

FRACTURE MECHANICS TO ILLUSTRATE CRACKING OF ALKALI-SENSITIVE GRAINS

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Abstract: Alkali-silica reaction (ASR) is one of the most severe attacks on concrete. There are several causes, one of which is the cracking of grains of slow/late aggregates in alkaline environment. Cracking can start in the interior of grains when there are defects or when there are minerals inside which dissolve due to the action of pore solution in the concrete. A silica gel can develop and swell which causes interior pressure in the grain. Researchers have postulated that the stresses lead to failure of the grain as soon as the tensile strength of the aggregate is reached. The new approach states, owing to the brittle nature of the mineral aggregates, that the critical stress intensity is the limiting factor for failure and not the tensile strength [1]. So, fracture mechanics principles will be employed in order to illustrate cracking of grains as a reason for ASR.

A test series has been carried out in order to prove the statement. Mechanical properties of various slow/late aggregates have been determined after exposure to alkaline environment for more than one year. It appears that the critical stress intensity factor decays such that cracking is feasible due to ASR.

1 INTRODUCTION

There are numerous publications on alkali-silica reaction (ASR) of concrete, see for instance the volumes of ICAAR [2]. The focus of this contribution to FraMCoS-8 lies on the initiation of cracking of slow/late aggregates. Slow/late aggregates react only after several years of exposure. While fast reacting aggregates have been investigated extensively and while the degradation mechanisms seem to be well understood the knowledge on slow/late aggregates is emerging recently after several failure cases have been discovered [3]. One theory that explains ASR states that the interior gel pressure in the aggregate grain

causes rupture as soon as the tensile strength has been reached [4, 5, 6]. However, here it is argued that cracks develop due to a dissolution process and that a critical crack length must exist before the grain can be split. The second argument is that the fracture toughness is the limiting criterion since mineral aggregates are rather brittle. This leads to the application of fracture mechanics principles to ASR. It should be noted that fracture mechanics has also been tried on ASR [7], however, there it was applied to concrete while this contribution uses fracture mechanics on the meso-level of the grain.

2 FRACTURE MECHANICS APPROACH

An aggregate grain is modeled as a sphere. In the center of the sphere, there is a penny-shaped crack with radius a . For a finite radius R of the sphere the stress intensity factor on the crack tip reads according to linear elastic

$$K_I = \frac{2}{\pi} \cdot p_0 \cdot \sqrt{\pi \cdot a} \cdot Y\left(\frac{a}{R}\right) \quad (1)$$

$$Y(a/R) = \frac{K_I}{K_I^\infty} = 1 + 1.5433 \cdot \left(\frac{a}{R}\right)^3 - 2.3870 \cdot \left(\frac{a}{R}\right)^5 + 2.3818 \cdot \left(\frac{a}{R}\right)^6 + 3.2711 \cdot \left(\frac{a}{R}\right)^7 - 6.4470 \cdot \left(\frac{a}{R}\right)^8 - 0.2107 \cdot \left(\frac{a}{R}\right)^9 + 0 \cdot \left(\frac{a}{R}\right)^{10} \quad (2)$$

Table 1: Numerical values of $Y(a/R)$ [8]

a/R	0	0.2	0.4	0.5	0.6	0.7	0.8	0.9
$Y(a/R)$	1	1.01176	1.08516	1.15549	1.27016	1.32240	1.47210	1.81071

3 INVESTIGATED AGGREGATES

The aggregates were greywacke (GW) and quartz-porphyrityte (QP) from a quarry in the middle of Germany, quartz-porphyrityte (QP1-OR), quartzite (QZ-OR), and another quartz-porphyrityte (QP2-OR) from sand pits of the upper Rhine valley as well as Diabase (DB) from North Bavaria. The alkali sensitivity of the rocks was assessed with the accelerated mortar test according to [9]. Additionally the alkali sensitivity of the rocks was assessed

fracture mechanics [8]. Eq. (2) is valid for $a/R \leq 0.60$. For greater values of a/R , numerical methods have to be applied. Table 1 gives some numbers [8]. Crack extension starts when the critical stress intensity factor K_{Ic} of the aggregate is reached. To determine K_{Ic} tests have been carried out.

within a period of 560 days with the fog chamber test at 40°C used in Germany, similar to the internationally usual concrete prism tests (RILEM AAR-3). With the mentioned tests, greywacke (GW), quartz-porphyrityte (QP), quartzite (QZ-OR), and the quartz-porphyrityte (QP2-OR) were found to be ASR sensitive while quartz-porphyrityte (QP1-OR) and diabase (DB) turned out to be insensitive.

