RILEM Recommended Specification: AAR-7.1—International Specification to Minimise Damage from Alkali Reactions in Concrete—Part 1: Alkali-Silica Reaction

1 General

This Part 1 of AAR-7 principally addresses aggregates containing reactive silica.

Part 2 of AAR-7 provides separate guidance on reactive carbonate aggregates.

Part 3 of AAR-7, which is currently available in preliminary form, provides specific guidance on very large, long-service structures, such as dams.

Alkali-Silica Reaction (ASR) in concrete is a result of reaction between the alkaline pore solution in concrete and reactive silica in the aggregate. The reaction leads to the formation of a gel which can absorb water and exert an expansive force on the concrete. In certain conditions these reactions can lead to damaging expansions and cracking in the concrete. For such damaging expansion to occur all of the following conditions must be present simultaneously:

- A sufficiently alkaline pore solution
- A critical amount of reactive silica
- A sufficient supply of water

Effective specifications to avoid damage from the reaction are based on ensuring that at least one of these conditions is absent.

Additionally, there are interactions with other environmental actions such as freezing and thawing, application of de-icing salts and exposure to a marine atmosphere for which allowance must be made.

Such specifications can result in greater costs and in adverse environmental effects, for example by restricting the choice of aggregates or disposal of alkaline cement kiln dust, so it is also important to tailor the precautions to the nature and service life of the structure.

Therefore, the development of the precautions should take the following form:

1. Determination of the necessary level of precaution;
2. Undertaking recommendations according to the level of precaution required.

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RILEM State-of-the-Art Reports 17, DOI 10.1007/978-94-017-7252-5_8

The assessment of the level of precaution and the appropriate precautionary measures are summarised in Fig. 1.

Note 1: *This flow chart may not apply without modification to dams and other similar structures (see Sect. 3.4).*

