APPLICATION OF FRACTURE MECHANICS TO INVESTIGATE DURABILITY OF CONCRETE UNDER LOAD

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Abstract: Service life of reinforced concrete structures is limited in most cases by migration processes of CO_2 and of dissolved aggressive compounds such as chlorides and sulfates in the pore space of concrete. The rate of these transport processes depends on the total porosity and the pore size distribution. Both values change with progressive hydration of cement. But the pore space and the pore size distribution can also be modified by an applied tensile of compressive load. In this contribution the influence of an external load on the pore space shall be investigated. Penetration of an aqueous solution into a crack and into the fictitious crack ahead of a real crack shall be described in detail. In addition mechanics of micro-crack formation in a porous material shall be studied. Finally the influence of an applied tensile and compressive load on the rate of chloride penetration and the rate of carbonation shall be considered. Results will help to form a basis for better understanding the reduced service life of reinforced concrete structures under combined mechanical load and environmental actions.

1 INTRODUCTION

Carbonation and chloride penetration are among the most frequent processes to limit service life of reinforced concrete structures. There exist a number of standardized test methods to determine the rate of carbonation or the diffusion coefficient of chloride ions experimentally in appropriately equipped laboratories. Values obtained in this way are often used to predict service life of reinforced concrete structures. By now, however, it has been documented and it is generally accepted that the rate of deterioration may be significantly accelerated under the influence of an applied mechanical load [1-3]. Similar aggravation of deteriorating processes can be observed when concrete exposed to aggressive environment may be damaged by frost action before or at the same time. In fact it can be shown that there exists a huge number of possible load combinations [3].

All migration processes in the composite structure of concrete depend on the total porosity and the pore size distribution. The pore size changes as soon as a tensile or a compressive stress is applied. If a critical stress is overcome micro-cracks are formed in the porous cement-based matrix of the composite material. Ahead of a real crack there is a so-called fictitious crack. In this zone the cement based material is damaged by micro-crack formation. It will be shown that water and aqueous solutions can preferentially penetrate this damages zone.

Because of the mechanical incompatibility of the natural aggregates and the hardened cement paste, cracks are also formed along the weak interface between the two components. Micro-cracks generated by an applied load serve as additional pathways for the transport of aggressive agents and dissolved ions.

In this contribution the influence of damage induced by mechanical load on the rate of carbonation and on the diffusion coefficient of chloride ions shall be investigated. It will be shown that migration processes are significantly modified if a concrete specimen is under load. This means that service life of reinforced concrete structures as predicted on the basis of simple laboratory test results, run without applying a load, overestimate service life of real structures considerably. The approach described in the following is meant to provide a basis for more realistic service life prediction.

2 CAPILLARY ABSORPTION OF CRACKS IN CONCRETE

Crack formation can be simulated in a realistic way by means of the fictitious crack model [4]. According to this model ahead of a real crack a fracture process zone is built up. Along the fictitious crack the tensile load bearing capacity is gradually reduced until it becomes zero at the crack tip. This gradual deterioration of the tensile strength of the material is due to progressive formation of micro-cracks.

In Fig. 1 capillary absorption of concrete with a crack, as observed by means of neutron radiography, is shown [5]. In order to stabilize crack formation two steel bars have been placed in the concrete samples. Their position can be seen by the two horizontal lighter bands. The left photo has been taken about one minute after the bottom has been put in contact with water. Even a crack with a width of 0.1 mm is immediately filled with water. The damaged interface between steel bars and concrete is quickly water filled too. Then the water penetrates from the water filled crack into the material by capillary absorption. The right photo in Fig. 1 has been taken 1.5 hours after contact with water. There it can be seen that the fictitious crack ahead of the real crack absorbs comparatively more water. This is clear evidence that damage induced into the material by mechanical stress reduces durability. Uptake of water and of aqueous salt solutions is significantly accelerated.

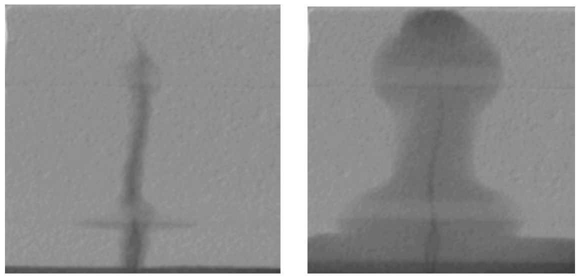

Figure 1: Visualization of water penetration into a crack and from the crack into undamaged and damaged concrete after 1 minute (left) and after 1.5 hours (right).

