High-Temperature Behavior of Textile Reinforced Concrete

Christian Kulas\textsuperscript{1}, Josef Hegger\textsuperscript{1}, Michael Raupach\textsuperscript{2} and Udo Antons\textsuperscript{2}

\textsuperscript{1} Institute of Structural Concrete (RWTH Aachen University), Aachen, Germany
\textsuperscript{2} Institute of Building Materials Research (RWTH Aachen University), Aachen, Germany

ABSTRACT: The high-temperature behavior of textile-reinforced concrete (TRC) has not been investigated so far. Thus, present applications are limited to members without requirements on the fire-behavior. This article presents the latest results on the high-temperature behavior of alkali-resistant glass (AR-glass) and carbon rovings as well as fine-grained concrete. Furthermore, strength reduction factors are derived, which are necessary for the design of TRC members under fire attack.

1 INTRODUCTION

Textile Reinforced Concrete (TRC) is an innovative composite material which uses reinforcements mainly made of alkali-resistant glass (AR-glass) or carbon. Since the textiles do not corrode like steel reinforcements, the concrete cover can be minimized and, thus, leads to extremely thin and slender concrete constructions. Due to the small roving distances of the textile meshes a fine-grained concrete is necessary to allow an unproblematic casting and penetration of the concrete through the meshes.

Since 1999, two Collaborative Research Centers (SFB) have been working scientifically on the main properties of TRC in Germany. While the SFB 528 at TU Dresden has been dealing with the retrofitting of steel reinforced concrete structures with TRC layers, the SFB 532 at RWTH Aachen University has been working on the properties of new TRC constructions. As a result of the fundamental research, properties of the textiles and fine-grained concrete as well as the load-bearing behavior and durability issues are well understood, see e.g. Orlowsky and Raupach (2006), Cuypers et al. (2007), Hegger and Voss (2008), Orlowsky and Raupach (2008), Büttner et al. (2010). Based on these findings, pilot projects were realized within the last years that encompass applications of ventilated façade structures, sandwich panels, Horstmann et al. (2008), and a pedestrian bridge, Hegger et al. (2010). The range of these applications is limited to constructions with no requirements to the fire-behavior, since the present design models for TRC are valid for room temperatures and, currently, calculation models for the high-temperature behavior of textiles and fine-grained concrete are not available. First investigations have been carried out focusing on composite TRC members, which were tested under fire conditions by Reinhardt et al. (2005). Ehlig et al. (2010) presented tests on polymer coated carbon textiles.

This article presents the results of high-temperature tests on the components of TRC. The focuses lie on non-impregnated AR-glass and carbon rovings as well as fine-grained concrete. By using a specially developed oven with a maximum temperature of about 1100 °C mechanical measuring systems are not appropriate. Thus, an optical measuring system with a high
resolution was used to determine the strains of the concrete specimens. Finally, reduction factors for ultimate stresses are derived and can be used for the design of TRC members exposed to high-temperatures.

2 MATERIALS

2.1 Rovings

The materials for the rovings investigated under high-temperatures are AR-glass and carbon, which are the most common materials for applications today. Both roving types have the same cross-section of $A_R = 0.89 \text{ mm}^2$ corresponding to 2400 tex (1 tex = 1 g / 1000 m) for AR-glass and 1600 tex for carbon is due to the different density. The main properties at room temperature are shown in Table 1.

Table 1. Main properties of AR-glass and carbon rovings at room temperature

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>AR-glass</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn count</td>
<td>tex$^1$</td>
<td>2400</td>
<td>1600</td>
</tr>
<tr>
<td>Diameter (filament)</td>
<td>µm</td>
<td>14 - 30</td>
<td>5 - 8</td>
</tr>
<tr>
<td>Cross-section (rovings)</td>
<td>mm$^2$</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>Density</td>
<td>kg / m$^3$</td>
<td>2680</td>
<td>1790</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>321</td>
<td>1249</td>
</tr>
</tbody>
</table>

$^1$ 1 tex = 1 g / 1000 m

2.2 Concrete

The fine-grained concrete used in the SFB (denotation: PZ-0899-01) allows for thin structures with thicknesses of only 20 - 30 mm. It has a maximum grain-size of 0.6 mm and a compressive strength of 99.6 N/mm$^2$ after 56 days as well as a high density which caused a long drying period. The properties of the concrete mixture are displayed in Table 2.

