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Water Permeability and Autogenous Healing of Cracks in Concrete

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The well-known practical phenomenon of autogenous healing in cracks plays a significant role in relation to the functional reliability of structures subjected to water-pressure loads. Due to the autogenous healing, the water flow through the cracks gradually reduces with time, and in extreme cases, the cracks seal completely. In the past, there has been no deliberate technical exploitation of self-healing, because too little is known about the phenomenon itself and about the chemical/physical processes involved.

Based on theoretical and experimental research, the effect of crack healing was investigated on a larger scale for the first time. The experimental studies showed the formation of calcite in the crack to be almost the sole cause for the autogenous healing. A comprehensive theoretical discussion of the laws, which govern the calcite nucleation and the subsequent crystal growth of water-bearing cracks in concrete, revealed that the crystal growth responds to two different crystal growth processes that are determined by the changes in the chemical and physical conditions in the crack. Further, the crystal growth rate is dependent on the crack width and water pressure, whereas concrete composition and water hardness have no influence on autogenous healing. On the basis of the experimental studies, an algorithm that can be used to estimate the reduction in water over time as a result of autogenous healing was developed.

Keywords: autogenous healing; concretes; cracking (fracturing); seepage; tests.

INTRODUCTION

Besides the durability and general stability, the water-tightness is of significant importance for the serviceability of reinforced concrete structures subjected to water pressure load, i.e., basements, water retaining structures, water service reservoirs, or waste water reservoirs. Water-tightness of the concrete can be insured either by using special membranes or by the concrete itself. However, 100 percent water-tightness can never be achieved. Cracks are unavoidable in reinforced concrete structures. The design method assumes the presence of cracks. Damages of structures show that tensile cracks resulting from the restraint of imposed deformations are normal, especially for water retaining structures. Due to the tensile cracks, the concrete structure will become water-permeable up to a certain degree, depending on the crack width, the crack length, the hydraulic gradient, etc.

At the same time, practical experiences demonstrate that cracks have the ability to heal themselves, e.g., the water flow will be reduced with time. In extreme cases, cracks can seal completely. The autogenous healing of cracks in concrete seems to be a complicated chemical/physical process. Although the autogenous healing has become part of the civil engineering folklore, the information about the process itself and the influencing parameters were limited. A quantification of the flow reduction degree has been lacking until recently. For the first time, the effect of crack healing was investigated on a larger scale through experimental[1,2] and theoretical studies.[3]

RESEARCH SIGNIFICANCE

The aim of the research described in this paper is to investigate the effects of autogenous healing upon the leakage of water through cracks in concrete so that recommendations can be made for engineering practice. The results can be used to cost optimize the design of water retaining structures.

WATER PERMEABILITY AND AUTOGENOUS HEALING

Water permeability

The model that was used to analyze the initial flow of water (flow before the autogenous healing occurs) through cracks in concrete was derived from the parallel-plate theory and is described in fluid mechanics textbooks.[4] This model assumes the flow to be an incompressible fluid that runs between parallel-sided plates where the laminar flow is fully developed. The equation, which is derived from this model to estimate the water flow through a smooth parallel-sided crack, can be written as

$$q_o = \Delta p \cdot b \cdot w^3 / 12 \cdot \eta \cdot d \qquad (1)$$

with

q_o = water flow of idealized smooth cracks, m^3/sec;
Δp = differential water pressure between inlet and outlet of the crack, N/m^2;
b = length of the crack (visible crack length at the surface of the structure), m;
w = crack width, m;
d = flow path length of a crack (thickness of the concrete structure), m; and
η = absolute viscosity, Ns/m^2.

Eq. (1), often referred to as Poiseuille Law, shows that the crack width is the dominant factor for the water permeability as the flow rate is proportional to the width cubed.

However, smooth parallel-sided cracks will not occur in concrete. Due to the roughness of the inner crack surfaces, the water flow will be much less than theoretically estimated according to Eq. (1). The reasons for the reduced water flow through cracks are:

- Roughness of the crack surfaces: macroroughness (crack development around the coarse aggregate) and microroughness (surface roughness of aggregates and paste);
- Variation of crack width along the flow path and the visible crack length;
- Local crack width reduction at the reinforcement;

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- Crack branching; and
- Physical effects (adhesion and cohesion).

Eq. (1) is therefore to be modified by a reduction factor ξ

$$q_r = \xi \cdot \Delta p \cdot b \cdot w^3 / 12 \cdot \eta \cdot d \qquad (2)$$

q_r = water flow of natural rough cracks, m^3/sec; and
ξ = reduction factor comprising the roughness of cracks.

