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# Despite Stanton: AAR from denial to remedy in the UK, Europe & the World

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## Abstract

*Stanton identified ASR within US concrete structures. It is now recognised as a worldwide problem. Typically countries initially deny ASR, then over time recognise it in some particular combinations of materials and conditions. Investigations determine the controlling factors, specific test procedures and guidance. Post 1945, global collaborative research has mitigated its effects. ICAAR conferences from 1974 have been invaluable. They have developed to include worldwide researchers and practitioners, including those keen to benefit from existing experience and others keen to share new findings. Lisbon is 16th in the series and a global consensus on testing and specifications is emerging, due to the co-operative spirit created, and practical work by RILEM and others. Worldwide advances in AAR risk assessment, initiated by Stanton 80 years ago, have successfully limited damage in new structures, but present management of existing AAR-affected structures typically only delays, rather than prevents, eventual replacement.*

***Keywords**: AAR; concrete; international-collaboration; reactive-aggregate*

## 1. INTRODUCTION

The problem of AAR deterioration of concrete was first recognised by Thomas Stanton during the late 1930s in structures on highways in California, USA. His investigations were published in 1940 [1] and 1941 [2] and have frequently been discussed in more recent years. In Stanton's original work, he identified the basic mechanism of the reaction, listed many of the aspects that could be involved and also developed test methods that have formed the basis of many of those in current use. All of this was based on data accumulated during his extensive laboratory investigations. Although this was thorough and detailed the deleterious nature of ASR in concrete, it was not recognised as a particular problem outside California until after the 1940s.

In 1967, Gunnar Idorn [3] submitted his PhD thesis on the durability of concrete structures in Denmark (see Figure 1.1). At a similar time in the 1950s, Harold Vivian was investigating ASR causes, methods of test and diagnosis in Australia [4], where no cases had then been identified. Slowly, engineers and scientists across the world became aware of the possibility of ASR problems in concrete structures. Yet, owners of large structures and governmental organisations around the world were reluctant to concede that ASR-affected concretes existed outside the USA. This short review examines the sequence of events whereby the recognition of the deleterious effects of ASR are first reported, then investigated, leading in turn to the types of testing and preventative measures relevant to each particular country. Although the particular circumstances differ in different countries, there has been a gradual recognition that aspects of the problem of ASR, its diagnosis, prevention and the assessment of inherent risk of failure have many common features, which allow a valuable global consensus to be postulated for dealing with and eventually mitigating its damaging effects.

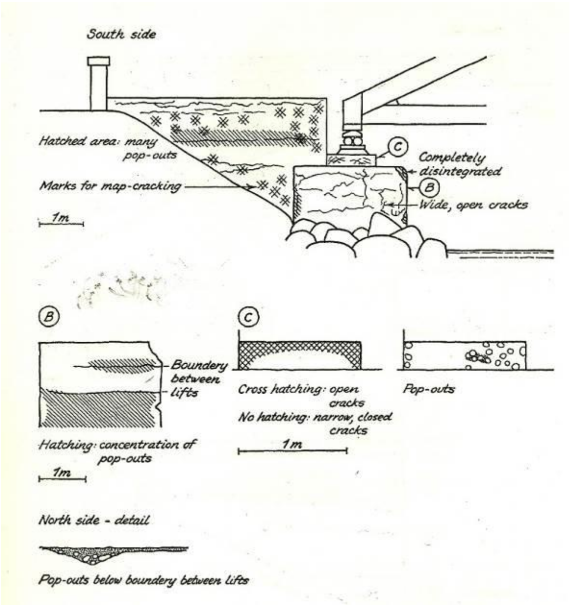


Figure 1.1: A field inspection report sketch of Vilsund Bridge, Denmark [3].

Figure 1.2: Thames Barrier, London (courtesy of commons.wikimedia.org).

## 2. THE APPROACH TO ASR IN THE UNITED KINGDOM

In the USA during the 1930s and 40s, diligent research had established the ASR mechanism, its key parameters and consequences, also the principles of many current test procedures. The first ASR tests on UK aggregates were actually carried out in the USA in 1947 [8], when a sample of British flint, present as 20% of the total test aggregate, had shown significant expansion in a test at 38 °C; an early sign of the dominant cause of ASR damage in the UK, which would only be recognised about 30 years later! A detailed account of ASR research in the UK, and its eventual road to a successful preventative strategy, is given in Sims and Poole [5].

