Laboratory vs. field performance of ASR-affected concrete: state of the art and paths moving forward using European and North American Guidelines

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Abstract

Alkali-Silica Reaction (ASR) is a severe concrete deterioration durability issue that has been recognized for over 80 years. With decades of research around the world, the ability to properly prevent ASR in new concrete is still a conundrum. Both North American and Europe have test methods that are similar, but each have their own variations due to some test methods work better in certain regions. Over the years, test methods have been showing improvement, but the ideal job mixture test method is still absent. The ability to link test methods to field concrete has become an important trend in both regions. Moreover, both North American and Europe in recent decades have developed ASR guidelines to help determine aggregate reactivity and proper prevention of ASR. This paper gives an overview and discusses sources of errors and challenges during laboratory testing, and recommendations for improving the reliability of ASR testing are given.

Keywords

Alkali-silica reaction, concrete durability, laboratory testing, field performance, guidelines

1. Introduction

The current paper is based on the key-note presentation by the authors at the 17th ICAAR 2024 in Ottawa, Canada that occurred in May 2024. Both authors have a combined 50-year experience in accelerated laboratory testing, field exposure sites and assessment of structures with Alkali-Silica-Reaction (ASR). This paper will provide a background on current test methods and guidelines to minimize ASR in both North America and Europe. In addition, the main sources of errors and challenges are properly discussed, and recommendations for improving the reliability of ASR testing are given. The paper will only refer to ASR and Alkali-Carbonate Reaction (ACR) is not covered.

1.1 Background

For about 85 years, since Stanton [1] discovered and initiated research on ASR, testing of the potential alkali-silica reactivity of aggregates has been a topic for debate. Some methods have been more popular than others. An overview of many test methods used in various regions worldwide was included in the 2nd edition of the "*Alkali-Aggregate in Concrete – A World review*" edited by Poole and Sims [2]. Over the years, some of the frequently used methods have shown to be less reliable and have thus been withdrawn. One example is the mortar bar method ASTM C227 [3] that was withdrawn due to alkali leaching issues.

For enabling the safe use of potentially alkali-silica reactive aggregates in concrete it is a prerequisite to have reliable accelerated laboratory performance tests. Such performance testing, e.g., testing the efficiency of a specific Supplementary Cementitious Material (SCM) (e.g. fly ash) or the potential reactivity of a concrete containing the reactive aggregates in question combined with a suited cementitious binder (for example an ordinary Portland Cement (OPC) added an SCM) became more common during the 1990s. An overview of the most frequently used performance test methods is also given in Poole and Sims [2]. Most of these test methods are just slightly modified versions of existing aggregate test methods. The question is whether this approach led to reliable test results, considering that performance testing is much more complicated and challenging compared to pure aggregate testing.

The main challenges connected to accelerated laboratory testing, in particular performance testing, are summed up in 1.2 Main challenges - sources of errors. In addition to questioning whether a test method can mimic what will happen in a real structure over time, setting correct acceptance criteria (expansion limits) for the various test methods is also a challenge. The latter requires that a link has been established between results from the laboratory test methods to field performance in different environments, as discussed in section 4 Field experiences. It is a fact that one test method can be well suited for testing the potential reactivity of an aggregate but might give unreliable results when used for performance testing. Before deciding which test method to use in a certain case or project, it is thus important to be aware of the aim with the testing:

- Testing aggregate(s) or aggregate combinations?
  - Test the potential for reaction? (i.e., to use a high alkali loading, e.g. as described for the concrete prism test (CPT) ASTM C 1293 [4])
  - Determine the “alkali threshold”? (i.e., the critical alkali limit in which the aggregate or aggregate combination starts to expand, e.g. according to the procedure described in RILEM AAR-10 [5])
  - Assess whether the aggregate might show a “pessimum” behaviour (i.e., that a certain, often limited, amount of the potential reactive rock type leads to a higher expansion than a higher amount, e.g. as experienced for the Danish porous flint [2])
- Performance testing of a cementitious binder or a concrete composition?
  - Efficiency of SCMs (how much to add for hindering ASR to develop?)
  - Approve a SCM containing binder? (in a region combined with a “worst case aggregate”, e.g. as has done in Norway since 1996 [6]; or when combined with a given aggregate combination)
  - Approve “job mixtures”? (as they do for example in the US and in Switzerland)

National (or regional) regulations and guidelines, and whether any (local) laboratories have experience with the different test methods will also influence the choice of test methods.

1.2 Main challenges- sources of errors

With respect to reliability of a test result, it is a huge difference whether the aim is to assess the potential for reaction of an aggregate or approve cementitious binders or concrete for long-term field performance. The latter is much more complicated and challenging, and the list of potential sources of errors are longer. One main source of error, illustrated in Figure 1 , is alkali leaching. When testing the potential for reaction of an aggregate, a high alkali Ordinary Portland Cement (OPC / CEM I) is normally used, enabling a high alkali loading in the concrete. Normally, for most ASR reactive aggregates, this high alkali loading is much higher than the critical alkali threshold for initiating ASR. When some alkalis leach out during the test period (the amount is very depending on the test procedure, as discussed by Lindgård [7] and Lindgård et al. [8]), the influence on the expansion will be moderate (slightly reduced). However, during performance testing most concrete compositions aim to lie in the area close to the alkali threshold for the aggregate combination. The consequences of alkali leaching will thus be higher and significantly influence the measured expansion. This is most pronounced for pure OPC (CEM I) binders that have proven to show a higher rate and extent of alkali leaching than binders containing e.g. fly ash [8]. The conclusion from the performance testing might be that the concrete composition is safe to use, while long-term field behavior (with limited alkali leaching) might show the opposite.

Correspondingly, if trying to compensate for alkali leaching and instead adding alkalis (either by submerging the prisms in an alkali solution or use an alkali containing wrapping), the influence on the expansion can be significant for cementitious binders close to the alkali threshold, but less pronounced for pure aggregate testing at high alkali loads, as illustrated in Figure 1. Concrete compositions that might show good long-term field behavior can thus be rejected based on performance testing if alkali supply is part of the test setup.

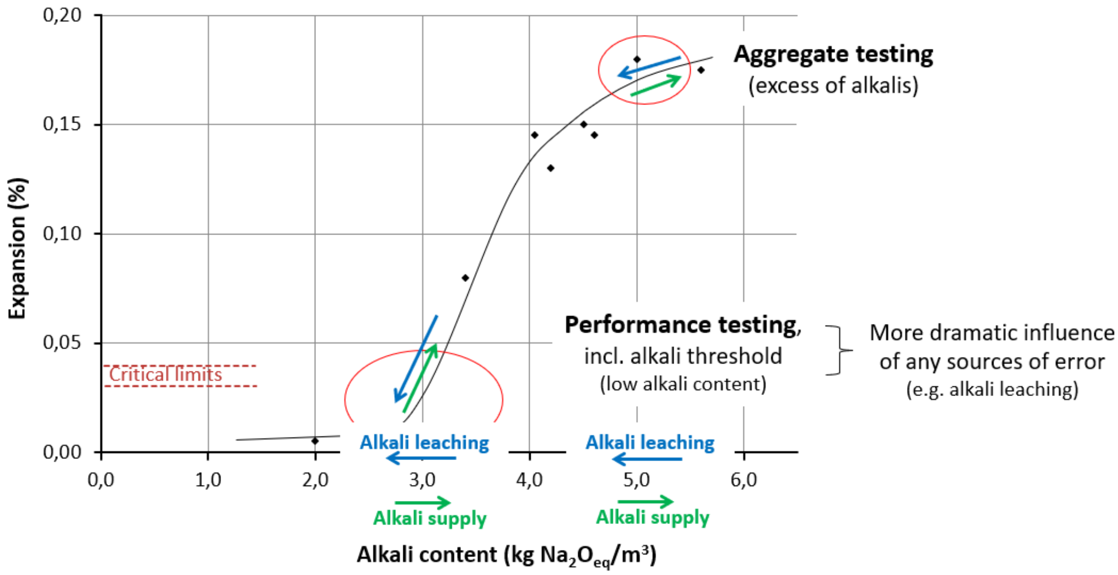

Figure 1: Principal figure showing the difference between ASR aggregate testing and ASR performance testing, including consequences of alkali leaching and alkali supply on the concrete prism expansion.

