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Acoustic emission monitoring of crack formation during alkali silica reactivity accelerated mortar bar test

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ABSTRACT

System of semi-continuous ultrasonic sounding and acoustic emission (AE) monitoring of experimental mortar bars subjected to ultra-accelerated (14-days lasting) alkali-silica reactivity (ASR) test was developed and assessed for refined interpretation of early stages of reaction. The experiments were carried out by using four different types of crushed stone (quartz from pegmatite, chert, quartzite, quartz-rich metagreywacke) exhibiting variable ASR potential from non-reactive to reactive. By analysing AE characteristics, these faithfully reflect microstructural changes during the first 3–5 days of the test. Early formation of ASR damage phenomena within aggregate particles showing variable ASR potential is accompanied with non-linear interaction of propagating or released acoustic waves. During the second half of the test, rapid attenuation of AE activity, specifically in the case of the two most reactive types of aggregates (quartz metagreywacke and chert), reflects deterioration of the (micro) structure of tested materials and decrease of quality of contacts between steel wave guides and experimental mortar bars. The later fact presents major limitation of current approach during later stages of ultra-accelerated mortar bar test. Despite this limitation, ultrasonic sounding and AE monitoring seems to be much more sensitive to early stages of development of brittle damage phenomena due to ASR than standard dilation reading is. This has been confirmed by subsequent direct observation of damage phenomena by backscattered imaging in scanning electron microscope.

1. Introduction

The alkali silica reaction (ASR) is one of the critical internal swelling reactions that affect the stability of concrete structures by cracking (Fournier and Bérubé, 2000). The use of non-reactive forms of aggregates seems to be the most effective way to mitigate this serious problem (Malvar et al., 2002). However, recognition of innocuous rock types is complicated and requires experienced examination and/or testing of the aggregate source rock. The direct search for reactive forms of silica by petrographic methods (Sims and Nixon, 2003; Nixon and Sims, 2016) combined with the expansion of experimental mortar bars or concrete prisms subjected to ASR accelerating conditions (Bérubé et al., 1995; Grattan-Bellew, 1997; Thomas and Innis, 1999; Rogers, 1999; Shon et al., 2002; Haha et al., 2007) represents the most widely employed approach; although analysis of the leaching potential of some aggregates by a chemical test method was previously considered as an alternative approach (Wakizaka, 2000).

Particularly for tests based on expansion measurements, a precise determination of the onset and progression of ASR are fundamental for further classification of the tested aggregate. This is based on the reading of expansion within a prescribed test period; however, no further data are obtained from the test. More recently, the expansion reading of experimental mortar bars or concrete prisms is supplemented with direct observations of cracks and/or gels associated with ASR by either microscopic observation (Shuguang et al., 2013; Šachlová et al., 2010) or by non-destructive testing (NDT) (Rivard and Saint-Pierre, 2009). The first approach provides the possibility of visualisation of the damage phenomena, thus linking the material composition to the destruction process of ASR. It also means that the test specimen (experimental mortar bar/concrete prism) must be removed from the accelerating alkaline solution, in order to have the possibility to prepare thin or polished sections from which the ASR related phenomena are derived. On the other hand, NDT offers the possibility to record changes of a test specimen's measured properties continuously (or with a high frequency of readings). Recent adoptions of non-destructive techniques to cope with ASR phenomena, both in the laboratory and *in situ*, cover several methodologies such as electric/electromagnetic, seismic, and/or acoustic (Rivard and Saint-Pierre, 2009; Stauffer et al., 2005; Saint-Pierre et al., 2007; Chen et al., 2008, 2009, 2010; Kodjo et al., 2009; Sargolzahi et al., 2010; Schurr et al., 2011; Leśnicki et al., 2011, 2013; Omikrine Metalssi et al., 2015). From the non-destructive

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methods used during tests, which lead to the development of brittle damage related to internal stress, the recording of acoustic emissions seems to be the most promising as demonstrated in numerous laboratory studies on brittle damage of rock specimens in rock mechanical tests (Yamada et al., 1989; Lockner, 1993; Přikryl et al., 2003) and/or concrete (Mindess, 1982; Ohtsu, 1996; Puri and Weiss, 2006; Aggelis et al., 2009; Ohno and Ohtsu, 2010; Proverbio, 2011). AE monitoring has also been successfully employed for *in situ* inspection of concrete structures (Shiotani et al., 2009; Antonaci et al., 2010; Van Tittelboom et al., 2012; Moradi-Marani et al., 2014). Thus, it is therefore interesting that except for one very recent conference paper (Weise et al., 2012), this method has not been employed during laboratory tests focused on the assessment of the ASR potential of aggregates by accelerated expansion (ASTM C1260-14, 2014); although its potential for detection of other corrosion/damage phenomena of concrete has been fairly well documented in the past decades (Rivard et al., 2000; Rivard and Saint-Pierre, 2009). To explore potential of AE monitoring during ASR testing, several materials rich either in quartz and/or in silica minerals with variable ASR potentials have been selected and subjected to the standard ultra-accelerated mortar bar test, supplemented with non-destructive readings of the ultrasonic and acoustic signals transmitting from a mortar bar. The main purpose of the recent study was to develop a test assemblage allowing for quasi-continuous recording of AE. After-test interpretation of the data focused on possible correlation of standard expansion values and AE characteristics. This evaluation was supported by direct microscopic observations of damage phenomena associated with the progress of ASR.

