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Significance of Water Repellent Treatment of SHCC for Durability and Service Life

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Abstract

Conventional concrete is a rather brittle material. The ultimate strain capacity is less than the strain imposed by shrinkage under normal climatic conditions. As a consequence cracks will be formed during the first decade of the envisaged service life. Observation in practice shows clearly that cracks are most often at the origin of early corrosion of the steel reinforcement in concrete. SHCC (Strain Hardening Cement-based Composites) is a comparatively new material with an ultimate strain capacity of up to 6 %. This pseudo-ductility, however, is reached by multi-crack formation. This contribution is focused on the capillary suction of cracks into SHCC during imposed strain and after unloading. Even very fine cracks absorb water or salt solutions deep into the material. This could be visualized and determined quantitatively by means of neutron radiography. From the surfaces of water filled cracks, the liquid penetrates further into the adjacent material. The surface of samples of SHCC has been impregnated with liquid silane. Then water penetration has been determined under imposed strain and in the unloaded state. It has been observed that capillary action of SHCC is inactivated by water repellent treatment. The potential of SHCC can be exploited fully only, if the material is made water repellent.

Keywords: SHCC, crack formation, surface impregnation, durability

1 Introduction

SHCC, a strain hardening cement-based composite, is a modern advanced material with promising properties for diverse applications. Due to multi-cracking of the cementitious matrix a stress-strain diagram is obtained, which resembles in some respect stress-strain diagrams of metals such as steel with pronounced. The marked difference, however, is that in SHCC cracks are formed in the strain hardening stage. In case a structural element made of SHCC has to carry mechanical load exclusively during the entire life time, this may be admissible. In many cases, however, SHCC is applied with the aim to reach high durability or to increase durability and service life of concrete structures in aggressive environment. In this latter case it is of utmost importance to know the critical strain, which can be imposed without allowing aggressive agents to penetrate into the material or in the case of a protective layer to pass through the material. This critical strain with respect to durability may be significantly lower than the ultimate strain capacity of SHCC.

In this contribution penetration of water into SHCC before loading and after multi-crack formation by imposed strain shall be investigated by means of neutron radiography. This is an extremely sensitive method to investigate migration of water in porous materials [1-3]. Water ingress can be considered to be the most effective transport mechanism for dissolved ions. In addition it shall be investigated to which extent water penetration can be reduced or prevented in a reliable way by water repellent treatment. If this goal can be reached it will be a decisive step to more durable and sustainable construction.

2 Experimental

2.1 Preparation of samples

A cement mortar was produced with 715 kg/m^3 ordinary Portland cement type I, 42.5, 306 kg/m^3 fly ash, 26 kg/m^3 micro silica, 715 kg/m^3 fine sand with a maximum grain size of 0.3 mm and 429 kg/m^3 water. This corresponds to a water-cement ratio of 0.6 and a water-binder ratio of 0.41. To this fine cement mortar 2 Vol. % of PVA fibres (Kuraray) have been added. To improve workability 3.5 % of a super-plasticizer (naphthalene type) has been added to the fresh mix. Part of specimens has been prepared with an addition of 2 % silane emulsion in order to make integral water repellent SHCC.

The fresh mix was cast into steel forms to produce dumbbell specimens for the direct tension test. The geometry and the dimensions of the dumbbell specimens are given in Fig. 1. The thickness of the specimens was 30 mm. The form of the specimens was removed after two days and then the samples were allowed to harden in a wet curing room at T = 20 °C and RH > 95 % for 14 days before testing.

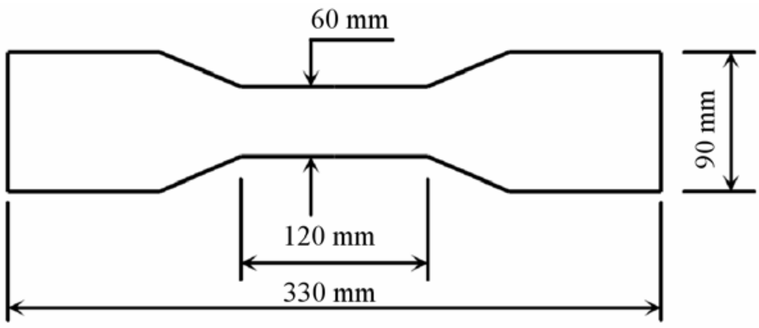

Figure 1: Geometry of dumbbell specimens with a thickness of 30 mm for direct tension tests

