaviour is sensitive to the applied strain rate at the temperatures of 22 °C, 60 °C and 100 °C. At room temperature, i.e. at 22 °C, the tensile strength increased from 4.48 MPa to 5.53 MPa

Table 2: Parameter variations in the in-situ uniaxial tension tests

Displacement rate [mm/s]	Strain rate [s^{-1}]	Temperature during the test [°C]			
0.0008	10^{-5}	22	60	100	150
0.024	$3 \cdot 10^{-4}$	22	60	100	150
0.8	10^{-2}	22	60	100	150

when the strain rate was raised from 10^{-5} s^{-1} to 10^{-2} s^{-1}, cf. Figure 2a. Also the first-crack strength σ_1 increased in a similar proportion, cf. Table 3. The first-crack strength was read as the maximum stress before the first drop in the stress-strain curve indicating the formation of the first fine crack crossing the entire specimen's cross-section or at least a large part of it. For the same testing conditions the strain capacity and the work-to-fracture decreased from 5.33% to 3.94% and from 17.76 J to 14.12 J, respectively. The strain capacity was defined as the strain at which the localization of failure occurred while the work-to-fracture was computed as the total area under the load-displacement curve. While the behaviour of SHCC tested at the rate of 10^{-5} s^{-1} was characterised by a pronounced strain-hardening response accompanied by the formation of many fine cracks, the SHCC response at 10^{-2} s^{-1}, revealed lower number of cracks when tested at 22 °C, cf. Figure 3. These results are in agreement with [6].

For the in-situ test temperature of 60 °C generally the same tendencies were observed as at room temperature: a clear increase in the first-crack strength and tensile strength as well as a decrease in strain capacity and work-to-fracture with increasing strain rate, cf. Figure 2b and Table 3.

For example, the strength increased from 3.55 MPa to 4.61 MPa and the strain capacity decreased around 42%, when comparing the results for the lowest and the highest applied strain rates. The specimens showed similar numbers of cracks in both cases; however, the cracks on the specimens subjected to the slower loading were wider, cf. Figure 3. It must be noted that the deformed specimens shown in Figure 3 are at different permanent (inelastic) deformation states.

