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Fernandes, Andiç-Çakır and Hooton

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Assessing aggregates for alkali–aggregate reaction potential

Isabel Fernandes PhD
Department of Geology, Faculty of Sciences of the University of Lisbon/ICT, Institute of Earth Sciences, Lisbon, Portugal
(corresponding author: mifernandes@fc.ul.pt)

Özge Andiç-Çakır PhD
Civil Engineering Department, Faculty of Engineering, Ege University, İzmir, Turkey

Doug Hooton PhD
Department of Civil Engineering, University of Toronto, Toronto, Canada

The identification of alkali-reactive aggregates has been a challenge since alkali–aggregate reactions were first diagnosed. Standards, test methods and recommendations have been developed on a local and international basis. The Rilem recommendations regarding alkali–aggregate reactions are based on a methodology in which a series of laboratory tests is suggested. The assessment starts with a petrographic examination of the aggregate, followed by rapid screening tests and concrete expansion tests. This methodology has been carried out by a number of laboratories worldwide. However, some of the tests have not been totally satisfactory as sometimes the results do not correlate with each other or with field performance. A summary of the thresholds, advantages and limitations of each test according to the findings of Rilem TC 219-ACS is presented.

1. Introduction

Since alkali–aggregate reactions (AARs) were first identified more than 70 years ago, research has been carried out in order to develop effective methods to prevent the occurrence of the reactions in future constructions. The most common type of AAR involves potentially reactive forms of silica and is called the alkali–silica reaction (ASR). When the reaction involves certain forms of dolomitic rocks, it is called the alkali–carbonate reaction (ACR), although the most recent findings indicate that cryptocrystalline silica might be the cause of AARs in some dolomitic rocks.

The guidelines developed to prevent AARs in concrete are aimed at avoiding the presence of at least one of the reactants: reactive aggregate, moisture or high alkali content. With extensive work having been carried out globally since 1988 by Rilem technical committees and, in particular, Rilem Technical Committee 219-ACS: Alkali–Aggregate Reaction in concrete structures: performance testing and appraisal (2007–2014), test methods have been developed for assessing the reactivity of aggregates (Nixon and Sims, 2016). A summary is presented here.

2. AAR-0: guide to the use of Rilem methods in the assessment of the alkali-reactivity potential of aggregates

Rilem TC 219-ACS developed a methodology to assess the reactivity of a certain aggregate (or combinations of aggregates). It is based on the performance of three types of tests in the order they should be carried out.

- Visual study by the petrographic method (AAR-1.1).
- Rapid screening tests for siliceous and carbonate aggregates (AAR-2 and AAR-5, respectively).
- Expansion tests on concrete prisms (AAR-3 and AAR-4.1).

This methodology leads to the classification of the aggregate as follows.

- Class I – very unlikely to be alkali reactive.
- Class II – alkali reactivity is uncertain.
- Class III – very likely to be alkali reactive.

When aggregates are classified as class II or class III, it becomes important to decide what further testing is required. This should be carried out using the flowchart given in Figure 1.

3. AAR-1.1: the petrographic method

A visual assessment of aggregates can be obtained within a short period of time. This involves identification of the rock type (from quarries) or particles (natural sedimentary deposits), which are designated according to their origin, mineral composition and texture. In Rilem AAR-1.1, two complementary methods are recommended: (*a*) identification at hand sample scale, with the use of hand lenses and (*b*) optical

