A CLASSIFICATION OF NORWEGIAN CATACLASTIC ROCKS FOR ALKALI-REACTIVITY

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ABSTRACT

The microstructural features of various Norwegian slow/late alkali-reactive rock types, have been quantified and related to alkali reactivity as measured by an accelerated mortar bar test. The majority of the rocks studied were of cataclastic origin subjected to ductile deformation. The study demonstrated that the grain size reduction of quartz promoted by the process of cataclasis enhances alkali reactivity by increasing the surface area of quartz grain boundaries available for reaction. The accelerated mortar bar test was used to study the sequential development of the reactions. Two different reaction styles were observed at the reaction sites involving dissolution of quartz along grain boundaries and crack generation within the aggregate, with the later being the main factor governing the amount of expansion produced by the reaction. High dislocation density associated with sub-grain boundaries was also found to enhance reactivity.

Keywords: Accelerated mortar bar test, Cataclastic rocks, Microcrystalline quartz, Petrographic examination

INTRODUCTION

The detection of slow/late alkali-aggregate reactions, has during the last few years been recognised as a concrete durability problem in Norway. Insufficient attention has internationally been given to the relationship between microstructural properties of potentially alkali reactive rock types, and their mechanisms of reaction. There is, therefore, a need to develop petrographic methods and procedures that enable the determination of potential reactivity of these aggregates, based on examination and quantification of microstructural features.

The introduction of a method to measure the undulatory extinction angle of strained quartz by Dolar-Mantuani (1981, 1983), has been used to quantify the reactivity of quartz-bearing rocks. However, some scientists have questioned this technique (Andersen & Thaulow 1989), and the method is no longer consider to be a reliable parameter for predicting alkali-reactivity (Grattan-Bellew 1986, 1992 and French 1992). It has been suggested that the reactivity may be due to the occurrence of microcrystalline quartz (Grattan-Bellew 1986, 1992). French (1992), however, noted that wherever meta-quartzites or rocks containing strained quartz are reactive, the quartz grains exhibit either strain lamellae, are cataclased or otherwise contain microcrystalline grains on larger grain boundaries or along fracture planes of various types. Zhang et al. (1990) investigated the microstructure of various reactive aggregates by transmission electron microscopy (TEM). This study suggested that the source of reactivity for certain types of slow/late alkali-reactive rock types is associated with large grain boundaries arising from smaller quartz grains, and the high density of dislocation present within many of these grains. Kerrick & Hooton (1992) showed that besides the effect of microcrystalline quartz, the reactivity of certain mylonites depended upon the degree of foliation (schistosity) in the rock.

In Sweden and Norway cataclastic rocks (especially mylonites) are found in structures in several areas exhibiting deleterious expansion due to AAR (Lagerblad & Trägårdh, 1992, Jensen, 1990, 1993). According to observations in Norwegian structures, cataclastic rocks are now considered as the most common source of alkali reactive rock types (Jensen, 1993). Thomson & Grattan-Bellew (1993) and Thomson, Grattan-Bellew & White (1994) showed that most reactive component in metamorphic deformed rocks appeared to be the microcrystalline quartz that had undergone significant sub-grain development, but not complete recrystallisation.

The main objective of this work was to relate the microstructural features of certain cataclastic rock types to expansivity obtained by the accelerated mortar bar test, in an attempt to develop a more reproducible method for the prediction and determination of the potential alkali-reactivity. It was also thought to be of interest to study the sequential development of AAR, in an attempt to identify possible differences in the behaviour of various rock types in relation to the degree of expansion.

METHODS

Materials

The aggregates (Table 1) investigated in this study were collected from five different geological areas in Norway. All the aggregates were crushed materials.

Determination and quantification of microstructural features

Rock samples were examined in thin-section (25 x 30 mm) under a polarising microscope. A classification of the cataclastic rocks in thin section was carried out according to that provided by Higgins (1971). Quartz grain sizes, including sub-grains, were measured for each rock type by point-counting approximately 200 points for each thin-section. For foliated rocks with elongated quartz grains, the direction of point counting was 45° to the parallel foliation of the rock in order to obtain an average grain size diameter. As a measurement of the grain size, the length of a quartz grain lying at the line was recorded. Determination of the *mean grain size of quartz,* the d_{50} was used.