An ASR research programme was initiated in 1952 at the UK's 'Building Research Station' ('BRS', now the 'BRE'), which would generate a series of research reports up to 1958 [6]. However, unfortunately, there seems to have been an underlying feeling in the UK that ASR was a 'foreign' problem. Sir Frederick Lea [6], then Director of the BRS, recognised the discoveries in the USA, but added *"Fortunately, no evidence has yet been obtained of large-scale failures in this country arising from this cause."* Wisely, Lea added *"nevertheless, some aggregate deposits which may be reactive in some degree do occur, and unfamiliar aggregates may need examination before use"*. The conclusions from this key research initiative now appear recklessly reassuring: *"the normal British aggregates so far tested, when used as whole aggregates, are not expansively reactive with high-alkali cements at normal temperatures".* This optimistic view would regrettably remain commonplace in the UK, including some authoritative textbooks and British Standards, until the early 1970s. In fairness to the BRS, a 1950s review of findings [10] reveals that they had, in fact, correctly identified one main potential ASR problem in the UK and added some prophetic words of caution: *"There remains the possibility therefore that some flints may be encountered which, under adverse conditions of 'dilution'* (ie. 'pessimum')*, alkali content, water content and temperature, may cause trouble".*

Realisation of the problem grew within the UK construction industry during the 1960s and 70s, largely because geologists identified the reactivity potential of certain mineral and rock varieties found in some aggregates for concrete~~.~~ Gunnar Idorn, researching Danish structures exhibiting deterioration that was frequently caused by ASR [3], involving some flint materials that might be stratigraphically related to those found across Southern England. Idorn was invited to address the UK's Concrete Society in 1968 and his message was published by the Concrete Society in 1969 [7]. Whilst Idorn himself did not presume to suggest that his findings in Denmark should necessarily be taken to mean that similar problems were occurring in the UK, it did inspire engineering geologist, Prof Peter Fookes [8], to recommend regular ASR testing of the flint aggregates then being used for concrete in construction of the Thames Barrier (see Figure 1.2), a critical flood-control structure downstream from London. This was probably the first time that ASR tests (gel-pat & mortar-bar tests) had been commercially applied in the UK.

The first major structure to be diagnosed with ASR in the British Isles was The Val de la Mare Dam in Jersey, Channel Islands, which is a concrete gravity dam, constructed between 1957 and 1961 [9]. Damage was first reported in 1971, with certain elements of the structure exhibiting discoloration, cracking and some displacement. The reactivity was associated with areas of secondary mineralisation, including opaline silica and chalcedony, within the local granodiorite that was quarried for the coarse aggregate. A good correlation was demonstrated between the damaged areas and those sections made using aggregate from the affected parts of the quarry. There are also other, though smaller, similarly-affected structures on the island, but the quarry is no longer used for concrete aggregate. The dam was successfully strengthened and repaired and remains in service.

Initially, the Val de la Mare Dam was something of a 'special case', being the only known affected structure in the British Isles and having no relationship with the complacency associated with flint aggregate. However, all this changed rather suddenly in the second part of the 1970s [10], initiated by discoveries of ASR-affected structures in Plymouth ~~(~~Devon, South-West England), shortly followed by many further cases elsewhere in Devon and then in South Wales and the English Midlands. In at least most or many of these cases, flint was the reactive aggregate constituent, typically within sands in mixtures with non-reactive coarse aggregates. As recognised by Stanton and BRS, reactive concrete mixtures were found to contain the flint constituent in a 'pessimum' proportion. In the London area, by contrast, flint tended to dominate both the coarse and fine aggregates, such that its overall content was well above 'pessimum' and no expansive reaction occurred.

In 1978, Palmer [10] of the 'C&CA' (now the 'BCA'), published a paper providing an update on UK occurrences of ASR, which included a small 1936 dam at Muckburn in Southern Scotland, wherein the reactive aggregate was a greywacke. At the time this was regarded as an unusual 'local' case. However, before long, it started to become became apparent that some other, often older and larger, structures were exhibiting evidence of a different and slower-developing form of ASR, involving greywacke aggregates, as shown on the map from Blackwell *et al*. [11]. This map (Figure 2.1) shows that several structures in Devon, Mid- and North Wales, Southern Scotland (including Muckburn) and Northern Ireland were all cases of ASR involving crushed greywacke. In due course, a protocol was developed, based on concrete prism testing, for distinguishing between reactive and non-reactive types of greywacke. The biggest structure affected by alkali-greywacke reaction was The Maentwrog Dam in North Wales (Figure 2.2), now submerged by an enlarged reservoir and superseded by a new dam. A nearby system of three dams in the Rheidol hydro scheme, one of which also displays ASR, have been researched by Thomas *et al*.[12], who found that the two non-damaged dams contained similar greywacke aggregates, but had fly ash in the mix.

From the mid-1970s, there was something of an 'epidemic' of ASR damage on the UK mainland, variously caused by contents of Cretaceous flint or Carboniferous chert that were frequently present in the sand & gravel aggregates at a proportion within the 'pessimum' range, across the South of England and/or the Midlands, plus the lower incidence of greywacke cases. Consequently, urgent steps were initiated, to find ways of minimising the future risk of ASR damage in new concrete construction, also diagnosing and assessing subject structures, leading to a systematic and urgent movement towards solving these challenges.

