# D-2-6 Influence of water repellent treatment on water penetration into multiple cracked strain hardening cement-based composites (SHCC)

**Folker H. Wittmann**
*Swiss Federal Institute of Technology Zurich (ETHZ), Germany.*
*Qingdao University of Technology (QUT), China.*
*wittmann@aedificat.de*

**Peng Zhang**
*School of Civil Engineering, Qingdao Technological University, Qingdao, China.*
*zhp0221@163.com*

**Yuan Cong**
*School of Civil Engineering, Qingdao University of Technology, Qingdao, China.*

**Tiejun Zhao**
*School of Civil Engineering, Qingdao University of Technology, Qingdao, China.*

*ABSTRACT: Strain Hardening Cementitious Composites (SHCC) are a comparatively young group of fiber reinforced cement-based materials with high strain capacity. If durability is an issue, however, the ultimate allowable strain is rather limited as water and aqueous salt solutions will penetrate deep into the material via the created cracks. In this contribution, the process of water penetration into SHCC, before and after application of a certain level of tensile strain, was investigated by means of neutron imaging. Results obtained indicate that water quickly penetrates deep into the material under imposed strain via the created cracks. To reduce water penetration into cracked SHCC, two different methods were applied. First samples of SHCC were prepared by adding a water repellent agent to the fresh mix. In this way integral water repellent samples are obtained. As an alternative, the surface of hardened SHCC was impregnated with a water repellent agent. The effectiveness of the two different approaches was studied and results are presented and discussed in this contribution. It could be shown, that water penetration into SHCC can be significantly reduced by integral water repellent treatment. But a certain amount of water can still enter the material under strain via the widest cracks. As an alternative method, surface impregnation with silane gel was applied. It is shown that this second method is more reliable to protect SHCC from water penetration when cracks are formed.*

*KEY-WORDS: Multiple cracks; strain hardening cementitious composites (SHCC); surface impregnation; integral water repellent treatment; water penetration.*

## INTRODUCTION

Concrete is a rather brittle material. This means that concrete may crack easily under thermal or hygral gradients and under an applied load. Cracks may be considered to be easy pathways for penetration of water and aqueous salt solutions. Recently ductility of cement-based materials was increased enormously by adding fibers with a high elastic modulus and high tensile strength to a fine grained mortar [1-3]. Initially this new material was called Engineered Cementitious Composites (ECC) but soon the more meaningful name Strain Hardening Cementitious Composites (SHCC) was generally accepted [2]. The ultimate strain of SHCC under tension can reach up to 5%, which is more than 300 times the ultimate strain of conventional cement-based materials. If this material is applied in a protected environment, without exposure to water or to salt solutions the full strain capacity can be used, as for instance for dampers for high rise buildings in seismic areas. However, as the extreme ductility of SHCC is reached by multi-crack formation, in cases where the material is exposed to natural environment, as for instance in contact with seawater or with de-icing salt solutions, durability and service life become a crucial problem. Under these conditions the high ductility reached by multi-crack formation must be considered to be a serious risk for durability in general and for service life in particular.

Penetration of water and salt solutions into the open pore space of concrete and into cracks can be reduced if not totally prevented by water repellent surface treatment [4-7]. Martinola et al. [4] and Sahmaran et al. [5] have studied the influence of addition of water repellent agents to SHCC on capillary water absorption. There are two different methods to avoid or reduce at least capillary water absorption of cement-based materials: (a) surface impregnation with a water repellent agent and (b) addition of a water repellent agent to the fresh mix. The influence of the imposed tensile strain on water repellent SHCC has not been studied in detail so far. In the past we could show that neutron imaging is a particularly powerful method to visualize and to study quantitatively water movement into porous materials and into cracked concrete in particular. In this contribution the influence of surface impregnation and of integral water repellent SHCC on capillary absorption and of water movement into fine cracks in particular shall be investigated. The influence of imposed strain on capillary water absorption was studied in particular.

