Global research and collaboration on alkali aggregate reactions in concrete: ICAAR-Conferences and RILEM TC achievements

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Abstract

It is now 80 years since Alkali Aggregate Reactions (AAR) were first reported as a deleterious deterioration mechanism in concrete. The first International Conference on AAR in concrete (ICAAR) was organised in Denmark in 1974. Since then, many researchers have presented an enormous volume of scientific papers, which have been presented in subsequent ICAAR Proceedings in a series of conferences hosted in different cities around the world. This important archive of research information and history has now been made accessible online for free download.

In 1988, the first Technical Committee (TC) on AAR in concrete was established by RILEM. Since then, a total of four TCs have successfully completed their work and published important research and guidance documents ranging from a petrographical atlas to test methods, recommendations for non-reactive concrete, case studies and diagnosis and appraisal of structures affected by AAR.

This paper presents an historical overview of the endeavours of international engineers and scientists to understand, control and prevent damage from AAR in concrete. In addition to the ICAARs, the continuing series of RILEM TCs has helped to harness international cooperation in this effort. The RILEM TC work has achieved some significant progress regarding recommendations and recently using a performance-based testing concept, to prevent damage by AAR in new concrete structures. Finally, this paper presents a summary of where we are today in AAR research, identifies key milestones and addresses some specific topics for future research.

Keywords: *AAR; ICAAR; research history; RILEM*

1. BACKGROUND

In simple terms, *Alkali Aggregate Reactions* (AAR) involve a variety of chemical reactions, which develop within the concrete and can result in mechanical damage. Reactive constituents within certain types of aggregates are susceptible to attack by OH^- ions present in the alkali pore solution in the concrete. Water in the concrete acts both as a solvent and as a carrier for the hydroxyl and alkali ions, and are required to enable the reaction products to expand. Traditionally there were two main types of AAR: *Alkali-Silica Reaction* (ASR) and *Alkali-Carbonate Reaction* (ACR). The reaction mechanisms of the latter are still debated. Problems due to AAR were first identified in the State of California in the 1930s and eventually explained and reported by Thomas Stanton (see Figure 1.1) in 1940 [1]. His studies demonstrated that the expansion of mortar bars was influenced by the alkali content of the cement, the type and amount of the reactive silica in the aggregate, the availability of moisture, and temperature. He further showed that expansion was negligible when the alkali content of the cement was below 0.60% $Na_2O_{eq.}$ and that expansion could be reduced by adding pozzolanic material, thus setting the groundwork for preventative measures. It is interesting to note that much of this information and the recommendations remain valid up to the present day.

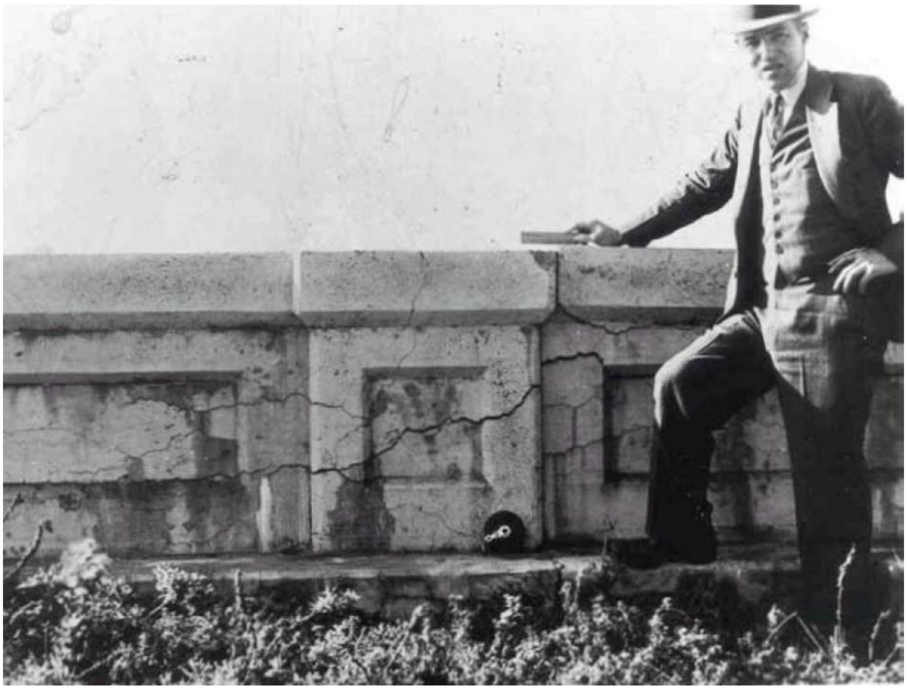

Figure 1.1: Thomas Stanton of the California State Division of Highways (photo kindly provided by California Department of Transportation)