As discussed by Thomas et al. in 2006 [9] no ideal ASR performance test exists. According to the authors experiences, this statement is still valid. Thomas et al. [9] listed several requirements to an ideal ASR test method. An ideal ASR performance test should be:

- Reliable
  - I.e., mimic long-term field performance
- Rapid
  - Calling for accelerated test conditions (that normally is done by increasing the exposure temperature and/or the alkali loading and/or the access to moisture)

- Be able to test all materials
    - All aggregates type (from non- to highly reactive, incl. “pessimum” aggregates)
    - Binders with all types of SCM
    - Binders with Lithium
    - Concrete with low and high alkali loading

It is very difficult (maybe impossible) to meet all these requirements. The author’s experiences are that various test methods, from old frequently used test methods to new recently suggested tests, have some sources of error making them less reliable (to a certain extent) if they are applied to some of the purposes listed above. Based on decades of experience, Lindgård gave the following statement during his key-note presentation at ICAAR 2024: *“Pick an expansion, and I can select a test method that gives you that expansion!”*. He followed up by listing the following possible sources of error during accelerated ASR performance testing (compared to field behavior):

- The alkali inventory in the concrete pore water is complex, and is often the “ruling parameter”
    - The main source of error is alkali leaching [8]
    - If compensating for alkali leaching by adding alkalis, the outcome might be too conservative results (i.e., too high expansion)
- Use of too high exposure temperature
    - Might give unrealistic conditions in the concrete pore water
    - Might lead to the expansion also of non-reactive aggregates (or the opposite)
- Influence of the moisture state
    - Might be too low in the interior of the concrete compared to some of the most exposed field structures (e.g. if a too low water/cementitious ratio (w/cm) is used [10] or the prism size is increased too much to compensate for alkali leaching)
    - Access to too much moisture will increase the rate and extent of alkali leaching [8]

- Some aggregates might show a “pessimum” behavior
  - Might lead to too low expansions if a “wrong aggregate composition” is tested (i.e., other aggregate combinations might be worse)
- When performing “residual expansion” measurements on drilled cores from structures, the potential errors listed above might be of higher importance
  - The alkali concentration in the concrete pore water will be lower when initiating the test (some alkalis have already been consumed in the ASR)
  - Additional sources of errors might also influence the outcome of the test [11].

2. Accelerated test methods

Many accelerated standardized test methods exist in both North America and Europe for testing aggregate reactivity or prevention of ASR. An overview of many of these tests are given in [2]. Overall, many of the test methods are rather similar between North America and Europe. However, discrepancies do exist in methodologies and analysis of the results. The choice of test method is often left to the user; however, testing in North America (particularly the U.S.) heavily relies on rapid tests such as the Accelerated Mortar Bar Test (AMBT) ASTM C1260 [12]. Contradictory, Europe and Canada to a long extent rely more on long-term Concrete Prism Test methods (CPTs).

2.1 North America

2.1.1 Test methods for assessing Aggregate reactivity

2.1.1.1 Aggregate reactivity – Accelerated Mortar Bar Test (AMBT)

The Accelerated Mortar Bar Test (AMBT) is a rapid 16-days test method to determine if an aggregate is reactive. ASTM (ASTM International), CSA (Canadian Standards Association) and AASHTO (American Association of State Highway and Transportation Officials) all have their version of the AMBT. The method was invented in South Africa by Oberholster and Davies for detecting potentially deleterious alkali-silica reactivity of aggregates [13]. In this test method mortar bars measuring 25 x 25 x 285 mm are cast using fine aggregate or coarse aggregate that is crushed to a fine aggregate. The same gradation (0-4.75 mm) is used for testing fine or coarse aggregate. The cement used is either an ASTM C150 or ASTM C595 Type IL cement. After casting, mortar bars are cured at 23°C for 24 hours (in a moist room or cabinet) and then placed in a container with tap water that are placed at 80°C for 24 hours. The bars are then immersed in 1 N NaOH that is already at 80°C. The bars are measured at least three times between 0 and 14 days during the exposure in the sodium hydroxide solution. Typically, for ASTM C 1260 [12] a 0.10% expansion at 14 days of exposure is the failure criteria. CSA A23.2-25A (Canada) uses an expansion limit of 0.20% to consider an aggregate truly reactive, and anything between 0.10% and 0.20% expansion are regarded as possibly reactive. Some agencies in North America use a 0.10% expansion at 28 days.

2.1.1.2 Aggregate reactivity - Concrete Prism Test (CPT)

The Concrete Prism Test (CPT) is a one-year test to evaluate aggregate reactivity of an aggregate or an aggregate combination, combined with an ASTM C150 or ASTM C595 Type IL cement. ASTM [4], CSA [14] and AASHTO [15] each have their designated test method for the CPT. The concrete prism test consists of a concrete mixture that is cast in 75 x 75 x 285 mm prisms. After casting, the prisms are cured for 24 hours (in a moist room or cabinet) and then placed above water in a sealed container with a wicking material placed around the inside of the container to maintain near 100% Relative Humidity (RH). The containers are placed in an oven at 38°C. The prisms are measured periodically for length change, and an expansion limit of 0.04% at one year is normally used to determine the potential for aggregate reactivity. According to ASTM C1778, ASTM C1293 is the most reliable test method for determining aggregate reactivity.

2.1.1.3 Aggregate reactivity – Miniature Concrete Prism Test (MCPT)

The Miniature Concrete Prism Test (MCPT) is a hybrid approach between ASTM C1293 CPT [4] and the ASTM C1260 mortar bar test [12]. The method is specified as AASHTO T380 [15] and has been a standardized test method since 2015. In this test, concrete prisms measuring 50 mm x 50 mm x 285 mm are cast using a maximum aggregate size of 12.5 mm, a w/cm of 0.45 and a coarse aggregate volume fraction of 0.65. A cement content of 420 kg/m^3 is specified. The prisms are moist cured for 24 hours at 23°C and then demolded and placed in a container with de-ionized water that is placed at 60°C for 24 hours. Then, an initial measurement is taken, and the bars are then placed in 1N NaOH that is already at 60°C. Length change measurements are made periodically, and the current suggested expansion limits are 0.025% at 56 days for aggregate reactivity. Rangaraju et al. [16] and Drimalas et al. [17] found that the results from the MCPT [15] and the ASTM C1293 CPT [4] showed a strong correlation for determining aggregate reactivity.

2.1.2 Prevention methods

Like determining aggregate reactivity, rapid (AMBT) and longer-term test methods (CPTs) are available in North America for performance testing, i.e., assessing the effectiveness of various preventive measures (e.g. a SCM) to hinder development of ASR. The AMBT is the most popular test in the US due to the short testing time (14 days or 28 days). Many users state that they do not have time to wait two years for an answer, and thus the ASTM C1293 CPT is less used in the US. The opposite is the case in Canada and Europe.

2.1.2.1 Prevention methods - AMBT

ASTM C1567 [18] has the same test procedures as ASTM C1260. The only difference is that ASTM C1567 allows testing of supplementary cementitious materials (SCMs) in combination with an ASTM C150 or ASTM C595 cement. A mortar mixture is comprised of the reactive aggregate and in combination of the cement and SCMs. A mixture that falls below the acceptance limit of 0.10% after 14 days of exposure to sodium hydroxide is allowed to be used to mitigate that particular aggregate in a concrete mixture.