2.2 Capillary absorption

If the surface of a porous material is put in contact with a wetting liquid, absorption by capillary action will take place. The related amount of liquid ΔW per unit of contact surface [kg/m^2] absorbed as function of time t can be described approximately within certain time intervals with the following simple equation:

$$\Delta W(t) = A_i \sqrt{t} \tag{1}$$

Where A_i is the initial coefficient of capillary suction [kg/(m^2 h$^{1/2}$)]. A_i can be expressed by means of the following physical material properties:

$$A_i = \Psi\, \rho \sqrt{\frac{r_{eff}\ \sigma \cos\Theta}{2\,\eta}} \tag{2}$$

In equation (2) Ψ stands for the water capacity [m^3/m^3] this is the volume, which can be filled by capillary action, and ρ stands for the density of the absorbed liquid, water or the salt solution [kg/m^3], while σ represents the surface tension of the liquid [J/m^2], Θ is the wetting angle and η represents the viscosity of the absorbed liquid [(N·s)/m^2]. r_{eff} finally is an effective pore radius [m] characterizing the complex pore size distribution of the material under investigation.

The time dependent penetration depth x(t) can also be described for many porous materials approximately and for limited time intervals as function of square root of time:

$$x(t) = B\sqrt{t} \quad (3)$$

When *A* has been determined, *B*, the coefficient capillary penetration [m/s$^{1/2}$], can be obtained by the following equation:

$$B = \frac{A}{\Psi \, \rho} \quad (4)$$

Any damage induced into the porous structure of a given material will be reflected by an increase of r_{eff} and Ψ and hence by an increase of A_i and *B* respectively. For this reason capillary absorption can be used as a sensitive method to investigate damage induced into porous materials.

For the capillary suction tests and for the neutron radiography the center part of the dumbbell specimens with the following dimensions has been cut out: 120 x 60 x 30 mm. In order to obtain moisture movement in one direction all the surfaces were covered by aluminium foils with the exception of the two opposite surfaces measuring 100 × 30 mm^2. On the remaining end blocks compressive strength could be determined.

2.3 Neutron radiography

Neutron radiography has proved to be a most sensitive method to follow quantitatively moisture migration into and in porous materials such as bricks, mortar or concrete (see for instance [4-6]). All experiments were carried out at Swiss Federal Research Centre PSI in Würenlingen, Switzerland. The experimental set-up is shown schematically in Fig. 2. Neutrons coming from a spallation source are passing through a collimator before they hit the target. In our case the target is a preconditioned concrete sample, which absorbs water during while under investigation. The neutron image obtained behind the sample with a scintillation screen is registered with a CCD camera. For quantitative evaluation the recorded data have to be further evaluated by specific software.

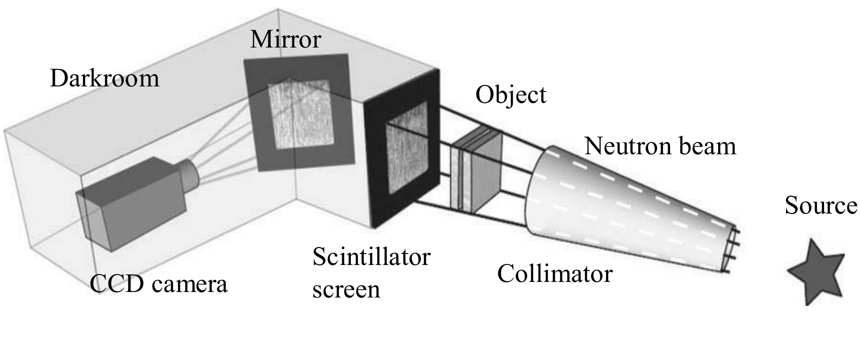

Figure 2: Schematic representation of the experimental set-up for Neutron Radiography

3 Results and discussion

3.1 Stress-strain diagram

Typical stress-strain diagrams as measured in a universal testing machine under direct tension are shown in Fig. 3. It can be seen that addition of 2 % silane emulsion reduces the maximum strain capacity slightly but higher stress can be supported at maximum. This behavior has already been observed before on similar specimens [7]. In this project capillary absorption has been determined on unloaded, i.e. undamaged, specimens and on specimens, which were strained up to 3% before the capillary absorption test.

