ALKALI AGGREGATE REACTIONS (AAR) IN CONCRETE. THE NORWEGIAN ENDEAVOUR DURING MORE THAN 3 DECADES OF RESEARCH.

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Abstract

It is now more than 80 years since Alkali Aggregate Reactions (AAR) first were reported as a deleterious deterioration mechanism in concrete. In Norway, AAR was recognised in the late nineteen-eighties. Norwegian experience and expertise have increased significantly since then and entered the international stage, with connections to leading research parties worldwide. Several Norwegian master's degrees, PhD theses and major R&D projects have been carried out, focused on test methods and corresponding criteria for the prediction of AAR as observed on Norwegian concrete structures. Reliable Norwegian test methods and guidelines have been developed, through the Norwegian Concrete Association, and linked to the European concrete standard, enabling use of local reactive aggregates, in a sustainable way, by documenting and producing non-reactive and durable concrete.

Norwegian researchers have participated actively in the various Technical Committees (TC's) on AAR in RILEM and have been in the leadership of the two most recent TC's since 2014. This work has recently achieved some significant progress regarding recommendations, and performance-based testing concept, to prevent damage by AAR in new concrete structures.

This paper is a review of the research carried out in Norway during more than 3 decades, parties involved, and the results and conclusions achieved. Eventually, this paper presents a summary of where we are today in international AAR research, identifies key milestones and addresses some specific topics for future research.

Keywords: Alkali Aggregate Reactions, Concrete durability, RILEM Recommendations

INTRODUCTION

Siliceous aggregate types are prone to dissolution by the alkaline pore fluid in concrete. A wide variety of aggregate types in common use across Norway are vulnerable to attack by the alkaline pore fluid in concrete. This attack, which in wet conditions produces a hygroscopic and hydraulic gel, can cause swelling and expansion. Expanding structural members may cause constraining forces, displacement of adjacent elements and unexpected load redistribution. The expansion of concrete leads to internal stresses and cracking, which further leads to reduction in tensile strength and Young's modulus of elasticity. In total, this may lead to serious structural problems for reinforced concrete structures. The deterioration mechanism is termed Alkali Aggregate Reaction (AAR) or, more specifically, for siliceous aggregates, Alkali Silica Reaction (ASR). Problems due to AAR were first identified in the State of California in the 1930s and eventually explained and reported by Thomas Stanton in 1940 [1].

CHRONICLES OF NORWEGIAN AAR RESEARCH

Before 1990: Preliminary evidence of AAR in Norway

In 1962 Musæus [2] presented a master thesis on the topic of AAR at the Technical University of Trondheim. In 1967 Idorn [3] presented findings from laboratory tests where basaltic sand from the Oslo region apparently was reactive. The first indication of damages in concrete structures was presented in 1978 [4] where it was claimed that an indoor swimming pool was damaged by AAR.

Accelerated mortar bar testing results with Norwegian materials were presented in a Master thesis by Haugen [5] in 1986. The Norwegian Water and Energy Administration (NVE) presented in 1989 [6] findings of damages in Norwegian concrete dams due to AAR. Obviously, the number of observations of deleterious AAR until 1990 in Norwegian structures justified further research into susceptible aggregate materials and concrete compositions.

From 1990 to the end of the millennium: Mapping the extent of AAR and initial recommendations

The first significant existence of AAR in Norwegian concrete structures was demonstrated in the research program ”*AAR in Southern Norway*” that was carried out from 1990 to 1993. The program primarily focused on mapping the occurrence of AAR and the identification of reactive rock types by petrographic examinations of cores, fluorescence impregnated polished half cores and thin sections from structures. It was found that AAR in Norwegian structures is caused by the "coarse" fraction of slow/late-expansive siliceous aggregates. Deformed-metamorphic rocks e.g. cataclasite and mylonite were observed as deleterious alkali reactive in about 50% of all the investigated Norwegian structures in the program. The program included three master thesis research projects at the Technical University of Trondheim [7], [8], [9] tied to the PhD-thesis of Jensen in 1993 [10]. As a result of this work, the petrographic method with point counting of thin sections was introduced as the first stage in the assessment of the AAR reactivity of aggregate materials [11]. Accelerated mortar bar testing served as the second stage, mainly when the first petrographic assessment gave ambiguous results.