2.1.2.2 Prevention methods – CPT

The concrete prism test ASTM C1293 [4] and CSA A23.2-14A [14] allows the use of a preventive measure such as incorporation of SCM or lithium nitrate to prevent ASR. However, unlike the 1-year test for aggregate reactivity, the test duration is extended to two years while the expansion limit of 0.04% is retained.

2.1.2.3 Prevention methods – MCPT

Like the AMBT and the CPT, the MCPT also allows for prevention options to be assessed by replacing portion of the Portland cement with an SCM (as ground granulated blast furnace slag, fly ash or silica fume). Mixtures are placed in a 1 N NaOH solution for 84 days. An expansion limit of 0.02% is set for a failing criterion (expansion limit). Latifee and Rangaraju [19] investigated eight different fly ashes with different chemistries as well as slag, silica fume and metakaolin to determine the correlation to ASTM C1293. The results showed a good correlation with ASTM C1567, but not a good correlation with ASTM C1293; i.e., the opposite conclusion compared with testing of the aggregate reactivity. Drimalas et al. [17] also used the MCPT to correlate to historical exposure blocks and found that MCPT with expansion limit of 0.02% at 84 days had a better correlation than ASTM C1293 results.

2.2 Europe

2.2.1 National test methods - development of RILEM test methods

In Europe, numerous ASR test methods have been used over the years to determine the potential alkali-reactivity of aggregates. There are two main reasons for this; 1) According to the EN standards, national test methods and guidelines should be used for assessing the risk for developing ASR; 2) In some countries, some of the aggregates show a "pessimum" behavior (e.g. aggregates containing flint), calling for special test methods to be used. This paper will not go further into details regarding these special test methods, rather refer to the overview given in the updated "*World review on ASR*" [2] and give a few examples of special test methods used. For example, in France and Switzerland, a quick chemical test [20] has been used for a long time, while various tests have been used in Denmark, including two special tests for fine aggregates, [21] and [22].

As a basis for possible future common ASR test methods world-wide and common EN standards in Europe, RILEM Technical Committees (TCs) has continued since the establishment of the first TC in 1989, as summed up by Wigum & Lindgård [23] and Wigum et al. [24]. In the first TCs, the focus was on developing reliable test methods for determining the potential reactivity of aggregates. In later TCs, the focus changed into developing reliable ASR performance test methods, [25] and [26]. A guide on how to use the various RILEM test methods, labelled RILEM AAR-0 [27], was also published in 2016 and later updated in 2021 as part of RILEM TC 258-AAA (2014-2019).

Regarding the ASR history in Europe, some countries like Iceland, Denmark and Germany, have been aware of the potential ASR risk for more than 50 years, and taken actions accordingly [2]. Other countries, for example Finland [2], have recently discovered that they have some structures with ASR, while a few countries still have not yet seriously checked if they have any ASR issues. When introducing a system for assessing the potential ASR risk in these latter countries, the RILEM methods are well suited as a basis for building up national experience with ASR and developing national acceptance criteria based on the local geology and environment.

2.2.2 RILEM test methods for assessing Aggregate reactivity

2.2.2.1 Aggregate reactivity – AMBTs

Different versions of the AMBT [13] are frequently used in Europe, often according to national standards or according to ASTM C1260 [12]. RILEM has also developed its own version of the AMBT, named RILEM AAR-2. The first version was published in 2000 [28], while an updated version was published in 2016 [29]. In RILEM AAR-2 there are two options for bar size, either option AAR-2.1 with bar size 25 x 25 x 285 mm ("long thin", as in ASTM C1260) or option AAR-2.2 with the alternative bar size 40 x 40 x160 mm ("short fat"). Criteria for the interpretation of the results of AAR-2 have not yet been finally agreed. However, based on trials carried out by RILEM on aggregates of known field performance from various parts of the world, it seems that the same criteria as used in Canada can be recommended if local experience does not state otherwise [27]. This means that "*in the case of aggregate combinations producing AAR-2 results (after 14 days of exposure) of 0.10% or higher for "long thin" bars (AAR-2.1) or 0.08% or higher for "short fat" bars (AAR-2.2), precautions will probably need to be taken to minimize the risk of ASR damage to any concrete in which the material is used unless concrete prism testing or field performance indicates otherwise".*

2.2.2.2 Aggregate reactivity – CPTs

Different CPTs have been frequently used in Europe, often according to national standards. Examples are the 1-year Norwegian 38°C CPT (using large prisms of size 100 x 100 x 450 mm) [30], the German 9-months "fog chamber" 40°C CPT [31] (also using large prisms of size 100 x 100 x 400 mm), and Portugal [32,33] using a more accelerated 60°C CPT (similar to RILEM AAR-4.1, see below). RILEM has developed its own CPTs for assessing the potential reactivity of aggregates. One of these methods has prisms exposed to 38°C (RILEM AAR-3; exposure period 12 months) and another accelerate method where the prisms are exposed to 60°C (RILEM AAR-4.1; exposure period > 20 weeks).

RILEM AAR-3 was first published in 2000 [34], while an updated version was published in 2016 [35] (prisms of size 75±5 x 75±5 x 250±50 mm). The main revision made from the first to the current version is that the prisms in the first version were wrapped in a moist cotton cloth and plastic (except the two end faces). However, Lindgård documented that this wrapping led to a high rate and extent of alkali leaching, and thus too low expansion [7, 8]. The current version exposes the prisms to 100 % RH like ASTM C1293.

The first versions of RILEM AAR-4.1, developed about 20 years ago, were only draft versions (using the same prism size as AAR-3); one wrapped version like the wrapped AAR-3 CPT [34] (except being exposed to 60°C) and one unwrapped version. The latter version of RILEM AAR-4.1 was published in 2016 [36]. The reason for withdrawing the wrapped version was the same as for withdrawing the wrapped AAR-3 version (see above) [7, 8].

None of the two CPTs AAR-3 and AAR-4.1 are recommended used for determination of alkali threshold for aggregates. The reason is the high rate and extent of alkali leaching, being highest at 60°C [7, 8]. RILEM rather recommends using RILEM AAR-10 [5] as discussed in 2.2.3 RILEM ASR concrete performance test methods.

2.2.3 RILEM ASR concrete performance test methods

For several European countries, performance testing has been part of the national regulations. As for aggregate reactivity testing, different test methods, according to national standards, have been used. Examples are the Norwegian 38°C CPT (using large prisms of size 100 x 100 x 450 mm; exposure period 12 or 24 months) [30] and Switzerland [37,38] using a more accelerated 60°C CPTs (similar to RILEM AAR-11, see below; exposure period 5-12 months), and Denmark using a special performance test for the Danish "pessimum" reactive flints where mortar bars (of size 40 x 40 x 160 mm) are submerged in saturated NaCl solution at 50°C for 20 weeks [21].

RILEM has developed its own concrete performance tests. The first test method exposes prisms to 38°C for a period of 12 or 24 months (RILEM AAR-10) [5]. The second method accelerated version exposes concrete prisms to 60°C for a period of 5 or 12 months (RILEM AAR-11) [39]. RILEM AAR-10 is based on RILEM AAR-3, but to reduce the rate and extent of alkali leaching larger prisms, like in the Norwegian CPT, are used (of size 100±2 x 100±2 x 400-450 mm). The scope of RILEM AAR-10 is [5] *1) Application 10-1: Assessment of how SCM content may reduce ASR susceptibility of an aggregate combination, and 2)*

Application 10-2: Assessment of how available binder alkali content can be reduced by SCMs (tested with a regional worst-case aggregate combination). RILEM also recommends using AAR-10 for determination of alkali threshold for aggregates.

