

AAR: TESTING, MITIGATION & RECOMMENDATIONS. THE NORWEGIAN APPROACH DURING TWO DECADES OF RESEARCH.

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Abstract

Over the past two decades, Norway has invested considerably in research on deleterious AAR in concrete, with strong focus on testing and appraisal criteria for AAR prevention. The research was done in collaboration of several institutions through large research projects, and has resulted in a number of master's and doctoral theses and a range of publications. Projects in the period 1990 – 1996 gave the fundamental knowledge about reactive aggregate types and testing methods, and formed the basis for the Norwegian guidelines first published in 1996. An extensive national research project in the period 1999 – 2003, lead to a revision of these guidelines in 2004. A national forum for AAR (FARIN) was established 1999.

This paper provides a review of the research carried out in Norway during the last 20 years, parties involved and the results and conclusions achieved. Eventually considerations about future path to follow are presented.

Keywords: alkali-aggregate reactions, petrographic analysis, accelerated mortar bar test, concrete prism test, national recommendations.

1 INTRODUCTION

1.1 General

Siliceous aggregate types common in NW Europe are prone to dissolution by the alkaline pore fluid in concrete. A wide variety of aggregate types in common use across Europe 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 cracking and disruption of the concrete. The deterioration mechanism is termed Alkali Aggregate Reaction (AAR) or, more specifically, for siliceous aggregates, Alkali Silica Reaction (ASR).

Research and development in Norway has provided reliable testing methods regarding AAR. This is the case both for classification of amount of reactive aggregates, the reactivity of the aggregate itself and the potential of the reactivity of various concrete mixes. Today a critical restriction of reactive constituents in the aggregates, based upon the petrography analysis, is accepted for making a non-reactive concrete, i.e. no other preventive actions are required. Critical limits are also set for the accelerated expansion of mortar bars after 14 days along with one year expansion for concrete prisms. Materials are subject to additional testing using above methods if not classified as innocuous from petrographic assessment.

The current set of measures to prevent AAR in concrete in Norway is considered to represent the same security level as corresponding systems for securing against durability damage from e.g. corrosion and freeze/thaw damage.

2 CHRONICLES OF NORWEGIAN AAR RESEARCH

2.1 Before 1990: discovery of deleterious ASR in Norway

In 1962 Musæus [1] presented a master thesis on the topic of AAR at the University of Trondheim. In 1967 Idorn [2] presented findings from laboratory tests where basaltic sand from the Oslo region apparently was reactive. The first indication of damages in concrete structures is presented in 1978 [3] where it is claimed that an indoor swimming pool is damaged by AAR. Accelerated mortar bar testing results with Norwegian materials were presented in a Master thesis by

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Haugen [4] in 1986. The Norwegian Water and Energy Administration (NVE) presented in 1989 [5] findings of damages in Norwegian concrete dams due to AAR. Obviously, the number of observations of deleterious ASR until 1990 in Norwegian structures justified further research into susceptible aggregate materials and concrete compositions.

2.2 Until 1995: Mapping the extent of ASR

The first significant existence of AAR in Norwegian concrete structures was demonstrated in the research program "AAR in Southern Norway" that ran from 1990 through 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. Dynamo-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 [6], [7], [8] tied to the PhD-thesis of Jensen in 1993 [9]. 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 aggregate materials [10]. 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 by petrographic analysis, accelerated mortar bar method and 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 most likely reason for unclear results was due the use of large storing containers where humidity could not be controlled satisfactory [11], [12].

The succeeding project "AAR in Northern Norway" from 1994 through 1996, [13], [14], [15] not only included mapping and identification like its southern predecessor, but also evaluated some field methods for monitoring moisture content (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 [16] 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 [17]. 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 [18]. The sequential development of AAR for slowly expanding alkali reactive aggregates in the accelerated mortar bar test was discussed by Wigum and French [19]. The accelerated mortar bar test was further examined by Wigum et al. [20] where discussions were made about the accuracy of the test, including effects of different mortar bar sizes.

2.3 The end of the millennium: Norwegian national forum FARIN

Based upon existing knowledge of AAR and test methods, the Norwegian Concrete Association published in 1996 a recommendation (NB21) [21] 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 of 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 by Lindgård et al. [10].

Completed in 1996, the "NORMIN 2000 pilot project" [22] 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 [11]. 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.

Thorough assessment of results from the NORMIN 2000 main project revealed that the limit of 20vol% for potentially alkali-reactive rock types did not correspond satisfactory to the limit of 0.10% 14-day expansion in the accelerated mortar bar testing. Which of these limiting criteria that ought to be most suitable for adjustment was realised as a challenge for future research. It was concluded there was a clear demand for a project sequel, specifically addressing the assessment of quantitative field data, as required to eventually revise the current criteria [23].