For specimens tested at 100 °C the strength

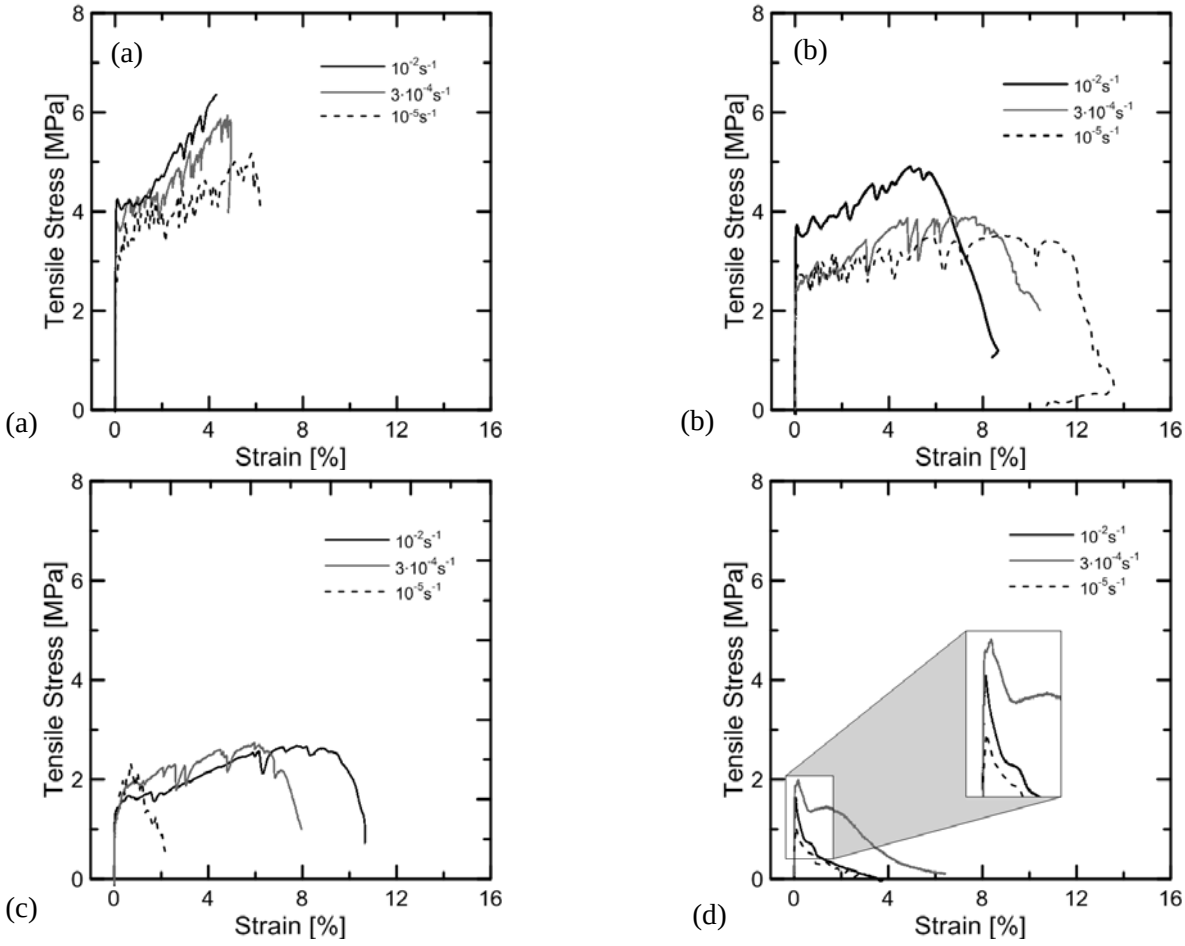


Figure 2: Effect of strain rate on the stress-strain response of SHCC tested at the in-situ temperatures of (a) 22 °C, (b) 60 °C, (c) 100 °C and (d) 150 °C, graphs show representative curves

Table 3: Summary of the in-situ tension test results; average values (standard deviations are given in parentheses)

Temperature [°C]	Strain rate [s^{-1}]	First-crack strength [MPa]	Tensile strength [MPa]	Strain capacity [%]	Work-to-fracture [J]
22	10^{-5}	2.62 (0.61)	4.48 (0.39)	5.33 (0.82)	17.76 (3.45)
	$3{\cdot}10^{-4}$	3.84 (0.39)	5.33 (0.45)	4.92 (0.14)	16.07 (1.92)
	10^{-2}	4.04 (0.26)	5.53 (0.58)	3.94 (0.74)	14.12 (3.06)
60	10^{-5}	2.62 (0.11)	3.55 (0.19)	10.33 (1.57)	28.28 (1.87)
	$3{\cdot}10^{-4}$	2.52 (0.20)	3.66 (0.13)	6.25 (2.69)	18.14 (7.59)
	10^{-2}	3.43 (0.35)	4.61 (0.61)	5.98 (2.47)	22.78 (6.27)
100	10^{-5}	2.02 (0.28)	2.26 (0.02)	0.53 (0.47)	3.06 (0.24)
	$3{\cdot}10^{-4}$	1.60 (0.07)	2.71 (0.18)	6.76 (1.45)	13.10 (2.37)
	10^{-2}	1.67 (0.27)	2.82 (0.50)	9.30 (0.47)	18.83 (4.63)
150	10^{-5}	1.65 (0.11)	1.65 (0.11)	0.06 (0.028)	0.84 (0.03)
	$3{\cdot}10^{-4}$	1.84 (0.15)	1.84 (0.15)	0.19 (0.026)	3.45 (1.04)
	10^{-2}	1.70 (0.21)	1.70 (0.21)	0.15 (0.099)	2.19 (1.65)