**EXPERIMENTAL**

The composition of SHCC prepared for this project was as follows: 550 kg/m$^3$ ordinary Portland cement Type 42.5; 650 kg/m$^3$ local fly ash; 550 kg/m$^3$ fine sand with a maximum grain size of 0.3 mm, and 395 kg/m$^3$ water. 26 kg/m$^3$ of PVA fibers with a diameter of 40 µm, produced by Kuraray Company, Japan, were added to the fresh mix. A second batch was prepared. In this case 2.0 % (related to the mass of binder) of an alkyl silane emulsion (Protectosil MH50, produced by Evonik, Germany) were added to the fresh mix to obtain integral water repellent SHCC.

After compaction in steel forms, all specimens were allowed to harden in the concrete laboratory under wet burlap for 24 hours. Then the steel form was removed and the specimens were stored for 21 days in a moist curing room (20 °C, 95% RH). In this project, dumbbell shaped specimens with a thickness of 30 mm and an overall length of 330 mm were cast in steel forms. The width at both ends is 90 mm and the center part with a length of 120 mm has a width of 60 mm, as shown in Fig. 1. In order to characterize mechanical properties of the SHCC under investigation in this project, stress-strain diagrams have been determined.Typical results are shown in Fig. 2. The average first cracking stress of this type of SHCC was approximately 2.1 MPa and the average ultimate tensile strain was approximately 3.8 %. Then the center part, which was subsequently subjected to a uniform tensile stress, had the following size: 120×60×30mm. Finally, in order to determine capillary water absorption by means of neutron digital imaging, the center part has been cut out of the specimen after a predetermined tensile strain had been applied.

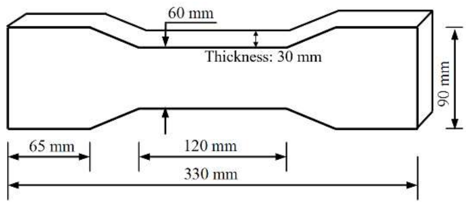


Fig.1. Geometry and dimensions of the dumbbell specimens.

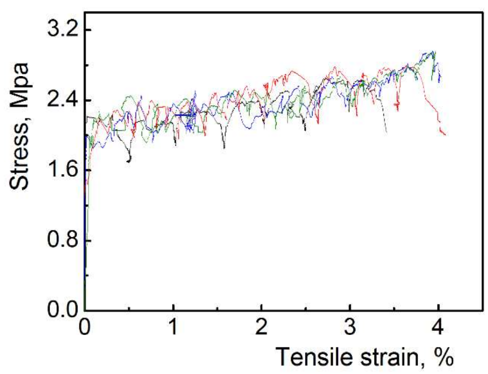


Fig. 2. Typical stress-strain diagrams of the SHCC under investigation.

After curing for 21 days, the specimens were fixed in a testing machine, which allowed applying a predetermined strain [8]. Tensile strain of 0.5 % and 1.5 % was applied for a duration of 15 minutes to both types of specimens, control specimens and integral water repellent SHCC specimens. After unloading, some of the stressed control samples were surface impregnated with 400 g/m$^2$ of silane gel (StoCryl HG200 distributed by STO, with about 85% of an alkyl alkoxy silane in ethanol).

In the next step all three types of specimens, the control, the integral water repellent, and the surface impregnated SHCC specimens were put in the neutron beam at Paul Scherrer Institute (PSI), Switzerland. A first image was taken from the dry specimens. Then one surface of the specimens (120 x 30 mm) was put in contact with tap water. While in contact with neutron images were taken in regular intervals to follow the process of water penetration into the pore space and the cracks of SHCC. More details can be found in recent publications [9, 10].

## RESULTS AND DISCUSSION

### Water penetration into un-cracked SHCC

As mentioned above first neutron images were taken on unloaded SHCC specimens. They served as reference. Images taken after 60 minutes of capillary absorption and the corresponding moisture distributions in a SHCC sample are shown in the left part of Fig. 3. For comparison a typical result as obtained on an ordinary concrete sample (W/C = 0.6) is shown in the right part of Fig. 2. It can be seen that, as expected, the specimen which has not been exposed to tensile strain absorbed very little water after contact with water for 60 minutes and compared to ordinary concrete. This indicates that undamaged SHCC absorbs comparatively little water.