In order to make a simple estimation of the grain boundary area of quartz, each quartz grain, including sub-grains, was assumed to be cubic in shape. Certain selected grain sizes were used to calculate a grain boundary area for specific parts of the quartz grain size grading. The area obtained was multiplied by the proportion of quartz grains within each specific parts of the grading, and all areas added together. By multiplying the grain boundary area by the amount of quartz in the rock type, as determined by XRD-analyses (Table 1), an estimate for the *total grain boundary area of quartz* (m^2/cm^3) in each sample was obtained (Table 1).

Accelerated mortar bar testing - procedure

The accelerated mortar bar procedure, described in 1986 by Oberholster & Davies and known as the NBRI Mortar Bar Test, is widely used to determine the potential for alkali expansivity of both rapid- and slow/late types of aggregates in concrete, and has become standard test procedures now established as the ASTM C1260-94 (ASTM 1994) and CSA A23.2-94 (CSA 1994).

A modified version of the NBRI Mortar Bar Test, was used to determine the expansion of the samples. The test was modified, by demoulding the mortar bars after 48 hours. In addition the mortar bars had dimensions according to the RILEM size; 40mm x 40mm x 160mm. After demoulding, these bars were immersed in water in closed containers and kept at a constant temperature of 80°C in an oven. After 48 hours, the lengths of the mortar bars were measured hot as a zero reading prior to immersion in a 80°C 1N NaOH solution, where subsequent expansion was measured after 4, 7, 14, 28, 42, and 56 days respectively.

The sequential development of the expansive reaction

Samples of mortar bars (25mm x 25mm x 250mm) with ultra-mylonite (sample 1.2), mylonite (sample 3.3) and micro-granite (sample 3.2) were used to examine the sequential development of the expansive reaction. Following the measurements at 4, 14, 28 and 56 days, selected bars were removed and transverse petrographic thin-sections (25mm x 25mm) were prepared, impregnated with a fluorescent dye, and used to follow the sequential development of any reaction. During storage and before the preparation of these thin-sections, samples were impregnated and sealed with epoxy resin to prevent carbonation.

RESULTS

Examples of some microstructural features in selected samples are given in figs. 1 to 4. The petrographic classification of the samples, as the mean quartz grain size (d_{50}), the amount of quartz, obtained by the XRD-analyses, and the total grain boundary area of quartz are given in Table 1.

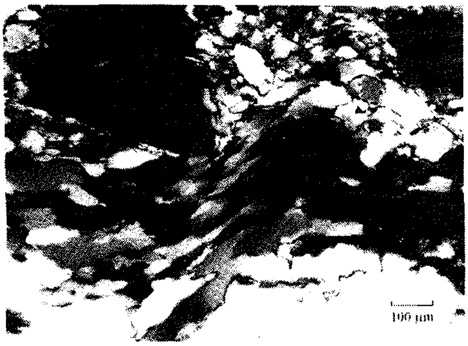

Fig. 1 Mylonite (Sample 1.3$_b$). Intensive strain has produced these elongated quartz grains exhibiting undulatory extinction, sutured grain boundaries, and sub-grain development. Note the alignment in the area of most strain, around the porphyroclast (Polarised light).

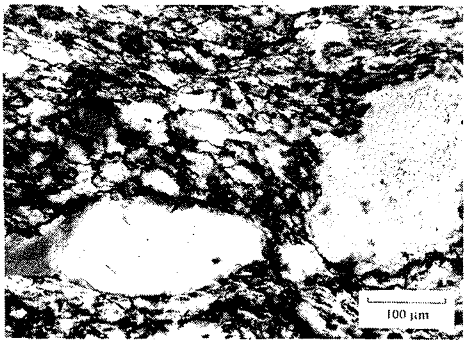

Fig. 2 Ultramylonite (Sample 1.2). Subhedral feldspars are surrounded by a matrix consisting of quartz and mica exhibiting foliation structures (Polarised light).

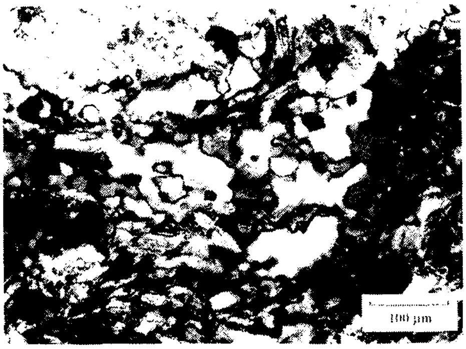

Fig. 3 Ultramylonite (sample 4.1). Sub-grain development in quartz (Polarised light).

