# FRACTURE CHARACTERISTICS OF AGGREGATES SUBMITTED TO ALKALI SILICA REACTIONS

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**ABSTRACT**

The effect of alkali silica reactions (ASR) on the fracture characteristics of some alpine rocks has been investigated. A series of specimen of different sizes had been cored from three alpine rocks and immersed into an alkaline solution up to six months. All the specimens were thoroughly characterized prior to study and then immersed into alkaline solutions. The samples obtained at different immersion time and with different sizes are characterized by direct tensile test and displacement-controlled four-point bend test. The three studied rocks fail in a brittle way accompanied by large tearing - as observed by SEM on fracture surfaces – and with a strong anisotropic effect for one of the rocks studied. Microscopic observations show that (micro) phase separation had occurred during immersion and silica gel has been formed into the reactive aggregates. The results show that the alkaline immersion reduces the specific fracture energy compared to the non-immersed case.

## 1 INTRODUCTION

The use of reactive aggregates in concrete may result in a chemical reaction in which particular constituents of the aggregates react with alkali hydroxides dissolved in concrete pore solution. These alkali hydroxides are derived mostly from the sodium and potassium in Portland cement and other cementitious materials, and occasionally from certain alkali-bearing minerals in the aggregates. The reaction products are hydrous gels whose chemical composition includes silica derived from the reactive aggregates. The damage in concrete is associated with subsequent expansion and cracking that occurs when the reaction products absorb water and swell.

The reaction may occur at the paste-aggregate interface. This is true in case of too reactive aggregates or waste glasses for example. However, the mineralogy of the slow reacting aggregates is complex. The reactive parts are embedded in non-reactive phases. The presence of such phases forms - in presence of sufficient water - a swelling gel which causes the fracture of aggregates.

In rock mechanics, fracture toughness is usually used as the main parameter to characterise the fracture behaviour of rocks [1-3]. In this study, the specific fracture energy is preferred because it is a global material parameter more efficient to capture the fracture and softening process.

Also, this parameter will be used as an input into an in-house numerical model specially developed for studying crack propagation and fracturing process of dam concrete. In this model, concrete is supposed to a heterogeneous material composed of elastic aggregates embedded into a viscoelastic matrix [4, 5]. The reactive sites are randomly distributed in the pre-cracked aggregates. The crack propagation which starts within the elastic aggregates may cross also the paste-aggregate interface and thus continues in the viscoelastic matrix.

Three aggregates form the Swiss Alps were studied. Petrographic examination indicated that aggregate A consisted of layer of chlorite interleaved with layers of quartz and feldspar. Aggregate B was a biotite schist containing phyllosilicates and aggregate C was also a biotite schist with feldspar and some muscovite. Four-point bend tests were carried out to determine the fracture characteristics of these rocks. The effect of sample immersion into an alkaline solution and the anisotropy observed in some aggregates were investigated. These properties will be used further as an input for a future study concerning the modelling of concrete fracture induced by ASR.

## 2 SAMPLE PREPARATION AND EXPERIMENTS

A four point-loading Chevron Notched Bend Beam (CNBB) is used as a testing method for the determination of specific fracture energy $G_f$ of various rocks from which the aggregates come, (Fig.1). A V-shaped chevron notch is used instead of straight-through notch because the length of crack front is gradually increased as the crack propagates. The V-shaped chevron notch causes crack initiation at the tip of the V and propagation in the notch plane along the specimen axis in a slow, stable and controllable manner. A second notch which starts from the chevron base up to bottom face of the specimen is also carried out to eliminate frictional effect. The four-point loading induces a constant bending moment between support rollers and thus zero shear forces in the ligament zone which in turn allows a pure mode I crack opening.

