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# Where is AAR Heading after the 10th International Conference?

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*Abstract*

*A brief overview of research on AAR presented at the 10th AARC is given, and new areas of research and future needs are highlighted. Some recent experimental data are presented as examples of details that we would need to understand in order to be able to interpret the effects of parameters such as temperature and chemical environment on the nature of the reactions occurring in the concrete, and on the results of tests carried out to determine the expansion behaviour of aggregates or concrete mixtures. Similar examples are needed for other areas, and it appears that understanding AAR and its practical management need further research efforts. © 1997 Elsevier Science Ltd. All rights reserved*

*Keywords:* Alkali-aggregate reaction (AAR), AAR-test parameters, AAR-paradoxes.

## INTRODUCTION

The 10th International Conference on Alkali-Aggregate Reaction was held in Melbourne, Australia in August 1996, and the proceedings of the conference contain 132 papers, amounting to 1063 pages. Some 200 delegates from 26 countries participated in the conference, and concern for AAR was reported for the first time from countries such as Korea, Iran, Israel, Portugal, Romania and Taiwan. Table 1 shows the grouping of the papers and the areas covered by the conference.

It should be noted that the six Keynote lectures are state-of-the-art papers from the other groupings. Due to the importance of these papers, and the fact that space limitation in the proceedings restricted their length, Professor Swamy, the editor of this journal, is kindly dedicating this Special Issue to the expanded version of these Keynote lectures. They form essential reading for researchers and others interested in the field of AAR. As the Keynote lectures are a prominent part of the conference proceedings and are presented in this issue, separate references are not made to them here. The paper by Professor Della Roy has been published elsewhere and, unfortunately, is not present in this issue.

**Table 1.** Grouping of the papers in the Proceeding of the 10th AARC

| *Group* | *Number of papers* |
|---|---|
| Keynote lectures | 6 |
| National reviews on alkali-aggregate reactive | 11 |
| General topics on alkali-aggregate reaction | 5 |
| Diagnosis of AAR in concrete | 9 |
| Testing for alkali-aggregate reactivity | 15 |
| Structural effects of AAR | 11 |
| Preventive effects of mineral admixtures on AAR | 13 |
| Effects of surface coatings and cathodic protection on AAR | 10 |
| Modelling of AAR | 5 |
| Aggregate reactivity | 11 |
| Mechanisms of AAR | 4 |
| Effects of environment on AAR | 5 |
| Other preventive measures for AAR | 5 |
| Theory and research topics | 6 |
| Microstructure in AAR | 6 |
| Repair and maintenance of structures affected by AAR | 10 |

## AAR PARADOXES

Professor Diamond, in his Keynote address has discussed some interesting issues; paradoxes that have been encountered in studies of AAR in concrete. Four paradoxes have been dealt with in some details as follows:

(1) The effects of alkali added in the mix water to the concrete (to accelerate alkali-aggregate reaction) on the chemistry of the pore solution. The hydroxyl ion concentration is not increased to the extent that is expected from the addition of the added alkali. Instead, the sulfate concentration is increased and may lead to delayed ettringite formation.

This practice is common in testing of aggregates, and researchers should be aware of the chemical changes that occur as a result of alkali addition to concrete mixes to accelerate the reaction.

In addition to the chemical changes, mechanical changes also occur in the properties of the cement paste, mortar and concrete as reported by Shayan and Ivanusec,[1] and Shayan.[2] Addition of alkali reduces the strength properties and makes it easier for AAR to cause cracking of the concrete. Therefore, cracking of the concrete, containing reactive aggregate at enhanced levels of alkali results from the accelerated reactivity as well as the weakening of the cementitious matrix of the concrete. Figure 1 shows an example of the influence of added alkali on the strength of the concrete. Figure 2 shows the effect of molarity of the NaOH solution on the strength of mortar (cement/sand = 1:2 and cement/water = 1:0.4) for fog-cured (23°C) and steam-cured (75°C) specimens. Clearly, the strength is significantly reduced due to the addition of NaOH. Table 2 shows how the concentration of NaOH in the mix water influences the chemistry of the pore solution extracted from the mortar.