3 NUMERICAL SIMULATION OF MICRO-CRACK FORMATION IN THE COMPOSITE STRUCTURE

3.1 Micro-crack formation in hardened cement paste

Hardened cement paste is a porous material with a very wide pore size distribution. In fact the range covers the nano-pores in the CSH gel and compaction pores. We consider a plate with thickness 1 and cylindrical pores, which are statistically distributed (see Fig. 2). The pores are assumed to have all the same radius r. If a compressive load q is applied cracks will start to grow in a stable way parallel to the direction of the applied load when the tensile strength of the material is reached at the poles. In this case nano-pores are considered to be distributed homogeneously in the material between the cylindrical pores.

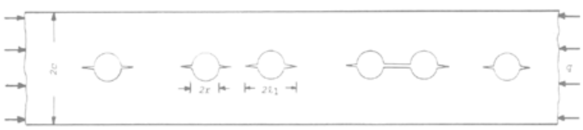

Figure 2: Plate with statistically distributed cylindrical pores [6].

Before a load is applied, the crack length is assumed to be zero. We consider here the related crack length λ:

$$\lambda = l/r \qquad (1)$$

with l being the crack length and r the radius of the pore. If the load increases the related crack length increases in a stable way as given by equation (1) [6]:

$$q = \sqrt{\frac{\pi E \gamma}{2r}} \sqrt{\frac{(1+\lambda)^7}{(1+\lambda)^2 - 1}} \qquad (2)$$

As soon as two cracks growing in opposite directions approach one another the overlapping stress fields lead to an "attraction" of the two cracks and finally they coalesce. This is schematically shown in Fig. 1. The two nearest cracks are already combined. The total crack length increases by a sudden jump. The total crack length S can then be calculated as

$$S = \frac{1}{r} \sum_{i=1}^{n} 2l_i \qquad (3)$$

In Fig. 3 the total crack length S is plotted as function of the related load q' for two statistically distributed representations of the porous plate with solid lines. The dashed lines in Fig. 3 are the result of the crack length as obtained in a plate with one single cylindrical pore by stable crack growth.

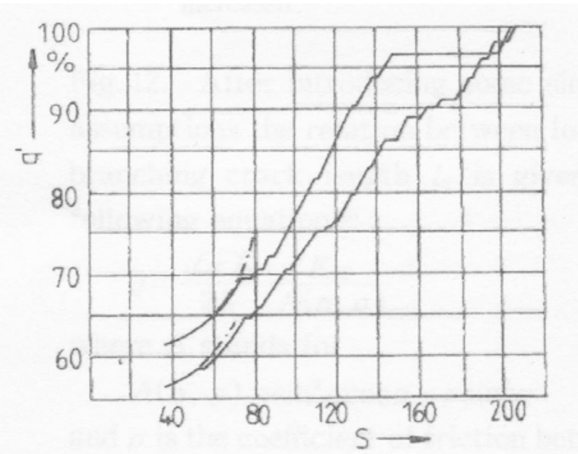

Figure 3: Total crack length as function of the applied related load.

The micro-cracks formed in the porous structure are additional pathways for the transport of aggressive agents such as CO_2 and aqueous salt solutions. We will see later that this deteriorating mechanism in the porous structure of hardened cement paste contributes to accelerating carbonation and chloride penetration.

3.2 Damage at the interface

The interface between hardened cement paste and aggregates is particular weak. Due to settlement of the fresh concrete initial cracks are often formed in the interface at an early stage (bleeding cavities for instance). If the composite material is loaded cracks will be generated or they will grow along the interface. As the load increases further the cracks will grow into the neighboring cement-based matrix. These different stages are shown in Fig. 4. The exact analytical solution of this problem is described in detail in the literature [6, 8]. The initial crack in the interface becomes unstable and spreads all along the plane A-B. The critical compressive load q_c depends on the fracture toughness of the interface, the length of the initial crack $2l_1$ and the inclination of the plane α. At even higher applied load q the crack growth in a steady way in parallel to the direction of the load into the cement-based matrix.

