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Durability of SHCC under imposed strain

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ABSTRACT: Strain hardening cement-based composites form a group of novel building materials with promising properties for more durable and sustainable construction. In normal cement concrete or mortar the strain capacity under tensile stress is very limited. The sum of thermal, hygral, and mechanical stresses is in most practical cases sufficient to create surface cracks. As cracks are known to be preferential paths for ingress of aggressive compounds such as chlorides or sulfates into concrete service life of reinforced concrete structures is often significantly reduced by crack formation. The ultimate strain capacity of SHCC is with more than 3% high enough to support most stresses induced by combined loads without macro-crack formation. The penetration of water into SHCC before loading and after imposed strain has been measured by means of neutron radiography. It can be shown that multi-crack formation facilitates water penetration although micro-cracks are formed only. With respect to durability and service life a maximum allowable strain has to be determined. Micro-cracks formed in water repellent SHCC do not absorb liquid water; that means higher strain is admissible in this type of SHCC without reduction of service life of reinforced structural elements.

1 INTRODUCTION

SHCC, a strain hardening cement-based composite, is a modern 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 with pronounced yielding such as steel. 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 this may be admissible. In many cases, however, SHCC is applied to reach high durability or to increase durability and service life of concrete structures in aggressive environments. 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 into SHCC 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 (see for example Wittmann 2004, Pleinert 2001). 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 Portland cement type 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 cement mortar 2 Vol. % of PVA fibres (Kuraray) have been added. To improve workability 3.5 % of a super-plasticizer (naphthalene) has been added to the fresh mix. A number of specimens have 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 Figure 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.

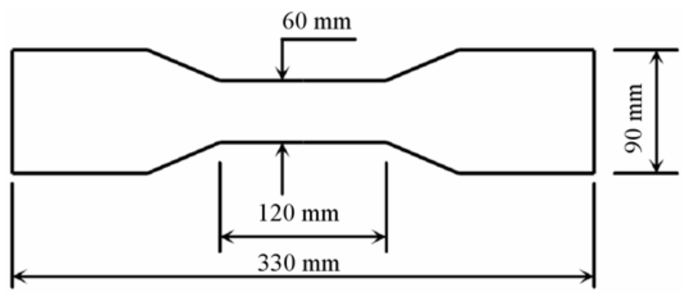

Figure 1. Geometry of dumbbell specimens with a thickness of 30 mm for direct tension tests.

2.2 *Capillary suction*

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 within certain time limits 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 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 as function of square root of time:

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

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

$$B = \frac{A}{\Psi\,\rho} \tag{4}$$

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 or B. For this reason capillary suction 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 aluminum 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 in porous materials such as bricks, mortar or concrete (Justnes et al. 1994, Pleinert 2001, Pleinert et al. 1997, Pleinert et al. 1998, Wittmann 2004, Zhang et al. 2010, Kamematsu et al. 2006). We did our experiments at the Swiss federal research centre PSI in Würenlingen, Switzerland. The experimental set-up is shown schematically in Figure 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 is allowed to absorb water during the test. Water has a particular big absorption coefficient for neutrons. 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.

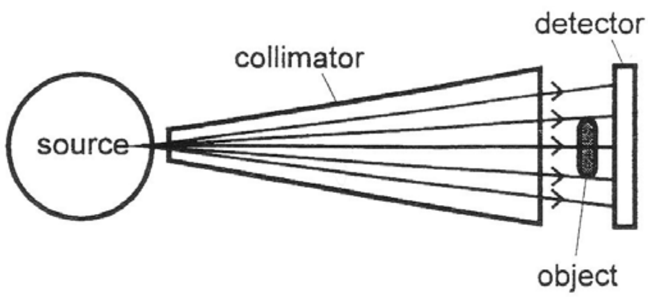

Figure 2. Schematic representation of neutron radiography.

3 RESULTS AND DISCUSSION

3.1 *Stress-strain diagrams*

Typical stress-strain diagrams as measured in a universal testing machine are shown in Figure 3. It can be seen that addition of 2 % silane emulsion reduces the maximum strain capacity slightly but higher stress can be supported. This behavior has already been observed before on similar specimens (Martinola et al. 2004).

In this project capillary suction has been determined on unloaded, i.e. undamaged specimens and on specimens, which were stained up to 3% before the capillary suction test.

