FIFTY YEARS OF INVESTIGATION AND CONTROL OF AAR IN NEW ZEALAND

D.A. St John
Industrial Research Ltd.
P.O. Box 31-310, Lower Hutt, New Zealand

S.A. Freitag
Central Laboratories, Works Consultancy Services
P.O. Box 30-845, Lower Hutt New Zealand

Abstract

The investigation of AAR carried out over the last fifty years is briefly reviewed and assessed in relation to current projects. Important initiatives over the last four years have enabled field surveys, petrographic examinations and chemical investigations to be satisfactorily correlated to explain why some unexpected cases of expansive reaction have occurred.
Keywords: Alkali-aggregate reaction, aggregate-pore solution interaction, silica fume.

Introduction

Volcanic aggregates used in New Zealand concretes have been of investigated for over fifty years. Engineers charged with the construction of major government projects recognised their potential for AAR and as early as 1943 commissioned investigation into aggregates and subsequently limited the alkali content in concretes by specifying the use of low-alkali cements. This approach has been adequate for most concretes and forms the basis of the current New Zealand code of practice for minimising AAR, (Cement & Concrete Association of New Zealand 1991).

In hindsight it is clear that if aggregates had not been investigated and limits on the alkali content of most cements imposed, serious and costly damage to a wide range of both publicly and privately owned structures would have occurred. This was confirmed when a data base on concrete aggregates showed that potentially reactive aggregates were currently being used in some 30% of concrete, (St John 1988). As a result the severity of AAR has been restricted with only minor to moderate effects on structures with less than ten cases of serious damage.

The success of the New Zealand investigations has depended on government agencies being able to conduct research independently of the construction industry over a long period. While initial work was concentrated in the laboratory investigation of affected structures has recently become more important. This paper reviews the research carried out over the last fifty years to control the incidence and severity of AAR in New Zealand.

Early laboratory studies (1945 - 1970)

Early laboratory work concentrated on the identification and testing of aggregates for reactivity and the use of pozzolans to suppress AAR, (Hutton 1945, Kennerley & Clelland 1959, Kennerley & St John 1969, Kennerley *et al* 1975, St John 1988). Extensive testing of aggregates carried out over two decades using ASTM 227 & 289 test methods, supplemented by some concrete tests, provided an excellent base for later work and clearly identified that the more acidic volcanics exhibited well defined pessimum proportions.

Several potential pozzolans were identified and tested. A naturally occurring diatomaceous pumicite was used in many major projects both as a workability aid and to supplement the use of low-alkali cement in suppressing AAR. Generally, the use of this pozzolan has been successful but there is now some indication from field investigation that in the long term this pozzolan may not be effective in completely preventing AAR where alkali is released by interaction from aggregates with the pore solution in concrete.

Inspection of structures (1975 - present)

The first case of AAR in a structure was not unequivocally identified until 1975 (St John 1975), some thirty years after testing started, and now about thirty definite and twenty possible cases have now been confirmed. Most are minor and do not affect the performance of the structure. Many would not have been identified without systematic inspection of structures by experienced concrete technologists supplemented by petrographic examination to confirm the presence of AAR (Freitag 1994). Such surveys require that the inspection team be thoroughly familiar with the appearance of AAR, especially the appearance of minor reaction, as well as other concrete defects.

Petrographic examination methods (1975 - present)

An integral part of the field inspections has been the ability to positively identify AAR in concretes using petrographic examination of thin sections. A decision was made to develop the use of large-area thin sectioning (St John & Abbott 1983) as it was considered that neither the smaller thin sections used by geologists nor large ground surfaces examined by incident light would be adequate for the examination of concrete. Danish (Andersen & Petersen 1961) and English (Jones *et al.* 1966) methods of thin sectioning were developed to the stage where large-area thin sectioning became routine.

With experience, it has been possible to identify minor AAR in structures where as little as 1% of reactive volcanics are present, and to evaluate the relationship of the expansive cracking to other faults present in the concrete. In many New Zealand concretes AAR tends to be localised and large differences can be found between cores taken from adjacent sites. The ability to cut a thin section of the complete axial plane of a 100 mm diameter core to a depth of 150 mm overcomes many of the problems associated with localisation and also gives a more realistic idea of the relationships existing between concrete components.

The effective association of inspection teams, critical sampling and petrographic examination has identified a number of previously unrecognised aspects of AAR. This success of this association requires that the petrographer be consulted on the number and size of samples needed to fully represent the concrete in question and also that samples be cut, transported and stored with care to ensure valuable information is not lost.