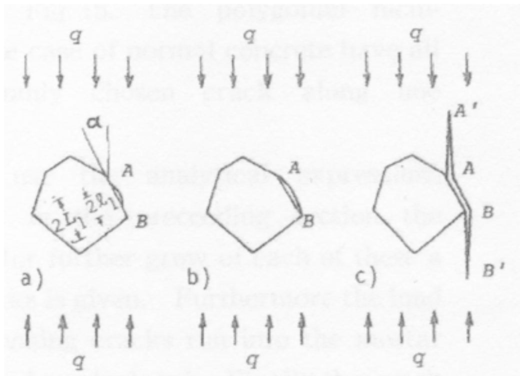

Figure 4: Development of a crack from the interface into the matrix.

In the composite material a crack cannot grow indefinitely as it will soon encounter another aggregate. At this point there are two alternatives, either the crack runs through the aggregate or it will be deviated. In a high strength concrete most cracks will run through the aggregates but in normal strength concrete the crack will run around the aggregate. The situation typically found in normal strength concrete is illustrated in Fig. 5.

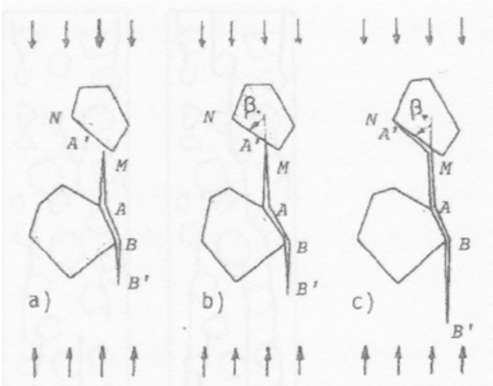

Figure 5: Crack branching out of the interface into the cement-based matrix of normal strength concrete.

3.3 Simulation of crack formation in hardened cement paste and concrete

Based on crack mechanics outlined in the previous sections we can simulate crack formation in hardened cement paste and in a composite material such as concrete. In Fig. 6 two numerical models are shown. On the left side the porous structure of hardened cement paste is shown. In this case cylindrical pores are randomly distributed in the plate with thickness 1. It is further assumed that each cylindrical pore has a pair of randomly distributed weakest poles; as a consequence the weakest planes along the crack can grow are randomly inclined with respect to the direction of load. Only cracks, which are oriented nearly parallel to the applied compressive load, however, will be activated.

In Fig. 6 the simulated crack formation at two different applied loads are shown for the porous structure of hardened cement paste (left) and for composite structure of concrete (right). The crack pattern at two different load levels are shown. At about half of the ultimate load some cracks are generated. These cracks tend to gro and new cracks are formed with increasing applied stress. The crack length and the crack density increase with. These cracks will contribute to accelerated ingress of aggressive agents under load. It can also be seen that the material becomes anisotropic.

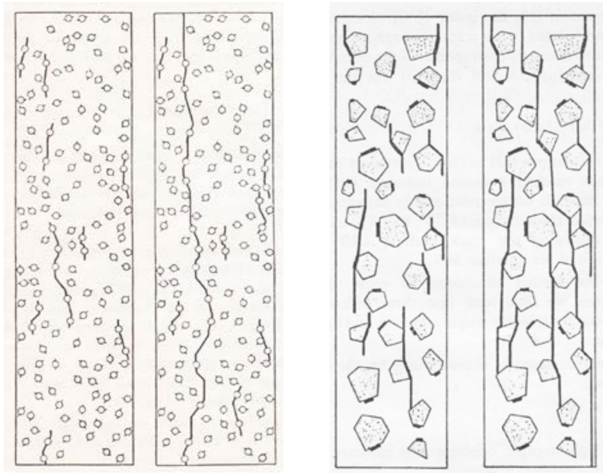

Figure 6: Crack growth in a random porous structure of hardened cement paste (left) and in a random composite structure of concrete (right) as determined for two different load.

4 COMBINED MECHANICAL STRESS AND ENVIRONEMENTAL ACTIONS

4.1 Mechanical stress and capillary absorption

Capillary absorption is a very powerful mechanism for absorption of water and aqueous solutions into the pore space of concrete, whenever he surface of concrete is in direct contact with the liquid. High water content may be at the origin of serious frost damage. In addition dissolved ions such as chlorides or sulfates may be transported deep into the porous material. For a single capillary or a bundle of capillaries, the amount of capillary absorbed water can be described as function of time the following way:

$$W(t) = A\sqrt{t} \qquad (4)$$

For a pore space with randomly distributed pores equation (4) is still valid for a limited period. The coefficient of capillary absorption A in equation (4) depends on the total porosity, the pore size distribution and the viscosity of the penetrating liquid. Under an applied tensile stress the pore space will increase. Therefore we may expect that the amount of capillary absorbed water for a given period will also increase. In Fig. 7 capillary absorption of concrete before loading and after having applied a tensile load corresponding to 65, 75 and 85 % of the ultimate load is plotted. It can be seen that the higher the applied tensile stress, the more and the quicker water is absorbed. The coefficient of capillary absorption A according to equation (4) can be determined from the inclination of the absorption curve below half an hour. Later gravity and other influences lead to deviation from the theoretical function.