1.1 The International Conferences on AAR - ICAARs

Idorn [2] describes the historical development of AAR-research, leading up to the first ICAAR. In a historical perspective of AAR research, Figg [3] indicates that by the early 1970s, an international group of researchers decided that it was time to re-evaluate the AAR situation. At that time, the main areas where AAR was a concern were Denmark, Iceland and West Germany. Motivators for the first initial gathering of researchers in Denmark (1974) were Katherine and Bryant Mather and Sidney Diamond from the USA, along with Gunnar Idorn from Denmark, and Friedrich Locher from West Germany. The first three of these gatherings were organised on a ‘by invitation only’ basis, but afterwards, as more countries around the world realised that they were also facing this particular problem with their concrete structures, the conferences became more popular and open to scientists worldwide. An overview of the full list of conferences is given in Table 1.1. Figg [3] describes his personal experiences of the seven first AAR-gatherings, which developed into the series of International Conferences on AAR (ICAARs). An important source of information has been the published proceedings from these ICAARs.

This paper covers a historical overview of all fifteen ICAARs, to be presented at the 16th ICAAR in Lisbon, Portugal. It is based upon previous presented overviews of the ICAARs [4], in addition to briefly scrolling through more than 1400 papers from the previous fifteen ICAAR-Proceedings.

1.2 RILEM Technical Committees

Since the first Technical Committee (TC) was established in 1988 by RILEM (*The International Union of Laboratories and Experts in Construction Materials, Systems and Structures*), a series total of four TCs have been continuously active, seeking to establish universally applicable test methods for assessing the potential alkali-reactivity of aggregates, and from later on, for concrete mixes. Micheline Moranville - Regourd proposed the formation of a RILEM TC, primarily because too many papers at the earlier ICAARs were suggesting new and competing tests & variations of tests. Her vision was that the RILEM TC would recommend a preferred set of tests for international application.

This paper covers a historical overview of these TC’s, and what has been delivered, partly based upon a previous presented overview [5].

Figure 1.2: Dr. Gunnar Idorn (left) and Dr. Bryant Mather at the 2nd ICAAR in Reykjavik (1975)

Table 1.1: The full list of ICAAR conferences

No.	Year	Place	Chairman	Nations	Delegates	Papers
1	1974	Køge, Denmark	Gunnar Idorn	4	23	13
2	1975	Reykjavík, Iceland	Haraldur Àsgeirsson	7	25	20
3	1976	Wexham Springs, UK	Alan Poole	13	48	27
4	1978	Purdue, USA	Sidney Diamond	8	54	26
5	1981	Cape Town, South Africa	Bertie Oberholster	12	52	38
6	1983	Copenhagen, Denmark	Gunnar Idorn	21	187	56
7	1986	Ottawa, Canada	Paddy Grattan-Bellew	23	~300	101
8	1989	Kyoto, Japan	Kioshi Okada	16	327	136
9	1992	London, UK	Alan Poole	29	320	150
10	1996	Melbourne, Australia	Ahmad Shayan	26	220	130
11	2000	Québec City, Canada	Marc-André Bérubé	24	230	142
12	2004	Beijing, China	Mingshu Tang	22	178	168
13	2008	Trondheim, Norway	Børge Johannes Wigum	27	172	133
14	2012	Austin, USA	Kevin Folliard	28	194	128
15	2016	São Paulo, Brazil	Haroldo de Mayo Bernardes	21	208	146
16	2022	Lisbon, Portugal	António Lopes Batista			

2. HISTORICAL DEVELOPMENTS AND ACHIEVEMENTS

2.1 The early ICAAR conferences (1974 – 1976)

2.1.1 ICAAR: 1st Denmark (1974), 2nd Iceland (1975) & 3rd United Kingdom (1976)

Gunnar Idorn chaired the first ICAAR in Køge, Denmark, in 1974. The 23 invited participants represented the five following countries: USA, England, West Germany, Denmark and Iceland. Only synopses of the 12 papers were recorded in the Proceedings [6], since it was anticipated that the authors would publish their papers elsewhere. Of principal concern was the means of identifying new types of reactive aggregates. An interesting and vital problem was raised by a representative from the cement industry. He stressed that it was important to know where the alkalis were located in the cement clinker and what effect they had on the development of AAR, because it might be possible to alter these factors during the production process. It was established that the reactivity of a cement is not only a function of its alkali-content. The discussion showed what was needed in continued research on AAR: basic research to clarify the kinetics of reaction and to describe where and how the reactions develop and how alkali-silica gel causes cracks and disruption. The discussion also showed the need for simple and reliable test methods for measuring the reactivity of cement and aggregates. In recognition of the expected increased use of high alkali cements, it was pointed out that further research was required to find methods and means of preventing AAR.