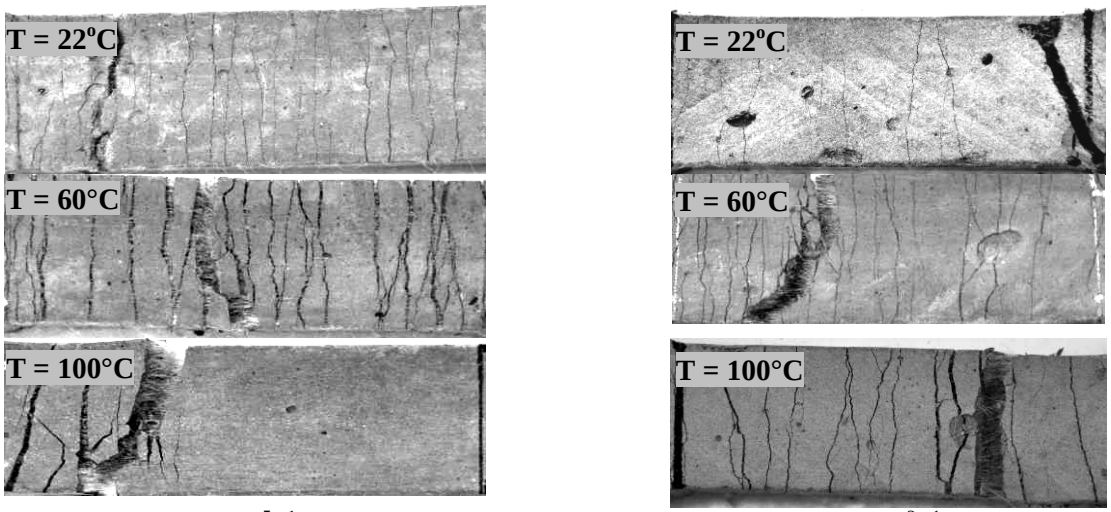
also increased with increasing strain rate, this time at a considerably lower level, from 2.26 MPa to 2.82 MPa, cf. Figure 2c. In contrast to results of the test at lower temperatures, the strain capacity increased from 0.53% to 9.30% as the strain rate was increased from the minimum to the maximum. Figure 3 shows that at the temperature of 100 °C and at the highest strain rate the specimens yield pronounced multiple cracking. The opening of these many cracks results in the higher strain capacity obtained at this rate.

In the test performed at the temperature of 150 °C, SHCC revealed no quasi-ductile behaviour anymore, but rather a softening behaviour for all strain rates under focus. No clear rate effect was observed on any of the material parameters (cf. Figure 2d and Table 3) and a single crack in the material was detected.

It can be seen that first-crack strength and tensile strength gradually decrease with increasing temperature, while the strain capacity reaches its maximum level at a temperature of 60 °C or 100 °C, dependent on the stain rate, and then decreases. The interpretation of this behaviour is given in the following section.

5 MICROSCOPIC INVESTIGATION AND DISCUSSION

The tensile strength decreases both with an increase in temperature and a decrease in strain rate. The exception lies in the results for the temperature of 150 °C: here no strain rate effect could be observed. When tested at the temperatures of 22 °C and 60 °C the strain capacity increased for all tested strain rates. At 100 °C the strain capacity only increased for the strain rates of $10^{-2}\,s^{-1}$ and $3{\cdot}10^{-4}\,s^{-1}$ and, finally, at 150 °C there is no noticeable strain rate effect on the strain capacity. The results for the strain capacity correlate well with the observed crack pattern. Regarding the first-crack strength SHCC acts very similar to well



(a) $10^{-5}s^{-1}$ (b) $10^{-2}s^{-1}$

Figure 3: Crack patterns of representative specimens tested in-situ at different temperatures: (a) strain rate of $10^{-5}s^{-1}$ and (b) strain rate of $10^{-2}s^{-1}$

discussed ordinary concrete.

To gain additional information to help explain the observed effects fracture surfaces of tested specimens were investigated by using the environmental electron microscope. The representative ESEM micrographs depicted in Figure 4 give a clear indication of the failure mechanisms of SHCC tested under the lowest and highest rate at room temperature. While fibre fracture is predominant in the tests with the strain rate of 10^{-2} s^{-1} (short fibre length in Figure 4a), fibre pullout is typical for the specimens tested with the strain rate of 10^{-5} s^{-1} (Figure 4b).