In 1992 an optional arrangement for acceptance and approval of aggregate for concrete was introduced by the Norwegian Control Council for Concrete Products (Kontrollrådet). A three-step test procedure was introduced consisting of petrographic analysis, the accelerated mortar bar method and the concrete prism method, where critical limits were presented for each test method. A year later, in 1993, the concrete test was withdrawn from the arrangement, as certain sedimentary aggregates in the test exhibited non reliable results (i.e. not in accordance to field experience). Later studies have however revealed that the ambiguous results were most likely due to the use of large storage containers in which the humidity could not be controlled [12], [13]. The succeeding project “*AAR in Northern Norway*” from 1994 through 1996, [14], [15], [16] not only included mapping and identification like its southern predecessor, but also evaluated some field methods for monitoring the moisture state (relative humidity, RH) and rate of expansion (crack development), and the effect of minor methodological adaptations on the reliability of petrographical assessment.

The PhD-study of Wigum from 1995 [17] focused on further improving the method of petrographic assessment towards enhanced quantification of relevant parameters, largely the grain size of quartz, as well as on the effect of adjustments on accelerated mortar bar testing. The majority of the rocks studied were of cataclastic origin which had undergone ductile deformation. These types of rocks were commonly found in glaciofluvial aggregates in Norway [18]. The study demonstrated that the grain size reduction of quartz, promoted by the process of cataclasis, enhances alkali reactivity by increasing the surface area of quartz grain boundaries available for reaction [19]. Moreover, the expansion development of AAR for slowly expanding alkali reactive aggregates in the accelerated mortar bar test was discussed by Wigum and French [20]. The accelerated mortar bar test was further examined by Wigum et al. [21] looking into the reliability of the test, including effects of different mortar bar sizes.

Based upon existing knowledge of AAR and test methods, the Norwegian Concrete Association published in 1996 a recommendation (NB21) [22] for production of durable non-reactive concrete with use of alkali reactive aggregates. The recommendation provided criteria for the maximum allowable alkali content of bulk concrete, dependant on the type of cement (OPC or the Norwegian fly-ash cement produced by Norcem) or use of a sufficient amount of silica fume. NB21 also described how to deal with blends of aggregates. Regarding aggregate classification NB21 referred to the testing procedures and the critical limits for individual constituents described in a SINTEF report from 1993 by Lindgård et al. [11].

Completed in 1996, the "*NORMIN 2000 pilot project*" [23], [24] made an inventory of the state-of the-art in alkali-reaction research in Norway, from which the most promising and urgent topics to be addressed in the subsequent "*NORMIN 2000*" main project were selected [12]. The primary goal of the main project was to set up a recommendation for the assessment of potentially alkali-reactive aggregate materials, using simple yet reliable testing methods. Guidelines, procedures and acceptance criteria had been based upon the available knowledge, which sometimes was quite incomplete or not proven to be reliable. Thus, the existing guideline obviously lacked a solid enough foundation to justify the criteria it referred to, which issue received highest priority in the main project to be resolved, and to check whether these criteria reflected the experiences from actual (Norwegian) structures.

As part of the main *NORMIN 2000 project* a revision was made of the classification chart for alkali-reactivity of Norwegian rock types. In addition, a detailed petrographic atlas with micrographs of the various Norwegian rock types was published [25]. Despite the vast amount and interesting content of data generated by this project, several essential matters of fundamental mineralogical and geochemical nature remained unresolved. To pursue research into these matters, a nationwide forum known by the acronym FARIN (*Forum on Alkali-Reactions In Norway*) was established in March 1999 [26].

During 1999, a major research project *("AAR in concrete – Field experiences)* was initiated, comprising quantitative measurements on drilled concrete cores from existing concrete structures. The research project was finished in March 2003 [27], [28], [29], [30]. The aims of the project were to:

- Use experience from concrete structures in the field, together with quantitative measurements of concrete cores (environment, type of aggregates and mix design of concrete), to carry out an assessment of the current critical limits given by the Norwegian petrographic method and the accelerated mortar bar test.
- Find a correlation between type of structures, local environment (humidity) and degree of damage in the field, with the ambition to obtain more reliable guidelines for production of non-reactive concrete.
- Make suggestions for revision of the current guidelines for production of durable concrete published by the Norwegian Concrete Association, i.e. NB21 [22].