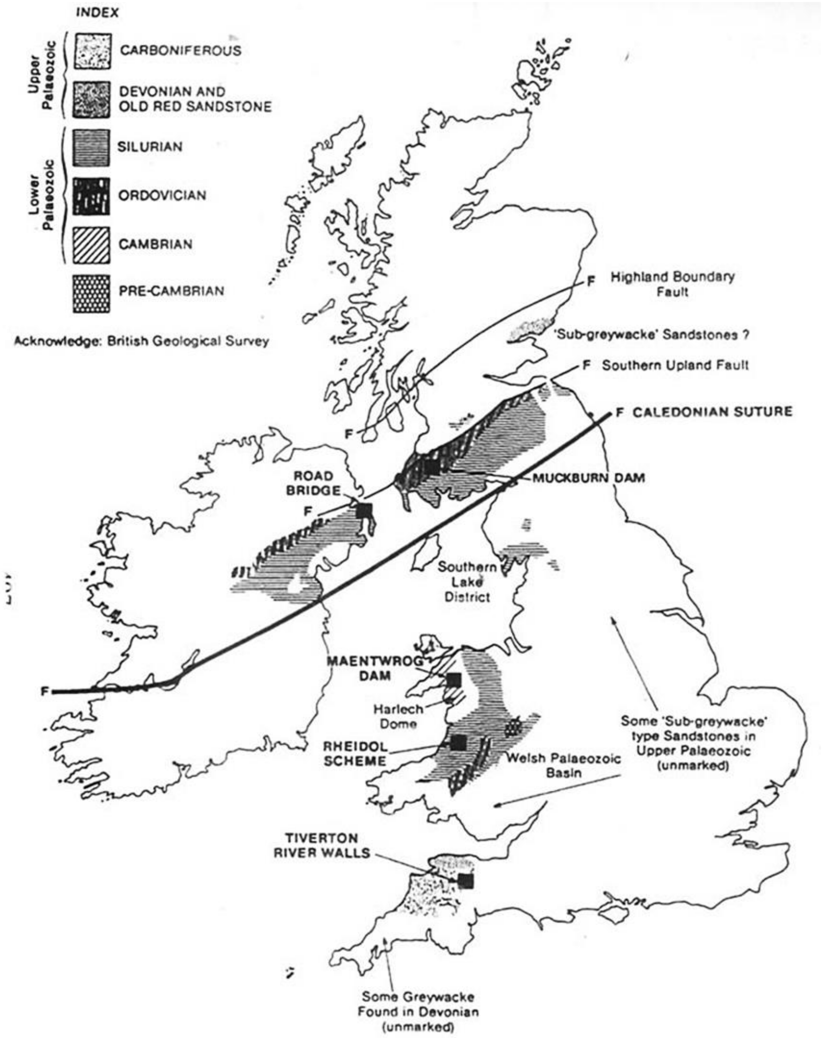
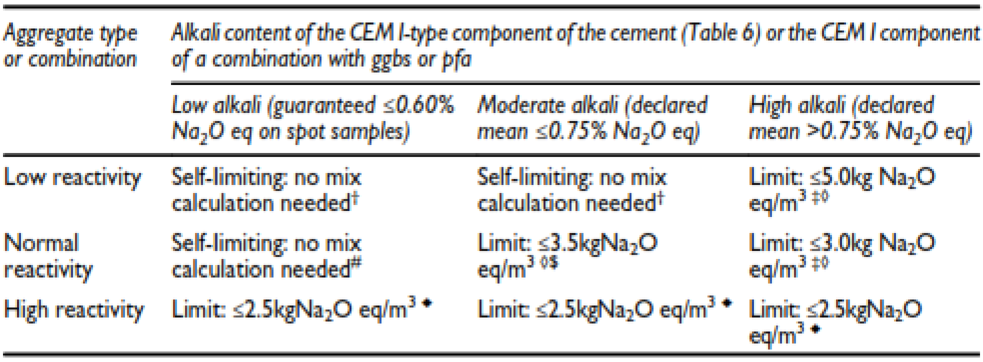


Figure 2.1: Map of the UK showing strata by geological age where greywacke occurs, also marking some of the main reported examples of affected structures (from Blackwell et al. [11]).

Figure 2.2: Maentwrog Dam, North Wales (left), showing cracking caused by ASR, but also suffering long-term water leaching and localised freeze-thaw damage (right).