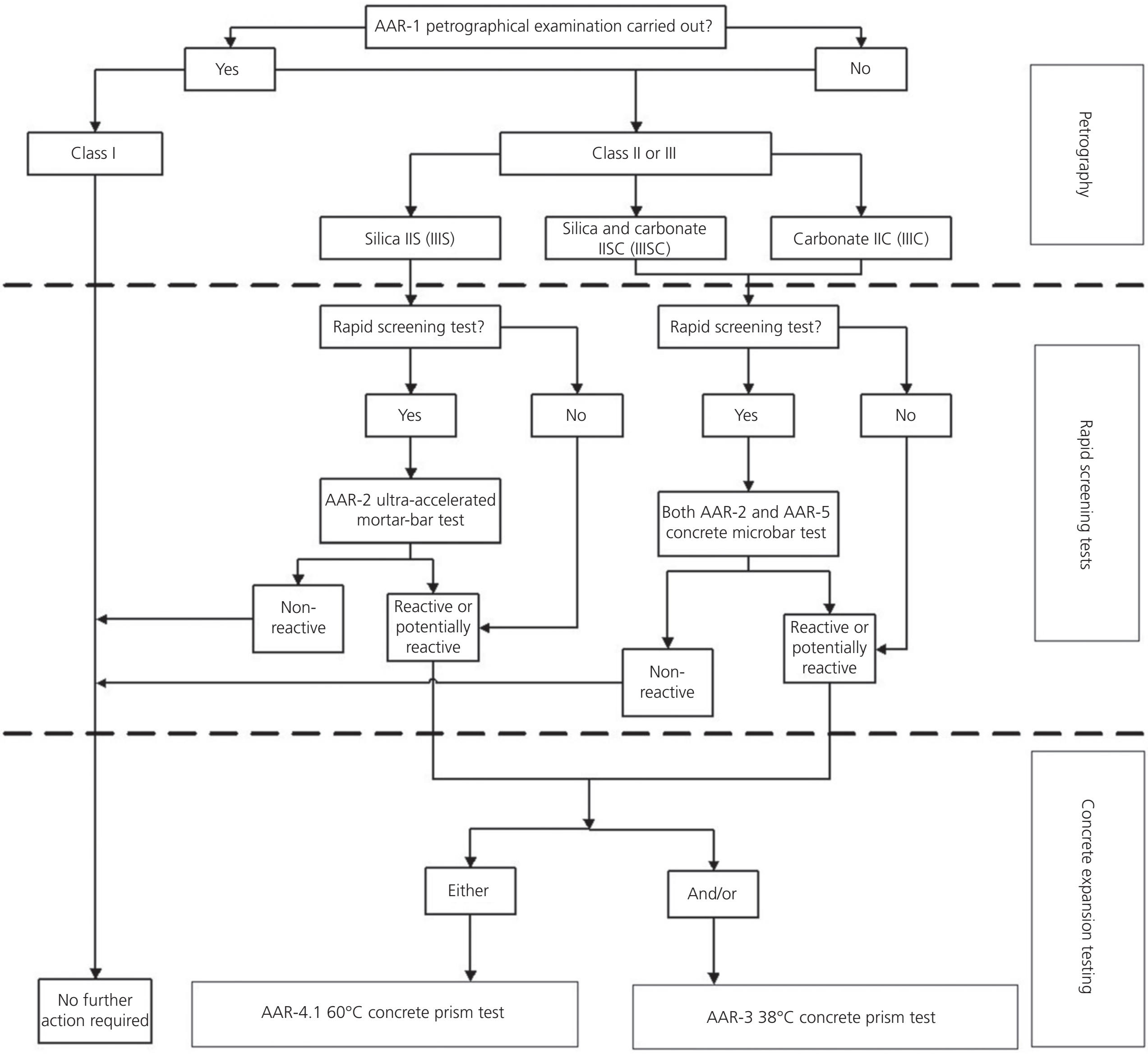


Figure 1. Integrated aggregate assessment scheme for AAR from Nixon and Sims (2016) (if no petrographical examination has been carried out, assume class II (or III))

microscopic examination of thin sections, whenever the hand sample scale is not sufficient to identify clearly the potentially reactive forms of silica.

Long lists of suspicious minerals and rocks have been published. Opal, tridymite, cristobalite and chalcedony are well-known reactive forms of silica due to their poorly crystalline structure. Moreover, cryptocrystalline quartz is reactive due to its large specific surface area, which facilitates access of the concrete fluids. Volcanic glasses of rhyolitic composition are considered reactive and strained quartz crystals show strain lamellae, bulging and subgraining. Alaejos *et al*. (2014), summarise the threshold content of cryptocrystalline silica, considered to be potentially reactive in different standards and countries.

However, the identification of potential reactivity for some types of rocks is difficult and is dependent on local experience and petrographic expertise. In this respect, the use of AAR-1.1 can be complemented with AAR-1.2 (Fernandes *et al.*, 2016), a petrographic atlas providing images of the most common alkali-reactive aggregates globally (Figure 2).