Intercomparison of Japanese and New Zealand volcanic rocks

In a co-operative study (Katayama *et al.* 1989) which compared Japanese and New Zealand volcanic rocks, the type of reactivity of the intermediate and acid types of volcanic rocks was shown to be related to the presence of interstitial glass, cristobalite and tridymite. It was found that when the silica in the bulk composition of the rocks falls below approximately 50% the composition of the interstitial glass changes to become non reactive and cristobalite and tridymite are usually absent. This suggested a chemical method of distinguishing reactive and non reactive rocks when the bulk silica content lies between basalt and andesite.

Further investigation of a range of New Zealand basalts was planned to confirm these conclusions but this work has not yet been carried out. In the case of volcanic rocks it has considerable potential to act as a quick screening method to determine whether particular aggregates require further testing for potential reactivity.

Investigation of fluorescence for petrographic examination

Impregnation of concretes with thin epoxy resin containing the yellow fluorescent dye Brilliant Yellow R to measure the porosity of the concrete for the determination of water cement ratio was investigated (St John 1994). For this investigation small thin sections of concrete were prepared. Determination of W/C ratio by fluorescence was found to be unreliable outside the range 0.4 to 0.6. In addition it was found that sections needed to be 25 µm thick or less and unless considerable care was exercised in ensuring full impregnation of the concrete, fluorescence in the thin sections varied and was difficult to interpret.

Investigation (St John 1994) of the uranyl acetate staining method for detecting alkali-silica gel described by Natesaiyer and Hover (1988) confirmed the effectiveness of this technique over other methods. However, it was found that the original zinc uranyl acetate solution described by Feigl (1958) gave better results than the uranyl acetate solution and may define areas of sodium concentration. Concretes that have been allowed to dry out for long periods cannot be used with either of these solutions for detection of alkali-silica gel even when freshly cut surfaces are thoroughly rewetted.

Measurement of residual expansion and its control in structures

In the case of seriously damaged bridges a prediction of residual expansion and cracking is required for planning economic maintenance of these structures. A programme designed to predict the likelihood of future expansion from the accelerated expansion of core samples has identified a qualitative relationship between in-situ and core expansions. A second programme used the accelerated core expansion test to assess the effectiveness of surface treatments on reducing expansion. The results of these programmes are reported elsewhere in these proceedings (Freitag & St John 1996).

Identification of cements and alkali analyses

The control of AAR in New Zealand has been based on the use of low alkali cement and more recently on the total soluble alkali content of concretes (Cement and Concrete Association of New Zealand 1991). As the number of structures identified with AAR has increased the question of validating this method of control becomes paramount. Few construction records are available and in some cases it is suspected that the nominated cement may not have been used. There are problems in analysing a concrete for its alkali content and even if the result is analytically correct, changes to the alkalies present caused by the environment may result in localised alkali contents differing from the original mix.

Chemical techniques have been devised by Goguel & St John (1992) to identify cements so that the original alkali content of a concrete can be reliably estimated. If the cement works can be identified the alkali content of the cement can be obtained from analytical records. When this figure is combined with a determination of cement content, the original alkali content of the concrete can be estimated. There is a another problem in that the usual method of determining alkali contents in concrete by acid dissolution gives erroneously high values. Investigation shows that dissolution of the hardened cement paste by an alkaline complexing solution to determine alkalies provides more meaningful results (Goguel 1995).

The application of these analytical methods to concrete samples obtained from structures has been effective. It has identified structures where the alkali content of the concrete has increased during the life of the structure resulting in AAR in spite of the use of low alkali cement. Some of the initial results using these methods were reported briefly at the last conference (St John & Goguel 1992). The combination of these analytical techniques together with field surveys has enabled reactive combinations of materials and mix designs to be identified (Freitag & St John 1996).

Aggregate pore solution studies and the release of alkalies from aggregates

Van Aardt and Visser (1977) showed that when feldspars are ground finely they react with saturated calcium hydroxide solutions and so release alkalies. Because of the unrealistically fine grain size used in their experiments the relationship of these results to concrete aggregates is in doubt.

In New Zealand structures where apparent increases of alkali have led to AAR, a process of elimination indicates that the only possible source for the alkali is from the aggregates. Investigations reported elsewhere in these proceedings (Goguel 1996) identify basalt as the principal aggregate involved. In addition it was found that the tendency to release alkali decreases from basalt to andesite to rhyolite.

If the results of Van Aardt and Visser (1977) are applied to the cases in the Auckland area it would appear that the feldspars in the finer fraction of the basalt crusher dust used may be releasing alkali. Other possible sources are the glassy matrix of the rock and nepheline but recent investigations (Goguel 1995) have shown that nepheline does not release alkalies to the pore solution and there is some question as to the extent of release of alkalies from the glassy matrix. Further investigation is required to determine the relationship between the mineralogy and grain size of the basalt and its ability to release alkalies to the alkaline pore solution. Our current hypothesis is that poorly crystallised feldspars formed in rapidly chilled basalt lava flows may be the principal source of the alkalies.

