DaCS

Durable advanced Concrete Solutions

Report No. 04

The impact of cracks on gas and liquid tightness of concrete

WP 1.3 Relevance of crack requirements

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ABSTRACT

Concrete is frequently used in structures where tightness towards gaseous and liquid substances is important. The current report constitutes a brief literature review that addresses 1) The governing mechanisms related to gas and liquid tightness of uncracked concrete, i.e. permeation, diffusion, capillary suction and adsorption, 2) Various concrete cracking mechanisms caused by e.g. volume changes, mechanical loading, environmental conditions and chemical reactions and 3) The impact of cracks on concrete tightness.

Cracks have a major impact on the gas and liquid tightness of concrete. Micro-, surface- and flexural cracks, i.e. cracks that do not go through the whole section, will increase the concrete permeability. Through-cracking, on the other hand, is the governing crack mechanism when it comes to gas and liquid tightness of concrete; under such conditions the permeability is no longer porosity-dependent but rather crack-dependent, and the concrete permeability increases considerably with increasing crack width.

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Preface

This report and the related work have been carried out within the research project “Durable advanced Concrete Solutions” (DaCS). The project started in 2015, and is a 4-years’ research program with focus on concrete structures for severe conditions. The main R&D objective is to enable production of sustainable and durable concrete structures for coastal and offshore arctic applications, considering both production and service life phases.

Multiple researchers from the Norwegian University of Science and Technology, SINTEF and industry partners, together with 3 PhD-students and a number of MSc-students, work on four focus areas:
- WP 1: Early age cracking and crack calculation in design
- WP 2: Production and documentation of frost resistant concrete
- WP 3: Concrete ice abrasion
- WP 4: Ductile, durable Lightweight Aggregate Concrete

The industry partners are leading multinational companies in the cement and building industry, together with Norwegian engineering companies and offshore industry. Together our aim is to improve the concrete material quality to produce environmentally friendly and durable concrete structures for future arctic offshore and coastal applications. Combining the existing knowledge and experience cross industries with the recognised research capabilities of NTNU and SINTEF, provides a good basis for both high quality and industry relevant research. Achieving the overall research objectives, will strengthen the Norwegian industry’s relevance, attractiveness and competitiveness.

The DaCS project partners are: Kværner AS (project owner), Axion AS (representing Stalite), AF Gruppen Norge AS, Concrete Structures AS, Mapei AS, Multiconsult AS, NorBetong AS, Norcem AS, NPRA (Statens Vegvesen), Norges Teknisk-Naturvitenskapelige Universitet (NTNU), SINTEF Byggforsk, Skanska Norge AS, Unicon AS and Veidekke Entreprenør AS. The project has received financial contribution from the Norwegian Research Council.
For more information, see https://www.sintef.no/projectweb/dacs/.

Summary

Concrete is frequently used in structures where tightness towards gaseous and liquid substances is important. For all such structures, concrete tightness is an essential part of the design. When it comes to the permeability of sound (uncracked) concrete, porosity is the decisive material parameter. Adequate porosity, and hence low permeability, can be obtained by carefully considered mix design, and more specific by keeping the water to binder ratio below 0.4.

Naturally, cracks have a major impact on the gas and liquid tightness of concrete. Micro-, surface- and flexural cracks, i.e. cracks that do not go through the whole section, will increase the concrete permeability. However, for such cracks, the gas or liquid still has to be transported through sound concrete and the permeability is thus still porosity-dependent. Through-cracking is the governing crack mechanism when it comes to gas and liquid tightness of concrete; under such conditions the permeability is no longer porosity-dependent but rather crack-dependent. The flow rate through a concrete through-crack is proportional to the width cubed, and hence the permeability increases considerably with increasing crack width. Concrete leakage rates can be estimated by calculation approaches, but such estimations are connected with great uncertainties due to variations in 1) the crack width throughout the section thickness (caused by e.g. reinforcement design and ratio, concrete inhomogeneity and possible self-healing), 2) crack surface roughness and 3) the actual cracking pattern in the given concrete structure.

Self-healing (also denoted autogenous healing) is the ability of a concrete to repair itself due to formation of calcite in the cracks: the water flow gradually decrease over time, and in some cases, the cracks seal completely. A critical upper crack width for complete self-healing is found to be approximately 0.2 mm for ordinary concrete, which most likely constitutes the background for some of the given crack width tightness requirements.

Requirements and specifications regarding concrete gas and liquid tightness can be found in prevailing codes and handbooks. Such requirements involve e.g. crack width limits, minimum compressive zones, minimum sectional thicknesses, maximum membrane stresses and maximum axial stress resultants. The background and reasons for the given requirements are not always self-evident, which is probably related to the fact that the research topic *"the impact of cracks on gas and liquid tightness of concrete"* is far from "solved" and still connected to uncertainties.

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References

1 Introduction

Concrete is well known for its load carrying capacity, but it is also frequently used in structures where tightness towards gaseous and liquid substances is important: gases and liquids have to be prevented from getting from one side of the concrete to the other. Sometimes concrete has to keep liquid and gases out, like for instance in basements, marine structures, tunnels, underground stations and subways. Other times, concrete has to keep liquid and gases in, e.g. in swimming pools, concrete dams, sewers and pipelines, liquefied natural gas (LNG) tanks and nuclear storage waste containers. For all such structures, tightness towards gaseous and liquid substances is an essential part of the concrete design.

The tightness of a concrete structure depends on both the tightness of the sound concrete, as well as the overall tightness of the structural concrete member. The former is governed by the permeability of the concrete, while the latter is also a function of parameters such as design, cracking and construction joints. The current memo focuses on the tightness of sound concrete, as well as the impact of cracks on the gas and liquid tightness of concrete.

2 Gas and liquid tightness of uncracked concrete

2.1 General

Gases and liquids can be transported through concrete by various transport mechanisms, and in particular permeation, diffusion, capillary suction and adsorption [CEB-FIP, 2013]. These transport mechanisms are further described in Section 2.2.1 – Section 2.2.3. The transport through a concrete structure is complex, and can also occur as a combination of the above listed mechanisms, as illustrated in Figure 2.1 [Herholdt et al., 1979].