The main message is that petrographic analysis of an aggregate is more than the designation of a rock in accordance with the traditional nomenclature (igneous, metamorphic and sedimentary rocks), since the mineralogical composition (presence of reactive forms of silica), the chemical composition (e.g. rhyolitic volcanic glass), the granularity and the texture (e.g. subgraining) are factors that influence potential reactivity. For some rocks, such as volcanic rocks and siliceous limestones, complementary tests might be needed (e.g. chemical bulk analysis, scanning electron microscopy/energy-dispersive x-ray spectroscopy (SEM/EDS) and electron probe microanalysis) (Figure 3).

For aggregates classified as class II or class III by the petrographic method, laboratory expansion tests are recommended. A lot of work has been carried out in order to find the test that best reproduces the field behaviour of an aggregate (Lindgård *et al*., 2010, 2012). These tests differ mainly in the size of the aggregates, the specimen and the conditions of exposure. Consequently, the tests have variable and often lengthy durations, making them less useful for the construction industry.

4. Screening tests

4.1 AAR-2: accelerated mortar-bar test

In the mortar-bar test, specimens ($25 \times 25 \times 285$ mm^3) are exposed to extreme temperature (80°C) and are stored in 1 N sodium hydroxide solution. The appeal of this test is the short time needed to obtain results (14 d), although it is considered very complex (e.g. Fertig and Tanner, 2012; Fournier *et al*., 2006; Grattan-Bellew, 1997). This method is used as a screening test in AAR-0, but it is not recommended for evaluating the performance of aggregates with specific binder combinations. It should also be noted that, if the aggregate is a coarse aggregate, the sample is crushed and sieved below 4 mm to obtain the standard mortar gradation. The crushing operation results in a higher surface area per volume of aggregate and may result in an increased reactivity level. Considering all of these factors, the test methodology has a strong safety margin.

Rilem methodology permits the use of $25 \times 25 \times 285$–300 mm^3 specimens (as in ASTM C 1260) as well as $40 \times 40 \times 160$ mm^3 specimens and different expansion limits are recommended for assessment of reactivity. A conversion factor of 0·54–0·65 was suggested, based on the work of Jensen and Fournier (2000). However, the methodology does not routinely permit, converting the expansion results from one type of specimen to the other by a fixed ratio.

