# ALKALI-AGGREGATE REACTION IN SOUTHERN NORWAY

**V.Jensen & S.W.Danielsen**
**SINTEF FCB the Cement and Concrete Research Institute, Trondheim Norway**

**AAR of the type Slow/Late-Expansive Alkali-Silicate/Silica reaction has recently been diagnosed in numerous Norwegian dams, hydropower plants and road bridges. AAR has been caused by a generally high alkali content in Norwegian cements during decades and rock aggregates (coarse fractions) of rhyolite, sandstone, graywacke, argillite, quartzite, phyllite and cataclastic rocks (mylonite and cataclasite). Field inspections of 483 structures older than 10 years have revealed map cracking and volume expansions as significant for AAR in Norwegian structures. Furthermore has map cracking been observed in about 70% of investigated structures with an increased cracking tendency in structures build around 1950-1960. Significant for AAR in concretes are: Reaction rims in broken faces of reacted aggregates, dark peripheral zonation in aggregates (clarified rim), white reaction products precipitated in larger air voids and cracked aggregates and cement paste. Reaction products (gel and cryptocrystalline) occur in cracks in aggregate and cement paste and in air voids. To minimize the risk for AAR in future structures the Norwegian Concrete Society recently has proposed a test procedure for aggregates used in concrete.**

## INTRODUCTION

**In Norway the awareness of Alkali-Aggregate Reaction (AAR) is rather new. However during the last 4-5 years an increased number of investigations have indicated AAR as a possible cause of concrete deterioration in several dams, hydropower plants and road bridges located in Southern Norway. Previous, during the period from 1976 to 1987, several investigations (some looking for AAR) were carried out in the Rjukan area. That because, reduction in the wheel base between shaft bearings and shafts in concrete turbine foundations in two hydropower plants owned by Norsk Hydro A/S, had caused several problems and speculation about the causality for this reduction. Experts and technical supervisors tried to solve and explain this "reduction" problem without success for several years. First by the diagnosis AAR and the knowledge that AAR might have caused expansions in the concrete foundations a reliable explanation of this reduction in the wheel base was given. During 1987-1990 cores from several concrete dams with distinct map cracking and the turbine foundations in Rjukan were examined by microscope techniques and scanning electron microscopy. In all the investigated concretes, AAR was diagnosed and claimed deleterious - Jensen (1), Svendsen and Torblaa (2).**
**A major Norwegian research project on AAR was started in late 1989 at SINTEF FCB the Cement and Concrete Research Institute, Trondheim and is planned concluded 1993. The scope is to establish a scientific basis for handling AAR for Norwegian aggregates, concrete use and exposure. A basic part of the project aims at determining the relation between AAR in concrete and the geological origin of Norwegian aggregates. The paper gives an overview of some results obtained by this research project.**

## NORWEGIAN CEMENTS

**Production of portland cement in Norway started up in 1892 at Slemmestad (Christiania Portland Cementfabrik A/S) near Oslo. In 1989 the production of cement at the Slemmestad cement factory was terminated. Today is Norwegian cement produced from two cement factories: Kjøpsvik in Nordland county in North Norway since 1919 and Dalen in Southern Norway since 1921. In 1968 these three cement factories merged to the Norcem A/S company.**

**According to Rønneberg (3) are several different cement types produced in Norway:**

- **P30:** Standard Portland cement, ASTM type I
- **MP30:** Modified Portland cement, ASTM type II, with about 20% fly ash has been produced since 1985 in Dalen cement factory.
- **RP38:** Quickly hardening Portland cement, ASTM type III
- **P30-4A:** Platform Portland cement is specially developed for the construction of offshore concrete platforms for the North Sea (high strength).
- **SR** Sulphate resistant Portland cement, ASTM type V