The previously performed experimental studies[5-7] show a large variability for the flow reduction factor ξ. The reduction factor varied between 0.02 and 0.17 in the water permeability tests on reinforced concrete slabs.[6] The measured water flow was always less than 1/6 of the Poiseuille-flow, calculated according to Eq. (1). The deviation of the reduction factor was even higher with $0.04 \leq \xi \leq 0.53$ at tests performed by Meichsner.[7]

Autogenous healing of cracks in concrete

In the literature,[5-8] the following chemical, physical, and mechanical processes may be the reason for the autogenous healing:

- Swelling and hydration of cement paste;
- Precipitation of calcium carbonate crystals;
- Blocking of flow path by water impurities; and
- Blocking of flow path by the concrete particles broken from the crack surface due to cracking.

The most significant factor, which influences the autogenous healing, is the precipitation of calcium carbonate. This will be confirmed by the author's investigations.[3] The building practice itself gives evidence of this process daily. White calcium traces at the surface of the concrete structure signify the formation of calcium carbonate at cracks (Fig. 1).

RESEARCH STUDIES

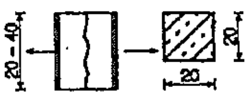
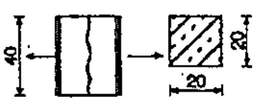
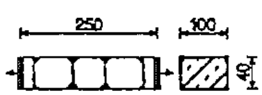
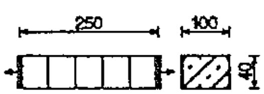
One aim of the experimental studies[1,2] was to determine the relationship between the width of a crack in concrete, as measured on the exposed surfaces, and the leakage of water passing through the crack. The other aim was to investigate the phenomenon of autogenous healing.

During Phase I, water permeability tests were conducted on small concrete test specimens [200 x 200 x 200 mm (300 and 400 mm)], each with a single tension crack, and varying the following parameters (Table 1):

- Crack width w (w = 0.10, 0.20, and 0.30 mm);
- Crack length d, i.e., thickness of the concrete element (d = 200, 300, and 400 mm);

Fig. 1—White calcium traces at concrete surface, indicating autogenous healing of cracks.

Table 1—Experimental test program[1,2]

Aims	Dimensions, cm.	Crack character	Test parameters		Test amount
Leakage and healing, $\Delta w = 0$		Static crack	w, p, l, water, concrete	Variable	80
Crack motion, $\Delta w \neq 0$		Dynamic crack	w, Δw, p	Variable	10
			l, water, concrete	Constant	
Artificial substances, $\Delta w = 0$		Static crack	Silica fume, bentonite, microcement		3
			w, p, l, concrete, water	Constant	
Crack branching, $\Delta w = 0$		Static cracks with crack branching	With skin reinforcement		1
			w, p, l, concrete, water	Constant	
		Static cracks without crack branching	Without skin reinforcement		1
			w, p, l, water, concrete	Constant	

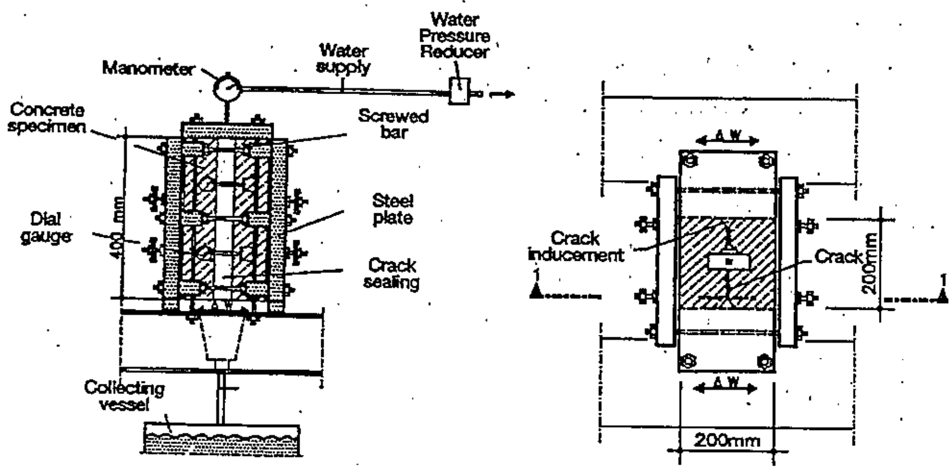


Fig. 2—Testing device for producing realistic tensile cracks under water pressure subjection.[1]

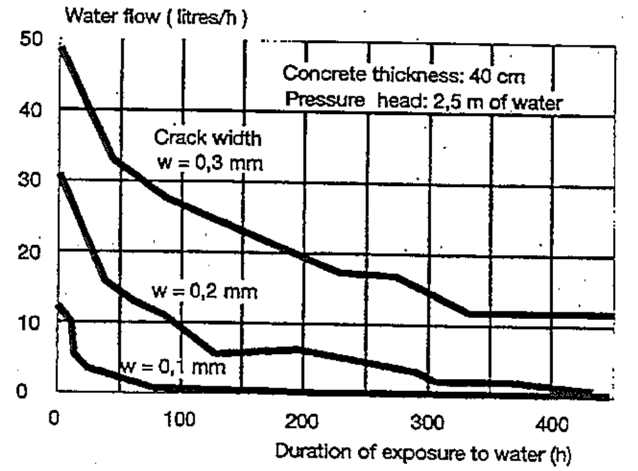


Fig. 3—Relationship between water flow and time for different crack widths (per m visible crack length).[1]

