# Influence of an Imposed Tensile Stress and Subsequent Self-healing on Capillary Absorption and Chloride Penetration into HPFRCC



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# INFLUENCE OF AN IMPOSED TENSILE STRESS AND SUBSEQUENT SELF-HEALING ON CAPILLARY ABSORPTION AND CHLORIDE PENETRATION INTO HPFRCC

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**Abstract**

HPFRCC, if tested in the laboratory, absorbs little water or aqueous salt solutions. This might be considered to be an indication for excellent durability and long service life. In practice, however, most structures and structural elements are designed to be exposed to mechanical stress. The influence of an applied tensile stress on capillary absorption is investigated in this contribution. It was found that the coefficient of capillary absorption increases rapidly after application of a tensile stress corresponding to more than half of the tensile strength. This observation has to be taken into consideration if HPFRCC is to be applied in an aggressive environment. Depending on the environment a maximum allowable strain must be indicated. Otherwise service life prediction will not be realistic.

In another contribution to this conference it is shown that application of a compressive stress has strong influence on durability and service life of structural elements built with HPFRCC too.

## 1. INTRODUCTION

Durability and service life of reinforced concrete structures depend to a large extend on capillary absorption of water and aqueous salt solution. Capillary absorption of water decreases strength of cement-based materials and as a consequence facilitates crack formation. At the same time the risk of frost damage increases with water up-take. But in context with durability it is most important that water penetration into the pore space of concrete is a most efficient mechanism for transportation of aggressive in water dissolved compounds deep into the pore space. This frequently observed deteriorating mechanism can be significantly reduced by surface impregnation with a water repellent agent [1].

HPFRCC has low pore space with narrow pores and as a consequence it can be considered to be a durable material in statu nascendi. Nearly all structural elements are designed to carry static or dynamic load in tension or in compression. By now it has been shown that durability of normal concrete depends strongly on an applied load [2-4]. Is this also true for HPFRCC?

In this contribution results of experimental investigations into the influence of an applied tensile stress on capillary absorption will be presented. It will also be shown that capillary absorption can be considered to be meaningful indication for durability or vulnerability of cement-based materials in aggressive environment. The influence of an applied compressive stress on durability is described in detail in another contribution to this volume [5].

## 2. ON CAPILLARY ABSORPTION

If a capillary with radius r or a porous material with a given pore size distribution, which may be characterized by an effective radius $r_{eff}$, gets in contact with a wetting liquid the absorbed mass of liquid as function of time $\Delta W(t)$ is given by the following simple equation:

$$\Delta W = A\sqrt{t} \tag{1}$$

In this equation $A$ stands for the coefficient of capillary absorption, which characterizes the porous material and determines the penetrating liquid driven by capillary under-pressure, and $t$ stands for the time of contact of the surface of the porous material with the liquid. $A$ in Eq. (1) is given by the following equation:

$$A = \Psi\rho\sqrt{\frac{r_{eff}\sigma\cos\theta}{2\eta}} \tag{2}$$

In equation (2) $\psi$ stands for the water capacity of the porous material, $\rho$ for the density of the penetrating liquid, $\sigma$ for the surface tension of the liquid, $\theta$ for the contact angle at the interface between the liquid and the inner surface of the porous material and $\eta$ for the viscosity of the liquid, while $r_{eff}$ is an effective radius, which represents the wide pore size distribution [2].

If the capillary absorbed water moves along a vertical axis into a capillary or into a porous material the mass of the already absorbed water slows down the rate of penetration of newly absorbed water by gravity and finally a maximum height, which depends on the pore size distribution will be reached. The influence of gravity can be taken into account by introducing a time-dependent coefficient of capillary absorption $A(t)$ [6. 7]. In case water moves horizontally into the pore space, however, gravity can be neglected. Under these conditions the coefficient of horizontal capillary absorption $A_h$ remains constant for a long time.

## 3. PREPARATION OF SPECIMENS

For the tests described in this contribution, the composition of the HPFRCC was first optimized by varying the composition in a systematic way. For the different mixes ordinary Portland cement Type 42.5, fly ash class F with an average diameter of the particles of 5.4 μm and silica fume with and average particle size of 0.03 μm were used. In addition fine quartz sand with a maximum grain size of 0.42 mm and steel fibres were added. The composition of the optimum mix is given in Table 1.

