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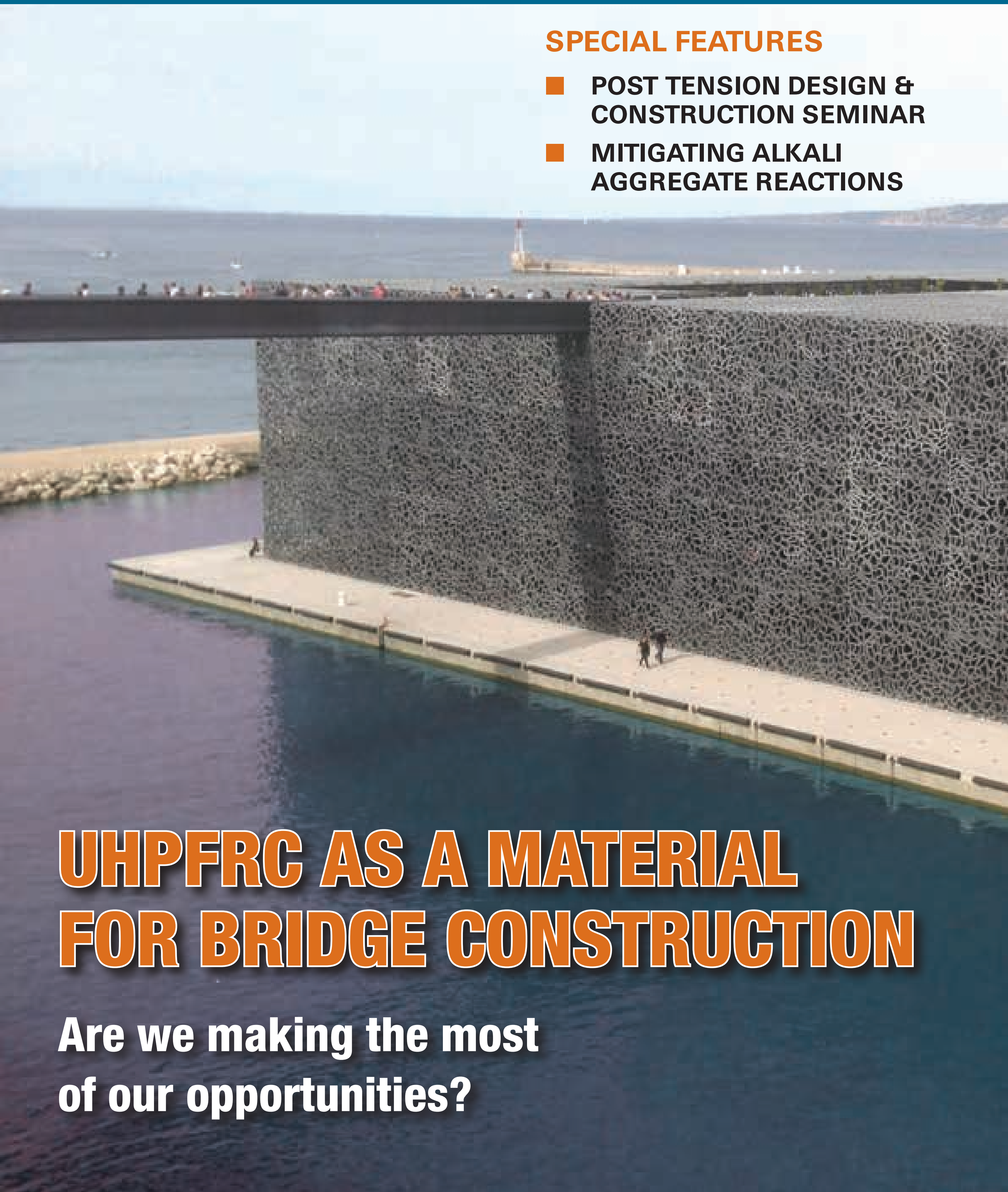

SPECIAL FEATURES

- POST TENSION DESIGN & CONSTRUCTION SEMINAR
- MITIGATING ALKALI AGGREGATE REACTIONS

UHPFRC AS A MATERIAL FOR BRIDGE CONSTRUCTION

Are we making the most of our opportunities?