As part of the NORMIN 2000 project a revision was made of the classification chart for alkali-reactivity of Norwegian rock types. For details of the alkali reactive rocks types, ambiguous and innocuous rock types, see Table 1. In addition a detailed petrographic atlas with micrographs of the various Norwegian rock types was published [24].

Despite the vast amount and interesting content of data generated by the NORMIN 2000 research program, several essential matters of fundamental mineralogical and geochemical nature remained unresolved after closure of the main project. To pursue research into these matters, a nationwide forum known by the acronym FARIN (**F**orum on **A**lkali-**R**eactions **I**n **N**orway) was established in March 1999, and has since then been chaired by B.J. Wigum, hosted by the Geological Survey of Norway (NGU) [25].

2.4 Until 2003: assessment of 160 field structures

During 1999, a major research project was initiated, comprising quantitative measurements on drilled concrete cores from existing concrete structures. The research project was finished in March 2003 [26], [27], [28], [29]. 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 petrographical method and the accelerated mortar bar test.
- Find correlation between type of structures, local environment (humidity) and degree of damage in the field, with the ambition of obtaining more competent guidelines for production of non-reactive concrete.
- Make suggestions for revision of the current guidelines for production of durable concrete given by the Norwegian Concrete Association [21].

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 in order to classify alkali reactive aggregates [30]. 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 petrographical analyses in a similar way as for “virgin material” [31]. The project also succeeded in characterising 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 [27]. The project showed that with one exception the degree of water saturation of the concretes was higher than 90vol% for all the structures with presence of AAR [29]. 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. is more severe) than the fine fractions. Thus, more strict 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 [32]. The wall exhibited map cracking in some segments, whilst other segments showed almost no surface cracking. The main difference between the two concretes revealed in the thin section analyses was represented by the internal distribution of initial air voids, cement and aggregates.

The overall experience gained in the research project was that the results obtained by the three Norwegian laboratory test methods correlated satisfactory with field experience, under supposition that some of the critical limits were changed. Thus, based on the results from the research project, specific suggestions were given for revision of the Norwegian guidelines for production of durable concrete given by the Norwegian Concrete Association, NB21 [21].

2.5 Present: detailed characterization

As part of his PhD-study, Broekmans [33] in 2002 characterized the nature of the silica/quartz of the same Norwegian mylonites as studied previously by Wigum, along with Ohio and Dutch cherts. His main conclusion was that the current determination of crystallinity indices by XRD to determine the alkali-reactivity potential of quartz and especially whole rock is very limited. About ten fundamentally different parameters are known to affect the solubility of quartz under geological conditions, but the effect of any of these parameters for the undesirable quartz dissolution under ASR conditions is virtually unknown, according to Broekmans [34]. Using advanced techniques from mineralogy and geochemistry, he proposes to characterize aggregates with a different geological background (e.g. chert, granite and mylonite), as well as identical aggregate from different resources (e.g. sandstone from Norway and the Netherlands) [35].

Pedersen [36], [37] investigated in his PhD-study in 2004 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 alkali-silica reactions. When testing the 0/20 μm fractions of the different fillers at 20°C, the materials could be divided into two distinct classes with respect to pozzolanity:

- The pozzolanic reactivity of fly ash, glass and rhyolite filler was distinct
- The pozzolanic reactivity of mylonite, cataclasite and quartz fillers was insignificant at the age of 28 days

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 alkali-silica reactions. This contradicts the predicted effect of these fillers by the concrete prism test. Testing of non-reactive limestone filler gave no effect at all on mortar bar expansion. This indicates that the effect of the Norwegian reactive rock fillers by this method is due to chemical and not physical effects. Due to the high temperature used by the accelerated mortar bar test (80°C), the quartz in these rock fillers was believed to react pozzolanic. 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.

SINTEF and Norcem (part of Heidelberg Cement company) participated actively in the European research project PARTNER (2003-2006) (www.partner.eu.com/publications.htm), where the issue was testing methods for concrete aggregates. Four of the ten testing methods applied were testing methods developed by the RILEM Technical Committee 191-ARP (2002-2006). Several Norwegian researches have contributed to the development of these methods.