Haraldur Ásgeirsson chaired, and was the editor of the Proceedings [7], of what became the 2nd ICAAR, held at the Building Research Institute in Reykjavik, Iceland in 1975. The second "AAR meeting" followed only 15 months after the first gathering, because of great concerns in Iceland where deleterious AAR affected domestic concrete houses. It is interesting to realise that this event was conceived between Idorn and Ásgeirsson, during a RILEM symposium in Denmark, in 1956. Bryant Mather claimed at that event that all aggregates are reactive; they differ only in the kind of reaction and the degree and rate to which the reaction proceeds and its effect. Main consensus of the conference was as follows: 1) The widely accepted 0.6% equivalent sodium oxide (Na_2O) limit on alkali content in cement should be applied. 2) Potentially reactive aggregates may not necessarily lead to deleterious reaction. Field examination may often reveal a reliable probability for the safe use of such aggregates without prescription of safeguards. 3) High temperature together with adequate moisture accelerates AAR. High temperatures combined with low water content and drying prevent AAR. 4) Low temperatures slow down AAR. In cold regions, this slowing can be almost, or to all practical purposes, indefinite. 5) AAR might only be a minor reason in cases of concrete failure, although often the one leaving the most spectacular evidence of destructive reaction. In an epilogue in the proceedings [7], Ásgeirsson, discussed the possibility that a “pessimum” amount of alkalis, i.e. a too high content of alkalis, will not lead to deleterious reactions. This view is therein supported by both Harold Vivian (from Australia) and Sidney Diamond (from the USA), and further explained that one of the reasons could be that a gel with a sufficient high sodium-to-silicate ratio will have a very low viscosity and cannot exert mechanical pressure and hence expansion.

In 1976, Alan Poole chaired and was the editor of the Proceedings [8], of the 3rd ICAAR, held in Wexham Springs (Slough), UK. The conference included a visit to the Val de la Mare Dam in Jersey, the largest of The Channel Islands. This case study was followed by other examples identified in the UK, often associated with the use of fine aggregate containing chert or flint. The universality of AAR in concrete was now recognised in countries worldwide, and the possibility of Middle East alkali-carbonate problems was realised for the first time. In countries where no reported cases have been identified, the industry was aware of the possible problems and had been conducting tests and complying with the specifications in place to avoid AAR in their concrete structures. Technical sessions included a reconsideration of pessimum effects, and an attempt to co-ordinate testing methods. In the end of the proceedings [8], Sidney Diamond gave a summary of the papers presented. He suggested that the papers could perhaps be grouped into the following general areas of study: 1) the effects of alkalis on concretes. 2) the effects of alkalis in cements. 3) the study of the potential reactivity of aggregates. 4) consideration of the detailed reaction mechanisms. 5) consideration of the effects of SCMs on reactivity. 6) field reports and case study investigations. 7) reports of remedial work and reviews. A number of new and important case studies were also reported and some new data on preventative measures had become available. There was also a recognised need for research on preventative measures and for reports of case studies where remedial measures had been taken. It was also noted that information was urgently needed concerning the structural consequences that might result from AAR. The conference proceedings [8] were published by the Cement & Concrete Association and reprinted by the

US Government Printing Office, because of partial funding of the meeting by the US Army Corps of Engineers (European Research office).

2.2 The ICAAR conferences (1978 – 2000), and the establishment of the first RILEM TC (1988)

2.2.1 ICAAR: 4th USA (1978), 5th South Africa (1981), 6th Denmark (1983), 7th Canada (1986), 8th Japan (1989), 9th UK (1992), 10th Australia (1996) & 11th Canada (2000)

Following the first three "by invitation-only conferences", the interest and concern within the construction industries around the world led to the need to open the conferences to all scientists and engineers from the construction industry, research organisations and academia. Consequently, there was a gradual increase in the number of participants and countries represented. In the period 1986 to 1992, more than 300 delegates from up to 29 countries took part (Table 1.1).

In 1978, Sidney Diamond [9] chaired the 4th ICAAR at Purdue University, USA. In the opening presentation, Gunnar Idorn stated that the ICAAR meetings had undeniably been successful in creating enhanced communication and exchange of results and hypotheses, and considered that one might envisage a continuity on this basis still for another 4 to 5 meetings. He stated that this would be beautiful in view of the cultural aspects of research as existing in its own right, but it would also be a distraction from the real responsibility of the present work to be done. An up-to-date literature review was made available to all delegates. Once again, the conference proceedings [9] were part-funded by the US Army Corps of Engineers.