The use of chevron-notched specimens with different dimensions may result in different monotonic crack extension and crack stability. Thus, the effect of notch geometry on test stability was investigated with various samples in order to optimise specimen proportions. This has been done through a parametric study in terms of specimen dimensions, notch length and chevron angle, since these influence the amount of crack extension and crack area developing during the experiment. It should be noted also that the stability of the test is improved when the surface of the ligament is decreased and the thickness of the sample is reduced. In fact, the sample, which is appropriate for the controlled rupture, should show the following characteristics: a height/length ratio neither low nor high, a lowest possible thickness and a sufficiently deep notch [6]. The most stable test was obtained with samples having the following dimensions: length ($L$=180 mm), width (W =70 mm); thickness ($b$ =20 mm), notch length ($a$=10 mm), chevron notch angle ($\theta$=55°).

In order to study the size effect various samples of different length are cored from rocks (Table 1). The smallest samples did not have perfect geometrical similitude with largest ones because it was not possible to decrease their thickness below 10mm.

Three types of aggregates were studied. Displacement-controlled tests at the rate of 0.01 mm/s were performed on 25 samples for each case. Additional tests were also carried out to determine the elastic modulus and the tensile strength of each rock.

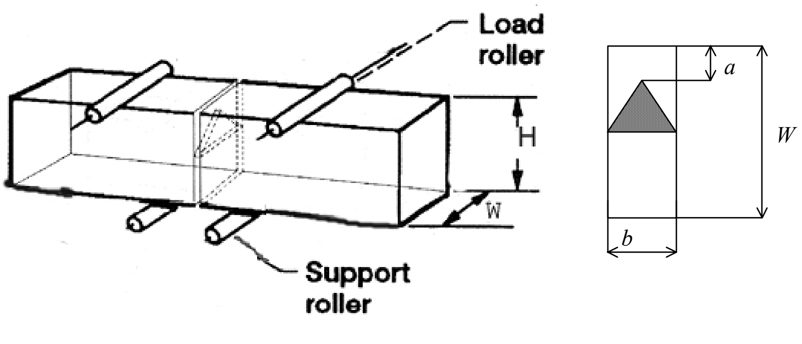


Figure 1. Chevron-notched beam in four-point bend test

Table 1: Dimensions of tested samples

| Sample sizes | Length $L$ (mm) | Depth $W$ (mm) | Thickness $b$ (mm) | Notch length $a$ (mm) |
|---|---|---|---|---|
| Large (L) | 180.00 | 40.00 | 20.00 | 10 |
| Medium (M) | 120.00 | 20.00 | 10.00 | 10 |
| Small (S) | 60.00 | 10.00 | 10.00 | 5 |

### *Immersion in alkaline solution*

Each sample is immersed in a saturated alkaline solution. Two initial water solutions were used: (1) pure water; (2) 0.6 M NaOH-equivalent solution. For each aggregate type, one experiment was performed at 40 °C. One set of samples was immersed for 60 days, the other for 180 days. Thus, samples were removed from the water solution and washed with alcohol.

## 3 RESULTS AND DISCUSSION

Table 2 presents the mechanical properties (tensile strength and the modulus of elasticity) of the various non-immersed (immersion time=0) aggregates in two orthogonal directions. Aggregate A presents a strong anisotropy (factor of 8 and 5 respectively for the modulus and the strength) whereas the aggregates B and C can be regarded as being isotropic.

Table 2: Mechanical properties of aggregates

| | Aggregate A | | Aggregate B | | Aggregate C | |
|---|---|---|---|---|---|---|
| | LD | TD | LD | TD | LD | TD |
| $\sigma_c$ (MPa) | 10 | 1.2 | 11.2 | 10.9 | | 10.3 |
| E (GPa) | 59.7 | 11 | 67.9 | 64.5 | 61.9 | 58.9 |

LD: longitudinal direction, TD: transverse section.

### *Influence of specimen size*

Figure 2 shows a comparison of load-deflection curves obtained on samples of different size from aggregates A and B. For the aggregate A, it appears that increasing the sample size seems to increase the brittleness of the material. However, this tendency is less obvious for aggregate B and C (not presented here). This difference can be explained by the fact that rocks B and C are more homogeneous and less fractured than A.