2. Materials and methods

2.1. Materials

This experimental study was performed using a set of quartz-rich rocks that exhibited different microstructural and quartz deformation characteristics (Table 1, Fig. 1). Microscopic characteristics of the studied quartz-rich rocks were described in detail elsewhere (Šachlová et al., 2017). Two of the selected aggregates (samples EMB2 and EMB3) are used in the construction industry as filler for both concrete and asphalt mixtures. The other two samples were obtained from a natural outcrop (sample EMB4) and from an abandoned quarry (sample EMB1). For each of the studied materials, chips and blocks varying in size from several cm to dm were sampled in amounts totalling 30–50 kg. The experimental specimens were selected in order to represent silica-rich materials with obviously different ASR potential.

2.2. Accelerated experimental mortar bar (EMB) test

A complementary set of EMB test was prepared, using the same aggregates, to perform an accelerated EMB test according to the requirements of the ASTM C1260-14 (2014) standard. Prior to the test, each of the sampled materials was crushed to obtain an aggregate of the desired granulometry. The mortar was then mixed using the 0.125/5 mm aggregate fraction, CEM I 42.5 Portland cement, and distilled water at the ratio of 2.25/1/0.47 (aggregate/cement/water). A set of four mortar bar specimens was prepared from each of the studied rock samples. After 24 h of hardening plus 24 h of tempering, the mortar bars were placed in 1 N NaOH solution at temperature of 80 °C. Expansion of the EMB specimens was measured for 14 days throughout the test period. Two of four mortar bars have been subjected to standard readings of expansion as recommended by the ASTM C1260-14 (2014) standard, the remaining two were used during experimental monitoring of AE and ultrasonic sounding as described below.

2.3. AE monitoring and ultrasonic sounding in a temperature controlled chamber

EMB specimens were prepared according to the requirements of the ASTM C1260-14 (2014) standard. For each sample, two mortar bars were placed in 1 N NaOH test solution at temperature of 80 °C (*i.e.*, the same conditions as for the accelerated mortar bar test according to the ASTM C1260-14 (2014) standard). Recording of the AE signals was made possible using a pair of ultrasonic AE sensors located outside of

Table 1
Geologic and macroscopic descriptions of selected samples (adopted and modified after Šachlová et al., 2017).

Aggregate sample No.	Q9A	Q0B	Q7C	Q3
Experimental mortar bar marking	EMB1	EMB2	EMB3	EMB4
Locality	Edsele	Těchobuz	Klövsjö	Litohlavy
Geological unit, age	SO, PP	BM, MZ	CO, BCM, JN	BM, TBU, P
Macroscopic characterisation	White-to-light-yellow, quasi-isotropic (compact), undistinguishable grain boundaries	Light grey colour, quasi-isotropic (compact), undistinguishable grain boundaries	Light white-to-yellow, quasi-isotropic (compact), undistinguishable grain boundaries	Dark grey with red veins, veined
Petrographic classification*	Quartz from pegmatite	Quartzite	Quartz meta-greywacke	Chert
Quartz/silica content (vol%)	100	71	74	35
Groundmass/matrix content (vol%)	–	–	26	65
Other min./pore voids (vol%)	–	29/0	–	–
Microstructure **	Grain boundaries of individual quartz grains impossible to be observed using naked-eye or captured in polarizing microscope, intruded by microcracks healed by fine-grained quartz, undulatory extinction and quartz subgrains	Homeoblastic, interlobate grain boundaries, undulatory extinction and origin of quartz subgrains	Heteroblastic, fine-grained quartz grains scattered in the matrix, partially exhibit grain-to-grain sutured boundaries, weak undulatory extinction, diagenetic alteration	Heteroblastic, microcrystalline quartz embedded with layers of fine-grained quartz partially exhibiting sutured grain boundaries, groundmass composed of cryptocrystalline silica, accessory hydrated iron oxides
Mean/max. grain size (mm)	>20	0.09/0.42	0.07/0.46	0.01/0.53
T-index	–	0.024	0.016	0.005

Abbreviations: BCM – Baltoscandian continental margin, BM – Bohemian Massif, CO – Caledonian Orogen, JN – Jämtlandian Nappes, MZ – Moldanubian Zone, PP - Palaeoproterozoic, P – Proterozoic, S – sample, SO – Svecokarelian Orogen, TBU – Teplá-Barrandian Unit. The separation of quartz from a pegmatite (specimen EMB1) was done mechanically according to the macroscopic characteristics of the other minerals. Classified according to: (*) Gillespie and Styles (1999) and Robertson (1999), and (**) Passchier and Trouw (2005). Geometric characteristics were determined after Přikryl (2001, 2006).