The Norwegian regulations to mitigate alkali aggregate reactions in concrete

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This paper outlines the historical developments in research on Alkali Aggregate Reactions (AAR) in Norway during the past 25 years. Norwegian regulations have proven to be valuable tools for mitigating AAR. A three step test procedure includes; the petrographical analysis, the accelerated mortar bar test and the overruling concrete prism test, the latter also used for the evaluation of binders and concrete compositions. Recent research focus has been on the utilisation of the concrete prism test as a performance test. Test results have shown that the AAR expansion is significantly influenced by the specimen "pre-treatment", the "test conditions" and the "prism crosssection", primarily due to the influence on the rate of alkali leaching during exposure. Further research on these topics, on alkali release from aggregates and on effect of artificial alkali addition (boosting) will be carried out, both by the newly established RILEM TC "AAA" and in a Norwegian R&D project.

1.0 INTRODUCTION

A wide variety of aggregate types in common use across the world, particularly those with a siliceous composition, 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 Reactions (AAR).

2.0 RESEARCH BACKGROUND FOR THE CURRENT NORWEGIAN AAR GUIDELINES

The presence of AAR in Norwegian concrete structures was demonstrated in research activities from 1990 to 1996, in cooperation with the PhD-study of Jensen (1993). It was 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 was caused by e.g. metamorphosed rhyolites, sandstones, siltstones, argillites (some carbonaceous), greywackes, and phyllites. More uncertain cases of AAR were reported with other aggregates, e.g. hornfels. Cataclastic rocks e.g. cataclasite and mylonite were observed deleterious alkali reactive in about 50% of all the investigated structures.

Furthermore, some research activities emphasised on laboratory test methods for AAR. As a result of these activities, it was introduced in 1992 as an optional arrangement for acceptance and approval of aggregates for concrete by a three step test procedure including petrographic analysis, accelerated mortar bar method and concrete prism method, where critical limits were presented for each test method. The methods were described in Lindgård et al. (1993).

The PhD-study of Wigum (1995a) focused on further improving the method of petrographical 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 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 (Wigum, 1995b). The accelerated mortar bar test was further examined by Wigum et al (1997) where discussions were made about the accuracy of the test, including effects of different mortar bar sizes. Recommendations were made that the volume of molar sodium hydroxide solution to the surface area of the mortar bar should be fixed at a ratio of 4:1 and separate container should be used for each set of bars. These recommendations have later been adapted to the Norwegian accelerated mortar bar test procedures.

In 1996, the Norwegian Concrete Association published a recommendation (NB21) 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 silica fume. NB21 also described how to deal with

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Table 1: Classification chart for alkali-reactivity of Norwegian rock types (Norwegian Concrete Association, 2004b).

Class 1. ALKALI REACTIVE ROCK TYPES *(Documented in structures)*	**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)* ***Sedimentary features should be observed.***	**5. AMBIGUOUS** *Examples*: **Quartzite/quartz schist** **Rock types with quartz** *(Modal quartz >20vol%)* **Limestone** *(contaminated with dispersed fine grained quartz)* **Hornfels** *(quart-bearing)* **Mylonites** low in free quartz (1-5vol%)	**6. MAFIC ROCK TYPES** **Basalt** **Greenstone** **Gabbro** **Amphibolite** ***All types of variations of the rocks, also metamorphic***
2. MYLONITE/ CATACLASITE **(Containing free quartz)** **Mylonites** **Cataclasites** **Mylonite gneiss** **3. ACIDIC VOLCANIC ROCKS** **Rhyolite** **Quartz keratophyre** **4. OTHER ROCK TYPES** **Microcrystalline quartzite** **Phyllite** **Quartz schist**	*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** **8. FELDSPATHIC ROCK TYPES** **9. OTHER/ UNIDENTIFIED** **Limestone** *(pure)* and **marble** Other non-reactive *(also single crystals)* Porphyry Quartz-free mylonites
Typical grain size of quartz; < 60 µm **<u>Exception</u>: Sandstone**	**Typical grain size of quartz; < 130 µm**	**Typical grain size of quartz; > 130 µm, or quartz not present**

blends of aggregate. In this recommendation, a classification chart for alkali-reactivity of Norwegian rock types was included. An updated version of this chart, with details of alkali reactive rock types, ambiguous and innocuous rock types, is presented in Table 1. In 1999 detailed petrographic atlas with micrographs of the various rock types was published (NORMIN-2000, 1999). An online version of the atlas is available at: www.farin.no. To pursue research into these matters, a nationwide forum known by the acronym FARIN (Forum on Alkali-Reactions In Norway) was established in 1999.

