ELIMINATING ALKALI-AGGREGATE REACTION FROM LONG-SERVICE STRUCTURES

Ian Sims [1*+], Philip Nixon [2] & Bruno Godart [3]

[1] Director, RSK STATS Limited, Hemel Hempstead, UK (Secretary, RILEM TC 219-ACS), isims@rsk.co.uk and/or ian@simsdoc.com

[2] Consultant, RSK STATS Limited, Hemel Hempstead, UK (Chairman, RILEM TC 219-ACS)

[3] Technical Director, Université Paris-Est, IFSTTAR, Paris, France (Team Leader, RILEM TC 219-ACS)

Abstract

RILEM has developed a testing and specification system to minimize AAR damage risk in new concrete structures. A performance test is being developed for particular mixes, usable on a project-specific basis; the challenge is proving a consistent relationship between test and field behaviours.

Long-service structures, including dams, can sometimes exhibit progressive AAR, despite meeting criteria that usually prevent damage. Moreover, slow reactions can continue inexorably in large dam structures, gradually threatening integrity and serviceability. RILEM is working with ICOLD (International Commission On Large Dams) to ensure preventative schemes are effective with dams.

Over an extended life, reactive alkalis are extracted from aggregates. A new 'releasable alkalis' test is being validated by RILEM. Usually unpopular but more reliable long-term expansion tests are more practicable with long-service structures than smaller projects, including assessing the influence of SCMs. An improved RILEM specification scheme is introduced, aimed at eliminating the AAR risk in future long-service structures, including dams.

Keywords: Alkali-aggregate reactivity, concrete dams, durability, releasable alkalis, preventative measures.

1 INTRODUCTION

As described at previous ICAAR conferences, RILEM has developed an integrated system of testing and specification that will minimize the risk of alkali-aggregate reaction (AAR) causing damage to new concrete structures. A full set of the latest versions of these schemes is due to be published by RILEM, as a special dedicated issue of their journal 'Materials & Structures', during 2011[1].

The Specifications were developed at the request in 2000 of the Organising Committee of the International Conference on Alkali Aggregate Reactions (ICAAR) and are intended to offer the basis for international specifications. The work first concentrated on alkali-silica reactions (ASR) and AAR-7.1, was first presented at the 12th ICAAR in Beijing [2]. Subsequently a second part was developed to deal with the particular case of alkali-carbonate reactions (AAR-7.2) and these proposals were first presented at the Marc-André Bérubé Symposium in Montréal [3]. The specifications are supported by the Methods of Test, AAR-1, AAR-2, AAR-3, AAR-4 and AAR-5 and the guidance to the use of these methods, AAR-0. The specifications

---

[*+] * Correspondence to: isims@rsk.co.uk offer a range of options that can be tailored to meet the needs of a particular country or region. It is hoped that the adoption of the measures in these specifications will give a very high degree of protection from damaging AAR in normal concrete structures.

However, through its liaison with the International Committee on Large Dams (ICOLD), the RILEM TC has become aware that there are examples of dams that have developed damage despite being constructed with preventive measures that, it is believed, would have accorded with the RILEM Specifications. This suggests that there may be special factors that make very large and long-service structures, such as dams, particularly vulnerable to the expansive forces generated by alkali-aggregate reactions. For example, Charlwood [4] has described a number of cases where there has been damage despite the application of preventive measures in the design and specification of the concrete.

In this paper we discuss the reasons for this vulnerability and how the RILEM International Specifications to minimize damage from alkali-aggregate reactions in concrete can be modified better to protect massive, long-service structures such as concrete dams.

2 RILEM SPECIFICATIONS TO MINIMIZE RISK OF AAR DAMAGE IN GENERAL CONCRETE CONSTRUCTION

The principle of AAR-7.1 is that the concrete should be designed so as to avoid the simultaneous presence of:

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

As the introduction of such considerations can result in greater costs and in adverse environmental effects, it is 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

2.1 Necessary level of precaution:

This will depend on the combination of the structural needs and planned service life of the structure and the environment to which the concrete is exposed. In the RILEM Specification, the structural needs and service life are characterised in terms of the risk associated with any damage. This will be influenced 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. Three levels of risk are identified:

S1 – low risk
S2 – normal risk
S3 – high risk

Criteria which will assist in making this decision are given in Table 1.

