Strength and fracture energy of concrete in seawater

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ABSTRACT: Strength and fracture energy of cement-based materials depend on surface energy of the solid skeleton. Surface energy, however, is influenced by the thickness of adsorbed liquid films and their surface energy. Strength of concrete decreases and the material expands if water is adsorbed on the surface of the nano-structure. This relation can be described adequately by means of the Bangham equation. If concrete is in contact with seawater the surface energy of the solid skeleton is even more reduced than by pure water. In this contribution the influence of seawater on strength and fracture energy has been investigated experimentally. The physical basis of the experimental findings is presented and discussed. Consequences of this phenomenon for the mechanical behavior and in particular for crack formation in concrete structures in contact with seawater or other NaCl-containing water are outlined.

1 INTRODUCTION

Whenever reinforced concrete structures are in permanent or temporary contact with water, containing aggressive compounds, protective measures are to be taken. Dissolved sulfates and ammonium salts for instance can deteriorate cement-based materials very quickly. If chloride-containing water is in the environment of concrete the diffusion through the porous structure is usually of primary interest, as corrosion of the steel reinforcement may start as soon as a critical chloride concentration is reached. So far the influence of chloride containing water on mechanical properties of concrete, however, has been widely neglected.

Nevertheless, some deteriorating chemical reactions of chlorides in cement-based materials are known. Magnesium chloride dissolved in seawater may form calcium chloride by ion exchange. As a second step of weakening cement-based materials, calcium chloride can be washed out of the porous structure, as it is very soluble. But calcium chloride can also react with calcium aluminates and form chloro-aluminates. This reaction is at the origin of expansion, which in some cases may damage concrete structures. Finally under alternating wetting and drying crystallization pressure may weaken the surface near zone of concrete.

In this contribution we will concentrate on the influence of surface tension of seawater on strength, fracture energy, and strain softening. If crack formation of a concrete structure, which is in contact with seawater, is to be predicted in a realistic way, these values have to be known.

2 THEORETICAL BACKGROUND

According to the Griffith criterion a crack with length 2c will grow in an instable way under an applied tensile stress σ in a material with an elastic modulus E and a surface energy γ if the following condition is fulfilled:

$$\sigma = \sqrt{\frac{2E\gamma}{\pi c}} \tag{1}$$

In a homogeneous and ideally brittle material under uni-axial tensile stress this simple equation describes crack formation and failure correctly. In a porous composite material under tension crack formation is more complex. Micro-cracks are being formed, followed by crack arresting mechanisms. Progressive damage leads to pseudo-ductility. Failure processes are even more complex under compressive stress. In this case micro-cracks are formed locally where the tensile strength has been reached. These micro-cracks grow as the load is increased or as function of time under sustained load and finally coalesce to form macroscopic cracks aligned in parallel with the direction of the applied compressive load (Zaitsev and Wittmann 1981). But in any case fracture energy is a controlling parameter for the elementary processes and the formation of cracks. We consider failure as a sequence of elementary processes.

Surface energy γ_0 of hardened cement paste is highest in the completely dry state. If water is adsorbed on the surface the surface energy is reduced. If we may assume that all other material properties remain constant, we can write the influence of reduced surface energy γ_h on the critical load for the formation of a micro-crack as follows (Wittmann 1983):

$$\left(\frac{\sigma_h}{\sigma_0}\right)^2 = \frac{\gamma_h}{\gamma_0} = 1 - \frac{\Delta\gamma}{\gamma_0} \tag{2}$$

In equation (2) σ_h stands for the critical load when a certain amount of water is adsorbed on the surface and σ_0 stands for the critical load in the dry state.

When adsorbed water films reduce the surface energy of the nano-particles in hardened cement paste length change, i.e. swelling, is observed. This hygral strain ε_h can be described quantitatively as function of the change of surface energy by means of the well-known Bangham equation (Bangham and Fakhoury 1931 and Bangham and Razouk R.I. 1937):

$$\frac{\Delta l}{l} = \lambda\left(\gamma_0 - \gamma_h\right) \tag{3}$$

l in equation (3) is a material constant and Hiller (1964) has showed that its physical meaning can be expressed as follows:

$$\lambda = \frac{O\rho}{3E} \tag{4}$$

0 stands for the internal surface of the porous material and ρ for the density of the material.