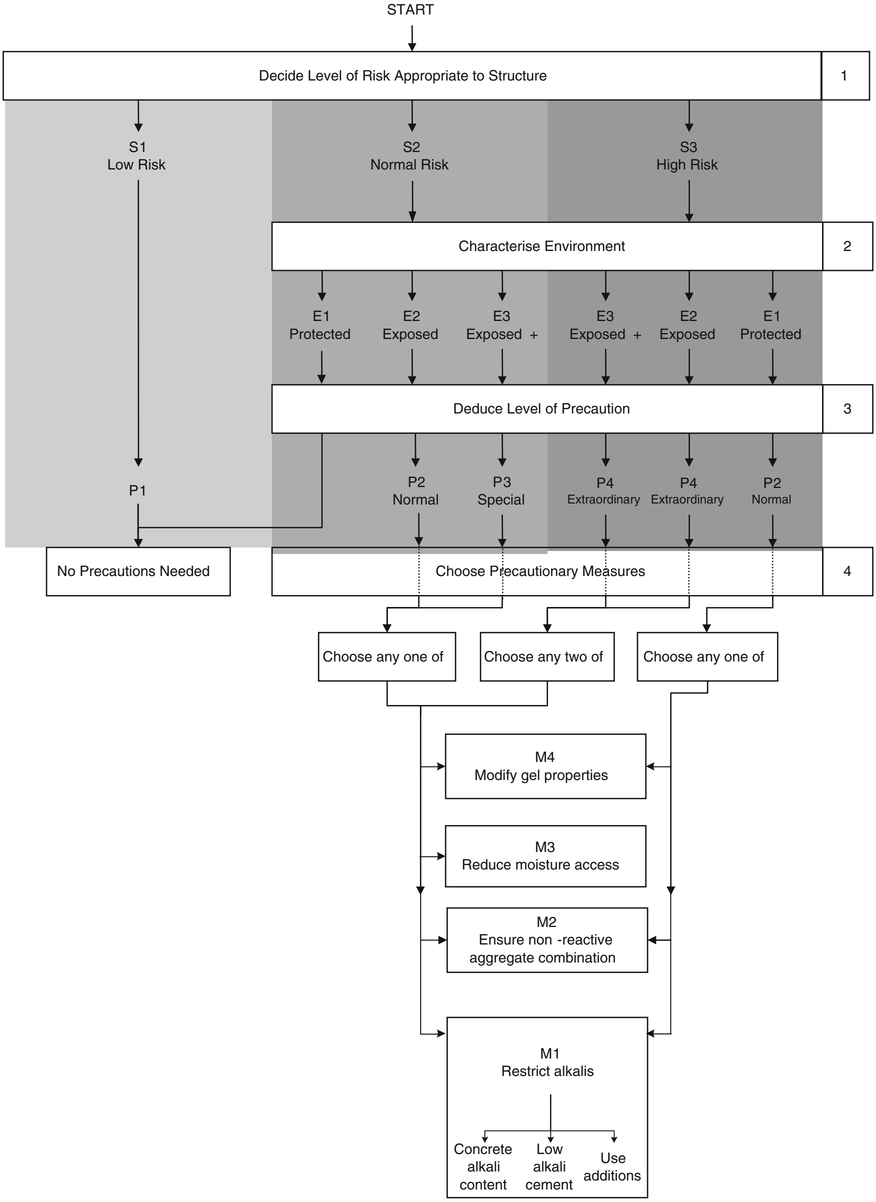

Fig. 1 Flow chart summarising the specification of siliceous aggregates

2 Determining the Level of Precaution

The key activities here are the characterisation of the structural needs and service life and the characterisation of the environment.

2.1 Structural Needs and Service Life

Damaging alkali-aggregate reactions are slow and progressive. Typically in temperate and cooler climates they begin to cause visible damage after 5–10 years and then may continue for 20 or 30 years or longer; in warmer climates the reactions are accelerated. Some slowly reacting aggregates, however, result in deterioration that takes much longer but can eventually be more destructive. The damage is evidenced as cracking and expansion of the concrete, occasionally leading to displacement of individual elements in a structure. While this has structural consequences, particularly if the reinforcement is insufficient, any deterioration will normally be evident well before there is danger to the integrity of the structure.

Three levels of categorisation of structure, according to the risks associated with any deterioration and the consequent need for precautions, are therefore appropriate:

S1—low risk
S2—normal risk
S3—high risk

It is the responsibility of the owner, or authority responsible for the structure, to decide on the appropriate level of risk in co-operation with the designer. This decision will be affected by the economic effects of any failure or deterioration as well as engineering and safety considerations. Other factors to be taken into account are the ease with which any deterioration can be detected, monitored and managed, the importance of the appearance of the structure and likely public perceptions of safety. Criteria which will assist in making this decision are given in Table 1.

2.2 Characterisation of the Environment

When all the necessary compositional factors are present, the likelihood and extent of damaging alkali-silica reaction is dependent above all on the supply of moisture. In the majority of cases, a supply of moisture extraneous to the concrete itself is necessary. Other, aggravating, factors which will influence the likelihood of damage and its severity include the application of sodium chloride based de-icing salts, exposure to seawater and the synergistic effects of freezing and thawing damage. In concrete roads the stress variation caused by fluctuating loads may also be an aggravating factor.

Table 1 Structures classified by risk category

Category-consequences of damage	Acceptability of ASR damage	Examples
S1 Safety, economic or environmental consequences of deterioration small or negligible	Some deterioration from ASR is acceptable	• Non load-bearing elements inside buildings • Temporary or short service life structures (likely design life 10–20 years) • Small numbers of easily replaceable elements • Most low-rise domestic structures
S2 Some safety, economic or environmental consequences if major deterioration	Minor ASR damage is acceptable/manageable	• Most building and civil engineering structures • Precast elements where economic costs of replacement are severe; e.g. railway sleepers • Normally designed for service life up to 100 years
S3 Serious safety, economic or environmental consequences if any deterioration	No significant damage acceptable	• Long service life (+100 years) or highly critical structures/elements where the risk of deterioration from AAR damage is judged unacceptable, such as • Nuclear installations, dams, tunnels • Exceptionally important bridges or viaducts • Structures retaining hazardous materials • Exceptionally critical elements impossible/very difficult to inspect or replace/repair • Structures where the economic risk of non-serviceability would be unacceptable

Three levels of categorisation of environment are therefore appropriate:

E1. The concrete is essentially protected from extraneous moisture

E2. The concrete is exposed to extraneous moisture

E3. The concrete is exposed to extraneous moisture and additionally to aggravating factors, such as sodium chloride based de-icing salts, freezing and thawing or wetting and drying in a marine environment

More detail on the factors affecting the environmental categorisation is given in Table 2.