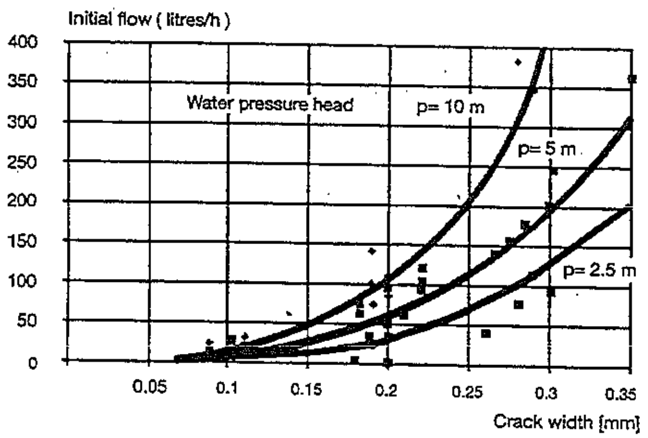


Fig. 4—Relationship between initial water flow and crack width for different water pressure (per m visible crack length).[1]

- Water pressure head p (p ranging from 2.5 to 20 m of water);
- Hydraulic gradient I (I ranging from 6.25 to 50), i.e., the water pressure head m divided by the thickness of the structure m;
- Hardness of water (soft water with approximately 70 mg $CaCO_3$/l, hard water with approximately 480 mg $CaCO_3$/l and distilled water);
- Cement (portland cement, slag cement, sulfate-resistant cement);
- Aggregate (granite, limestone, basalt); and
- Filler (limestone dust, fly-ash).

To produce a realistic tension crack and subject it to water pressure, a special testing device was developed (Fig. 2). The leakage and temperature of the water were continuously measured during the exposure to water pressure. The water (before and after passing through the crack) was chemically analyzed to get information about the consumption of calcium carbonate (hydrogen carbonate). After the tests were finished (test period ranging from 5 to 20 weeks), the surfaces of the crack path were examined for blocking material by means of optical microscopy (polished and thin sections), scanning-electron-microscope-observations, and x-ray-diffraction-analyses.

Other essential, relevant factors, affecting the autogenous healing, such as:

- Crack motions (active cracks with varying crack width);
- Artificial substances present in the water (microcement, silica fume, and bentonite); and
- Crack branching near the surface of the concrete structures due to skin reinforcement

were investigated in Phase II. The influence of crack branching on the leakage of water and autogenous healing was examined by conducting water permeability tests on reinforced concrete slabs (2500 x 1000 x 400 mm) (Table 1). The influence of crack motions and artificial substances was examined by water permeability tests conducted on the previously mentioned small test specimens.

RESULTS

Dormant cracks

Fig. 3 presents some results of the investigations[1] with single crack specimens and dormant cracks. The characteristic flow curve of concrete cracks during autogenous healing shows a significantly decreasing rate at the early stages. The initially high leakages quickly dropped to a reduced level.

About 50 percent of the concrete specimens with crack width (mean value) of w = 0.20 mm and a water pressure head of p = 2.5 m (I = 6.25) healed completely during 7 weeks of water exposure. Even for p = 10 m (I = 25), 25 percent of the cracks were healed up to the extent that the flow completely stopped (w = 0.20 mm, 7 weeks of water exposure).

Fig. 4 shows the relationship between the initial flow and the crack width. There is a large distribution of the results that can be preliminary attributed to the large variability of the measured crack widths (a well-known problem at investigations with the crack width as test parameter). Despite the variability of the results, the validity of Eq. (1) was confirmed, which indicates that

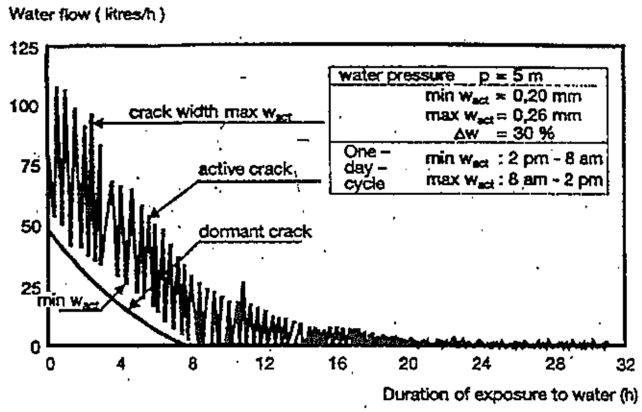


Fig. 5—Relationship between flow and time for active cracks (per m visible crack length).[1]