If we substitute γ_h in equ.(1) with equ.(2) we obtain a relation between the related critical stress and the hygral strain:

$$\left(\frac{\sigma_h}{\sigma_0}\right)^2 = 1 - \frac{1}{\lambda\gamma_0}\frac{\Delta l}{l} \tag{5}$$

From equation (2) we see that the square of the related strength of a material decreases linearly with a decrease in surface energy and equation (5) tells us that this strength decrease is accompanied by a hygral length change (swelling). Equations (2) and (5) are valid in the humidity range below 50 % RH. At higher humidity disjoining pressure in the nano-pores influences both strength and hygral length change. The Munich Model (Wittmann, 1973, 1976, and 1977, Setzer and Wittmann, 1974) describes these relations in detail. Horii (1962), Cook and Haque (1974), Pihlajavaara (1974), and Ogishi et al. (1986) have reported similar results. More recently Matsushita and Onoue (2006) have studied static strength and fatigue of concrete impregnated with different liquids. They come to the same conclusions. The influence of surface energy on strength and hygral length change is well documented by a solid theoretical approach and by numerous experimental investigations.

Equation (3) also indicates that if we replace water in the porous system of hardened cement paste by a solution with a higher surface tension than water, then the resulting strength can be expected to be lower than the strength of water saturated hardened cement paste. Water has a surface tension of 0.073 N/m at 20 °C. Seawater has a higher surface tension. Matsushita and Onoue (2006) have prepared artificial seawater with a 4 mol NaCl solution and measured a surface tension of 0.090 N/m. With this solution they determined the strength reduction and the influence on fatigue strength.

In this contribution we will report on investigations to study the influence of seawater on fracture energy and strain softening. In case fracture energy is reduced by seawater as compared to normal aqueous pore solution, this effect has to be taken into consideration in the prediction of service life of concrete structures in marine environment; but also for design of concrete structures of the infrastructure, which are in periodic contact with water containing NaCl as deicing agent.

3 EXPERIMENTAL

Concrete with a water-cement ratio W/C = 0.6, a cement content C = 350 kg/m^3, and a maximum aggregate diameter d = 20 mm has been produced for the test series. Two types of specimen geometry have been chosen:

(a) Cubes with the following dimensions 100 x 100 x 100 mm were prepared for wedge splitting tests according to AAC 13.1

(b) Prisms with the following dimensions 100 x 100 x 510 mm have been prepared for three-point bending tests according to FMC-50

Fresh concrete has been cast in steel moulds, compacted with a vibrating table, and unmoulded after 24 hours. The unmoulded concrete specimens were then stored in a humid chamber at a temperature of 20 °C and RH > 95 % until an age of 7 days. First force-CMOD diagrams and force-bending diagrams have been determined on the young concrete by means of the wedge splitting test and the three-point bending test respectively. Remaining specimens have been dried in an aerated oven at T = 50 °C for 7 days. After cooling down to room temperature dried specimens have been tested. Half of the remaining dried specimens has been placed in water and the other half has been placed in seawater for 14 days. Companion specimens have been placed in the laboratory environment at T = 20 °C and RH = 75 % after drying, so that they could adsorb water again.

Fracture energy and strain softening has been determined by the wedge splitting test and by the three-point bending test after each step of the curing described above.

4 RESULTS AND DISCUSSION

The mean function of the experimentally determined force-CMOD relation as measured on the young concrete, and on the dried concrete is shown in Fig. 1. Each curve is the average of at least 5 experimental results. In this figure the results obtained on specimens, which were stored in the laboratory to allow re-adsorption of moisture are also shown. It can be seen that the drying process accelerated hydration of the young concrete and therefore strength and fracture energy increased considerably during the drying process. The time for reaching hygral equilibrium of the dried specimens with the surrounding was not long enough; therefore the difference between dried and re-humidified specimens may be too small.

The corresponding results as obtained by the three-point bending test are shown in Fig. 2. The force-deflection diagrams show clearly again that the drying process accelerated hydration and therefore the bending strength and the fracture energy have increased considerably. In this case a modest reduction of strength and fracture energy of the partly re-humidified specimens can be observed. The strength reduction has been expected due to the reduced surface energy.

Results obtained on water saturated and seawater saturated concrete are shown in Figs. 3 and 4. In Fig. 3 the averaged curves obtained by wedge splitting test are plotted. For comparison the results obtained on dried concrete, as plotted in Fig. 1, are shown again. In Fig. 4 the force-displacement relation as obtained on water and seawater saturated concrete is shown and for comparison results obtained on dried concrete from Fig. 2 are shown again.

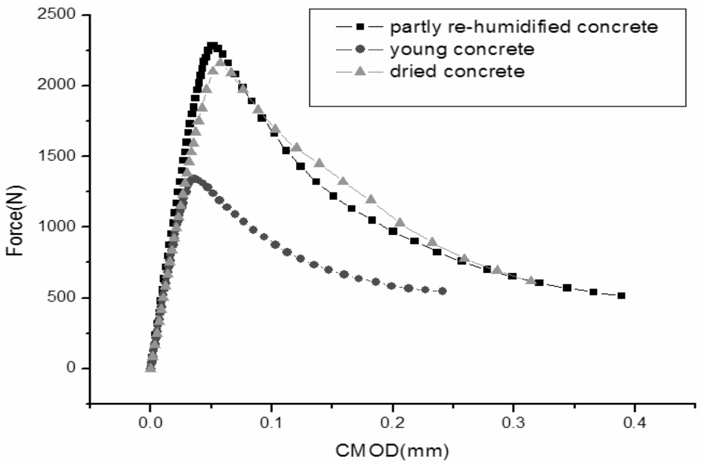

Figure 1. Force-CMOD diagram as obtained on young, dried, and partly re-humidified concrete by wedge splitting test.

