**MIGRATION OF WATER THROUGH CRACKED TEXTILE REINFORCED CONCRETE APPLIED AS A PROTECTIVE LAYER FOR RC STRUCTURES**

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**Abstract**

Understanding the transport of liquids in and through concrete is essential to an assessment of its durability. The research at hand presents insights into the transport mechanisms of water in and through composite concrete specimens made of a cracked ordinary concrete (OC) as a substrate and textile reinforced concrete (TRC) as a cover layer for its strengthening and repair. The TRC cover layer was assessed with regard to its efficiency as a protective layer against the ingress of water. Since in real applications such TRC layers may actually be or presumed to be cracked, thereby activating the load-carrying function of the textile reinforcement, the TRC layer was cracked for purposes of this study. The water transport in the OC specimens without TRC layer was used as reference. Neutron radiography served as the main testing technique.

It was found that water entered very quickly into the OC through its macro-cracks; migration continued by capillary transport into the matrix via the cracks and the wetted specimen surface. The water-front reached the depth of 60mm within 6 hours and saturation was observed after 23 hours. The specific crack pattern of the TRC with numerous but very narrow cracks resulting from tensile loading affected the water migration in the composite specimen fundamentally. The TRC layer (thickness 14mm) was saturated after as long as 6 hours. From then on, a horizontal water-front migrated into the cracked OC. Due to the low transport rate the macro-cracks could not activate their intense suction force, although the water migrated only by capillary suction through the OC matrix. After 23 hours, the depth of the water-front in the OC substrate was only approximately 15mm.

Additionally, the permeability of the cracked TRC material was investigated by means of water and oxygen permeation tests. Furthermore, the effect of self-healing phenomena on the transport properties of TRC was investigated. The self-healing of the fine cracks led to a very pronounced reduction in the transport rates over time.

**Keywords:** textile reinforced concrete, multiple cracking, water transport, neutron radiography, self-healing
1. INTRODUCTION

Mechanically loaded, reinforced concrete structures must be cracked to activate the load bearing capacity of the steel reinforcement. Given this, cracks do not necessarily represent damage, but they can be a characteristic feature of a concrete structure. However, these cracks may affect the durability of the structure negatively as they are very viable pathways for liquids and gases into the interior of the concrete and, in turn, onto the steel reinforcement. Water and chemical substances can cause severe damage there, leading to a considerable shortening of the service life of the structure. With respect to the durability of the concrete itself, it must be said that nearly all deterioration processes are related to the transport of water and, more particularly, of the ions it carries in solution. As prominent examples the easy transport of water through cracks increases the danger of damage due to frost and to de-icing agents. To prevent the deterioration of concrete and steel reinforcement in the cracked areas, the water uptake from the surface must be inhibited.

As a cover layer to strengthen existing concrete structures, textile-reinforced concrete (TRC) can be applied to advantage [1]. Its outstanding features include its high tensile strength and strain capacity. However, to activate its efficiency fully, the TRC must be cracked; a characteristic crack pattern forms with numerous, very narrow cracks [2]. So far, investigations of durability issues have focussed on the transport properties of the TRC itself, the durability of fibres and the deterioration of the fibre-matrix interface [2-4].

In this work, water transport in the composite element made of an ordinary concrete (OC) as substrate and a TRC-shroud is treated. Although the TRC-layer covers the macro-cracks of the substrate, concerns can arise in respect of the effect of the narrow cracks in the TRC. Under loading these cracks appear primarily in the vicinity of the macro-crack in the substrate. The effect of different TRC top layers on the kinetics of water uptake of cracked compound specimens made of OC and TRC was studied here by means of neutron radiography [5] as the chief method.

2. EXPERIMENTATION

2.1 Materials, specimen preparation

In use were two types of TRC developed in the framework of the Collaborative Research Centre 528 of the German Research Foundation [4], cf. Table 1 and 2.