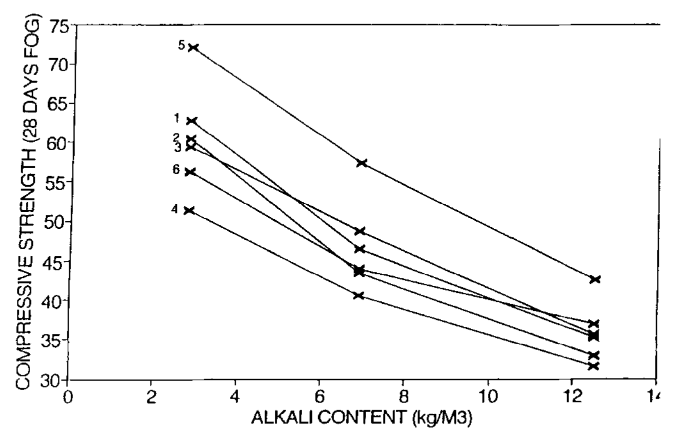


**Fig. 1.** 28-day compressive strength (MPa) of concretes, made with six different aggregates, at different levels of alkali content ($Na_2O$ equivalent) in kg/m$^3$. Note that only very little reaction may take place at this age.

These results are in agreement with the statements made by Professor Diamond. The higher sulfate concentration at higher alkali levels shows that ettringite is unstable under these conditions. X-ray diffraction analysis showed that for the steam-cured specimens, ettringite formation was significantly inhibited at an NaOH concentration of 0.5 M and above. The

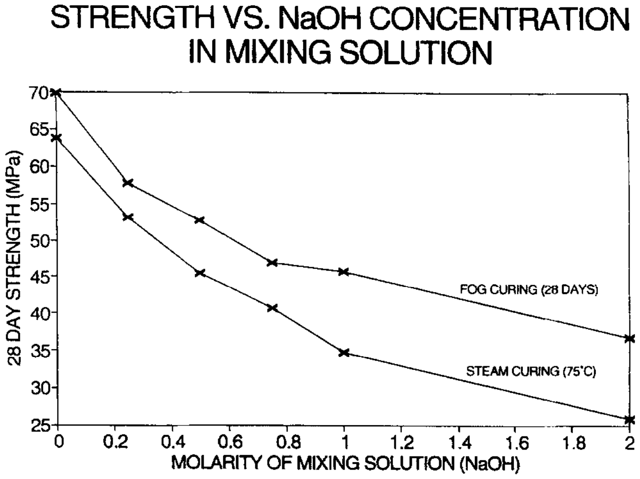


**Fig. 2.** 28-day compressive strength of 25-mm mortar cubes (sand/cement = 2, solution/cement = 0.4) cured either in fog (23°C) or steam cured at 75°C. The solution phase varied in its concentration of NaOH. Each data point is the average of four determinations.

**Table 2.** Composition of pore solution of mortar specimens containing various alkali levels (steam-cured at 75°C and stored at 40°C, 100% RH for 28 days)

| *Mixing solution* | *Ca (mM)* | *Na (M)* | *K (M)* | *OH (M)* | *$SO_4$ (mM)* | *Si (mM)* | *Al (mM)* |
|---|---|---|---|---|---|---|---|
| Water | 0.36 | 0.465 | 0.295 | 0.450 | 70 | 1.3 | 0.05 |
| 0.5 M NaOH | 0.36 | 0.995 | 0.229 | 0.638 | 169 | 10 | 0.05 |
| 1 M NaOH | 0.13 | 1.517 | 0.212 | 0.825 | 286 | 14 | 0.15 |

so-called 'U-phase', a sodium-substituted monosulfate, formed instead of ettringite. For the fog-cured specimens, which show a similar strength trend to that in Fig. 2, ettringite formation was not significantly affected up to NaOH concentrations of 1 M, and the 'U-phase' was detected only in the specimen made with the 2 M NaOH solution. These observations show that the observed strength drop is not entirely related to the inhibition of ettringite formation. The results of Way and Shayan[3] had indicated that incorporation of Na in the CSH phase may have had an important influence on the strength loss. Cement pastes containing NaOH remain more dispersed than those without it and are of a lower density, which probably result in lower strength.