Table 1. Structures classified by risk category

Category - consequences of damage	**Acceptability of ASR damage**	**Examples**
S 1 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 to 20 years) • Small numbers of easily replaceable elements • Most low-rise domestic structures
S 2 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 100years
S 3 Serious safety, economic or environmental consequences if any deterioration	No significant damage acceptable	• Long service life (+100years) 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 • Aesthetic structures, historical monuments

2.2 Environment:

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. 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

The level of precaution:

The structural and environmental categorisation is then combined into the level of precaution in Table 2, 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 2. Determination of level of precaution

Category of Structure	**Environment Category**		
	E1	**E2**	**E3**
	Level of Precaution		
S1	P1	P1	P1
S2	P1	P2	P3
S3	P2	P4	P4

The measures taken to avoid ASR damage are then determined by the level of precaution. In summary, these are:

Level of precaution P1: No special precautions against AAR damage are necessary, but appropriate standards and guidance must followed for the specification of the concrete and good practice employed in its placing and curing. With this level of precaution, 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.

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 (see below) should be applied.

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 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.

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 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.

Available precautionary measures:

The following precautionary measures may be applied. Of these, the precautionary measures M1 and M2 are best established and are recommended by RILEM. There is a detailed discussion of how to apply these measures in AAR-7.1[1].

M1: Measures to restrict the alkalinity of the pore solution.

There are several ways of achieving this:

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

M2: Measures to ensure 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. It is important to test different aggregate proportions as with some aggregates small amounts of reactive silica can be more damaging (the “pessimum” effect).

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

This is difficult to ensure, particularly in wetter climates and/or with water-retaining structures, and it is recommended that it should not be applied as the only precautionary measure in S3 structures.

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

This, which at present essentially means the use of lithium salts, is not yet well proven and should be used with caution and only after trials to establish the effective dose.

3 SPECIAL FACTORS AFFECTING MASSIVE, LONG SERVICE STRUCTURES

The RILEM specification is intended to minimize the risk of damaging ASR in general concrete structures. Although its principles can be applied to massive, long-service structures, there are several special factors that need to be taken into account in applying AAR-7.1 to such structures [5]:

- slow reactions, which might cause limited harm and/or terminate within smaller concrete structures, may continue inexorably in large structures, sometimes gradually leading to deformations and even wholesale movements that threaten the integrity and serviceability of the structure. Conventional test methods for aggregate reactivity may not identify such reactions,
- often, the need for structural safety is paramount in such structures.

In the case of dams there are also specific points:

- by definition the concrete will be wet'
- dams are often built in relatively remote areas where the choice of materials is limited and, in particular, there will be strong economic and environmental reasons for using local aggregates'

- the horizontal restraint imposed by the contact of the dam with the earth or rock at its extremities can lead to bending or bowing of the dam if the concrete expands, especially in arch dams or with gravity dams that have an angular profile'
- any concrete expansion can lead to the serviceability of a dam being threatened by distortion of connections to spillways, gates, machineries and other installations.

Such factors will inevitably mean that these structures will be classified as S3, high risk, in terms of structural risk and E3, exposed with aggravating factors in terms of environment. Although it could be argued that a structure built in an environment where freezing and thawing is unlikely could be classified as having an E2 environment, the possibility of the synergistic effects of other internal stresses, such as those originating in delayed ettringite reactions, means that this would be unwise. Whatever the classification adopted, E2 or E3, the combination with category S3 leads to the inevitable conclusion that the Necessary Level of Precaution is P4, the highest category.

The advice given in AAR-7.1 for this situation is that it will necessitate the combined application of at least two separate precautionary measures (basically M1 and M2) and additionally the concrete 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. However, in the case of these long-service structures, especially concrete dams, this may need to be modified in several ways. Firstly, as mentioned above, the facts of construction in remote areas may restrict the choice of materials, especially aggregates, which could lead to difficulties in applying measure M2. Secondly, the continuously wet environment and extreme longevity may lead to special problems. In particular, there is concern about the possibility of some types of aggregates (and/or even some SCMs) acting as a reservoir for alkalis, which then maintain the reaction over a longer time scale than would be expected in normal structures. Even if the aggregate itself does not contribute alkalis, the large volume of concrete will provide a reservoir of alkalis which may be concentrated to damaging amounts by moisture movements within the concrete. There is also the suggested mechanism whereby alkalis can be recycled from gel as earlier deposits alter and crystallise [6].