Table 2 Environmental classes

Environmental class	Description	Environment of concrete (see table Notes)
E1	Dry environment protected from extraneous moisture	• Internal concrete within buildings in dry (1) service conditions
E2	Exposed to extraneous moisture	• Internal concrete in buildings where humidity is high; e.g. laundries, tanks, swimming pools • Concrete exposed to moisture from the external atmosphere, to non-aggressive ground or immersed in water. • Internal mass concrete should be included in this category (2)
E3	Exposed to extraneous moisture plus aggravating factors	• Internal or external concrete exposed to deicing salts • Concrete exposed to wetting and drying by seawater (3) or to salt spray • Concrete exposed to freezing and thawing whilst wet • Concrete subjected to prolonged elevated temperatures whilst wet • Concrete roads subject to fluctuating loads

Notes

1. A dry environment corresponds to an ambient average relative humidity condition lower than 75 % (normally only found inside buildings) and no exposure to external moisture sources.

2. A risk of alkali-silica reaction exists for mass concrete elements in a dry environment because the internal concrete may still have a high relative humidity. Vulnerable mass concrete elements are those with a least dimension of 1 m or more.

3. Concrete constantly immersed in seawater does not suffer a higher risk of ASR than a similar element exposed to humid air, buried in the ground, or immersed in pure water, because the alkali concentration of sea water is lower than the alkali concentration of the pore solution of most concretes, and the penetration of chloride ions is usually limited to a few centimetres.

2.3 The Level of Precaution

The structural and environmental categorisation is combined into the level of precaution in Table 3, where four levels of precaution are identified:

P1. No special precautions against AAR
P2. Normal level of precaution
P3. Special level of precaution
P4. Extraordinary level of precaution

Table 3 Determination of level of precaution

	Environment category (see Table 2)		
	E1	E2	E3
Category of structure (see Table 1)	Level of precaution		
S1	P1	P1	P1
S2	P1	P2	P3
S3	P2	P4	P4

3 Specifications Appropriate to the Level of Precaution

The following precautionary measures may be applied:

(see Sect. 4 for more details).

M1: Measures to restrict the alkalinity of the pore solution

M2: Measures to ensure the use of a non-reactive aggregate combination

M3: Measures to reduce the access of moisture and maintain the concrete in a sufficiently dry state

M4: Measures to modify the properties of any gel such that it is non-expansive

Note 2: *Precautionary measures M1 and M2 are well established and are recommended by RILEM.*

Note 3: *The efficacy of M3 is difficult to assure, particularly in wetter climates, and it is recommended that it should not be applied as the only precautionary measure in S3 structures (see note in Sect.* 4.3).

Note 4: *M4 is newly developed and should be applied with caution.*

Note 5: *A reliable performance test for the concrete mix to be used could incorporate M1, M2 and M4. RILEM is developing such a test.*

3.1 Level of Precaution P1

No special precautions against AAR damage are necessary.

Ensure that appropriate standards and guidance are followed for the specification of the concrete and good practice employed in its placing and curing.

Note 6: *If this level of precaution is adopted, some damage from ASR is possible. Therefore the structure must be able to withstand this and the level of damage must be acceptable to the owner.*

3.2 Level of Precaution P2

This normal level of precaution against AAR damage is appropriate to structures where minor ASR damage is acceptable or damage can be monitored and managed. In precaution level P2 one of the precautionary measures M1, M2, M3 or M4 should be applied in the case of S2 (normal risk) structures, or one of the precautionary measures M1, M2 or M4 in the case of S3 (high risk) structures.