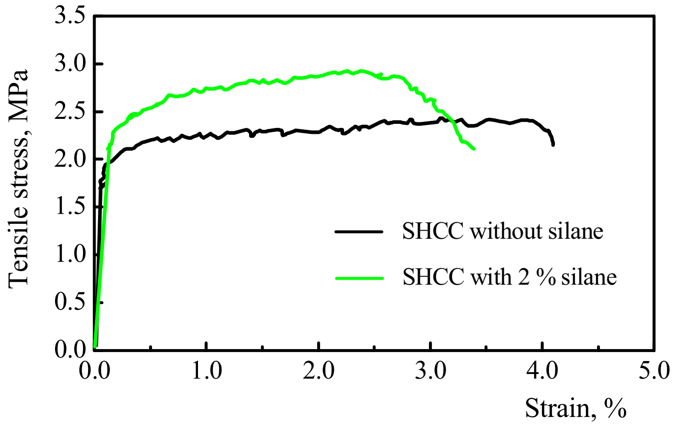

Figure 3. Characteristic stress-strain diagrams of neat SHCC and of SHCC containing 2 % of silane emulsion.

3.2 *Penetration of water into uncracked neat SHCC*

Mainly for comparison capillary suction of undamaged SHCC has been determined first. Direct observation of the rising water into SHCC after contact time of 60 min and 120 min is shown in Figure 4.

The water front can hardly be seen by the naked eye. But after evaluation of the recorded data the moisture profile is obtained. The area marked with a rectangle in Figure 4 has been chosen for the quantitative evaluation of the original data. The result is shown in Figure 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 Zhang et al. 2010).

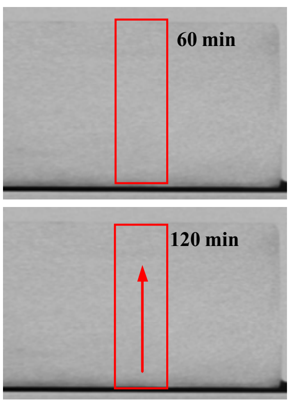

Figure 4. Direct visualization of penetrating water into undamaged SHCC.

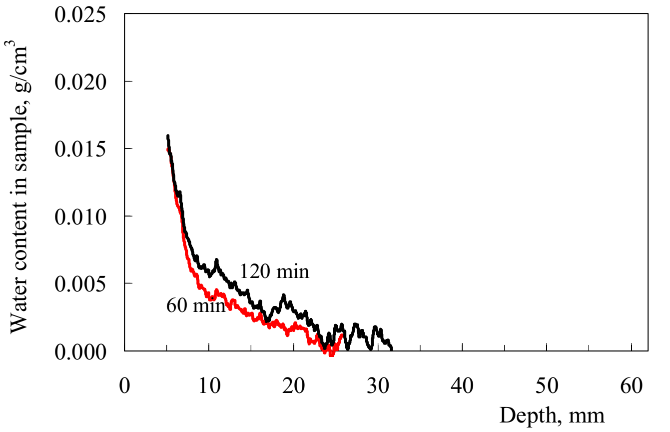

Figure 5. Moisture profile as obtained by numerical evaluation of the radiographs shown in Figure 4.

3.3 *Penetration of water into SHCC after imposed strain*

Strain of 3 % has been imposed on dumbbell specimens as shown in Figure 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 Figure 6.

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. It can also been seen that water from the water filled cracks gradually migrates horizontally into the material. The pattern of microcracking can be nicely visualized by neutron radiography.

Now we will have a look into the quantitative evaluation of the fields marked with horizontal rectangles first. Results are also shown in Figure 6. The lower rectangle corresponds to the moisture distributions shown in the right column of Figure 6. In the centre column the moisture distribution in the upper rectangle is shown after different contact times. Near the peaks the measured width of the corresponding cracks is indicated. After one minute the lower part of cracks with a width between 80 and 140 μm is water filled, while the water front just reaches the field marked with the upper rectangle. But after 15 minutes already 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).