Table 1: Composition of HPFRCC prepared for these test series, kg/m$^3$

| Portland Cement | Fly ash | Silica fume | Quartz powder | Quartz sand | Water | SP | Steel fibres |
|---|---|---|---|---|---|---|---|
| 526.4 | 225.6 | 263.2 | 203.1 | 791.9 | 201 | 20.3 | 150 |

Dumbbell specimens were prepared for the test series described in this contribution. The characteristic shape and the dimensions of the samples are given in Fig. 1. The center part, which was exposed to uniform tensile stress, has the following size: 120×60×30 mm.

After compaction in steel forms on a vibrating table all specimens were allowed to harden in the laboratory (T ≈ 20 °C) under wet burlap for 24 hours. Then the steel form was removed and the specimens were further cured in a hot water bath at 90 °C for 72 hours. Finally the specimens were dried in a ventilated oven at 50 °C until equilibrium. After that the average tensile strength was determined to be 11.6 MPa.

All dumbbell specimens were exposed to sustained tensile stress in a stiff steel rig with the following stress levels: 30, 50, and 80 % of the tensile strength. Capillary absorption under imposed constant strain has been measured by means of a modified Karsten tube. In this case a surface of 40×100 mm was put in contact with a box containing water or salt solution and the amount of absorbed liquid could be measured as function of contact time with a scaled pipette. In addition to capillary penetration of water capillary penetration of 5 % NaCl solution was measured in order to study the penetration of chloride into un-cracked and cracked HPFRCC. The chloride profiles were determined by milling thin layers starting from the surface, which was in contact with the salt solution. The chloride content of the powder obtained was determined chemically.

In addition some specimens were unloaded after exposure to tensile stress for 15 minutes at three different stress levels. Capillary absorption of and chloride penetration into these pre-loaded specimens were also determined. Other pre-loaded specimens were further cured in a saturated $Ca(OH)_2$ solution for 28 days immediately after application of the tensile stress. After self-healing both capillary absorption and chloride penetration were determined experimentally.

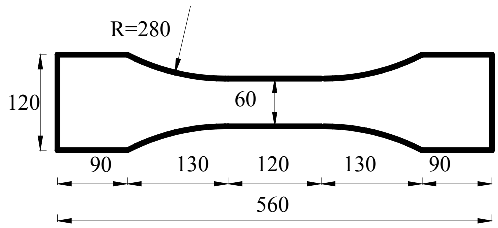


Figure 1: Shape and dimensions of the dumbbell specimens with a thickness of 30 mm

## 4. RESULTS AND DISCUSSION

### 4.1 Influence of imposed tensile stress and subsequent self-healing on capillary absorption of HPFRCC

Capillary absorption of HPFRCC samples, which were under tensile stress corresponding to 30, 50, and 80 % of the tensile strength is shown in Fig. 2. For comparison capillary absorption of specimens without applied stress is also shown. Immediately after contact between the surface of the HPFRCC samples with water very little water is absorbed. It takes about 15 minutes before the surface near zone is completely wetted and the water penetrates into the pores, which are in contact with the surface. Then only the actual process of capillary absorption begins and on a logarithmic scale of time the absorbed amount of water increases linearly. This is in good agreement with the prediction of Eq. 1. The coefficient of capillary absorption remains constant as function of time.

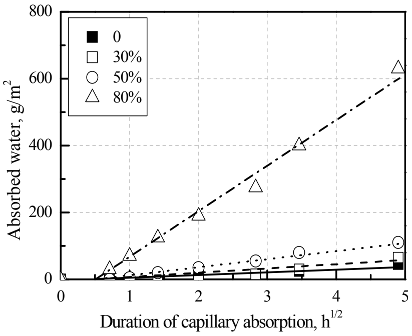


Figure 2: Influence of an applied tensile stress on capillary absorption of HPFRCC

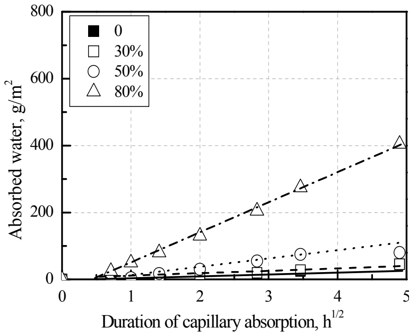


Figure 3: Influence of an applied tensile stress on capillary absorption after unloading

