CAPILLARY ABSORPTION AND CHLORIDE PENETRATION INTO NEAT AND WATER REPELLENT SHCC UNDER IMPOSED STRAIN

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Abstract

Ductility of SHCC is due to multi-crack formation. Cracks are preferential pathways for ingress of water and salt solutions into the composite material. Direct tensile tests have been run on dumbbell specimens made of SHCC. The material has been characterized by the strain hardening relation. With the aim to prevent penetration of water into cracks part of the test specimens were made with integral water repellent SHCC (IWR SHCC) by adding silane emulsion to the fresh mortar. The surface of another group of specimens has been impregnated with silane gel (SI SHCC). It could be shown that capillary absorption of neat SHCC increases significantly with progressing strain hardening as more and wider cracks are being formed. The liquid transgresses the entire thickness of the specimen (30 mm) in a short time. If chloride solution enters the cracks a typical chloride profile is established close to the surface in contact with the salt water. Later chloride accumulates near the opposite surface too. Results have been confirmed by direct observation of moisture migration by means of neutron radiography. According to the results obtained, the tolerable strain has to be limited to values well below 0.5 % if the material is to protect reinforced concrete structures in aggressive environment.

1. INTRODUCTION

Durability of reinforced concrete structures can be tightly linked with crack formation. The ultimate strain capacity of concrete is with a value of about 0.015 % rather modest. Therefore a number of different actions such as hygral and thermal gradients and a combination thereof may cause cracks even before a structural element is loaded. Under service load in tension or bending more cracks are created. It is well documented by now that cracks are preferential pathways for water and aggressive compounds dissolved in water [1, 2]. Water and salt solutions may be absorbed by capillary action and penetrate deep into the material in a short time.
Many attempts have been undertaken to increase ductility of cement-based materials in order to reduce the risk of crack formation. Polymer concrete, polymer modified concrete and fibre reinforced concrete are just some typical examples for these attempts. Results, however, remained modest. First test results with SHCC provided new hope for a more ductile and more durable cement-based material for applications in aggressive environment [3]. But, strain hardening and extreme ultimate strain capacity in this case is obtained by multi-crack formation in the cementitious matrix. In case a structural element will be exposed permanently to a dry indoor environment formation of micro-cracks will have no significant influence on durability and service life. But when a structural element is to be placed in an aggressive environment, automatically the question arises: do the fine cracks formed during strain hardening also serve as preferential pathways for water or other deteriorating liquids? More specifically one may ask: what is the maximum tolerable crack width, with respect to a required service life? In case the fine cracks formed in the strain hardening range absorb water by capillary action, one may ask: can capillarity be inactivated by water repellent treatment?

Answers to these questions shall be presented and discussed in this contribution, based on recent results of different research projects.

2. EXPERIMENTAL

The composition of SHCC has been optimized for these test series by varying the amount of the different components in a systematic way. Ordinary Portland cement Type 42.5 and a local fly ash have been used. Sand with a maximum grain size of 0.3 mm and PVA fibres (Kuraray Company, Japan) have been added. The final composition is indicated in Table 1.

2 \% of silane emulsion has been added to the fresh mix of a number of samples in order to produce integral water repellent SHCC.

Table 1: Composition of the SHCC prepared for these test series; mass is indicated in kg/m³

<table>
<thead>
<tr>
<th>Cement</th>
<th>Fly Ash</th>
<th>Sand</th>
<th>Water</th>
<th>Fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>650</td>
<td>550</td>
<td>395</td>
<td>26</td>
</tr>
</tbody>
</table>

Dumbbell specimens have been prepared for the test series described in this contribution. The shape and the dimensions of the samples are given in Fig. 1. The centre part, which has been under uniform tensile stress, had the following size: 120 x 60 x 30 mm. To determine capillary water movement by means of neutron radiography, this centre part has been cut off with a diamond saw.

After compaction all specimens were allowed to harden in the laboratory under wet burlap for 24 hours. Then the steel form has been removed and the specimens were stored until an age of 7 days in a moist curing room (T = 20 °C, RH > 95 \%). Then the specimens were stored in a room with RH = 50 \% for another 7 days. After this drying period some specimens were surface impregnated with 400 g/m² of silane gel. The silane was allowed to react for 7 days before the specimens were tested. All specimens had an age of 21 days when they were tested.

All tests have been carried out in a stiff steel test rig, which allowed us to keep a certain strain constant until the crack distribution and in some cases the capillary water absorption had been measured.

In order to determine the crack distribution under imposed strain, the surface of the part of the samples, which is under uniaxial tensile stress, has been subdivided into ten equal areas.
3. RESULTS AND DISCUSSION

3.1 Stress-strain diagram

A typical stress-strain diagram of the SHCC tested in this project is presented in Fig. 2. The tensile strength of the cement-based matrix is approximately 2 N/mm$^2$ and the ultimate strain capacity is about 4 %.

![Stress-strain diagram](image)

Figure 2: Typical stress-strain diagram of the SHCC under investigation.