3.3 Level of Precaution P3

This special level of precaution is appropriate where minor ASR damage is acceptable or damage can be monitored and managed but where the structure is exposed to aggravating factors such as de-icing salts, freezing and thawing or wetting and drying in a marine environment. In such cases one of the precautionary measures M1–M4 should be applied and additionally the concrete should be designed to resist the aggravating factor; e.g. it should be freeze/thaw resistant or it should resist the ingress of de-icing salts or seawater.

3.4 Level of Precaution P4

This extraordinary level of precaution is only needed in structures where the consequences of any deterioration are unacceptable. In general it will necessitate the combined application of at least two of the precautionary measures M1–M4 and additionally the concrete in environmental class E3 should be designed to resist any aggravating factors such as freezing and thawing whilst wet, de-icing salts or wetting and drying in a marine atmosphere. This level should not be specified without careful thought and good reason, as it will almost certainly result in increased construction costs.

In some large/remote structures such as dams, where for environmental and/or economic reasons, it is necessary to use local materials, it may not be possible to apply two separate precautionary measures. In that case extra protection can be obtained by the more rigorous application of one of the precautionary measures; e.g. the use of a low alkali limit (see Sect. 4.1.1) and the inclusion of a fly ash or slag (see Sect. 4.1.2), or the use of a non-reactive aggregate combination (see Sect. 4.2) subject to a lower acceptance limit in the testing. Additionally, extra protection can be achieved through design and construction measures, such as detailing of the reinforcement, weather protection of critical elements, drainage or inclusion of expansion joints. More specific guidance for such structures is given in AAR-7.3, which is now available in preliminary form.

4 The Precautionary Measures

4.1 Precautionary Measure M1: Limiting the Alkalinity of the Pore Solution

There are various ways of achieving this:

- Limiting the alkali content of the concrete;
- Use of a low alkali cement;
- Inclusion of a sufficient proportion of a low lime-fly ash, other pozzolana demonstrated to be effective, or ground granulated blastfurnace slag in the concrete.

4.1.1 Limitation of the Alkali Content in the Concrete

In many respects this is the most easily applied and monitored of the measures. As it is now well demonstrated that the alkalinity of the pore solution is primarily dependent on the alkali content of the concrete mix, it is also the method recommended by RILEM to achieve Precautionary Measure M1.

Alkalis in Portland cement

The principal source of alkalis that control the alkalinity of the concrete pore solution is the alkali content of the Portland cement. This is usually expressed as the equivalent sodium oxide content:

$\%\ Na_2O$ equivalent = $\%\ Na_2O + 0.658\ \%\ K_2O$

Alkalis in concrete

The alkali content of the concrete is then the equivalent alkali content of the cement multiplied by the cement content of the mix plus any other reactive alkalis that should be included:

Concrete alkali (kg/m^3) = cement alkalis (%) × cement content (kg/m^3) + other sources of alkali

The effective application of this measure requires the support of the cement manufacturing and/or supply industry in a particular country, as it needs both the quality assured declaration of the average cement alkali level from a particular works and a measure of its variability. This is now done in several countries (e.g. France, UK) as part of the control and standardisation process of concrete. Alternatively users will need to assess cement alkali content by the reliable independent analysis of representative samples of the cement.

Other sources of alkali

There is no universal consensus on what other sources should be included. The general practice is to include alkalis from these sources:

- Residual salt in marine aggregates;
- Cementitious additions such as fly ash and slag;
- Admixtures;
- Mix water, especially if not from potable sources.

The proportion of alkalis that should be included from fly ash and slag is dependent on the proportion used and their reactivity (see Sect. 4.1.2). In a blended cement containing fly ash or slag, the manufacturer will need to declare an "effective" alkali content, calculated from the alkali in the Portland cement and the alkalis to be included (if any) from the fly ash or slag on the basis of Sect. 4.1.2.

Note 7: *Such manufacturers declarations are already available in some countries.*

Admixtures, particularly some superplasticisers, can contain substantial alkalis. The calculation of the alkali in the concrete will need to be based on the effective alkali declared by the manufacturer.

More problematic is the question of alkalis originating in the body of the aggregate. Many aggregates contain alkalis, but the extent to which these are released and contribute to the pore solution alkalinity remains uncertain and possibly variable. A method for assessing the potentially releasable alkali content of aggregates is being developed by RILEM as AAR-8.