The damage induced by an applied tensile stress is visualized in Fig. 2. In Eq. (2) the water capacity $\psi$ and the effective radius $r_{eff}$ increase under the influence of an applied tensile stress, while the other values may be expected to remain constant. Damage under the influence of an applied tensile stress of 30 % of the tensile strength is small but it increases when a stress of 50 % of the tensile strength is applied. Damage becomes very serious if a stress corresponding to 80 % of the tensile strength is applied. This influence of an applied tensile stress on capillary absorption has to be taken into consideration if service life of structural elements made of HPFRCC is to be predicted.

HPFRCC is rich in Portland cement and pozzolanic materials. Because of this specific composition it can be expected that part of the damage induced by application of a tensile stress can be restored by self-healing by continuing hydration and by pozzolanic reaction, if the specimens are placed in a humid environment and even better in a $Ca(OH)_2$ solution. Capillary absorption of specimens which were pre-damaged by application of tensile stress but then placed in $Ca(OH)_2$ solution for 28 days was measured too. Results are shown in Fig. 4. It can be clearly seen that the capillary absorption is significantly reduced after self-healing.

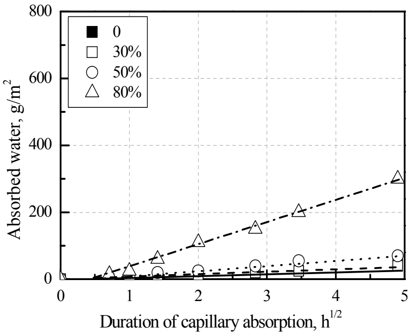


Figure 4: Capillary absorption of pre-damaged HPFRCC after unloading and self-healing

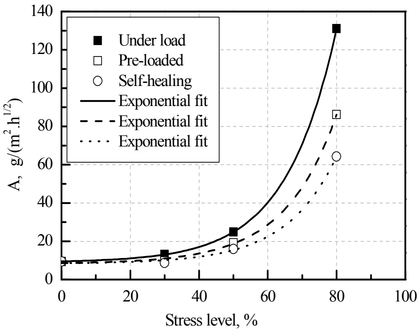


Figure 5: Coefficient of capillary absorption as function of the applied stress level

This is additional evidence that capillary absorption can be considered to be a useful tool to quantify damage of cement-based materials as induced by mechanical stress.

In Fig. 5 the coefficient of capillary absorption $A(\sigma)$ as function of the applied tensile stress $\sigma$ as determined on the basis of results shown in Figs. 2 to 4 is shown. It can be clearly seen that application of stress corresponding to 30 % of the tensile strength induces little damage. The induced damage after application of stress corresponding to 50 % of the tensile strength is more significant. But as expected, damage after application of tensile stress corresponding to 80 % of the tensile strength is really serious. If a stress of 80 % of the tensile strength is applied about ten times more water or more aqueous salt solution is absorbed as compared to the undamaged material. High tensile stress can be originated by drying shrinkage for instance. Part of this mechanically induced damage can be restored, however, by self-healing under favorite storage conditions as shown in Fig. 5.

The influence of an applied tensile stress on the coefficient of capillary absorption $A(\sigma)$ can be expressed mathematically by an exponential function:

$$A(\sigma) = A_0 + a \exp(b\,\sigma) \quad (3)$$

The values obtained by fitting equation (3) with the experimental data shown in Fig. 5 are given in Table 2. With these data the influence of an applied stress on capillary absorption can be predicted. At the same time the damage, which remains after unloading and the recovery by self-healing can be estimated.

Table 2: Parameters A0, a and b of Eq. (1) as determined by fitting the equation with results shown in Fig. 5

| Parameters of Eq. (3) | $A_0$ | $a$ | $b$ |
|---|---|---|---|
| Under appl. stress | 9.013 | 0.528 | 0.068 |
| After stress removal | 8.216 | 0.369 | 0.067 |
| After self-healing | 8.326 | 0.230 | 0.069 |

### 4.2 Influence of imposed tensile stress and subsequent self-healing on chloride penetration into HPFRCC

Capillary absorption of porous materials may lead to several different but dangerous consequences. Thermal and electrical conductivity may be increased substantially. High humidity content may accelerate steel corrosion in reinforced concrete. It is well known that the risk of frost damage increases significantly with increasing humidity content. But water penetration also serves as transport of aggressive compounds deep into concrete by convection. Therefore we have run tests with an aqueous NaCl solution. The cement-based samples were put in contact with 5 % NaCl solution for 28 days.