In 1981, R.E ('Bertie') Oberholster chaired and was the editor of the Proceedings [10] of the 5th ICAAR in Cape Town in South Africa. This event marked a change from a gathering of research scientists to an important International Conference. According to Figg [3], the conference volume [10] reached uncomfortably large dimensions but included photographs and potted biographies of the contributors. The 38 papers were divided into various sessions/topics, including: 1) Role of alkalis in cement manufacturing. 2) Influence of alkalis on the properties of cement and concrete. 3) AAR – occurrence and manifestation. 4) Testing for potential reactivity of aggregate and cements. 5) Appraisal, prevention and rehabilitation. 6) AAR in concrete pavements. 7) AAR: mechanisms, 8) Mineral additions and the prevention of AAR. 9) Petrographic and electron microscope examination of aggregates and concrete.

In 1983, Gunnar Idorn and Steen Rostam chaired and were the editors of the Proceedings [11] of the 6th ICAAR held in Copenhagen in Denmark. A total of 56 papers were divided into various sessions, where the chairmen summarised the main discussion after each session. In the session regarding; "*Engineering and Industrial Aspects of Alkalis in Cement and Concrete*", W. Schrämli noted that one should not expect the cement producers to come up with more low-alkali cements in the future. The beneficial effect at preventing AAR of using SCMs, such as fly ash, silica fume and other natural or artificial pozzolans, was highlighted. However, it was admitted that it was still difficult to convince design engineers, contractors, building owners and state officials to accept this as a reliable remedy. In the session regarding; "*Alkalis in Concrete – Engineering Education Aspects*", Torben C. Hansen called attention to the fact that there was general agreement among the speakers that scientists and engineers cannot communicate efficiently when it comes to discussing effects and control of alkalis in concrete. He suggested that a professional society, comparable to RILEM as an example, could establish a committee with joint scientific and construction experience, to provide the necessary interface for unified concrete engineering education. The session regarding: "*Mechanisms of Reaction of Alkalis in Concrete*" was summarised by Jan Skalny and Ian Sims. It was realised that the chemistry of pore solution is very complicated subject with many variables needing to be taken into consideration. Several types of reaction products were recognised. Discussions revealed no clear conclusion regarding the effect of relative humidity. The role of sodium chloride was emphasised as one had experienced deleterious AAR in swimming pools. Once again, the communication gap between the researchers and engineers was highlighted, and Sims was wondering if there could be support for an international working party to achieve international agreement between scientists and practising engineers. In the session regarding; "*Methods of Examination*", C. Duncan Pomeroy indicated that this session clearly demonstrated the need for specialists who could use highly sophisticated equipment in the study of the underlying factors that control the AAR. He suggested it was possible that some of the most advanced techniques were understood by only a small proportion of the audience. The role of the petrographer in classifying the aggregates was very much stressed. In the session regarding; "*Testing Methods and Criteria*", Udo Ludwig summarized various test methods to determine the reactivity of different aggregates, including chemical testing, osmotic cell testing, mortar bar method, concrete prism testing, rock cylinder testing, gel pat testing and other test methods. It was concluded that: "*Correct assessments of all the tests are essential and should be made only by an experienced assessor*". In the session regarding; "*Effects in Practice of Alkalis in Concrete*", Bryant Mather appreciated the participation of structural design engineers in the discussion. He said that we know how to make concrete that will not deteriorate; however, research is needed better to judge risk and evaluate materials, proportions and practices so we will have practical, economical means of assuring non-deterioration. "*Concrete need not deteriorate*". The International organising Committee (IOC) appeared first at this ICAAR, appointed for that particular conference.

In 1986, P.E. ('Paddy') Grattan-Bellew chaired and was the editor of the Proceedings [12] of the 7th ICAAR in Ottawa, Canada. The proceedings were: "*Dedicated to the many researchers who have gone before, the known and the unknown, whose unsung labours have created the pool of knowledge in which we are immersed and which permits us to move forward however hesitatingly*". In the foreword of the Proceedings, it is mentioned that it was 30 years since the description of the first recorded case of AAR in Canada, published by E.G. Swenson of the National Research Council of Canada. This initial discovery was followed shortly after by the finding of a new type of AAR in Kingston (Ontario), i.e. "the alkali-carbonate reaction". In the preface by Grattan-Bellew, it was stated that the rapid increase in the number of cases of concrete deterioration due to AAR throughout the world underscores the urgent need for engineering solutions to this complex problem. In contrast with earlier conferences where the emphasis was generally on the mechanisms of reaction and the development of tests for identifying potentially reactive aggregates, at this ICAAR, the largest number of presentations was on assessment and repair of AAR in concrete. It was also mentioned that the proposed new test methods are not, however, without their problems and that considerably more testing and evaluation will be necessary before any of the methods can be applied with some degree of confidence.