RILEM AAR-11 is based on RILEM AAR-4.1 (prisms of size 75±5 x 75±5 x 250±50 mm). The scope of RILEM AAR-11 (Application 11-1 and 11-2) is the same as for RILEM AAR-10, but additionally a third application (11-3) is [39] *Assessment of the ASR resistance of specific concrete compositions to verify their suitability in a performance test* (i.e., testing "job mixtures"). The exposure period is 52 weeks if SCMs are added.

RILEM has also developed a 60°C version with alkali supply (NaCl-solutions; referred to as RILEM AAR-12) [40]. The same three applications as for AAR-11 are valid, but the AAR-12 CPT is designed for performance testing of concrete for pavements. Drying cycles are also part of the testing procedure. Another special test developed with the same purpose as RILEM AAR-12 is the "Weimar climate simulation chamber" [41], where the prisms are exposed to various exposure conditions, from drying, alkali supply, high humidity and freeze-thaw cycles.

Finally, RILEM has also developed a wrapping procedure (RILEM AAR-13) [42]. The wrapping procedure was originally proposed by a technical committee of the Japan Concrete Institute [43]. As stated in the scope, *AAR-13 provides a wrapping method that aims to prevent loss of alkalis by providing an equilibrium of alkali concentration at the specimen surface while also supplying additional moisture for concrete prisms during expansion tests for ASR. The wrapping procedure should be used in combination with various concrete prism tests such as RILEM AAR-3, AAR-4.1, AAR-10 & AAR-11.*

2.3 Assessment of test methods

Many accelerated laboratory tests for assessing the potential alkali-silica reactivity of aggregates materials or for performance testing to evaluate mortars and/or concretes to prevent ASR exist world-wide. For all these methods one or more sources of errors, that one should be aware of, might influence the test results (as debated in 1.2 Main challenges - sources of errors). The outcome of an ASR test is thus strongly dependent on the test method selected for testing [7, 8]. Some test methods, for example the AMBT, are reliable for many aggregate types but might give false positive results (i.e. erroneously classify as reactive) or false negative results (i.e. erroneously classify as non-reactive) for other types of aggregates. At many international AAR conferences (ICAAR) and in many journal papers several authors have discussed which aggregates that are more vulnerable to show unreliable results with this method. For the CPTs, e.g. ASTM C1293, one of the main influencing errors is alkali leaching. But, when trying to compensate for the alkali leaching by supplying alkalis, e.g. as in the MCPT, one might "overcompensate" and supply too much alkali resulting in a too conservative conclusion. In the PARTNER project, an assessment of the suitability of the draft RILEM aggregate test methods and some national European test methods was assessed [44]. After comparing the laboratory results with expansions measured on monitored concrete cubes exposed for 15 years on the eight field exposure sites established in Europe, Borchers et al. [45] concluded that *the RILEM AAR-4.1 60°C CPT [36] and the Norwegian 38°C CPT [30]* (similar to RILEM AAR-10 [5]) *seem to be best suited to identify the potential reactivity of moderately reactive aggregate combinations*. These methods, as several of the other test methods included in the study, were also able to correctly identify all the non-reactive and highly reactive aggregate combinations tested.

Moreover, a method could be well suited for testing the alkali-silica reactivity of an aggregate composition, but less suited for performance testing. Also, one should take caution if "pessimum" reactive aggregates, for example flint of chert, are present in the aggregates that are considered for use. Beyond this critical point giving the highest expansion, called the ''pessimum'', the ASR expansion decreases. When using such "pessimum" aggregates one could risk that the aggregate composition used has a higher reactivity than the compositions tested.

Additionally, the acceptance criteria (expansion limits) to a specific test method might vary from one country to another (for the same test method) based on national experiences. Consequently, for obtaining reliable test results knowledge is needed about the aggregate properties, available ASR test methods (in that region) and their possible sources of errors, the local climate, and local field experiences (i.e., within the region in which the concrete is to be used). The latter is the basis for evaluating (deciding) the acceptance criteria (expansion limits). Often, such a link from laboratory to field is documented by establishing field exposure sites (see 4.3 Field Exposure Sites) with concrete containing different types of aggregates and different cementitious binders [46].

Generally, it is thought the more you accelerate a test method the more you move away from actual field exposure conditions. Hence, when using a quick performance test (AMBT at 80°C) the outcome of the test is more questionable. RILEM rather recommends using long-term concrete performance tests [27], like RILEM AAR-10 [5] or alternatively RILEM AAR-11 [39] (provided that a link to field is established for the latter). In the 80°C AMBT method the main source of alkalis is Na origin from the high alkaline 1N NaOH solution in which the bars are submerged. Thus, the main controlling factor for the expansion (i.e., development of ASR provided that the aggregate is potentially reactive) is the rate of ingress of alkalis. Consequently, a higher porosity (higher permeability) corresponds to a higher rate of ingress of alkalis and therefore a higher rate of expansion. When adding a SCM to the mixtures for mitigation ASR, normally the permeability will be reduced, the ingress of alkalis will be slowed down, and thus the rate and extent of expansion will be lower. Contradictory, in the field, the main controlling factor for ASR (when using a reactive aggregate) is the alkali content (pH) in the concrete pore water (mainly supplied by the cement clinker, but reduced when adding SCM to the mixture), and not the permeability of the concrete (even though it to some extent will influence the rate of expansion).

3. Guidelines

3.1 North America

In North America, there is uniform guidance on how to evaluate aggregate reactivity and sections of either a preventive or prescriptive based approach for preventative measures for reactive aggregates. CSA first developed the model which has now expanded into other organizations. Collaboration between Canadian and US researchers has led to this unified approach. Between FHWA, ASTM, AASHTO and CSA the general approach to identifying potential alkali-aggregate reactivity is shown from the ASTM C1778 guidance document [47] which was developed in 2016.

The first step of these guidance documents is to determine if the aggregate is reactive and determines the level of reactivity. Once the potential for reactivity is known, two general approaches are possible to proceed for concrete construction:

1. If the aggregate is determined to be non-reactive, it can be used without any further preventive measures.
2. If the aggregate is determined to be potentially reactive, it can be used following either a performance-based approach or a prescriptive-based approach.

The performance-based approach allows for either the ASTM C1567 14-day AMBT test or the ASTM C1293 two-year concrete prism test to determine the SCM amount needed to prevent ASR for a given aggregate. ASTM C1778 provides the guidance that the expansion limit for ASTM C1567 must not exceed 0.10% at 14 days and for ASTM C1293 the expansion limit must not exceed 0.04% at two-years. SCMs that have high alkalis are not allowed to be used in ASTM C1567 and must follow ASTM C1293.

The prescriptive based approach follows a risk-based decision tree to minimize the risk of ASR. The prescriptive based approach follows this decision tree and determines the aggregate reactivity, structural classification, environmental conditions, and structural type. Aggregate reactivities are based on either ASTM C1260 or ASTM C1293 expansions. The classification of aggregate reactivity ranges from R0 (non-reactive) to R3 (very highly reactive). R3 reactivity would have an ASTM 1260 value greater than 0.45% at 14 days or ASTM C1293 expansion value greater than 0.24% at 1 year. The determination of ASR risk is based on a sliding scale between levels 1-6 when combining aggregate reactivity with the size and exposure conditions of the structure. The lowest risk level (1) would be for low reactive aggregate in a non-massive structure in a dry environment and the highest risk level (6) would be for all concrete with a R3 aggregate exposed to alkalis in service. The structural classification (SC1-SC4) is then chosen from a table. After these are determined, the following preventive measures can be followed which are based on risk.

- Limiting the alkali content of the concrete
- Use of fly ash, slag cement or silica fume
- Use of ternary blends (i.e., a mixture of two SCMs)

A prescriptive table in ASTM C1778 provides the SCM amount needed to minimize the risk of ASR. The higher the risk of ASR, the greater amount of an SCM is recommended.