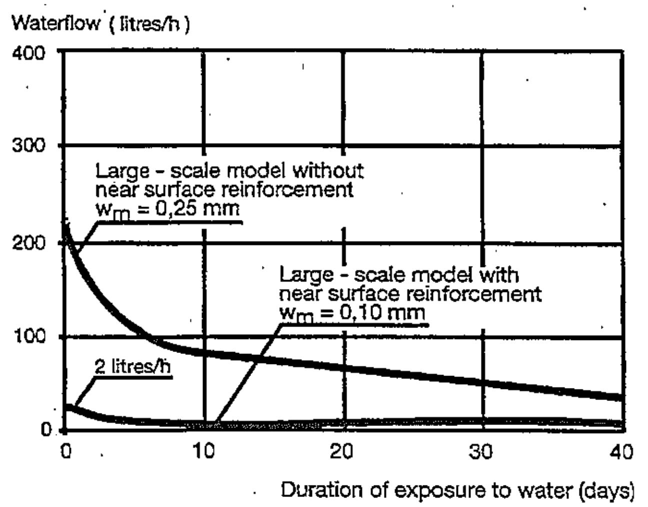


Fig. 6—Relationship between flow and time for reinforced concrete slabs with and without crack branching (per m^2 concrete area under water pressure of 2.5 m).[2]

the leakage of water through cracks in concrete is proportional to the width cubed.

Active cracks

Fig. 5 presents the water flow of an active crack (crack motion corresponding to 1-day cycle) in comparison with a dormant crack with a comparable crack width ($w_{dorm.}$ = min. $w_{act.}$) and water pressure.[1] The figure shows that an autogenous healing also occurs in active cracks. The autogenous healing of active cracks is comparable to dormant cracks at minimum crack width (min. $w_{act.}$), whereas the healing takes more time at maximum crack width (max. $w_{act.}$). Compared with dormant cracks, the period for total healing at maximum crack width will be increased by at least 15 weeks.

Crack branching

For the two slabs[2] with comparable main reinforcement, the mean surface crack width could be reduced from 0.25 mm (Slab S2 without skin reinforcement) to 0.10 mm (Slab S1 with skin reinforcement) at comparable steel stresses (skin reinforcement considered). Crack branching, which is caused by the skin reinforcement, has a significant reduction of the crack widths at the surfaces of S1, whereas the crack widths in the middle of the two slabs were comparable. Fig. 6 shows that the initial flow could be reduced by two orders of magnitude due to the skin reinforcement, and that the branched cracks of S1 healed up to negligible flow rates after one month of exposure to water. It seems that, besides the visible crack branching at the surface of the S1, contractions in the inner crack path exist and reduce the initial flow and support the autogenous healing further.

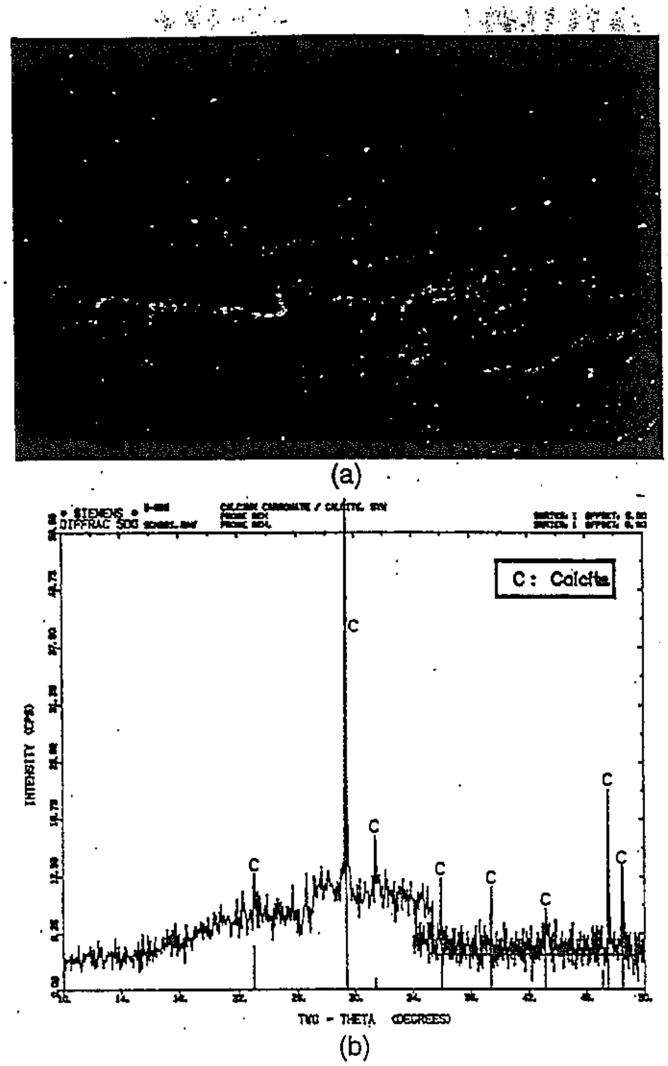


Fig. 7—(a) Crack blockade of $CaCO_3$ crystals (crack width = 0.20 mm); and (b) x-ray diffractogram from crack border showing calcite as main element.[3]