### Water penetration into un-cracked SHCC

As mentioned above first neutron images were taken on unloaded SHCC specimens. They served as reference. Images taken after 60 minutes of capillary absorption and the corresponding moisture distributions in a SHCC sample are shown in the left part of Fig. 3. For comparison a typical result as obtained on an ordinary concrete sample (W/C = 0.6) is shown in the right part of Fig. 3. It can be seen that, as expected, the specimen which has not been exposed to tensile strain absorbed very little water after contact with water for 60 minutes and compared to ordinary concrete. This indicates that undamaged SHCC absorbs comparatively little water.

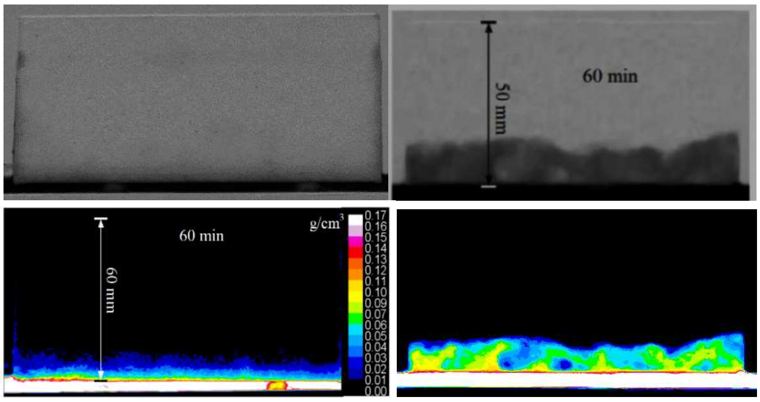


Fig.3. Neutron images of water penetration into un-cracked SHCC (left) and into ordinary concrete (W/C=0.6) after 60 minutes of contact of the lower surface (120 x 30 mm) with water. In the upper row the water content is given as grey level, while in the lower row the water content has been converted into colors.

### Water penetration into cracked neat SHCC

The process of water penetration into neat SHCC exposed to different levels of tensile strain can be visualized by neutron imaging. Selected images taken after 5, 15 and 90 minutes of capillary absorption are shown in Fig. 4. It can be seen from these results that after exposure to 0.5 % tensile strain, in the type of SHCC prepared for this project few cracks are created. Wide cracks, become water filled up to the height of the specimens within 15 minutes. After this period finer cracks become visible. The moisture distribution in SHCC in contact with water was quantitatively determined after 15 and 90 minutes. Results obtained in the two rectangular areas in Fig. 4 are shown in Fig. 5. Water profiles obtained after 15 and 90 minutes of capillary absorption on specimens exposed to a tensile strain of either 0.5 % or 1.5 % are shown. Obviously, the lower part absorbed more water than the center of the specimen. The wide cracks, which reach the upper surface, soon contain significantly more water than the fine cracks. The profiles show that in the sample subjected to 1.5 % tensile stress, more and wider cracks were formed. As a consequence they absorb significantly more water. From these results we may conclude that SHCC exposed to 0.5 % and 1.5 % of strain cannot be considered to provide long term protection in aggressive environment.

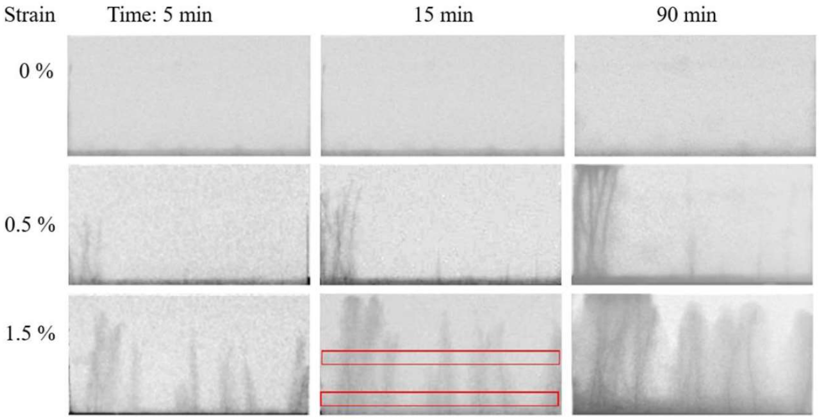


Fig.4. Neutron images of water penetration into control SHCC before and after imposed tensile strain of 0.5 % and 1.5 %.

