ALKALI SILICA REACTIVITY STUDY OF ACCELERATED MORTAR BAR BY MEANS OF ACOUSTIC EMISSION AND ULTRASONIC SOUNDING

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Abstract

Semi-continuous ultrasonic sounding and acoustic emission were used to study the accelerated alkali silica reactivity (ASTM C1260) of experimental mortar bars with different aggregates. To confirm ultrasonic results, expansion test and SEM/EDS examination of ASR-related damage were carried out. It was found that high reactivity aggregates pronounced by high mortar bar dilatancy result in significant decrease of P-wave velocity and high ultrasonic signal attenuation. Acoustic emission can be used for ASR study mainly during first days of ASTM C1260 study to monitor origin of ASR. Later stage of study is limited by high signal attenuation caused by material deterioration. Ultrasonic sounding and acoustic emission monitoring can be used as an effective supplementary tools for the monitoring of internal structure of expanding mortar bars during laboratory tests for the evaluation of alkali silica potential of aggregates.

Keywords: Alkali silica reactivity; experimental mortar bars; ultrasonic sounding; acoustic emission; swelling reactions

1. Introduction

Alkali silica reaction (ASR) is one of the critical internal swelling reactions that affect stability of concrete structures by cracking (Fournier and Bérubé 2000). Use of non-reactive forms of aggregates seems to be the most effective way how to mitigate this serious problem (Malvar et al. 2002). Direct search for reactive forms of silica by petrographic methods (Sims and Nixon 2003) combined with expansion of experimental mortar bars or concrete prisms subjected to ASR accelerating conditions (Berube et al. 1995, Grattan-Bellew 1997, Thomas and Innis 1999, Rogers 1999, Shon et al. 2002, Haha et al. 2007) presents the most widely employed approach, although analysis of leaching potential of aggregate by chemical tests is also common. Specifically for tests based on expansion measurement, the precise determination of the onset and the progression of ASR are fundamental for further classification of tested aggregate. More recently, the expansion reading of experimental mortar bars or concrete prisms is supplemented with direct observation of crack and/or gels associated with ASR by microscopic observation (Lukschová et al., 2009) or by non-destructive testing (NDT) (Rivard and Saint-Pierre 2009). NDT offers possibility to record change of measured property of test specimen continuously or with high frequency of readings. Recent adoption of non-destructive techniques to cope with ASR phenomena both in laboratory and in situ scales cover several methods such as electric/electromagnetic, seismic and/or acoustic (Stauffer et al. 2005, Saint-Pierre et al. 2007, Chen et al., 2010, Kodjo et al. 2009, Sargolzahi et al. 2010, Schurr et al. 2011, Lešnicki et al., 2013, Omikrine Metalssi et al. 2013). From non-destructive methods used during tests leading to the development of brittle damage related to internal stress, recording of acoustic emission...
seems to be most promising as shown on numerous laboratory studies on brittle damage of rock specimens in rock mechanical tests (Přikryl et al., 2003). We have decided to examine possible adoption of NDT during the standard ultra-accelerated mortar bar test. By using aggregates exhibiting wide range of ASR potential, we have focused on the development of test assemblage allowing quasi-continuous recording of acoustic emission (AE) and after-test interpretation of the obtained data. These data were correlated to standard expansion values and to direct microscopic observation of microstructural changes (aggregate damage due to microcracks, pores filled with alkali silica gel) caused by developing ASR.

2. Experimental

2.1. Material

The experimental study was performed using a set of quartz-rich rocks exhibiting different microstructural and quartz deformation characteristics (Table 1). Two of selected aggregates (Sample Nos. EMB2 and EMB3) are used in the construction industry as filler for both concrete and asphalt mixtures as well as gravel basements. Other two samples were sampled from natural outcrop (Sample No. EMB4) and from the abandoned quarry (Sample No. EMB1). For each of the studied materials, chips and blocks several cm to several dm large were sampled in total amount of 30 – 50 kg.

Table 1. Petrographic and macroscopic descriptions of selected samples.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Q9A</th>
<th>Q0B</th>
<th>Q7C</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample marking</td>
<td>EMB1</td>
<td>EMB2</td>
<td>EMB3</td>
<td>EMB4</td>
</tr>
<tr>
<td>Locality</td>
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<td>Těchobuz</td>
<td>Klövsjö</td>
<td>Litohlavy</td>
</tr>
<tr>
<td>Petrographic classification</td>
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<td>quartzite</td>
<td>quartz meta-greywacke</td>
<td>chert</td>
</tr>
<tr>
<td>Quartz content (vol. %)</td>
<td>100</td>
<td>71</td>
<td>74</td>
<td>35</td>
</tr>
<tr>
<td>Mean/max. grain size (mm)</td>
<td>&gt; 20</td>
<td>0.09/0.46</td>
<td>0.07/0.68</td>
<td>0.01/0.53</td>
</tr>
</tbody>
</table>