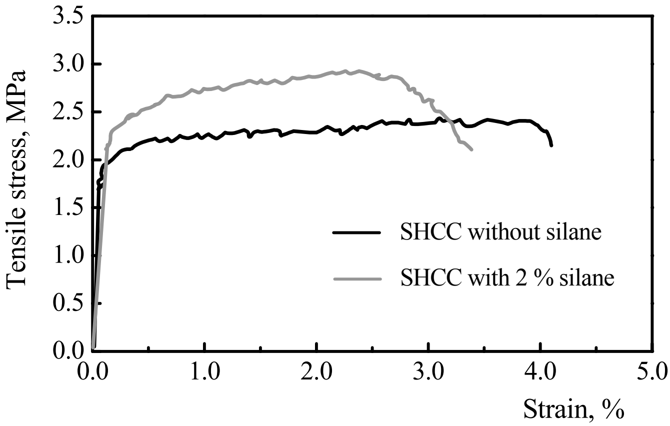

Figure 3: Stress-strain diagram of neat SHCC and of SHCC to which 2 % of silane has been added in the fresh state

3.2 Capillary absorption of undamaged SHCC

Capillary absorption of undamaged SHCC has been determined first to provide a basis for comparison. Direct observation of the capillary rising water into SHCC after contact for 60 min and for 120 min is shown in Fig. 4. The water front can hardly be seen by the naked eye. But after evaluation of the recorded data the moisture profile can be obtained. The rectangular area marked in Fig. 4 has been chosen for the quantitative evaluation of the original data. The result is shown in Fig. 5.

The cementitious matrix of SHCC produced for these tests is very dense. After 2 hours of contact with water the moisture content in the samples at a depth of 10 mm has reached a value of 0.006 g/cm^3. In normal concrete at the same depth and after the same duration of contact the moisture content is 5 to 7 times higher (see for example Ref. [8]).

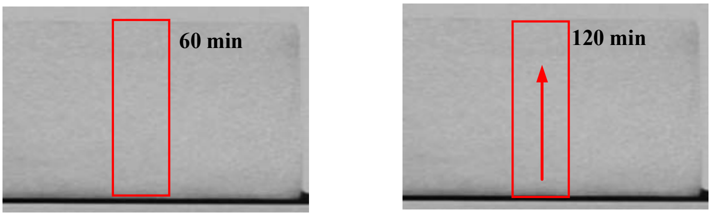

Figure 4: Visualization of water penetration into undamaged SHCC by means of Neutron Radiography

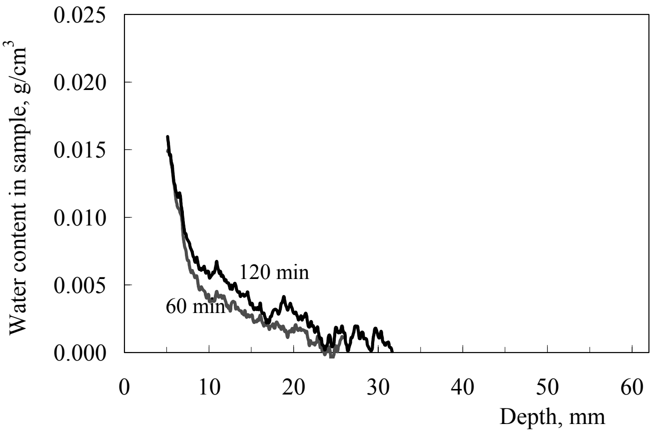

Figure 5: Moisture profiles as determined by evaluation of the radiographs shown in Fig. 4

3.3 Capillary absorption of SHCC after imposed strain

A strain of 3 % has been imposed to dumbbell specimens as shown in Fig. 1 under uniaxial tensile stress in a universal testing machine. Then the centre part of the specimens has been cut out with a diamond saw and exposed to the neutron beam while in contact with water. One side surface 100 × 30 mm^2 was put in contact with water only. The immediate result of rising water is shown in Fig. 6.