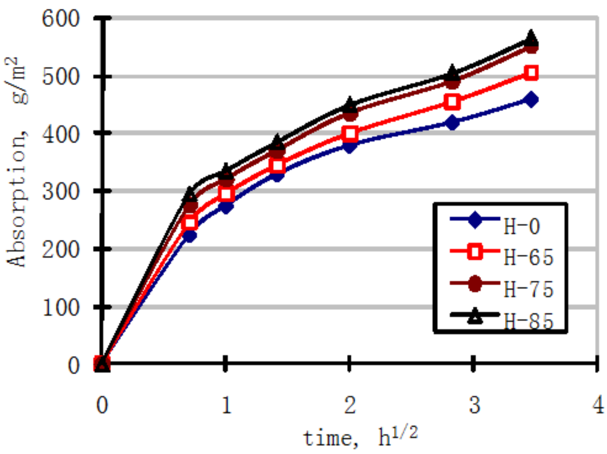

Figure 7: Capillary absorption of concrete before loading and after application of 65, 75 and 85 % of the tensile strength.

4.2 Mechanical stress and chloride penetration

If capillary absorption is accelerated by an applied tensile stress, it may be anticipated that chloride penetration is also accelerated as immediately after contact of the surface of concrete with salt solutions or seawater most chloride is transported into the pore space by convection with the capillary absorbed liquid. In Fig. 8 chloride profiles as determined after 3 months of contact of the concrete surface with a 3 % NaCl solution are shown. These profiles have been determined by grinding thin layers starting from the surface, which was in contact with the salt solution. The chloride content of the fine powder obtained in this way can then be determined analytically.

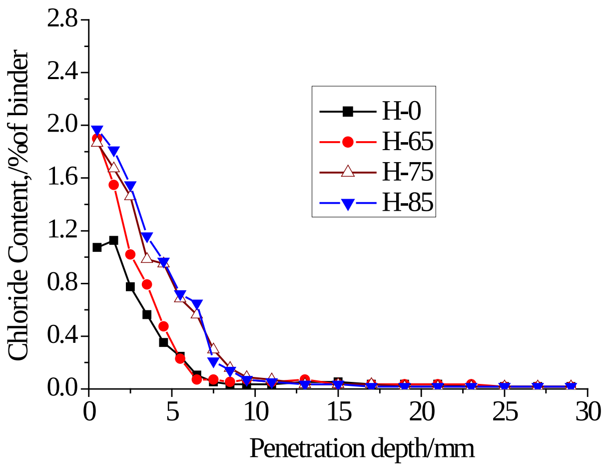

Figure 8: Chloride profiles as determined after three months of contact of the surface with a salt solution of specimens before loading (H-0) and of specimens loaded with 65 % (H-65), 75 % (H-75) and 85 % (H-85) of the tensile strength.

From Fig. 8 we learn that the higher the applied tensile stress is, the more and the deeper penetrates chloride into the pore space of concrete. During the first month of contact capillary absorption is the dominant transport mechanism as mentioned already. Therefore we have determined the diffusion coefficient of chloride for the period between one month and three months and six months respectively. Results are compiled in Table 1. The observed increase is partly due to widening of the existing pores and partly due to the formation of new pathways in form of micro-cracks as described above.

Table 1: Diffusion coefficient of concrete before applying tensile stress and after having applied 65, 75 and 85 % of the tensile strength

Diffusion period, months	Related tensile stress, %	App. Diff, Coeff. 10^{-12} mm^2/s
One to three months	0	1.28
	65	1.33
	75	3.26
	85	2.83
One to six months	0	0.97
	65	1.04
	75	1.27
	85	1.36

4.3 Carbonation under compressive and tensile stress

The rate of carbonation depends on a number of parameters such as humidity content, CO_2 concentration and temperature. If all of these parameters may be considered to be constant the rate of carbonation will depend essentially on the pore space and the pore size distribution. Gas permeability depends on the geometry of the porous system.