3.2 Europe

As debated in 2.2 Europe, national test methods and guidelines should be used for assessing the risk for developing ASR. This might be challenging for the aggregate producers exporting aggregates to other European countries. With respect to assessment of ASR, one can risk that an aggregate should be treated as reactive in the country of origin, but “non-reactive” in the place of use, or the opposite. Moreover, which precautions to take to avoid ASR (mitigation measures) with the same potentially reactive aggregate will also vary from country to country, i.e., the national regulations differ due to local experiences.

One example of an "old" national guidance document is the Norwegian ASR regulations that has been used successfully for about 30 years. The ASR test methods were first published in 1993 (SINTEF report). In 1996, the Norwegian Concrete Association (NCA, labelled "NB" in Norwegian) published "NB21" [6]. In this document, acceptance criteria for the three aggregate test methods included in the SINTEF report (petrographic analysis, AMBT and the Norwegian Concrete Prism Test (NCPT)) were given. If below the critical expansion limits, the aggregate can be used without any limitations. In addition, performance testing of concrete with SCMs was introduced. NB21 has been updated twice (in 2004 and in 2017) based on new research regarding links from laboratory to field. The main use of the NCPT [30] for performance testing has been for approval of all blended cements (or OPC mixed with a SCM) used in Norway. Then the binder in question is tested versus a "worst case" Norwegian aggregate combination. Before a new blended cement or a new SCM are introduced on the market they must be pre-tested for determination of the maximum allowed alkali content in the concrete. Since a "worst case" aggregate combination is used in the tests, the documentation of the binder is valid for all other Norwegian natural aggregates. I.e., the documentation can be used by all the concrete producers without any supplementary testing.

In 2016, RILEM published a guide on how to use the various RILEM test methods (labelled RILEM AAR-0). Some recommendations regarding acceptance criteria were also given. This guide was updated in 2021 [27] as part of RILEM TC 258-AAA.

In 2016, RILEM also published a guidance document labelled RILEM AAR-7.1 "International Specification to Minimize Damage from Alkali Reactions in Concrete" [48]. Part 1 deals with alkali-silica reactive aggregates, while Part 2 provides separate guidance on reactive carbonate aggregates (ACR). Part 3 gives specific guidance on very large, long-service structures, such as dams. The two latter documents will not be discussed further in this paper.

Part 1 of AAR-7.1 is built up similarly to ASTM C1778. First, the level of risk (S1-low, S2-normal or S3-high) appropriate to the structure is decided based on consequences of any ASR damage. Typical structures belonging to each of the risk levels are listed in a table. For example, nuclear installations, dams and tunnels are in the highest risk class. Next, the exposure conditions are categorized in three environmental classes (E1-E3). By combining the environmental class and the risk level, the level of precaution is decided. Then, for each of the four levels of precautions (P1-P4) precautionary measures are recommended. Finally, four precautionary measures (M1-M4) are recommended. For example, precautionary measure M1 limits the alkalinity of the pore solution, either by limiting the alkali content of the concrete, by use a low alkali cement or by adding sufficient of a SCM. Based on the aggregate reactivity (low, medium or high) AAR-7.1 also recommends minimum addition of fly ash, ground granulated blast-furnace slag, silica fume and metakaolin. Also, proportions of alkali from the fly ash and the slag that should be included in the calculation of the alkali content of the concrete mix are given.

After about 35 years of work within RILEM for developing ASR test methods, the first meeting in a CEN committee aiming to develop common European ASR test methods (EN standards) was launched in December 2024. The work will be based on the RILEM test methods and some national methods. In the draft concept, the plan is to prepare several test methods published as EN standards. However, which test methods to adopt in a country and the determination of the acceptance criteria should be up to each country to decide.

4. Field experiences

4.1 Establishing a link from laboratory to field concrete

For benchmarking the reliability of various accelerated laboratory test methods to field concrete, and for determination of the acceptance criteria (expansion limits) for the different test methods, it is crucial to have a link to field. However, only occasionally a link to concrete structures has been documented and published (see 4.2 Existing concrete structures).

Normally, the link from laboratory to field concrete is established through field exposure sites (see 4.3 Field Exposure Sites). Then one can easily and rather cost-efficiently test many aggregates, concrete and SCMs, including new types of SCMs. The access to follow up and measure the samples prepared is also easy and can be performed when the weather conditions are suitable (i.e., stable temperature within certain limits and at the same time avoid too much heating from the sun). Moreover, most concrete samples on the field exposure sites do not contain any reinforcement. Thus, any expansion due to ASR will not be retained by the rebars, and thus the expansion will be higher compared to a reinforced concrete structure.

As part of the work of RILEM TC 258-AAA (2014-2019) information about all known ASR field exposure sites world-wide and approximately 15 concrete structures from around the world were collected. However, this data has not yet been published.

4.2 Existing concrete structures

The ability to tie laboratory tests to existing structures is difficult to capture. It is known that throughout North America and Europe thousands of structures are deteriorating from ASR when mixtures do not incorporate SCMs. This can easily be linked to test methods that focus on aggregate reactivity. However, there is limited knowledge between the connection between laboratory testing and structures with SCMs. This may partly be due to structures with SCMs may not be showing significant deterioration which shows the importance of mitigation measures to prevent ASR.

An example of a well-known field site linking laboratory test methods to field concrete is the Lomas Blvd test section in Albuquerque, New Mexico. The site was developed in 1992 by the New Mexico State High and Transportation Department. Table 1 provides the AMBT results for the different test sections. For both aggregate types used, the laboratory test results show that the lowest calcium fly ash mix is below the expansion limit at 14 days. Figure 2 shows the field observations of each test section. In this figure, also results for concrete added LiOH are included. Generally, there is a good correlation between the test results and the field observations. The low calcium fly ash is showing minor cracking after 16 years.

Table 1: Laboratory test results for Lomas Blvd test section [49].

Aggregate	Test Sections (type of fly ash)	Expansion after 14 days
Shakespeare	No fly ash	Fail > 0.50 %
	Class C (high calcium)	Fail > 0.50 %
	50/50 Class C and Class F Ash	0.125 %
	Class F (low calcium)	0.045 %
Placitas	No fly ash	Fail > 0.50 %
	Class C (high calcium)	Fail> 0.40%
	Class F (low calcium)	0.055 %

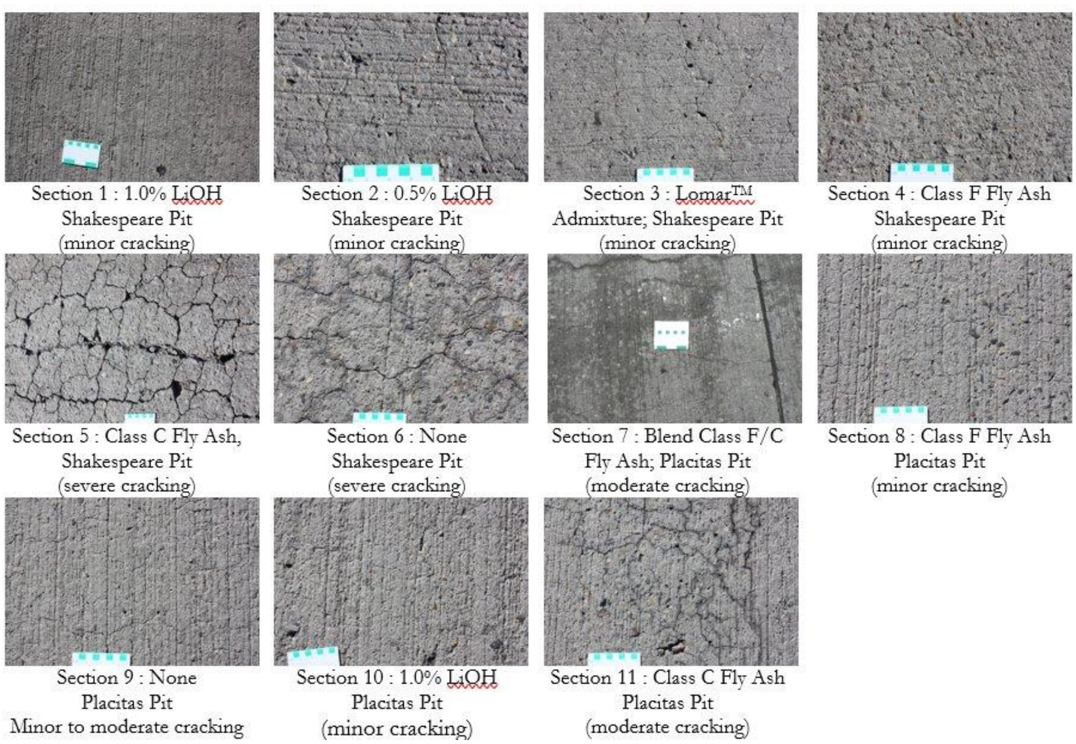

Figure 2: Field observations of Lomas Blvd test sections after 16 years [50].