These results underline the fact that SHCC has a high strain capacity. If the mechanical properties are of main interest in a given application, then one can take full advantage of the strain capacity. If durability is an issue, however, the ultimate strain that may be allowed is rather limited.

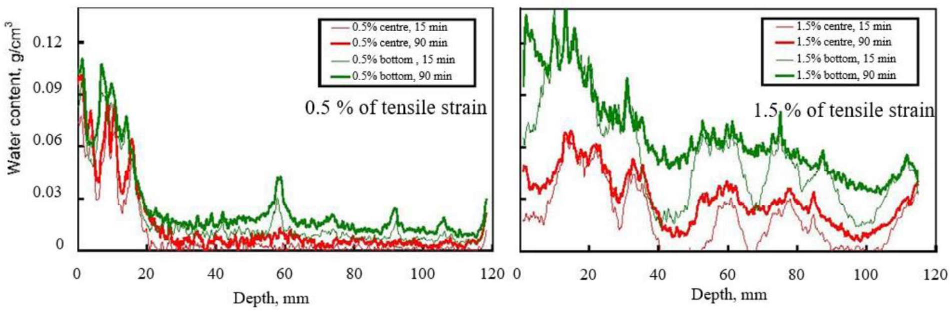


Fig. 5. Horizontal quantitative water profiles in the center and at the bottom of cracked SHCC, as indicated with rectangular areas in Fig. 3 after imposed tensile strain of 0.5% (left) and 1.5 % (right).

**Water penetration into cracked integral water repellent SHCC**

By addition of silane emulsion to the fresh mix of SHCC integral water repellent SHCC was produced. The water repellent cementitious matrix should prevent or at least reduce water absorption. Water penetration into the cracks formed under the influence of tensile strain should also be avoided or at least reduced. Typical results are shown in Fig. 6. Specimens which were not exposed to an applied strain practically do not absorb any water after 90 minutes of contact with water. Even after application of 0.5 % strain, a small amount of water can be observed in the cracks only. However, when a strain of 1.5 % was imposed, wider cracks begin to absorb water and water penetrates up to the upper surface of the specimens.

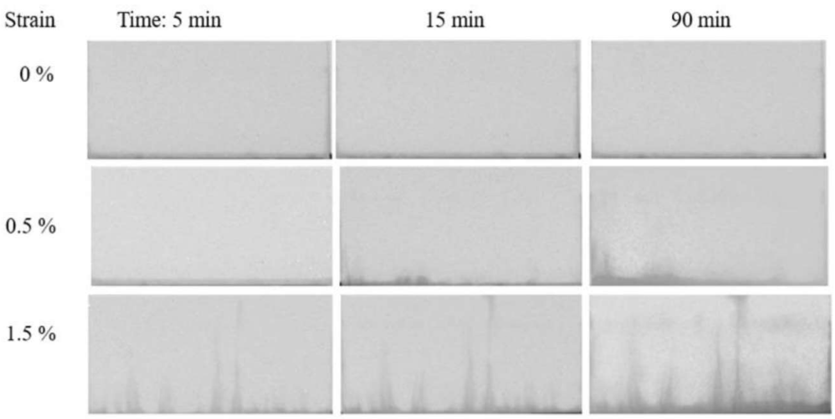


Fig.6. Neutron images of water penetration into integral water repellent SHCC before and after imposed tensile strain of 0.5 % and 1.5 %

The moisture profiles for the integral water repellent SHCC after application of 0.5 % and 1.5 % strain are shown in Fig. 7. Compared with the results shown in Fig. 5, far less water enters the crack-free zones and fewer cracks absorb water. However, water enters the cracks and migrates into the matrix. This means that integral water repellent treatment is effective in protecting SHCC from penetration of water or aqueous salt solutions as long as there are no cracks. But once micro-cracks are formed under a certain level of imposed tensile strain water can still penetrate into the matrix of the SHCC. This underlines again that SHCC is beneficial only under mild mechanical strain and under imposed moderate strain it is not a reliable protection in aggressive environment.