Table 2. Components of fine-grained concrete (PZ-0899-01)

<table>
<thead>
<tr>
<th>Components</th>
<th>Unit</th>
<th>PZ-0899-01</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52,5 R</td>
<td>kg/m$^3$</td>
<td>490</td>
</tr>
<tr>
<td>Fly ash</td>
<td></td>
<td>175</td>
</tr>
<tr>
<td>Silica fume</td>
<td>kg/m$^3$</td>
<td>35</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>280</td>
</tr>
<tr>
<td>Sand 0.2-0.6 mm</td>
<td>l/m$^3$</td>
<td>714</td>
</tr>
<tr>
<td>Superplasticiser</td>
<td>l/m$^3$</td>
<td>10.5</td>
</tr>
</tbody>
</table>
3 EXPERIMENTAL PROGRAM

3.1 General

To investigate the temperature-dependent material behavior, two testing procedures can be distinguished, e.g. Schneider (1982). In a steady-state test the load is increased until the specimen fails, while the temperature is kept constant. In contrast, in the transient tests the temperature is increased until failure, while the stress is kept constant. Since the latter simulates the real conditions of a structural member exposed to fire, the material behavior was determined by transient tests.

The overall strain $\varepsilon^\sigma$, which is measured during a transient test, is the summation of the strain after applying the load $\varepsilon^\sigma_0$, the creep strain $\varepsilon^\sigma_c$ at room temperature, the elongation due to increasing temperature $\varepsilon_T$ induced by the thermal expansion and the demanded stress-inducing transient strain $\varepsilon^\sigma_T$ (Figure 1 and equation (1)).

$$\varepsilon^\sigma = \varepsilon^\sigma_0 + \varepsilon^\sigma_c + \varepsilon_T + \varepsilon^\sigma_T$$  (1)

![Figure 1. Components of the measured transient test strain $\varepsilon^\sigma$](image)

While the mechanical strain $\varepsilon^\sigma_0$ was directly read off out of the temperature-strain diagram at room temperature, $\varepsilon^\sigma_c$ was determined in a separated test at room temperature, where the desired stress was applied, e.g. at 50 % of the material's strength, and kept constant. The strain due to thermal expansion $\varepsilon_T$ was investigated also in a separated test where the elongation of an unloaded specimen exposed to high-temperatures was measured. Finally, the stress-inducing transient strain $\varepsilon^\sigma_T$ can be calculated.

3.2 Rovings

The rovings were laid around a reverse roller inside the oven while both ends were fixed with rope grips to a load cell installed outside the oven. Due to the test setup the heated roving length was 0.6 m. The temperature was raised with 25 K/min.

In Figure 2a the results of the transient tests of the AR-glass rovings are shown as temperature-strain curves, where the strain is the temperature induced strains $\varepsilon_T + \varepsilon^\sigma_T$. Six different stress-states were applied (each stress-state consists of up to 15 single tests), where the stress is increased up to 90 % of the strength at room temperature (see Table 1). To avoid an undulating of the rovings it was necessary to apply a slight load of about 3 % of the strength.

For the curves of the unloaded rovings and those with 17 % of the failure stress it was noticed that straight before failure the testing-velocity rose suddenly. The resulting high-failure strains of the AR-glass rovings are due to melting effects of the glass and did not occur at the high-stressed rovings, where a sudden failure was observed. Thus, according to Ruge and Winkelmann (1977) a failure criterion was defined based on the strain velocity calculated with equation (2). Here, the maximum strain and temperature is reached, if the strain velocity is higher than $10^{-4}$ 1/s (dashed lines in Figure 2).
Figure 2. AR-glass: a) total transient creep strain $\varepsilon_T + \varepsilon_T^{0}$, b) normalized to 140 °C.