**Other special types of cements are produced in Norway too, and used for special construction purposes e.g. oil well cements. Before the production of fly ash modified Portland cement in 1985, all Norwegian standard cements were of the type P30 cement. These cements have probably "always" been high alkali cements of same type as the P30 cement produced today (personal communication - Lundeval, Norcem A/S). Unfortunately analysis results of the alkali content in cements produced before 1959 are not available (have most likely not been systematically carried out) except some few random analytic results.**

**Figure 1 shows the annual average alkali content in P30 cements produced at Dalen cement factory in the period 1959-1990 - Søpler (4). Figure 1 depicts the average alkali content (% in weight) of $K_2O$, $Na_2O$ and eq. $Na_2O$. The analysis results from 1983 and 1984 are reported as MP30 cement. Note the high alkali content in P30 cements produced in Dalen cement factory.**

**Table 1 gives average alkali content from the three Norwegian cement factories.**

**TABLE 1 - Average alkali content in standard cement produced in Dalen, Kjøpsvik and Slemmestad cement factories - Søpler (4), Lundeval (5) and Musæus (6).**

| CEMENT FACTORY | % $Na_2O$ | % $K_2O$ | eq.% $Na_2O$ | $K_2O/Na_2O$ |
|---|---|---|---|---|
| Dalen 1959-1990 | 0.45 | 1.16 | 1.21 | 2.58 |
| Kjøpsvik 1971-1990 | 0.66 | 0.66 | 1.09 | 1.06 |
| Slemmestad 1961* | 0.38 | 1.23 | 1.19 | 3.24 |

*** Two analyses**

**Note that all the standard cements produced contain a high alkali content with variate potassium oxide/sodium oxide ratio, which seems to be characteristic for each factory.**

Ground Granulated Blast-Furnace Slag has been used only in few structures in Norway. In two older structures laboratory examinations of cores have not shown any sign of AAR even potentially alkali reactive aggregates has been used in the concrete. This is probably due to the low alkali content in the used slag.

## ALKALI REACTIVE AGGREGATES

In Norway many rock types have now proved to be alkali reactive in concrete structures and in laboratory tests. Those are igneous rocks, sedimentary rocks and metamorphic rocks of different types. Cataclastic rocks developed by dynamic metamorphism of quartzo-felspatic rocks have caused deleterious AAR in about 50% of the structures investigated by the authors. The alkali reactivity of cataclastic rocks has been given little attention by concrete petrographers, but is lately reported to have caused deleterious AAR in Sweden by Lagerblad and Niemann (6). The Norwegian alkali reactive aggregates all belong to the group of aggregates which causes Slow/Late-Expanding Alkali-Silicate/Silica Reaction.

Figure 2 shows an outline of potentially alkali reactive rocks in Southern Norway.

> Rhyolite of Proterozoic age are mostly situated around Rjukan. Smaller outcrops of rhyolite occur in scattered areas in western parts of Norway.
>
> Sandstones (sparagmites), quartzite and argillites of Late Precambrian age occur in a large continuous area north of Oslo, and as smaller scattered outcrops further north in the Trondheim area.
>
> Phyllites of Cambrian to Late Ordovician age occur as elongated areas along the Caledonian range of mountains (SW-NE).
>
> Graywackes and intermixed phyllites of Ordovician to Lower Silurian age occur mostly in the Trondheim area.
>
> Marl or carbonaceous argillites (clay-siltstones) of Ordovician and locally Lower Silurian age occur around the Oslo area.

The map shown in figure 2 is rather simplified and the drawn areas with potentially alkali reactive rocks occasionally include supposed innocuous rocks e.g. in the graywacke areas occasional greenstones occur in some places (Greenstone has been proved to be innocuous by laboratory test). Reaction caused by fine grained gneiss, granite and hornfels have also been reported in few structures.