The full details of the counter-measures developed for minimising ASR risk and of the procedures for achieving reliable diagnoses and structural assessments, are to be found in Sims & Poole [5]. In summary, the counter-measures were developed by an inter-industry working party, chaired by Michael Hawkins (County Engineer for Devon), which published its first guidance in 1983 [13]. A second edition was published by the Concrete Society as TR 30 in 1987, including revised notes and 'Model Specification Clauses', and the current third edition was issued in 1999 [14]. Rather confusingly at times, there has also been a BRE Digest (330) [15] that covers similar ground to the Concrete Society TR30, but happily these two documents are now in harmony [15]. In the background, the BSI had developed relevant procedures for the petrographic examination of aggregates (BS 812-104, with BS 7943:1999 providing guidance on interpretation for ASR, including a gel-pat test for opaline silica [16]). The similar principles established in CSTR 30 and BRE Digest 330, for 'resistance to ASR' (see Table 2.1) have now been embedded in BS 8500-2 [17].

Table 2.1: Simplified version of the recommendations introduced by BRE Digest 330 [15], based upon the 2004 edition; see Digest 330 (2004) for a complete version with its accompanying notes.



| *Aggregate type or combination* | *Alkali content of the CEM I-type component of the cement (Table 6) or the CEM I component of a combination with ggbs or pfa* | | |
|---|---|---|---|
| | *Low alkali (guaranteed ≤0.60% $Na_2O$ eq on spot samples)* | *Moderate alkali (declared mean ≤0.75% $Na_2O$ eq)* | *High alkali (declared mean >0.75% $Na_2O$ eq)* |
| Low reactivity | Self-limiting: no mix calculation needed† | Self-limiting: no mix calculation needed† | Limit: ≤5.0kg $Na_2O$ eq/$m^3$ ‡◊ |
| Normal reactivity | Self-limiting: no mix calculation needed# | Limit: ≤3.5kg$Na_2O$ eq/$m^3$ ◊$ | Limit: ≤3.0kg $Na_2O$ eq/$m^3$ ‡◊ |
| High reactivity | Limit: ≤2.5kg$Na_2O$ eq/$m^3$ • | Limit: ≤2.5kg$Na_2O$ eq/$m^3$ • | Limit: ≤2.5kg$Na_2O$ eq/$m^3$ • |

## 3. THE APPROACH TO ASR IN EUROPE

Sadly there has been no unified approach to AAR within Europe. Section 2 of this paper focused on the situation in the UK (Chapter 6 in Sims & Poole [5], whilst Chapters 7 & 8 cover most of the rest of Europe (Nordic & Mainland Europe). We have selected three European countries that played key roles in learning to live with AAR: Denmark, France & Germany, but others have made significant contributions. In Denmark, inspired by Stanton's findings in the USA [1], the Danish National Institute of Building Research and the Concrete Research Laboratory jointly launched a preliminary 200-structure survey in 1951, which confirmed that much concrete in Denmark was affected by ASR. A co-ordinated programme of structure inspection, aggregate examination and laboratory investigation followed, which identified problems associated with porous calcareous and opaline varieties of flint (frequently in the sand) with pronounced 'pessimum' behaviour. The first actual ASR discovery in Denmark has been credited to Poul Nerenst, but the culmination of the programme was Idorn's 1967 PhD thesis [3]. Idorn would soon unknowingly secure fame by initiating the series of international AAR conferences with a modest first gathering in 1974 in Køge, near Copenhagen.

In France, the first cases of ASR damage were diagnosed in the 1970s and featured several concrete dam structures, including the Chambon dam, where the aggregate was a metamorphic rock and clearly very different from many of the aggregates commonly associated with ASR elsewhere. Moreover, it was sometimes difficult to account for the levels of alkali that were generally expected to be available for ASR to occur, which led to speculation that, in some circumstances, additional alkalis, sufficient to support ASR, could be released from some aggregates. Other cases of ASR were identified in the North of France and were sometimes broadly similar to cases occurring in the UK, but there were other cases in which the reactive aggregate was a siliceous limestone, including that from the Tournai region. By 2008, more than 400 structures had been identified [18]) and about 10 structures had been demolished. Some of these structures were found to found to exhibit deterioration rather earlier than was typical for ASR and even when the alkali contents were low, which led to the discovery of cases of co-existing ASR and delayed ettringite formation (DEF). Overall, France has benefited from an impressive, integrated national laboratory network, with a main central establishment in Paris (LCPC). It is claimed that, since the 1994 implementation of the LCPC recommendations for preventing ASR damage, no new case of ASR has occurred.