4.3 Field Exposure Sites

4.3.1 Overview

As summed up by Fournier et al. in the review of existing field exposure sites [46], "*over the past 50 years, outdoor exposure sites have been developed in several countries with the objective of validating data obtained from laboratory testing for various combinations of reactive aggregates and SCM, as well as for determining long-term performance of specific mix designs*". Several other papers also sum up some of the experiences with linking experiences from laboratory to field, see for example [51,52,53,54]. These exposure sites consist of large-scale concrete blocks (with different dimensions) that are placed outdoors. At least 25 (11 in North America and 14 in Europe) ASR exposure sites are known to exist around the world. The oldest in North America is about 80 years, and the oldest European site is about 55 years.

In some studies, field cubes have been cast in one laboratory and shipped to other sites enabling documenting the influence on environmental conditions on development of ASR [46]. Examples are the European PARTNER project (2004), the "COIN" study (2010) and the "LNEC cube study" (2015) (see 4.3.3 European sites). "NCHRP 1083" (2023) (see 4.3.2 North America sites) is a recent project that cast exposure blocks and transferred blocks to sites across North America.

4.3.2 North America sites

In North America, nearly 3000 exposure blocks are monitored yearly to be linked to accelerated laboratory testing. Figure 3 shows the locations of these field exposure blocks. The first exposure site was developed at Treat Island, Maine in the 1940s. The locations at University of Texas at Austin and CANMET in Ottawa provide the exposure sites that contain the most exposure blocks. In North America, two block dimensions are used at each site. Block dimensions are either 400 x 400 x 760 mm or 400 mm cubed blocks.

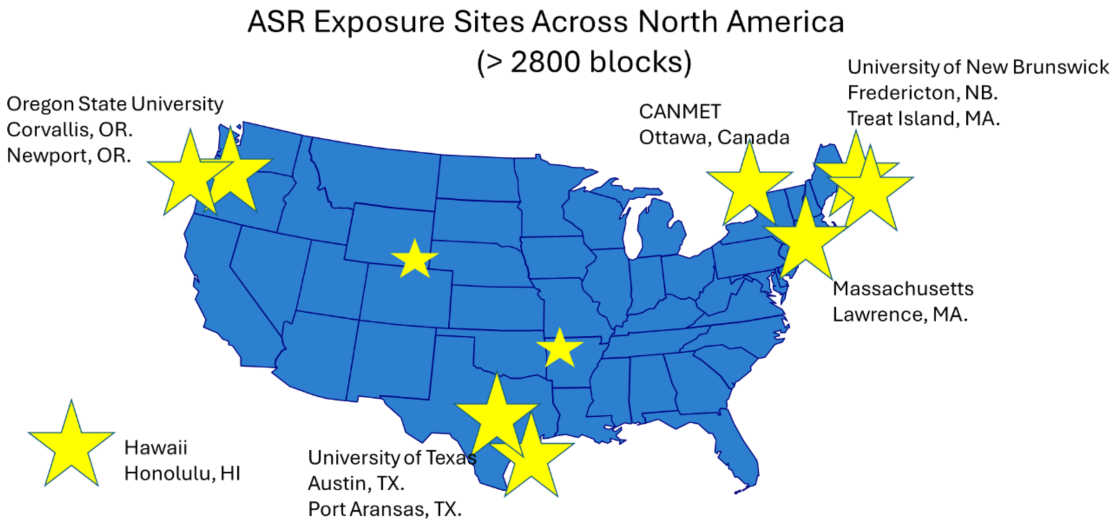

Figure 3: Exposure site locations in North America.

Recent findings in North America have shown a disconnect between accelerated laboratory testing and field exposure blocks [17,46,53]. Figure 4 and Figure 5 show the correlation for the two most common performance test methods in North America compared to boosted exposure blocks (i.e., blocks where the alkali content of the concrete is boosted with sodium hydroxide to an alkali equivalent of 1.25% Na_2O_{eq}). The critical expansion limits are also included in the figures. For the concrete blocks, normally an expansion limit of 0.040 % is used. Exposure blocks after 10-15 years of exposure at the CANMET site (Ottawa) and University of Texas site (Austin) are expanding and showing a disconnect with accelerated laboratory testing. The ASTM C1293 CPT is showing even a lesser correlation than the AMBT. The CPT prisms and the exposure blocks were cast from the same concrete mixture.

Table 2 provides the three main test methods in North America and correlates them to historical exposure blocks containing SCMs. The exposure blocks are boosted by taking the cement portion of the mixture and increasing the alkalis to 1.25% sodium equivalent. The CPT and MCPT mixtures are also boosted to 1.25% sodium equivalent. The current specified test method's duration and expansion limit are shown in bold. The MCPT provides the best correlation at 75% to historical exposure blocks. The ASTM C1293 CPT provides a poor correlation of only 28%. Extending the duration in ASTM C1567 to 28 days increases its correlation from 44% to 81%. Today, many agencies in North America use a 28-day duration.

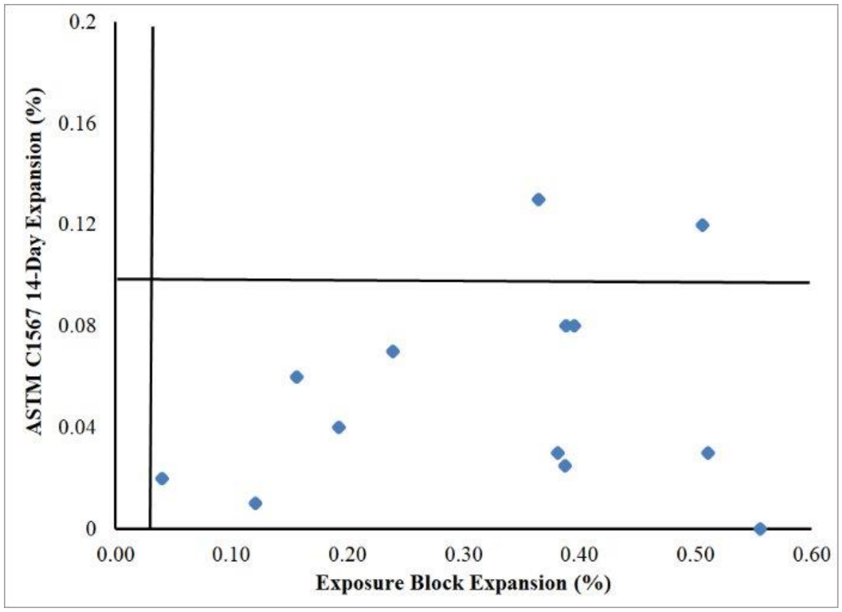

Figure 4: Comparison of ASTM C1567 results to boosted exposure blocks with SCMs after 10-15 years of exposure at the field sites at Austin, Texas and Ottawa, Canada [17].