3 CURRENT NORWEGIAN GUIDELINES

3.1 General

As mentioned before, the first Norwegian guideline NB21 to combat deleterious AAR was originally published in 1996 by the Norwegian Concrete Association [21], but was not formally referred to by any applicable standards or regulations otherwise. Nevertheless, NB21 did serve as the de facto Norwegian standard and was included in specifications for most building and construction projects. Consequently, it had no formal status, and the use of it was voluntary. Despite of this, NB21 was referred to in most of the Norwegian construction projects and served in general as the Norwegian regulations with respect to production of non-reactive concrete.

Based upon national- and international research work since 1996, a revision of the NB21 publication started late 2002 and was finalized in 2004 [38]. In addition, the Norwegian test methods along with requirements to laboratories were published in a new publication, NB32 [39].

An English summary of the NB21 publication has been presented by Dahl et al. [40], and an English translation will be published in 2008. The 2004 revision of NB21 publication has now a formal status as a harmonised normative reference document to the new concrete materials standard, NS-EN 206-1 [41]. The NB21 is considered as a key element in the Norwegian system for preventing AAR.

The 2004 revision of NB21 is critically assessed by Jensen [42]. After thorough assessment of point counting statistics, the limits in NB21 are allegedly too conservative and restrictive, while intrinsic uncertainties are too large. This poses questions as to the applicability of the point counting method for classification of (Norwegian) aggregate regarding AAR. The most reliable method to assess aggregate appears to be concrete prism testing, as suggested by good correlation with long-term

observations on field structures, in agreement with the NB21 revision committee. Thus, results from concrete prism testing may under circumstances overrule results from petrographic point counting or other methods referred to in NB21 and/or NB32 [39]. However, the NB21 revision committee is still convinced that petrographic point counting is a reliable method to assess the reaction potential of Norwegian aggregate provided the requirements to operator and laboratory specified in NB32 are fulfilled.

3.2 Current test methods and critical limits

Evaluation of material parameters regarding effect of AAR in Norway is since 2004 based upon three different test methods; the Norwegian petrographic analysis, the Norwegian accelerated mortar bar test and the Norwegian concrete prism test [39].

The Norwegian petrographic method is in agreement with the RILEM AAR-1 method [43], [44]. The accuracy of the method has been examined by Wigum et al. [30]. If the total volume content of potentially reactive aggregate is below the limit defined at 20.0vol% (Table 2), then the aggregate classifies as non-reactive and no further assessment is required. The aggregate is then considered suitable for any type of concrete mix. The Norwegian accelerated mortar bar test is mostly in agreement with the RILEM AAR-2 [45] method, but European standards (NS-EN) are followed for sieving, conditioning and moulding. Mortar bar prisms of 400×40×160 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 as shown in Table 2, i.e. since the coarse aggregates have proven to be more harmful than fine aggregates a lower limit is applied for coarse aggregates.

The Norwegian 38°C concrete prism test is carried out using concrete prisms with dimension 100×100×450 mm. When a potential reactive fine or coarse aggregate is tested, it shall be combined with a specified non-reactive coarse or fine aggregate, respectively; in a 60/40 mix representing the practical “worst case”, i.e. 60 % of the potential reactive aggregate shall be applied. The critical limits presented in Table 2 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 alkali-reactivity of various types of aggregates, binders and concrete recipes can be documented by performance testing using the Norwegian concrete prism method. The acceptance criteria for different types of binders and concrete recipes are presented in Table 3. A performance test shall be based on one or more batches. If based upon more than one batch, test results shall be plotted in an expansion versus alkali content-diagram as illustrated in Figure 1. By assuming a linear relationship between concrete prism expansion and alkali content, a limit of maximum accepted alkali content can be obtained. For added safety, the maximum allowable Na₂Oeq./m³ is decreased by 0.2 kg Na₂Oeq./m³.

4 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, and the new NB32, 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.

Despite all precautions, alkali reactivity remains a complicated problem, particularly in Norway with its diversity in aggregate composition and mineral content related to complex geology, and more research is essential for better understanding. The petrographic method has proved to be a cost and time efficient engineering tool in order to classify the alkali reactivity of various types of aggregate. A possible further development of the current method may however in the future make the method able to distinguish better between the reactivity of different rock types. Assessments and testing of new advanced techniques could provide clarification in more detail about microstructural properties of reactive minerals and rock types. This prospective new knowledge, along with automated image analysis, might be a path forward for strengthening and consolidate the petrographic method. A PhD-study by Nélia Castro is scheduled to start at the Norwegian University of Science and Technology (NTNU) in 2008, aiming to study the relationship between aggregate petrological properties and

expansion test results, by detailed characterization of reactive quartz in aggregate, both focussing on mineralogy and geochemistry.