A three year project comprising quantitative measurements on drilled cores from about 50 concrete structures (mainly bridges) was completed in 2003 (Lindgård & Wigum, 2003; Lindgård et al, 2004a). The aims of the project, where about 160 concrete structures were surveyed in field, 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 (NB21) given by the Norwegian Concrete Association in 1996.

The project succeeded in developing a technical and economical feasible method for separating the sand 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" (Haugen et al, 2004). It was also possible to "link" most of the aggregates to geological areas and known deposits. Results were used to strengthen the petrographic method for "virgin materials".

It was concluded that the Norwegian petrographic method appeared to be appropriate as a screening engineering tool in order to classify alkali reactive aggregates (Wigum et al, 2004). The degree of variation in the method was set to ± 5vol%-point. However, recommendations were made for further development and strengthening of the method, including advanced image analysis systems.

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 three crack parameters in the plane polished sections (Lindgård et al, 2004b). This method is similar to the Damaging Rate Index (DRI)-method, but is more simplified and adjusted to the Norwegian experience with our late expansive aggregates. A good correlation was found between the "Crack Index" in the plane polished sections, the degree of water saturation and the presence of AAR.

These findings were also verified by statistical analyses. 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 sand fractions. Thus, more strict requirements were suggested to a coarse aggregate compared to sand aggregate. The overall experience gained in the research project was that the results obtained with the three Norwegian laboratory test methods correlate satisfactorily with field experience, under supposition that some of the critical limits were revised. 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 (1996). These guidelines were updated in 2004 (see later).

3.0 CURRENT AAR GUIDELINES

Until 2001, the NB21 publication – published by the Norwegian Concrete Association – enjoyed the status of an industry standard but was by then formally referred to by the concrete construction standard.

Based on the referred national research and some international research work, a revision of the NB21 publication started late in 2002 and was finalised in 2004 (Norwegian Concrete Association, 2004a). In addition, the Norwegian test methods along with requirements to laboratories were published in a new publication, NB32 (Norwegian Concrete Association, 2004b). An English summary of the NB21 publication has been presented by Dahl et al. (2004).

Both these publications are now available in English translations. The updated NB21 publication has a formal status as a harmonised normative reference document to the new concrete materials standard, NS-EN 206:2013+NA:2014 (Norwegian Committee for Standardization, 2013), and is considered as a key element in the Norwegian system for preventing AAR.

3.1 Current test methods and critical limits

Evaluation of material parameters regarding effect of AAR in Norway is since 2004 based on three different test methods; 1: the Norwegian petrographic analysis, 2: the Norwegian accelerated mortar bar test and 3: the Norwegian concrete prism test (Norwegian Concrete Association, 2004a).

1. The Norwegian petrographic analysis – This method is a compulsory first step to evaluate the reactivity of aggregate types. The test is carried out by sieving a sand sample into two fractions (1/2 mm and 2/4 mm), respectively by crushing and sieving a coarse aggregate sample into one fraction (2/4 mm). The sieved samples are embedded in an epoxy resin, which allows the preparation of thin sections for petrographic examination. Two thin sections (25 x 35 mm) are made with particles in the fraction 2/4 mm and one in the fraction 1/2 mm. Approximately 1000 points are counted in each fraction. The volume percentage of alkali reactive rock types, ambiguous rock types and innocuous rock types (see Table 1) is obtained by calculating an average of the results from both fractions.

The critical reactive component in an aggregate is the summation of alkali reactive rock types and ambiguous rock types. According to the method description, the reactivity of the particles as a whole is evaluated. However, there are some exceptions from this procedure, e.g. if a mylonite zone occurs in a granite grain. Then the mylonite zone is counted as a mylonite, while the rest of the particle is counted as granite. The petrographic analysis should be performed by an experienced and approved petrographer (Norwegian Concrete Association, 2004b). This is important, because Norwegian rocks are very varied and hence often difficult to identify and classify correctly.