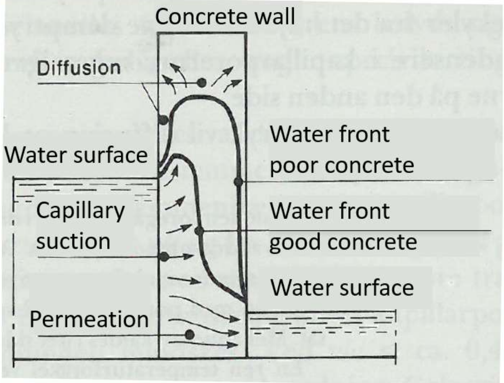


Figure 2.1; Examples of transport mechanisms by which water can be transported through a concrete structure [Herholdt et al., 1979]

Hardened concrete is a porous material, and this porosity determines the concrete permeability. Concrete pores can be subdivided into two groups: Gelpores and Capillary pores. Gelpores are a part of the cement paste, where they constitute about 28% of the hardened cement paste volume. Capillary pores constitute between 0 and 40%, depending on the water to cement ratio and the degree of hydration [Neville, 1972].

The transport of gaseous and liquid substances mainly takes place in the pore system of the hydrated cement paste, the interface zone (the contact zone between the cement paste and aggregate) and in micro-cracks resulting from internal stresses. Concrete permeability is thus strongly dependent on the size, distribution and connectivity of the concrete pores. Among these parameters, the connectivity of the capillary pores is found to be the most significant microstructure characteristic. The interconnectivity is however closely connected to the volume of pores; studies have shown a clear relation between the connectivity of the capillary pores and the total capillary porosity, [Bentz et al., 1991] and [CEB-FIP, 2013]. The amount and interconnectivity of the capillary pores, and hence concrete permeability, decreases with decreasing water to binder ratio and increasing hydration degree [Powers et al., 1954] [Powers et al., 1959]. The literature suggest that a "watertight" concrete should have a water to cement ratio below 0.4 - 0.5, e.g. [Neville, 1972], [Sellevold, 2004], [JSCE, 2010] and [CEB-FIP, 2013].

2.2 Transport mechanisms through uncracked concrete

2.2.1 Permeation

Permeation is the flow of gases or liquids caused by a pressure gradient, Figure 2.2, while permeability is the measure of the ease with which the fluids can flow.

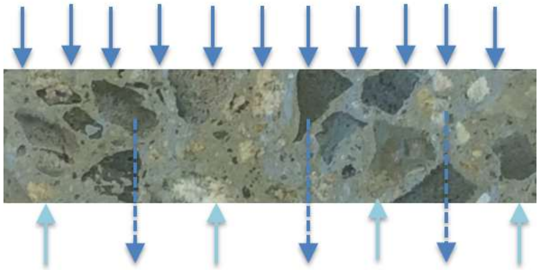


Figure 2.2; Permeation, the flow of gas or liquids caused by a pressure gradient

The flow of liquid over time is often modelled by Darcy's law. Equation 2.1 expresses the transport of water (by Darcy's law) as described by [CEB-FIP, 2010].

$$V = K_w \frac{A}{l} \Delta h_w t \qquad \text{Equation 2.1}$$

where V is the volume of water, K_w *is the coefficient of water permeability, A is the penetrated area, l is the thickness,* Δh_w *is the hydraulic head (pressure difference) and t is the time*

Most of the parameters in Equation 2.1 describe surrounding conditions, e.g. material dimensions, pressure gradient and time. All the internal microstructure characteristics are described by only one parameter: the permeability coefficient. The permeability coefficient is expressed in speed; the higher the coefficient, the easier and faster the liquid or gas flows. The coefficient of permeability is strongly related to concrete porosity and consequently also to the water to binder ratio. Figure 2.3 shows the relation between the coefficient of water permeability and 1) water to cement ratio and 2) capillary porosity for a cement paste as found by [Powers, 1958] and [Powers et al., 1959].

fib Model Code 2010 provides an estimation of the water permeability coefficient by the mean compressive strength of the given concrete. Such an estimation should be handled carefully, as the compressive strength represents a substitute value for the microstructure as well as a mean value over the whole cross-section. Consequently, when an accurate prediction of transport characteristics is required, the coefficient of permeability should be determined experimentally [CEB-FIP, 2013]. Similar approaches, like for instance coefficient of permeability estimations based on the concrete water to cement ratio, can also be found, e.g. [JSCE, 2010].

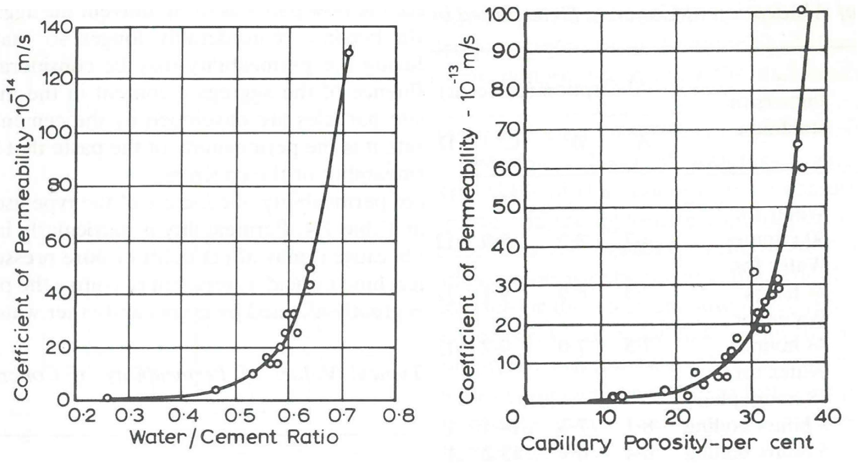


Figure 2.3; Relation between coefficient of Permeability and 1) water to cement ratio (left) and 2) capillary porosity (right) for a cement paste [Powers, 1958] and [Powers et al., 1959], as cited by [Neville, 1972]

The flow of gas over time can be modelled analogously to the flow of liquids. The internal microstructure is then described by the coefficient of gas permeability for the given material. The permeation of gas is dependent on the relative pore humidity of the concrete in addition to the microstructure. As the relative humidity decreases, the moisture content in the capillary pores is reduced, increasing the interconnectivity and leaving more pore space available for gas transport [CEB-FIP, 2013].