In 1989, Kiyoshi Okada chaired the 8th ICAAR in Kyoto, Japan. The preface of the proceedings [13], edited by Okada, Nishibayashi and Kawamura, noted cracking in concrete piers of the Hanshin Expressway in Osaka detected in 1985, which was found to be caused by AAR. Actually, delegates participating to the post-conference tour had the opportunity to examine damaged/repaired piers of the structure. Since then, nation-wide investigations revealed that many concrete structures were damaged by AAR, almost all over Japan. Figg [3] revealed that much still remained to be accomplished before a complete understanding of reaction mechanisms and kinetics is attained.

In 1992, Alan Poole chaired and was the editor of the Proceedings [14] of the 9th ICAAR in London, UK. The 150 papers, in the two volume proceedings, were grouped into session order regarding the following topics: 1) Reactive aggregates, 2) Undulatory extinction of quartz, 3) Testing aggregates by standard methods, 4) Testing concrete, 5) Evaluation of structural effects, 6) Damaged structures – evaluation – management & repair, 7) Chemistry and mechanisms of reaction, 8) Review of guidance and specification and regional reviews and 9) Cement replacements and additives.

In 1996, Ahmad Shayan chaired and was the editor of the Proceedings [15] of the 10th ICAAR in Melbourne, Australia. In the preface of the Proceedings, it is mentioned that it was suggested by the International Organising Committee (IOC) to organise this conference in Australia. The keynote lectures included a presentation by Sidney Diamond on some paradoxes regarding AAR, and by Gunnar Idorn on the Australian AAR research from the 1940s'. Moreover, Paddy E. Grattan-Bellew presented a critical review of accelerated AAR tests, Micheline Moranville – Regourd talked about Modelling of expansion induced by AAR, and UK-based R. Narayan Swamy spoke about Assessment and rehabilitation of AAR – affected structures. After the conference, Gunnar Idorn (pers. comm.) opined in a memo that the contribution from France, Asia and Australia/New Zealand comprised 51% of the presented papers and herein were the new approaches, which were the most promising for making predictions of the possible risk of harmful reaction versus the potential for harmless reaction. The remaining 49% contributions – from North America, Europe (apart from France), the Middle East, and South Africa were predominantly representing updating of conventional research with less innovative value.

In 2000, Marc-André Bérubé chaired the 11th ICAAR in Québec City, Canada. In the preface of the Proceedings, edited by Bérubé, Fournier and Durand [16], it was stated that deterioration of concrete structures due to AAR had been recognised in more than 50 countries. The papers presented were in accordance with the main themes covered at the conference: 1) Mechanisms of alkali-carbonate (ACR) and alkali-silica (ASR) reactions (14 papers). 2) Factors affecting reactivity: temperature, moisture, salts, alkali content and cathodic protection (10 papers). 3) Testing aggregates for AAR: existing and new test methods, standards and specifications (32 papers). 4) Preventative measures against AAR: testing effectiveness of SCMs, modelling, mitigation and repair (29 papers). 5) Special symposium on AAR in

Highway Structures and Pavements (15 papers). 6) Special symposium on AAR in Hydraulic Plants and Dams (16 papers).

2.2.2 RILEM 1st TC 106 (1988 – 2000)

Although the presentations given in the earlier conferences identified and discussed most of the significant issues related to AAR in concrete, the later conferences expanded and refined the test methods, whilst also identifying the criteria for specifications to avoid this problem. This led to the acceptance of general specifications and testing methods by many countries, although each retained the methods and criteria relevant to their particular climatic conditions and materials. However, in order to enhance the international cooperation, the first global RILEM Technical Committee (TC) regarding AAR was established in 1988 as TC-106, with Philip Nixon from the Building Research Establishment (BRE) in the UK as the Chairman, and Ian Sims from Sandberg, UK (now with RSK Environment Ltd) as the Secretary. Micheline Regourd-Moranville had proposed the establishment of this TC, which was reported at the 8th ICAAR in Kyoto (1989), where the second and third TC meetings were held immediately before and during the conference. The primary objective of the TC was to develop tests for aggregate reactivity that could form the basis for internationally agreed methods and monitoring of progress, as presented by Nixon and Sims [17]. The main findings and progress were also presented at the 9th ICAAR in London in 1992, the 10th ICAAR in Melbourne in 1996 and the 11th ICAAR in Québec City in 2000. In 1993, an interim report was presented by Nixon and Sims [18], on the progress of TC-106 in developing tests for aggregate reactivity that could form the basis for internationally agreed methods. In 1996, TC-106 had members from 21 countries, including virtually all those, who at that time, were regarded as having significant AAR problems. The TC conducted a survey of test methods in use in the participating countries, presented by Nixon and Sims [19]. Following trials to demonstrate their effectiveness in differentiating reactive and non-reactive aggregate combinations worldwide, TC-106 finalised two expansion tests in 2000, presented by Nixon and Sims [20] at the 11th ICAAR in Quebec City. The concrete prism test (CPT) was considered reliable for most aggregate combinations, and an accelerated mortar-bar test was usually found to be suitable for predicting behaviour in the concrete test. The work of TC-106 culminated in 2000 in an integrated assessment scheme, presented by Sims and Nixon [21]. After considering a wide range of methods for assessing aggregates for AAR, TC-106 concentrated on a three-stage procedure: 1) Petrographical examination (AAR-1) (2003); 2) Accelerated mortar-bar expansion test (AAR-2) (2000) and 3) Concrete prism expansion test (AAR-3) (2000).

