A WORLDWIDE VIEW OF AAR: UPDATING SWAMY

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Abstract

Timed to coincide with the 9th ICAAR in London in 1992, Emeritus Professor Narayan Swamy edited a book entitled 'The Alkali-Silica Reaction in Concrete'. It was a unique contribution to the limited number of text-books devoted to ASR. As well as several chapters summarising the essential principles of the mechanism, its consequences and options for its prevention or management, there were chapters describing the experiences of ASR in various countries.

Over the succeeding nearly 25 years, Swamy's book has become increasingly out of date and the regional chapters now seem rather an eclectic collection, with major areas being unrepresented, despite sometimes undertaking fundamental and/or practical research into AAR . As a result, Prof Swamy kindly invited the authors to undertake an updating of the book, which they have achieved with the generous assistance of a large number of AAR experts worldwide.

In addition to bringing the general science and engineering aspects of AAR and AAR-affected structures up to date, two major changes have been implemented. Firstly, the title has been subtly changed to refer to 'the alkali-*aggregate* reaction' as opposed to 'the alkali-*silica* reaction', facilitating an opportunity for the work to provide a state-of-the-art account and update of the controversy over the very existence or otherwise of 'alkali-carbonate reactivity' (ACR) and some other variants that do not wholly conform to the classic ASR model. Secondly, it was decided that the national and regional reviews would seek a complete worldwide coverage. This paper will introduce the new edition of Swamy's valuable book and celebrate the impressive international co-operation that has enabled it to be brought together.

KEYWORDS Concrete, Aggregates, Alkali-Aggregate Reactivity (AAR), Durability, Worldwide Occurance

1 INTRODUCTION

Although the premature deterioration of concrete structures due to the expansive products of a chemical reaction was identified since the late 1930s [1] and became known as the alkali-aggregate reaction (AAR) in North America, engineers and scientists were slow to recognise that this materials problem was common world-wide. Post 1946 a slowly developing awareness of AAR problem among engineers and scientists led to the holding of the first international conference on the subject in 1974 (the first ICAAR conference) in Koge, Denmark. This first conference was followed by others up to the 15th ICAAR in 2016 as engineers and scientists round the world realised that AAR was a general problem affecting some concrete structures in their own countries.

Professor R Narayan Swamy, a celebrated Civil, Structural & Mechanical Engineer, at Sheffield University in the UK and taking a particular interest in the effect of AAR on the engineering performance of concrete and structures (Figure 1), edited a unique book that was the first global review of the problem [2]. The book, with its distinctive cover (Figure 2) was published in 1992, to coincide with the 9th ICAAR in London that year and proved to be ground breaking in its global approach, introducing scientists in many parts of the world to the possibility of ASR deterioration in concrete structures for the first time.

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It included four initial chapters summarising the essential principles and considerations of the mechanism, the consequences of AAR and options for its prevention or management. Seven later chapters described the differing experiences of AAR in various countries of the world. These chapters were contributed by experts from those countries. Table 1 lists the countries and the author of each particular contribution.

It is clear from Table 1 that, although a review of the problem of alkali-silica reaction in concrete covered many of the countries of the world and was written by internationally recognised experts, there are many important omissions from a truly global coverage of countries. A second omission was that the controversial and much rarer alkali-carbonate reaction in concrete is not discussed.

Although in many ways this book was a ground breaking first review of ASR as a global problem for concrete structures, there have been many advances since 1992 in the recognition, investigation and treatment of this problem.

2 A SECOND EDITION: ALKALI-AGGREGATE REACTION IN CONCRETE

In view of the omissions from the 1992 edition and the many more recent advances in understanding of the mechanisms involved, methods of diagnosis and the investigation methods of avoidance, management and repair of affected structures, it was decided to produce a Second Edition. This time, there would be an endeavour to cover all the major regions of the globe and to include the results of the more recent work on alkali-aggregate reaction in concrete including the controversial possibility of an expansive and damaging issue associated with alkali-carbonate reaction in concrete. This second edition has the amended title: 'Alkali-Aggregate Reaction in Concrete, A World Review'. As with the first edition, the chapters have been written by acknowledged experts from the various countries and regions and this time it has been edited, at the invitation of and with encouragement from Emeritus Professor Swamy, by Ian Sims and Alan Poole.

Figure 3 gives an indication of the better global coverage of the second edition. The countries shown in red all have published reports of concrete structures affected by AAR, those shown in yellow are countries where the authorities are aware of the potential problem posed by AAR, but no published case study reports are available. Most of these countries have specifications and test procedures in place to avoid the potential for AAR to affect their concrete structures. The uncoloured areas are of those countries where no information is currently available.