2.2.2 Diffusion

Diffusion is the transport of mass by random motion of free molecules or ions caused by a concentration gradient, as illustrated in Figure 2.4.

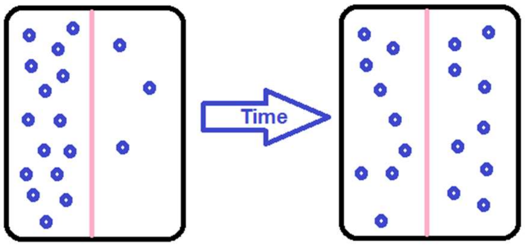


Figure 2.4; Diffusion

The diffusion of gases, liquids and dissolved substances can be modelled by Fick's first law of diffusion, Equation 2.2 as described in [CEB-FIP, 2013]. The diffusion flow rate is proportional to the concentration gradient and the diffusion coefficient *D*.

$$Q = D\frac{c_1 - c_2}{l}At \qquad \text{Equation 2.2}$$

where Q is the amount of transported substances, D is the diffusion coefficient, (c1-c2) is the concentration gradient, l is the thickness of the penetrated area, A is the penetrated area and t is the time

Analogously to permeation, most parameters in Equation 2.2 describe the surrounding conditions, while the diffusion coefficient *D* comprises the internal microstructure characteristics of the given material. The diffusion coefficient is roughly estimated by the mean compressive strength in ***fib*** Model Code 2010 [CEB-FIP, 2010]. It is however emphasised that the coefficient should be determined experimentally when accurate predictions are needed.

In most cases, transient diffusion phenomena occur. This means that the amount of diffusing substances is not a constant and may depend on a number of parameters in addition to time; e.g. local concentration, location, temperature and relative pore humidity. The diffusion of water vapour is for instance very dependent on the relative pore humidity, where the diffusion coefficient is increasing with increasing relative pore humidity. Analogously, the diffusion of gases is also mostly controlled by the moisture content in the concrete pore system.

Diffusion mechanisms are also very important when it comes to the penetration of carbon dioxide (carbonation) and chloride ions into the concrete.

2.2.3 Capillary suction and adsorption

Capillary suction is the take-up of a liquid in a porous solid caused by surface tensions in the capillaries (which makes the interface curved), Figure 2.5. Influencing parameters are the viscosity, the density and the surface tension of the liquid.

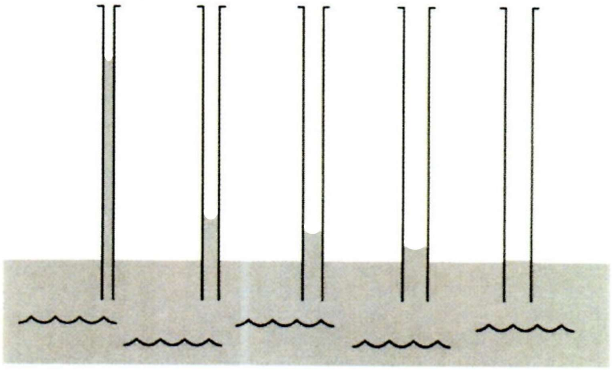


Figure 2.5; Illustration of capillary suction

When it comes to capillary suction, irregularities within the pore system complicates the theoretical relations. Therefore, empirical relations have been established to described the adsorption of a liquid by capillary suction in concrete, e.g. Equation 2.3 [CEB-FIP, 2013].

$$w = M_w t^n$$ *Equation 2.3*

where w is the water absorbed per unit area at time t, M_w is the coefficient of water absorption, t is the time and n is an exponent to characterise the time-development

As for permeation and diffusion, the internal porestructure characteristics influencing capillary suction are described by one parameter: the coefficient of water absorption. Also for this coefficient, the ***fib*** Model Code 2010 provides a rough estimation by the mean compressive strength [CEB-FIP, 2010].

Similar to the water permeability, capillary suction is strongly dependent on the moisture content of the concrete, where the rate of water adsorption decreases with increasing pore humidity. Seasonal temperature changes have no major impact on the water uptake, however, in general, a temperature increase leads to a significant increase of transport properties.

3 Cracks in concrete structures

3.1 General

During its lifetime, a concrete structure may be subjected to different kinds of cracking mechanisms, some of which are illustrated in Figure 3.1. While cracking may be necessary with respect to reinforcement utilisation, concrete cracking may be unfavourable when it comes to durability, aesthetics and tightness. The main reasons for crack development in concrete are; volume changes, mechanical loading, environmental conditions and chemical reactions, as briefly described in Section 3.2 - Section 3.4.

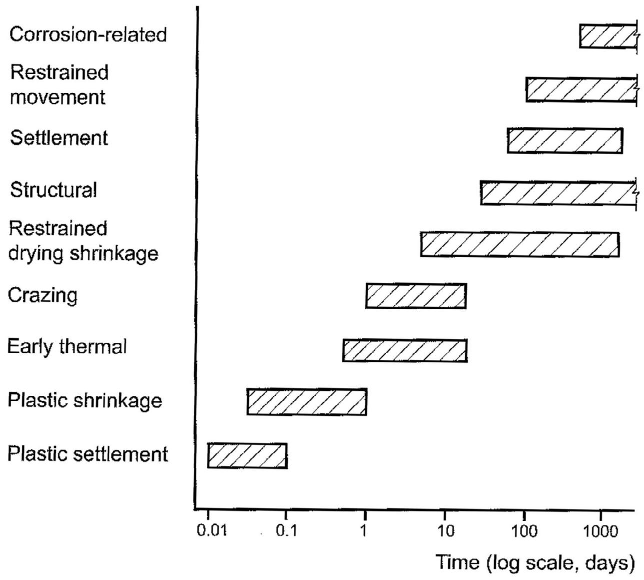


Figure 3.1; Cracks in concrete structures [Richardson, 2002]

3.2 Cracks due to volume changes

A brief summary of various volume changes that can occur in concrete is given in the following. If such volume changes (especially contraction) are restrained, the tensile stress may exceed the tensile strength and thus lead to cracking of the concrete.