In common with other countries, Germany was initially sceptical that ASR could occur in Germany, primarily on the basis of geological considerations. However, this initial complacency changed abruptly in 1965, when the Lachswehr Bridge in Lübeck had to be closed after 1 year, due to an alarming bending of the superstructure, and was replaced in 1968, after which investigations demonstrated the cause to have been ASR associated with opaline sandstone and flint from Northern Germany. For some time afterwards, test methods and regulations in Germany were designed to combat this particular variety of ASR, but gradually it was found that other more slowly reactive aggregates were sometimes involved, including greywacke, and some accelerated expansion tests were introduced. In the late 1990s, it was recognised that an increasing number of road surfaces (and a runway) in Middle Germany had deteriorated within 10 years, despite evidence of compliant construction, albeit using untested aggregates previously assumed to be non-reactive [19]. As a result, new advice was introduced in 2005, with a bespoke performance test being required for concrete pavements from 2013. It is claimed that no ASR damage has been detected in pavements constructed since this new advice was introduced.

# 4. THE GLOBAL APPROACH TO ASR

The pioneering work to identify and then learn to manage the mechanism now known as ASR or AAR, was carried out in the USA, but its important message was slowly extended around the world after the 1940s. As we have seen for the examples in Europe, there was typically an initial reluctance by countries to accept that these reactions affected their concretes, but nevertheless there was a curiosity to discover whether they might. The outcome, eventually, has been a realisation that AAR occurs widely around the world, involving an extensive range of aggregate types and several related mechanisms. Thus, whilst local variations in detail and approach have emerged, there is an underlying similarity that enables the global materials engineering community to collaborate to seek and develop universal methods for recognition, mitigation, diagnosis and remediation.

## 4.1 The role of RILEM & the ICAARs

Although ASR was revealed in Stanton's 1940 paper [1], it would be another 34 years before it was the subject of an international 'conference', and even then it would be a meeting of just 23 delegates from 4 nations, meeting in Køge, Denmark. The next two meetings, in Iceland and the UK, would be similarly modest, with delegate numbers not exceeding 50 until the 5th conference in Cape Town. The 6th Conference, in Copenhagen, reached nearly 200 delegates, whilst the 7th, in Ottawa, had around 300. Micheline Regourd observed that one feature of these conferences had become the tendency for many papers to introduce new variants of existing tests, for the reactivity of aggregates, so she proposed the formation of a RILEM Technical Committee, primarily to review and recommend the best test options for international use. The first 'TC' for this purpose was formed in 1988, with Chairman, Dr Philip Nixon, and its first meeting at an 'ICAAR' was that in Kyoto in 1989. The ICAARs became a regular gathering, driving both local and worldwide research. In the background, Dr Nixon would lead 3 successive RILEM Technical Committees until 2014, more than fulfilling the objectives originally set by Micheline Regourd. The main achievements would be an integrated assessment scheme for aggregate reactivity, together with test procedures and international specifications [20], plus guidance on ASR diagnosis [21] and a Petrographic Atlas [22] specific to ASR. After 2014, chairmanship passed to Prof Borge Wigum, whose succeeding RILEM TC has built on the earlier work and especially to develop a performance testing approach to avoiding ASR problems; their recommendations are currently in preparation and might be discussed at the ICAAR in Lisbon.

Although RILEM is based in Paris, it has a truly international membership and the original ambition for the series of TCs led by Nixon was that its aggregate assessment scheme, and allied specifications, would provide a truly global solution. However, that might have been over-ambitious, especially given the existence of a well-established and developing set of ASTM procedures for use with recognising and controlling ASR. However, as there was no comparable system of ASR prevention across Europe, it seemed reasonable to suppose that the researched and ready-made RILEM scheme might sensibly be adopted in Europe, where most component nations had agreed to work together through the 'CEN'. However, CEN has steadfastly resisted introducing any ASR-related procedures. The sole exception, so far at least, has been interest in adopting a procedure for assessing the potential release of alkalis from aggregates, which was started under Nixon and continued during Wigum's chairmanship, but remains to be completed [23]. CEN has reportedly agreed in principle to embrace this method, although Wigum's TC has advised that the development work is not yet finished and there are serious concerns over how the results might best be used.

## 4.2 Global recognition of AAR as a problem

In order to chart the history of first recognition, diagnoses, testing and avoidance specifications, it is appropriate to begin with the USA and Canada, where, in the latter, Gillott [24] was the first to describe a de-dolomitisation reaction of some aggregates that was associated with expansive effects due to a supposed ‘Alkali-Carbonate’ Reaction (ACR) with some concrete in Ontario, Canada, which was later cited as also a possible problem in South America and China. More recently, it has been considered a particular variety of ASR, at least in most cases [25 & 26]. The global awareness of the possible premature deterioration of concrete by AAR mechanisms is summarised in Figure 4.1. A number of countries around the world have had no reported cases to date (shown in yellow), but are aware of the potential risks and have specifications in place to avoid AAR in new concrete structures.