2.3 The ICAAR conferences 2004 – 2012, and 2nd & 3rd RILEM TCs (2000-2014)

2.3.1 ICAAR: 12th China (2004), 13th Norway (2008) & 14th USA (2012)

In 2004, Mingshu Tang chaired the 12th ICAAR in Beijing, China. In the preface of the two volume Proceedings, edited by Tang and Deng [22], it was noted that there are still many issues, that needed to be investigated, such as the release of alkalis from aggregates, the long-term effectiveness of mineral and chemical admixtures, the improvement of existing test methods, the relationship between laboratory testing results and field behaviours, field inspection, and repair techniques. Due to the complexity of AAR, this will require interdisciplinary knowledge and experience.

In 2008, Børge Johannes Wigum chaired the 13th ICAAR in Trondheim, Norway. Programme & Abstracts were in a printed booklet, whereas the proceedings, edited by Broekmans & Wigum [23], with all full peer-reviewed papers were searchable electronically on a CD-disc, which also included printing-on-demand, including printer-ready soft- and hardcover design. Principal themes of the conference were: 1) Diagnosis & appraisal, 2) Performance testing & prevention, 3) Structural modelling, 4) Rehabilitation & management, 5) Collaborative research programmes, 6) Case studies and 7) Supplementary cementing materials. Other "hot topics" were: 1) Breakage of rebars: AAR- or metallurgical problem? 2) Use of lithium for AAR mitigation: treat, or trick? 3) Genuine ACR versus genuine ASR: truth, whole truth, nothing but?. Since the last ICAAR, Gunnar Idorn had passed away in 2006, 86 years old. As the "*father of ICAAR*", and a researcher that had made a huge impact during decades of AAR-research, it was decided to establish; "*The Gunnar Idorn Award for Life Achievement*". This was done in agreement with his widow, Birgit Idorn, who was very happy that he was remembered in that way. Tetsuya Katayama from Japan received the award in Trondheim.

In 2012, Kevin Folliard chaired the 14th ICAAR, in Austin, Texas, USA. The proceedings, edited by Drimalas, Ideker & Fournier [24], were included on a flash drive, where peer-reviewed papers were indexed for ease of navigation, searching and printing. The various presentations covered amongst others the following issues: 1) Testing for evaluating potential AAR of aggregates using various types of laboratory test methods/approaches and field exposure sites. 2) Standard documents and specifications on AAR. 3) Mechanisms of ASR and ACR in concrete, including modelling; comparison with other deleterious mechanisms causing deterioration in concrete (e.g. freeze-thaw cycles, corrosion, DEF). 4) Evaluation of preventative measures against AAR in concrete (e.g. SCMs, lithium-based admixtures, control of concrete alkali contents, etc.) through field and/or laboratory investigations, and studies on the mechanisms involved. 5) Diagnosis of concrete infrastructure affected by AAR, using field (non-destructive methods) and laboratory (petrography, mechanical, non-destructive methods) investigations/test methods. 6) Evaluation of the potential for future expansion (prognosis) and deterioration of concrete infrastructure affected by AAR, using field (monitoring) and laboratory (expansion testing on cores, chemical analyses) investigations/test methods. 7) Evaluation of the mechanical properties of concrete affected by AAR and of the structural effects in concrete infrastructures (including modelling). 8) Management actions (repair methods and treatments, monitoring of efficacy) on concrete infrastructures affected by AAR. In Texas, Philip Nixon from the UK received "*The Gunnar Idorn Award for Life Achievement*".