(2) The effects of partial drying of the concrete on the concentration of alkali ions in the pore solution of the concrete. Although it is expected that drying of concrete would increase the concentration of alkali ions in the solution, in fact, some 'fixation' of alkali occurs due to this process, particularly in the presence of carbon dioxide, such that the pore solution concentration of alkali ions is considerably reduced. It has been suggested that drying may have a more positive effect on arresting the progress of AAR than previously expected.

(3) Based on reported cases of the effects of silica fume on AAR in concrete, it is suggested that the addition of silica fume to concrete may cause AAR due to the reaction of undispersed agglomerates, rather than preventing it.

Although there have been some adverse reports in the literature in relation to the use of silica fume in prevention of AAR, the present author believes that no such problem would be encountered if adequate amounts of silica fume (e.g. ~10%) are added in a well-dispersed form to the concrete. In fact, examination of concrete drilled from a bridge made with a triple mix (5% silica fume) showed that the dispersed silica fume had reacted rapidly, and no agglomerates could be detected at ages from 1 week to 1 year. In the successful application of silica fume for prevention of AAR in concrete, three important factors need to be considered, viz. an adequate amount (~10%), well dispersed form, and low alkali content.

(4) The effects of addition of lithium on the $OH^-$ concentration of the pore solution. Lithium salts are added to the concrete to eliminate the expansive properties of the AAR gel, whereas the addition increases the concentration of $OH^-$ ions in the pore solution and increases the possibility of AAR. The correct amount of the salt, which would depend on the $Na_2O$ equivalent of concrete, must be added to achieve the desired effect. Other papers presented at the conference provide data in favour of using Li-salts for this purpose.

These paradoxes highlight the need for further research in these areas, particularly with regard to the confusion that exists in relation to the cause(s) of damage to concrete structure by AAR and/or delayed ettringite formation. Also, the need for a chemical approach to eliminate the expansive properties of AAR gel would probably result in further research effort in these areas in the near future.

## AAR STUDIES FOR SPECIAL PROJECTS

Professor Roy's paper showed how a careful selection of materials is needed and is performed for sensitive concrete structures such as the one that she studied for the storage of radioactive nuclear wastes. Readers are encouraged to read the full paper in the conference proceedings.

## TESTING FOR AAR

Dr Grattan-Bellew, in his critical review, dealt with the difficult issue of accelerated testing for AAR, and concluded that although there is promise in the use of 1 M NaOH at 80°C for storage of mortar bars, one must interpret the results cautiously. Many papers under the groupings of 'Testing for AAR' and 'Aggregate Reactivity' dealt with the application of, or deficiencies in, the various test methods for assessing aggregate reactivity. A specific case of the history of AAR research in Australia was presented by Dr G. M. Idorn.

The present author in the 'Guest Editorial' of the Special Issue of this journal on testing for AAR (Vol. 16, No. 3, pp. 161–162) had teasingly hoped that by the end of the 10th IAAR

Conference in Melbourne, all the problems of identifying reactive aggregate would be solved worldwide. The review by Grattan-Bellew and the papers presented at the conference showed that we are still a long way from a universally accepted test method, or set of test methods. This will probably not eventuate, and different countries will continue to refine the test methods that suit them best.