NEW FINDINGS ON MECHANISM OF AUTOGENOUS HEALING[3]

Cause of autogenous healing

All the chemical and mineralogical investigations[1,2] of the crack fracture surfaces have shown the formation of crystalline $CaCO_3$ as practically an exclusive cause of autogenous healing (Fig. 7). Irrespective of the investigated experimental parameters, it was possible to prove the presence of calcite formation in all the cracks, thereby also in cracks with a large width (w = 0.30 mm), a large movement (Δw = 50 percent), and a high water pressure head (p = 10 m of water). An analysis of the possible influence of hardened swelled cement paste on the reduction of the leakage rate revealed to be of lesser importance. The influence from mechanical processes (blocking of the flow path by suspensions or loose concrete particles) was observed equally small.

$CaCO_3$ formation in water flown-through crack

A comprehensive theoretical discussion of the laws that govern the calcite nucleation and the subsequent crystal growth of water-bearing cracks in concrete is given in Reference 3 based on the findings of the investigations presented in Reference 1 and 2. The important results of these considerations[3] are given in the following.

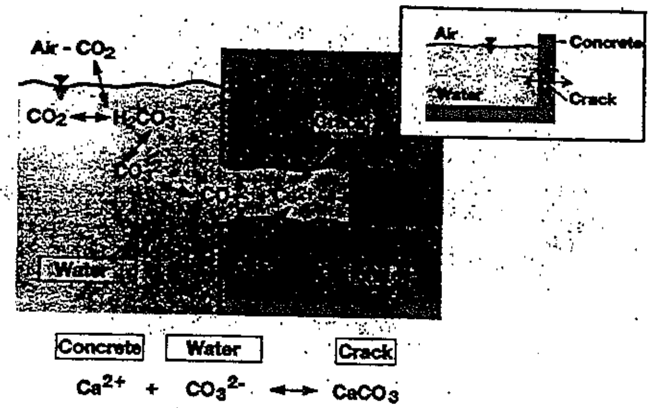


Fig. 8—Media, interfaces, and reactions in $CaCO_3$-CO_2-H_2O system.[3]

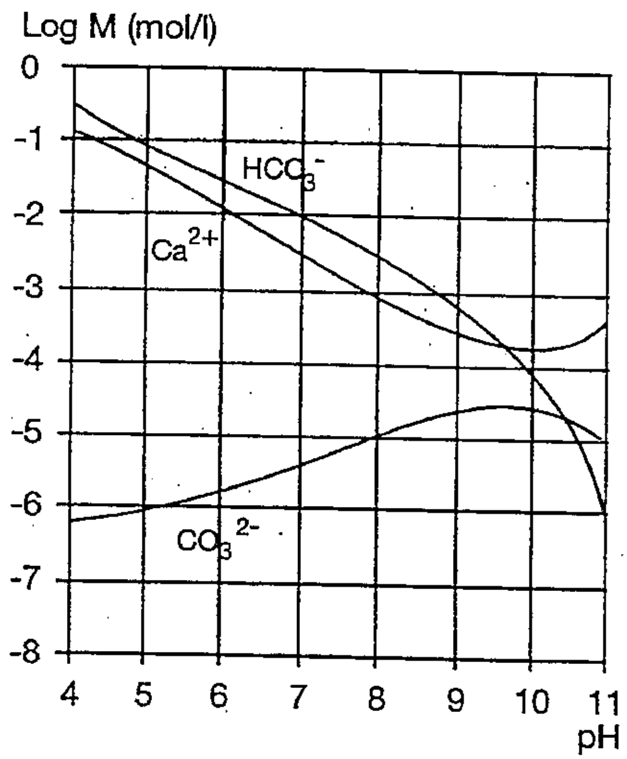


Fig. 9—Equilibrium concentrations at saturation of Ca^{2+}, CO_3^{2-}, and HCO_3^- as a function of pH.[9]

A calcite formation in the area of water-bearing cracks takes place in the material system $CaCO_3$-CO_2-H_2O according to the following reactions[9-12]

$$Ca^{2} + CO_3^{2-} \Leftrightarrow CaCO_3\ (pH_{water} > 8) \quad (3a)$$

$$Ca^{2+} + HCO_3^- \Leftrightarrow CaCO_3 + H^+\ (7.5 < pH_{water} < 8) \quad (3b)$$

