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Alkali thresholds in concrete; the balanced alkali approach in ASR mitigation

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Abstract

The Alkali Silica Reaction (ASR) is a deleterious reaction in concrete that poses significant durability concern worldwide. As a preventative measure, total alkali content of general purpose Portland cements can be limited. In Australia, like in other countries, general purpose cement is limited with a conservative alkali content of 0.6%, this may be unnecessary, as low risk non-reactive aggregates and SCM blends are effective in reducing ASR prevalence. Indeed there is a growing argument to transition to risk assessed methods in choosing cement alkali levels. ASTM in the USA has employed a prescriptive approach to selecting preventative measures that incorporates a variety of cement alkali contents without compromising on safety. Similar balanced alkali approaches such as those recommended in Europe, Canada and New Zealand may be applicable in Australia. Raising alkali limits to a level greater than 0.6% in cement used in conjunction with alternative mitigation techniques would reduce the economic and environmental impact associated with alkali removal during cement production. This literature review discusses the Australian approach to alkali limits in contrast to the methods used around the world and explores the continuing research into alkali's mechanistic contribution to ASR.

***Keywords**: alkali-silica reaction; durability; alkali limit; mitigation; ASR*

1. INTRODUCTION

The alkali-silica reaction (ASR) is a deleterious reaction in concretes that poses significant durability concern worldwide. Three primary reaction components perpetuate ASR in concrete: (i) the availability of alkali metal cations, ostensibly sodium and potassium introduced primarily by cement binder, (ii) the presence of reactive silica (SiO_2) in a variety of reactive forms (from strained quartz to amorphous opal) introduced by aggregates, and, (iii) the presence of water which provides the medium for dissolution and is required for deleterious expansion to occur. Deleterious ASR proceeds with a two-step mechanism, first the gel precipitates out of solution proceeded by the sorption of water causing the gel to swell, inducing mechanical stresses on the surrounding concrete which leads to expansion and cracking in the second step [1,2]. Generally, damage due to ASR requires remediation or replacement of affected structures, leading to additional cost and environmental impact [3,4].

To reduce the potential for ASR, it is common to place an alkali content limit on Portland cement. In Australia, alkali contents in concrete are limited to 2.8 kg/m^3 Na_2O_{eq} (= Na_2O + 0.658 K_2O by weight) [5]. Based on the concrete alkali content limit, which is calculated based on the cement alkali content, the specified cement alkali content is limited to 0.6% Na_2O_{eq} by ATIC SP-43 of 0.6% Na_2O_{eq} [6]. An alkali content of <0.6% is generally considered low-alkali cement [7]. To meet low cement alkali limits, extra infrastructure in manufacturing is required. As an example, in preheater or precalciner kilns, waste dust with high alkali content must be extracted using a bypass, which diverts exhaust gas flow and removes the particulates for disposal, increasing heat losses, energy demand and maintenance costs [8]. The high alkali kiln waste dust poses an environmental challenge in disposal [9]. In addition, the added energy demands produce additional CO_2 which adds to the already substantial contribution of concrete to anthropogenic emissions [10]. In general, the cement industry is working towards sustainable development, striving to reduce greenhouse gas and particulate emissions by establishing cleaner processing and development mechanisms [11].