Overall, the preference for very long term protection is still for the application of at least two separate precautionary measures. However, if this is impractical then the more rigorous application of one precautionary measure, combined with planning of the design and construction to minimize the effects of any expansions, will give a high level of protection.

4 PROTECTION BY CHOICE OF MATERIALS

As explained above, the usual precautionary measures are designed to avoid either or both of a high alkalinity in the concrete (M1) and the presence of a critical amount of reactive silica in the aggregate (M2). In respect of these rules, the combination of non-reactive aggregates with a reasonably low alkalinity in the concrete appears to be a basic solution.

The alkalinity in the concrete mainly arises from the alkalis in cements and is modified by the inclusion of slags and pozzolanic materials (but see discussion of alkali from aggregates below). As cements, slags or pozzolanic materials will inevitably have to be imported to the construction site and are, in any case, a less bulky component of the concrete than the aggregate, their choice will be a normal one of what is available in the region. Careful choice of the cement and use of slags and pozzolanas can, however, give very powerful protection to the concrete. In the case of aggregates it may be necessary, for economic and environmental reasons, to use local materials. Often this will mean opening new quarries, so there will not be a history of use and effective testing becomes particularly important. On the positive side, however, the long planning involved in a large project does allow the testing programme to be planned and carried out effectively, including the use of long-term tests, in contrast to many construction projects where there in not enough time for adequate assessment.

4.1 Cementitious materials:

As summarised above, the alkalinity of the pore solution in the concrete can be kept to a level where damaging reaction with silica in aggregates is unlikely by limiting the alkali content of the concrete mix, by the use of a low-alkali cement or by inclusion in the concrete of a sufficient proportion of a low-lime fly ash, or other pozzolana demonstrated to be effective, or ground granulated blastfurnace slag. AAR-7.1 advocates that the limit on the alkali content of the concrete and the minimum amounts of ash or slag used should be based on the reactivity of the aggregate. In the case of these massive long-service structures, extra protection for the concrete can be obtained by ensuring that the alkali level in the concrete is kept to a particularly low level, regardless of the aggregate reactivity and by additionally using high levels of a low-lime fly ash or good quality ground granulated slag. If it is assumed that the aggregate is of high reactivity, according to AAR-7.1 the limits and quantities shown in Table 3 would apply.

Table 3. Limits for concrete containing high reactivity aggregate

Alkali level in concrete (Na_2Oeq)	≤2.5-3.0 kg/m^3
Low-lime fly ash (<8% CaO and <5%Na_2Oeq.)	>40%*
Ground granulated blastfurnace slag (<1.5% Na_2Oeq)	>50%*

**% by mass of total cementitious material. Provided that these minimum proportions are used, and subject to local experience , the alkali content of the fly ash or slag need not be included in the calculation of the "reactive" alkalis in the concrete.*

Meeting these low alkali levels in the concrete may not be too onerous as the cement content in massive structures is likely to be low to avoid heat rise problems and similarly ashes and slags are often used in such structures for the same reason.

If it is required to use two precautionary measures, these can be the combined use of a cement with a low-alkali content and sufficient ash or slag to meet these limits. If this is done, it will be important to ensure that the basic strength gain of the concrete is sufficient, as the reactivity of the ash or slag is aided by a higher level of alkalis in the cement. Other pozzolanic materials, such as natural pozzolanas, silica fume or metakaolin, can give good protection, but their use is less well established and cannot yet be recommended in critical structures like dams unless their effectiveness has been demonstrated by a performance test, which will also establish the optimum proportion required.

4.2 Performance tests:

The ideal would be to test the effectiveness of the actual cement/aggregate combination in a performance test and RILEM has an active programme to develop such a test. In order to do this, the committee has been looking in depth at the parameters that influence expansion [7,8] and also gathering data on long-term service performance of actual structures with known mixes and field test data, so that the results of such a test can be calibrated. Current thinking is that initially such a performance test should be based on the AAR-3.1 (38° C) method.

In the case of mixes containing pozzolanic materials, it is particularly important that such performance tests are backed up with long-term outdoor field tests or by site experience, because some accelerated laboratory tests, using elevated humidity and temperatures, may give unrealistically optimistic results for the effectiveness of pozzolanic materials in combating ASR expansion (the test conditions can enhance the activity of the SCMs). Similarly, it not yet known how effective such a performance test would be in identifying the slow reactions that are of concern in these very large structures.