Table 2: Major mineral components of the rocks used

Rock type	Mineral composition [%]						
	quartz	feldspar	plagioclase	chlorite	carbonate	mica	kaolinite
Greywacke (GW)	29.0	6.8	32.9	14.1	3.2	10.8	3.2
	quartz	feldspar	plagioclase	chlorite	carbonate	mica	hematite
Quartz-porphyrityte (QP)	22.0	33.7	34.5	2.6	1.8	4.6	0.6
	quartz	feldspar	plagioclase	chlorite	carbonate	mica	hematite
Quartz-porphyrityte (QP1-OR)	17.4	22.7	41.9	9.8	1.1	6.7	0.3
	quartz	mica					
Quartzite (QZ-OR)	96.4	3.6					
	quartz	feldspar	plagioclase	carbonate	hematite		
Quartz porphyrityte (QP2-OR)	37.9	0.9	58.2	1.9	1.1		
	quartz	plagioclase	carbonate	chlorite	mica	hematite	
Diabase (DB)	3.0	40.3	19.9	28.2	8.0	0.5	

The mineral composition has been determined by X-ray diffraction. The results are given in Table 2. The structure of greywacke is very dense. However, there are veins of pyrite and calcite visible in the interior. The accessible pore volume amounted to 0.41 %. Quartz-porphyrite belongs to the group of rhyolites. They show relatively large feldspar crystals and veins of hematite and chlorite. The accessible pore volume amounted to 0.57 %. The quartzite consists mainly of quartz and contains some percent of mica. It shows rather large crystals. The accessible pore volume was 1.43 %. Diabase is a volcanic rock which consists for a great part of plagioclase with clefts healed with carbonate. The accessible pore volume amounted to 0.82 %. All rocks are very dense with low accessible porosity. However, there are inclusions which may be prone to deterioration.

4 TESTING METHODS

4.1 Determination of fracture toughness

Fracture toughness has been measured as critical stress intensity factor on circular rods with a chevron notch. The method follows the proposal of the International Society for Rock Mechanics (ISRM) [10] applying the so-called CENRBB specimens (Chevron Edge Notch Round Bar Bending).

A central force F is applied while the crack mouth opening displacement (CMOD) is used as the control quantity. The constant crack mouth opening displacement rate was 0.13 $\mu\text{m/s}$. The length of the specimen is denoted L , the diameter D , the chevron angle θ , the depth of the notch tip is at a_0 , and the width of the notch is denoted t .

The specimens were drilled from large size blocks taken from the quarry or from large rounded rocks from sand pits. The critical stress intensity factor can be calculated with Eq. (3)

$$K_{Ic} = \frac{A_{\min} \cdot F_{\max}}{D^{1.5}} \quad (3)$$

with F_{\max} the maximum force, D the

diameter of the specimen, and A_{\min} a geometrical factor which follows from Eq. (4)

$$A_{\min} = \left[1.835 + 7.15 \cdot \frac{a_0}{D} + 9.85 \cdot \left(\frac{a_0}{D} \right)^2 \right] \cdot \frac{S}{D} \quad (4)$$

with a_0 the notch-tip depth and S the span of the specimen. This calculation is valid for linear-elastic material. Since rock is not ideally elastic one has to consider a correction factor which can be calculated in a rather elaborate procedure.

The reader is referred to reference [10] for the detailed use of the method. It should be noted that the corrected critical stress intensity factor K_{Ic}^c is always larger by 5 to 40 % than the critical stress intensity factor of linear-elastic material K_{Ic} . The increase depends on the type of rock which will be shown later.

The CENRBB test allows also to calculate the elastic modulus by using Eq. (5) which reads

$$E = g_0 \cdot \frac{dF}{d(\text{CMOD})} \cdot \frac{1}{D} \quad (5)$$

with g_0 a geometrical factor and $dF/d(\text{CMOD})$ the slope of the force-crack mouth opening curve. g_0 follows from

$$g_0 = 20.8 - 19.4 \cdot \frac{a_0}{D} + 142.3 \cdot \left(\frac{a_0}{D} \right)^2 \quad (6)$$

The parameters E and K_{Ic}^c will be used for further calculations.