Minimising the environmental impact from the removal of alkalis is important for the development of more sustainable and economically efficient concrete. The use of high alkali cements may be an important step toward this goal in certain areas where the application permits. To address this issue, it is important to first recognise problems with the application of cement alkali limits. Currently, in Australia, GP cement is specified to have an alkali limit of 0.6% Na_2O_{eq} regardless of the application [6]. This may not be needed as there are a variety of concretes where deleterious ASR development is not observed even in the presence of a higher alkali cement such as those incorporating unreactive aggregates or sufficient supplementary cementitious material (SCM). SCMs such as fly ash's and blast furnace slags are commonly blended with Portland cements, that, when used at appropriate replacement ratios, effectively mitigate expansion due to ASR [12,13]. Concretes manufactured from cements with alkali levels of 1.0% and higher may not expand when combined with appropriate SCM quantities; higher levels of SCMs should be used as cement alkali levels rise [14]. Canadian standards for example allow alkali contents up to 1.25% Na_2O_{eq} when used with SCMs and moderately reactive aggregates [15]. Alkali contributions from other sources such the aggregate, SCM, admixtures and water are not factored in to determining cement alkali limits and the cement and binder content of concrete varies depending on the type of concrete required. Alkali contributions from other mix components are however factored in calculating the total alkali content of the concrete mix, thus the total alkali content in concrete is a more reliable value on which to base an alkali limit.

ASR is a pore solution reaction where the alkali is primarily released during the hydration of the cement into the pore water. The limit of alkali in the cement is designed to limit the pore solution concentration of alkali and hence the hydroxide ion concentration, $[OH]^-$, although alkali concentrations will vary slightly in localised areas throughout the concrete [16]. Alkali limits in cement and concrete suggest alkali content thresholds for deleterious ASR to occur. The $[OH]^-$ threshold is the concentration in the pore solution at which the reaction slows sufficiently to cause no expansion or structural damage. This idea is applied on a macro scale in the form of threshold alkali limits for concrete which is defined as the minimum alkali content of the concrete to promote the deleterious expansion due to ASR with a specified aggregate-binder combination. RILEM (Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages) outlines their recommended method for threshold testing in RILEM AAR-3.2 [17]. The method RILEM recommends is to prepare a program of concretes with identical mix designs however with alkali contents that vary incrementally. The typical range suggested is between 2 and 5.5kg/m^3, within this range the highest alkali content to not display significant expansion is considered the threshold alkali content. Typically, when an alkali threshold for an aggregate-binder system is determined, a safety margin is implemented to allow for differences observed between laboratory and field studies, RILEM suggests a safety margin of 1.0 kg/m^3 [18].

Aggregate reactivity is extremely important when determining alkali thresholds as different aggregates have compositions that result in varying levels of reactivity, these differing reactivity levels are determined through accelerated expansion based test methods. Primarily, determinations of aggregate reactivity are based on standardised accelerated test methods. These commonly used methods for determining aggregate ASR reactivity are the concrete prism test (RILEM AAR-3) and the accelerated concrete prism test (RILEM AAR-4.1) [19,17].

As an example of concrete threshold alkali limit (TAL), classifications have been proposed based on aggregate reactivity, where aggregates classified as rapidly reactive via RILEM AAR-3, are suitable for concrete mixes with <2.8 kg/m^3 Na_2O_{eq}, moderately reactive with the range $2.8 \geq TAL \geq 5.5$, slowly reactive within $5.5 < TAL < 7.4$ and finally non-reactive with ≥ 7.4 kg/m^3 Na_2O_{eq} [20]. A common literature recommendation for the total alkali limit in concretes is 3.0 kg/m^3 Na_2O_{eq} and this is supported by threshold expansion studies Na_2O_{eq} [21,22]. This approach to applying alkali content limits is beneficial versus fixed limits as it allows for a greater flexibility in binder alkali content as a higher alkali cement and SCMs could be mixed with aggregates of lower reactivity.

Standardised methods such as the concrete prism test, where prisms are exposed to a high humidity atmosphere and elevated temperatures, incur leaching of alkalis from the internal pore solution into the storage environment, leading to reduced alkali content available to the reaction compared to field specimens [7,23,24]. This indicates that the expansive properties of an aggregate or mix combination may be underestimated due to the reduced alkali content of the test specimens. The leaching effect on the sample will cause a greater degree in deviation from field results in lower alkali mixes, the result of this is that an aggregate that may appear unreactive in the accelerated test, may be seen to be reactive in the absence of leaching in field exposure [25]. To combat this, a number of investigations have been conducted and are underway to develop and analyse the efficacy of methods designed to eliminate the leaching issue via the wrapping of specimens or immersion of concrete prisms in alkaline solutions [26-

29]. Eliminating the issues such as leaching in current methods could lead to procedures that more closely correlate with field studies. This will lead to more reliable determinations of alkali thresholds and accurate alkali content limits.