The water-insoluble $CaCO_3$ is evolved from a reaction between the calcium ions Ca^{2+}, derived from the concrete, and the in-water available bicarbonates HCO_3^-, or carbonates CO_3^{2-} (Fig. 8). Whether and where in the crack the calcite formation develops with a subsequent crystal growth depends—apart from the temperature, pH value, and CO_2 partial pressure—very decisively from the saturation index Ω of calcite $[\Omega = (Ca^{2+})(CO_3^{2-})/K_c]$ and with it from the concentration of the ions $(Ca^{2+})(CO_3^{2-})$ in the solution and the solubility product of calcite K_c.[13-16] Laboratory experiments on corresponding test

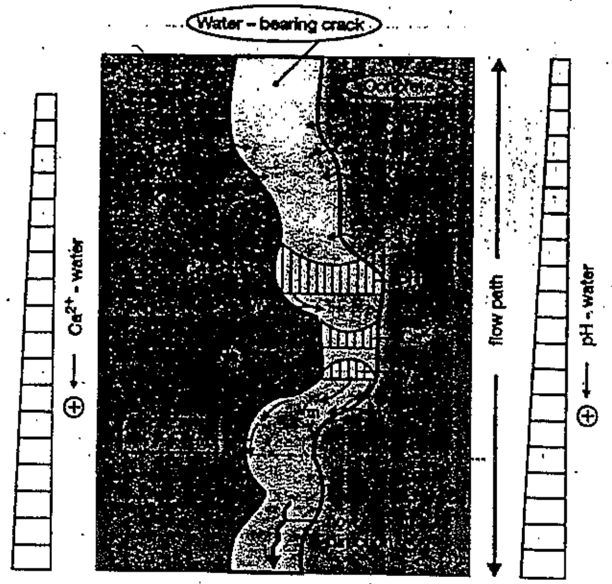


Fig. 10—Conditions in water-penetrated concrete crack.[3]

tube solutions[15,16] show that in a homogeneous nucleation, a saturation of $\Omega = 20$ is necessary to trigger a calcite nucleation with subsequent crystal growth. When a concrete surface acts like a catalyst to the nucleation process, one has to assume a heterogeneous nucleation, and that a far smaller saturation ($\Omega << 20$) will be necessary for the nucleus formation in a water bearing crack.

Furthermore, thermodynamic considerations of $CaCO_3$ formation have shown that the following circumstances favor a $CaCO_3$ precipitation in a crack:

- Rising water temperature;
- Rising pH value of the water; and
- Falling CO_2 partial pressure in the water.

Fig. 9 shows the equilibrium concentration of the $CaCO_3$ formation's participating components Ca^{2+}, CO_3^{2-}, and HCO_3^- as function of pH value of the solution. According to this, the solubility curve for the $CaCO_3$ passes through a minimum at a pH value of approximately 9.8 where there is the least Ca^{2+} requirement to trigger off a primary calcite precipitation.

The solubility minimum of $CaCO_3$ occurs, therefore, at a pH value that lies between that of hardened cement paste (pH = 13.5) and that usually encountered in water (pH = 5.5 to 7.5). This is of great importance for a flowed-through concrete crack in which an intermixing of the two aqueous solutions (pore water and exposure water) takes place along the crack path. It is only a question of where the intermixed water in the crack reaches the earlier-mentioned pH value of the solubility minimum and sets off a primary $CaCO_3$ precipitation.

By taking into account the experimental results[1,2] a model was developed[3] for the autogenous healing of cracks as a result of calcite formation. In the following, the main elements of the autogenous healing model will be presented. For a more detailed illustration, refer to Reference 3.

The autogenous healing model assumes that the water entering the crack exhibits the usual pH value (pH = 5.5 to 7.5) and the usual CO_2 content ($P_{CO_2} = 10^{-3.5}$). Apart from the bicarbonates and carbonates, the water contains a certain amount of Ca^{2+} (Fig. 10). It is, however, still undersaturated in relation to a $CaCO_3$ precipitation. While this CO_2 containing water penetrates the hardened cement paste, it dissolves additional Ca^{2+} ions from the $Ca(OH)_2$ and the CSH phases of the hardened cement paste, and the pH value of the water will rise. At the same

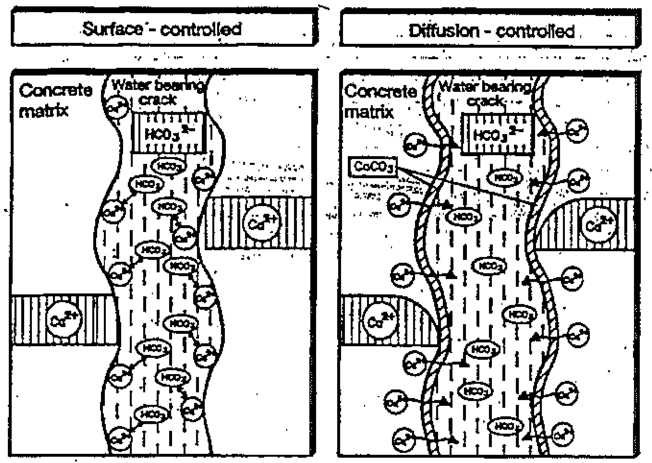


Fig. 11—Surface- and diffusion-controlled process of calcite growth.[3]