\[
\frac{d\varepsilon}{dt} = \dot{\varepsilon} = \frac{\Delta \varepsilon}{\Delta t} = \frac{\varepsilon_{t_2} - \varepsilon_{t_1}}{t_2 - t_1} \leq 10^{-4} = \dot{\varepsilon}_{\text{crit}}
\]

Up to a temperature of 140 °C the strain is affected by the degradation of the polymeric size, Priller (1998), which is noticeable for the high-stressed rovings (57 % to 91 %, Figure 2a). The increase of the strain of each stress-state was comparable to the increase from unloaded rovings. Accordingly, each curve was transferred to an initial temperature of 140 °C (Figure 2b).

Figure 3. Stress-inducing transient creep strain $\varepsilon^\sigma_T$: a) AR-glass, b) carbon

After excluding the free temperature strain $\varepsilon_T$ the curves in Figure 3a show the stress-inducing transient creep strain of the AR-glass. The carbon rovings have been investigated in the same way, but due to a different polymeric size and mechanical performance the transferring to 140 °C could be omitted. The results are shown in Figure 3b.

3.3 **Fine-grained concrete**

The compressive behavior of the fine-grained concrete was determined on specimens with dimensions of 40 x 40 x 160 mm. The load application areas (40 x 40 mm) were grinded to
achieve a smooth surface and to avoid stress-peaks. To prevent the influence of humidity the specimens were dried until their moisture content reached 0.1 % by mass. In Figure 4a the results of the transient tests adjusted from the deformation under load and the creep deformation at room temperature are depicted. For every stress-state five single tests with a temperature heating rate of 5 K/min had been conducted. The displayed temperature is the one measured in a depth of 10 mm.

From room temperature up to approximately 100 °C the quantity of the applied load has no significant influence on the strain-behavior. Schneider (1982) explained that in the range of about 100 °C to 120 °C the evaporation of the water in the large pores is responsible for a weight loss of the concrete specimens. In Figure 4a the changing of the gradient of the lines at this temperatures is due to this weight loss and, thus, the gradient decreases with increasing stress-state. After the concrete has reached 180 °C the cement paste starts to degrade which leads into a further reduction of the stiffness. At 450 °C the change of the cement paste is completed and the decomposition of the elementary hydration products starts. Similar to the tension tests the free temperature strain was removed from the curves in Figure 4b.

4 STRENGTH LOSSES IN STATE OF FAILURE

4.1 Rovings

The temperature-dependent tensile strength of the rovings is of major interest for a proper design of TRC members under fire attack. Thus, on the basis of the transient tensile tests, reduction factors are calculated with equation (3) where the stress-state at the temperature at which the rovings failed $f_T$ is divided by the strength at room temperature $f_{23°C}$. The results are shown in Figure 5 for 2400 tex AR-glass and 1600 tex carbon rovings

Reduction factor: \[ k_T = \frac{f_T}{f_{23°C}} \] (3)

Due to the transient tests, where the applied stress remains constant, the single test results are arranged horizontally in the diagrams with different failure temperatures. For AR-glass (Figure 5a) a linear correlation between reduction factor and failure temperature was observed and can be described with equation (4b). At 426 °C the strength of the material began to decrease, which is in the range of a standard steel-reinforcement (e.g. BSt 500, DIN (2006)).
By comparing the results of the AR-glass tests with the high-temperature behavior of glass-fibre reinforced polymer (GFRP) bars presented by Nadjai et al. (2005), it is obvious that the inclination of both lines are nearly the same due to the same basic material of the filaments. Only the point where first strength losses appear is different: The reduction of the strength of the GFRP-bars starts already with slightly higher temperatures than room temperature, because the GFRP-bars are impregnated with a resin which connects the single filaments with each other. Since the resins for these tests have glass transition temperatures lower than 100 °C the mechanical properties, e.g. tensile strength, decreases right from elevated temperatures. The assessed rovings are not impregnated and, thus, this effect does not occur here.

\[
AR\text{-glass:} \quad k_T = 1,0 \quad \text{for} \ 23 \ ^\circ C \leq T < 426 \ ^\circ C \quad (4a)
\]
\[
k_T = 2,35 - 0,00317 \cdot T \geq 0 \quad \text{for} \ T \geq 426 \ ^\circ C \quad (4b)
\]

Figure 5. Reduction factors for ultimate strength over temperature: a) AR-glass, b) carbon.