2. INTERNATIONAL APPROACH TO ALKALI LIMITS

Due to the wide range of aggregates used in concrete, the application of a broad based alkali limit results in low limits in order that potentially reactive aggregates can be accommodated. Applying an alkali content based on the threshold alkali content for ASR reactivity, however, allows flexibility in the alkali limits and results in more sustainable construction materials. ASR mitigation strategies internationally have recognised this. For example, RILEM has developed *The RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures,* which specifies precautionary measures to reduce ASR prevalence in Recommended Specification Section AAR-7.1; AAR-7.1 prescribes precautionary steps on a risk assessed basis. The recommendations given in AAR-7.1 are world leading guidelines based on strong international collaboration with the intention that it is used as a basis for other regions to establish AAR controls [18].

Contributing factors to the risk assessment in AAR-7.1 include a structures service life and its environmental exposure to moisture as well as materials factors. These factors are considered to determine the level of precautionary measures which define the allowable or required concrete composition parameters such as aggregate reactivity, SCM usage and alkali Limits. AAR-7.1 notes the drawbacks of low alkali cement limits and recommends the benefit of using alkali content thresholds of a concrete mix for specific aggregates as the preferred option for minimising the risk of ASR. The benefit to this approach is that it can allow for a greater variety of materials to be used while adequately reducing risk. The European Committee for Standardisation has published a *Framework for a specification on the avoidance of a damaging Alkali-Silica Reaction (ASR) in concrete* which offers succinct recommendations, heavily influenced by RILEM AAR-7, outlining precautionary measures based on environmental categories and structure use case [30].

Worldwide, national standard bodies have followed this approach and prescribed methods for risk minimisation due to ASR while allowing flexibility in alkali contents based on assessed risk. ASTM prescribes mitigation and risk reduction methods in their Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete (ASTM C1778-20) [31], which serves as the primary guide for minimising ASR in the USA. The guide Prescriptive Approach for Selecting Appropriate Measures outlines options for preventative measures in a similar approach to that prescribed by RILEM AAR-7.1 and CSA A23.2-28A [31,32] . The premise of the prescriptive approach is to prescribe preventative methods based on a risk assessment of the structures susceptibility to ASR and the ramifications were it to structurally fail. SCM replacement levels are recommended based on the risk level of the structure, part of this specification includes considering the alkali content of the cement used. A minimum SCM content is recommended if a cement with an alkali level is >0.7% and the recommended SCM content increases when alkali contents up to 1.25% are used, above which there is no recommendation. The practice is outlined by the American Association of State Highway and Transportation Officials (AASHTO) where the prescriptive approach was originally published as a guideline in the United States under AASHTO PP65-11, now superseded by R80:2017 [33]. The Cement & Concrete Association of New Zealand (CCANZ) technical report TR 3 Alkali Silica Reaction also offers a leading approach to alkali content limits in concrete by specifying alkali limits based on precautionary level determined from structure use case [34]. With this approach CCANZ TR3 allows for the use of high alkali cements without compromising on safety. Similarly, Canadian standards allow alkali contents up to 1.25% Na_2O_{eq} when used with SCM's and moderately reactive aggregates [15].