Another approach, which has been applied in France in cases when non-reactive aggregate are not available, is to use a performance test to determine the 'alkali threshold' for the particular aggregate/cement combination (using aggregates representative of the ones to be used in the structure) and then apply a safety factor to the alkali level actually used in the structure. The alkali threshold is the lowest alkali level in the concrete at which a damaging expansion is found in tests and a method for determining this is given in AAR-3.2. In France the performance test on concrete is done at 60°C, according to AFNOR NF P 18-454[9]; this is the method on which AAR-4.1 and 4.2 are based, but at present RILEM is recommending the AAR-3.2, (38°C) method for this purpose. Once the alkali threshold has been determined, the project mix can be designed with a safety factor in the form of a lower alkali level. Depending on the criticality of the structure and the confidence with which the alkali threshold has been determined, a safety factor can be applied by reducing the alkali level in the project mix by between 1.0 and 2.0 kg/m^3 Na_2Oeq. below the alkali threshold This seems a promising approach and it will also give some protection against possible long-term alkali contribution from aggregates.

Aggregate assessment:

The suite of RILEM test methods together with overall guidance in AAR-0 allows a reliable assessment of the reactivity of aggregates. In summary, the assessment should start with a petrographic examination according to AAR-1. This will enable the choice of the best test methods for a full assessment and will also reveal the uniformity of the aggregate sources and determine how the sampling for subsequent tests should be undertaken. Then, optionally, AAR-2, the accelerated mortar-bar test can be used for initial screening, leading on to the longer-term concrete tests in AAR-3.1 and AAR-4.1. If there are carbonate aggregates, these can be assessed using the procedure in AAR-0 and the combined test methods of AAR-2 and AAR-5.

The inter-laboratory tests carried out by RILEM [10,11] and the PARTNER project [12], which assessed the RILEM methods for use in Europe, both showed that that AAR-3.1 and AAR-4.1 can reliably identify non-reactive aggregate combinations and aggregate combinations that will become reactive in normal timescales. The methods were least reliable in identifying aggregate combinations that were marginally reactive or reacted over long timescales and in the case of long-service structures this could be important. Of the two, AAR-4.1, the accelerated (60°C) concrete test, was more effective in identifying these marginal/slow reactions in the normal test period, although the effectiveness of AAR-3.1 could be improved by extending its normal 1 year test period and with an extended test period this method was found by the PARNER project to show the best correspondence to field experience. In the case of important, long service structures there is a good argument for carrying out both methods.

In such structures there may also be a need to reconsider the normal expansion limits. For AAR-3.1 these are that expansions exceeding 0.05% at 1 year indicate the possibility of a harmful alkali-reaction, while in AAR-4.1 the limit is 0.03% at 15 weeks. Given the likely imprecision of the test methods [12], it is probably unrealistic to use lower critical limits. A more reliable procedure is to extend the test period to 2 years, if possible, in the case of AAR-3.1 and to 20 weeks for AAR-4.1 and then to examine the expansion curves for any sign of continuing expansion. Overall, an expert consideration of the combined results from a petrographic examination and the results of AAR-3.1 and AAR-4.1 will give the most reliable assessment

Alkalis in aggregates:

Many minerals in aggregates, for example feldspars, can contain significant amounts of alkalis. Given that the aggregate makes up such a high proportion, perhaps 75% by weight, of the concrete, these alkalis have the potential to contribute large amounts of alkali to the pore solution. Generally, however, the alkalis are not readily soluble in the pore solution, at least in timescales appropriate to most concrete structures. In the case of structures designed for very long service lives, however, there is concern that the aggregates can contribute alkalis in the long-term and negate the precautions taken in designing the concrete.

Unfortunately, there is presently no consensus on how to test for releasable alkalis in aggregates. The result of testing for these alkalis depends very heavily on the extraction solution that is used. Various solutions have been used experimentally, including water, alkaline, acid and saturated lime, and the results vary widely. Moreover, it has proved difficult to correlate the results of laboratory tests to what happens in field concrete. RILEM is developing a standardised test, AAR-8, to determine releasable alkalis from concrete, possibly employing an extraction solution similar to that of concrete pore solution, but this is not yet available. Even then, further practical research will be required, to establish criteria for use with AAR-8.

