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Microstructure parameters affecting alkali–silica reactivity of aggregates

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HIGHLIGHTS

- Quantitative analysis of ASR of aggregates.
- Quantitative analysis of microstructural parameters of aggregates.
- Factors affecting ASR of metamorphic rock types.
- Influence of quartz deformation on ASR.

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ABSTRACT

Quartz-rich aggregates were investigated, with the purpose of detecting the parameters facilitating the alkali–silica reactivity (ASR) of aggregates. ASR was attributed to their microstructure. Both decreasing grain size and elongated grain shape increase the specific surface, and increase the ASR. The degree of deformation and recrystallization is suggested to be responsible for ASR, due to its effects on grain size and grain shape. A high degree of ASR was found to be connected with those samples which had recrystallized by a low-temperature recrystallization regime, characterised by very small grains.

1. Introduction

The alkali–silica reaction (ASR) is a heterogeneous solid–liquid reaction, during which alkalis attack the aggregates within concrete. The reaction occurs if the following factors are fulfilled with: (1) the presence of alkali–silica reactive aggregates, (2) high alkaline conditions in the cement, and (3) water input (e.g. [1]). The main source of alkalis is derived from the cement itself, but aggregates are regarded to be a supplementary source of sodium or potassium [2]. SiO_2 hydrates in the aggregates form silanol groups which react with alkaline cations, then resulting in the growth of alkali–silica gels [3]. The alkali–silica gels can absorb water molecules, which increase their volume. The internal pressure may exceed the consistency limits of the concrete, leading to mechanical failure of the structures. Open air cracks and white coatings (efflorescence and exudations) represent the typical macroscopic manifestations of alkali–silica reaction on concrete surfaces (e.g. [1]).

Opal, chert, and volcanic glass are well known and have been established to be highly reactive aggregates (e.g. [4]). More complicated is the ASR of quartz. Dehills and Corvalan [5] proposed a method to measure the angle of undulatory extinction, which quantifies the degree of strain affecting the rock during the deformation processes. The angle of undulatory extinction has been applied by some researchers and correlated with the ASR of quartz [6,7]. During the last three decades, many questions have arisen connected with the usefulness of this parameter (e.g. [8,9]).

Various metamorphic quartz-rich rocks were investigated with the aim: (1) to quantify their alkali–silica reactivity; (2) to quantify the rock microstructure, including the geometrical parameters of rock-forming minerals such as grain size, grain shape, and spatial arrangement of minerals visible in micro-scale; and (3) to find the microstructural parameters connected to ASR. Accelerated mortar bar method was employed and combined with polarizing microscopy and image analysis. Special attention has been paid to the deformation and recrystallization characteristics of quartz. Also mentioned, are the possible influences of other minerals on ASR.

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2. Experimental

2.1. Sampling

The samples were selected based on the following criteria: (1) the rocks are used in the construction industry; (2) quartz represented the principal compound; (3) quartz showed different deformation and recrystallization characteristics; and (4) variable feldspars and micas were included.

Most of the rocks were sampled from quarries located in the Czech Republic, as well as some from Sweden (Table 1, [10–12]). One sample was taken from a natural outcrop (sample No. A7), previously investigated as a potential area for a new quarry [13]. Three other samples (sample Nos. A17, A18, and A19) had been investigated prior, due to other engineering activities (dam and road construction, [14]).

Metamorphic rocks are well known for their variable microstructure with respect to their degree of foliation (e.g. [15]). Two oriented samples were taken from each quarry or outcrop (one perpendicular to the foliation; one parallel to the foliation), with the purpose to better characterise the samples.

2.2. Polarizing microscopy combined with image analysis

A Leica DMLP polarizing microscope was employed (Optical Laboratory, Institute of Geochemistry, Mineralogy, and Mineral Resources, Charles University in Prague). Uncovered polished thin sections were used. A series of microphotographs were taken (using an Olympus digital camera), which later served for the image analysis.

The image analysis consisted of the following steps: (1) image acquisition, which refers to the selection of a measured area within the thin sections (the size of the analyzed area is controlled by the average grain size; at least 200, although preferentially 400 grains, were measured); (2) image digitisation, which refers to the step in which selected area of the thin section is photo-documented using a digital camera; (3) image pre-processing, which includes the step in which the images are graphically modified, with the objective to increase the contrast between the measured objects and the background by image analysis, as well as to prepare an accurate "map" of the minerals; (4) image measurement, where the image analysis software was employed and selected parameters (e.g., area) are measured; and (5) the data analysis [16].

The process of image analysis is semi-automatic. Thus, the difference between the objects measured, and the background, as well as the objects' characterization are controlled by the operator. The following parameters were evaluated using image analysis: area, major and minor axis lengths, perimeter, and the shape factor (see definitions of the individual parameters in Table 2). More details connected with the image analysis can be examined elsewhere (e.g. [17,18]).

