

DETERMINATION OF THE RESIDUAL REACTIVITY OF  
ALKALI SILICA REACTION IN CONCRETE

Niels Thaulow and Mette R. Geiker  
G.M. Idorn Consult A/S, Denmark and  
COWiconsult, Consulting Engineers and Planners AS, Denmark

The present paper discusses the various methods available for the determination of the residual reactivity of concrete structures affected by alkali silica reaction. A combined method has been developed and tested based on fluorescence thin section petrography, scanning electron microscopy with energy dispersive microanalyses and pore solution expression combined with chemical analyses. Practical experience gained from concrete structures is presented, and the applicability of the various methods is discussed.

INTRODUCTION

Appropriate management and maintenance strategies for concrete structures affected by alkali silica reaction (ASR) are needed. For the planning of maintenance and repair it is important to be able to determine to which degree ASR has matured. Whether repair or a "wait and see" strategy is adopted depends on how far the reaction is believed to have proceeded.

From the literature regarding laboratory and field testing of mechanical effects of ASR it can be observed that the development in expansion tends to follow a certain pattern (S-curve). Thus, it is common that once damage is initiated by ASR, the rate of development of expansion may initially be high but as time passes, the rate of expansion decreases until a point is reached where no further expansion will occur.

Unfortunately, it appears that it is not possible from an existing curve to determine what the residual expansion will be, unless approximately 80% of the reaction has depleted and a large part of the S-curve is known.

The present paper discusses the various methods available for the determination of the residual reactivity of ASR affected concrete structures. A combined method has been developed and tested based on fluorescence thin section petrography, scanning electron microscopy with energy dispersive microanalyses and pore solution expression combined with chemical analyses.

### DIRECT MEASUREMENT OF EXPANSION

The traditional approach for determining the residual reactivity of concrete in a structure is to measure the residual expansion either in situ on the structure, or in the laboratory on drilled concrete cores. These methods provide useful information but often require a long period of time, several months or even years.

#### In Situ Measurement of Expansion

To obtain guidelines for the managing of concrete structures affected by ASR, including planning of maintenance and repair, measurement of the expansion of the actual structure has been carried out. The methods applied are: a) Repeated levelling (Thaulow (1), Oberholster (2), Ichihara et al. (3), Tuthill (4), Berthelsen (5)); b) Repeated measurement of crack width (Hansen (6), Ishizuka et al. (7)) and c) Repeated measurement of expansion using an extensometer (Holm et al. (8), Calvalcanti and Silveira (9)).

Measurement of expansion should preferably be performed over a length of several meters to eliminate the influence of existing cracks. Measurement of crack width may give erroneous results as both expansion and drying will cause a crack to open further. To reduce the risk of measuring earth movements instead of expansion of the structure levelling could be based on a fixed reference point on the actual structure.

#### Determination of Residual Expansion from Concrete Cores

To estimate the potential for further expansion of concrete affected by ASR, cores may be drilled and their expansion monitored while they are stored under accelerating conditions. Typical storage conditions are: a) Above hot water (Oberholster (10), Hobbs (11)); b) In hot water ((1), (11), Stark (12), Strunge et al. (13)); c) In hot sodium hydroxide solution ((11), (12)) and d) In hot sodium chloride solution ((1), (13)).

When interpreting laboratory expansion data, as pointed out by Hobbs (14), observation of expansion does not necessarily mean that the actual concrete structure, from which the core was taken, will continue to expand.

Initial expansion of the cores may be caused by change both in chemical and physical equilibrium conditions (e.g. saturation, relaxation). Expansion caused by the uptake of water by ASR products present in the aggregate may also contribute to the initial expansion (10). Cores stored over or in hot water may lose alkalis by leaching. This will reduce the reaction and the measured expansion during testing. To reduce the risk of misinterpretation (13) it was suggested that the residual ASR be determined as the difference in expansion of cores stored in hot water and cores stored in a hot sodium chloride solution.

Cores stored in an unlimited supply of hot sodium hydroxide

or sodium chloride solution may give too pessimistic results, as the concrete in the actual structure may show no or only little expansion due to a limited internal alkali supply.

#### INDIRECT METHODS

Analyses of the chemical composition of alkali silica gel in concrete suggest that ASR may be treated as a chemical reaction with a fixed ratio of alkali to silica. Ultimately, when one of the reactants is depleted, the reaction stops.