In the meantime, the recommended approach is to use a petrographic examination to identify minerals that are believed to be potentially susceptible to alkali release and if possible to avoid the use of aggregates containing them. Most concern has focused on feldspars, which are common rock-forming minerals, especially when geological alteration or weathering has initiated degradation of the feldspar, with associated formation of secondary clay minerals. Many sedimentary rocks will also contain some clay minerals, which could be a source of releasable alkalis. Experience has shown that many metamorphic rocks (such as gneiss and mica schist) may also release alkalis.

Synergistic effects:

There is evidence that other mechanisms that produce expansive forces in concrete, such as freezing and thawing and delayed ettringite formation (DEF), can have a synergistic effect with alkali-aggregate reactions; each making the other worse [13]. Avoidance of these effects, important in itself, should therefore be seen as an integral part of avoiding long-term alkali-aggregate damage in very long-service structures.

5 PROTECTION BY STRUCTURAL DESIGN

From a structural point of view, the designer of a major structure always prefers the choice of a non-reactive concrete formula. It is only when the concrete carries some AAR risks that the designer may be induced to introduce special aspects of structural design to mitigate the consequences of any expansion.

The first choice is weather protection and drainage. Most importantly, the structure must be designed so as to avoid, to the greatest extent possible, water accumulation and stagnation zones as well as preferential flow paths due to run-off; this necessitates predicting the slope profiles and shapes that allow for rapid water drainage. In the case of dams, the upstream face is generally in permanent contact with water, so that it is important to implement an appropriate drainage system inside the dam in order to avoid water accumulation inside the mass of concrete and to channel run-off water; shafts and galleries are particularly adapted for drainage purposes.

Sometimes, it could be useful to apply a membrane or a coating on the exposed faces of the structure, to limit humidity and/or water penetration into concrete. The coating could be paint, a thin protective layer or a thick layer. However, this type of coating only maintains its efficiency over a limited life cycle, so that a number of coating replacements will be needed during the service life of the structure.

Another pragmatic way to mitigate AAR effects is to make allowance for possible expansion. For example, it is possible to design sufficiently wide joints between blocks of concrete to accommodate the expansion of the concrete. In some cases, it could be necessary to use 3D detailed reinforcement or prestressing bars and tendons in the construction of some critical elements that have high levels of tension stresses. Additionally, during the service life of the structure, it is necessary systematically to inspect the parts deemed to be critical, so as to detect any cracks that may appear and allow water to penetrate into the concrete. Structural monitoring is also highly recommended to identify any deformations.

6 NEEDS FOR RESEARCH

This discussion has shown that there are urgent needs for research to better understand the factors that may eventually produce damaging alkali-aggregate reactions in such massive, long-service structures. It is suggested that this research needs to address:

- Nature of the reactions in such structures, including the effects of combined, synergistic mechanisms.
- Effects of alkalis in aggregates on long-term reactions in concrete and how to assess these 'releasable alkalis' in a realistic manner.
- Effectiveness of performance tests in predicting the long-term behaviour of concrete mixes in such structures.

7 SUMMARY OF PRECAUTIONS FOR MASSIVE, LONG-SERVICE STRUCTURES

These structures are inherently vulnerable to damaging alkali-aggregate reactions because of their longevity and environment. In terms of the RILEM International Specification, AAR-7.1, the necessary level of precaution is P4, the highest category, and classified in AAR-7.1 as an Extraordinary level of Precaution.

Moreover, it may not be straightforward to apply the two separate precautionary measures that are recommended for this level of Precaution because the frequent need to use locally available materials, particularly aggregates, may restrict the available choices. However, although the application of at least two separate precautionary measures is still the preferred solution, where necessary, a high level of protection can be achieved by the more rigorous application of one precautionary measure, combined with design and construction measures to minimize the effects of any expansion.

These more rigorous precautionary measures are summarised in Table 4.