2.3.2 RILEM 2nd TC 191-ARP (2000 – 2007)

The second RILEM committee TC 191-ARP (*alkali-reactivity & prevention – assessment, specification and diagnosis*), formed in 2000, continued the work on an accelerated test for concrete (AAR-4) and on a specialised test procedure for carbonate aggregates (AAR-5). This TC also had wider scope seeking international consistency in approaches to diagnosis/appraisal (AAR-6.1) [25] and specifications (AAR-7) and in the assessment of alkali release from aggregates (later, AAR-8). Following discussions at the 11th and the 12th ICAAR, and in a request by the International Organising Committee (IOC), TC 191-ARP developed the basis of specifications to avoid AAR damage to concrete worldwide. The overall progress of TC 191-ARP was presented by Nixon et al. [26] and Sims et al. [27] at the 12th ICAAR in Beijing in 2004, and later in 2006 by Nixon and Sims [28] and Sims and Nixon [29].

2.3.3 RILEM 3rd TC 219-ACS (2007 – 2014)

The third TC 219-ACS was established in 2007, presenting findings at the 13th ICAAR in Trondheim (2008) [23] and the 14th ICAAR in Austin (2012) [24]. The committee terminated its activities in early 2014, and concluded the work of the three TCs with Philip Nixon as the Chairman with Ian Sims as the Secretary for 25 years. TC 219-ACS also focused on the assessment of the effect of the cement/binder on AAR – that is, performance testing. Several documents/recommendations were prepared by the TC, or in connection with the TC, e.g. Lindgård et al. [30] and [31]. The full set of RILEM recommendations were finally published as a RILEM "State-of-the-art" (STAR) Report in 2016 [32]. This comprehensive and up-to-date-report contains five recommended test methods for aggregates (designated as AAR-1 to AAR-5) and an overall recommendation that describes how these should be used to enable a comprehensive aggregate assessment (AAR-0). Additionally, in this report, there are two recommended international specifications for concrete (AAR-7.1 and −7.2) and a preliminary international specification for dams and other hydraulic structures (AAR-7.3), which describe how the aggregate assessment can be combined with other measures in the design of the concrete to produce a concrete mixture with a minimised risk of developing damage from AAR. There was also considerable effort made towards publishing a petrographic atlas by Fernandes et al. (2016) [33], which is complementary to the petrographic method described in RILEM AAR-1.1. It is designed and intended to assist in the identification of alkali-reactive rock types in concrete aggregates by thin-section petrography.

2.4 The ICAAR conferences 2016 – 2020, and successor RILEM TCs

2.4.1 15th ICAAR Brazil (2016)

In 2016, Haroldo de Mayo Bernardes chaired the15th ICAAR in Sao Paulo, Brazil. In the foreword to the Proceedings, edited by Bernardes and Hasparyk [34], Selmo Kuperman listed the topics to be presented at this ICAAR, including tests aimed to correctly identify and mitigate potential reactive aggregates, importance of alkali release from aggregates, the influence of other mechanisms inducing substantial expansion in concrete such as delayed ettringite formation (DEF), methods to predict the future behaviour of AAR-damaged structures, repairs and remedial measures to restrain expansions and improve durability and long term behaviour of affected structures. In addition, he mentions one important topic that should be addressed, i.e. the quantification of the expansion level attained by AAR-affected structures. Unfortunately, at this ICAAR, the tradition of awarding senior AAR-researchers with *"The Gunnar Idorn Award for Life Achievement"* was not continued.

2.4.2 RILEM 4th TC 258-AAA (2014 – 2020)

In 2014, the RILEM TC 258-AAA (A*voiding alkali aggregate reactions in concrete – performance based concept*) was established, chaired by Børge Johannes Wigum from HeidelbergCement Northern Europe, Norway, and with Jan Lindgård from SINTEF, Norway, as the Secretary. The main purpose of this 4th TC was to develop and promote a performance-based testing concept for the prevention of deleterious AAR. Strong emphasis was put on the implementation of the RILEM methods and recommendations as national and international standards. The TC was terminated by the end of August 2020. The revised former Outline Guide from 2016 (RILEM AAR-0), along with the following RILEM recommended test methods, were submitted during end of 2020 for publication to the journal: "*Materials & Structures*":

- RILEM AAR-0 (2021) Outline Guide to the Use of RILEM Methods in the Assessment of the Alkali-Reactivity Potential of Concrete.
- RILEM AAR-8 (2021) Determination of Potential Releasable Alkalis by Aggregates in Concrete.
- RILEM AAR-10 (2021) Determination of binder combinations for non-reactive mix design using concrete prisms – 38°C test method.
- RILEM AAR-11 (2021) Determination of binder combinations for non-reactive mix design or the resistance to alkali-silica reaction of concrete mixes using concrete prisms – 60°C test method.
- RILEM AAR-12 (2021) Determination of binder combinations for non-reactive mix design or the resistance to alkali-silica reaction of concrete mixes using concrete prisms – 60°C test method with alkali supply.
- RILEM AAR-13. (2021) Application of alkali-wrapping for concrete prism test assessing the expansion potential by alkali-silica reaction.