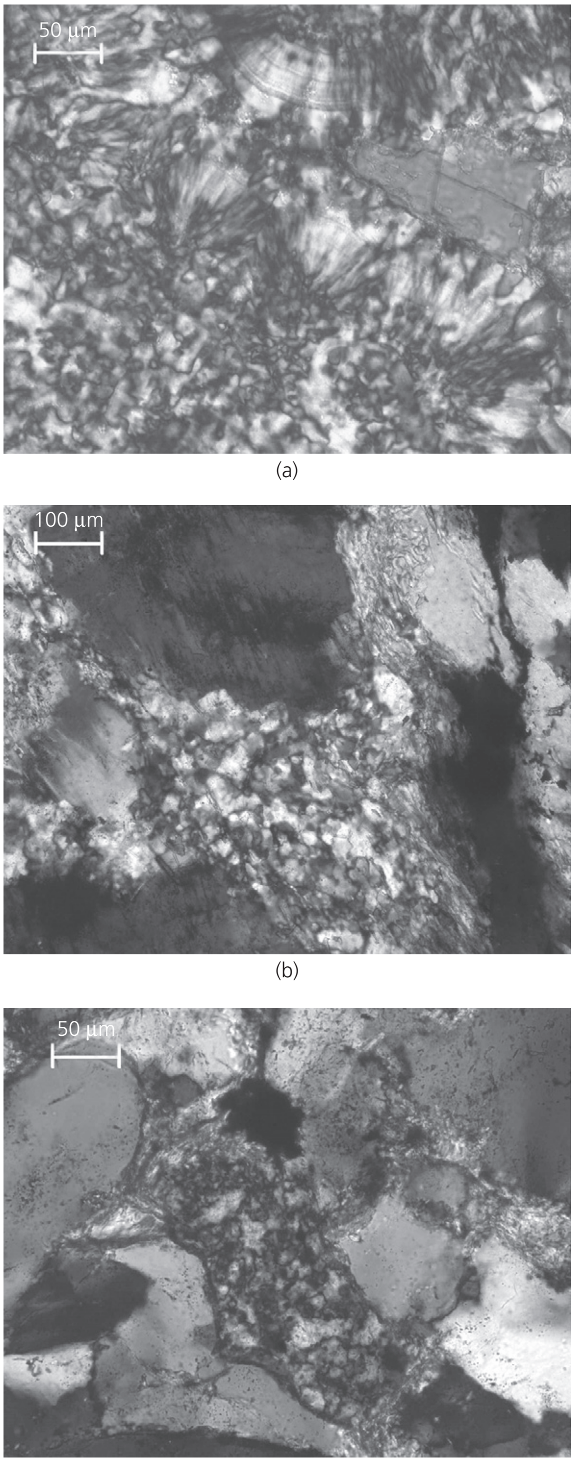
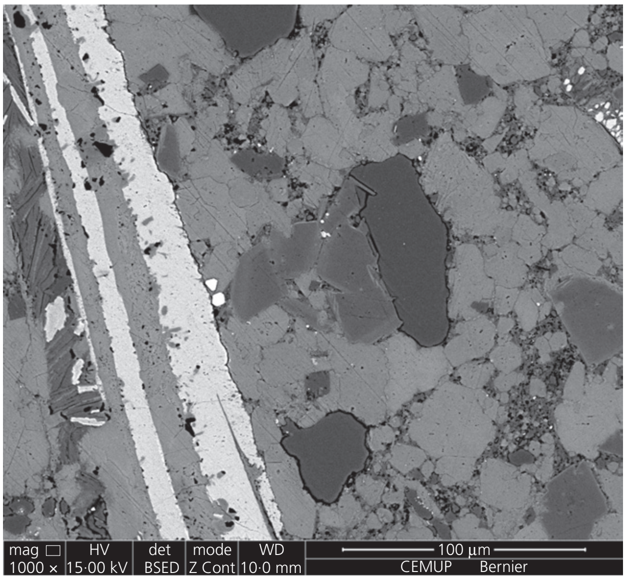
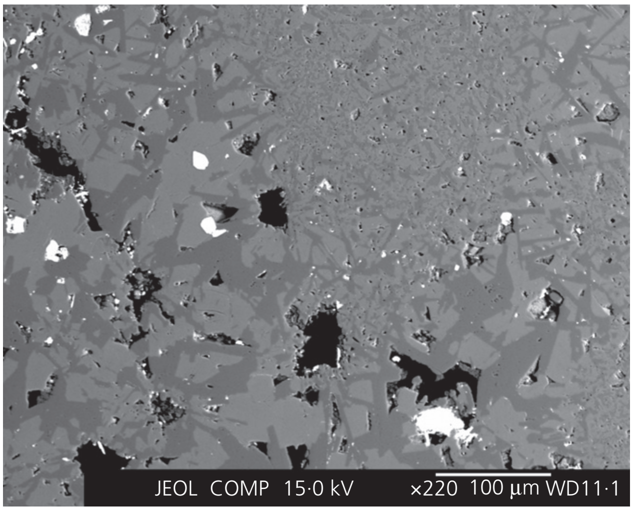


Figure 2. Aspects of the most common forms of silica considered as potentially reactive to alkalis: (a) chalcedony in a limestone; (b) subgraining in deformed granite; (c) cryptocrystalline quartz in a chert grain in sandstone



(a)



(b)

Figure 3. Typical textures of alkali-reactive aggregates. Examples of information obtained by SEM/EDS: (a) cryptocrystalline quartz in limestone (the darkest grey is quartz); (b) very fine intergrown crystals of quartz (darker grey) and alkali feldspar in rhyolite (lighter grey)

AAR-2 can be used to detect ‘pessimum’ behaviour, but the pessimum proportion indicated by the test does not reflect the behaviour of the aggregate in a comparable concrete mixture.

In addition, this test has shown many limitations, for example, when the aggregates pass the mortar-bar test but fail the concrete prism test: examples are granites, granitic gneisses, metabasalts and greywackes, as well as aggregates containing more than 2·0% porous flint (e.g. Deng *et al*., 2008; Fernandes *et al*., 2015; Freitag *et al*., 2000; Hooton and Rogers, 1992; Shayan *et al*., 2008; Soers, 1990). For slowly reactive granitic aggregates, an extended 90–100 d test period and a different limit were suggested by Alaejos *et al*. (2014) and Santos Silva *et al*. (2014).