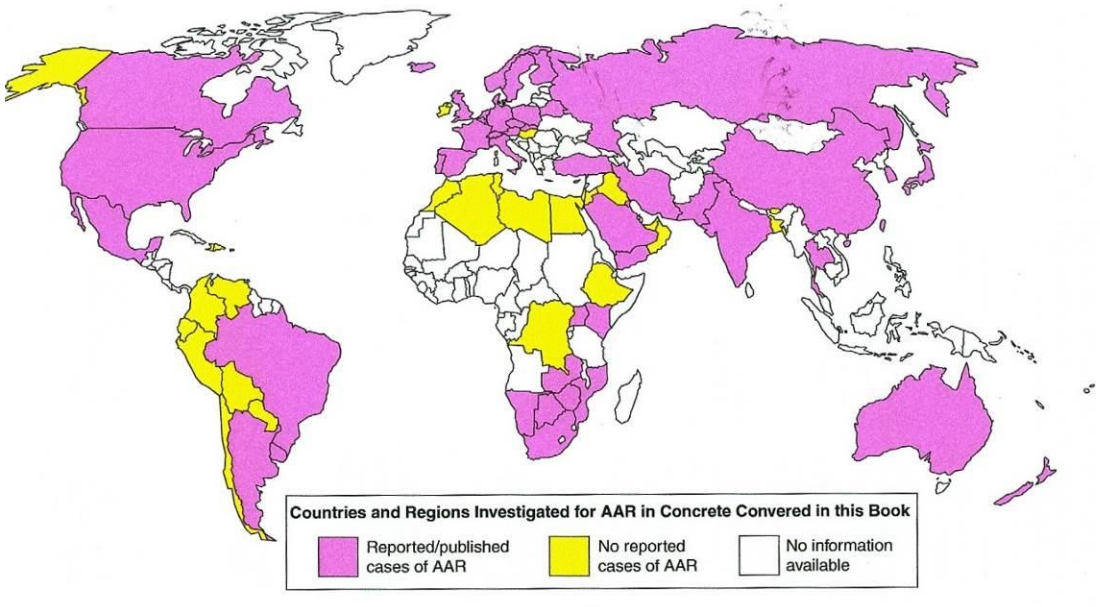


Figure 4.1: An indicative map of worldwide AAR (from Sims & Poole, 2017 [5]).

## 4.3 North America

Not only did Stanton identify the problem and the principal aggregate mineral types likely to react with alkalis in the pore solution of concrete, but by 1941 he had developed test procedures with mortar mixes with differing reactive opal and alkali contents to study the expansions produced, which were the forerunners of the ASTM mortar-bar tests. He noted that increased temperature of testing increased the rate of reaction. He was also the first to identify the ‘pessimum proportion’ concept, being the proportion of a reactive aggregate that produces the maximum expansion in laboratory tests. He recognised the use of pozzolana as a cementitious additive which can significantly reduce ASR expansion, and also proposed that the risk of ASR expansion could be minimised if total alkali equivalent in cement was limited to below 0.6%.Today cases of ASR in concrete structures have been identified in most states across the USA and there are potentially reactive aggregates in every State. It has also been found that, in general, the addition of silica fume as a mineral admixture appears effectively to reduce the risk of ASR damage to concrete in the USA.

In Canada, the first reports of ASR in concrete structures appeared in 1957 [27] and ASTM tests were in common use, including the C586 rock cylinder test for carbonates. An accelerated concrete prism test, using 75 x 75 x 250mm concrete prism stored at 38˚C was first published by CSA in 1986, and is now designated CSA A23-14A [28]. A similar test, designated ASTM C1293 [29], was published in 2008 and these tests are considered by many to be the most reliable identifiers of aggregate reactivity. A standard practice for selecting tests and performance limits is summarised by ASTM C1778-14 [30]. The most important structures affected were dams and bridges. In the case of the Mactaquac Dam, ASR damage reduced its life expectancy significantly and, in the case of the Gardiner Dam, it was found that, although 25% fly ash was used as an admixture to limit ASR expansion, its high alkali content (containing 7- 8% $Na_2O$eq.) allowed damaging ASR to occur.

## 4.4 South and Central America

The global map (Figure 4.1) shows that, although there are reported cases of ASR concrete structures in Argentina, Brazil, Mexico, and Uruguay, there are no reported cases in other countries in South or Central America. Most of these countries are aware of ASR and the potential reactivity of some of the aggregates used, but they adopted test measures and specifications for the avoidance of the problem. It remains likely that unreported ASR affected structures do exist in these countries.