A very important rock type namely cataclastic rocks have reacted in numerous Norwegian structures and have there caused damage to the concrete. Cataclastic rocks (mylonites and cataclasites) occur mostly in major faults and Caledonian thrust zones. Two larger areas with mapped cataclastic rocks (mylonites) occur in the Southeastern part of Norway. These are the Precambrian (1600-1500 mill years old) Mjøsa-Vanern mylonite zone which can be followed into Sweden (to Lake Vanern) and further south the mylonite zone from Øyern to the Swedish border -Oftedahl (8). Cataclastic rocks, major faults and thrust zones are not shown in Figure 2.
According to Higgins (9) is cataclasis:

> A process by which rocks are broken and granulated due to stress and movement during faulting; granulation and comminution. A cataclastic rock is a general term for any rock produced by cataclasis, regardless of whether or not the rock is coherent.

Cataclasis is caused by dynamic metamorphism and therefore mostly occurs in thrusts and fault zones. The texture of cataclastic rocks is characteristically complex and inhomogeneous and depends on the inter-relation of temperature, pressure, strain rate, presence of solvent and on the mechanical properties of the minerals in the rock. The main effects of granulation and milling is a reduction in grain size. Relict crystals (porphyroblasts) become smaller, more rounded and lenticular as the deformation becomes more intense. The matrix surrounding the porphyroblast (if any) is generally microcrystalline - fine crystalline, but can also be submicroscopic and even glassy (hyalomylonites). The matrix can be more or less recrystallized. In case most of the matrix is recrystallized the rock is classified as blastomylonite. Massive cataclastic rocks are classified as cataclasite and foliated cataclastic rocks as mylonites. If less than 10% matrix, the rock is classified as tectonic breccia or conglomerate -Spry (10).

Mielenz (11) postulated in 1958 that some coarsely crystalline quartz is reactive and that its reactivity is due to defects in the crystal lattice:

> "Convincing evidence has recently been obtained to demonstrate that coarsely crystalline quartz which is intensely fractured, strained and granulated internally as the result of metamorphic processes during geological time.... can cause a deleterious degree of expansion of mortar or concrete containing a high-alkali cement".

This description fits very well to cataclastic rocks as previously described.

Based on thin section examination of Norwegian reactive rocks it is suggested, that microtextural features are very important, and microtextural investigations should be carried out together with traditional classification of rocks to distinguish potentially alkali reactive aggregates.
In most of the alkali reactive Norwegian aggregates the mineral quartz-feldspar-muscovite is most frequent.

## FIELD INSPECTIONS

Field investigations of Norwegian structures have mainly been based on concrete dams, hydropower plants and road bridges. A preliminary map based on results from two survey inspections carried out in 1988 and 1989 has previously been drawn and published (1). This map showed potentially reactive Norwegian rock types and the distribution of structures with AAR. To get an overview about the extent of AAR also outside potentially reactive areas, a field inspection of randomly scattered road bridges and dams older than 10 years was carried out in the whole Southern Norway during the summer 1990. Up to now 483 structures in Southern Norway have been investigated.

Information obtained by the field inspections as well as other available information have been processed into a database for all inspected structures. Data processing of results from this database have revealed that about 70% of investigated structures are more or less map cracked. A surprising peak height of increased crack width has been revealed to occur in structural elements built around 1950-1960. This peak height is most significant in structures situated in supposed innocuous bedrock areas. Two dam investigations (not investigated for AAR) carried out in the 1960s Heggstad and Myren (12) and in the 1990s Gautefall (13) have reported that structures built around 1960s were generally more cracked (note, not map cracked) compared to structures built at other times. The cause of this increased cracking in structures built around 1960s is unknown.

## STRUCTURES

Map cracking is the most frequent type of cracks in Norwegian structures affected by AAR, this is similar to what has been reported all over the world where AAR has been diagnosed. In later stages of AAR, wide and predominantly longitudinal cracks often occur in upper surfaces of structural elements e.g. abutments, retaining walls, piers and foundations. Very often surfaces facing south are more extensively cracked than shaded surfaces, probably due to sun heating. In dams and road bridges, the most extensive cracking occurs on the upper surfaces of piers, towers, walls, around spillways or regulation gates, and in concrete close to outlet tunnels.