A slightly modified version of the accelerated mortar bar method is now under development in Europe (RILEM AAR-2 method) [45]. Both the bar size used in Norway (40×40×160 mm) and the longer thinner bars (25×25×285 mm) are allowed to be used, and both sizes were included in the test program in the EU-project PARTNER [46]. Some discussions have been made regarding the correlation of results between the different bar sizes. It appears difficult to make proper comparison of results for different bar sizes for different types of aggregate.

Results by the Norwegian concrete prism method appear to echo the field performance of concrete adequately. However, test results are limited in Norway and often limited to commercial projects with particular conditions and limitations. Many more test results need to be obtained and correlated to long term field performance, enabling sufficient statistical assessment of the test method, the critical limits and the many factors affecting the results, including effects of additives such as various types of fly ash and silica fume. In addition the possible leaching effects from concrete prisms must be investigated further.

To reduce the testing time, the suitability of new accelerated concrete prism tests (e.g. the RILEM AAR-4 method) should be investigated for Norwegian aggregates and concrete recipes, with focus on performance testing of recipes and field performance. International experiences have shown these types of tests, where concrete prisms are stored at 60°C, to provide reliable results after only 12 weeks [47]. However, the possible leaching effects from the prisms in this method need to be studied further.

Several Norwegian researchers are still active in the international work carried out in the new RILEM Technical Committee, TC ACS (2006-2011): “Alkali-aggregate reactions in Concrete Structures”. One of the main aims for the task group TC ACS-P “Performance testing” is to develop one or more performance tests suited to document the alkali reactivity of real concrete mixes (“job mixes”). The task group is chaired by dr. Rønning from Norcem. The test(s) must be able to take into account the effects of aggregate grading, blends of aggregates, the mitigating effect of supplementary materials such as silica fume, fly ash or slag, lithium, in addition to determine the critical alkali limits for various concrete mixes or a given aggregate combination. The co-author of this paper has recently started a PhD-study at NTNU. The main aim of the study is to develop a performance based testing concept. This work is part of the Norwegian research project COIN (Concrete Innovation Centre by SINTEF Building and Infrastructure) and will be performed in conjunction with the RILEM task group TC ACS-P.

In order to strengthen the work of the RILEM committee it was recognised the importance to establish a commission within the task group TC ACS-P. An initiative by Norwegian researchers was made to set up an International Performance Testing Cooperation (IPTC-AAR) in order to collect international data and regional experience, co-ordinate the research activities world wide on this issue, plus initiate inter-laboratory trials to compare with field data.

In task group TC ACS-R “Releasable alkalis” the aim is to examine the potential alkali release from aggregates. The task group is chaired by dr. Maarten Broekmans from Geological Survey of Norway (NGU). The RILEM Committee has also proposed an extension of the petrographic atlas developed by the PARTNER project. NGU, in close cooperation with NTNU, have responded to this challenge and will recruit contributors for the extension of the petrographic atlas containing micrographs by optical microscopy (PPL, XPL, fluorescence), SEM, optical cathodoluminescence, etc.

By improving current tests, or introducing new tests, the current critical acceptance limits need to be available for revision. However, it is important to always bear in mind that the reality always has to be found in real concrete structures, and critical acceptance limits should always attempt to echo these conditions.

Studies of concrete structures have shown that the influence of relative humidity (RH), and particularly sources of water locally, is of great significance for the development of deleterious AAR. Limiting the access of water in future concrete structures, by tailoring and shaping the structures in a proper way, may in many cases reduce the effect of deleterious AAR in the future.

An essential subject for further research will be the development of procedures and methodologies used to systematically make diagnosis and prognosis of damage to concrete in structures due to AAR. A draft guidance regarding this topic has been prepared by a task group under the direction of RILEM TC 191-ARP, Technical Committee [48], [49]. The guidance is designed to include aspects such as, field inspection of the structure, sampling, petrographic examination of core samples, and supplementary tests and analyses on cores such as, the compressive and tensile strengths,

stiffness, chemical analysis, expansion tests (which may be required for structural analysis), and prognosis about potential future risks, where necessary.

Norwegian researchers recognise the necessity to continue the cooperation with the owners of concrete structures in Norway, in order to evaluate and examine the state of the concrete in the structures. This will increase the knowledge for the research community.