Plastic shrinkage

Plastic shrinkage is caused by evaporation of water from the concrete surface during the fresh phase. Cracks caused by plastic shrinkage are often serious: they may appear as wide surface cracks (up to 2-3 mm) and with a depth over the cover zone or even deeper [Bjøntegaard, 2009].

Plastic settlement

Plastic settlement is the downward (vertical) movement of solid particles in fresh concrete, i.e. an overall settlement of the concrete surface. A differential in the settlement over a cross-section, caused by e.g. reinforcement or a varying cross-section dimension, will cause a risk of crack formation [Bjøntegaard, 2009]. Plastic settlement cracks are surface cracks, and may appear as wide (1-3 mm) and long cracks which may reach down to the reinforcement or even further [Kompen, 1994].

Drying shrinkage

Drying shrinkage occurs as hardened concrete gradually dries out when exposed to dry air. Drying shrinkage starts at the concrete surface and spreads further into the concrete over time. Shrinkage and hence stress gradients will therefore occur over the cross-section, leading to tensile stresses at the surface that may result in drying shrinkage cracks in the surface zone [Bjøntegaard, 2009].

Autogenous deformation (AD)

Autogenous deformation (AD) is the self-induced volume change of concrete. AD is a consequence of chemical shrinkage: the absolute volume of the hydration products is less than the total volume of the reactants (cement and water). A part of this inner volume loss also appears as an external shrinkage which is the AD [Lynam et al., 1934]. Volume changes caused by AD are found to be especially predominant in high performance concrete [Sellevold et al., 1982] [Lura, 2003], and also strongly influenced by the concrete curing temperature [Bjøntegaard, 1999] [Klausen, 2016]. AD works over the whole cross-section of a concrete, and volume changes by AD (in combination with thermal dilation) can cause severe through-cracking in the hardening phase if restrained.

Thermal dilation

Concrete hydration is an exothermic process that can cause a considerable temperature increase in the concrete (more than 40 °C). Such temperature increase will lead to a concrete expansion, followed by a contraction as the hydration process decreases and the concrete cools down. These temperature-induced volume changes (in combination with AD) can cause severe through-cracking of the concrete for restrained structural members, see for instance [Bjøntegaard, 1999] and [Klausen, 2016]. Concrete structures are also exposed to temperature variations in the operation phase, which also may induce cracking. Examples are seasonal and daily temperature variations in outdoor structures, as well as variations in working temperatures in industrial applications, e.g. LNG tanks and structures for thermal energy storage.

3.3 Cracks due to mechanical loading

Mechanical loading, both static and cyclic, can lead to crack development in concrete. Different types of cracks may develop when loading a concrete member, e.g. through-cracking (axial tensile stress), flexural cracking (flexural moment) and shear cracking (shear forces). However, cracking is not always alarming and also properly designed concrete structures may develop cracks during their lifetime: the concrete reinforcement is designed to carry stresses, but also to reduce crack widths and obtain a satisfying distribution of cracks [E-C107, 2006]. Unplanned cracking may occur if a structure is overloaded (exposed to loads larger than it was designed for). An overload may for instance occur if the design load is applied to the structure before the concrete has developed full strength.

3.4 Cracks due to environmental conditions and chemical reactions

A brief summary of various environmental conditions as well as chemical reactions that can cause cracking is given in the following.

Freeze-thaw deterioration

Freeze-thaw deterioration in concrete structures is very dependent on the moisture content in the pore system of the concrete. As water in moist concrete freezes, it produces pressure in the pores of the concrete. If this pressure exceeds the local tensile strength of the concrete, the pores will dilate and rupture. The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause expansion and cracking, scaling, and crumbling of the concrete. Both laboratory and field experience have shown that properly air-entrained concrete with sufficient strength obtain satisfying resistance to cycles of freezing and thawing. On the other side, pre-existing cracks in the concrete may amplify the freeze/thaw damage, e.g. [Wang et al., 1997] and [Jacobsen et al., 1998].

Alkali-silica reaction (ASR)

Alkali-silica reaction (ASR) can cause serious expansion and cracking in concrete. ASR is caused by a reaction between the hydroxyl ions in the alkaline cement pore solution in the concrete and reactive forms of silica in the aggregate. A gel is produced, which increases in volume by taking up water and so exerts an expansive pressure, resulting in fracture of the concrete. In unrestrained concrete (that is, without any reinforcement), ASR causes characteristic 'map cracking' [Lindgård, 2013].

Corrosion

Corrosion products are larger in volume than the total volume of the corrosion reactants, and this will cause an expansion and tensile stresses around the reinforcing steel. Once sufficient corrosion has occurred, splitting cracks develop. These cracks frequently propagate to the surface resulting in concrete spalling and loss of bond, e.g. [Neville, 1972] and [Beeby, 1978].

Sulphate attack

Sulphate attack is also a mechanism where the final reaction product occupies a larger volume than the original constituents. This type of deterioration is the result of two chemical reactions: the combination of sulphates with lime to form gypsum, and the combination of sulphates with hydrated calcium aluminates to form ettringite [Neville, 1972].

4 Impact of cracking on concrete tightness

4.1 General

As described in Section 3, there are many causes for crack development in concrete. These various crack mechanisms will further cause different types of damage to the concrete structure, e.g. internal micro-cracks, surface cracks, flexural cracks and through-cracks, see Figure 4.1. The impact of cracks on gas and liquid tightness of concrete is very dependent on which type of cracking the concrete is exposed to. For internal micro-cracks, surface cracks and flexural cracks, the gas or liquid still has to be transported through sound concrete, i.e. the concrete permeability is still porosity-dependent, Section 4.2. When through-cracking occurs, gases and liquids have free passage through the material, and the concrete permeability thus becomes crack-dependent, Section 4.3.