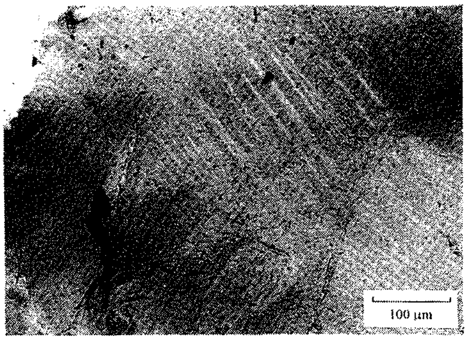

Fig. 4 Granite (Sample 1.4). Parallel deformation (strain-) lamellae in coarse quartz grain (Polarised light).

The mortar bar expansion and the sequential development

The expansion given for different aggregates, presented in fig. 5, is an average measure-ments of three mortar bars. The results show that the ultramylonite (sample 1.2) exhibited the highest expansion at 0.30% after 14 days. All the cataclastic rocks gave an expansion greater than 0.10 % after 14 days, and are classified as reactive according to the Norwegian 14-days expansion limit (Norsk Betongforening, 1991). The micro-granite (sample 3.2), gneiss (sample 4.2) and porphyritic granite (sample 1.4) were below the 0.10% expansion limit after 14 days. However, these innocuous rock types show a relatively unexpected high expansion. The expansion given by the mylonite (sample 3.3) was relatively low to 7 days, but thereafter this increased to the highest rate of expansion recorded after 14 days.

A summary of the observations made of the sequential development at different ages, with particular reference to crack development, is given in Table 2.

Table 1. Petrographic classification and determined microstructural features

Sample code No.	Rock names	Quartz grain size d_{50} (mm)	Amount of quartz, determined by XRD	Total grain boundary area of quartz (m^2/cm^3)
1.1	Mylonite	0.02	26 %	0.130
1.2	Ultramylonite	0.01	32 %	0.160
1.3_a	Mylonite	0.04	26 %	0.057
1.3_b	Mylonite,	0.04	22 %	0.046
1.4	Porphyritic granite	0.35	10 %	0.003
2.1	Cataclasite	0.03	90 %	0.297
3.1	Blastomylonite	0.05	16 %	0.022
3.2	Micro-granite	0.17	14 %	0.007
3.3	Mylonite	0.04	31 %	0.112
4.1	Ultramylonite	0.02	24 %	0.110
4.2	Gneiss	0.09	25 %	0.020
5.1	Mylonite	0.04	19 %	0.042

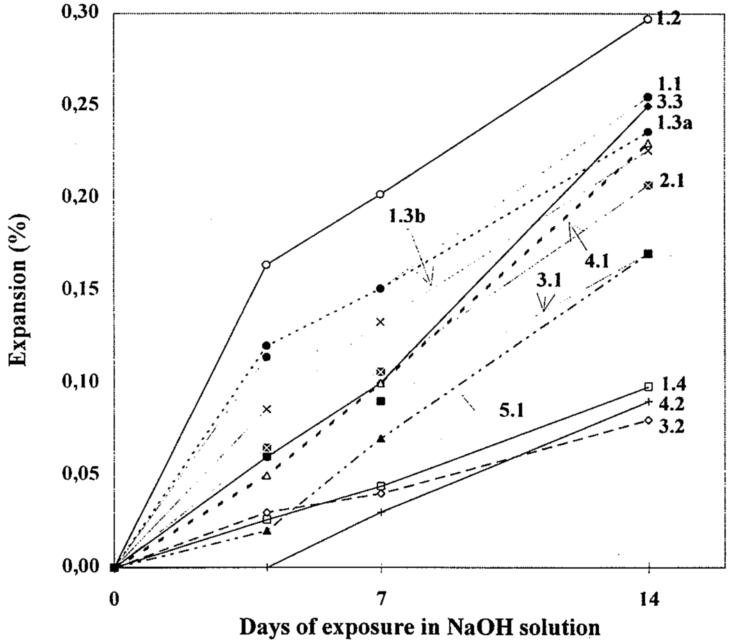

Fig. 5 The average mortar bars expansion development for all the twelve aggregates