Andesites also release alkalies, although at a lesser rate than basalt. A number of structures have been identified where minor AAR has occurred with the use of low alkali cement and andesite aggregate. In these cases the only aggregate present is andesite usually derived from alluvial sources. The amount of extra alkali found in the concretes is much less than occurs with basalt but appears to have been sufficient to initiate the first stages of AAR.

The reactivity of silica fume

On the basis of the many reports in the literature it was assumed that silica fume would be an effective and safe pozzolan for the prevention of AAR. As the following investigations show, which initially were unrelated to our AAR studies, silica fume may cause expansive cracking.

A major investigation into the mixing and fabrication of ultra high strength mortar, known as DSP, using New Zealand cements and aggregates produced expansive cracking due to AAR in test specimens subjected to wetting and drying and outdoor exposure (St John et al. 1994). This AAR was found to be caused by undispersed agglomerates of silica fume greater than about 50 µm in diameter and the very high alkali content of the DSP derived from the high cement and superplasticiser contents used. As only small amounts of alkali-silica gel are associated with the reacting silica fume agglomerates it is difficult to identify petrographically. Similar results have been reported by Pettersson (1992) and Shayan et al (1993).

Investigation of a range of silica fumes (St John 1994) confirmed Japanese results (Asakura et al. 1993) which showed that dispersibility of silica fume could be measured by its change in particle size distribution with ultrasonic dispersion in water. Some silica fumes continue to remain dispersible irrespective of densification and time of storage while in others dispersibility was reduced. Particle size measurement clearly shows that while the average particle size of the individual spheres of silica fume is about 0.1 µm the effective average particle size can vary from 1 to 50 µm due to agglomeration. More importantly, in some densified silica fumes the larger agglomerates are extremely difficult to disperse. Whether the silica fume is used as a powder or a slurry does not seem to affect its tendency to agglomerate.

Our examination of some of the fumes by transmission electron microscopy shows that they all consist of well-formed spheres which range in size from about 20 nm to 1 μm in diameter. However, close examination of the micrographs reveals that a significant proportion of the spheres are connected to at least one other sphere and also that chains of spheres are present. It is hypothesised that this interconnection of some of the spheres could explain why some agglomerates are difficult to disperse. Where agglomerates are largely held together by Van der Waals forces mixing will break them up, but agglomerates which contain entangled chains will be difficult to disperse even with vigorous mixing. Even where the silica fume is interground with the cement it appears that some agglomerates may persist in the concrete (Sveinsdottir & Gudmundsson 1993).

This lack of dispersion applies to both concrete and mortars. Our recent investigation of a commercial high strength concrete containing 10% by weight of silica fume clearly showed the presence of well formed silica fume agglomerates ranging from 25 to 200 μm in diameter. The alkali content of the concrete was less than 2.5 kg/m^3, giving some protection against AAR. In DSP mortars containing agglomerates of silica fume, the high cement and superplasticiser content combined with the alkali in the silica fume can lead to alkali contents as high as 10 kg/m^3. With this level of alkali the extent of AAR is determined by whether sufficient water can penetrate the DSP to enable the AAR to proceed and the number and size of agglomerates present.

There is a need for further investigation of silica fumes to try and explain their different dispersibilities and find some means to improve the properties of those fumes which are difficult to disperse. Work is also required to determine the amounts and sizes of silica fume agglomerates that remain undispersed in mortars and concrete to allow a better estimate of their potential for AAR. This is necessary because there are some indications that agglomerates larger than about 30 μm persist in concrete and mortars as potentially reactive aggregates and are not consumed by pozzolanic reaction.

Discussion and conclusions

The decision to largely concentrate investigation of AAR to work on field structures has produced excellent results. The success of these investigations have relied on skilled inspection teams and devising methods for the analysis of concrete using chemical and microscopic techniques. Wet chemical techniques have made it possible to unequivocally determine that alkalies are being leached from some New Zealand basalt enabling us to explain the cause of a number of anomalous cases of AAR.

Similarly the expansive reactivity of some silica fumes challenges the concept of this material as a cement dispersant and pozzolan. It underlines the need to thoroughly investigate the expansive reactivity of pozzolans with very fine particles sizes when used in concrete and mortar containing high alkali contents.

References

Andersen, P.E. & Petersen, B.H. 1961, 'Drilling of concrete cores and preparation of thin sections', *Rilem Bulletin*, (11), 94-106.

Asakura, E. Yoshida, H. Nakato, T. & Nakamura, T. 1993, 'Effect of characters of silica fume on physical properties of cement paste', *JCA Proceedings of Cement and Concrete*, 47, 178-183 (In Japanese, English abstract).

Cement & Concrete Association of New Zealand. 1991, 'Alkali-aggregate reaction. Minimising the risk of damage to concrete. Guidance notes and model specification clauses', *Cement & Concrete Association Report No: TR 3*.