The coverage of the new edition is clearly more comprehensive than was the case in the first edition, but the pattern of introducing aspects of the AAR problem in the first 5 chapters, followed by chapters 7 to 16 reviewing the experience of AAR in the different regions follows the same general scheme. A listing of the chapters and the name of the contributing authors are given in Table 2.

3 ADVANCES IN UNDERSTANDING AND MANAGING AAR PROBLEMS WITH CONCRETE

The global awareness of damaging alkali-aggregate reaction in concrete since 1992 and its cost implications has led to has led to expansion and intensification of research efforts to:

- Understand the mechanisms involved in the reactions;
- Investigate the mineral components of aggregates which react with alkalis;
- Develop test methods to assess the potential for reactivity in aggregates and concrete;
- Develop specifications that reduce the risk of alkali-reaction being initiated in concrete;
- Investigate structural effects and evaluate possible mitigation and repair procedures.

3.1 Alkali-Aggregate Reaction types and Mechanisms

It has slowly become clear that the various types of AAR recognised initially may have many features in common. Initially three distinct types have been identified:

1. The most common, alkali-silica reaction, involves silica minerals that are poorly crystalline, amorphous or strained, such as crypto- to micro-crystalline quartz, opal, chalcedony, chert, cristobalite, tridymite and volcanic glasses present as components of the concrete aggregate. These minerals may react with the alkali hydroxyl pore fluids in the concrete leading to the development of a hygroscopic gel which can expand on absorbing moisture with forces up to several MPa [3]. Typically the reaction takes between 6 and 12 years to cause noticeable damage to a concrete structure.

2. A second slowly reacting type of ASR which involves disordered forms of silica often found as sub-microscopic particles in sedimentary, metamorphic and sometimes igneous concrete aggregates. This reaction may not exhibit damaging expansion until the structure is perhaps 20 or 30 years old, but the expansion of the concrete will continue slowly for 50 or 70 years or perhaps longer.

There is no clear distinct division between the first and second type and the difference is considered to be related to the type of reactive silica and its surface area and accessibility to alkali pore fluids. Forms of this second type was initially described as alkali-*silicate* reaction [4,5] but this name is no longer used.

3. Alkali-carbonate reactivity (ACR) applies to a reaction between the alkaline pore solution in concrete and any aggregate made from carbonate rocks such as limestones or dolomitic limestone or dolomite. However, the term alkali-carbonate reaction is applied only to the reaction between certain argillaceous dolomitic limestones and the alkaline pore solution in concrete that gives rise to rapid expansion and cracking of concrete. De-dolomitised reaction rims are commonly observed round dolomitic aggregate particles in a concrete, but these rims do not normally cause any expansion of the concrete. A concrete pavement in Kingston, Ontario was observed to develop damaging expansion within a year of placing [6]. However, recent very careful research studies [7] suggest that it was ASR, involving extremely fine-grained silica, rather than alkali-carbonate reaction that was the cause of the concrete expansion reported from Kingston. However, some controversy concerning the role of alkali-carbonate reactivity remains [8,9].

It is thus probable that the three types of alkali-aggregate reaction in concrete noted above may all be variants of the most common alkali-silica reaction, and that the differences stem from the variation in the morphology of the reactive siliceous component in the aggregate, its surface area, porosity and accessibility to the pore fluids in the concrete.

3.2 Potentially Reactive Concrete Aggregates

Initially the alkali-reactivity of concrete aggregates had been identified as component silica minerals in the aggregate that were poorly crystalline or amorphous; examples were opal, chalcedony, chert, cristobalite, tridymite and volcanic glasses. The number of aggregate rock types identified as containing these minerals increased as additional case study information became available from around the world.

Many countries produced national lists of rocks or aggregates which may contain these potentially alkali-reactive mineral components (or sometimes lists of materials that did not). These lists have sometimes been used as national criteria for requiring a more detailed petrographic investigation and/or testing of the particular aggregates concerned. Several accelerated tests were established by the pioneering research in the USA during the 1930s to1960s period and these became used around the world, but increasingly researchers devised a proliferation of new tests and especially variants of existing tests, sometimes being 'validated' by comparison with other tests.

In 1988, the Paris-based international organisation, RILEM, formed a Technical Committee (TC 206), charged with identifying reliable accelerated tests for assessing the ASR potential of aggregates worldwide [10]. The work was further refined through two later RILEM TCs (TC 191-ARP & TC 218-ACS), with the final outcome, an integrated scheme for the assessment of AAR potential, being published recently [11]. This RILEM scheme describes a three-stage approach, from petrography, through optional screening tests, to dependable expansion tests. To enhance the effectiveness of the petrographic assessment, TC 219-ACS has produced an excellent Atlas of potentially reactive aggregates [12] based upon the research information and samples from many countries.