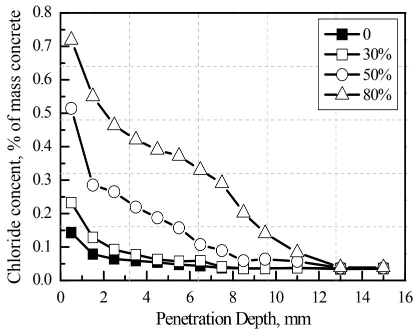


Figure 6: Influence of imposed stress on chloride penetration into HPFRCC under tensile stress after direct contact with 5% NaCl for 28 days

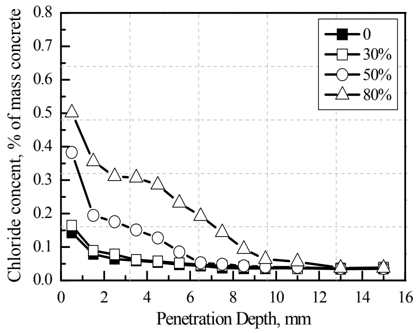


Figure 7: Chloride profiles of pre-loaded HPFRCC after direct contact with 5% NaCl for 28 days

In Fig. 6 chloride profiles as determined in HPFRCC after exposure of the NaCl solution for 28 days are shown. It can be seen that under these conditions HPFRCC without applied load absorbs a small amount of chloride only. The amount of penetrated concrete increases slightly only if the material is exposed to a tensile stress corresponding to 30 % of the tensile strength. In case the applied tensile stress is increased to 50 % and 80 % of the tensile strength considerable amounts of chloride are transported into the pore space. It would last very long time before the same amount of chloride could penetrate by diffusion into the porous material. Compared to convection diffusion is nearly negligible in this case at least. Damage induced into the material by application of a tensile stress is most significant for durability and service life of cement-based materials.

The chloride content as shown in Fig. 7 is significantly reduced as compared to the chloride content shown in Fig. 6. In this case the absorption was measured on pre-loaded specimens after removal of the applied tensile stress. The pore space is reduced by elastic deformation after removal of the applied tensile stress. This reduction of the pore space can also be expressed in terms of the reduction of the water capacity $\psi$ and the effective radius $r_{eff.}$

As we have shown before, part of the damage induced into the porous structure of the material can be restored by self-healing. Chloride profiles as determined on samples after self-healing are shown in Fig. 8. As can be seen, significantly less chloride penetrated into HPFCC after self-healing during storage in saturated $Ca(OH)_2$ solution, as compared to the chloride profiles shown in Figs. 6 and 7. Continuing hydration and pozzolanic reaction restore part of the induced damage.

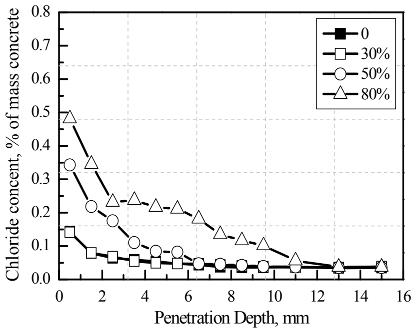


Figure 8: Chloride profiles as determined in damaged HPFRCC after self-healing.

## 5. CONCLUSIONS

From the results presented in this contribution it can be concluded:

- HPFRCC is a durable cement-based material, even in aggressive environment.
- If the material is exposed to tensile stress higher than 50 % of the tensile strength, however, capillary absorption is significantly increased.
- High amount of chloride can be transported deep into the pore space by convection and subsequent diffusion.
- If the influence of an applied tensile stress is not taken into consideration, prediction of service life will be necessarily unrealistic.
- Part of the mechanically induced damage can be restored by self-healing in an appropriate environment.

## ACKNOWLEDGEMENTS

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