The Norwegian petrographic method is in agreement with the RILEM AAR-1 method (Jensen and Lorenzi, 1999; RILEM, 2003). The accuracy of the method has been examined by Wigum et al (2004). In order to make judgment regarding AAR of the aggregates tested by the petrographic analysis, some recalculations of the results are required according to NB21 (Norwegian Concrete Association, 2004a). A comparative value, *Sv*, is calculated. The calculation includes:
- Use of a "serial factor", i.e. a weighted average is obtained from all the six last individual petrographic analyses.
- In order to take into account the fact that coarse aggregates have proven to be more harmful than sand aggregates, a "grain size factor" is applied. For fine aggregates (0/4 mm and 0/8 mm) the factor is 1.0, while for coarse aggregate (8/16 mm and 16/22 mm) the factor is 2.0. For fine coarse aggregate (2/8mm and 4/8mm) the factor is 1.5.
- Finally a safety margin is added in order to take into account the number of analyses that form the basis for the weighted average value.

If the calculated *Sv* is less than the critical limit (see Table 2), no further documentation is required, i.e. the aggregate is considered to be non-reactive and may be used in any concrete mix.

2. The Norwegian accelerated mortar bar test – The test is carried out using mortar bars (40·40·160 mm) exposed in 1N NaOH at 80 °C for 14 days. The method is mostly in agreement with the RILEM AAR-2 method, but European standards (NS-EN) are followed for sieving, conditioning and moulding. The method can be used for testing single aggregates or blends of aggregates. However, as a standard aggregate grading is used, the method is not able to evaluate the reactivity of different aggregate fractions. The experience is that a sand and a coarse aggregate from the same deposit give similar expansion values. Since the coarse aggregates have proven to be more harmful than sand aggregates in field, a lower limit is thus applied for coarse aggregates (see Table 2).

3. The Norwegian concrete prism test – The test is carried out using concrete prisms with dimension 100·100·450 mm (400 kg OPC cement and 5.0 kg of alkalis/m^3). The prisms are stored in 100% RH at 38 °C in small containers, similar as described in the Canadian standard CSA A23.2-14A, and in the American standard ASTM C1293.

The critical expansion is measured after one year. The test may be used for testing of a sand, a coarse aggregate or a combination of both. 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 (0.040% after one year of exposure). However, for blends of aggregates a slightly higher critical limit is specified (0.050% after one year of exposure). The reason for this is that in real life an aggregate classified as "non-reactive" may give a certain contribution to the overall expansion.

3.2 Performance testing

The alkali-reactivity of various types of aggregates, binders and concrete recipes can be documented by performance testing using the Norwegian concrete prism method. Binders shall be tested in concrete with a specified "reference" highly reactive Norwegian aggregate (Norwegian Concrete Association, 2004b). 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 normally varying the alkali content by adding (some) extra alkali (boosting) and keeping the binder composition and w/c-ratio constant. The motivation is to take into account possible alkali content variation of the product(s). If based on 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

Table 2: Overview of critical limits for the three Norwegian test methods for documentation of alkali-reactivity of single aggregates or blends of aggregates (Norwegian Concrete Association, 2004a).

	Critical limits for the three Norwegian laboratory test methods[1]		
Documentation of	**Petrographic analysis, Sv (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] Sv 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/m^3 Na_2O eq.
[6] A maximum of 15% of the calculated value is allowed to come from the coarse aggregate.