However, there is a need to understand particularly the chemical processes that are involved when important test parameters (largely temperature and chemical environment) are varied. This understanding will enable us to explain the results obtained in a particular test method. For example, Berube and Frenette[4] tested concrete prisms in 1 M NaOH and 1 M NaCl solutions at 38°C and 80°C, using two very reactive Canadian aggregates, high and low alkali contents and various storage conditions. They found that, with both aggregates, concrete prisms expanded much more in the 1 M NaCl than 1 M NaOH solution when they were stored at 38°C, and the alkali content of the concretes was high (3.9 kg $Na_2O$ eq./$m^3$, achieved by adding NaOH in the mix water). However, when the alkali content of the concrete was low (1.7 kg $Na_2O$ eq./$m^3$), expansion in 1 M NaOH was much larger than in 1 M NaCl, under the same storage temperature of 38°C. Berube and Frenette[4] were surprised at this result, and related it to permeability considerations. They were even more surprised that when the storage temperature was 80°C, expansion of concrete prisms stored in 1 M NaCl solution was much smaller than in 1 M NaOH solution for both high and low alkali contents.

The above observations show that we need to develop a better understanding of the processes involved when test parameters are varied. Earlier work by the present author[5] had shown that storage of concrete prisms (made with some slowly reactive Australian aggregates) in saturated NaCl solutions at 50°C caused deleterious expansions only when alkali hydroxide had been added to the mix water to increase the hydroxyl ion content of the concrete. This observation showed that, for the slowly reactive aggregates used, the NaCl solution did not have a primary role in the expansion. Recent results obtained on the effects of temperature and some salts on the hydration of cement has shown that NaOH and NaCl behave differently and that temperature has an important effect on the hydration reactions. Figures 3, 4 and 5 show X-ray diffraction (XRD) patterns of cement slurries made with water, 1 M NaOH and 1 M NaCl, respectively, and stored for 14 days at temperatures of 23, 40 and 80°C.

Figure 3 shows that in the presence of water alone, significant amounts of ettringite form at 23°C and 40°C (peaks at about 9.61 Å, designated E), but no crystalline sulfoaluminate forms at 80°C. Also, tobermorite, which produces the peaks at about 3.01 Å at the lower temperatures, is absent at 80°C. When the mixing solution is 1 M NaOH (Fig. 4), ettringite does not form in the slurry, and the nature of

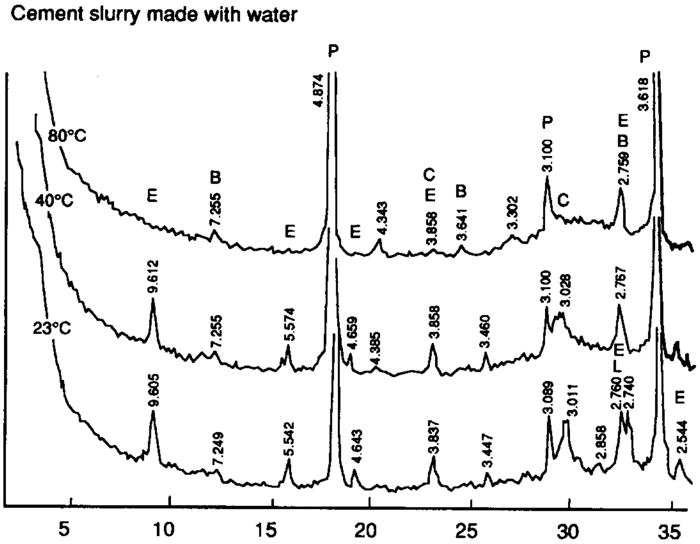
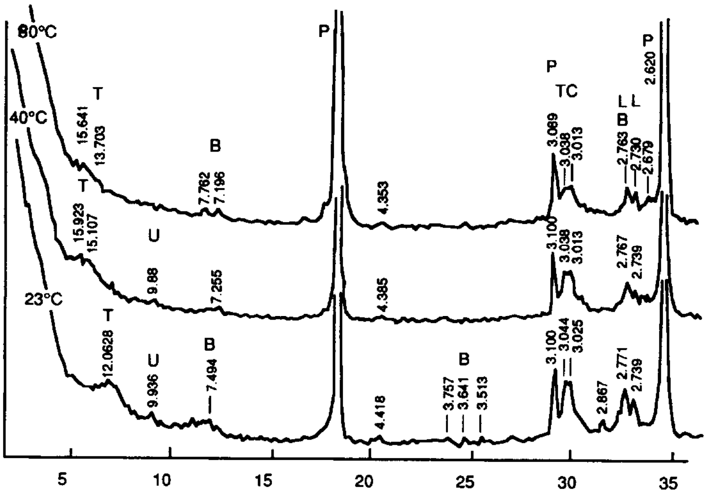