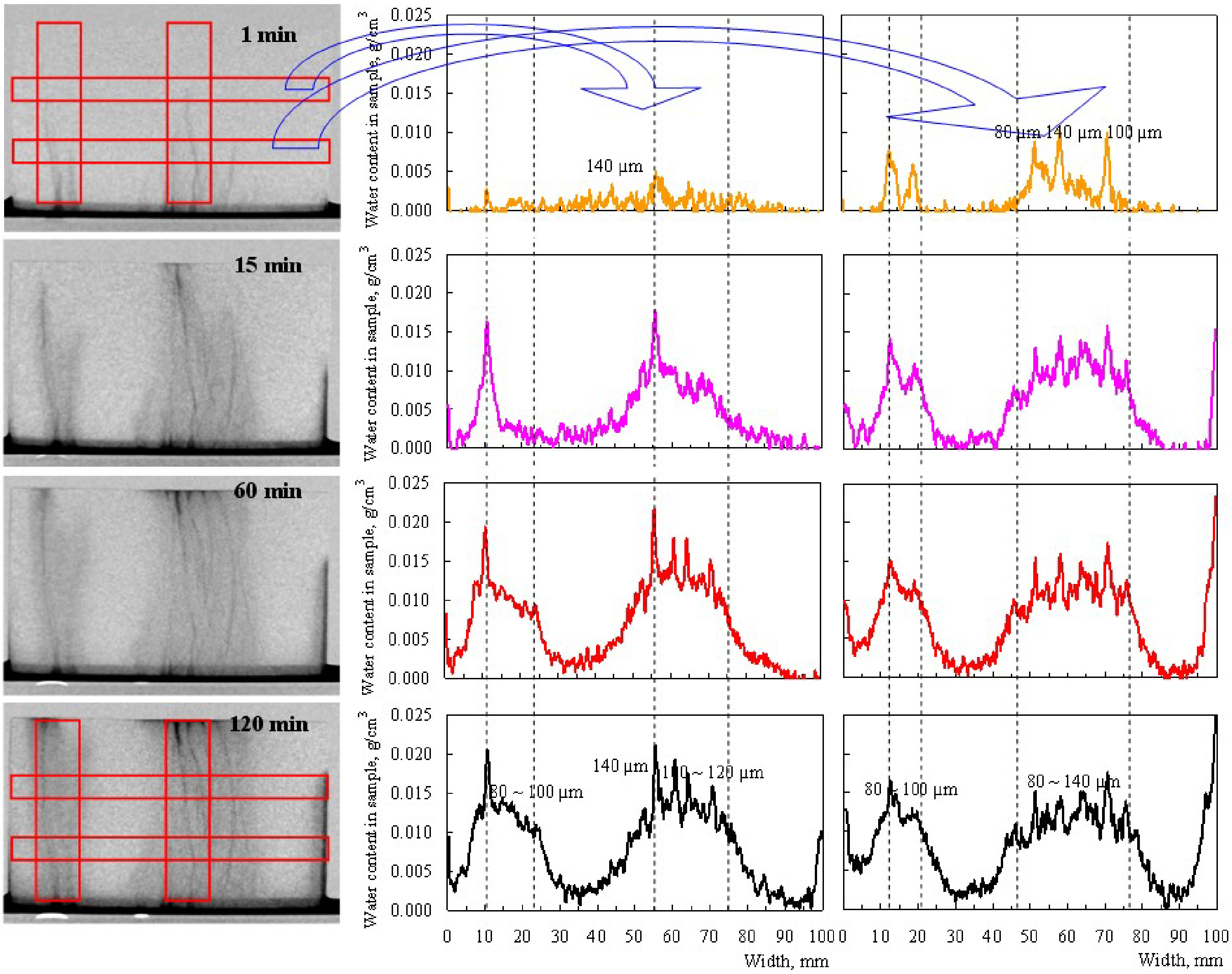

Figure 6. Neutron radiography of SHCC after imposed strain of 3 %. The lower surface is in contact with water. The fields marked with rectangles will be evaluated quantitatively.

The moisture distribution in the fields marked with vertical rectangles has also been quantified. Results obtained in the two fields are very similar and therefore we will present results of the right rectangle only because of space limits.

The moisture distribution as determined after different capillary suction times in the field marked with the right vertical rectangle is shown in Figure 7. The left side in Figure 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 one minute of contact with water, entering water is observed in the lower part only. After 15 minutes the lower half is more or less saturated, while the moisture content in the upper part still increases. There is obviously a strong border effect. This may be due to drying of the surface near zone before the test started. It may partly also be due to a certain degree of orientation of fibres close to the boundaries.

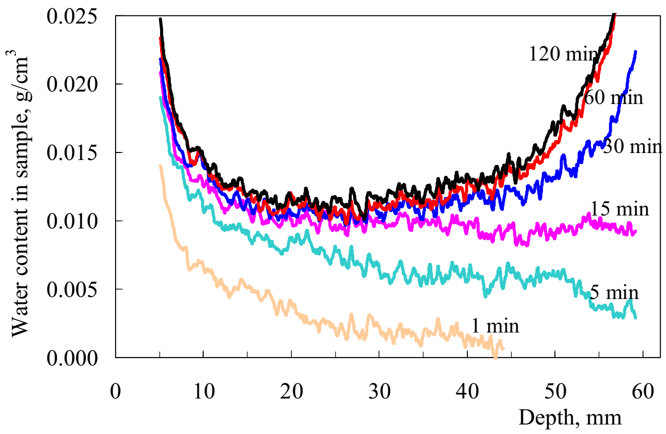

Figure 7. Moisture distribution in the right vertical field marked in Figure 6. Contact time is indicated as a parameter.

3.4 *Penetration of water into water repellent SHCC after imposed strain of 3 %*

As mentioned above some SHCC specimens have been prepared with 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. This process renders the material water repellent. In Figure 8 neutron radiographies taken 60 minutes and 120 minutes after contact of one surface with water are shown. In this case again the bottom surface was in contact with water. Visually no water penetration can be observed. The fields marked with a rectangle shall be further evaluated.