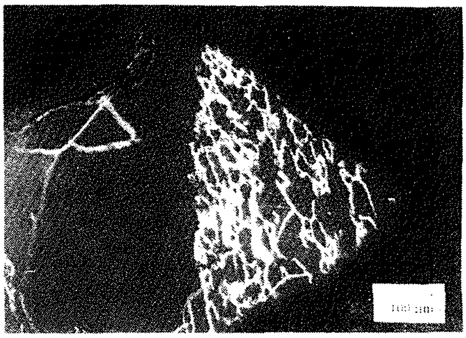

Fig. 6 Thin-section micrograph showing dissolution structures in sub-grained part of mylonite particle in 56 days old mortar bar specimen (UV light).

Fig. 7 Polarised light shows dissolution structures (right part of the particle) associated with sub-grain development. No dissolution structures are seen (left part of the particle) where strong undulatory extinction are observed (Polarised light).

Table 2. A summary of the reaction development observed for some of the samples in thin-sections at different ages.

Aggregate types	Observations of reaction, after certain test ages			
	4 days	14 days	28 days	56 days
Ultramylonite	Micro- cracks appear near the edge of the bar.		Dissolution starts to occur.	Dissolution increases further
Mylonite		Slight micro-cracking near the edge of the bar.	Significant micro-cracking and dissolution occur all over the bar.	Micro-cracking and dissolution increase further, all over the bar.
Microgranite		Dissolution starts	Dissolution more marked	Dissolution increases further

DISCUSSION

This work has shown that a logarithmic relationship is evident for both the inverse of the mean quartz grain size of quartz (d_{50}), and the total grain boundary area of quartz (m^2/cm^3), when correlating with the average result of the mortar bar expansion after 14 days (figs. 8 and 9). Additionally results of two supplementary crushed rock samples (mylonite gneiss and gneiss - black dots) were included to obtain more information of rock types exhibiting low expansion (0.03-0.05% after 14 days). The porphyritic granite (sample 1.4) and the cataclasite (sample 2.1) are excluded from fig. 9. These two rock samples, were regarded as outliers. The anomalous data for these samples can be explained as follows; The porphyritic granite contains relatively coarse quartz grains which contribute little to the total grain boundary area of quartz. The relatively high expansion measured was probably due to the occurrence of strain lamellae observed in some of the quartz crystals which was not measured as sub-grain boundaries. The occurrence of myrmekite with thin rods of quartz within the feldspar, might also have been significant by increasing grain boundary area leading to an enhanced grain solubility.

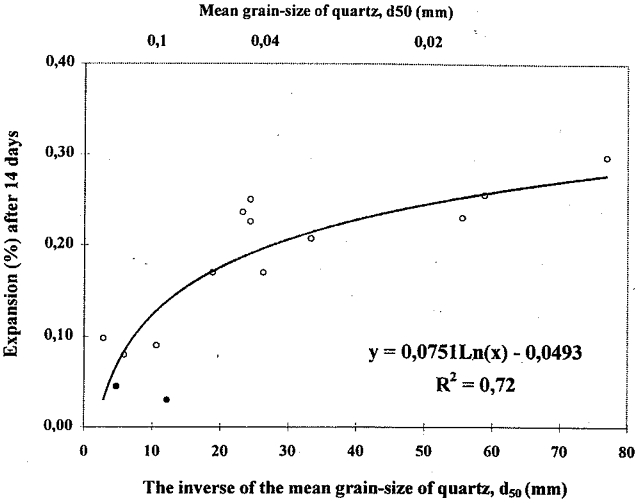

Fig. 8 Correlation between the inverse of the mean grain size of quartz, d_{50} (mm), and the average expansion after 14 days. The two black dots represent the two supplementary samples.