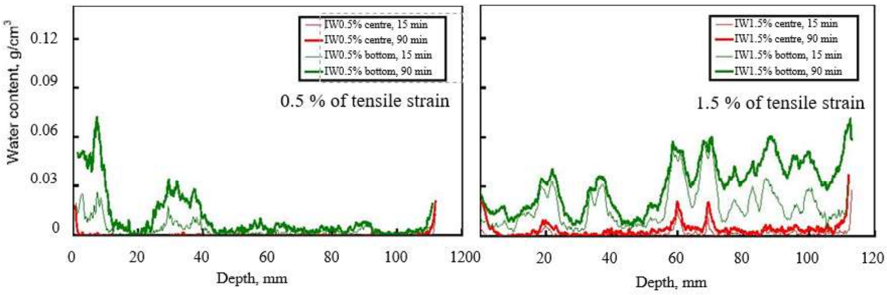


Fig.7. Horizontal quantitative water profiles in the center and at the bottom of integral water repellent SHCC after imposed tensile strain of 0.5 % (left) and 1.5 % (right).

**Water penetration into cracked surface impregnated SHCC**

After preloading to a tensile strain of 2.0 %, the cracked surface of the selected sample was impregnated with 400 $g/m^2$ of silane gel. In this way, the surface near region of SHCC sample became water repellent. Neutron image of water contact with the impregnated surface of SHCC after imposed strain of 2.0 % is shown in Fig. 8. On the surface of these two samples more than twelve micro cracks with crack width between 35 µm and 55 µm could be observed. It can be clearly seen from the results shown in Fig. 7 that no water moved into the cracked zone after surface impregnation. This is a clear evidence that surface impregnation is a more promising approach to protect SHCC when multiple cracks are expected to be formed.

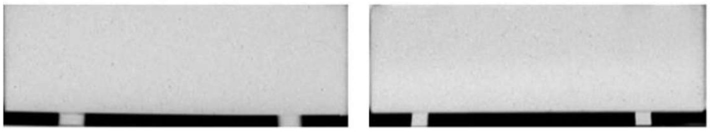

Fig.8. Neutron images of water penetration (after 24 h immersion) into pre-stressed SHCC samples (0.5% left, and 1.5% right) that were surface impregnated with silane gel.

**Chloride penetration into neat and water repellent SHCC**

Chloride profiles in neat SHCC under different levels of strain and after contact with a 3.1 % NaCl solution for three hours have been determined. Results are shown in Fig. 9 (left). In the unstrained sample a typical chloride profile has been observed. But if a strain of 0.5 % is applied only, chloride is transported through the entire thickness of the specimen to the opposite surface. On the opposite side water evaporates and chloride becomes concentrated. On specimens, which have been strained up to 2 % this effect is even more pronounced. Chloride profiles as measured in integral water repellent SHCC are shown in Fig. 9 (right). It can be seen that the chloride penetration into integral water repellent concrete is significantly slowed down as compared to neat SHCC. But, if a strain of 2 % is imposed, the resulting cracks are wide enough to transport dissolved chloride through the entire thickness.