In addition, an extensive State-of-the-art report, including topics regarding; "Laboratory expansion vs. field exposure" and "Overview of the alkali-inventory in concrete" is scheduled to be finalised during 2021. A detailed overview of the deliverables of this TC is presented in another paper at this 16th ICAAR [35].

3. SUMMARY - FUTURE CHALLENGES AND RESEARCH

Through the initial gathering of a limited number of researchers, from a few countries, with the succeeding participation of engineers from an increasing number of countries, the ICAARs have now developed into the main global events of AAR-related presentations and discussion. All ICAAR Proceedings are now made electronically searchable and available for open access for new generations of AAR-scientists.

Through decades of international effort, we now know much more about mineralogical properties, reaction kinetics and mechanisms of various types of reactive aggregates, and how they behave in various concrete compositions. For example, the previous "popular" measurement of undulatory extinction of quartz is not recommended anymore or at least only used as an indicator of potential reactivity. The ACR was first identified as a possible potential problem in the 3rd ICAAR (1976) in London. Then, it appears in various ICAARs, including the 5th (1981) in Cape Town, but perhaps most notably in a series of papers (including Chinese experience) in the 7th (1986) in Ottawa. At the 11th ICAAR (2000) delegates were taken to see the Kingston Limestone pavement expansion during the post conference technical visits. The story goes on with particular emphasis on Chinese concrete studies until Katayama's and Grattan-Bellew's questioning work culminating in a paper [36] in the 14th ICAAR in Austin (2012).

Improvement of accelerated test methods has continuously been a research topic for about 45 years. The global cooperation through ICAARs and subsequently through the RILEM Technical Committees has fortunately provided fewer, but more uniform and reliable test procedures. New performance test methods have also been developed in the last decade, taking into account the alkali leaching from concrete prisms, facilitating the assessment of various mitigating measures, including the alkali threshold, in order to produce non-deleterious concrete, even with the use of reactive aggregates.

Numerous case studies around the world have provided information about the consequences of deleterious AAR in various concrete structures. The systematic approach used today includes assessing the phenomenon, following the evolution of deterioration through visual and/or microstructural inspection, monitoring the structure by instrumentation and adopting remedial measures where necessary. By developing advanced models, designers are better able to understand the effects of AAR and select more appropriate remedial measures to protect the structure from deterioration by on-going AAR-expansion. However, much more research is needed on these topics. The same is valid regarding reliable measurement and prediction of residual expansion in affected structures.

Even though we now understand a great deal more about the reaction between certain aggregates and the alkali hydroxides from the concrete pore solution, still many topics remain ambiguous or not fully examined/understood. The effect of sodium chloride, and whether it promotes the dissolution of SiO_2 directly is still unclear and a topic of debates between scientists. The "old" discussion about the possibility of a potential pessimum alkali content has not been followed up in the last decades. The recently developed RILEM AAR-8 method shows that certain types of aggregate, at least in the fine fraction, can potentially release significant amounts of alkalis, under accelerated conditions in the laboratory. However, verification and calibration of the potential contribution of alkalis in real structures are still unclear and premature, and further research is necessary. This includes the whole complex picture of making an inventory of alkalis when testing concrete mixes, including issues such as leaching, boosting, recycling, concentration and release of alkalis, and whether or not all alkalis in the cement are available for reaction.

Many field exposure sites around the world provide very important data about how various aggregates and concrete mixes behave under field exposure for various climatic conditions. Often, it seems that field cubes exhibit more expansion than observed in concrete prism testing in laboratories. However, implementing realistic critical expansion limits for laboratory testing, based upon the field data, and developing corresponding AAR regulations are still a challenge, as discussed by Lindgård et al. [37]. Due to different climatic conditions, this should preferably be dealt with nationally/locally.

Other forms of swelling mechanisms in concrete, including Delayed Ettringite Formation (DEF) and rapid expansive reactions caused by occurrence of certain sulphide minerals (e.g. pyrrhotite) in concrete aggregates can also cause damage alongside AAR, and might exhibit a sort of symbiotic relationship. AAR and coupled AAR/DEF mechanisms are now among the topics presented at the ICAARs.

One might say that RILEM facilitated the first ICAAR. In its initial form, the International Organising Committee (IOC) strengthened both the ICAARs and the first RILEM TC, by assisting cooperation between these parties. Unfortunately, the role of this Committee has been somewhat vague during the years. We hope that we will see a strengthening in global cooperation in both research, consultations and education, for a new generation of AAR-scientists and engineers, participating in future ICAARs and RILEM TCs. So far, only a few countries have implemented the RILEM recommendations as national guidelines. However, with the new updated RILEM AAR-0, and new corresponding recommendations, based upon performance based concepts, there is reason to believe that many more countries will follow.

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