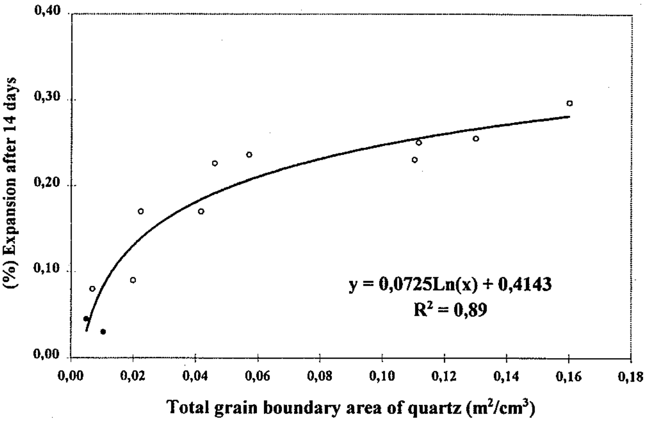

Fig. 9 Correlation between the total grain boundary area of quartz (m^2/cm^3) and the average expansion after 14-days. The two black dots represent the two supplementary samples.

In the case of the cataclasite (sample 2.1), a high content of microcrystalline quartz resulted in a very high grain boundary value. As opposed to the ductile deformed rocks, where the applied deformation energy is stored in the material as high dislocation density, the energy for cataclasites is used in the crushing processes. Additionally the extremely high amount of quartz (90%) in the sample gave a very high value for the total grain boundary area, when multiplied with the quartz amount resulting in an unpredictable behaviour.

Based on the line of best fit of the logarithmic relationship, aggregates with a measured mean grain size of quartz less than approximately 0.12 mm, would be expected to exceed 0.10% mortar bar expansion. This is in agreement with what has been suggested by Grattan-Bellew (1992), who claimed that an enhanced solubility of quartz occurs when the mean grain size of quartz is less than 0.10 mm. When comparing two rock samples with the same mean grain size the sample with a higher amount of quartz and a higher proportion of microcrystalline quartz will give a significantly higher available total surface area, and thus enhanced reactivity. Hence the total grain boundary area of quartz, gives a higher correlation coefficient ($R^2 = 0.89$), than when only considering the mean grain size ($R^2 = 0.72$).

On the basis of the properties of sub-grains, it is expected that these grains will contribute more to the reactivity than ordinary grains of similar size. However, the enhanced reactivity of sub-grains versus other quartz grains of equivalent size has not yet been established. No attempts were made to distinguish between sub-grains and other recrystallised microcrystalline grains of quartz in this study due to practical limitations of the thin-section examination. However, most of the observed microcrystalline quartz was due to sub-grain development and consequently, was the major contributor to the grain boundary area. In the case of microcrystalline material without sub-grains development (i.e. gneiss, blastomylonite and cataclasite), incorrect estimations might be obtained.

The sequential development

The present study shows that different types of reaction take place with some aggregates showing mainly microcrack development while others show gel formation along the grain boundaries in composite quartz grains. Expansion seems to be related to microcrack development rather than total gel development. It is important to emphasise that signs of the reactions were first recognised in aggregate particles near the edge of the mortar bars cross-section, and it appears that the reaction develops successively through the cross-section of the mortar bars. The highest rate of expansion was associated with the incidence of cracking rather than the dissolution. No cracks running into the cement paste were observed in association with the process of grain boundary dissolution.

It is observed that the alkali-aggregate reaction is associated with the appearance of sub-grains of quartz, which have enhanced reactivity through high dislocation density at sub-grain boundaries, which provide preferential sites for silica dissolution. In addition the occurrence of sub-grain may also promote the ability of the alkali-rich fluid to gain access to the reaction site, as observed in all the samples, and was in particular observed in samples from 28 days of age.

No significant reaction could be associated with the undulatory extinction, even though the sub-grain boundaries in the same particle (figs. 6 and 7) showed severe dissolution .

CONCLUSION

- The accelerated mortar bar test can be used to distinguish between different types of reactive aggregate. However, some innocuous rock types might show significant expansion.
- The alkali-aggregate reaction appears to be associated with microcrystalline quartz, in particular with the occurrence of sub-grain development.
- The total grain boundary area of quartz is related to the expansivity of certain aggregate types. The value will enhance the effectiveness of the petrographical examination as an engineering tool to screen potentially reactive aggregates.
- Considering only the mean grain size of quartz, might give unpredictable results, in particular for materials with high or low amounts of quartz.
- No significant reaction could be observed with coarser quartz grains dominated by extensive undulatory extinction.
- Two main processes are associated with alkali-aggregate reaction; a process of dissolution, and a process of cracking. Even though dissolution appears to produce the largest amount of the gel, the process causing cracking contributes most to the expansion and relates most closely to the rate of expansion.

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