For the carbon rovings (Figure 5b) strength losses occur not below 393 °C which is in the same range as for the AR-glass rovings. Due to a better temperature stability of carbon the inclination of the straight line is about 37 % less than the inclination of AR-glass. In none of the tests higher temperatures than approximately 650 °C were achieved. At this temperature combustion of the carbon rovings was observed, which is considered by the vertical line in Figure 5b. A continuous melting process, as for the AR-glass rovings, was not observed for carbon. The reduction factors can be described with the equations (5a) to (5c):

\[
\text{Carbon:} \quad k_T = 1,0 \quad \text{for} \ 23 \ ^\circ C \leq T < 390 \ ^\circ C \quad (5a)
\]
\[
k_T = 1,78 - 0,0020 \cdot T \quad \text{for} \ 390 \ ^\circ C \leq T < 651 \ ^\circ C \quad (5b)
\]
\[
k_T = 0 \quad \text{for} \ T \geq 651 \ ^\circ C \quad (5c)
\]

4.2 Fine-grained concrete

The reduction factors for the fine-grained concrete mixture PZ-0899-01 is derived from the transient tests in analogy to the ones for rovings (Figure 6). Here, the effect of the strength loss due to the weight reduction (see section 3.3) is considered by a reduction to 0.75 between 50 °C and 100 °C (see also Schneider (1982)). This effect is similar to the behavior of high-performance concrete (HPC) according to Eurocode 2, DIN (2006). In DIN (2006) three strength classes are distinguished in relation to the concrete strength class, namely class 1
(C 55/67 and C 60/75), class 2 (C 70/85 and C 80/95) and class 3 (C90/105). The fine-grained concrete matrix PZ-0899-01 can be classified into the concrete strength class C 70/85 (Brockmann (2005)) and, thus, into class 2. From 100 °C to 488 °C the reduction factor stays constant, while most of the stress losses occurred beyond 488 °C. Since this value is the temperature 10 mm under the concrete surface, the surface temperature is in the range of 560 °C. This is near the quartz inversion at 573 °C and, therefore, resulted in strength losses which are fitted in a linear way up to the ultimate temperature of $T_u = 1005 °C$. The mean test values in Figure 6 show slightly higher reduction factors than the values for class 2.

Figure 6. Reduction factors for ultimate strength over temperature for fine-grained concrete (PZ-0899-01)

The strength reduction factors for the fine-grained concrete mixture PZ-0899-01 can be calculated with equations (6a) to (6d).

$$k_T = \begin{cases} 1 & \text{for } 23 °C \leq T < 50 °C \\ 1.25 - 0.00500 \cdot T & \text{for } 50 °C \leq T < 100 °C \\ 0.75 & \text{for } 100 °C \leq T < 488 °C \\ 1.46 - 0.00145 \cdot T & \text{for } T \geq 488 °C \end{cases}$$

5 SUMMARY AND CONCLUSIONS

The article deals with the high-temperature behavior of textile reinforced concrete (TRC) and presents results of transient tensile tests on AR-glass and carbon rovings as well as transient compression tests on a fine-grained concrete matrix. Using an optical measuring system it was possible to investigate the deformations and determine the transient creep strains of the concrete specimens.

To assess the behavior of TRC members exposed to fire, reduction factors for the tensile strength of the rovings and compressive strength of the fine-grained concrete were derived out of the transient tests. Here, the AR-glass and carbon rovings show a steady behavior until approximately 400 °C. Beyond this temperature melting effects of AR-glass leads to a reduction of the tensile strength. For carbon an ultimate temperature of 651 °C was observed, where the carbon rovings degrades. The fine-grained concrete matrix showed slightly higher reduction factors than comparable of high-performance concrete.
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