Volume expansion due to AAR has been observed in several Norwegian structures. Closure of expansion joints, sometimes with an extrusion of jointing and sealing material, and relative displacement of adjacent concrete blocks are field observations that strongly indicate the occurrence of AAR, but AAR has always to be confirmed by laboratory methods.

In some structures volume expansion caused by AAR has given problems:

> During regular inspection of turbines in two hydropower plants in Rjukan, expansions in concrete foundations have moved shaft bearings several millimetres. Since late 1987 have expansion measurements been carried out in the turbine foundations from these two hydropower plants by Winsnes (14). These measurements show that the accumulated expansion in late 1991 is measured to 1.35 mm/6m or the concrete foundation has increased 0.023% in volume during four years.
> Another safety issue caused by expansion in concrete has been observed in one dam where the gates close to the spillways became stuck.

## DIAGNOSIS

To obtain the most reliable results, investigations for AAR in Norwegian structures have been carried out by useing different methods, including: visual inspection of structures, visual inspection of drilled cores, fluorescence impregnated polished half cores, fluorescence impregnated thin sections and scanning electron microscope (SEM/EDX analysis). Results from all these methods have been used to describe the appearance of AAR, diagnose "deleterious" AAR and identify reactive aggregates.

It is very important to use sufficiently large dimensions on cores and to obtain concrete material from the inside of the structure and not only from the concrete surface. This because AAR caused by slow/late reaction in Norway (and elsewhere) is mostly caused by aggregates in the stone fraction and AAR is often more frequent 20-100 mm from the concrete surface. For investigation of AAR SINTEF FCB use cores with the dimensions Ø 100mm and length 200-500mm - if possible.

Significant for AAR in Norwegian cores are reaction rims on broken faces of aggregates and white reaction products precipitated mostly in larger airvoids.

Dark zonations or "clarified rims" are also common in fluorescence impregnated polished half cores from concretes with AAR. Characteristic for AAR caused by Slow/Late-expansive aggregates is cracked aggregates. In all investigated fluorescence impregnated polished half cores such cracks have been quantified by counting.

Examination of thin sections of Norwegian concretes with AAR shows a rather uniform reaction pattern even though different aggregate types have caused the reaction. Generally, the sign of reaction caused by AAR could be described as cracks which are partially or totally filled with gel and cryptocrystalline reaction products (occur only in aggregates and "larger" air voids). Cracks occur in aggregates, running from aggregates into the cement paste, and in more advanced stages connect one or several reacted aggregates with the consequence that the concretes are heavily cracked. Very often cracks occurring in reacted aggregates have been widened up and enlarged near the interface to the cement paste suggesting partial dissolution of mineral crystals. Dissolution groves in microcrystalline quartz crystals have also been observed by SEM (1). This confirms that

**microcrystalline quartz has reacted.**

**Macroscopic ettringite-like crystals in cracks and air voids have been observed in thin sections with and without AAR. Generally concretes with AAR contain more ettringite-like crystals compared to concretes without AAR. The higher amount of ettringite in Norwegian concretes with AAR could be caused by a generally higher humidity in concretes affected by AAR rather than due to AAR or sulphate attack.**
**Whatever the development process of ettringite has been, expansion resulting from ettringite formation may have an effect on the expansion of concretes or contribute to the expansion in concretes with deleterious AAR.**