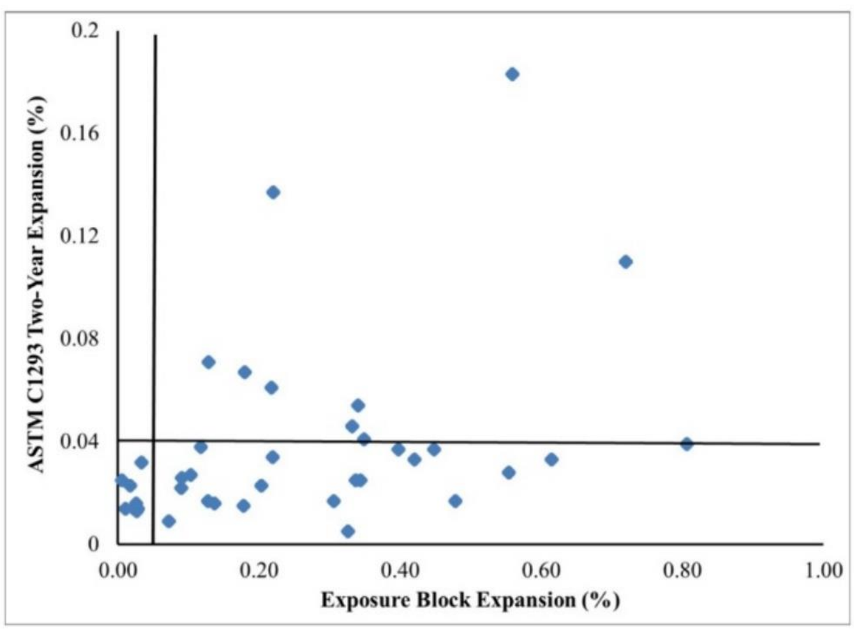

Figure 5: Comparison of ASTM C1293 results to boosted exposure blocks with SCMs after 10-15 years of exposure at the field sites at Austin, Texas and Ottawa, Canada [17].

Table 2: Determining the accuracy of boosted historical exposure blocks to accelerated laboratory test methods [17]. The current specified test method's duration and expansion limit are shown in bold.

Test method	Accuracy of test methods matching the historical concrete blocks		
ASTM C1567 [18]	**14 Day Expansion Limit = 0.100%**	14 Day Expansion Limit = 0.080%	14 Day Expansion Limit = 0.060%
	44%	56%	72%
ASTM C1567 [18]	28 Day Expansion Limit = 0.100%	28 Day Expansion Limit = 0.080%	28 Day Expansion Limit = 0.060%
	81%	88%	94%
ASTM C1293 [4]	**2 Year Expansion Limit = 0.040%**	2 Year Expansion Limit = 0.030%	2 Year Expansion Limit = 0.020%
	28%	39%	56%
AASHTO T 380 [15]	84 Day Expansion Limit = 0.030%	**84 Day Expansion Limit = 0.025%**	84 Day Expansion Limit = 0.020%
	63%	**75%**	81%

4.3.3 European sites

The oldest known field exposure sites in Europe are located at VDZ in Germany (1970s), the Icelandic Building Research Institute in Iceland (1974) and at BRE in UK (1989). In 2004, six new sites were established as part of the PARTNER project were concrete cubes (including 13 combinations of European aggregates combined with a high alkali cement) were shipped to 8 locations (incl. to the existing sites at VDZ and BRE) from north to south in Europe [44,45] (see Figure 6). Another example of a joint R&D project that included field exposure sites is the "LNEC cube study" (2015) [55] were concrete cubes (included four aggregates, high alkali cement (control) and addition of 20% and 30% of a class F fly ash, respectively) were produced at LNEC in Lisbon and shipped to 10 field sites, 7 in Europe (see Figure 6) and 3 in North America (Austin, Ottawa and Treat Island; see Figure 5) [46]. The "LNEC cube study" was part of the work in RILEM TC 258-AAA.

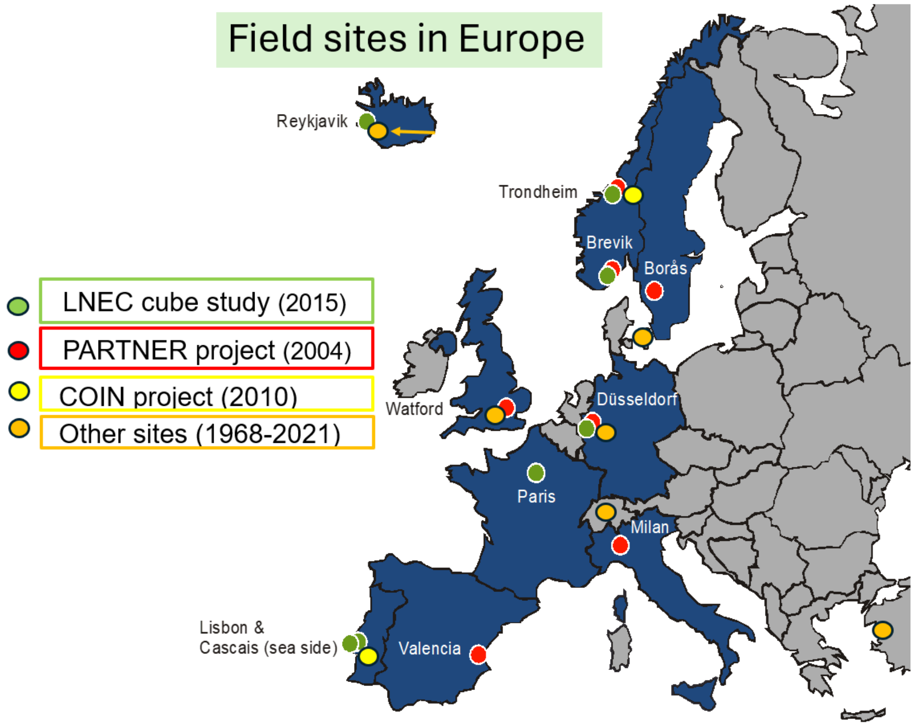

Figure 6: Known exposure site locations in Europe.

Today, 14 known field exposure sites exist in Europe, as shown in Figure 6. At most sites 300 mm concrete cubes are stored. Each cube is monitored on two side faces and the top face, enabling measuring the expansion in two directions on each side face. In this figure, also the "COIN" study initiated in 2010 is included [56]. From each of the 20 concrete mixtures included one cube was produced and transported to LNEC in Lisbon, Portugal, while a parallel cube is stored at SINTEF in Trondheim. Five aggregate combinations and various cementitious binders (included OPC ("alkali threshold" determination"), fly ash and ggbf slag) were part of the study. For each of the concrete mixtures, five to seven of the modified CPT procedures included in the preceding laboratory COIN study [7] were included enabling comparison with long-term field data in two environments (south and north of Europe). The laboratory testing involved the three "standard" CPTs, i.e. Norwegian CPT [30], ASTM C1293 [4] and RILEM AAR-4.1 [36], in addition to pilot testing using wrapping added alkalis (for preventing alkali leaching). An example from the "COIN" study (still to be published) is shown in Figure 7. The aggregate composition in both mixtures is the non-reactive Årdal fine and the alkali-reactive coarse Ottersbo cataclasite from Norway. The total alkali content of the two OPC binders is 2.0 and 2.8 kg/m^3 Na_2O_{eq}, respectively. The first concrete is not expanding in the laboratory when tested according to the Norwegian 38°C CPT [30] (similar to RILEM AAR-10 [5]), while the latter is expanding far beyond the expansion limit. The "alkali threshold" for this aggregate combination thus lies between these two alkali contents, most likely between 2.0 and 2.5 kg/m^3 Na_2O_{eq} when accounting for the minor alkali leaching during laboratory testing with the Norwegian CPT [8]. After 13 years of exposure in Lisbon, the match between the laboratory data and the field cubes is very good. The cube with the 2.0 OPC binder is not expanding (still shrinking), while the expansion of the 2.8 OPC binder kicks off after about 3.5 years in field but levels off after about 9 years of exposure at an expansion level significantly lower than the 2-years expansion of the laboratory prisms. Also, the expansion of field cubes with higher alkali levels (3.7 and 5.5 kg/m^3 Na_2O_{eq}, respectively) is shown in the figure. As expected, the rate and the level of expansion increases with increasing alkalinity in the concrete pore water.