For capillary suction experiments, composite specimens of OC (Table 1), reinforced with steel bars, and a 14mm TRC shroud with 4 textile layers were produced. As reference, reinforced OC was the sole material investigated. Slabs made of OC had a width of 30cm, a length of 100cm and a thickness of 6cm. After demoulding they were stored in water for 7 days, followed by a standard climate over 21 days (20°C, 65% RH). They were then pre-cracked in a four-point bending test (span length: 90cm). Subsequently the surface was grit-blasted and manually laminated with TRC. The slabs were then covered with wet wraps for 7 days, followed by storage in the standard climate for 21 days. Further bend loading was then applied to induce cracking in the TRC layer. After unloading, the beams were cut into slices of 2cm thickness in a direction perpendicular to the cracks for purposes of neutron radiography.

For the permeability experiments under uniaxial loading, pure TRC specimens were produced. Their thickness, production technique, and number of textile layers corresponded to
the parameters of the TRC-shroud in the composite specimens. The specimens were of dimensions 10cm by 60cm. Further details of the production process may be found in MECHTCHERINE and LIEBOLDT [2].

Table 1: Concrete compositions [kg/m³]

<table>
<thead>
<tr>
<th>Substance</th>
<th>Ordinary concrete</th>
<th>TRC with glass fibre</th>
<th>TRC with carbon fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>350 (CEM I 32.5 R)</td>
<td>550 (CEM III B 32.5 N-NW/HS/NA)</td>
<td>861 (CEM I 32.5 R)</td>
</tr>
<tr>
<td>Fly ash</td>
<td>35</td>
<td>248</td>
<td>-</td>
</tr>
<tr>
<td>Silica fume suspension</td>
<td>-</td>
<td>55 (solids cont. 50 mass%)</td>
<td>-</td>
</tr>
<tr>
<td>Aggregate</td>
<td>1,760 (size 0/8)</td>
<td>1,101 (size 0/1)</td>
<td>1,148 (size 0/1)</td>
</tr>
<tr>
<td>Water</td>
<td>182</td>
<td>248</td>
<td>287</td>
</tr>
</tbody>
</table>

Table 2: Textiles used as reinforcements in TRC

<table>
<thead>
<tr>
<th>Yarn material</th>
<th>Unit</th>
<th>Alkali resistant (AR) glass</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness</td>
<td>[tex]</td>
<td>1,280</td>
<td>2,400</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>[µm]</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>[-]</td>
<td>3,200</td>
<td>1,600</td>
</tr>
<tr>
<td>Yarn spacing</td>
<td>[mm]</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Mass/area</td>
<td>[g/m²]</td>
<td>374</td>
<td>676</td>
</tr>
<tr>
<td>Polymer content (as yarn coating)</td>
<td>[mass%]</td>
<td>2.7</td>
<td>0</td>
</tr>
</tbody>
</table>

2.2 Methods

Neutron radiography measurements were performed at the thermal neutron radiographic facility NEUTRA at the PAUL SCHERRER Institute [5]. The samples were positioned upright in a container with the cracked surface facing downwards. A distance of 2mm was kept between the bottom of the container and the specimen. Water was poured into the container for absorption by the specimens. The water distribution was monitored for 23 hours using the neutron beam. The quantitative evaluation followed the method described by ZHANG et al. [6].

For the description of the permeability cell for experiments under axial loading, refer to MECHTCHERINE and LIEBOLDT [2].

At an age of 56 days, oxygen permeation measurements in uncracked, non-loaded TRC specimens were performed as a reference. The recording of permeation data began after a stationary flow condition had been established, as was done with each subsequent step. The specimens were then preloaded up to a strain of 0.5% to produce a system of multiple cracks. Afterwards, the specimens were unloaded and eventually reloaded stepwise for particular
strain levels, and herewith for different crack opening widths, at which the permeation was measured. First the oxygen permeability experiments were performed; then the water permeability was investigated in similar fashion using the same specimens. To determine water permeability the specimens must be fully saturated by water so that the water flow rate through the specimen under a given pressure is approximately constant over time. Thus, before applying tension, each specimen was saturated with water for at least 24 hours. At each strain level, a waiting period of up to 4 hours was necessary until a quasi-stationary flow rate was established. After the in situ permeation test, the sample was left in the permeation cell.