The results obtained on the specific fracture energy $G_f$, defined as the area under load-deflection diagram per unit fractured surface, are compiled in Table 3. The statistical variability of this parameter, estimated from a set of 25 samples for each case, was found to be less than 5%. The obtained results clearly show that there is a tendency of $G_f$ to decrease when the sample size increases. This can be explained by the fact that the larger the specimen sizes the higher pre-crack density, particularly for quasi-brittle materials as rocks. This result is also in accordance with the increase of brittleness in function of specimen size. The area under the load-deflection diagram becomes smaller for quasi-constant critical load.

Table 3: Specific fracture energy $G_f$ [N/m] obtained under alkaline solution

| | Aggregate | A | | | B | | | C | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Immersion time (Days) | 0 | 60 | 180 | 0 | 60 | 180 | 0 | 60 | 180 |
| Sample size | Large (L) | 148.3 | 135.9 | 133.5 | 165.3 | 157.6 | 160.1 | - | - | - |
| | Medium (M) | 165.7 | 155.8 | 149.5 | 169.7 | 160.3 | 162.5 | 158.2 | 154.3 | 151.2 |
| | Small (S) | 208.3 | 198.9 | 195.2 | 181.4 | 180.9 | 179.2 | 172.4 | 169.9 | 168.2 |

### ***Influence of alkaline solution***

The results on the influence of immersion time are compiled in table 3. Fig.3 presents load-displacement curves from tests performed on samples (largest size) immersed during 6 months into an alkaline and non alkaline solutions for both aggregates A and B. This reveals that the presence of ASR product seems to increase the brittleness of the rock. On another side, Fig.4 shows the evolution of average specific energy versus the immersion time for and also for the reactive aggregate (A) and the non-reactive one (B). It is clearly shown that specific fracture energy decreases with increasing immersion time for the reactive aggregates - in particular for largest samples - while there no significant effect on the non-reactive aggregate. These differences can be attributed to different expansion rates and spatial distributions of alkali silica gel, which induces the development of microcracks along the reactive zones inside each sample as shown in Fig. 5.

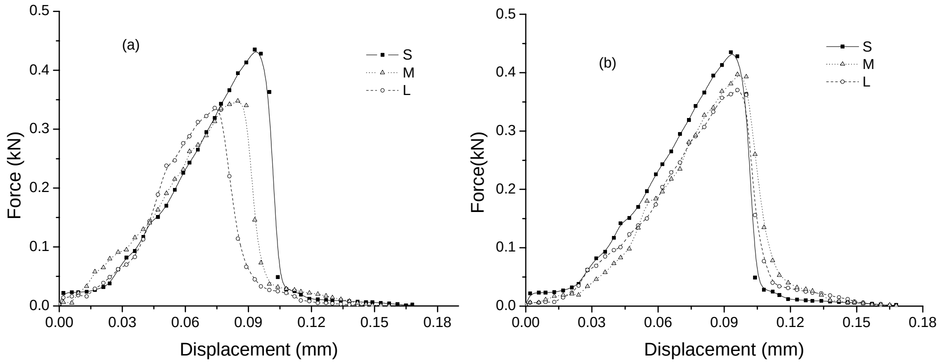


Fig. 2 Load-displacement diagram vs. specimen size before ASR
(a) Aggregate A, (b) Aggregate B