Feigl, F. 1958, *Spot tests in inorganic analysis*, Elsevier Publishing Co, New York.

Freitag, S.A. 1994, 'Alkali aggregate reaction: research by Works Consultancy Services, Central Laboratories - 1989-1994', *Central Laboratories Report 93-24140*.

Freitag, S.A. & St John, D.A. 1996, 'Alkali aggregate reaction in existing structures - what can it tell us?' *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction*, Melbourne.

Goguel, R. 1995, 'Alkali release by volcanic aggregates', *Cement & Concrete Research*, 25(5).

Goguel, R. 1996, 'Selective dissolution techniques in AAR investigation: Application to an example of failed concrete', *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction*, Melbourne.

Goguel, R. & St John, D.A. 1993, 'Chemical identification of Portland cements in New Zealand concretes. I. Characteristic differences among New Zealand cements in minor and trace element chemistry. II. The Ca-Sr-Mn plot in cement identification and the effect of aggregates', *Cement & Concrete Research*, 23(1), 59-69, (2), 283-293.

Hutton, C.D. 1945, 'The problem of reaction between aggregate materials and high-alkali cement, *New Zealand Journal of Science & Technology*, 46B, 191-200

Jones, J.C. Hawes, R.W.M. & Dyson, J.R. 1966, 'Semi-automatic preparation of ultra-thin and large-area thin sections', *Transactions British Ceramic Society*, 65,603-612.

Katayama, T. St John, D.A. & Futagawa, T. 1989, 'The petrographic comparison of some volcanic rocks from Japan & New Zealand - potential reactivity related to interstitial glass and silica minerals', *Proceedings 8th International Conference on Alkali-Aggregate Reaction*, Kyoto, Japan, 537-542.

Kennerley, R.A. & Clelland, J. 1959, 'An investigation of New Zealand pozzolans', *Bulletin 133*, DSIR, New Zealand.

Kennerley, R.A. & St John, D.A. 1969, 'Reactivity of aggregates with cement alkalies', *Proceedings National Conference on Concrete Aggregates,* Hamilton, New Zealand.

Kennerley, R.A. St John, D.A. & Smith, L.M. 1975, 'Alkali-aggregate reactivity in New Zealand', *Proceedings Conference on Alkali-Aggregate Reactivity, Preventative Methods*, Reykjavik, Iceland.

Natesaiyer, K.C. & Hover, K.C. 1988, 'Insitu identification of ASR products in concrete' *Cement and Concrete Research*, 18(3),455-463.

Pettersson, K. 1992, 'Effects of silica fume on alkali-silica expansion in mortar specimens', *Cement and Concrete Research*, 22(1),15-22.

St John, D .A. 1975, 'Confirmation of alkali-aggregate reaction in Te Henui bridge', *New Zealand Journal of Science*, 18,405-416.

St John, D.A. 1988, 'Alkali-aggregate studies in New Zealand', *DSIR Chemistry Division Report No. 2390*.

St John, D.A. 1988, 'Alkali-aggregate reaction and synopsis of other data on AAR', *N.Z. Concrete Construction*, April & May.

St John, D.A. 1994, 'The use of fluorescent dyes and stains in the petrographic examination of concrete', *Industrial Research Limited Report No.243*.

St John, D.A. 1994, 'The dispersion of silica fume', *Industrial Research Limited Report No. 244*.

St John, D.A. & Abbott, J.H. 1983, 'Semi-automatic production of concrete thin sections', *Industrial Diamond Review*, 1/83,13-17.

St John, D.A. & Goguel, R. 1992, 'Pore solution/aggregate enhancement of alkalies in hardened concrete', *Proceedings 9th International Conference on Alkali-Aggregate Reaction in Concrete*, London, 894-901.

St John, D.A., McLeod, L.C & Milestone, N.B. 1994, 'The durability of DSP mortars exposed to conditions of wetting and drying', *Workshop on High Performance Concrete*, Bangkok.

Shayan, A. Quick, G.W. & Lancucki, C.J. 1993, 'Morphological, mineralogical and chemical features of steam-cured concretes containing densified silica fume and various alkali levels', *Advances in Cement Research*, 5(20),151-162.

Sveinsdottir, E.L. & Gudmundsson G. 1993, 'Condition of hardened Icelandic concrete. A microscopic investigation', *Proceedings of the Fourth Euroseminar on Microscopy Applied to Building Materials*, eds J E Lindqvist & B Nitz, Swedish National Testing and Research Institute, Building Technology SP Report 1993:15.

Van Aardt, J.H.P. & Visser S. 1977, 'Calcium hydroxide attack on feldspars and clays: Possible relevance to cement-aggregate reactions', *Cement and Concrete Research*, 7(6),643-648.