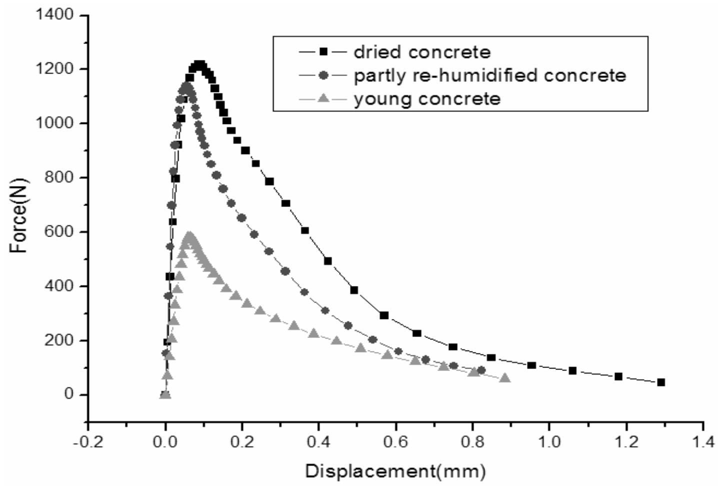

Figure 2. Force-displacement diagram as obtained on young, dried, and partly re-humidified concrete by three-point bending test.

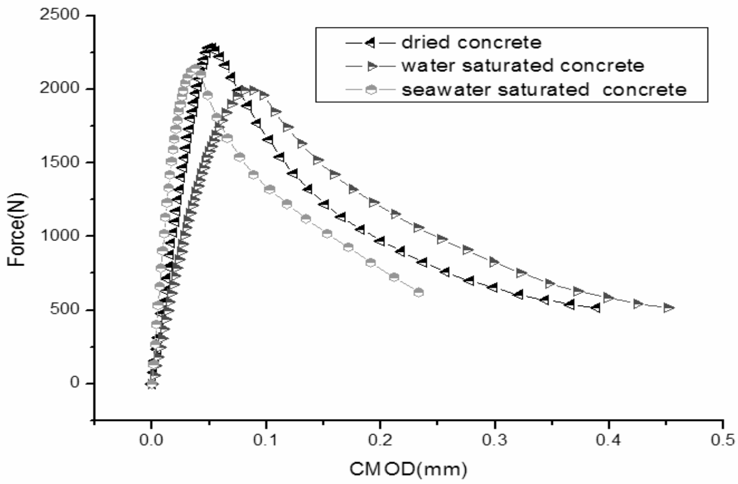

Figure 3. Force-CMOD diagram as obtained on water saturated and seawater saturated concrete. For comparison the corresponding result of dried concrete as shown in Fig. 1 is shown once more.

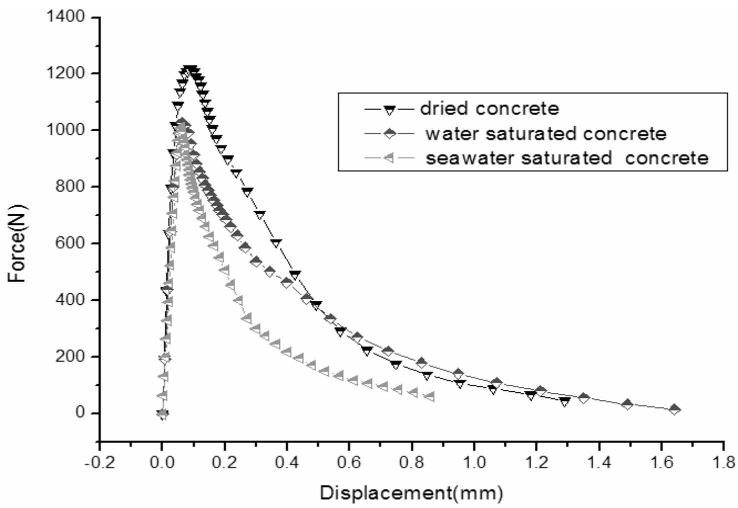

Figure 4. Force-displacement diagram as obtained on water saturated and seawater saturated concrete. For comparison the corresponding result of dried concrete as shown in Fig. 2 is shown again.