At present, it is recommended that, unless there is national evidence to the contrary, this source of alkalis should not be included in the calculation except in concrete in S3 structures. In such structures the possibility of alkali release by the aggregate should be considered when using aggregates containing significant amounts of altered and/or weathered feldspar, or other minerals capable of releasing alkalis.

There is good evidence that the use of sodium chloride based de-icing salts can exacerbate ASR reactions. However, it is not possible to quantify this effect in order to include it in the calculation of the alkalis in the concrete. Instead, it is taken into account in deciding the environmental class of the concrete where it is one of the aggravating factors that lead to classification of the environment as E3.

Note 8: *There is recent evidence from the USA that de-icing salts containing sodium or potassium formates and acetates can cause ASR-like damage to concrete, even that containing 'non-reactive' aggregates.*

Alkali limits and aggregate reactivity

These must be set by national guidance. To enable the most efficient use to be made of the aggregate resources available in a particular country, the RILEM methods should be used to identify levels of aggregate reactivity that can then be used to set alkali limits (AAR-0). Aggregates that are essentially non-reactive can be identified by petrographic methods (AAR-1). The reactivity of more reactive materials is best defined in terms of the alkali threshold at which damaging ASR is first identified. To establish this threshold, the AAR-3.2 concrete prism method can be used. Alternatively, a particular country can designate the reactivity of particular rock types on the basis of their geology and known behaviour on concrete structures.

Three levels of aggregate reactivity can usefully be differentiated:

1. Low reactivity aggregates:
   These correspond to the aggregates identified as "non-reactive" in AAR-0;
2. Medium reactivity aggregates:
   These are aggregates that fall neither into the low nor high reactivity categories. They may well be the majority of aggregates in some countries, e.g. the UK (where these medium reactivity aggregates are termed "normal reactivity"), and include the siliceous sands and gravels that are found widely. They will have alkali thresholds of exceeding 4.0 kg/m^3 sodium oxide equivalent (Na_2O eq.);
3. High reactivity aggregates:
   This category corresponds to the aggregates shown by tests using concrete specimens (AAR-3) to have low alkali thresholds; typically 4.0. kg/m^3 Na_2O eq. or less. Such aggregates are likely to be rare.

Note 9: *Aggregates containing substantial proportions of opal are likely to be even more reactive than high reactivity aggregates and should either not be used in concrete or only with special precautions that have been proven effective by trials or performance tests* etc. *Such aggregates fall outside these recommendations.*

Note 10: *When classifying the reactivity of an aggregate it is important to assess the whole aggregate combination in order to allow for any "pessimum" effects* (*see Sect.* 4.2).

Examples of using the aggregate reactivity categories to set alkali limits are shown in Table 4.

Note 11: *The alkali limits in the example given in Table* 4 *allow a "safety margin" compared with the alkali thresholds determined in the laboratory (e.g. if the determined threshold was 4.0 kg/m^3, in this example the limit has been set at 3.0 kg/m^3: i.e. a 1.0 kg/m^3 safety margin). This is to allow for the known differences between laboratory and field specimens, experimental uncertainty (e.g. from alkali leaching) and site batching variability. National specifications making use of such limits will need to decide on an appropriate "safety margin" from local experience.*

Where, in a particular country, the alkali contents of the cements used are within a known narrow range, restrictions on the cement content according to aggregate reactivity and environment, can be used as an alternative method of limiting the alkali levels in the concrete mix. This can be easier for the concrete producer to apply, but care must be taken as the compositions of the cements may change over time because of, for example, changes in raw materials or import of cements.

Table 4 Alkali limits and aggregate reactivity

Aggregate reactivity	Alkali limit (kg/m^3 Na_2O eq.)
Low	None required
Medium	Typically 3.0–3.5 kg/m^3
High	Typically 2.5–3.0 kg/m^3

Low Alkali Cements

Although less precisely connected with the alkali concentration in the concrete pore solution, this is the longest established and most pragmatic countermeasure. In the case of low alkali Portland cements an upper limit of 0.60 % Na_2O equivalent is generally applied. The use of such low alkali cements has been found to be effective in some regions in preventing AAR damage, although there are occasional reports of damage despite their use and there is evidence from field trials in North America that with some aggregates damaging expansion can occur in concrete specimens made with low alkali cements.