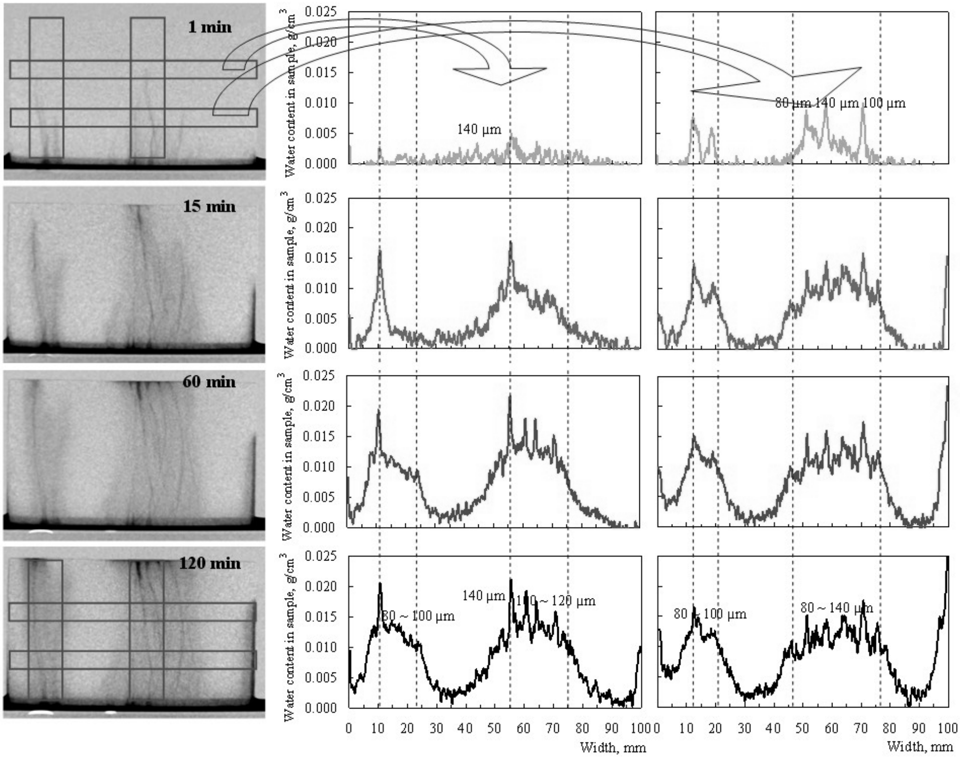

Figure 6: (a) left column: Radiographs of capillary water absorption up to 120 minutes. (b) centre and right column: Quantitative evaluation of water content in the two horizontal levels marked with rectangles

Already after one minute major cracks become visible by the contrast of the penetrating water. The height of the specimens is 60 mm that means that water has penetrated more than 30 mm into the material after one minute. After 15 minutes water has migrated through the widest crack to the top of the sample, i.e. 60 mm. After 60 minutes water migrating through a number of finer cracks has also reached the top. The crack width of these cracks is well below 100 µm. It can also be seen that water from the water filled cracks gradually migrates horizontally into the material. It is obvious that the pattern of micro-cracks in SHCC can be visualized precisely by neutron radiography.

Results of a quantitative evaluation of the water content in the fields marked with horizontal rectangles are shown in the centre and right column in Fig. 6. The lower rectangle corresponds to the moisture distributions shown in the right column of Fig. 6. In the centre column the moisture distribution as determined in the upper rectangle is shown after different contact times. Near the peaks the measured width of the corresponding cracks is indicated. After 15 minutes the dominating crack pattern is completely water filled. Then horizontal moisture movement is observed. This movement, however, is very slow as observed in undamaged SHCC (see Fig. 4 and Fig. 5).

The time dependent moisture distribution in the fields marked with vertical rectangles in Fig. 6 has also been quantified. Results obtained in the two fields are nearly identical and therefore we will present results of the right rectangle here only, in Fig. 7.

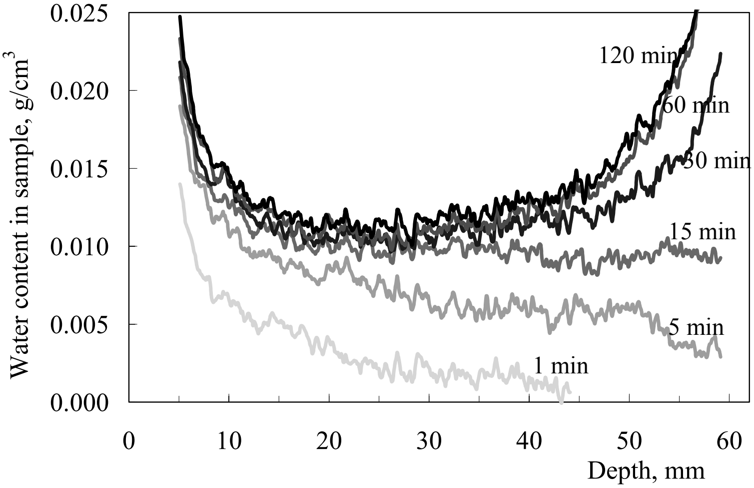

Figure 7: Moisture distribution as determined in the right vertical field marked in Fig. 6. Absorption time is indicated as parameter

The left side in Fig. 7 corresponds to the surface in contact with water. It can be clearly seen that the moisture distribution as function of the penetration depth is not uniform. After 15 minutes the lower half of the specimen is more or less water saturated, while the moisture content in the upper part still increases. There is obviously a strong border effect. It may partly be due to a certain degree of distribution and orientation of fibres close to the boundaries.