Table 4. Summarised Precautionary Measures for massive long-service structures

CM1	Use of non-reactive aggregate combination	Expansion : $< 0.05\%$ at 2 years (AAR-3.1) $< 0.03\%$ at 20 weeks (AAR-4.1)
CM2	Avoidance of releasable alkalis in aggregates	On basis of petrographic examination until AAR-8 available
CM3	Alkali level in concrete	<2.5 kg/m^3 (Na$_2$Oeq) or Safety factor of 1, 1.5 or 2 kg/m^3 (Na$_2$Oeq) below the alkali threshold determined by a performance test on the actual concrete composition
CM4	Use of low-lime and low-alkali fly ash ($<8\%$ CaO and $<5\%$Na$_2$Oeq.) or Use of ground granulated blastfurnace slag ($<1.5\%$ Na$_2$Oeq)	At least 40%* At least 50%*
CM5	Design and construction measures	Drainage, Protection by membranes or coatings, Detailing of reinforcement or prestressing of critical elements, Inclusion of expansion joints.

* *by mass of cementitious material*

8 REFERENCES

[1] *Materials and Structures*, Special Edition, 2012 - *in preparation*

[2] Nixon, P J, Hawthorn, F, Sims, I, 2004, Developing an international specification to combat AAR proposals of RILEM TC 191-ARP, In: Tang, M, Deng, M (eds), *Proceedings of the 12th International Conference on Alkali-Aggregate Reaction in Concrete*, Beijing, China, Volume I, 8-16.

[3] Nixon, P J, Sims, I, 2006, An international specification to combat AAR: Proposals of RILEM TC 191-ARP, In: Fournier, B (ed), *Marc-André Bérubé Symposium on Alkali-Aggregate Reactivity in Concrete*, Montréal, Canada, 195-215 (part of the Proceedings of the 8th CANMET International Conference on Recent Advances in Concrete Technology).

[4] Charlwood, R, Scrivener, 2011, Expanding concrete in dams - long term challenges. 79th ICOLD Annual Meeting, Lucerne, Switzerland, 29 May to 3 June.

[5] Sims, I, Nixon, P J, Godart, B, 2011, Protecting new dams from the effects of alkali-aggregate reactions, In: *CDA/ACB Abstracts and Electronic Proceedings 2011 Annual Conference, Surveillance and Safety, Fredericton, New Brunswick, 15-20 October*, Canadian Dam Association/Association Canadienne des Barrages, Toronto, Canada, 406-416.

[6] French, W J, 2005, Presidential Address 2003: Why concrete cracks - geological factors in concrete failure, *Proceedings of the Geologists' Association*, 116(2), 898-105.

[7] Lindgård, J (main author & editor), Andiç-Cakir, Ö, Borchers, I, Broekmans, M, Brouard, E, Fernandes, I, Giebson, C, Pederson, B, Pierre, C, Rønning, T F, Thomas, M D A, Wigum, B J, 2011, *RILEM TC 219-ACS-P: Literature survey on performance testing*, COIN Project report 27, SINTEF Building and Infrastructure, Trondheim, Norway.

[8] Lindgård, J, Andiç-Cakir, Ö, Fernandes, I, Thomas, M D A, Rønning, T F, 2012, Literature review on parameters influencing laboratory performance testing, *Cement and Concrete Research*, 42(2), 223-243.

[9] AFNOR, 2004, Reactivity of a concrete formula with regard to the alkali-aggregate reaction, *Association Française de Normalisation*, Paris, France, AFNOR NF P 18-454, plus AFNOR FD P 18-456 (Interpretation criteria for NF P 18-454).

[10] Nixon, P J, Sims, I, 2000, Universally accepted testing procedures for AAR: the progress of RILEM Technical Committee 106, In: Bérubé, M-A, Fournier, B, Durand, B (eds), Proceedings, 11th International Conference, Alkali-Aggregate Reaction in Concrete, Québec City, Canada, 435-444.

[11] Sims, I, Nixon, P J, 2006, Assessment of aggregates for alkali-aggregate reactivity potential; RILEM International Recommendations, In: Fournier, B (ed), *Marc-André Bérubé Symposium on Alkali-Aggregate Reactivity in Concrete*, Montréal, Canada, 71-91 (part of the Proceedings of the 8th CANMET International Conference on Recent Advances in Concrete Technology).

[12] Lindgård J, Nixon P J, Borchers I, Schouenborg B, Wigum J B, Haugen M, Åkesson U, 2010, The EU PARTNER project – European standard tests to prevent alkali reactions in aggregates: Final results and recommendations, *Cement and Concrete Research*, 40, 611-635

[13] LCPC, 2009, Recommendations for preventing disorders due to Delayed Ettringite Formation.