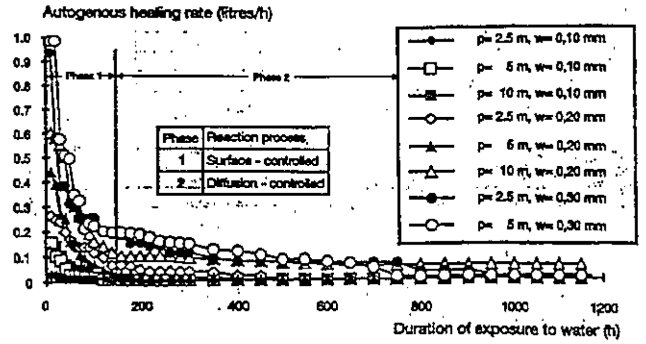


Fig. 12—Healing rates (flow reduction rate) for different crack widths and pressure gradients (per m visible crack length).[3]

time, the in-the-pore-water-contained alkalis, KOH and NaOH, effect a rise in the pH value (pH > 8), and the in-water-present-bicarbonates will be converted into carbonates. As a result of the concentration gradient, the dissolved Ca^{2+} ions will diffuse into the through-flowing water and be removed with it. The pH value, as well as the Ca^{2+} ion concentration, will thereby rise over the flow path length. A gradient in the pH value, as well as in the Ca^{2+} ion concentration, are also to be expected over the crack width because of the smaller flow velocity v_r in the area of the rough, angled crack walls, especially in the area of hollow depressions (where standing water may also be present), fewer Ca^{2+} ions are transported away than in the middle of the crack where the water is flowing nearly undisturbed with mean flow velocity v_m.

These regions with a low flow near the crack walls favor a supersaturation of the water, so that a primary calcite precipitation corresponding with Eq. (3a) takes place. Beside this primary calcite precipitation, further nucleations can take place in any other places along the course of the crack so far as the conditions for a precipitation corresponding with Fig. 9 are satisfied. The precipitation conditions (high pH value and a good supply of Ca^{2+}) are better realized in the contact area between water and hardened cement paste than at the contact area between water and aggregate grain. The subsequent crystal growth responds to different crystal growth processes that are determined by the changes in the chemical and physical conditions in the crack (Fig. 11). In the initial phase of exposure to water, the kinetics of crystal growth is surface controlled as long as sufficient Ca^{2+} ions are available directly on the crack walls (Fig. 11) on the left. As soon as they are used up, further Ca^{2+} ions will be transported from the inside of the concrete to the crack walls by means of diffusion. In this phase, a diffusion-controlled crystal growth takes place.

The transition from the surface-controlled crystal growth to the diffusion-controlled crystal growth causes the characteristic autogenous healing behavior of water-bearing cracks (Fig. 12). As long as there are sufficient Ca^{2+} ions directly on the crack walls, a very rapid crystal growth takes place. After the consumption of the Ca^{2+} ions on the crack wall, a Ca^{2+} diffusion will develop because of the concentration gradient. In this case, the period in which the Ca^{2+} ions require to diffuse through the concrete and the already available calcite layer is greater than the period required for their absorption and incorporation into the crystal lattice. Therefore, the crystal growth rate and the thereby conditioned autogenous healing rate depend on the diffusion velocity of the Ca^{2+} ions through the concrete and the $CaCO_3$ boundary layer. As a consequence, water flow-through cracks exhibit a pronounced crystal growth and an attendant crack width reduction in the initial phase (the first 3 to 5 days). The result is a strong discharge decrease or autogenous healing rate. Subsequent to the surface controlled crystal growth, the very slowly progressing diffusion controlled crystal growth causes only very small cross-sectional reductions and small discharge reductions that are reflected in the nearly parallel curve shape of the autogenous healing rates in Fig. 12.

Influencing parameters

To a considerable degree, the autogenous healing process is influenced by the crack width and the prevailing water pressure, whereas the type of cement, aggregate, and filler and the hardness of the water are of an lesser influence.

The analyses[1,2] of water revealed that not all the CO_3^{2-} and HCO_3^- ions present in the water will be consumed for the precipitation. This means that the carbonate content in the water is not the limiting factor for the $CaCO_3^-$ precipitation, even when the water is very soft [urban low pH (acid) rain water], which was confirmed by the experimental investigation with such type of water.