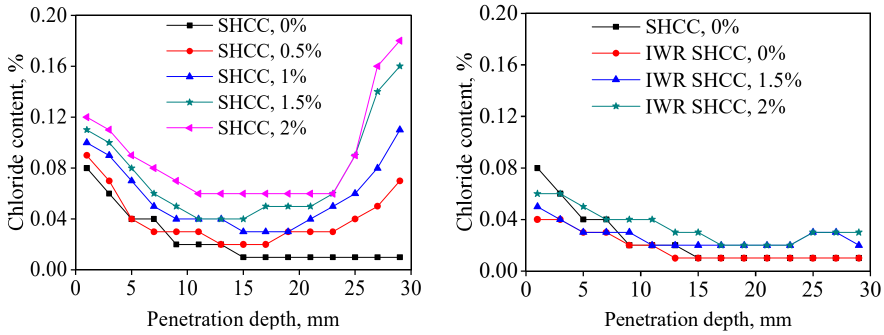


Fig.9. Chloride profiles as observed in neat SHCC (left) and integral water repellent SHCC (right) under imposed strain after contact with a 3.1 % NaCl solution for three hours

## CONCLUSIONS

Based on the results described in this contribution the following conclusions can be drawn:

1. Neutron imaging is a powerful tool to observe and quantify the process of water penetration into SHCC. A small amount of water penetrates into unstrained SHCC as compared to ordinary concrete. But if a tensile strain of around 0.5 % is applied, the induced micro-cracks are quickly filled with water. If the imposed strain is higher, more and wider cracks are formed and therefore more water will penetrate into the material.

2. Less water penetrates into integral water repellent SHCC. But under increasing imposed strain wider cracks are formed and water will penetrate. Under these conditions SHCC may not be considered to be a safe protection of underlying structural elements in aggressive environment.

3. Surface impregnation with silane gel after crack formation due to imposed strain has proved to be an efficient protection of SHCC in contact with water or aqueous salt solutions. Therefore, if a given structure is exposed to an aggressive environment, protection can be provided by surface impregnation with silane gel.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge substantial financial support by Natural Science Foundation of China (51420105015, 51778309), Basic Research Program of China (2015CB655100) and 111 Project.

## REFERENCES

[1] F. H. WITTMANN, *Specific aspects of durability of strain hardening cement-based composites.* Int. J. Restoration of Buildings and Monuments, 13 (2006):109-118.

[2] V. ZIJL, G. PAG, F. H. WITTMANN, *Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC),* State-of-the-Art Report. Rilem TC 208 HFC, SC 2, (2011). Springer Publishers.

[3] V. C. LI, G. FISHER, M. LEPECH, *Crack resistant concrete material for transportation construction.* In Transportation Research Board 83rd Annual Meeting, Washington, D.C., Compendium of Papers CD ROM, (2004). Paper 04-4680.

[4] G. MARTINOLA, M. F. BÄUML, F. H. WITTMANN, *Modified ECC by means of internal impregnation.* Journal of Advanced Concrete Technology, 2 (2004): 207-212.

[5] M. SAHMARAN, V. C. LI, *Influence of micro-cracking on water absorption and sorptivity of ECC.* Materials and Structures 42 (2009):593-603.

[6] F. H. WITTMANN, P. GUO, T. ZHAO, *Influence of cracks on the efficiency of surface impregnation of concrete*. In Proc. Hydrophobe V, 5th Int. Conf. Water Repellent Treatment of Building Materials, (2008): 287-298, ed. H. DeClercq and A. E. Charola, Aedificatio Publishers, Freiburg.

[7] H. ZHAN, F. H. WITTMANN, T. ZHAO, *Relation between the silicon resin profiles in water repellent treated concrete and the effectiveness as a chloride barrier.* Int. J. Restoration of Buildings and Monuments, 11(2005):141-150.

[8] P. WANG, *Deterioration mechanism of strain hardening cementitious composite.* Doctoral Thesis. Qingdao Technological University, (2014). Qingdao.

[9] P. ZHANG, F. H. WITTMANN, T. ZHAO, E. H. LEHMANN, P. VONTOBEL, S. HARTMANN, *Observation of water penetration into water repellent and cracked cement-based materials by means of neutron radiography.* Int. J. Restor. Build. Monum. 15 (2009):91-100.
[10] E. H. LEHMANN, G. KUHNE, P. VONTOBEL, *The NEUTRA and NCR radiography stations at SINQ as user facilities for science and industry.* In Proc. 7th World Conference of Neutron Radiography, (2002): 593-602. Italian National Agency for New Technologies, Rome, Italy.