## PREVENTIVE MEASURES

**The Norwegian standard NS 3420, L5 from 1986 requires that alkali reactive aggregates in harmful amounts must not be used as concrete aggregate, but no methods for minimizing the risk of AAR are presented in the code of practice.**
**Very recently (November 1991) the Norwegian Concrete Society - the aggregate committee - has proposed an optional arrangement for declaration, control and approval of aggregates used for concrete purpose (15). The proposed test procedure is carried out in three steps, namely first a petrographic analysis, second an accelerated test by NBRI-M, and third a concrete test according to CAN3-A23.2-14A. In case more than 20% potentially alkali reactive aggregates have been observed by the petrographic method the second and/or third test is recommended to be carried out. The limit values of 20% potentially alkali reactive aggregates chosen to distinguish between supposed innocuous and potentially alkali reactive aggregates probably provides a satisfactory margin of safety because the "deleterious" content of alkali reactive aggregates is likely to be higher in Norwegian concretes deteriorated by AAR.**
**Laboratory tests of Norwegian aggregates are further being described by P.A.Dahl and I.Meland in another paper presented at the present conference.**

## REFERENCES

1. Jensen,V., 1990, Proceedings of The Seminar on Alkali-Aggregate - The European Dimension, The Geomaterials Unit Queen Mary and Westfield College University of London, pp 69-85

2. Svendsen, V.N. & Torblaa, E.J.,1989, "Alkalireaksjoner i norske betongdammer", Publication no. v 20, Norwegian Water and Energy Administration, Oslo, p 20 (in Norwegian)

3. Rønneberg,H., 1989, "Lectures", University of Trondheim, NTH (in Norwegian)

4. Søpler,B., 1991, Cement analyze Results Given in a Meeting at The Norwegian concrete Association 26 February 1997

5. Lundeval, G., 1991, Cement analyze result given to the authors

6. Musæus,H.B., 1962, Dissertation for MSc degree (geology), University of Oslo (in Norwegian)

7. Lagerblad,B. & Niemann,C., 1991, Betong Nr 1, Sweeden (in Swedish)

8. Oftedahl.Chr., 1980, Norges geologiske Undersøkelse, Nr 356, Bulletin 54, Universitets forlaget, Trondheim

9. Higgins,M.,W. 1971: "Cataclastic Rocks". Geological Survey Professional Paper 687, United States Government Printing Office, Washington

10. Spry,A., 1983: "Metamorphic Textures", Pergamon Press Ltd, Oxford

11. Mielenz, R. C., 1958, Highway Res. Board Bull. 275:39, 44

12. Heggstad,R. and Myran,R., 1967, Commission Internationale Des Grands Barrages, Istanbul

13. Gautefall,O., 1990: "Status for Dammer av Betong i Norge" SINTEF STF65 A90072, Trondheim (in Norwegian)

14. Winsnes,H, 1991: "Expansion measurement carried out in the period late 1987 to late 1991. Glidemikrometer - ISETH in a 6m borehole from a turbine foundation, Såheim Powerplant". Result received by the author, december 1991, Noteby A/S

15. Norsk Betongforening's Publikasjon Nr 19, 1991: "Deklarasjon- og godkjenningsordning for betongtilslag" (in Norwegian)


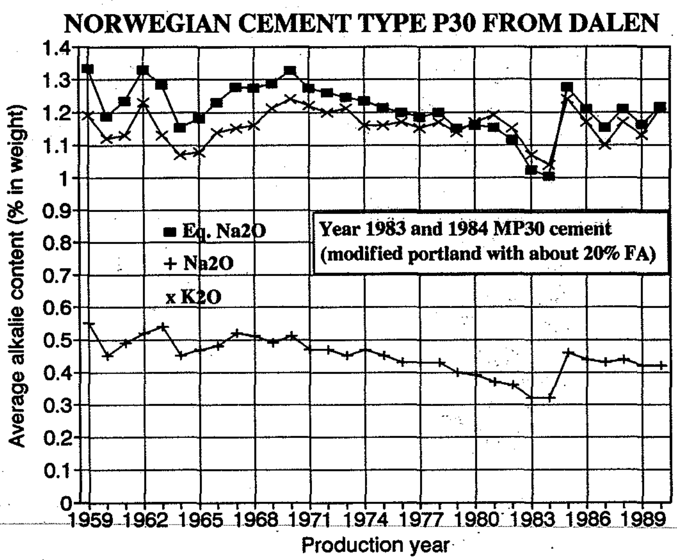


**Figure 1** Annual average alkali content in P30 cements produced at Dalen cement factory in the period 1959-1990 - Søpler (4)