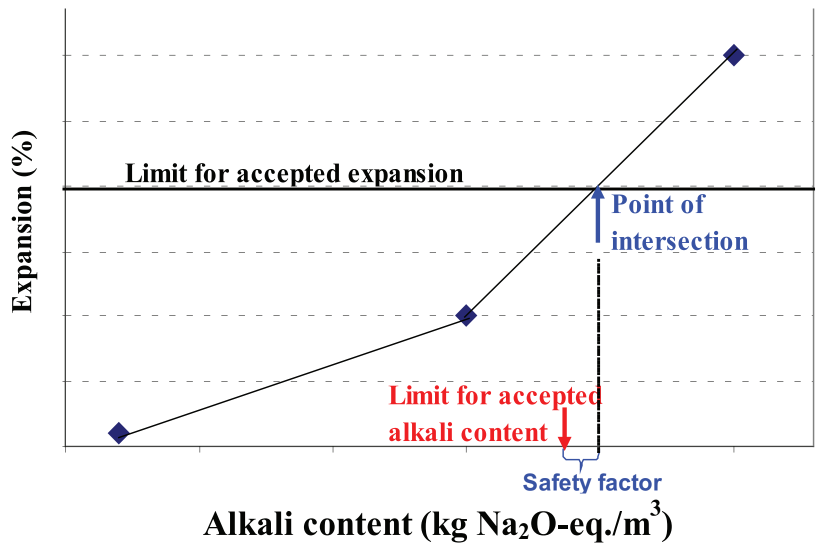

Figure 1: Principle diagram for determination of acceptable critical alkali limit based on critical limit for accepted expansion and results from performance testing of three concrete mixes with different levels of alkalis. (Norwegian Concrete Association, 2004a).

can be obtained. A safety factor of 0.2 kg Na_2O eq./m^3 is required to be subtracted to obtain the critical alkali limit. The observed alkali leaching during accelerated laboratory testing (Lindgård, 2013 – see later) was not an issue when the level of this safety factor was agreed.

4.0 THE PATH FORWARD

In Norway, the aggregate, cement, and concrete industries are aware of the potential problems related to AAR. With the revised AAR regulations (NB21, 2004) and the revised test methods (NB32, 2005), suitable tools have been established to perform the required tests for the industry on a regular basis, and according to European standards, where NB21 gives the Norwegian national requirements for handling the AAR-problem.

However, AAR is complicated, and in Norway, with all the many variations in the aggregate materials due to the complex geology, we still need research to fully understand the mechanisms. The petrographic method has proven to be a cost and time efficient screening tool for various types of aggregates. 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 by new advanced techniques could provide clarification in more detail about micro structural properties of reactive minerals and rock types. The PhD-study of Castro (2012) was an important step in this direction. This prospective new knowledge, along with automated image analysis, might be a path forward for strengthening and consolidating the petrographic method.

During the last years, the research focus has been on the

Table 3: Maximum permitted expansion values for the Norwegian concrete prism test (Norwegian Concrete Association, 2004a).

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%

utilisation of the Concrete Prism Test (CPT) as a performance test. The PhD-study of Lindgård (2013) was performed in cooperation with the international "performance testing" task group of RILEM TC 219-ACS. His results clearly show that parameters of importance for the development of AAR are significantly influenced by the specimen "pre-treatment", "AAR exposure conditions" and prism cross-section.

It was documented that in general a high fraction of the in-mixed alkalis are leached out of the concrete prisms during the AAR exposure. In fact, the rate of alkali leaching during the first weeks of exposure is the parameter found to have the highest impact on the development of the ultimate AAR expansion, in particular when exposed to 60 °C. Fortunately, due to the relative large prism cross-section of the Norwegian concrete prisms (100·100 mm), the Norwegian CPT showed less alkali leaching compared with all the other CPTs included in the study and consequently the highest expansions (Lindgård, 2013).

Norwegian scientists have recently taken the chair of the newly established RILEM Technical Committee (TC) "AAA" (2014-2019). The purpose of this TC is to develop and promote a performance based testing concept for the prevention of deleterious AAR in concrete. In connection to the development of performance tests, an assessment of the correlation between field structures versus laboratory results will be carried out.

The challenges of potential alkali release from certain types of aggregates will also be addressed. Strong emphasis will be put on the implementation of the RILEM methods and recommendations as national- and international standards. The activities in RILEM will be in cooperation with a recently established Norwegian R&D project (2014-2018) dealing with many of the same topics. The issues of implementation of aggregate alkali release on the alkali threshhold limits and limitation of alkali boosting are two vital research areas considered critical for future adoption of CPT for performance testing.

In addition, to improve the current test methods, the current critical acceptance limits need to be available for revision. It is the intention to initiate a new revision of NB21 in the near future. 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.

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