**Fig. 3.** X-ray diffraction patterns of the solid phases of cement/water slurries hydrated at the indicated temperatures for 14 days. All the slurries set hard and formed solid cakes of hydrated cement, separated from the supernatant liquid. B = brownmillerite, C = calcite, E = ettringite, L = larnite, P = portlandite.



Cement slurry made with 1 M NaOH solution

**Fig. 4.** X-ray diffraction patterns of the solid phases of cement/(1 M NaOH) slurries hydrated at the indicated temperatures. The slurries stored at 23 and 40°C did not set hard and remained fluid. B = brownmillerite, C = calcite, L = larnite, P = portlandite, T = tobermorite.

the tobermorite phase (12.06 Å peak, at 23°C) is altered at higher temperatures (peaks at 13.7–15.9 Å, at 40°C and 80°C). For the slurry made with 1 M NaCl solution (Fig. 5), ettringite forms at 23°C and 40°C, but not at 80°C (similar to the slurry made with water, but unlike that made with 1 M NaOH). In addition, calcium-chloroaluminate (Friedel's salt, 3CaO $Al_2O_3CaCl_2.10H_2O$) forms at 23°C and 40°C but not at 80°C. Therefore, there are important mineralogical differences firstly between specimens subjected to 1 M NaOH and 1 M NaCl solutions, particularly at the lower temperatures, and secondly between the higher and lower temperatures for each solution.

Based on these mineralogical changes, the present author can explain the differences in expansion observed by Berube and Frenette[4] of concrete prisms containing high and low alkali contents, and subjected to the 1 M NaOH and 1 M NaCl solutions.

The following explanations are offered:

(1) 38°C storage conditions

Observation: The low alkali concrete prisms expanded significantly in the presence of NaOH, but not NaCl.

Explanation: This is simply because the very reactive aggregates require sufficiently high concentrations of $OH^-$ ions for the reaction and expansion to occur. Obviously, this condition is lacking in the low-alkali concrete prisms stored in the 1 M NaCl solution. Therefore, this behaviour is to be expected, and was later noted by Duchesne and Berube.[6] However, if the $C_3A$ content of the concrete is high (e.g. 12%), then its interaction with NaCl could perhaps generate enough additional $OH^-$ to cause expansion with very reactive aggregates.

Observation: The high alkali concrete prisms expanded much more in 1 M NaCl than in 1 M NaOH solution.

Explanation: Close examination of Fig. 1 of Berube and Frenette[4] shows that, for the high alkali concrete prisms, the initial expansion up to the age of about 6–7 months was in fact higher in the 1 M NaOH than in the 1 M NaCl solution. High alkali concrete prisms produced high expansions even when stored at 100% relative humidity, and about 0.25% expansion had occurred at this age under all these three conditions. It is only after this stage that expansion in NaCl exceeds that in the NaOH solution or at 100% R.H. It is suggested that the 0.25% expansion in the concrete prisms at the earlier stage must have been associated with significant internal microcracking, and storage in 1 M NaCl resulted in the formation of both ettringite and Ca-chloroaluminate in the microcracks and