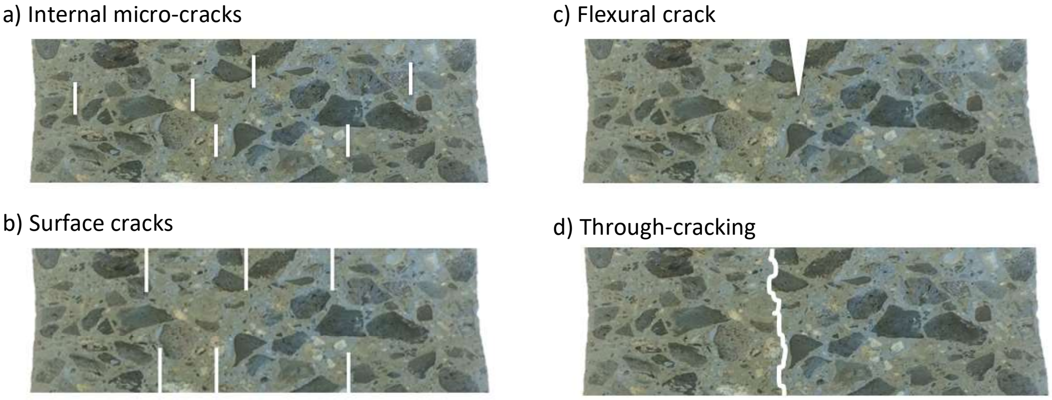


Figure 4.1; Different crack types in concrete

Tightness is particularly important for some concrete structures, e.g. LNG tanks and nuclear storage waste containers. For such structures, there are several ways to detect and alert if there is a leakage, for instance by pressure measurements, optical sensors and gas sensors. For other structures and situations, the definition of a leakage is not always clear. If the evaporation rate from a concrete surface to its surroundings is higher than the leakage rate, the leakage will not be visible and thus hard to detect. In an analogous situation, where the surrounding air has a higher RH and the evaporation rate from the surface is correspondingly lower, the leakage may become visible in the form of wet spots. A question of what is the "acceptable amount of leakage" may also arise, which can cause differences and conflicts between contractors and owners.

4.2 Surface-, flexural- and microcracks

For concrete members with surface cracks, microcracks and/or flexural cracks, the concrete permeability is still porosity-dependent. However, such cracks will affect the concrete permeability as they interconnect flow paths and thus generally increase the permeability. This permeability increase will further allow more water or aggressive chemical ions to penetrate into the concrete, causing even more deterioration. This negative chain reaction may eventually lead to destructive deterioration of the concrete structure [Wang et al., 1997], see Figure 4.2.

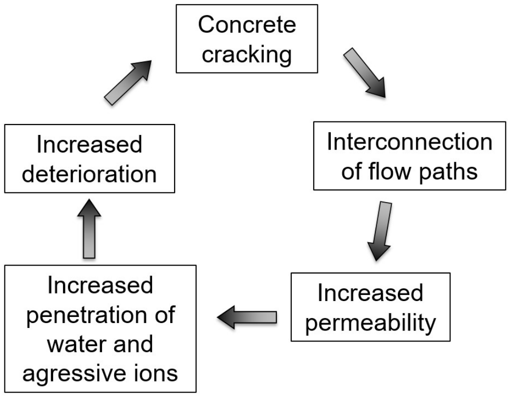


Figure 4.2; Cracking of concrete: negative chain reaction [Wang et al., 1997]

[Picandet et al., 2001] investigated the effect of microcracking on gas permeability. They exposed concrete samples to a compressive load of between 60% and 90% of the ultimate strength, and afterwards he performed permeability tests on the samples, using nitrogen gas. The hypothesis was that the gas flow through a damaged sample could be divided into two flows: 1) gas flow through an undamaged sample and 2) gas flow through the internal crack network. The test results showed that compared to undamaged samples, a uniaxial compressive load at 90% of the ultimate strength would increase the axial permeability (after unloading) by about one order of magnitude due to microcracking. Grasley, who studied water permeability of concrete pastes and concrete, made similar observations [Grasley et al., 2007].

[Zhu, 1997] investigated the effect of micro- and flexural cracks on concrete permeability. His main findings and conclusions are listed in the following: 1) microcracks in the compression zone have no influence on the total concrete permeability, 2) generally, concrete with microcracks will behave as uncracked concrete for liquids with high viscosities (a clear definition of the term "high viscosities" was however not defined), 3) microcracks will affect the concrete permeability only when subjected to a pressure (above 1.4 meter hydraulic head) and 4) transport in concrete has a pronounced anisotropic behaviour, where the transport velocity in the concreting direction is slower than normal to it. Zhu also concluded that transport efficiency through flexural cracks would decrease due to adsorption in the crack propagation zone.

4.3 Through-cracking

As previously described, through-cracking is the governing crack type when it comes to the permeability of concrete. The permeability is in this case no longer porosity-dependent but rather crack-dependent. The flow of a liquid or fluid through a crack depends on the crack width throughout the crack, the crack tortuosity (how the crack twists and bends through the concrete), the crack surface roughness and the crack length.

The flow of liquids through a concrete crack can be modelled based on fluid mechanics and the theory of compressible flow between two smooth parallel plates, Equation 4.1.

$$q_r = \xi \cdot w^3 \cdot \frac{\Delta p \cdot l}{12 \cdot \eta \cdot d}$$ *Equation 4.1*

where q_r is the flow rate, ξ is the flow reduction factor (ξ = 1.0 for a laminar flow between smooth boundaries), w is the crack width (effective crack width throughout the crack), Δp is the pressure difference, l is the crack length, η is the dynamic viscosity and d is the section thickness

The flow reduction factor ξ in Equation 4.1 describes the surface roughness of the crack. A reduction factor of 1.0 (100%) represents a laminar flow between smooth boundaries. Smooth boundaries are however not the case for a typical concrete crack, see Figure 4.3. If the crack roughness increases, the flow slows down and the flow rate is reduced, i.e. the flow reduction factor (and hence the flow rate) decreases with increasing roughness.