Carbonation has been measured in the compression and tension zone of concrete prisms under four point bending. The prisms had the following dimensions: 100 x 100 x 400 mm and they were exposed to an atmosphere with 70 % RH and a concentration of CO_2 of 10 % at 20 °C. Typical results are shown in Fig. 9.

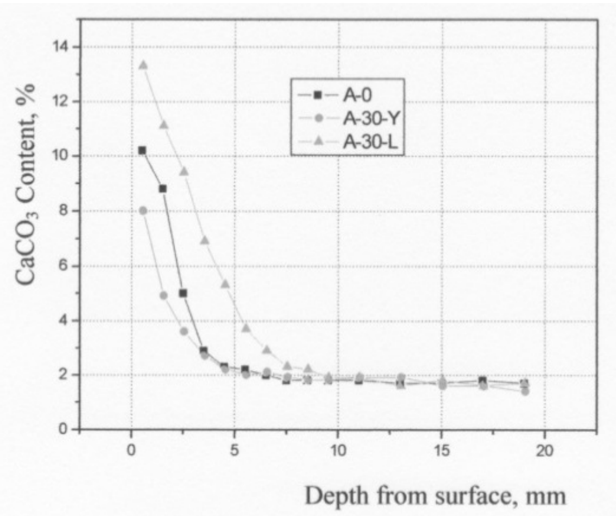

Figure 9: Carbonate profiles as observed in the compression zone (A-30-Y) and in the tension zone (A-30-L); for comparison the chloride profile has also been determined on concrete without load (A-0).

From Fig. 9 we learn that the penetration depth of carbonation increases under the influence of an applied tensile stress while it decreases under the influence of an applied compressive stress as compared to the carbonation depth reached under the same conditions but without applied stress. Obviously the pore space is modified under the influence of an applied stress. The total pore space and the effective pore radius both will be reduced under compression. These modifications are partly reversible and partly irreversible.

As an approximation the time dependent carbonation depth x(t) of a concrete specimen without load can be described as function of time with the following equation:

$$x(t) = C\sqrt{t} \qquad (5)$$

In this equation the quality of concrete and the type of cement can be taken into consideration by the constant C. To take the influence of an applied stress σ into consideration a correction factor k_σ is introduced. Then equation (5) reads as follows:

$$x(t) = C\, k_c \sqrt{t} \qquad (6)$$

The correction factor k_σ has been determined on the basis of experimental results obtained by numerous test series. The functions obtained for k_σ for tensile and compressive stress are shown in Fig. 10. As can be seen, the rate of carbonation increases steadily with increasing applied tensile stress. Under moderate compressive stress the pore space is first slightly reduced and the rate of carbonation decreases until a minimum is reached at about 30 % of the maximum stress.

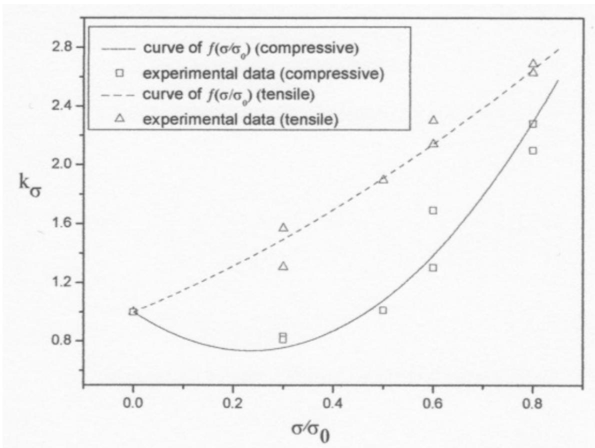

Figure 10: Correction factor k_σ as introduced with equation (6) as function of the related tensile (upper curve) and compressive stress (lower curve).

At higher compressive stress new micro-cracks are being formed and as a consequence the rate of carbonation increases at higher applied compressive stress. This observation is in good agreement with the results obtained by simulation of micro-cracks under load as described above.

5 CONCLUSIONS

Based on the results described in this contribution we can draw the following conclusions:

(1) The porous micro-structure of concrete is gradually damaged under the influence of a tensile and a compressive stress. The growth of micro-cracks can be simulated numerically.

(2) Cracks in the composite structure of concrete can be initiated in the interface between hardened cement paste and the aggregates under load. Numerical simulation shows that these cracks grow into the cement-based matrix if the applied stress is high enough.

(3) The length and the density of micro-cracks in concrete both grow with increasing applied load. The damage induced by micro-cracks is at the origin of accelerated penetration of chloride into concrete and of accelerated rate of carbonation.

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