5 REFERENCES

- [1] Musæus, HB (1962): Alkali-kiselsyre-reaksjoner i betong. Unpublished masters thesis, Geological Institute, Technical University of Trondheim (in Norwegian).
- [2] Idorn, GM (1967): Durability of concrete structures in Denmark: a study of field behavior and microscopic features. PhD-thesis, technical University of Denmark, Copenhagen, 208 pp.
- [3] Kjennerud, A (1978): Alkaligrusreaksjoner påvist i Norge. Skadene vanligere enn antatt? Plan & Bygg (1). (in Norwegian) 3 pp.
- [4] Haugen, M (1986): Mulige alkalikiselreaksjoner i betong, med enkelte norske tilslagsmaterialer. Unpublished MSc thesis Engineering Geology, technical University of Trondheim, NTH, (in Norwegian) 84 pp.
- [5] Svendsen, VN & Torblaa, EJ (1989): Alkalireaksjoner i norske betongdammer. Norges Vassdrags- og Energiverk (V20), (in Norwegian) 32 pp.
- [6] Hagby, C (1990): Alkali aggregate reactions in concrete with aggregate from the bedrock area of southeast Norway. Master thesis, 1990, The Norwegian Institute of Technology University of Trondheim (in Norwegian), 83 pp.
- [7] Haaland, K. (1990): Alkali aggregate reactions in concrete with aggregate from the Oslo area and local bedrock areas. Master thesis, 1990, The Norwegian Institute of Technology, University of Trondheim (in Norwegian), 96 pp.
- [8] Wigum, BJ (1990): Alkali aggregate reactions in concrete with aggregate from the Trondheim area and Gauldalen. Master thesis, 1990, The Norwegian Institute of Technology University of Trondheim (in Norwegian), 88 pp.
- [9] Jensen, V (1993): Alkali Aggregate Reactions in Southern Norway, Doctor Technical Thesis, The Norwegian Institute of Technology, University of Trondheim, 1993, 262 pp + Appendices.
- [10] Lindgård, J Dahl, PA & Jensen V (1993): Rock composition – reactive aggregates: Test methods and requirements to laboratories, SINTEF report no. STF70 A93030, Trondheim, 1993, (in Norwegian). 9 pp.
- [11] NORMIN-2000, (1999): Alkali Aggregate Reaction in Concrete - Main project report (in Norwegian). Edited by B.J. Wigum, 1999_a, Oslo, 166 pp.
- [12] Jensen, V & Fournier, B (2000): Influence of different procedures on accelerated mortar bar and concrete prism test: Assessment of seven alkali-reactive aggregates. Proc. of the 11th Int. Conf. on AAR in Concrete, Quebec City (Canada), June 2000, Bérubé, Fournier & Durand Editors, pp. 345-354.
- [13] Jensen, V & Haugen M (1996_a): Alkali aggregate reactions in Northern Norway. Report No. 1: Field- and laboratory testing. SINTEF report STF22 A96805, 1996_a, (in Norwegian) 35 pp.
- [14] Jensen, V & Haugen, M (1996_b): Alkali aggregate reactions in Northern Norway. Report No. 2: Natural gravel quarries and petrographic analyses. SINTEF report STF22 A96806, 1996_b, (in Norwegian) 37 pp.
- [15] Jensen, V & Haugen, M (1996_c): Alkali aggregate reactions in Northern Norway. Report No.3: In-situ measurement of humidity and dilatation. SINTEF report STF22 A96807, 1996_c (in Norwegian), 46 pp.
- [16] Wigum, BJ (1995_a) Alkali-Aggregate Reactions in Concrete; Properties, Classification and Testing of Norwegian Cataclastic Rocks. PhD. thesis 1995:98, 1995_a, Inst. for Geologi og Bergteknikk, NTNU, Trondheim 1995, 227 pp.
- [17] Wigum, BJ & Jensen, V (1995): Petrographic examination of Norwegian glacial aggregates: interpretations of mechanisms leading to high content of cataclastic rocks. Geological Survey of Norway, NGU Bulletin 427, 1995, pp 33-48.
- [18] Wigum, BJ (1995_b) Examination of microstructural features of Norwegian cataclastic rocks and their use for predicting alkali-reactivity in concrete. Engineering Geology (40) 1995_b: pp 195-214.
- [19] Wigum, BJ & French, WJ (1996): Sequential examination of slowly expanding alkali-reactive aggregates in accelerated mortar bar testing, Magazine of Concrete Research, 48, No 177, 1996, pp. 281-292.