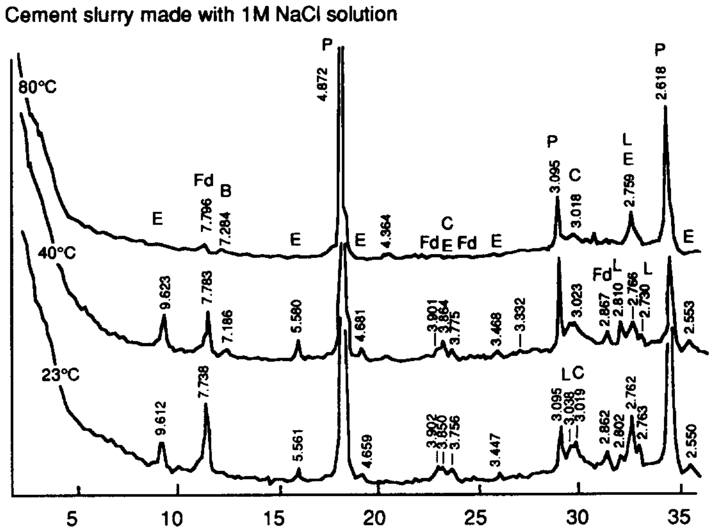


**Fig. 5.** X-ray diffraction patterns of the solid phases of cement/(1 M NaCl) slurries hydrated at the indicated temperatures for 14 days. All the slurries set hard and formed solid cakes of hydrated cement, separated from the liquid phase. B = brownmillerite, C = calcite, E = ettringite, Fd = Friedel's salt (calcium chloroaluminate), L = larnite, P = portlandite.

enhanced the expansion. Also, the microcracking implies further penetration of the NaCl into the concrete matrix and reaction with the aluminate phases, which probably could cause greater expansions than the formation of these phases in the microcracks. This also explains the observations of Sibbick and Page[7] in relation to the effects of NaCl solution on the expansion of concrete prisms containing high alkali levels, for which they did not offer an explanation. The mechanism involved is, in fact, a salt attack that has resulted after the concrete had been damaged by AAR.

(2) Storage condition of 80°C

Figures 3, 4 and 5 show that neither ettringite nor Friedel's slat form under this curing condition. Therefore, the observed expansion is related to AAR alone, which is evident when the storage solution is 1 M NaOH. Storage in 1 M NaCl and water cause similar expansions, which are far less than that caused by 1 M NaOH. (Note: figs 2 and 3 in Berube and Frenette[4] are misnumbered, i.e. fig. 3 should read fig. 2, and fig. 2 should read fig. 3.) This is due to a lack of adequate $OH^-$ concentration in 1 M NaCl and water. The fact that the high alkali concrete prisms did not expand in water or the NaCl solution is very likely related to the leaching of the alkali hydroxide[5] from the concrete into these solutions, and also to the short period of storage.

Therefore, all the observations made by Berube and Frenette[4] can be explained with the help of the information obtained from the study of the test parameters such as the effects of temperature and chemical environment on the mineralogy of phases formed in the cementitious phase.

## STRUCTURAL EFFECTS OF AAR

Papers presented on structural effects of AAR offer different views, but an important outcome seems to be that evaluation of cores extracted from AAR-affected structures may underestimate the mechanical capacity and strength properties of the structure. The papers confirm that AAR expansion results in some loss of compressive and tensile strengths and stiffness, and that steel reinforcement can inhibit these effects, particularly in the direction of reinforcement. These losses are said not to significantly influence the load-carrying capacity of structures. A point of disagreement is that in one paper, it is concluded that although applied confining stresses can inhibit expansion in both the direction of applied stress and perpendicular to it, at a certain lower level of axial stress, expansion increases in the radial direction. In another paper, the conclusion is that the radial expansion can be ignored. This effect has important implications because the former conclusion would indicate that a three-dimensional restraint is required to inhibit AAR expansion in concrete elements, whereas for the latter, a uni-directional restraint would be indicated.

In another paper, it is correctly stated that the structural effects of AAR cannot be generalised with respect to the performance of various elements. The effects would depend on the particulars of individual concrete members, their size, reinforcement details and loading history (also confinement) during the reaction and expansion phase. An important point is that although the strength of AAR-affected concrete may be reduced, it could still exceed the design strength. In fact, it has been stated that due to the prestressing effects of AAR in reinforced concrete, the shearing strength of the AAR-affected concrete element increases. Nevertheless, durability aspects of concrete should also be considered, not just strength, which are put at risk in the presence of AAR-cracking in the concrete.