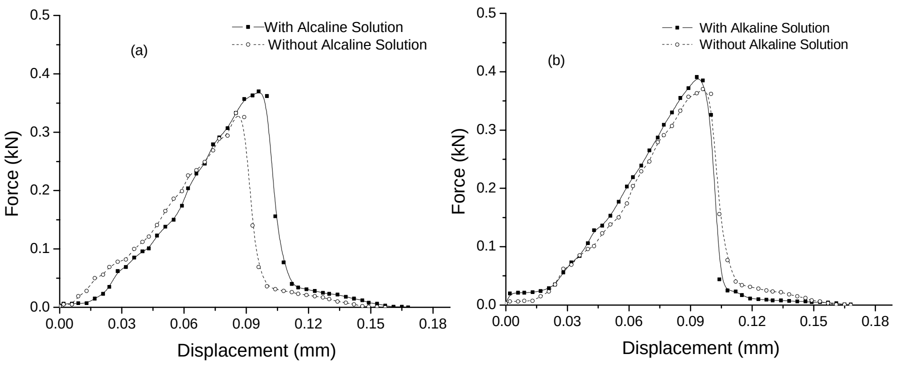


Fig. 3 Load-displacement diagrams obtained under alkaline solution and non-alkaline solution
(a) Aggregate A (reactive), (b) Aggregate B (non-reactive)

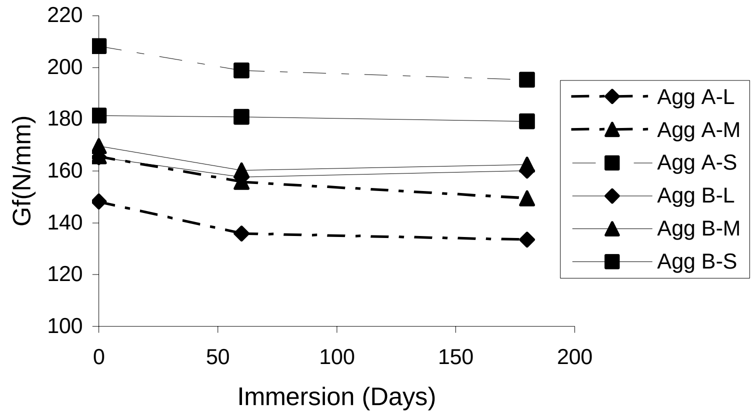


Fig.4: Specific fracture energy versus immersion time
for reactive aggregates (A) and non-reactive aggregates (B)

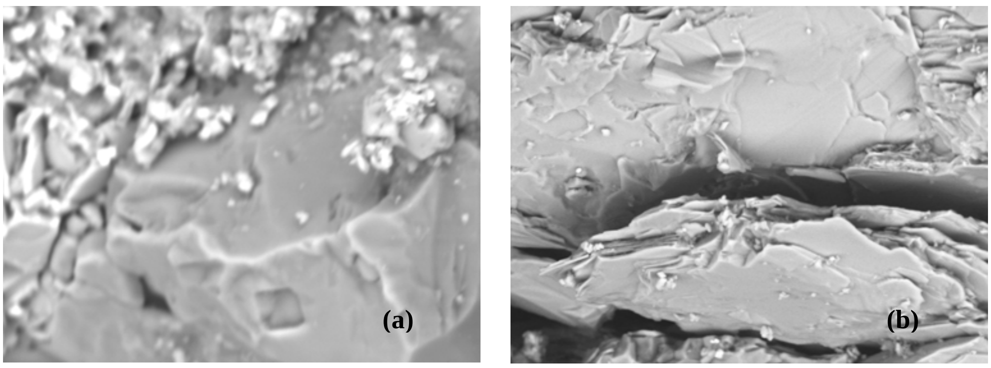


Fig. 5: Fractured surface of aggregate A: (a) before immersion, (b) After 6 months of immersion into alkaline solution

## 4 CONCLUSION

The determination of fracture properties of brittle materials through the four-point bend test has been described and specimen proportions have been optimised to ensure a stable displacement-controlled testing. The specific fracture energy has been investigated in terms of size sample and immersion time into an alkaline solution. The obtained results reveal that the fracture energy decreases and the brittleness of the rock increases as the specimen size increases. Nevertheless this size effect needs to be more deeply investigated through additional experiments in terms of sample width $W$ and notch length to width ratio $a/W$. The results on the influence of immersion time also show that the ASR-induced products may reduce both the fracture energy and the brittleness of the reactive rocks.

## ACKNOWLEDGEMENT

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