Drawbacks are that cements guaranteed to meet this limit will often be more costly and, to achieve it, the manufacturer may have to discard kiln dust with adverse environmental effects. Moreover, this measure may not be effective in the case of concretes with unusually high cement contents, if there are significant sources of internal or extraneous alkali, or if the passage of moisture concentrates the alkalis in certain parts of the structure.

Some countries have also designated low alkali slag cements. In Germany, for example, two types of low alkali blastfurnace slag cement are defined, the allowable alkali content depending on the percentage of slag. In Austria there is good experience of using Portland-slag cements, compliant with particular Austrian standards, which have quite high alkali levels. With local experience, such approaches can be an effective way of using these supplementary cementing materials in avoiding ASR damage.

4.1.2 Use of Fly Ash, Slag, Other Pozzolanas and Other Mineral Additions

The use of concrete containing such additions, and of cements in which they are interground or mixed during manufacture, has been the subject of much controversy and research. It is clear that some of these materials can be very effective in combating AAR damage. However, their variability, internationally, makes it problematic to give specific RILEM Recommendations. The following advice summarises the general consensus ascertained by RILEM.

Low lime fly ashes, e.g. to EN 450 [1] or ASTM C618 class F [2], and ground granulated slags that are well established as effective cementitious materials or

Table 5 Recommended minimum fly ash and slag proportions

Aggregate reactivity	Low lime fly ash (<8 % CaO and <5 % Na_2O eq.)	Medium lime fly ash (8–20 % CaO and <5 % Na_2O eq.)	Ground granulated blastfurnace slag (<1.5 % Na_2O eq.)
	% by mass of total cementitious material		
Low	Any	Any	Any
Medium	25	30	40
High	40	Not recommended	50

constituent materials of the cement, will provide effective protection against AAR damage provided a sufficient proportion (as a proportion of the total cementitious material) is used. The proportion necessary will depend on the reactivity of the aggregate (Table 5).

Provided that these minimum proportions are used, and subject to local experience with particular materials, the alkali content of the fly ash or slag need not be included in the calculation of the "reactive" alkalis in the concrete.

If lower proportions of addition are used, some countries (e.g. UK, France) recommend that a proportion of the alkali content of the ash or slag is included in the calculation of the alkali content of the concrete mix. Based on these, a tentative RILEM recommendation is given in Table 6.

There is also good evidence that other highly active pozzolanic additions such as silica fume and metakaolin can be effective in protecting against ASR damage. It is tentatively recommended that for concrete containing medium reactivity aggregates the following minimum proportions are used:

Silica fume (>85 % SiO_2): 8 %
Metakaolin (>45 % SiO_2): 15 %

At present this approach is not recommended for concrete containing high reactivity aggregates.

Note 12: *It is vital that such materials are well dispersed in the concrete. Agglomerations of silica fume have caused damaging ASR expansions.*

Table 6 Alkali contributions from lower proportions of additions than are recommended in Table 5

Proportion of addition in cement	Proportion of alkali from addition to include in calculation of alkali content of concrete mix
Slag	
25–39 %	50 %
<25	100 %
Fly ash	
20–24 %	20 %
<20	100 %

Otherwise, sources of fly ash (e.g. high lime {>20 % CaO}) or slag that are not well established, or other pozzolanic materials or mineral additions, should only be used if their performance has been established by a concrete performance test based on, for example, the AAR-3 method. It is preferable that such performance tests are backed up with long-term outdoor field tests or by site experience, since some accelerated laboratory tests, using elevated humidities and temperatures, may give unrealistically optimistic results for the effectiveness of some pozzolanic materials in combating ASR expansion.

Note 13: *Such a performance test is being developed by RILEM.*

4.2 Precautionary Measure M2: Ensuring the Use of a Non-reactive Aggregate Combination

In the context of ASR, reactive silica occurs almost exclusively in the aggregate. Therefore to make use of this precautionary measure, the RILEM Recommended methods should be used, in accordance with AAR-0, to identify "non-reactive aggregate" combinations.