In Argentina, the earliest studies of ASR were undertaken in the 1950s. Maiza et al. [31] reported cases of degraded pavements in 1999. In the north eastern region, basalts are the principal source of aggregate and these aggregates are also ASR reactive in pavements [32]. In Brazil, ASR problems have been reported with numerous hydraulic structures. Typically granite/granite gneiss aggregates were used in the concretes. The first indication of ASR damage was detected in the Brazilian Jupia hydropower plant in the 1960s, where the aggregate used contained reactive chalcedony. As in Argentina, the suspect coarse aggregates in Brazil contain micro-crystalline quartz in a range of aggregates including migmatites, quartzites and schists while some fine aggregates contain unweathered volcanic glass. Since 1999, a significant number of cases of ASR damage to pavements, hydraulic and other structures have been reported in both Argentina and Brazil. The test and specification procedures pioneered by ASTM in the USA were adopted widely within countries in South America. In 2008, the Brazilian Standard ABNT NBR 15577 was published and offered guidance on the prevention of AAR, involving petrography and expansion tests. Also pozzolana is being used extensively as a means of reducing the risk of ASR in new concrete structures. In Argentina in 1996, the possibility of alkali-carbonate de-dolomitisation reactions of marble aggregates was explored by Milanesi, Marfil and others [33], but they concluded that de-dolomitisation does not cause expansion, and ASR was the more likely mechanism.

## 4.5 The African Continent

Much of the reported information relating to AAR in concrete on the African Continent relates to well investigated cases in South Africa [34], although such other information that is available on sub-Saharan Africa comes from Namibia, Kenya, Zambia, Mozambique, Zimbabwe, Uganda and Zaire. Oberholster chaired the 5th ICAAR in Cape Town in 1981 and was also responsible for developing the accelerated mortar-bar test [35], which is now the main variant of the mortar bar approach, adopted by ASTM and RILEM. There is ASR damage to mast foundations in Namibia, where granite gneiss is the coarse aggregate. In Kenya the Kambura dam spillway using gneiss aggregate concrete has developed ASR to the extent that after eight years the gates were jamming. In Zambia the Itezhitezi Dam built in 1973 - 76 developed coarse ASR cracking expansion in the intake towers although the red granite aggregate had tested as innocuous according to ASTM C227. In Mozambique, the Cahora Bassa Dam expanded in height by 11mm between 1977 and 1994. Also dams in Zimbabwe and Zaire and a hydro power plant in Uganda have all developed ASR expansions of the concrete.

In the South African handbook, ‘Concrete Technology’, first published in 1957 [36] Fulton first drew attention to the possibility of AAR in South African Concrete, but research into AAR really commenced in 1977 at the NBRI and by 1994 problems with AAR in concrete had been identified in the South Western and Eastern Cape Provinces, Gauteng, the Free State Provinces, the Kwa-Zulu Natal and Mpumalanga Provinces. The observed ASR damage was present in numerous hydraulic structures, bridges and other buildings. The potentially deleterious aggregates included quartzites, shales, metasediments, sandstone and Archean granites and gneisses. A programme of petrographic screening, indicator testing, such as ASTM C1260 (2014), the method originally developed in South Africa, and performance testing, for example ASTM C1293 [29] and RILEM AAR 4-1 [20] are now in use. Also specifications to avoid ASR damage include using cement replacements and placing upper limits to alkali contents of below 2.8 kg/m$^3$ of concrete for new structures.

## 4.6 The Russian Federation

The first studies of AAR damage to concrete in Russia (then the USSR) were undertaken in 1962 [37]. A considerable volume of experimental research was carried out between 1963 and 1969 by the NIS Gidrproyekt Laboratory of stone materials and a long list of possible ASR reactive aggregate rock types was assembled. Concrete prisms and larger concrete beams were used in the programmes. In recent decades the Research Institute of Concrete and Reinforced Concrete (NIIZhB) investigated 50 crushed stone, gravel and sand aggregates, finding alkali-soluble silica from 20 to 1100 mmol/l. This test was regarded as an important diagnostic indicator. Other wide ranging studies by the three methods specified by GOST 8269, found that only 3 of 18 aggregates were identified as reactive by all three methods. The conclusions reached following this extensive testing were that the accelerated mortar bar test was unable to differentiate ultrafine silica additives in controlling ASR expansion and that long term concrete tests were better at differentiating the effectiveness of controlling ASR expansion. It was also demonstrated that, in principle, treatment with solutions of lithium nitrate, formate and hydroxide could halt ASR expansion in laboratory tests.

ASR damage to concrete structures reportedly include house foundations, railway sleepers, concrete port and building structures, with the first examples of hydraulic structures in the Volga Region in 1962 [38]. More recently reported cases include precast railway sleepers, footings of transmission towers of the railway overhead system, which developed after only three years of service. Highway pavements and hydraulic structures have also been identified as suffering ASR damage. In some examples, high-alkali cements appear to be the cause of the damage to concrete structures. There is concern that improvements to dust recycling in cement manufacture and increased alkali level in the raw materials are increasing the alkali content of cements. This has led to a specification for some construction projects of a maximum alkali content limit of 3kg/m$^3$ for concrete.