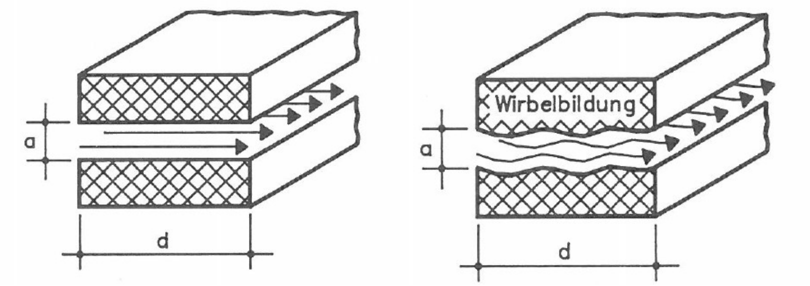


Figure 4.3; Flow between: smooth surfaces (left) rough surfaces (right) [Edvardsen, 1996]

Through testing, the reduction factor has been seen to show a considerable variety. It is dependent on a number of factors, for instance the dimensions of the test samples from which the factor was determined, [Edvardsen, 1996] and [Bick et al., 1997]. The reduction factor can be modelled by different approaches. In NS 3473, and also in the new Eurocode 2 draft, the reduction factor is assumed to be a constant of 0.125 (i.e. 12.5%). On the other hand, [Ripphausen, 1990] proposed a model where the reduction factor was dependent on both crack width and section thickness, Equation 4.2.

$$\xi = \frac{1}{1 + 0.0002 \cdot (\frac{d}{w})^{1.5}}$$ *Equation 4.2*

where ξ is the flow reduction factor, d is the cross-section thickness and w is the crack width

A comparison between the constant reduction factor of 12.5% and the corresponding reduction factor found by Equation 4.2 [Ripphausen, 1990] is given in Figure 4.4 (where the continuous line is the 12.5% reduction factor, while the dots represent the estimations by Ripphausen). The figure shows the estimated reduction factor for cross-sections with a thickness of 500, 1000 and 1500 mm. The reduction factors found from the two above-described methods differ considerably.

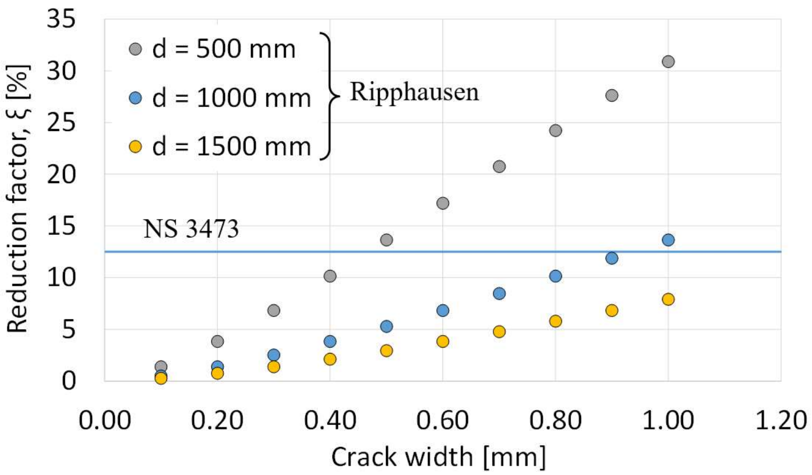


Figure 4.4; Estimations of the flow reduction factor, NS 3473 (continuous line) versus [Ripphausen, 1990] (dottet lines)

The concrete leakage rate is generally calculated based on the visible surface crack width. This approach will in most cases lead to an overestimation of the leakage, as the effective crack width throughout the section thickness will be smaller than the visible surface crack width. The crack width of a concrete through-crack will vary over both the crack length and also throughout the section thickness as it is affected by several parameters: e.g. reinforcement design and ratio, crack surface roughness, concrete inhomogeneity and self-healing. [Yannopoulos, 1989] performed tests on long reinforced tension members to determine the relation between the crack width at the reinforcement steel surface (ø16) and the concrete surface (30 mm cover). He found that the ratio between the mean crack width at the surface and the mean crack width at the reinforcement steel was decreasing with increasing load, approaching a value of 0.45 for higher steel stresses (beyond 150 MPa). [Bick et al., 1997] incorporated the effect of crack width variations throughout the section thickness into the flow reduction factor. They found that for unreinforced concrete, the mean value of the flow reduction factor would be approximately 0.085 (8.5%), while the corresponding factor for reinforced concrete would be approximately 0.040 (4.0%). Permeability studies performed by [Hubert et al., 2015] concluded that increasing the reinforcement ratio would reduce the concrete permeability considerably. This was explained by the fact that an increase in reinforcement would cause more and finer (thinner) cracks, reducing the effective crack width and hence the permeability.

Consequently, flow rate calculations according to Equation 4.1 must be considered as simplified and quite rough estimations due to the uncertainties connected to 1) the crack width throughout the section thickness (influenced by e.g. reinforcement design and –ratio, concrete inhomogeneity and self-healing) 2) crack surface roughness (flow reduction factor) and 3) the actual cracking pattern in the given concrete structure.

Several permeability studies of cracked concrete can be found in the literature, however, most of these studies were performed on unreinforced concrete specimens. Each such study can be divided into two main parts: 1) pre-cracking of the concrete specimens and 2) permeability studies on the pre-cracked samples. In 1997, Wang evaluated the permeability of cracked concrete by water permeability tests [Wang et al., 1997]. From his tests, he found the following relation between crack width w and permeability: For $w < 0.05$ mm, the permeability would only experience a limited increase, for 0.05 mm $< w <$ 0.2 mm, the permeability would increase rapidly, and for $w > 0.2$ mm, the permeability would increase steadily, see Figure 4.5 (left). Aldea performed corresponding permeability tests on cracked concrete in 1999 [Aldea et al., 1999], and he obtained very similar results as Wang, see Figure 4.5 (right).