5 DEGRADATION OF ROCKS DURING EXPOSURE

To simulate the condition of a grain in concrete in respect of the concentration of OH^- rock bars were stored in synthetic potassium hydroxide solution at the maximum concentration of OH^- (1000 mmol/l). The pH value of the synthetic hydroxide solution was 14.0. The temperature of the solution was kept at 40°C. This is the temperature level of the fog chamber test used in Germany for testing alkali-sensitive aggregates in concrete which follows the RILEM test AAR-3 [11]. The bending tests with CENBRR samples were

carried out after 0 (virgin state), 35, 70, 140, 280, and 560 days of storage in the potassium hydroxide solution.

The degradation of slow/late aggregates is regarded as a two-step-process. The first step concerns the dissolution of the pyrite and calcite veins in the grain for which a high alkalinity in form of high pH value is necessary. The dissolution creates open cracks in the aggregates. The second step concerns the formation of a alkali-silica gel which precipitates in the cracks. The gel swells and forces the crack to open as soon as the pressure is high enough and the critical stress intensity factor is reached. Both processes occur simultaneously and cannot be separated at the time being [12].

6 EFFECT OF EXPOSURE ON FRACTURE TOUGHNESS AND MODULUS OF ELASTICITY

When the sensitive rock is exposed to an alkaline solution the mechanical performance declines. As an example, this can be observed from Fig. 1 where the force vs. crack mouth opening displacement curves for quartz-porphyrine at the beginning and after 35, 70, 140, 280, and 560 days of exposure to alkaline solution are plotted.

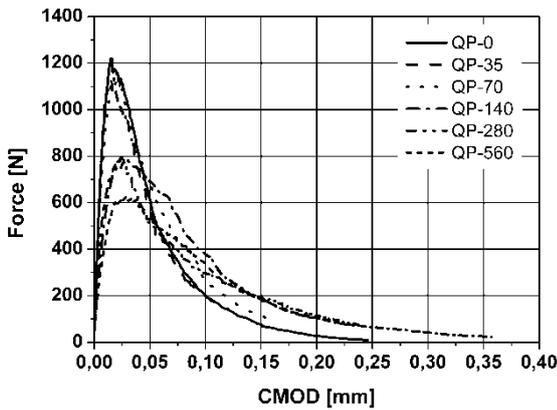


Figure 1: Force vs. crack mouth opening displacement curves for quartz-porphyrine at the beginning and after 35, 70, 140, 280, and 560 days of exposure to alkaline solution

The plot shows that the maximum force decreases and that the softening branch gets flatter with increasing exposure time. Since the maximum force determines the critical stress

intensity factor proportionally it will decline accordingly (see Eq. 3). The inclination of the linear part of the initial loading branch decreases as well with increasing exposure time. Since this determines the elastic modulus (see Eq. 5) it will decrease as well. The softening branch is responsible for the difference between K_{Ic} and K_{Ic}^c .

Similar curves as Fig. 1 have been evaluated with Eq. (3) for the determination of the critical stress intensity factor K_{Ic} after the intervals of exposure as stated above. The loading cycles have been also evaluated acc. to [10] which resulted in the adjusted critical stress intensity factor K_{Ic}^c which is always greater than K_{Ic} . Young's modulus has been calculated using Eq. (5).

As an example, quartz-porphyrine (QP) shows the development in Fig. 2. The values of all three quantities are almost constant during the first 70 days. After that time, a drop occurs. The elastic modulus drops from 75 to 25 GPa whereas the critical stress intensity factor K_{Ic} falls from 2.3 to 1.1 $MN/m^{1.5}$ and K_{Ic}^c goes down from 2.9 to 1.5 $MN/m^{1.5}$.

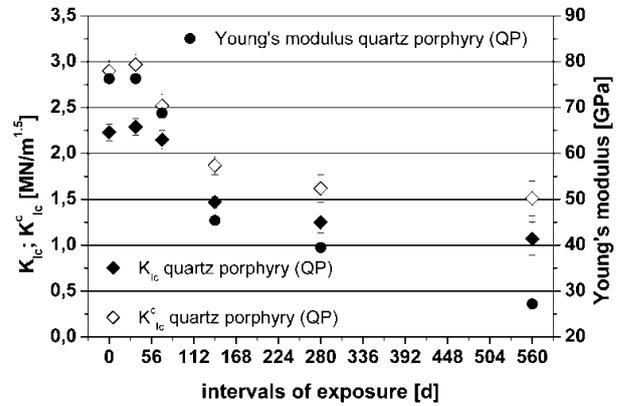


Figure 2: Critical stress intensity factors and Young's modulus of quartz-porphyrine (QP) as function of exposure time

The values of the other rocks are given in Table 3. The three quantities of quartz-porphyrine (QP1-OR) show a small increase after 280 days. Another sample of quartz-porphyrine (QP2-OR) show a different behavior. The elastic modulus and K_{Ic} of greywacke are almost constant during the first 140 days of exposure. After that period of time, the values decrease. The elastic modulus

decreases from about 75 GPa to 40 GPa while the K_{Ic} value decreases from 2.5 to 1.7 MN/m^{1.5}. The adjusted K_{Ic}^c follows an almost

linear decrease from 3.3 to 2.1 MN/m^{1.5} during the 560 days exposure time.