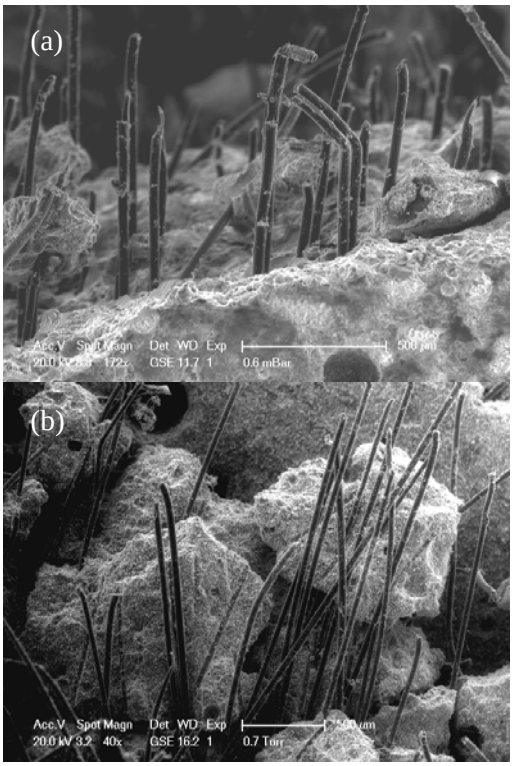


Figure 4: Fracture surfaces of representative specimens tested at a temperature of 22 °C at strain rates of (a) 10^{-2} s^{-1} and (b) 10^{-5} s^{-1}

Regarding the appearance of the individual fibres tested with the lowest strain rate, fibres show some hydration products on their surfaces and no signs of fracture, thus demonstrating that they were pulled out of the matrix. In contrast, the fibres from specimens tested with a rate of 10^{-2} s^{-1} are ruptured. These phenomena can be traced back to the increase in the bond strength between fibre and matrix with higher strain rates, cf. [5, 6].

It can be assumed that the gradual detachment of the fibre from the matrix is less pronounced when SHCC is loaded with a higher strain rate. This means that only small free lengths of fibres can develop and therefore only small crack openings can be attained prior to the failure localisation.

The phenomena and tendencies described above hold true also for the tests performed at the temperature of 60 °C. Additionally, it should be noticed that SHCC specimens tested at this temperature with the strain rate of 10^{-5} s^{-1} exhibited much wider openings of multiple cracks in comparison with those tested with the strain rate of 10^{-2} s^{-1}. One of the reasons is the smaller free lengths of the fibres crossing the crack in the case of the higher strain rate. The detachment of the fibre from the matrix is a time-dependent process which leads both to an increase in the bond strength and to a decrease in the fibre free length when faster loading is applied. Elevated temperatures intensify this effect. Relative changes in the tensile strength and strain capacity measured at 60 °C were much higher than those observed at room temperature.

Additionally to the given reasons the following mechanism seems to be important. Since the PVA fibres used in this study are coated with an oiling agent, it is likely that this agent is sensitive to temperature increases already at moderate temperatures. The physical and, possibly as well, the chemical properties of the agent may have changed when exposed to 60 °C or higher temperatures. Thus, the fibre bond strength, both frictional and chemical, was likely reduced, contributing to a lower strength, wider cracks (cf. Figure 3), and higher strain capacity of the composite system.

In the tension tests performed at the temperature of 100 °C, the specimens tested with the strain rate of 10^{-5} s^{-1} exhibited a lower strain capacity than those tested with the strain rate of 10^{-2} s^{-1}; thus, an opposite tendency in comparison to the results obtained from the tests at 22 °C and 60 °C. The specimens tested at low strain rates showed few cracks, while SHCC tested with high strain rate had pronounced multiple cracking. The

microscopic investigations of fracture surfaces revealed a pronounced fibre pullout for both loading rates. However, an obvious difference in the appearance on the fibre surface could be noticed. Fibres pulled out at the high loading rate had longitudinal groves (cf. Figure 5a,b), while fibres from the tests with the low strain rate exhibited much smoother surfaces (cf. Figure 5c). The longitudinal groves indicate that severe plastic deformations occurred during the pullout process, so contributing to the energy absorption capacity of the composite.

Obviously, the properties of the bond are also beneficial for this combination of strain rate and temperature; see multiple cracking in Figure 3b. A strong bond is demonstrated by the fact that some (but only few!) broken fibres were observed. They showed marked narrowing, indicating distinct plastic deformations; cf. Figure 5b. It is very likely that the weakening of the bond strength with increasing temperature and an increase in bond strength with increasing strain rate produced a favourable combination with respect to the mechanical performance of the SHCC. It is also probable that in the case of slow loading the bond strength is not strong enough to transfer high stresses across first cracks; therefore, fibres are prematurely detached from and pulled out of the matrix, so that no marked strain-hardening occurs.