4.2 AAR-5: carbonate testing

This method is used as a screening test to evaluate the potential alkali reactivity of carbonate aggregates. Microbars of $40 \times 40 \times 160$ mm^3 are prepared with a coarse aggregate of size 4/8 mm. A curing and exposure procedure similar to AAR-2 is applied for 14 d. To evaluate reactivity, the AAR-2 test should also be performed on the same aggregate. For ASRs, it is expected that the reactivity level and the expansions will increase by decreasing the size of the particles. Reduced expansion may indicate a different reaction – for example, an ACR. Thus, concrete prism tests are recommended for further assessment.

4.3 AAR-3: concrete prism test

The concrete prism tests ($75 \times 75 \times 285$ mm^3) better reproduce the conditions in field structures. In Rilem AAR-3 (Nixon and Sims, 2016), specimens are exposed to a temperature of 38°C for 1 year. Using the same expansion limit, the AAR-3 test can be used for two different purposes.

(a) *Evaluating the reactivity of an aggregate combination (AAR-3.1)*. It is possible to evaluate the reactivity degrees of different aggregate combinations by this method. Otherwise, if a fine aggregate is in question, it may be tested using a non-reactive coarse aggregate and vice versa. Particular aggregate combinations are tested with a total concrete alkali level of 5·5 kg/m^3 Na_2O_{eqv}.
(b) *Establishing the alkali threshold of a particular aggregate (AAR-3.2)*. At least three concrete mixes with alkali loadings in increments between 2 and 5 kg/m^3 Na_2O_{eqv} are tested. The threshold alkali level corresponds to the minimum alkali loading that results in deleterious expansion. As the concrete prism method permits a substantial amount of alkali leaching, the alkali threshold level determined will be higher than the one for field concrete. This is considered as a safety margin.

4.4 AAR-4.1: accelerated concrete prism test

The need to shorten the duration of the tests led to the development of AAR-4.1. This method is similar to AAR-3 but uses prisms stored in reactor cabinets at 60°C for 12–20 weeks (Lindgård *et al*., 2010), depending on the criterion used. The criterion for the evaluation of AAR 4.1 is still under investigation but 15 weeks is being considered (Nixon and Sims, 2016). In AAR-0 tentative guidance on criteria is given.

Besides test duration, different expansion limits have been suggested (Lindgård *et al.*, 2010; Rilem AAR-0 (Nixon and Sims, 2016)). For slowly reactive aggregates, Santos Silva *et al.* (2014) found that AAR-4.1 is conservative as it identifies a larger number of aggregates as potentially reactive, namely slowly reactive aggregates (Fernandes *et al.*, 2015; Shayan *et al.*, 2008), while Ramos *et al.* (2015) found that this test shows the best correlation with the results from petrographic analysis. However, due to factors such as mass loss, leaching and incorporation of certain non-reactive fine aggregates, lower expansion values were sometimes found for the accelerated concrete prism test (60°C) than for the concrete prism test (38°C) (Fournier *et al.*, 2006; Ideker *et al.*, 2010). This may lead to inaccurate predictions concerning aggregate reactivity. In this respect, Ideker *et al.* (2010) demonstrated that the selection of the non-reactive fine aggregate plays an important role in expansion results in both 38°C and 60°C concrete prism tests.

5. Concrete prism tests and approach for performance testing

In a EU partner project (Lindgård *et al.*, 2010; Nixon *et al.*, 2008), the test methods developed by Rilem and some local tests were evaluated with a variety of aggregates from different countries in Europe. In total, 24 partners from 14 countries participated in the project and 22 aggregates were evaluated in this multi-laboratory study (Nixon *et al.*, 2008). In addition to laboratory samples, field exposure sites were established at eight different sites. The selected aggregates were classified as

- reactive in normal timescale (5–20 years)
- slowly reactive (>20 years)
- non-reactive.

For the aggregates corresponding to 'reactive in normal timescale' group, all of the test methods and field exposure site results agreed with each other except for a sample that showed a pessimum effect. In the group of 'slowly reactive' aggregates, all the test methods were effective in identifying the reactivity, but AAR-3 had the benefit of demonstrating the 'slow' behaviour of the reaction.