3.2 Crack distribution

The number of cracks related to the length $l_0$ of the part of the dumbbell specimens under uniaxial stress ($l_0 = 120$ mm) has been determined as described above. Results obtained at an imposed strain of 1.25 % and 3.5 % are shown in Fig. 3 as an example. The measured distribution of the crack width has been fitted with a lognormal function. More details on the
3.3 Capillary absorption

As mentioned above, capillary absorption has been measured by means of a specially designed modified Karsten tube with a scaled pipette. Results obtained on neat SHCC are shown in Fig. 4. Capillary absorption of neat SHCC is rather modest. But, after a strain of 0.5% is imposed, the amount of capillary absorbed water is more than doubled. With increasing imposed strain, the amount of capillary absorbed water increases steadily. At an imposed strain of 2% more than 1200 g/m² of water is absorbed after one hour of contact of the formed surface with water. Quite obviously, the newly formed cracks absorb under these conditions more water than the porous matrix.

Similar tests have been run with integral water repellent SHCC and with surface impregnated water repellent SHCC. It might have been expected that cracks in the water repellent matrix do not absorb water or at least much less water than neat SHCC [1, 2]. It has been found that integral water repellent samples without imposed strain absorb significantly less water than neat SHCC samples. But, if a strain of 1.5% and 2% is imposed, the amount of capillary absorbed water increases significantly.

Water repellent surface impregnated SHCC absorbs a very small amount of water if no strain is imposed. This small quantity enters the porous space as water vapour and therefore no chloride can be transported by this moisture migration. However, in case a strain of 1.5% and more is imposed, cracks are formed and a considerable amount of water may be taken up.

3.4 Chloride penetration

For these experiments, water in the modified Karsten tube has been replaced by a 3.1% NaCl solution. The contact between SHCC and the salt solution has been maintained for 3 hours. Then thin layers have been removed successively from the surface, which has been in contact with the salt solution, by milling. The chloride content of the obtained powder has been determined analytically. Results obtained on neat SHCC, which has been strained up to

Figure 3: Measured crack width distribution functions of neat SHCC after imposed strain of 1.25% and 3.5%. Fitted lognormal distribution functions are also shown [4].

Evolution of the crack width distribution as a function of imposed strain are given in another contribution to this volume [4] (see also Ref. [5]).

Figure 4: Capillary absorption of neat SHCC.
different levels, are shown in Fig. 5. In the unstrained sample a usual chloride profile has been observed. Chloride penetrated approximately up to 10 mm into the neat material. This corresponds roughly to the capillary penetration depth of the salt solution. But if a strain of 0.5 % is applied only, chloride is transported through the entire thickness of the specimen to the opposite surface. There water evaporates and as a consequence the salt content increases with time. On specimens, which have been strained up to 2 % this effect is even more pronounced.

Chloride profiles as measured in integral water repellent concrete and in surface impregnated water repellent concrete are shown in Fig. 6 and Fig. 7. It can be seen that the chloride penetration into integral water repellent concrete is significantly slowed down as compared with neat concrete. But, if a strain of 2 % is imposed, the resulting cracks are wide enough to transport dissolved chloride through the entire thickness within three hours.
Figure 6: Influence of imposed strain on chloride profiles as observed in integral water repellent SHCC after contact of one surface with a 3.1 % NaCl solution for three hours.

Figure 7: Influence of imposed strain on chloride profiles as observed in surface impregnated water repellent SHCC after contact of one surface with a 3.1 % NaCl solution for three hours.

Surface impregnated water repellent concrete prevents chloride penetration even after imposed strain of 0.5 %. It seems that the maximum tolerable strain of surface impregnated concrete has to be limited to values well below 0.5 % for durable protection of reinforced concrete structures.

3.5 Neutron radiography

Neutron radiography has proved to be an advanced and powerful method to study moisture content and moisture migration in porous materials such as concrete and mortar [6, 7]. The capillary water uptake of neat SHCC (N-SHCC) and integral water repellent SHCC (IWR-SHCC) has been observed by means of neutron radiography. Selected results are shown in Fig. 8.

In the unstrained sample of neat N-SHCC the capillary absorbed water has reached a higher level than in the unstrained IWR-SHCC. But at some areas the water penetrated deeper
Figure 8: Comparison of capillary water absorption of neat SHCC (N-SHCC) and of integral water repellent SHCC (IWR-SHCC) after 30 minutes of contact of the lower surface with water.

into the material. This is most probably due to shrinkage of the specimen. The hygral gradient is at the origin of the formation of fracture process zones in the drier surface near layer. These damaged zones absorb water into the newly created pore space. If a strain of 0.5 % has been applied, a number of cracks become visible in N-SHCC, while locally some water is absorbed by IWR-SHCC only. If the strain is further increased to 1.5 % in N-SHCC many water filled cracks become visible, while in IWR-SHCC only one crack runs through the entire section of the sample. The capillary absorption of very fine cracks obviously is inactivated in the water repellent matrix. It can also be seen that more water is absorbed out of the water filled cracks by neat SHCC.

4. CONCLUSIONS

Based on the experimental results presented in this contribution the following conclusions can be drawn:
- Neat SHCC absorbs water and salt solutions by capillary action if the surface is in direct contact with the liquid just as all other cement-based materials.
- Ingress of water and ions dissolved in water can be slowed down considerably by adding silane emulsion to the fresh mix in order to obtain integral water repellent SHCC.
- Surface impregnation of SHCC with silane acts as a chloride barrier if the imposed strain remains below 0.5%. At higher crack width the efficiency of surface impregnation is improved if the impregnation is carried out after crack formation.
- The huge strain capacity of SHCC can be used exclusively in dry indoor environment. The tolerable strain capacity of untreated SHCC in aggressive environment must be limited to values well below 0.5%.

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