#### Reactivity of Aggregates

Analysis of the reactivity of the aggregates can be used as a first estimate of the reactivity of the concrete. No further expansion due to ASR is expected if the remaining amount of reactive aggregates is small. If the amount of reactive aggregates is high, other factors, i.e. alkali and moisture content, will determine whether deleterious ASR will occur in the actual structure.

The residual reactivity of the aggregates can be determined in several ways, e.g. petrography and by measurement of the chemical shrinkage.

**Petrography.** Thin section petrography has become the most important tool for diagnosis of ASR (Idorn (15)). ASTM C856, Practice for Petrographic Examination of Hardened Concrete, gives valuable guidance. The use of fluorescence impregnation and the combination of optical microscopy and scanning electron microscopy on polished thin sections are major steps forward in assessing the reactivity of aggregate in concrete (Andersen and Thaulow (16), Thaulow et al. (17), Jakobsen et al. (18)). It is common to find potentially reactive silica in concrete affected by ASR. The amount of non-reacted silica can be estimated by point counting. The limit of acceptance when testing residual reactivity is yet to be determined.

Conclusions regarding residual reactivity of concrete based on determination of the amount of non-reacted silica by petrography are mostly cautious for two reasons:

- 1 Silica judged to be potentially reactive may in practice not be so due to its low porosity. This is the case for dense flint.
- 2 In concrete structures with no external alkali supply, the amount of silica is often higher than the alkalis may consume. A simple calculation may illustrate this point:

Assume a limit of 3 kg Na<sub>2</sub>O to 36 kg SiO<sub>2</sub> (approximately 2% of sand). A typical gel contains 4.5 kg of SiO<sub>2</sub> per kg of Na<sub>2</sub>O. 3 kg of Na<sub>2</sub>O may react with 3x4.5=13.5 kg SiO<sub>2</sub> to form 3+13.5=16.5 kg of anhydrous gel. A substantial amount (36-13.5=22.5 kg or 62%) of SiO<sub>2</sub> remains non-reacted when the alkali has been consumed.

Chemical Shrinkage. Like cement hydration, ASR is accompanied by a reduction of the total volume of the system (Geiker and Knudsen (19)). This decrease in volume is designated chemical shrinkage. As measurement of chemical shrinkage provides a means for rapid determination of the reactivity of sand, a standard method for measuring chemical shrinkage has been developed (Knudsen (20)).

Recently, the chemical shrinkage method has been combined with the extraction of sand from drilled cores used for the estimation of the residual reactivity (Eriksen (21)). The limit of acceptance when testing residual reactivity is yet to be determined.

### Reactivity of Concrete

The residual reactivity of concrete affected by ASR can be determined by analysing the amount and distribution of fixed and available alkali and reacted and non-reacted silica in concrete cores drilled from the affected concrete structures.

A combined method has been developed and tested based on fluorescence thin section petrography, scanning electron microscopy with energy dispersive microanalyses and pore solution expression combined with chemical analyses.

Combined Method. The combined method is based on the following assumptions:

- 1 ASR is a chemical reaction, i.e. alkali and silica reacts in fixed weight ratios. An average (or typical) gel composition can be found by SEM-EDX.
- 2 The total alkali in the system (reacted and non-reacted) may be determined as acid-soluble alkali. The alkali available for further reaction is present as soluble alkali in the pore solution. The concentration may be determined on expressed pore solution. Alkali in solution, but below a threshold concentration of 0.2 N hydroxide, is not available for reaction.
- 3 Alkali in non-reacted clinker particles, CSH gel, ASR gel and aggregate is not available to any significant degree.
- 4 Water is not a limiting factor.
- 5 Calcium hydroxide is not a limiting factor.
- 6 The amount of reactive silica can be determined by thin section microscopy or by measurement of the chemical shrinkage.

Individually, the analytical methods are well established tools in cement and concrete research. For several years equipment has been available which enables the investigation of the composition of the pore solution in hydrated cement paste,

mortar or concrete (Diamond (22)). Care is needed to avoid carbonation of the small amount of pore solution expressed from concrete samples.

If the concrete is too dry it may be necessary to saturate the samples before expressing the pore solution. Care should be taken to avoid carbonation of the samples or leaching of alkalis. Time should be allowed for equilibrium to be established.