The proportion of silica that can lead to the most damaging reaction will depend on the reactivity of the silica. A small amount of highly reactive silica in the aggregate will be most damaging, whereas, if the aggregate contains a high proportion of such highly reactive silica, there may be little damage. If an aggregate containing highly reactive silica is mixed with a non-reactive one, the behaviour of the mix will vary from very damaging to not damaging at all, depending on the proportions of the mix. This feature is known as the "pessimum" effect. Conversely, in aggregates containing low reactivity forms of silica or where the silica is not easily exposed to the alkaline pore solution, the worst damage may occur when the greatest amount of silica is present.

Because of this, it is important that the whole aggregate combination is assessed, as amounts of reactive silica that are innocuous in either the fine or coarse aggregate alone may be damaging in the combined aggregate. Conversely, apparently reactive fine or coarse aggregates may be safe when used in combination. Both AAR-3 and AAR-4 are suitable for assessing the combined aggregate. When used correctly, controlling this 'pessimum' effect can be an effective way of combating AAR damage and making use of available natural resources.

4.3 Precautionary Measure M3: Reducing Moisture Access and Maintaining the Concrete Sufficiently Dry

This can be achieved at the design stage by the use of, for example, external cladding or tanking (protection using a completely waterproof barrier). Inclusion of well designed drainage that can be inspected and maintained is also important. Use of cladding on a concrete structure in a cold and very humid environment may however not sufficiently reduce the moisture content in the air behind the cladding. The use of cladding is regarded as most feasible in a warm and dry environment.

The effectiveness of surface treatments (coatings and impregnations) in preventing (or in arresting) AAR damage has been found to be variable, and thus surface treatment is not regarded as a sufficient precautionary measure.

Note 14: *If a surface treatment is applied as an extra precaution measure, it should be vapour permeable so that the concrete can dry out when the humidity is low. The maintenance of any coating and/or drainage measures used is vital.*

4.4 Precautionary Measure M4: Modifying the Properties of the Gel Such that It Is Non-expansive

Inclusion of sufficient, soluble, lithium salts in the concrete mix water is an effective means of counteracting AAR damage. It is believed to operate by modifying the nature of the ASR gel such that it does not absorb water and exert an expansive force.

Lithium nitrate is the preferred salt. The recommended dosage levels depend on the alkali level in the concrete and the nature of the aggregate. North American research [3] suggests that lithium salts are not equally effective with all reactive aggregate types. Some aggregates require much higher doses of lithium than others, whilst expansion with other reactive aggregates can sometimes be controlled with lower lithium doses than have previously been recommended. Unlike other measures based on using additions, such as fly ash or ground granulated blastfurnace slag, the lithium dose required does not appear to be related to the degree of aggregate reactivity. Accordingly, it is not possible at present to recommend a single dosage of lithium nitrate that will be effective for all aggregates. Instead, performance testing to evaluate its effectiveness and determine an appropriate lithium dosage is recommended for those considering the use of precautionary measure M4 in new concrete.

Note 15: *A suitable performance test is being developed by RILEM. Until that is available, North American experience suggests evaluation using a version of AAR-3 with an acceptance criterion of 0.04 % after two years. Also, a suitable performance test based on a modified version of the AAR-2 type of accelerated mortar-bar test is currently under development in North America.*

References

1. EN 450-1:2012 & EN 450-2:2005, Fly ash for concrete, Part 1: Definition, specifications and conformity criteria (+Amendment A1:2007), & Part 2: Conformity evaluation.
2. ASTM C618-08A, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, *American Society for Testing and Materials*, West Conshohocken, Pennsylvania, USA.
3. Tremblay, C, Berube, M-A, Fournier, B, Thomas, M D A, Folliard, K J, 2007, Effectiveness of lithium-based products in concrete made with Canadian natural aggregates susceptible to alkali-silica reactivity, *ACI Materials Journal*, Title 104-M23, 104 (2), 195–205.