2.3. SEM/EDS method

Scanning electron microscopy, with energy diffraction analysis (SEM/EDS analysis), was conducted at the Laboratory of Electron Microscopy and Microanalysis (Institute of Petrology and Structural Geology, Charles University in Prague). The measurements were performed on a Tescan Vega instrument, with an energy-dispersive analytical system (Oxford Instruments LINK ISIS 300) under the following conditions: 0.8 nA; 180 s counting time; and a 30 kV accelerating voltage. A 53 Minerals Standard Set #02753-AB (SPI Supplies) was used for the standard quantitative calibration.

2.4. Accelerated mortar bar test

The alkali–silica reactivity of aggregates was measured based on an accelerated mortar-bar test (following the standard ASTM C1260, [22]). The testing conditions included a 14-day testing period, 1 M NaOH accelerating solution, and an accelerating temperature of 80 °C. The accelerated mortar bar test was made in cooperation with the laboratories of ZKK Ltd.

Table 1
The list of samples including their geologic characterisations.

S. no.	Quarry/outcrop	Geological unit	Area	Regional geological unit	Rock type
A13	Podhůra	Bohemian Massif	Cretaceous	Bohemian Cretaceous Basin	Quartzite
A7	Račí údolí	Bohemian Massif	Lugicum	Orlica-Snieznik dome	Gneiss
A15	Těchobuz	Bohemian Massif	Moldanubian Zone	Drosendorf Unit	Quartzite
A8	Branná	Bohemian Massif	Moravo-Silesian	Silesian	Phyllite
A9	Bohutín-Zbová	Bohemian Massif	Moravo-Silesian	Silesian	Schist
A10	Krásné u Šumperka	Bohemian Massif	Moravo-Silesian	Silesian	Schist
A11	Olbramovice	Bohemian Massif	Moravo-Silesian	Brunovistulian Unit	Granodiorite
A12	Olbramovice	Bohemian Massif	Moravo-Silesian	Brunovistulian Unit	Granodiorite
A14	Svrčovec	Bohemian Massif	Upper Proterozoic	Tepla-Barrandien Area	Phyllite
A1	Stoningsberget (Umea)	Fennoscandia	Svecofennian Province	Västerbotten Country	Gneiss
A2	Kulbäcksliden	Fennoscandia	Svecofennian Province	Västerbotten Country	Quartzite
A3	Orrberget (Vannas)	Fennoscandia	Svecofennian Province	Västerbotten Country	Gneiss
A4	Gettberget	Fennoscandia	Svecofennian Province	Southern Norrland	Phyllite
A19	Hornträsket	Fennoscandia	Svecofennian Province	Västerbotten Country	Schist
A5	Forsnacken	Transcandinavian Igneous Belt	Caledonides	Upper Allochton	Schist
A6	Klovsjo	Transcandinavian Igneous Belt	Caledonides	Middle-to-lower Allochton	Quartzite
A17	Abelwattnet	Transcandinavian Igneous Belt	Caledonides	Upper Allochton	Schist
A18	Abelwattnet	Transcandinavian Igneous Belt	Caledonides	Upper Allochton	Schist

Table 2
Parameters measured using petrographic image analysis. Q – quartz, F – feldspar, M – mica. * – definitions accepted from SigmaScanPro 5 software [16].

Parameter	Unit	Definition
Area (A)	Pixels, mm^2	*Area reports the area for the selected object
Mineral composition	%	Mineral composition reflects the proportions of individual minerals in the rock calculated as total area of individual mineral divided by total area of the rock (e.g., mineral composition = Q (40%), F (40%), M (20%); Q = $\sum A_Q/\sum A_{TOT}$; F = $\sum A_F/\sum A_{TOT}$; M = $\sum A_M/\sum A_{TOT}$))
Equivalent diameter	Pixels, mm	Equivalent diameter is calculated as a diameter of circle, which has the same area (A) as measured object – $D_{equiv} = (4 \times A/\pi)^{1/2}$ [19]
Major axis length	Pixels, mm	*Major axis of the object (defined by the two most distant points on the object) reports the length of the axis
Minor axis length	Pixels, mm	*Minor axis of the object (defined by the two most distant points on the object that creates a line perpendicular to the major axis) reports the length of the axis
Perimeter (P)	Pixels, mm	*The measurement account perimeter by approximating the vertical, horizontal and diagonal components of the object's true perimeter. The larger the object (in pixels), the more accurate the perimeter calculation will be
Aspect ratio	–	Grain elipticity reflects the ratio between the major and minor axis lengths. Minor-to-major axis ratio close to 1 indicates isometric grains. Increasing minor-to-major axis ratio indicates more elongated grains [17]
Shape factor (SF)	–	*Shape factor indicates circularity of investigated object (resp. grains). Ideal circle shows a shape parameter 1, objects with elongated or irregular shape show a shape factor close to 0. SF = $4 \times \pi \times A/P^2$ [20]
Specific surface	mm/mm^2	Calculated from total perimeter (P) divided by total area (A) (e.g., [21])