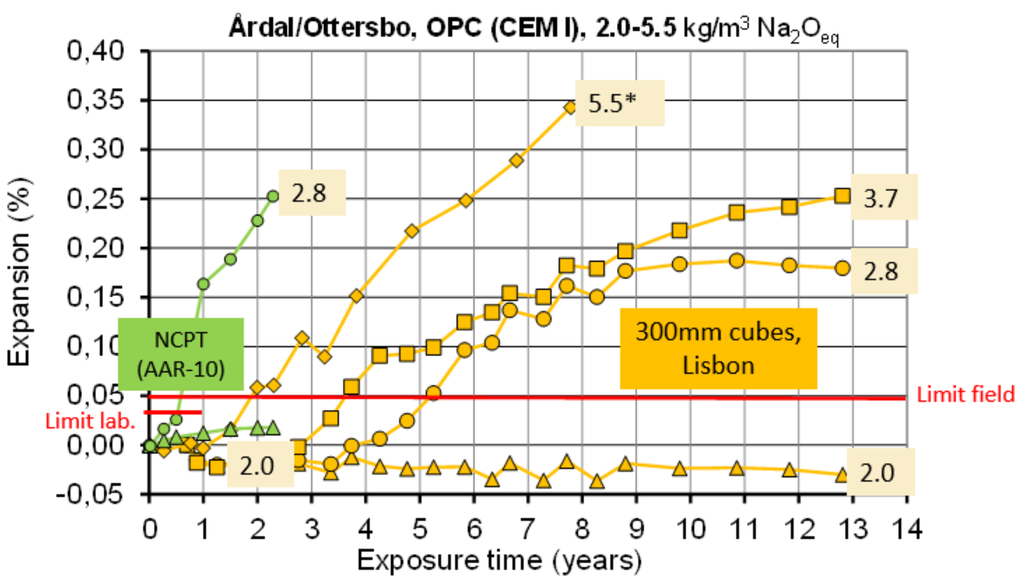

Figure 7: Example from the "COIN" study showing the link from laboratory testing with the Norwegian CPT to 300 mm field cubes stored in Lisbon. The numbers represent the nominal alkali content (kg/m^3 Na_2O_{eq}) of the OPC binders *(* Part of the "LNEC cube study")*.

5. Summary and recommendations

Despite that accelerated laboratory ASR testing has been performed for many decades, the ability to reliably test various ASR preventive measures in new concrete is still a conundrum. Over the years, some test methods have improved, but the ideal job mixture test method is still absent. Both North American and Europe have test methods that are similar, but each have their own variations, both due to some test methods work better in certain regions and based on historical performance (i.e., what the market requests). The selection of a test method is decided on a national level. A general trend is that the US heavily relies on rapid tests such as the 14-day Accelerated Mortar Bar Test (AMBT), i.e., ASTM C1260 [12] for aggregate testing and ASTM C1567 for prevention testing [18]. Contradictory, European countries and Canada to a long extent rely more on long-term Concrete Prism Test methods (CPTs), either at 38°C (1 to 2 years of exposure) or at 60°C (normally ½ to 1 year of exposure). RILEM has developed their own CPTs (see overview in [27]), and some of these test methods are forming the basis for the work recently initiated within CEN for development of common European ASR test methods (EN standards). However, which of the new EN ASR test methods to select for use in a country and the corresponding acceptance criteria (expansion limits) will most likely be up to each nation to decide.

This paper, that only refers to ASR (i.e., not ACR), provides background on current test methods and gives an overview of guidelines in both North America and Europe to help assess proper prevention of ASR. As part of the assessment of the laboratory test methods, some recommendations for improving the reliability of ASR testing are given. These recommendations are based on the author's combined 50-year experience in accelerated laboratory testing, field exposure sites and assessment of structures with ASR, supported by relevant literature. However, the paper does not include a complete literature review on the topic. Moreover, the paper also gives a world-wide overview of existing field exposure sites developed for benchmarking the laboratory test methods to field concrete and helping to decide the acceptance criteria that might vary from one country to another (for the same test method) based on national experiences and environmental conditions.

The introduction part includes a comprehensive discussion of sources of errors and challenges during laboratory testing (see section 1.2). With respect to reliability of a test result, it is a huge difference whether the aim is to test the potential alkali-silica reactivity of an aggregate or approve cementitious binders or concrete for long-term field performance. The latter is much more complicated and challenging, and the list of potential sources of errors are longer. One main source of error, illustrated in Figure 1, is alkali leaching. But, when trying to compensate for the alkali leaching by supplying alkalis, e.g. as in the MCPT [15], one risk is to "overcompensate" and supply too much alkali resulting in a too conservative conclusion. The outcome from test methods with alkali supply is to a high extent controlled by the permeability of the mortar/concrete, i.e., another parameter than the main parameters controlling ASR in field concrete.

In general, the conclusion from an ASR test is strongly dependent on the method selected for testing. Consequently, for obtaining reliable test results knowledge is needed about the aggregate properties (not all test methods work on all aggregates), available ASR test methods (in that region) and their possible sources of errors, the local climate, and local field experiences (i.e., within the region in which the concrete is to be used). The latter is the basis for evaluating the acceptance criteria. This can be done by investigating real structures provided those exist and reliable documentation of the concrete composition is available or can be obtained by analyzing drilled cores from the structures. However, often such a link from laboratory to field is documented by establishing field exposure sites with concrete containing different types of aggregates and different cementitious binders [46]. As discussed in section 4.3, at least 25 (11 in North America and 14 in Europe) ASR exposure sites are known to exist around the world. The oldest in North America is about 80 years, and the oldest European site is about 55 years.

Another general trend experienced in North America is a disconnect between laboratory test methods and field exposure blocks. Often, the expansion measured in field is higher. In many cases the conclusions from laboratory and field are thus contradicting, as discussed in section 4.3.2. Less papers are available in Europe regarding benchmarking of the laboratory test methods against field experiences, but some exist, see for example Borchers [57]. However, several new papers from interesting lab-field studies are under way soon. In addition to extensive knowledge about the materials and the challenges with ASR laboratory testing (as discussed above), it is crucial to develop new and continue following-up current field exposure sites for obtaining more reliable results in the future from ASR performance testing. This is also important for reliably testing new cementitious binders that will be available in the near future.

Our last comment is regarding the testing laboratories. Previous research has shown the importance of using a qualified test laboratory that is experienced using the actual test method [44]. If the testing is performed at a laboratory that has no experience running the actual test method, the outcome from the testing can be misleading. Experiences show that when such cases occur, it is a risk of obtaining "False negative" results and consequently approve aggregates and concrete mixtures that will fail in field.

In summary, Lindgård's statement during the key-note presentation at ICAAR 2024; *"Pick an expansion, and I can select a test method that gives you that expansion!",* is for sure something to bear in mind when selecting which test method(s) to use. It is crucial that the test method selected shows acceptable correlation to the field experience with the aggregates present in the region or country in question. Moreover, the climatic conditions will also influence the lab-field correlation and thus the decision about acceptance criteria (expansion limits) for the various test methods.

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Competing interests

None of the authors have any competing interests that have influenced the work.

Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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