- [20] Wigum, BJ, French, WJ, Howarth, RJ & Hills, C (1997): Accelerated Tests for Assessing the Potential Exhibited By Concrete Aggregates for Alkali-Aggregate Reaction. Cement and Concrete Composites, Vol. 19, 1997, pp 451-476.
- [21] Norwegian Concrete Association, (1996): Durable concrete containing alkali reactive aggregates, NB21, 1996, 5 + 27 pp including appendices. (in Norwegian).
- [22] NORMIN-2000, (1996): Alkali Aggregate Reaction in Concrete - preliminary project report (in Norwegian). Edited by B.J. Wigum, 1996, Oslo, 86 pp.
- [23] Wigum, BJ (2000): "NORMIN 2000" – A Norwegian AAR Research Program. Proc. of the 11th Int. Conf. on AAR in Concrete, Quebec City (Canada), June 2000, Bérubé, Fournier & Durand Editors, pp. 523-531.
- [24] NORMIN-2000, (1999_b): Alkali Aggregate Reaction in Concrete – Petrographic Atlas (in Norwegian). Edited by B.J. Wigum 1999_b, Oslo, 14 pp. [English version available at www.farin.no].
- [25] Broekmans, MATM & Wigum, BJ (1999): Alkali-aggregate reaction research in Norway: current status and future quo. Proc. of the 7th Euroseminar on Microscopy Applied on Building Materials, 1999, Pietersen, HS, Larbi, JA and Jansen, HHA (editors), pp. 241-244.
- [26] Lindgård, J & Wigum, BJ (2003): Alkali Aggregate Reaction in Concrete – Field experiences. SINTEF report STF22 A02616, 2003, (in Norwegian). pp 127 + appendices.
- [27] Lindgård, J, Haugen, M, Skjølvold, O, Hagelia, P & Wigum, BJ (2004): Experience from evaluation of degree of damage in fluorescent impregnated plane polished sections of half-cores based on the "Crack Index Method", Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 939 – 947.
- [28] Lindgård, J, Wigum, BJ, Haugen, M, & Skjølvold, O (2004): Field experience from investigation of more than 100 Norwegian bridges with respect to Alkali Aggregate Reactions (AAR), Nordic Concrete Research, Publication No. 32, 2004, pp. 114-128.
- [29] Lindgård, J, Rodum, E, Pedersen, B (2006): Field experience from Alkali-Silica Reactions in Concrete – Relationship between Water Content and Observed Damage on Structures. Paper submitted to the Seventh CANMET/ACI International Conference on Durability of Concrete, Montreal (Canada), 2006.
- [30] Wigum, BJ, Haugen, M, Skjølvold, O & Lindgård, J (2004): Norwegian Petrographic Method – Development and Experiences During a Decade of Service, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 444 – 452.
- [31] Haugen, M, Skjølvold, O, Lindgård, J & Wigum, BJ (2004): Cost effective method for determination of aggregate composition in concrete structures, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 907 – 911.
- [32] Hagelia, P (2004): Origin of map cracking in view of the distribution of air-voids, strength and ASR-gel, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 870 – 881.
- [33] Broekmans, MATM (2002): The alkali-silica reaction: mineralogical and geochemical aspects of some Dutch concretes and Norwegian mylonites. PhD-thesis University of Utrecht, *Geologica Ultraiectina* (217), 2002, pp. 144. (Free downloadable from: <http://igitur-archive.library.uu.nl/dissertations/2002-0528-111558/inhoud.htm>).
- [34] Broekmans, MATM (2004_a): The quality of quartz and its susceptibility for ASR. *Materials Characterization* (53/2-4), Special Issue (29), 2004_a, 129-140.
- [35] Broekmans, MATM (2004_b): Qualities of quartz and the alkali-silica reaction in concrete. In: Pecchio, M, Andrade, FRD, D'Agostino, LZ, Kahn, H, Sant'Agostino, LM, and Tassinari, MMML (editors): *Proceedings 8th International Congress on Applied Mineralogy*, Aguas de Lindoia, Brazil, September 19-22, 2004_b, pp. 661-664.
- [36] Pedersen, B. (2004_a): Alkali-reactive and inert fillers in concrete. Rheology of fresh mixtures and expansive reactions. Doctoral Theses at the Norwegian University of Science and Technology. 2004_a, 198 pp.
- [37] Pedersen, B & Mørtzell, E (2004_b): Effect of alkali-reactive crushed fillers on expansion due to ASR, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004_b, Tang & Deng Editors, pp. 764 – 772.
- [38] Norwegian Concrete Association, (2004_a): Durable concrete containing alkali reactive aggregates. NB21, 2004_a, 22+12 pages including appendices, (in Norwegian).
- [39] Norwegian Concrete Association, (2004_b): Alkali aggregate reactions in concrete. Test methods and requirements to laboratories, NB32, 2004_b, (in Norwegian).