2.2. Accelerated experimental mortar bar (EMB) test

A complementary set of EMB was prepared by using same aggregates to perform accelerated EMB test according to requirements of ASTM C1260-14 (2014) standard. The mortar was mixed using aggregate fraction of 0.125/5 mm, CEM I 42.5 Portland cement, and distilled water in the ratio of 2.25/1/0.47 (aggregate/cement/water). Four different mortar bar specimens (EMB1 – EMB4) were prepared from each sample. After 24 hours of hardening and 24 hours of tempering, the mortar bars were placed in 1M NaOH solution at 80°C. Expansion of the mortar bar specimens was measured for 14 days through the test period.

2.3. Acoustic emission monitoring (AEM) and ultrasonic sounding in a temperature controlled chamber

Experimental mortar bars (EMB) were prepared according to requirements of ASTM C1260-14 (2014) standard. For each sample, two mortar bars were placed in the 1M NaOH test solution at 80°C, i.e. same conditions as for the accelerated mortar bar test following ASTM C1260-14 (2014) standard. Recording of acoustic signals was possible by using a pair of ultrasonic AE sensors, located outside of the heating chamber. Sealed steel 316L waveguides
were used to enable transmission of ultrasonic signals to AE sensors. As a sensors, a pair of wide-band, high-temperature-resistant sensors manufactured by the 3S Sedlak company, was used for each tested bar. AE was monitored by means of Vallen AMSY multichannel automatic recording system, which enables also regular ultrasonic sounding of mortar bars during the test. AE was monitored continuously during the whole test period, reading of propagating ultrasonic signal (P-wave velocity measurement together with determination of true energy and amplitude of transmitted signals during the test) was performed with a 10 minutes interval. Concentration and level of the test solution was controlled during the test; concentration was checked/corrected every second day, level of the solution was monitored automatically.

Figure 1. Technical layout of heating chamber equipped with waveguides and ultrasonic sensors.

3. Results and discussion

3.1. Expansion of experimental mortar bars

The studied materials show expansion due to ASR from 0.05% to 0.55% after 14 days of testing (Fig. 2). Based on these data, only one material (sample from pegmatite, EMB1) can be considered as non-reactive, whilst the remaining fit to the category of reactive ones. However, their reactivity potential is different as can be seen from expansion values and from supplementary measurements by ultrasonic sounding and acoustic emission monitoring as described below.

Figure 2. Expansion curves of mortar bars EMB with different aggregates.
3.2. EMB Ultrasonic sounding

Ultrasonic sounding data are shown in Figure 3. Dependence of P-wave velocity propagation is shown in Fig 3A. It can be observed that samples with different aggregate activity reflect different dependencies. P-wave velocity of “fresh” mortar bars was in the range between 3.3 to 4.1 km/s. Starting from these values we can observe increase of P-wave velocities. After some time (0.8 to 3 days) we can observe continues decrease/stabilisation of P-wave velocity. Samples with higher expansion values show higher decrease of P-wave propagation velocity. Similar behaviour reflects maximum amplitude of transmitted ultrasonic signal – see Fig3 B.

![Ultrasonic sounding data](image)

Figure 3. Ultrasonic sounding: Changes of P-wave velocity (A) and amplitude of ultrasonic signal (B) for specimens studied during the first ten days of experiments.

There is observed continues decrease of P-wave amplitude maximum of ultrasonic signal recorded in the course of regular ultrasonic sounding. It can be observed that mortar bars with higher activity aggregates shows higher decrease of recorded maximum ultrasonic signal amplitude.

3.3. Acoustic emission of EMB

As concerns the AE activity of studied mortar bars, expressed as number of AE hits numbers (Fig. 4), AE energetic parameters (full cumulative energy and/or AE energy rate – Fig. 5) and

![Acoustic emission data](image)

Figure 4. Basic AE characteristics of studied mortar bars during first ten days of experiment: cumulative distribution of AE hits (A) and AE hits rate (B).
AE maximum amplitude radiation of individual events (cumulative AE maximum amplitude and/or AE maximum amplitude rate – Fig. 6), the studied samples exhibit different behaviour that can be only partly explained by microstructural changes due to formation of brittle microcracks associated with ASR. Prior to the assembly of the current test procedure, our expectation was that materials that are more susceptible to ASR should provide more AE events due to the development of ASR-related brittle damage. Although this presumption was confirmed by later direct observation of polished sections prepared from mortar bars, the AE activity is more complicated. AE rate data are shown normed to maximum value for each sample and/or data.