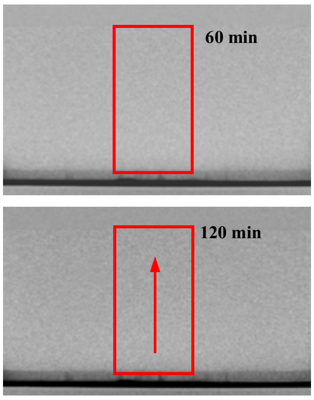

Figure 8. Neutron radiographies taken 60 and 120 minutes after contact with water.

The result of the quantitative evaluation of the rectangle marked in Figure 8 is shown in Figure 9. Traces of water have penetrated within two hours of contact with liquid water only. As the pores remain open after water repellent treatment it is assumed that a small amount of water vapour enters the pore space by diffusion.

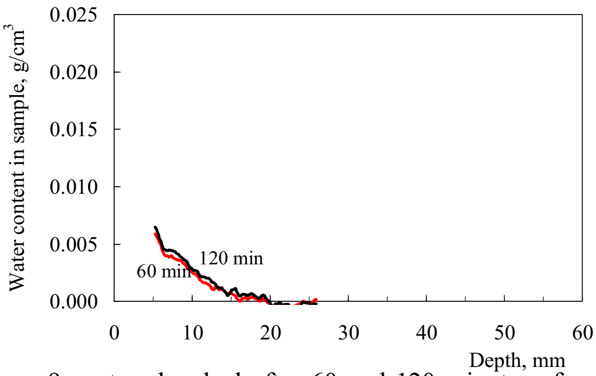

Figure 9. water absorbed after 60 and 120 minutes of contact with water by water repellent and strained SHCC.

4 CONCLUSIONS

It has been shown that the cementitious matrix of SHCC is a very dense porous material. Water uptake by capillary suction is significantly less than in ordinary concrete. In the unstrained state it can be considered to be quite durable.

If SHCC is strained up to 3 % a characteristic crack pattern is formed with cracks ranging between 20 and 140 μm. The wider cracks are quickly water filled whenever the surface is in contact with water.

As penetrating water is one of the most efficient mechanisms for transportation of aggressive agents dissolved in water into porous materials service life of concrete structures, which should be protected by SHCC, can be significantly shortened. For this reason a strain limit with a realistic safety margin must be introduced with respect to durability.

If the cement-based matrix of SHCC is made water repellent a wider range of ductility can be used in practice.

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REFERENCES

Justnes H., Bryhn-Ingebrigtsen, S. & Rosvold, G. O. 1994. Neutron radiography – an excellent method for measuring water penetration and moisture distribution in cementitious materials. *Adv. Cement Research* 6: 67-72

Kamematsu, M., Maruyama, I., Noguchi, T. & Iikura, H. 2006. Visualization of water penetration into concrete through cracks by neutron radiography. Proc. Int. Seminar on Durability and Lifecycle Evaluation of Concrete Structures. R. Sato (ed.) Higashi Hiroshima, Japan. P. 69-76

Martinola G., Bäuml, M.F. & Wittmann F.H. 2004. *J. Adv. Concr. Technology* 2: 207-212

Pleinert, H., Sadouki, H. & Wittmann, F. H. 1997. Study of moisture transport by numerical modeling and neutron transmission analysis. Int. Jour. Restoration of Buildimgs and Monuments 3: 355-370

Pleinert H., Sadouki H., & Wittmann F. H. 1998. Determination of moisture distributions in porous building materials by neutron transmission analysis. Materials and Structures 31: 218-224

Pleinert, H. 2001. Determination of moisture distributions in porous building materials – Neutron signal transfer analysis. In Building Materials Reports 14. Aedificatio Publishers Freiburg.

Wittmann, F.H. 2004. Zeitabhängige Feuchtigkeitsverteilungen in porösen Werkstoffen des Bauwesens – Numerische Simulation und Validieren numerischer Modelle mit Hilfe der Neutronenradiogaphie. Int. Jour. Restoration of Buildings and Monuments 10: 37-50

Zhang, P., Wittmann, F.H., Zhao, T., Lehmann, E., Vontobel P. & Hartmann, S. 2009. Observation of water penetration into water repellent and cracked cement-based materials by means of Neutron Radiography. *Int. Jour. Restoration of Buildings and Monuments* 15: 91-100

Zhang, P., Wittmann, F.H., Zhao, T., Lehmann, E., L. Tian, & Vontobel, P. 2010. Observation and quantification of water penetration into multi-cracked strain hardening cement-based composites (SHCC) by means of neutron radiography. *Nuclear Instruments and Methods in Physics Research A* (accepted for publication)