- [40] Dahl, PA, Lindgård, J, Danielsen, SW, Hagby, C, Kompen, R, Pedersen, B. & Rønning, TF (2004): Specifications and guidelines for production of AAR resistant concrete in Norway, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 499-504.
- [41] Norwegian Committee for Standardization, (2001): NS-EN 206-1:2001, Concrete Part 1: Specification, performance, production and conformity, (Amendment (in Norwegian) prA1:2003 incorporated), 2003, 90 pp.
- [42] Jensen, V (2005): Assessment of methods and critical limit values in the revised Norwegian guideline NB21 “Durable concrete with alkali reactive aggregate”. 10th Euroseminar on Microscopy Applied to Building Materials, June 2005, Paisley, Scotland.
- [43] Jensen, V & Lorenzi, G (1999): RILEM petrographic method for analysis of alkali reactive concrete aggregates. In: Pietersen, HS, Larbi, JA, and Janssen, HHA (editors): Proceedings of the 7th Euroseminar on Microscopy Applied to Building Materials, 1999, pp. 143-153.
- [44] RILEM TC 191-ARP, (2003): RILEM Recommended Test method AAR-1: Detection of potential alkali-reactivity of aggregates – Petrographic method, Materials and Structures, Vol. 36, 2003, pp. 480-496.
- [45] RILEM, (2000): Recommended Test Method AAR-2 (formerly TC-106-2), 2000: Detection of Potential Alkali-Reactivity of Aggregates: A - The Ultra-accelerated Mortar-bar Test. Materials & Structures, Vol 33, No 229, 2000, 283-289. (revised edition of AAR-2, including AAR-2.1 & AAR-2.2, in preparation for publication in Materials & Structures).
- [46] Jensen, J (2006): Report 3.2 Experience from testing of the alkali reactivity of European aggregates according to the RILEM AAR-2 method. SINTEF report No. SBF52 A06020, 43 pp incl. 4 appendices.
- [47] Fournier, B, Chevrier, R, Grosbois M, Lisella, R, Folliard, K, Ideker, J, Shehatad, M, Thomas, M & Baxter, S (2004): The accelerated concrete prism test (60°C): Variability of the test method and proposed expansion limits, Proc. of the 12th Int. Conf. on AAR in Concrete, Beijing (China), October 2004, Tang & Deng Editors, pp. 314 – 323.
- [48] RILEM Technical Committee, TC 191-ARP, (2004): Alkali-Reactivity & Prevention. Assessment, Specification and Diagnosis. Guide to Diagnosis and Appraisal of AAR Damaged to Concrete in Structures, Part I: Diagnosis, 2nd Draft AAR-6, May 2004. Version 3, pp 60.
- [49] RILEM Technical Committee, TC 191-ARP, (2003): Alkali-Reactivity & Prevention. Assessment, Specification and Diagnosis. Guide to Diagnosis and Appraisal of AAR Damaged to Concrete in Structures, Part II: Appraisal – Assessment of Future potential Risks of Failure, 2nd Draft AAR-6, December 2003, Version 2, pp 25.

TABLE 1: Classification chart for alkali-reactivity of Norwegian rock types [30].

Class 1. ALKALI REACTIVE ROCK TYPES <i>(Documented in structures)</i>	Class 2. AMBIGUOUS ROCK TYPES	Class 3. INNOCUOUS ROCK TYPES
1. SEDIMENTARY ROCKS Sandstone Arkose Quartz sandstone Claystone (including shale) Siltstone (including shale) Marlstone (including schistose and/or metamorphic) Greywacke (also metamorphic) <i>Sedimentary features should be observed.</i>	5. AMBIGUOUS Examples: Quartzite/quartz schist Rock types with quartz (Modal quartz >20vol%) Limestone (contaminated with dispersed fine grained quartz) Hornfels (quartz-bearing) Mylonites low in free quartz (1-5vol%)	6. MAFIC ROCK TYPES Basalt Greenstone Gabbro Amphibolite <i>All types of variations of the rocks, also metamorphic</i>
2. MYLONITE/ CATACLASITE (Containing free quartz) Mylonites Cataclasites Mylonite gneiss	All quartz-containing rock types could be potentially reactive. This however depends on petrological parameters such as grain size of quartz, degree of deformation and other microstructural features. Various types of quartzites have reacted in concrete. Microcrystalline quartzite (quartz grains <60 µm) should be classified as alkali reactive. Quartzite with quartz grains <130 µm, should be classified as ambiguous. Quartzite with quartz grains >130 µm, should be classified as innocuous, even if the quartzite contains "strained" quartz.	7. ROCK TYPES CONTAINING QUARTZ Granite/Gneiss Quartzite/quartz schist Mica schist
3. ACIDIC VOLCANIC ROCKS Rhyolite Quartz keratophyre		8. FELDSPATHIC ROCK TYPES
4. OTHER ROCK TYPES Microcrystalline quartzite Phyllite Quartz schist		9. OTHER/ UNIDENTIFIED Limestone (pure) and marble Other non-reactive (also single crystals) Porphyry Quartz-free mylonites
Typical grain size of quartz; < 60 µm Exception: Sandstone	Typical grain size of quartz; < 130 µm	Typical grain size of quartz; > 130 µm, or quartz not present