On the basis of the combined analyses it is possible to make an alkali-balance for the concrete and assess how much of the total alkali is present in an available form for further ASR. Figure 1 illustrates the alkali distribution in the concrete.

Reaction between reactive silica and alkali hydroxide may only proceed until a certain threshold concentration in the pore liquid is reached. Based on measurements (22) it is suggested by the present authors that the threshold limit for further reaction is approximately 0.2 N alkali hydroxide (pH 13.3). Below this limit the rate of reaction is negligible.

At the present time the combined method has been used on a limited number of concrete structures. The method is further studied in the on-going BRITE-EURAM project: "Performance Tailoring of Structural Concrete".

Table 1 shows results from an old concrete structure affected by ASR. The results show that the reactions are approaching termination due to alkali starvation.

TABLE 1 - Analysis of Alkali Concentration in Pore Liquid and acid soluble Alkali in Concrete.

Sample	$K^+ + Na^+$ mol/l	Equivalent $Na_2O$ kg/m <sup>3</sup>	Threshold $Na_2O$ kg/m <sup>3</sup>	Available $Na_2O$ kg/m <sup>3</sup>	Acid Soluble $Na_2O$ kg/m <sup>3</sup>
1	0.26	0.65	0.62	0.03	4.8
2	0.30	0.74	0.62	0.12	5.9
3	0.32	0.79	0.62	0.17	2.7

#### DISCUSSION

The applicability of various methods for determining residual ASR in a concrete structure in environments with and without alkalis is outlined in Table 2.

For concrete structures not exposed to alkalis, the combined method provides a suitable means of determining the

amount of residual ASR to be expected and is as such a useful substitution for the more time consuming measurements of expansion.

Petrography and chemical shrinkage measurement, on the other hand, are suitable tools in the judgement of the risk of further ASR in concrete structures exposed to external alkalis.

TABLE 2 - Applicability of Methods for determining residual ASR of Concrete.

Method	No Alkalies from Environment	Alkalies from Environment
Expansion measurement, in situ	Applicable	Applicable
Expansion measurement on cores in:		
100% RH	Applicable	Not applicable
Salt solution	Pessimistic	Applicable
Petrography	Pessimistic	Applicable
Chemical shrinkage measurement	Pessimistic	Applicable
Combined method	Applicable	Not applicable

The chemical shrinkage method and petrography are most suitable for detecting residual alkali reactivity of the sand fraction of aggregates. The chemical shrinkage involves in its present description testing of aggregates with maximum grain size 4 mm.

Both the combined method and chemical shrinkage measurement have only been used in a few cases to estimate residual ASR. For these two methods the reproducibility should be determined in a round-robin test.

Furthermore, for all the methods, except measurement of expansion on the actual concrete structure, the limit of acceptance is still to be assessed.

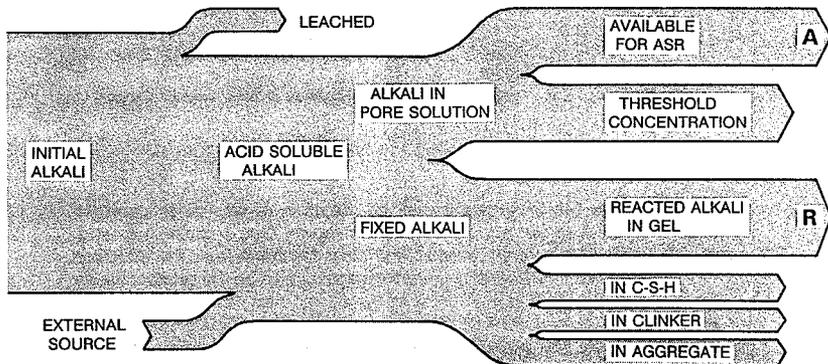
CONCLUSIONS

Several methods are available for determining the residual alkali silica reactivity of concrete. The combined method provides a promising rapid method for the determination of the risk of residual ASR of concrete not exposed to alkaline environment.