Table 3: Critical stress intensity factors K_{Ic} and K_{Ic}^c and modulus of elasticity as influenced by exposure time

	days	GW	QP	QP1-OR	QZ-OR	QPZ-OR	DB
K_{Ic} , [MN m ^{-1.5}]	0	2.42	2.23	1.96	1.19	1.74	2.17
	140	2.76	1.47	2.46	0.77	0.58	2.70
	280	2.24	1.25	2.62	0.60	0.21	2.04
	560	1.81	1.07	-	-	-	1.54
K_{Ic}^c , [MN m ^{-1.5}]	0	3.25	2.90	2.37	1.51	2.23	2.44
	140	2.80	1.87	3.02	1.09	0.81	3.15
	280	2.60	1.62	2.55	0.88	0.50	2.35
	560	2.07	1.51	-	-	-	2.03
E , [GPa]	0	76.0	76.3	59.5	26.4	49.1	75.8
	140	79.1	45.4	71.5	5.9	8.9	99.2
	280	69.8	39.5	65.5	4.2	3.3	84.9
	560	38.1	27.2	-	-	-	79.2

A decay of the elastic modulus and the critical stress intensity factors K_{Ic} and K_{Ic}^c can be observed in contrast to the results of QP1-OR. The results document that the variability of properties of the rocks of the upper Rhine valley is very large.

The elastic modulus of quartzite (QZ-OR) starts at 26 GPa and drops to 5 GPa while the K_{Ic} values decrease from 1.2 to 0.6 MN/m^{1.5} and the K_{Ic}^c values drop from 1.5 to 0.9 MN/m^{1.5}. Although the diabase (DB) is known to be not sensitive to alkali-silica reaction it shows some slight influence of the exposure on the critical stress intensity factors. Summarizing the experimental results of the exposure experiments it can be noted that most of the tested rocks deteriorate as function of time.

7 CRACKING DUE TO INTERNAL GEL PRESSURE

The mechanism of aggregate grain splitting is assumed to be the following. Alkali ions from the concrete pore solution diffuse into the grain. They react in the interior of the grain with silicon, calcium, and aluminum ions and form an alkali-silica gel. This can happen in existing cracks or flaws or in veins which dissolve due to the pore solution. The gel expands due to the absorption of water and exerts a pressure on the flaw boundaries inside

the grain. Whether this situation will lead to a splitting failure of the grain depends on the gel pressure on the one hand and on the crack length and the critical stress intensity factor of the rock on the other hand. As soon as the critical stress intensity factor is reached the grain will split.

In order to describe the interdependence of crack length, Eq. (1) together with Table 1 has been numerically evaluated for several grain sizes. The relation reads

$$K_I(a; R; p_c) = \frac{2}{\pi} \cdot p_c \cdot \sqrt{\pi \cdot a} \cdot Y\left(\frac{a}{R}\right) \quad (7)$$

with a = crack length, R = radius of the grain which is idealized as sphere, p_c = maximum gel pressure. The gel pressure has not been investigated in this study but is taken from the literature. The literature distinguishes between those investigations of gel pressures due to ASR which were gained on mortar specimens [13-15] and those which were received from synthetic alkali gels and alkali-silica solutions [16, 17]. For our investigations, only those results are relevant which were obtained from alkali gels and alkali-silica solutions. The synthetic gels of [17] reached pressures of 11 MPa. Mansfeld [16] has measured gel pressures in synthetically produced alkali gels and found values between 7.5 and 16 MPa. A maximum

pressure of 20 MPa is reported in [18, 19]. Additionally, a pressure of 30 MPa has been taken as upper limit. The deliberations in [15] which are based on a two-phase model with complete restraint of the expanding gel lead to pressures of 361 MPa which seems unrealistic in a real concrete. So, this pressure value is not considered further.

The results of the evaluation of Eq. (7) is plotted as function of a/R in Fig. 3 for a grain size of 16 mm.