In case of AE events, one can observe their continuous increase, mainly during the first days of the experiment (Fig. 4). Change in the slope of AE activity during the experiment (cumulative number of AE hits, Fig. 4A) is obvious specifically for the specimen EMB4 exhibiting the highest reactivity (black curve on Fig. 4A) and for non-reactive specimen EMB1 (green line, Fig. 4A). In the case of the most reactive specimen EMB4, AE activity is the most pronounced during first 2 days of the test and then rapidly diminishes during the third day (Fig. 4B), although this specimen follows to expand very rapidly during the next days (Fig. 2). On contrary, non-reactive specimen EMB1 exhibiting very slow quasi-linear expansion (Fig. 2) shows very slow continuous increase of AE events during the first 5 days, followed by non-linear acceleration of AE activity from 5th to 8th day of experiment and very steep linear increase of AE events from then. Higher AE activity of this specimen can be explained due to the development of microstructure due to the ongoing hardening of concrete mixture (Reinhardt & Grosse, 2004). The remaining two samples EMB2 and EMB3 (also reactive), show low to moderate quasi-linear increase of AE events (Fig. 4A).

Development of energetic parameters of AE events is even more complicated. The trend of full energy released of AE events (expressed as cumulative number, Fig. 5A) apparently exhibits similar trend as linear expansion does: two most expansive materials EMB3 and EMB 4 possess much higher increase of full energy compared to less expansive EMB2 and non-expansive EMB1 specimens. However, focusing on full energy rate (Fig. 5B), one can see rapid drop of this parameter for the most expansive sample EMB4 (black line, Fig. 5B) although this material continues to expand during the whole test period. On contrary, non-
expansive sample EMB1 (green line, Fig. 5B) exhibits change (initiation of rapid increase) in full energy rate from about 7th day of the test. Similar behaviour can be observed also for the cumulative maximum amplitude release (Fig. 6A) and maximum amplitude rate (Fig. 6B) which rapidly increases for the same sample from the 7th day of the test. However, its value remains very low for the most expansive specimen through the whole test, and rapidly drops from relatively high values to very low one for the second most expansive samples EMB3 (red line, Fig. 6B).

Figure 6. Parameters of AE activity of studied mortar bars during first ten days of experiment: cumulative distribution of AE amplitude (A), AE amplitude rate (B).

3.5. Effect of test assembly and conditions on the quality of recorded data

Although the observed behaviour of AE events is linked preferentially to the development of ASR in the studied material, some additional effects can play role as well. As the individual mortar bars expand during the test, there was no chance to secure constant contact conditions between the mortar bar and transducer, resp. wave guide. This fact can have serious impact on the quality of signal transmitted from mortar bar through the wave guide. Development of open brittle fractures, that are filled with test solution or newly formed alkali silica gels during the test can affect the quality of the signal transmission through the mortar bar; in reality can lead to serious attenuation of signals.

The current experimental set-up prohibited possibility of constant contact conditions due to the fact that wave guides were fixed to the walls of experimental chamber (in order to prevent leaching off the test solution from it). As the mortar bar change its dimensions during the test, the contact conditions at the mortar bar/wave guide could not be constant. This can be overcome by further development of test heating chamber, which will unify sensors contact conditions. Development of such a test assemblage will be matter of our further research.

4. Conclusions

Ultrasonic sounding and acoustic emission monitoring can be used as an effective supplementary tools for the monitoring of internal structure of expanding mortar bars during laboratory tests for the evaluation of alkali silica potential of aggregates. In general, P-wave velocity rapidly increases during the first 2-5 experiment days, but then starts to deteriorate for reactive materials. This can be explained by formation of brittle microcracks, resulting in
microstructural mortar bar changes – expansion. More reactive materials exhibit faster P-wave velocity decrease compared with less reactive ones. Similar relationship was observed for the maximum amplitude of ultrasonic signal; the degree of ultrasonic signal attenuation is proportional to the degree of expansion due to ASR. Acoustic emission monitoring can be performed by using same sensors that are used for quasi-continuous (readings each 10 minutes) ultrasonic sounding in the recent experimental set-up. Acoustic emission of materials prone to ASR and of innocuous materials exhibits considerable difference that is qualitatively and quantitatively dependent not only on the brittle damage character of the reaction but also on the formation of reaction products – alkali silica gels. Their presence leads to the significant attenuation of AE signals (specifically diminishes their amplitude and energy); their reading in expanding specimens can be further complicated by expansion of mortar bars and change of the quality of contact between specimen and transducers. All these factors make interpretation of AE more complicated during the later stages (from about 10th day) of mortar bar test. Further development of experimental set-up (improvements of specimen/transducer contact) could contribute to wider adoption of AE monitoring during the ASR testing.

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