3.3 The development of the pessimum concept

An important research finding relating to aggregate was the observation that some reactive aggregates (most commonly including flint or chert) appeared to exhibit a maximum concrete expansion when a particular proportion of reactive material was present in otherwise non-reactive aggregate. This 'pessimum proportion' of aggregate was first investigated experimentally [13]. More recent investigations [14,15] have provided further evidence of a pessimum effect with some aggregates, but have pointed to difficulties in the explanations of the reduction of expansion effect occurring when the proportion of the reactive component in the aggregate is increased above the pessimum proportion. An important consideration is the distinction between the measured concrete expansion obtained from tests and the actual reactive process and type, chemical composition and quantity of expansive gel produced.

3.4 The Alkali Content of Cement and Concrete

Until it became clear that most, though not always all the alkali involved in AAR was derived from the cement used in concrete, the alkali levels in cements were sometimes approaching 1% sodium equivalent, (weight percent K_2O + 0. 658 Na_2O), [16]. These alkali concentrations were usually derived from the clay/shale raw material used in cement manufacture, sometimes further enhanced by recycling of alkali rich flue dusts into the feed materials. The realisation of the importance of specifying alkali limits for Portland cements has now been generally accepted world-wide with typical specification limits used in many countries of 0.6% Na_2O(eqv.), or 3kg/m^3 for concrete.

An alternative approach that has become very important as a control for inhibiting ASR is the use of mineral additions (termed 'supplementary cementitious materials' or SCMs in North America), such as silica fume, ground granulated slag (ggbs), fly ash (pfa) or pozzolanic material, with the cement and today is perhaps the most commonly used method for minimising the risk of development of AAR in concrete. One major effect of such additions is dilution and hence reduction of the alkali concentration in the concrete so that the AAR is not initiated. However, there is evidence that some additions have beneficial effects beyond those explicable by alkali dilution.

3.5 Specifications to avoid alkali-reaction in concrete

Many countries have developed strategies for minimising the risk of AAR within their own boundaries and applying to their materials, conditions and construction traditions; an example is Digest 330 in the UK [17]. However, the increasing global interchange of concrete constituents and expertise of usage and in design favours an international approach. The RILEM TCs mentioned in subsection 3.2 have prepared specifications for international application [11), including one for ASR (designated AAR-7.1) and another for ACR (designated AAR-7.2). Also, in response to the growing recognition that large, long-service concrete structures, such as dams, might not always be adequately protected by conventional measures [18,19], RILEM has also included a preliminary version (AAR-7.3) for such structures. The current RILEM TC (TC 258-AAA) is aiming to develop guidance on performance testing for the evaluation of AAR potential for particular project concrete mixes [20].

A parallel but essentially similar approach has been devised in North America [21], whereby a risk analysis assesses the 'criticality' of a structure and results in six potential levels of precaution. In the case of the need for more stringent prevention, there are greater restrictions on concrete alkali contents, guidance on the use of mineral additions (or 'supplementary cementitious materials') and quite frequently both measures in controlled combination.

3.6 Advances in Repair and Remediation of Concrete Structures

Various methods of remediation of concrete structures have been reported in recent years from many counties round the world. The demolition and complete replacement of damaged elements of a structure are commonly reported in case studies discussing remediation. Early ideas hinged upon the need to prevent moisture ingress into the concrete and thus removing one key component from the reaction. Hydrophobic coatings, paints and penetration injection of epoxy based polymers have all been used but with varying success. Relief of the stresses caused by the AAR expansion by slot cutting through the structure have also been used with some success for sluice gates and dams [22].

Some more recent research and case study reports suggest techniques involving lithium ion which although reactive forms non-expansive gel. Lithium impregnation of concrete has had some success and is reported in ICAAR conferences mostly post 2000. One method involves replacing the sodium and potassium ions in the concrete pore fluid by impregnation with lithium nitrate solution [23]. Another method involves adding a finely ground lithium containing glass as a mineral admixture [24] and a third involves electrolysis to migrate lithium ions into the structure [25,26]. However, despite these theoretically encouraging trials, generally the use of lithium has not so far emerged as being a practically effective solution.