To investigate the effect of self-healing, further water permeation measurements were carried out in the unloaded, saturated state at time intervals of 7 days. To eliminate the influence of swelling, the specimens were dried after water storage of up to 35 days, and oxygen permeability was measured once again. The self-healing became apparent by comparing the gas permeability measured before and after the water storage. The crack closing by newly formed materials was further characterized using the environmental scanning electron microscope (ESEM).

3. RESULTS AND DISCUSSION

3.1 Crack pattern and capillary suction

The most efficient transport mechanism for damage-inducing aqueous media is capillary suction via cracks. The suction behaviour of composite specimens made of OC and a shroud of TRC was characterised using neutron radiography. The OC specimens showed macro-cracks with opening widths of 100-200µm at the surface at a distance of 60-75mm from each other (Figure 1). The crack depth was approximately 30 to 40mm. Such crack patterns can be considered as representative for RC members subjected to bending. After the water very rapidly entered the crack, the water-front started migrating by capillary transport through the capillary pore system from the saturated crack and from the specimen surface in contact with water. At an early age of only 30 minutes after beginning contact with the water, the water-saturated crack can be observed clearly by the neutron radiography measurements and the capillary transport into the matrix is in progress, cf. Figure 3a. Due to ongoing capillary transport, which continues from the bottom of the specimen as well as from the crack, the specimen is totally saturated after 23 hours, cf. Figure 3b.

Figure 1: Crack pattern of the preloaded steel-reinforced OC as the substrate for TRC
Figure 2: Crack pattern of the composite slab made of pre-cracked steel-reinforced OC concrete with a TRC shroud after loading
The composite specimens with a TRC protective layer showed the expected characteristic crack pattern of TRC when loaded in bending cf. Figure 2. The distance from one micro-crack to the other was measured either as 7mm or 14mm, which coincided with the (simple or double) distance of the yarns of the textile reinforcement (cf. Table 2). After unloading, crack widths of approximately 20µm remained, which are significantly narrower than those in ordinary concrete. Apart from this, the capillary pores’ system in the TRC is finer due to the concrete recipe (low water-to-binder ratio).

Figure 4 shows the effect of the TRC layer, here made with carbon fibre, on water suction. First, the fine cracks in the TRC were filled. Additionally, transport of water from the cracks by the yarns due to capillary action of the inter-filament spaces could be observed. Then, the TRC matrix became saturated, starting with the suction surface and from the crack flanks as well. Six hours after the beginning of water contact, the water-front reached the interface with the ordinary concrete, i.e., a suction height of 14mm. From this point on, the water was transported by the capillary pore system of the ordinary concrete. The existing macro-cracks could not activate their intense suction force due to the very moderate volume flow rate through the TRC layer. After 23 hours of water suction from the bottom side, the water-front had moved only about 15mm into the ordinary concrete, i.e., the suction depth in the OC substrate part of the composite specimen at this time point reached only 25% of that of the plain, cracked, ordinary concrete.
Quantitative evaluation of the images at different points in time after the beginning of the exposure to water provided more distinct information on the temporal development of the moisture distribution in the specimens Figure 5. The given moisture profiles confirm the data read visually from the neutron radiography images but in addition yield the average values for the water content at different distances from the exposed specimen surface. The results presented for the TRC made with carbon fibre are in essence representative also for the TRC made with AR glass [7]. Thus, the specific crack pattern and the very narrow crack opening widths of the TRC led for all investigated TRC-layers to a protective effect.