During the three years project, a total of about 160 concrete structures (mainly bridges) were examined with respect to AAR. The Norwegian petrographic method appeared to be appropriate as an engineering tool to classify alkali reactive aggregates [31]. The project succeeded in developing a technical and economical feasible method for separating the fine- and coarse aggregate fractions from the drilled cores, and thus made it possible to perform petrographic analyses in a similar way as for "virgin material" [32]. The project also characterised the degree of damage in the drilled cores by introducing a so-called "Crack Index" (CI), based on counting of 3 crack parameters in the plane polished sections [28]. The project showed that, with one exception, the degree of capillary water saturation of the concretes was higher than 90vol% for all the structures with presence of AAR [29], [30]. No good correlation was found between the observed damage due to AAR (i.e. measured CI) and the water/binder ratio or the air content of the concrete, respectively. A reasonable correlation was found between the content of reactive rock types in an aggregate and the "Crack Index". It seemed likely that coarse aggregates lead to more damage (i.e. more severe) than the fine fractions. Thus, stricter requirements were suggested to a coarse aggregate compared to fine aggregate. As part of the project, a concrete retaining wall in Norway was studied more in detail by Hagelia [33]. The wall exhibited map cracking in some segments, whilst other segments showed almost no surface cracking. Based on the results from the project, specific suggestions were given for revision of the Norwegian guidelines for production of durable concrete given by the Norwegian Concrete Association, publication NB21 [22].

A new millennium: Further research

As part of his PhD-study, Broekmans [34] in 2002 characterized the nature of the silica/quartz of the same Norwegian mylonites as studied previously by Wigum. His main conclusion was that the applicability of the current determination of crystallinity indices by XRD to determine the alkali-reactivity potential of quartz and especially whole rock is very limited. Using advanced techniques from mineralogy and geochemistry, he proposed to characterize aggregates with a different geological background (e.g. chert, granite and mylonite), as well as identical aggregates from different resources (e.g. sandstone from Norway and the Netherlands) [35], [36].

In his PhD-study in 2004, Pedersen [37], [38] investigated the possible mitigation effect of alkali-reactive fillers (particles less than 0.125 mm) from two Norwegian cataclastic rocks, along with fillers of Icelandic glassy rhyolite and crushed bottle glass. Non-reactive reference fillers were included in the study, as well as silica fume and fly ash known to mitigate AAR. All the materials being highly pozzolanic were found to have a distinct amorphous silica phase, while the silica phase of the non-pozzolanic materials was shown to be well crystalline quartz. The accelerated mortar bar test predicted the Norwegian reactive rock fillers to inhibit expansions due to AAR. This contradicts the predicted effect of these fillers by the concrete prism test. Methods such as the accelerated mortar bar test, or other methods using very high temperatures, should consequently not be used to evaluate the effect of rock fillers containing silica, unless their pozzolanic reactivity are also evident at lower temperatures.

In his PhD-study in 2011, Hagelia [39] examined the deterioration mechanisms affecting steel fibre reinforced sprayed concrete used for rock support in tunnels. He concluded that AAR is an insignificant durability problem in this type of concrete.

In her PhD-study in 2012, Castro [40] investigated the relationship between aggregate petrological properties and expansion test results, by detailed characterization of reactive quartz in aggregate, both focussing on mineralogy and geochemistry. As a result, a better understanding of some characteristics of the silica minerals that influence the potential alkali-reactivity of the aggregates was achieved.

In his PhD-study in 2013, Lindgård [41] investigated the suitability of various concrete prism test procedures for reliable use as a performance test. The focus was on detecting and assessing various sources of error. The main conclusion was that leaching of alkalis from the concrete prisms during the testing period was the most important parameter that gave rise to unreliable results by reducing the AAR expansion compared to field structures where the influence of alkali leaching is minor. This work was part of the Norwegian research project *COIN (Concrete Innovation Centre* managed by SINTEF Building and Infrastructure) and was performed in conjunction with RILEM TC 219-ACS (2007-2014). The PhD study gave valuable input to the improvement of the RILEM AAR aggregate test methods AAR-3 and AAR-4 [42] and the development of the RILEM AAR-10 concrete performance test [43].

In the R&D project "*KPN-ASR*" (2014-2019) following up the *COIN* project, the overall objective was building up new knowledge on several important AAR issues as a basis for 1) developing and implementing new binders containing SCMs; 2) securing safe use of local alkali-reactive aggregate resources, and 3) handling existing AAR-affected structures. The main technical objectives were 1) proposing a set of improved performance test methods for national and international application, and 2) assessing the reliability of promising performance test methods through a verification program, focusing on the laboratory/field correlation (basis for assessing the critical expansion limits). In the extensive R&D project, secondary objectives included assessment of various test procedures of importance for assessing AAR, for examples 1) quantification of cracking (in field and in the lab.); 2) internal alkali content; 3) relative humidity and 4) residual expansion procedures. The project co-operated closely with the RILEM TC 258-AAA (2014-2019). Important findings in the project are presented at ICAAR 2022.