4 GLOBAL SPREAD OF AAR AWARENESS SINCE 1992

The limited worldwide recognition of AAR as a general threat to the durability of concrete structures is indicated by the somewhat incomplete coverage in the regional section of the first edition of Swamy's 1992 book. Although ASR was first described in 1940, it would be 34 years before the first ICAAR was held, in Denmark in 1974, when just 4 nations were represented. Over the next four ICAARs, the number of participating nations increased only modestly, being 12 at Cape Town, South Africa, in 1981. In this period, it seemed almost to be like a members' club, when admittance was only possible after AAR had been discovered in the country concerned; even then, participants were likely to be research engineers and scientists, with structure owners (often governments or their agencies) being somewhat in denial. In addition to the publication of Swamy's book in 1992, which, as we have seen earlier, summarised the AAR experience in just 7 countries, the ICAAR in London that year also attracted the greatest number of participating nations (29), both up to that time and indeed since. Afterwards, there seems to have been a gradually increasing acceptance that AAR is quite widespread and not stigmatic, and also that is becoming better understood and more confidently controlled.

The first edition of Swamy's book covered the experience of AAR in only three European countries, none of which was one of the larger European mainland nations. Not surprisingly, in view of the country of publication, the largest of these chapters described the situation in the UK, where the occurrence of ASR had finally been accepted after about 30 years of regarding it as an interesting 'foreign' problem (the second edition updates this and also includes Ireland). The other European chapters concerned Denmark and Iceland, each of which was confronted with serious ASR problems. In the second edition of Swamy's book, justice is done to the huge amounts of excellent research that have been carried out in France, Germany and many other European nations, plus all the Nordic countries and the adjoining parts of Russia and Turkey.

Surprisingly, given the origin of the 'discovery' and initial explanation of AAR, the first edition of Swamy's book did not include a regional review of the USA, although there was good coverage of the experience in Canada, including the emerging recognition of three types of reaction (ASR, slow/late expanding silica/silicate and ACR), plus the aggravating influence of the use of de-icing chemicals. Otherwise, there were large tracts of the world where no information about AAR was available as far as the regional summary went in 1992. Two of these were China and the whole of South and Central America, each of which are thoroughly addressed in the second edition. Another omission from the first edition was Australia, despite some excellent AAR research carried out there by Harold Vivian (see Figure 1) in the 1950s to 1970s, but again this is corrected in the new edition.

In completing the second edition of Swamy's book and especially achieving more complete global coverage, particular challenges remained and have been addressed with the assistance of some very determined chapter authors. Undoubtedly the most problematic for the editors, in ensuring areal coverage of the world, was completing the chapter on Russian Federation, which occupies a very large part of Asia and Eastern Europe. The result will hopefully be of great interest and usefulness to readers who, like the editors, are not exactly conversant with the Russian language. Finally, there was a need to fill the gap represented by the so-called 'Middle East' and also North Africa, which might be important in terms of AAR, given that some areas of that region combine intense concrete construction in recent decades with local conditions of heat and humidity that might be expected to be conducive to reaction (being similar to those used for accelerated expansion tests). In earlier years, concrete structures in the Arabian Gulf probably experienced more fundamental short-term challenges than AAR, but, as these have been surmounted by better understanding and improved techniques, modern construction in that area either already specifies against the risk of AAR, or will need to consider the risk more seriously in the future.

5 CONCLUSIONS

In the nearly 25 years since Swamy's unique book, 'The Alkali-Silica Reaction in Concrete' was published in 1992, recognition of the global occurrence and risk of AAR has spread to all countries. Moreover, greatly improved and disseminated understanding of the reactions involved, of the mechanisms by which they can affect the performance and durability of concrete structures and of the various ways in which the risk of damage can be assessed and minimised, has enabled concrete to be used with confidence all around the world. Confronting the mysteries of AAR is no longer the preserve of certain afflicted nations, but simply a widespread issue to be addressed using internationally agreed procedures. It is thus a good time to introduce the imminent second edition of Swamy's book, subtly re-titled 'The Alkali-*Aggregate* Reaction in Concrete', in which the general science and engineering of AAR are completely brought up to date and the previously incomplete and somewhat eclectic regional reviews are now rendered much more complete and truly global in their coverage.

6 ACKNOWLEDGEMENTS

The preparation of this new edition of Swamy's book, which has been achieved with the support and selfless encouragement of Emeritus Professor R Narayan Swamy, has only been possible because of the generous assistance of many expert authors from countries across the whole world and from all the continents. We celebrate this international co-operation in confronting a topic of significance to all users of concrete, wherever they operate and whatever materials and conditions pertain.