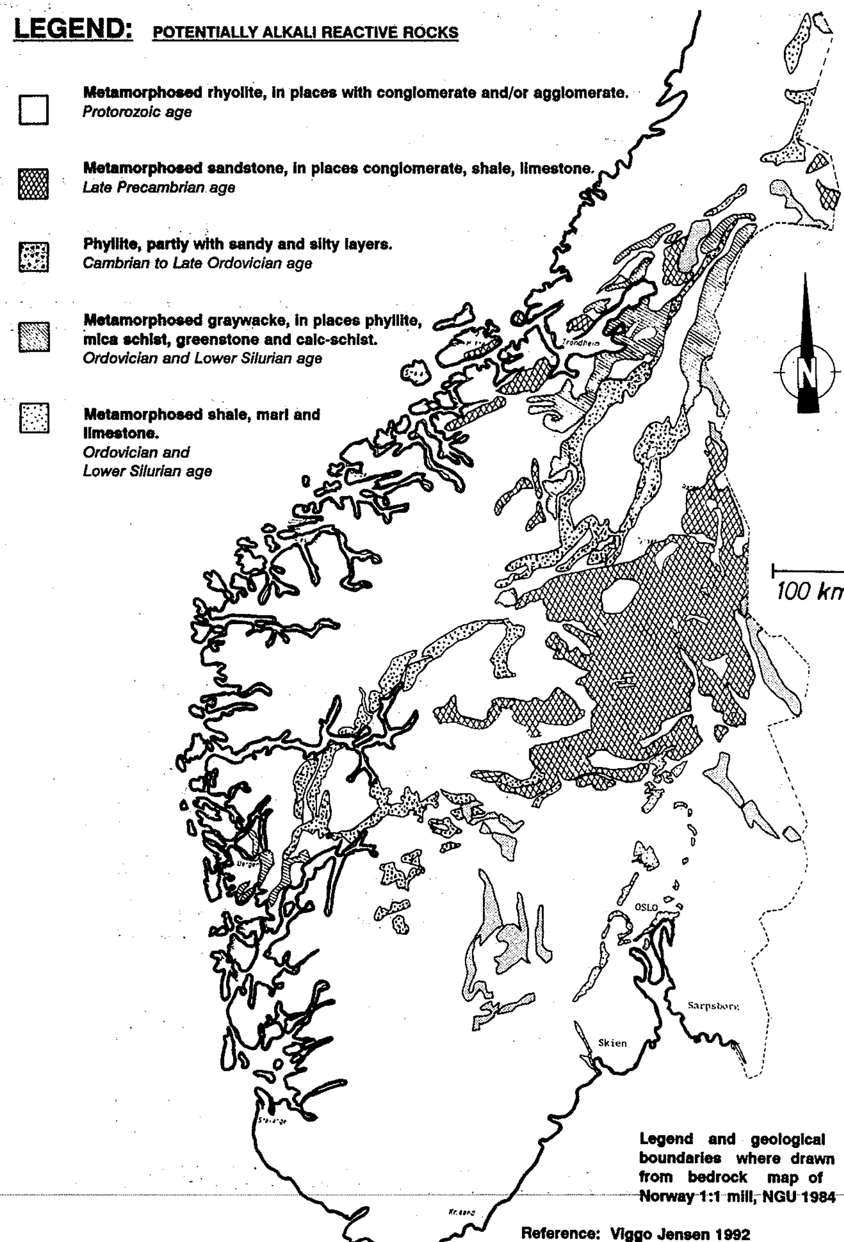


**Figure 2 Distribution of potentially alkali reactive rocks in Southern Norway.**