3. AUSTRALIAN APPROACH TO ALKALI LIMITS

The Australian standard guide for prevention of ASR is the Standards Australia handbook HB79 for *Alkali Aggregate Reaction – Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia*. HB79 outlines a detailed guide for minimising the effect of ASR and prescribes precautionary measures based on the consequence and acceptability of ASR damage, the service life of the structure and the impact on the environment on the likelihood of ASR [5]. The risk assessment focusses on the reactivity of aggregates and the use of SCM in mitigation of reactivity whilst prescribing a conservatively low alkali content limit for concrete. If there is any risk of ASR damage, HB79 specifies a limit the concrete alkali content at 2.8 kg/m^3 Na_2O_{eq} thus applying a single low alkali limit approach irrespective of the inherent assessed risk. The corresponding specification for cement is 0.6% Na_2O_{eq} (ATIC SP-43) thus retaining a focus on maintaining low alkali cement as the binder in concrete. If potentially reactive aggregates are used, then other strategies of ASR mitigation must be implemented such as appropriate level of SCM addition to the binder. If non-reactive aggregates are used and, in conjunction, SCMs are incorporated in the binder resulting in concrete with a very low risk of ASR, the limit of 2.8 kg/m^3 is still applied. It is in the latter cases in which there is little risk of ASR, where there is potential for flexibility in alkali limits, i.e. a balanced alkali content approach, but these cases must be assessed for each binder-aggregate mix. If the balanced alkali approach can be applied and alkali limits in risk assessed concretes can be relaxed along with the cement alkali content limit of 0.6% Na_2O_{eq}, the economic and environmental impact of concrete would be reduced. It is important to stress that the assessment of a concrete alkali content level must be carried out for each concrete and on a risk assessed basis, in order to maintain high safety and service life requirements.

HB79 does have a risk assessed method for applying SCM contents and aggregate reactivity classifications. It would be ideal, economically and environmentally, to expand this recommendation to include provision for higher alkali limits similar to that of ASTM C1778-20 and RILEM AAR7.1, however there is yet to be a robust assessment of the viability of the balanced alkali approach in the Australian context. An empirical approach, such as that outlined by RILEM, identifying thresholds through expansion based methods whilst correlating expansion with microstructural characterisation and ASR gel composition would allow for correlation between alkali thresholds and field performance. Some inherent issues in expansion test still need to be overcome for reliable alkali threshold determination, in particular, alkali leaching in CPT which may result in an overestimate of the true alkali threshold. The importance of overcoming such issues in determining alkali thresholds is exhibited by the relationship between pore solution alkali content and concrete durability [35]. In order to attempt to address the limitations of these empirical methods of threshold determination, a systematic parallel investigation has been initiated in our laboratories where alkali threshold tests using the approach outlined in RILEM 3.2 is compared with CPT test specimens immersed in 28 day pores solutions synthesised based on the composition of expressed pore solutions from cement pastes aged to 28 days. This investigation is currently in its infancy. The basis of the experimental methodology is outlined in this paper with a view to presenting the outcome of this work in ICAAR 2024.

4. CONCLUSION

The alkali limit placed on cement in Australia may be overly conservative in its use when compared to leading international guidelines. The material restrictions imposed by specifications on cement and concretes result in the inefficient use of the materials available. This can be seen as the necessary inconvenience caused in order to minimise the risk of deleterious ASR and maintain the long term integrity of built infrastructure. However, a balanced alkali approach may allow for long term durability of infrastructure while contributing to lessening anthropogenic emissions. The use of additional mitigation measures such as the incorporation of SCMs allow for the use of higher alkali cements while mitigating the deleterious effects of ASR within an acceptable tolerance. If these restriction can be relaxed or modified while still maintaining a high safety guarantee, then a greater variety of materials can be utilised leading to less waste which is economically efficient. The economic efficiency is paralleled by the reduction in environmental impact, unused quarry product and highly alkaline bypass dust will not need to be discarded as waste which would reduce the environmental strain. The environmental benefit would be significant, as in addition to reduced waste, less energy would be consumed and associated carbon emissions reduced. For Australia, adopting a similar approach to RILEM and ASTM in applying the use of wider cement alkali contents is a positive step toward this goal.

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