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TABLE 1: Chapters 5 to 11, title and contributing authors from Swarmy [2]

Chapter	Chapter Title	Chapter Author(s)
5	Alkali-Silica Reaction – UK Experience	I. Sims
6	Alkali-Silica Reaction – Danish Experience	S. Chatterjee, Z. Fordos, N. Thaulow
7	Alkali-Silica Reaction – Icelandic Experience	H. Olafsson
8	Alkali-Silica Reaction – Canadian Experience	P. E. Grattan-Bellew
9	Alkali-Silica Reaction – New Zealand Experience	D. A. St.John
10	Alkali-Silica Reaction – Japanese Experience	S. Nishibayashi, K. Okada, M. Kawamura, K. Kobayashi, T. Kojima, K. Nakano, K. Ono
11	Alkali-Silica Reaction – Indian Experience	A. K. Mullick

TABLE 2: The chapter titles and the contributing authors in Alkali-Aggregate Reaction, A World Review (2016) Eds. I. Sims and A.B. Poole

Chapter	Chapter Title	Author(s)
1	Chemistry and Mechanisms of AAR	A. B. Poole
2	Assessment Testing and Specification	P. Nixon, B. Fourier
3	The So-called Alkali-Carbonate reaction	P. Grattan-Bellew, T. Katayama
4	Prevention of Alkali-Silica Reaction	D. Hooton
5	Diagnosis, Appraisal, Repair & Rehabilitation of Structures	B. Godart, M.R de Rooij
6	The United Kingdom and Ireland	I. Sims
7	Nordic Europe	J. Lindgaard
8	Europe and Mainland Turkey	I. Fernandes
9	Russia and Neighbouring Asian Countries	S. Falikman, A. B. Poole
10	North America (USA and Canada)	K. Folliard
11	South and Central America	E. Fairbain
12	Southern and Central Africa	M. Alexander, G. Blight
13	Japan, China and South East Asia	T. Miyagawa, K. Yamamda
14	Part I Australia, Part II New Zealand	A. Shayan (I), S. A. Freitag (II)
15	The Indian Sub-Continent	A. K. Mullick
16	The Middle East and North Africa	T. Kay, A. B. Poole

FIGURE 1: Prof Swamy discussing ASR with Australia's Harold Vivian [in 1992?]

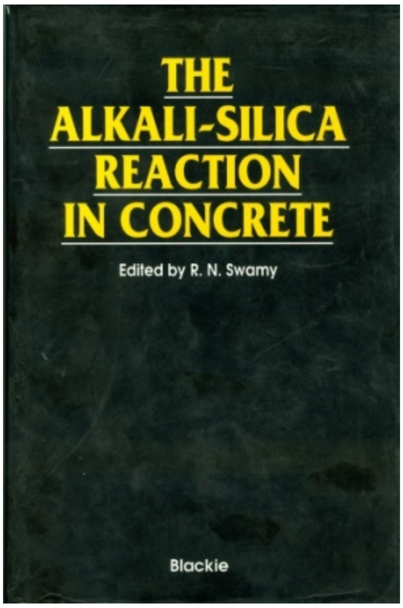

FIGURE 2: The distinctive black cover of the first edition.

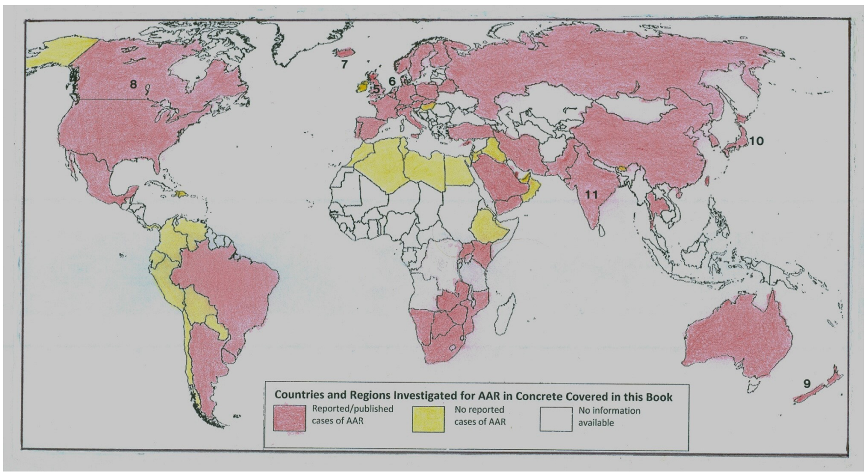

FIGURE 3: A world map showing the numbers of the Chapters (5 – 11) in Swamy, 1992 which covered those countries where the ASR problem was reviewed. The map also shows countries (coloured red or yellow) that appear in Chapters 7 to 16 of the new edition.