## 4.7 Japan, China and South East Asia

Japanese researchers were perhaps the first in this region to investigate the mechanisms, causes and methodologies for avoiding and supressing ASR in concrete. In 1986, following identification of a series of ASR-affected highway structures, especially associated with an andesite aggregate containing volcanic glass, they had developed a wide range of tests and specifications including some modified from ASTM C289 and C227, a rapid ‘autoclave method’ (JIS A 1804) and setting an upper alkali limit of 3 kg/m$^3$ on concrete. These tests, subject to more recent modifications, are still considered effective, although there is continuing research on diagnosis including petrography and on long term performance evaluation. In 1989, Japan hosted an ICAAR in Kyoto, which had the largest attendance of any ICAAR before or since. In 2008, at the ICAAR in Trondheim, Tetsuya Katayama became the first recipient of the Gunnar Idorn Award for Life-time Achievement in AAR research, having successfully challenged the case for a separate form of reaction in what he termed as ‘the so-called alkali-carbonate reaction’. He demonstrated that the carbonate rocks in question actually contained a very fine grained reactive silica and were thus a special case of ASR [25 & 26].

China has a very wide range of rock types used as aggregates, which were summarised in 2004 by Deng et al. [39]. Numerous cases of AAR damage to concrete structures have been reported across the whole of China [40]. It is also important to note that a number of cases of alkali-carbonate reactivity have also been reported by Deng [41] and other researchers. However, as already noted, Katayama [25] has concluded that the actual expansions observed in carbonate rocks are at least often due to crypto-crystalline quartz within the carbonate rock.

## 4.8 Australia and New Zealand

Although Australia and New Zealand may be grouped together geographically with recorded cases of ASR damage to concrete, the approaches to dealing with the problem differ. Australia was one of the first countries to be aware of the ASR problem, with initial studies being undertaken by the CSIRO from 1942. Most of this work was undertaken by Harold Vivian [4] and has since been recognised worldwide. Australian research was also reported by Alderman et al. in 1947 [42], relating to 68 Australian aggregates, reaction mechanisms and storage conditions for mortar bar tests. Further studies continued into the early 1960s. In the 1980s further research led to publication of national guideline HB79 in 1996 and three new standard tests for reactivity potential were published in 2015. Since 1996, many cases have been recorded along the eastern seaboard and in Perth and Darwin. A wide range of potentially reactive aggregate types have been identified, including sandstones, deformed granites and gneisses, acid igneous rocks, schists, quartzites, hornfels and greywacke. Structures affected by ASR include dams, bridges, precast and pre-stressed concrete structures.

In New Zealand, research studies into ASR also began in the 1940s. Most aggregates in use were greywackes and had tested ‘reactive’ in 80°C mortar bar tests, but no cases of ASR involving these aggregates have been recorded to date. Low-alkali cement was specified for use with volcanic aggregate for a major hydroelectric development, but in the 1950s & 60s most cements ranged from 0.6 to 0.8% $Na_2O$eq. From 1963, alkali levels were typically 0.5% or lower. The first reported cases of ASR-affected concrete structures were identified in 1970 and led to extensive investigations of bridges, where damage was minor. Isolated cases of ASR damage to precast units containing acid & intermediate volcanic aggregates have been identified, also in concrete containing rhyolite sand used for hydro power stations in the Waikato area, despite low alkali cement and pozzolana having been used in the concrete. ASR damage was also apparent on an airport pavement built in the 1960s, which was replaced in the 1980s. ASR damage has also been recorded in precast and pre-stressed beams, bridge decks and in piles to three bridges in South Island where the damage included both cracking and structural displacements. Current provisions for ASR avoidance include some private sector specifications requiring the use of non-reactive aggregates and precautions specified in New Zealand Technical Report 3 [43]. The current 2012 edition of TR3 is presently being revised.

## 5. CONCLUSIONS

The mechanism, diagnostic approach, testing and specifications relating to the ASR deterioration of concrete were thoroughly investigated by Stanton before and after 1940. ASTM based a series of guidance and test procedures on this work and has updated these from time to time. A few scientists were quick to recognise the potential problem and instigated research programmes without any case study evidence of ASR in their own countries at that time, including Australia, Denmark, UK and Argentina. During the 1970s and 80s, in spite of initial scepticism, concrete structures damaged by ASR were being identified in many countries and ASTM methods and national variants of them became widely used in investigations. The ICAAR conferences and RILEM organisation focussed on the global similarities of ASR damage and its avoidance. The first RILEM technical committees on AAR, chaired by Nixon from 1988, reviewed various global test methods and produced a series of tests and guidance, including risk assessment and specifications, which the Wigum TC has built upon. Nevertheless, ASR damage identified in structures worldwide has led to numerous repair and remediation schemes. These often bespoke remedies have usually proved to be only temporary measures and eventual complete replacement appears the most common final solution. Eighty years ago, Stanton brought AAR to the world's attention; who will now bring us the definitive cure?

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