LIST OF REFERENCES

1. Thaulow, N., 1983, "Alkali-Silica Reaction in the ItezHITEZHI Dam Project, Zambia", Proc. 6th Int. Conf. on Alkalies in Concrete, Copenhagen, Denmark.
2. Oberholster, R.E., 1989, "Alkali-Aggregate Reaction in South Africa: Some Recent Developments in Research", Proc. 8th Int. Conf. on Alkali-Aggregate Reaction, Kyoto, Japan.
3. Ichihara, H., Shimamura, M., Koshiishi, I., 1989, "Alkali Aggregate Reaction in Railway Prestressed Concrete Bridges", Proc., 8th Int. Conf. on Alkali-Aggregate Reaction, Kyoto, Japan.
4. Tuthill, L.H., 1982, Concr. Int., 32.
5. Berthelsen, H., 1992, Projektjtjensten, DSB, Denmark (Private communication).
6. Hansen, O.R. et al, 1980, "Concrete Durability, an Investigation of Recently Constructed Motorway Bridges in Denmark", Danish Ministry of Transport, Danish Road Directorate.
7. Ishizuka, M., Utho, S., Kuzume, K., 1989, "Characterization of Road Structures Damaged by AAR on the Hanshin Expressway Due to Continuous Observation", Proc. 8th Int. Conf. on Alkali-Aggregate Reaction, Kyoto, Japan.
8. Holm, J., Idorn, G.M. and Braestrup, M.W., 1989, "Investigation, Re-evaluation and Monitoring of the Lucinda Jetty Prestressed Concrete Roadway", Proc. DABI symposium on Re-evaluation of Concrete Structures. Copenhagen, Denmark.
9. Calvalcanti, A.J.C.T. and Silveira, J.F.A., 1989, "Investigation on the Moxoto Powerhouse Concrete affected by Alkali-Silica Reaction", Proc. 8th Int. Conf. on Alkali-Aggregate Reaction, Kyoto, Japan.
10. Oberholster, R.E., 1983, "Alkali Reactivity of Siliceous Rock Aggregates. Diagnosis of Reaction, Testing of Cement and Aggregate and Prescription of Preventive Measures". Proc. 6th Int. Conf. on Alkalies in Concrete. Copenhagen, Denmark.
11. Hobbs, D.W., 1985, "Testing for Alkali Silica Reactivity". Cement and Concrete Association Test Methods. Slough, England.
12. Stark, D., 1985, "Alkali Silica Reactivity in Five Dams in Southwestern United States". REC-ERC-85-10. Bureau of Reclamation, Denver, Colorado, USA.

13. Strunge, H., Chatterji, S. and Jensen, A.D., 1991, II Cemento 88, 158.
14. Hobbs, D.W., 1988, "Alkali Silica Reaction in Concrete". Thomas Telford, London, England.
15. Idorn, G.M., 1967, "Durability of Concrete Structures". Copenhagen, Dissertation, 208 p.
16. Andersen, K.T., and Thaulow, N., 1990, "The Study of Alkali Silica Reactions in Concrete by the Use of Fluorescent Thin Sections". ASTM STP 1061 "Petrography Applied to Concrete and Concrete Aggregates". Erlin/Stark editors. Philadelphia, USA.
17. Thaulow, N., Lee, R.J., and Holm, J., 1991, "An Integrated Optical SEM Method for the Identification of Alkali Silica Reaction in Concrete Sleepers". Proc. Int. symposium on Precast Concrete Railway Sleepers. Madrid, Spain.
18. Jakobsen, U.H., Thaulow, N. and Johansen, V., 1991, Cement and Concrete Research, (in press).
19. Geiker, M. and Knudsen, T., 1985, "Chemical Shrinkage". Engineering Foundation Conf. Research on the Manufacture and Use of Cements, Proceedings, Henniker, USA.
20. Knudsen, T., 1986, "A Continuous Quick Chemical Method for the Characterization of the Alkali-Silica Reactivity of Aggregates", Proc. 7th Int. Conf. on Alkali-Aggregate Reaction, Ottawa, Canada.
21. Eriksen, K., 1991, "The Chemical Shrinkage Project - Phase II". COWIfoundation, Denmark, Annual Report.
22. Diamond, S., Barneyback, R.S., and Struble, L.J., 1981, "On the Physics and Chemistry of Alkali Silica Reactions". Proc. 5th Int. Conf. on Alkali Aggregate Reaction in Concrete. Cape Town, South Africa.



The degree of reaction,  $\alpha$ , for ASR can be defined as:  
 $\alpha = R/(A+R)$ , where A is the amount of alkali available for ASR and R is the amount of alkali already reacted. The residual reactivity is  $1-\alpha$ .

Figure 1 The distribution of alkalies in concrete.