ANALYSIS OF RESULTS AND RECOMMENDATIONS[3]

Initial water flow

Due to the large distribution of water leakage, Eq. (1) seems to be a reasonable assumption to use to estimate the water flow. A regression analysis of all the test results (Phase I) gives a mean value of $\xi = 0.25$ for the reduction factor in Eq. (1). Assuming a water temperature of 20 C ($\nu = \eta/\rho = 1.00$ mm²/sec) the initial flow can be estimated from Eq. (1) for a visible crack length of $b = 1.00$ m to

$$q_o = 740 \cdot I \cdot w_m^3 \cdot k_t \tag{4}$$

where

q_o = initial water leakage per meter visible crack length, l/h;
I = hydraulic gradient, m of water head/m;
w_m = crack width (mean value) at the surface, mm; and
k_t = factor comprising different water temperatures, -.

Water temperatures different from 20 C are to be corrected by the factor k_t.

Rate of autogenous healing

The relationship between the flow (mean value) and the period for all tests of Phase I are shown in Fig. 13. This graphic model can be used to estimate the water flow at any time considering the autogenous healing effect (valid for dormant and active cracks).

A regression analysis of the results gives Eq. (5) to estimate the influence of autogenous healing. The experiments demonstrated that the influence of the hydraulic gradient on the water flow

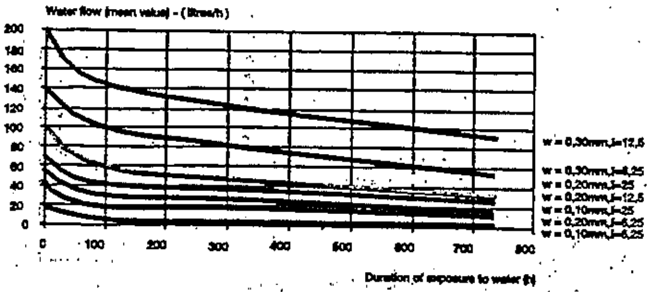


Fig. 13—Graphic model to estimate reduction of water flow with time (per m visible crack length).[3]

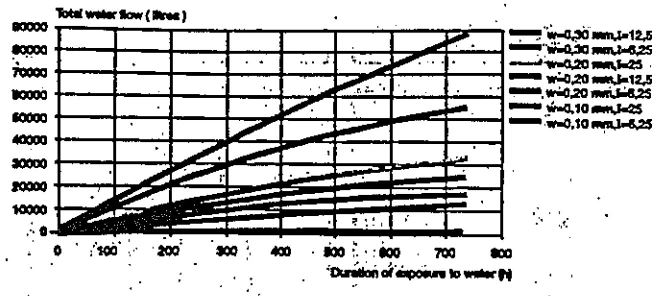


Fig. 14—Relationship between total amount of water and time for different crack widths and pressure gradients (per m visible crack length).[5]

Table 2—Permissible crack widths for autogenous healing[3]

Hydraulic gradient, m/m	w_k, mm*	w_k, mm†
40	0.10 to 0.15	≤ 0.10
25	0.15 to 0.20	0.10 to 0.15
15	0.20 to 0.25	0.15 to 0.20

*$\Delta w \leq$ 10 percent.
†10 percent < $\Delta w \leq$ 30 percent.

is less significant than that of the crack width. Therefore, the differences in hydraulic gradient were not considered in favor of a simplified handling:

$$q_{(t)}/q_o = 65 \cdot w_m^{-1.05} \cdot t^{(-1.3+4w)} - 10^5 \cdot w_m^{5.8} \qquad (5)$$

with

$q_{(t)}$ = water leakage at time t, l/h;
q_o = initial water flow, l/h, according to Eq. (4);
w_m = crack width (mean value) at the surface, mm; and
t = water exposure time, h.

Total water leakage

Fig. 14 shows the total amount of water (mean value) for all tests in Phase I. The total water flow until the stage of total healing of the crack can be estimated (very rough estimate) at $500 - 1000 \cdot q_o$.

Permissible crack widths

With the test results and a careful extrapolation, permissible crack widths (w_k = design crack width), which can be expected to obtain an almost total self-healing after few weeks of water pressure exposure, can be derived from Table 2.

CONCLUSIONS

The following conclusions are derived from the presented research.[1-3]

1. Concrete cracks, both dormant and active, subjected to water pressure are able to heal themselves with time.

2. The greatest autogenous healing effect occurs within the first 3 to 5 days of water exposure, where the then-still-available water leakage, depending on the crack width and water pressure, makes up 1 to 20 percent of the initial water leakage rate.

3. The participation of calcium carbonate crystals ($CaCO_3$) in the crack is almost the sole cause for the autogenous healing of the cracks.

4. The growth rate of the $CaCO_3$ crystals depends on crack width and water pressure, whereas concrete composition (type of cement type and aggregate, respectively) and type of water (i.e., hardness of water) has no influence on the autogenous healing rate.

5. The formation of $CaCO_3$ responds to two different crystal growth processes. In the initial phase of the water exposure, the kinetics of crystal growth is surface controlled; later, it turns to a diffusion controlled crystal growth.

6. An additional skin reinforcement proves to be highly effective in supporting the autogenous healing process.

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