Figure 6 shows a representative micrograph of fracture surfaces of SHCC tested at a temperature of 150 °C. Fibres are strongly plastically deformed, which can be traced back to very high deformability and low strength of PVA fibres at this relatively high temperature, although the thermal degradation process of PVA fibres only starts at 256 °C, as shown by [9]. Thus, fibre cannot take over the tensile load when the matrix fails, which explains why only one crack could be observed in the experiments at 150 °C.

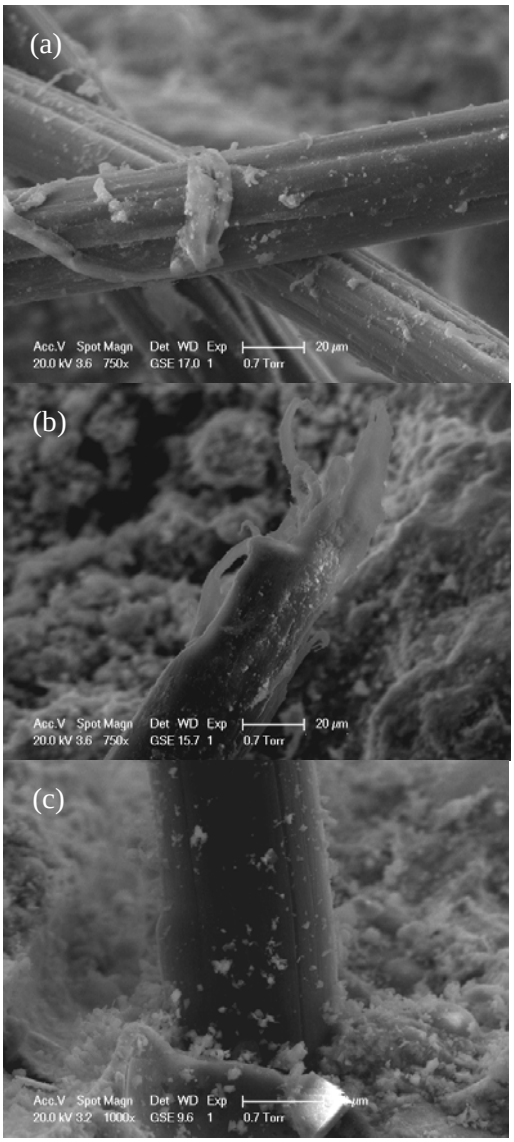


Figure 5: Appearance of PVA fibres on the fracture surface of specimens tested at a temperature of 100 °C and strain rates of (a, b) 10^{-2} s^{-1} and (c)10^{-5} s^{-1}

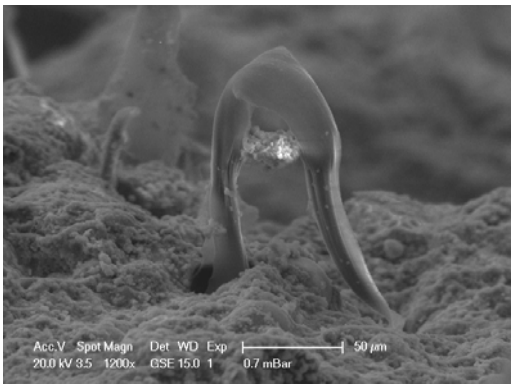


Figure 6: Fracture surface at a temperature of 150 °C

To prove some of the assumptions, made above, the authors plan for their further research to perform residual and in-situ fibre pullout tests at the same temperature used in this study. Additionally, the mechanical behaviour of fibre and matrix will be investigated in separate tests.

6 CONCLUSION

The following conclusions can be drawn from the present work on the tensile behaviour of SHCC at various combinations of temperature and strain rate:

- At room temperature (22 °C) and 60 °C SHCC shows an increase in tensile strength and reduction in strain capacity when increasing strain rate. Values of strain capacity were much higher than at the room temperature.
- At 100 °C the strain capacity increased and the strength decreased when increasing the strain rate.
- Finally, at 150 °C SHCC lost its ductility.

Additional tests on this topic were performed with residual heated specimens. The findings of these experiments and a comparison to the in-situ tested specimens can be found in [11]. More research is needed to quantify these changes and to be able to use this knowledge for the material and structural design purposes.

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