The *NEWSCEM* project (2018-2022), a Norwegian innovation project lead by the Norwegian cement producer Norcem, has the aim to find alternative supplementary cementitious materials (SCMs) for Norwegian cement production. Siliceous fly ash is currently the most commonly used SCM in Norway, but it is becoming scarcer thereby obliging us to find alternatives. One of the major requirements for the alternative SCMs is their capability to mitigate AAR. Petter Hemstad's PhD study, which is connected to *NEWSCEM*, is looking into how the SCMs affect the solid phase and pore solution composition, and how this relates to the capacity of the SCMs to mitigate AAR expansion during laboratory performance tests. For the most promising SCMs, corresponding monitored field cubes have been produced and exposed at SINTEFs field exposure site in Trondheim and at LNEC in Lisbon.

The *ARA* project, Alkali Release from Aggregates, initiated in 2020, has the aim to verify alkali release from aggregates determined by the RILEM AAR-8 method [43] in laboratory and field concrete. The AAR-8 method is a leaching method where alkali release is determined on 100g sand (0-4 mm) in contact with 400 mL 0.7M NaOH or KOH solution at 38ºC for 26 weeks. Within the project several Norwegian aggregates were submitted to the AAR-8 test. In addition, verification of potential alkali release was performed on field samples exposed at Sandnessjøen for 26 years. However, due to the uncertainty of the share of alkali from the cement present in the pore solution and the relatively low potential alkali release from the investigated aggregate, no reliable verification was possible. In 2021, AAR-8 testing of more aggregates and a verification study on field cubes containing potentially high releasing Icelandic aggregates were initiated. In 2022, Mahsa Bagheri has started a 2-year post-doc project which is partially related to the *ARA* project. She will look into verification of alkali release during accelerated AAR performance testing. This work will be linked to the work in the new RILEM TC on AAR (see later).

During the last ten years, the Norwegian Public Roads Administration has initiated several R&D activities on maintenance and structural consequences within the research programs *Durable Structures* (2012-2015) [44] and *Improved Bridge Maintenance* (2017-2022) [45]. Guidelines for inspection of bridges suffering from AAR have been developed based on results from field and laboratory examinations performed on several bridges [44, 45 & 46]. A field test program on the mitigating effects of surface treatment of affected structures was initiated in 2014, in which preliminary results were reported by Rodum et al. [47]. Preliminary guidelines for structural analyses of AAR affected bridges was published in 2016 [48]. The research has been performed in close cooperation with NTNU and SINTEF within the research project *ARKON* (2018-2022), being continued within the new project *MESLA* (2021-2025). Since 2017, several Master theses focusing on structural analyses and capacity control on existing bridges has been performed at NTNU [45], and the PhD studies of Kongshaug [49, 50 & 51] and Stemland [52] are in their final stages.

INTERNATIONAL ENGAGEMENT

Since the late 1990-ties, Norwegian researchers have participated actively in international development of methods to mitigate deleterious AAR, led by RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures). Parallel to these activities, SINTEF and Norcem (part of HeidelbergCement) participated actively in the European research project "*PARTNER"* (2003-2006), where critical assessment of RILEM aggregate test methods was carried out [53].

In the 6-year period from 2014 to 2020, the RILEM Technical Committee (TC) 258-AAA developed a performance-based testing concept for the prevention of deleterious AAR in concrete. This TC was chaired by the Norwegian scientists Børge J. Wigum and Jan Lindgård. The TC has emphasised the importance on implementing the RILEM methods and recommendations as national- and international standards. The revised former Outline Guide from 2016 (RILEM AAR-0), along with the following RILEM recommended test methods, are recently published in a topical collection [43]:

- 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 – 38ºC 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 – 60ºC 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.

A recent established RILEM TC -ASR: "*Risk assessment of concrete mixture designs with alkali-silica reactive (ASR) aggregates*" (2021–2025) is also partly chaired from Norway, with Klaartje De Weerdt as co-chair of the TC and several Norwegian researchers leading and participating in the Task-groups. The overall goal of the proposed TC ASR is to develop the basis for a model to predict the risk for AAR for a given mix design, exposure and structural classification. The TC is divided in three work packages (WPs), where the first WP1 will validate AAR performance tests by looking into the reliability and applicability of various accelerated laboratory tests; WP2 looks into the efficacy of SCMs to mitigate AAR and alkali balance in the concrete system. The data from these validation efforts of WP1 and WP2 will serve as input for WP3 which deals with the development of a decision-making model. The Norwegian scientists will primarily be contributing to the TC on the following topics: 1) alkali release from aggregates in connection to the *ARA* project, 2) impact of SCMs on AAR with input from the *NEWSCEM* project, 3) alkali threshold and 4) lab-field correlation based on long-term experience in a series of R&D projects e.g. *PARTNER* [53], *COIN* [54] and *KPN-ASR* [55].