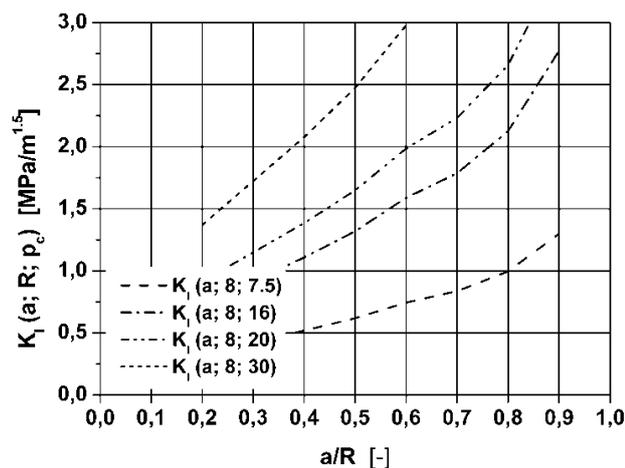


Figure 3: Stress intensity factor as function of a/R for 16 mm grain size and gel pressures of 7.5, 16, 20, and 30 MPa

In order to know whether splitting occurs one has to determine the intersect of a horizontal line at the relevant position of $K_I = K_{Ic}^c$. For instance, greywacke shows a K_{Ic}^c of $2.07 \text{ MN/m}^{1.5}$ at 560 days. This means that splitting of a 16 mm grain would occur at a gel pressure of 16 MPa and a crack length of $0.75 \times 16 = 12 \text{ mm}$. The theoretical prediction of crack length vs. gel pressure shall be discussed in the following, especially the question seems to be relevant whether the crack lengths which are necessary for crack propagation have been observed. Greywacke and quartz-porphyrite will be considered because these two rocks show large cracks and they are most suited for the application of fracture mechanics principles.

If one assumes for greywacke a gel pressure of 16 to 30 MPa and a grain of 16 mm diameter and considers the appropriate critical stress intensity factor of $2.60 \text{ MN/m}^{1.5}$ the

penny-shaped crack should have a diameter of 14.0 to 8.4 mm. Such large defects have been observed due to the dissolution of pyrite veins. Also calcite veins and earlier cracks which are healed by calcite are such defects. Also the texture of layers in a grain represents a large defect. This would mean that not only crushed greywacke may be prone to ASR but also rounded greywacke grains as has been reported by Stark et al. [20].

The critical stress intensity factor for quartz-porphyrite was assumed to $1.72 \text{ MN/m}^{1.5}$. This would mean that a grain of 16 mm diameter would need crack length of 10.7 and 4.8 mm depending on the gel pressure of 16 and 30 MPa. The defects of this size are veins which were originally healed by chlorite and hematite. These veins are dissolved in alkaline environment and form the necessary starter cracks. Besides these defects there are micro clefts which originated from the cooling process of the molten rock.

Whether cracking will occur depends on the alkali hydroxides in the pore solution, which react with the reactive SiO_2 and the availability of calcium because these components are necessary for the formation of alkali-silica gel. When the gel forms and precipitates in the cracks the gel expands due to absorption of water. The dissolution of minerals and the formation of a gel depend on a high pH. When all prerequisites are met cracking of the grain will occur.

It can be concluded that the fracture mechanics approach is very valuable to explain the cracking of slow/late aggregates in alkaline environment. Further research will address the correlation between aggregate cracking and ASR of concrete.

8 CONCLUSIONS

Theoretical and experimental investigations have brought up the following results:

- a) Linear elastic fracture mechanics principles have been applied to aggregate grains, i.e. the critical stress intensity factor is regarded as decisive parameter which governs cracking of slow/late aggregates.

- b) The critical stress intensity factor of rocks decreases with the time of exposure in alkaline environment.
- c) Greywacke and quartz-porphyrite which were taken from a quarry showed strong degradation in alkaline solution.
- d) Quartz-porphyrite from sand pits of the upper Rhine valley behaved very differently. One rock degraded considerably while another did not. The differences of deposited rocks can be very large.
- e) A quartzite rock from the upper Rhine valley degraded also.
- f) The degradation is due to the dissolution of chlorite, hematite, pyrite, and calcite filled veins.
- g) The emptied veins form starter cracks.
- h) With sufficient supply of soluble silica and calcium a alkali-silica gel forms and precipitates in the cracks. The gel expands due to absorption of water and generates a splitting pressure.
- i) A correlation between the cracking of rocks, the size of the aggregate grains, and the gel pressure was established.
- j) Further research is necessary to establish a correlation between the fracture of aggregate grains and ASR of concrete.

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