3.2 Permeability under uniaxial tensile loading

Figure 6 shows the time-dependent flow rates at different strain levels as measured during the in-situ water permeation tests on TRC made with AR glass yarns (2400tex). It can be seen that the constant water transport rate was established approximately four hours after the beginning of the test. Similar behaviour was observed also for other TRC compositions.
In the quasi-stationary state a considerable, strongly over-proportional increase in the transport rate was found with increasing strain; see Figure 7. The particular values of the water volume flow rates varied with the kind of the textile reinforcement which could be traced back to the corresponding variation in the number and widths of fine cracks in TRC. It is worthy of mention that similar material behaviour could be observed in the oxygen permeability measurements although the absolute values of volume flow were significantly smaller in the water permeability tests since water has a higher viscosity than that of oxygen.

3.3 Self-healing of the TRC with multiple cracking

Following the in situ water permeation measurements, the samples were left in the permeation cell. To investigate the effect of self-healing on the transport properties of TRC, further water permeation measurements were carried out in the unloaded, saturated state. Figure 8 shows the time-dependent reduction of the transport rates. No measureable flow occurred after continued water exposure over 21-35 days. Whether this decrease was caused by matrix swelling or formation of self-healing products was explained by repeated oxygen permeation experiments after the specimens had been dried. Table 3 summarises the specific oxygen permeability values. The data after cracking, wet storage under load, and subsequent drying correspond well to those obtained for the virgin, uncracked specimens. This proves that newly formed crystalline matter indeed closed the cracks.

Using an Environmental Scanning Electron Microscope (ESEM), cracks before and after exposure to water were investigated. The pictures showed that the newly formed crystals closed the cracks to transport (cf. Figure 9). The predominant crystalline product was calcite.

<table>
<thead>
<tr>
<th>Yarn material</th>
<th>Unit</th>
<th>AR glass, coated</th>
<th>AR glass, coated</th>
<th>AR glass, non-coated</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness of yarns</td>
<td>[tex]</td>
<td>1,280</td>
<td>2,400</td>
<td>2,400</td>
<td>800</td>
</tr>
<tr>
<td>k uncracked</td>
<td>$[10^{-17} \text{ m}^2]$</td>
<td>2.4</td>
<td>1.6</td>
<td>4.7</td>
<td>2.1</td>
</tr>
<tr>
<td>k cracked, after water treatment and drying</td>
<td>$[10^{-17} \text{ m}^2]$</td>
<td>2.7</td>
<td>1.8</td>
<td>5.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

The transport of liquids and gases through the cracks and pores of a cement-based matrix determines very basically the limits on the durability of concrete structures. This has to be considered, especially if textile-reinforced concrete is applied for repair and strengthening of existing structures, since it may function as a protective layer. The authors conclude the following from the experimental results described in the previous sections:

- TRC has a finer crack distribution and smaller opening width of the individual cracks than ordinary concrete.
- In ordinary concrete, quick and deep ingress of water through relatively wide macro-cracks (100 to 200µm), followed by transport through the capillary pore system, causes saturation of large areas in a rather short time. TRC applied to the OC surface reduces the ingress of water to a large extent. Its small crack widths of approximately 20µm modify the suction behaviour fundamentally. In the cracked substrate of ordinary concrete, capillary suction is obviated, and transport through the pore system of the matrix becomes the prevailing transport mechanism, based on the suction force characteristic of capillary pores. Not only is the mechanism altered, but the transport of water deep into inner regions is significantly retarded as well.
- Water permeability experiments of TRC specimens in situ under uniaxial loading showed an over-proportional increase in permeability with increasing strain. Higher textile fineness and an improved matrix-textile bond as a result of textile coating led to finer crack patterns and smaller crack opening widths. In this manner the corresponding transport rates could be reduced considerably.
- The presence of water triggers the self-healing of cracks in TRC in the form of self-closing by crystallisation of CaCO₃. After a maximum period of seven weeks, no further volume flow could be detected.

The application of TRC in strengthening RC-structures has been reported previously. According to the new findings presented in this paper, TRC layers can fill protective functions as well, which, if TRC is used, prompts the expectation of a very positive effect on the durability and serviceability of repaired or strengthened concrete structures.

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REFERENCES