CURRENT NORWEGIAN GUIDELINES

Based upon an active cooperation between the industry and academia in Norway, and national- and international research work, as presented in this paper, a revision of the NB21 publication was finalized in 2004 [56], and a subsequent revision was completed in 2017 [57]. In addition, the Norwegian test methods along with requirements for laboratories were published in a publication, NB32 [58]. The 2004, and later 2017, revision of NB21 publication, has now a formal status as a normative reference document to the national application rules of the concrete materials standard, NS-EN 206-1 [59] (no common EN standard exist on AAR in Europe). NB21 is considered as a key element in the Norwegian system for preventing AAR.

Evaluation of material parameters regarding the effect of AAR in Norway is based upon three different test methods: the Norwegian petrographic analysis, the Norwegian accelerated mortar bar test and the Norwegian concrete prism test [58].

- <u>The Norwegian petrographic method</u> for aggregate assessment is in agreement with the RILEM AAR-1 method [42].
- <u>The Norwegian accelerated mortar bar test</u> for aggregate assessment is mostly in agreement with the RILEM AAR-2 [42] method, but European standards (NS-EN) are followed for sieving, conditioning and moulding. Mortar bar prisms of 40×40×160 mm are used. As the mortar consists of a given grading the method is not able to evaluate the reactivity of different aggregate fractions, i.e. the experience is that a fine- and a coarse aggregate from the same deposit give similar expansion values. This has been accounted for by differentiating the critical limits; since the coarse aggregates have proven to be more harmful *in field* than fine aggregates, a lower limit is applied for coarse aggregates. The mortar bar test results may be used to overrule those of the petrographic assessment.
- <u>The Norwegian 38°C concrete prism test</u> has two applications, one for aggregate assessment and one for concrete mix design assessment. It is carried out using concrete prisms with dimension 100×100×450 mm. The method is in agreement with, and formed the basis for, the newly published RILEM AAR-10 method [43].
    - For aggregate assessment, the critical limits are based on the assumption that the concrete prism test is capable to take into account the effect of different reactivity of various grain sizes. Consequently, the same limit is applied for fine and coarse aggregates. However, for blends of aggregates a slightly higher critical limit is specified. The reason for this is that in real life an aggregate classified as "non-reactive" may give a certain contribution to the overall expansion. The results from the concrete prism test may be used to overrule those from petrography or mortar bar testing.

- Performance testing (mix design assessment) is mainly used to determine modified alkali content limits when combining reactive aggregates (specific sources or reference aggregates) with specific binder composition, especially when designing cement products for generic use.

THE PATH FORWARD

A considerable research effort has been made in Norway leading to the recommendations recently revised for preventing AAR in concrete. The aggregate, cement, and concrete industries are aware of the potential problems related to AAR. With the revised NB21 [57], and the NB32 [58], reliable assessment methods have been established to perform the required tests for the industry on a regular basis, according to European standards where NB21 gives the national requirements for handling the AAR-problem.

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 recently developed RILEM AAR-8 method [43] 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, adsorption, and release of alkalis, and whether all alkalis in the cement are available for reaction. This will be dealt with in the *ARA* project (2019-2023).
- The effect of sodium chloride, and whether it promotes the dissolution of SiO_2 directly is still unclear and a topic of debate between scientists.
- There is a need to develop methods to better distinguish the reactivity of different rock types.
- Results from the Norwegian concrete prism method appear to echo the field performance of concrete adequately. However, to improve the reliability, assessment of the critical expansion limits and the safety margins through benchmarking against the field exposure sites established and real concrete structures is needed.
- Norwegian researchers recognise the necessity to continue the cooperation with the owners of concrete structures in Norway to evaluate and examine the state of the concrete in the structures. This will increase the knowledge for the research community.
- It is important to further develop the calculation tools for structural strength analyses and capacity control of existing structures suffering from AAR. One of the main input parameters for such calculations is the extent of expansion, as this is controlling the additional loads and is also directly coupled to the micro cracking resulting in stiffness and strength reductions. There is therefore a need to develop more accurate and reliable field - and laboratory methods to estimate the expansion levels up to date and to predict the future expansion levels, as well as the degradation in mechanical properties. These topics are included in the recently initiated Norwegian R&D project *"MESLA"* (2021-2025).
- There is a need to further understand deleterious expansion of light-weight aggregates, along with 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.

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