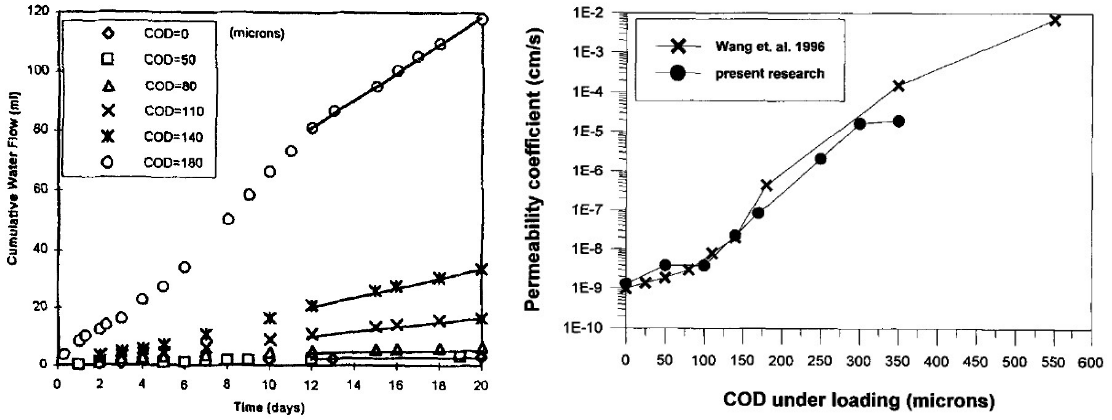
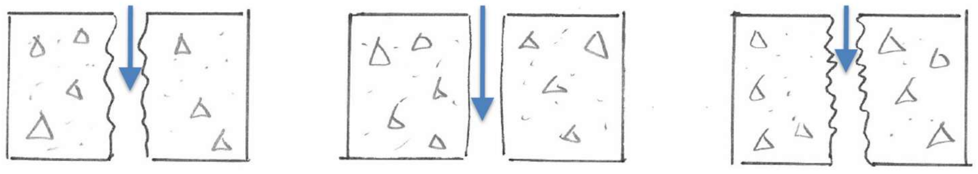


Figure 4.5; Water flow versus time for various crack widths [Wang et al., 1997] (left) and permeability coefficient versus crack width [Aldea et al., 1999] (right)

In 2009, Picandet performed both gas (nitrogen) and water permeability tests on cracked concrete [Picandet et al., 2009]. The tests were performed on ordinary concrete (OC), high-performance concrete (HPC) and high-performance fibre-reinforced concrete (HPFRC). Picandet found that for the tested concretes, the gas and water permeability[1] (m^2) were quite similar. He further reported that for HPC, the crack surfaces were smoother than for OC. Consequently, the reduction factor (i.e. the flow rate) was higher for HPC when compared to OC, Figure 4.6. When adding fibre-reinforcement to the HPC, both the tortuosity and the crack roughness were found to increase, causing a reduction in the flow rate. In addition, fibre-reinforcement causes a higher number of narrower cracks, which is beneficial for permeability reduction as the flow rate is proportional to the crack width cubed. Consequently, fibre-reinforced concrete appears to be a more effective structural material than plain concrete in terms of permeability, e.g. [Picandet et al., 2009] and [Hubert et al., 2015].



Ordinary concrete (OC)

High-performance concrete (HPC)

High-performance fibre-reinforced concrete (HPFRC)

Figure 4.6; The effect of concrete mix design on crack surface roughness and flow rate

4.4 Self-healing

Self-healing (also denoted autogenous healing) is the ability of a concrete to repair itself: water flow through cracks gradually decrease over time, and in some extreme cases, the cracks seal completely. According to the literature, the main reasons for self-healing have been claimed to be: 1) the formation of calcite (calsium carbonate crystals), 2) unhydrated cement reacts with water 3) blocking of flow path by water impurities and 4) blocking of flow path by concrete particles. Several studies indicate however that formation of calcite

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[1] Permeability calculated by the Hagen-Poiseuille relationship, e.g. $k_{water} = \frac{q_r \cdot \eta \cdot L}{A \cdot \Delta p}$, [Picandet et al., 2009]

(calsium carbonate crystals) in the cracks is almost the sole reason for autogenous healing, e.g. [Edvardsen, 1996]. Edvardsen concluded that the crystal growth rate was dependent on crack width and water pressure, while concrete composition and type of water were found to have no influence on the autogenous healing rate. The main part of the self-healing occurs early, within the first 3-5 days of water pressure. Both [Jacobsen et al., 1998] and [Edvardsen, 1999] state that the critical upper crack width for complete self-healing is about 0.2 mm for ordinary concrete.

The roughness of a crack may increase the contact surface between water and cement matrix, and thus accelerate the self-healing kinetic. As fibre-content increases the crack roughness, the presence of fibre will also increase the concrete self-healing ability. In addition, adding fibre reinforcement to concrete will cause multiple cracking. Instead of one wide crack, several small cracks will occur. Small cracks will heal more easily, thus increasing the concretes self-healing capacity.

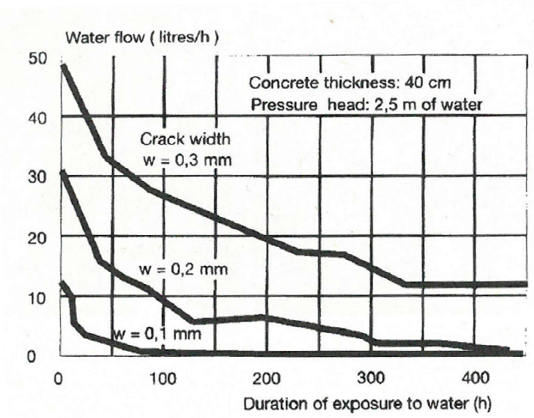

Figure 4.7; Self-healing: water flow versus time for various crack widths [Edvardsen, 1999]

Reinhardt performed permeability tests on reinforced pre-cracked samples at different temperatures levels: 20, 50 and 80 °C [Reinhardt et al., 2003]. He found that smaller cracks healed faster than greater ones, and that a higher temperature would favour a faster healing process. His experiments showed that for HPC subjected to a 1.0 MPa hydraulic gradient, all cracks with an average surface crack width below 0.1 mm would close due to the self-healing phenomena.