All measured force-CMOD and force-deflection diagrams have been further evaluated in order to obtain fracture energy and strain softening of the differently conditioned concrete samples. We used the CONSOFT software, originally developed by Professor Slowik and his group at University of Applied Sciences, Leipzig. First we fitted a bi-linear function for the strain softening but it turned out that a multi-linear function represents experimental data better. Typical results of a fitted strain softening relation with a bi-linear function are shown in Fig. 5. The reduction of fracture energy by water and seawater impregnation of dried concrete can be clearly seen. The corresponding strain softening is plotted in Fig. 6 but in this case fitted with a multi-linear function.

The fracture energy of the differently conditioned concrete samples has also been determined by means of CONSOFT. Results are compiled in the Table. It can be seen that due to the drying process at elevated temperature the fracture energy increases considerably. Maximum fracture energy is observed on dried concrete. Re-humidification in an environment of 75 % RH reduces the fracture energy due to adsorption of water layers on the internal surface. This observation is in agreement with results of tests to determine tensile and compressive strength of concrete or mortar. Water impregnation also reduces fracture energy but seawater impregnation reduces fracture energy even more. The physical relations given and discussed above explain these results.

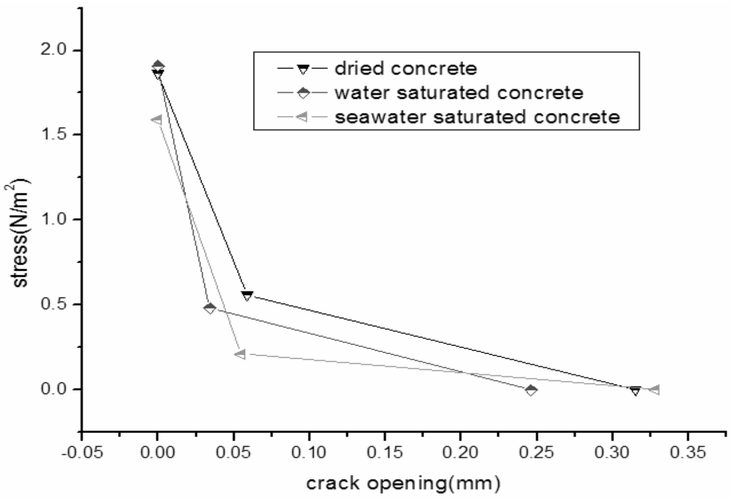

Figure 5. Bi-linear strain softening as obtained by data fitting from three-point bending test.

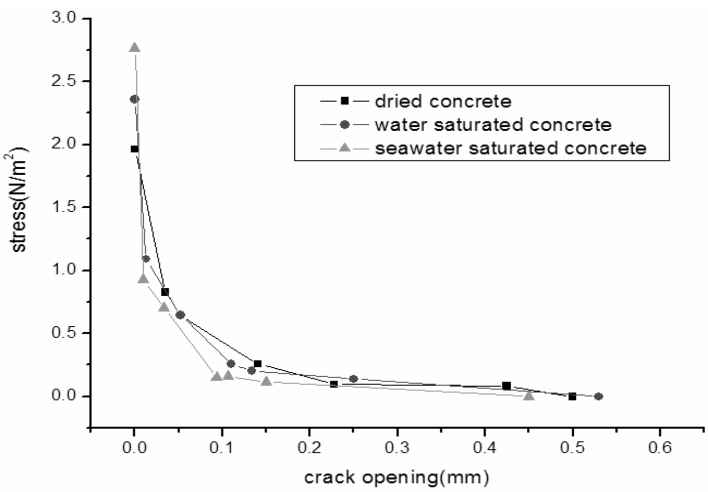

Figure 6. Multi-linear strain softening as obtained by data fitting from three-point bending test.

Table: Fracture energy in N/m as determined by three-point bending test (3PB) and by wedge splitting test (WST) of young concrete at an age of 7 days, after drying at 50 °C, after re-humidification in an environment of 75 % RH, after water saturation, and saturation with seawater.

Test	young	dried	75 % RH	Water sat.	Sea-water sat.
3PB	72.8	146.8	118.9	116.8	83.8
WST	47.6	114.0	115.1	110.0	88.5

5 CONCLUSIONS

It has been shown that fracture energy is maximal if concrete is completely dry. Adsorbed water films reduce fracture energy. This is the reason for the observed reduction of compressive and tensile strength with increasing water content.

If concrete is in contact with seawater or with saline water from deicing agents the fracture energy is even more reduced than by pure water. This effect has to be taken into consideration if load bearing capacity and crack formation is to be predicted.

To the knowledge of the authors the influence of seawater on fracture energy has been observed for the first time. Investigations to further quantify this effect and to estimate the consequences for practical applications are on their way.

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