3.4 Penetration into integral water repellent SHCC

In order to study the influence of water repellent treatment on water penetration into SHCC specimens have been prepared with an addition of 2 % silane emulsion. The silane emulsion reacts in the pore space of the cement-based material and finally a network of silicon resin is formed on the surface of the hydration products. The cement-based matrix of this second type of SHCC has become integral water repellent.

In Fig. 8 neutron radiographs taken 60 minutes and 120 minutes after contact of the surface with water are shown. In this case the bottom surface was in contact with water again. Visually no water penetration can be observed. Close to the surface water has penetrated the widest cracks, but it cannot further penetrate into the integral water repellent matrix. The water distribution in the fields marked with a rectangle in Fig. 8 has been quantified by further evaluation of the data.

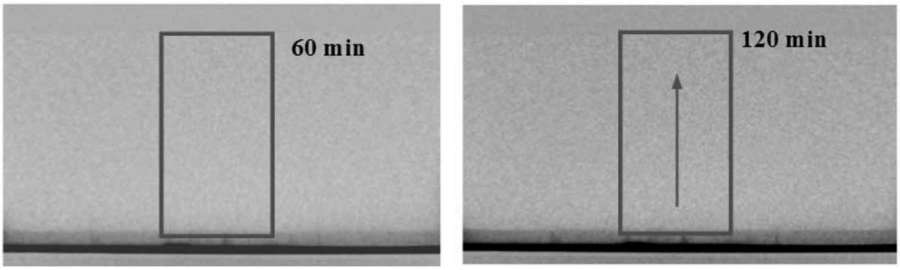

Figure 8: Neutron radiographs of integral water repellent SHCC after 60 and 120 minutes of contact with water

Results of the quantitative evaluation of the moisture distributions as measured in the rectangles marked in Fig. 8 are shown in Fig. 9. A small amount of water has penetrated within two hours of contact with liquid water only. Capillary action in integral water repellent SHCC is practically suppressed, but pores and cracks remain open. Therefore water vapour can still diffuse into the pore space. This explains why slowly small amounts of moisture penetrate the material. But salts dissolved in the liquid, which is in contact with the surface of the porous material cannot be transported by vapour diffusion into the pore space.

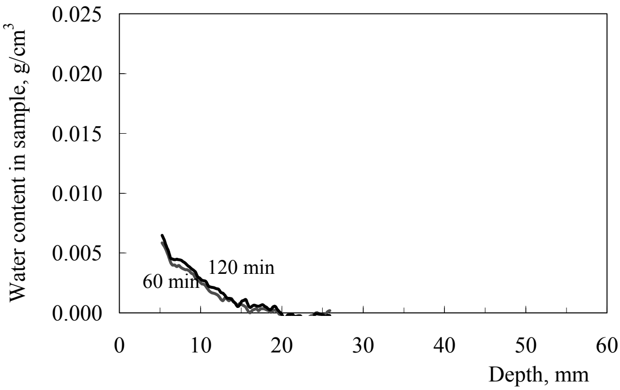

Figure 9: Moisture distribution in the rectangular fields marked in Fig. 8

4 Conclusions

It has been shown that SHCC absorbs very little water in the unstrained and undamaged state. Under these conditions the material may be considered to be durable in an aggressive environment.

SHCC is applied in most cases, however, because of its extreme strain capacity. After imposed strain of 3 % a characteristic crack pattern with cracks having a width between 20 and 140 μm is formed. This leads to a dramatic increase of capillary absorption. Micro-cracks serve as preferential paths for up-take of water or salt solutions. Under these conditions the material becomes sensitive with respect to frost action and aggressive compounds such as chlorides and sulphates can be transported deep into the material.

The wide range of ductility of SHCC can be exploited only, if the material is made water repellent. It is recommended to add water repellent agents such as silane emulsion, metal soaps or natural products to the fresh mix of SHCC to make the material integral water repellent.

Acknowledgement

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