5 Code requirements regarding tightness

Below follows requirements and specifications from a small selection of codes and handbooks regarding concrete gas and liquid tightness.

Model Code 2010

fib Model Code 2010 paragraph 7.6.4 differentiates between limited leakage and minimal leakage. If the leakage should be minimal, no continuous cracks are allowed and a compression zone of at least 50 mm should be available [CEB-FIP, 2010]. The model code also states that when it comes to fluid-tightness, different crack width limits may apply, and hence special recommendations should be used.

Eurocode 2

The Eurocode 2 requirements [NS-EN 1992-1-1:2004] regarding concrete tightness are given in Eurocode 2 - Part 3: Liquid retaining and containment structures [NS-EN 1992-3:2006, 2006]. The standard operates with four different tightness classes, where class 2 and class 3 are defined as *"leakage to be minimal"* and *"no leakage is permitted"*, respectively. To provide adequate assurance that cracks do not pass through the full width of a section for structures of these two classes, the compression zone is specified to be at least the lesser of 50 mm or $0.2 \cdot h$ where h is the element thickness. If a section is subjected to alternate loadings, cracks are considered to pass through the full thickness of the concrete section unless it can be shown that at least *"the lesser of 50 mm or 0.2·h"* of the section thickness always will remain in compression. The standard also requires that *"special care should be taken where members are subject to tensile stresses due to the restraint of shrinkage or thermal movements"* [NS-EN 1992-3:2006, 2006], without further specifications on how to fulfil this requirement.

Eurocode 2 recommends a minimum cross-section thickness of 200 mm for structures in tightness class 3 (no leakage is permitted), the Norwegian National annex NA.9.11.1 [NS-EN 1992-3:2006, 2006].

NS 3473

NS 3473 is actually withdrawn and superseded by Eurocode 2, but the standard is still used for offshore concrete installations in Norway as Eurocode 2 is defined not to cover such structures. NS 3473 specifies a number of considerations that should be taken into account when it comes to tightness towards gas and liquid substances; e.g. mix design and permeability, geometrical design and casting joints. The standard further states that to prevent a deteriorating flow of gases and liquids, one or more of the following requirements should be fulfilled: 1) minimum sectional thickness 2) maximum tensile stress 3) minimum compression zone and 4) maximum crack width limit [NS 3473:2003, 2003].

Requirements regarding gas- and liquid tightness are further elaborated in NS 3473 Appendix A. The standard differentiates between a) normal and b) special requirements for tightness. For structures with special requirements for tightness, the section thickness should be at least 200 mm, the compression zone should be at least the lesser of 0.25 h and 100 mm and the axial stress resultant should be compressive. The latter point can however be disregarded if the minimum compression zone is increased to 200 mm. In some cases, the tightness criteria is connected to a flow rate limitation. NS 3473 provides a calculation method for rough estimations of the flow rate for such cases, see Section 4.3 for further details.

In addition to the above described specifications, gas- and liquid tight structures have extended minimum reinforcement requirements in NS 3473; the minimum reinforcement should be twice the amount obtained from the equations given in the standard, and the reinforcement centre distance should not be more than 300 mm [NS 3473:2003, 2003].

JSCE Guidelines for Concrete: "Standard Specifications for Concrete Structures-2007, Design"

The JSCE (Japan Society of Civil Engineers) standard differentiates both between high and normal level of water tightness, as well as whether the structural member in question is subjected to axial tension or flexural moment, paragraph 10.6 [JSCE, 2010]. For members with the highest level of required water-tightness, and where axial tension is the dominant force acting on the cross-section, no cracks are allowed. In this case, the standard additionally states; *"Concrete stresses due to stress resultant should be in compression at whole sectional area. Minimum compressive stress should be greater than 0.5 N/mm^2. In cases when detailed analysis is carried out the value may be determined differently"* [JSCE, 2010]. For structural members with the highest level of water tightness subjected to flexural moment, the standard allows for a maximum crack width of 0.1 mm. The standard also specifies that for members with the highest level of required water-tightness, the permissible crack width for alternate loading should be determined in a manner similar to that under axial tension, i.e. no cracks are allowed.

Comments

Both ***fib*** Model Code and Eurocode 2 specify no continuous cracks through the section and a minimum compression zone for gas- and liquid tight structures. Eurocode 2 elaborates this requirement, and states that for alternate loadings (e.g. two-sided flexural cracks), it must be shown that at least the lesser of 50 mm or 0.2·*h* of the section thickness always will remain in compression. In ***fib*** Model Code this is not as clear and it could be argued that two-sided flexural cracks do not fulfil the requirement: *"no continuous cracks are allowed AND a compression zone of at least 50 mm should be available"*, as these cracks can overlap and thus by definition go through the whole cross-section.

Both NS 3473 and JSCE provide rough estimations of the flow rate, and thus methods to verify the water tightness by satisfying a flow rate limitation. ***fib*** Model Code 2010 and Eurocode 2 do not include such estimations, however, a leakage rate estimation very similar to the one in NS 3473 is included in the draft for the new Eurocode 2, Annex H.

It should also be noted that while NS 3473 specifies increased minimum reinforcement for gas- and liquid tight structures, this was not found in the other codes. In addition, Eurocode 2 states that *"special care should be taken where members are subject to tensile stresses due to the restraint of shrinkage or thermal movements"*, while such comments could not be seen in the other codes.

The above listed standards also provide methods for crack width calculations. These methods differ between the standards, but they are neither described nor discussed in the current memo.

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