Research has been carried out on comparing the 38°C method and the accelerated version of the concrete prism test 60°C. Similar methods have been developing in North America, using essentially the same approach. The comparisons reveal that 13-week expansions at 60°C were about 60% lower than 52-week 38°C expansions for fine aggregates and about 53% for coarse aggregates (Folliard *et al.*, 2004). It was also found that the use of 'non-reactive' fine aggregate for testing the coarse aggregate may affect the results at elevated temperatures. The increase in alkali leaching at increased temperatures and the increase in sulfate concentrations in pore solutions are the factors that affect the accelerated concrete prism test reliability (Ideker *et al.*, 2006, 2010).

Rilem AAR-3 (Nixon and Sims, 2016) is assumed to be better for demonstrating the rate of reaction, due to the lower temperatures applied in comparison with AAR-4.1, as observed by Shayan *et al.* (2008) using a concrete prism test similar to Rilem AAR-3. It is useful for testing aggregate combinations and for the determination of the alkali threshold of a particular aggregate combination. Ramos *et al.* (2015) found that expansions did not level off for 1 year when using granitic aggregates, suggesting that a longer exposure period is needed, making the test less useful for the construction industry. However, a good correlation was found by Fernandes *et al.* (2015) between AAR-3 and AAR-4.1 results for these slowly reactive aggregates and by different authors, as summarised by Fournier *et al.* (2004) (Figure 4).

Parameters influencing a reliable laboratory performance testing were discussed by Lindgård *et al.* (2011, 2012)

- porosity and internal moisture state of concrete prisms
- concrete (water) transport properties
- alkali leaching from the concrete prisms
- storage conditions during (accelerated) curing.

Lindgård (2013) also indicated that for lower water-to-cementitious-materials ratio (w/cm ratio), the concrete internal moisture state and the transport properties significantly influence the rate of ASR expansion. Consequently, larger concrete

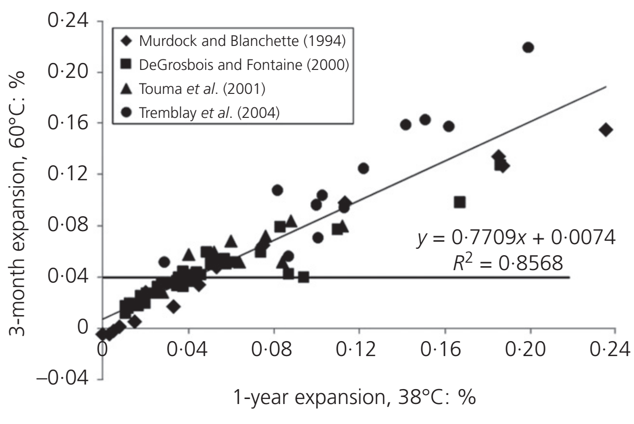


Figure 4. Comparison of concrete prism expansions (38°C against 60°C) obtained in various studies (Fournier *et al.*, 2004)

prisms (100×100 mm^2 cross-section) exhibited higher expansion due to less alkali leaching (Lindgård, 2013; Lindgård *et al.*, 2012).

National efforts to develop a performance test for special applications such as pavement concrete (Giebson *et al.*, 2012) and self-compacting concrete (Yüksel *et al.*, 2016) have also been published.

6. Summary and outlook

A number of tests have been developed to evaluate the potential reactivity of aggregates. In most recommendations and standards, especially AAR-0, there are two main methods for the evaluation of aggregates: the visual method with petrographic analysis (guided by AAR-1.1 and AAR-1.2) and expansion laboratory tests, namely the mortar-bar (AAR-2) and concrete prism tests (AAR-3 and the accelerated version AAR-4.1). These tests are arranged in a series starting with the quickest tests (petrography and mortar-bar) and extending to longer term concrete prism tests. The main advantage of AAR-2 is its quickness, but there are a number of limitations due to incorrect results with certain types of aggregates. Changing the expansion limit and/or extending the test duration needs further study. The 1-year AAR-3 test, although better simulating the field conditions, is often too slow for the construction industry unless the test is performed by each aggregate producer. The accelerated concrete prism test (AAR-4.1) seems to be a good compromise between correct identification of potentially reactive aggregates and the time needed to perform the test (12–20 weeks, depending on the criterion used). However, the present version still has drawbacks when compared with AAR-3, namely increased alkali leaching at higher exposure temperatures.

Recent results have suggested that for certain slowly reactive rocks, the threshold for reactivity and/or the duration of the tests might have to be changed. These changes have to be evaluated by different laboratories, using different types of aggregates in order to be accepted internationally.

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