TABLE 2: Overview of accept/reject criteria for the current Norwegian test methods for alkali-reactivity, for single and blended size fractions [38].

Documentation of	Critical limits for the three Norwegian laboratory test methods ¹⁾		
	Petrographic analysis, S_r , vol% (adjusted results) ²⁾	Accelerated Mortar bar method (%) ³⁾	Concrete prism method (%) ⁴⁾
Fine aggregate and blend of fine	20.0	0.14	0.040 ⁵⁾
Coarse aggregate and blend of coarse		0.08	0.040
Fine coarse aggregate		0.11	n/a
Blend of a fine- and coarse aggregate, where the fine or coarse is alkali-reactive	20.0 ⁶⁾	0.11	0.050

- 1) A single aggregate or a blend of aggregates shall be classified as innocuous if the values obtained are lower than the specified critical limits.
- 2) S_r shall be compared with the critical limit.
- 3) The measured expansion after 14 days of exposure shall be compared with the critical limits.
- 4) The measured expansion after 1 year of exposure shall be compared with the critical limits.
- 5) A fine aggregate or a blend of fine shall be tested with a coarse non-reactive reference aggregate. A coarse aggregate or blend of coarse shall be tested with a fine non-reactive reference aggregate. The binder used shall have an alkali content of 5.0 kg/m³ Na₂O eq.
- 6) A maximum of 15% of the calculated value is allowed to come from the coarse aggregate.

TABLE 3: Maximum permitted expansion values for the Norwegian concrete prism test [38].

Documentation of	Concrete containing pozzolanes or slagg?	Time of exposure	Maximum permitted expansion value after one year of exposure
CEM I binders, CEM II/A-V and CEM II/A-D, in addition to potential added silica fume and concrete recipes with these binders	No	1 year	< 0.050%
	Yes	1 year	< 0.030%
All other types of binders and concrete recipes with these other types of binders	Yes and No	1 year	<0.030%
	Yes and No	2 years	<0.060%

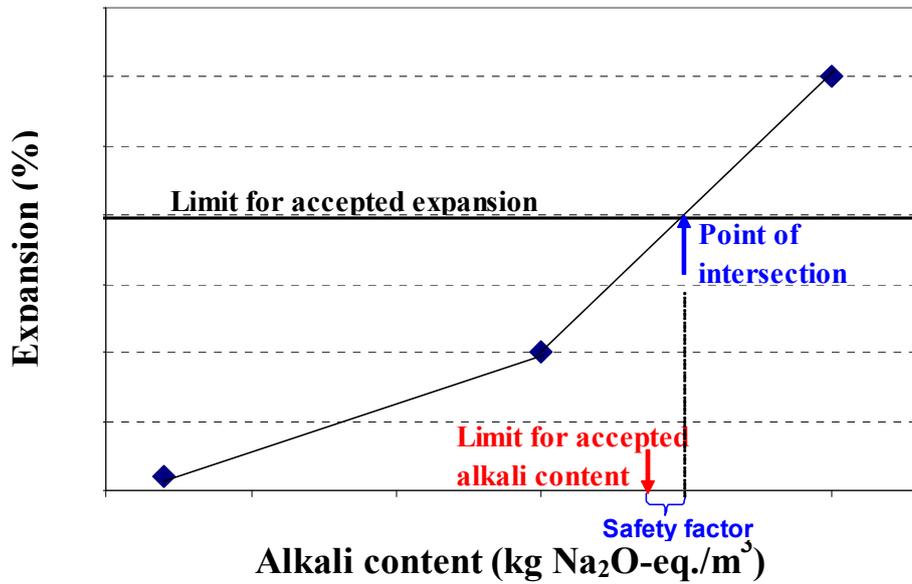


Figure 1: Principle diagram for determination of acceptance limit for alkali content [38].