## PREVENTION OF DELETERIOUS AAR

On the issue of prevention of AAR, the papers presented at the conference confirm that the limitation of the alkali content of concrete, and the use of suitable mineral additives are effective means of control of the reaction. Some disagreement persists as to how much of the alkali present in mineral additives contributes to the alkali loading of the concrete, but this is very likely related to the different chemical and mineralogical properties of individual mineral admixtures and needs to be individually assessed.

Chemicals such as salts of lithium have been proposed as effective means of prevention, but this area requires further study to elucidate the mechanisms involved. The paper presented by Bian *et al.*[8] suggests that other chemicals, particularly salts of lithium and calcium could be used to inhibit AAR, and the effectiveness of the chemical is related to the surface charge density of the cations and anions involved. However, this is a preliminary study, and much further work is needed on this topic before any recommendation could be made. The same applies to the use of alkali-chelating catalysts in order to remove alkali from existing structures to suppress the AAR expansion.[9]

## APPLICATION OF SURFACE COATINGS TO SUPPRESS AAR

In relation to the use of surface coatings to inhibit the progress of AAR and its damage to structures, several systems of coating have been rated as successful. These include single component systems such as silanes and acrylic rubber, or mixed systems such as polymer cement, and a combination of the two systems. Some papers indicate that materials such as epoxy resin and polyurethane paints have not been effective as surface coatings to suppress the progress of AAR. However, it must be realised that exposure conditions have a paramount effect on the effectiveness of the surface coating systems, applied to inhibit AAR damage. Long-term results are needed to verify their continued effectiveness. The size of the specimens and their volume/surface area ratio will also determine how effectively the surface coatings will change the moisture content of the specimens and influence AAR expansion. The alkali content of the AAR-prone concrete also influences the expansion, such that it is more difficult to arrest the expansion when the alkali content is high.

Sound judgement is essential in applying a material that has been effective under one set of conditions to other conditions.

## ASSESSMENT AND REHABILITATION OF AAR-DAMAGED STRUCTURES

Professor Swamy presented his Keynote lecture on the important issue of assessment and rehabilitation of affected structures, the emphasis being placed on an integrated approach encompassing materials and structural design, testing methodologies for assessment of structures and their rehabilitation. The influence of exposure to the environmental conditions on the rate of deterioration of concrete structures is emphasized. A strategy is put forward to deal with all these aspects when faced with a practical case of assessment and rehabilitation. This type of comprehensive approach is expected to find more application as we face more deteriorated structures that need to be rehabilitated in order to extend their service lives.

Other papers in this category dealt with specific issues of rehabilitation such as the influence of cathodic protection on the enhancement of AAR in concrete. This issue needs much more research as definitive and comprehensive results are not available. Many factors, such as the type of materials used and the magnitude of impressed current, are expected to influence the outcome of such research work, and care must be taken not to generalise the results of specific research on this aspect to other cases.

The assessment of structural effects of AAR is followed by selection of materials and methods for the rehabilitation of the affected structure. Although some of the papers presented at the conference indicate that the load-carrying capacity of AAR-affected reinforced concrete structures is not reduced, it is stated that the elastic properties of the affected elements deteriorate. The reported reduction in the strength properties of affected concrete would assume different levels of significance depending on the size, location and function of the element, and generalisation could be dangerous. Accordingly, some elements may only need crack injection and surface coating, whereas others may need more substantial treatments such as steel plate bonding or other mechanical support and strengthening. Carbon fibre sheets have also been suggested for this purpose.

Because of rather limited data in this area, there is a need for a comprehensive document based on the review of the existing literature and also on new results from research program on the total issue of structural assessment and management of AAR-damaged structures. Unfortunately, such a document is lacking at present.

## MODELLING AAR IN CONCRETE

A field of activity in AAR research that was new at the 10th AARC related to modelling of AAR in concrete. Professor Moranville-Regourd presented a very interesting Keynote address on the topic, which explained the expansion of concrete based on thermodynamics and kinetics of the chemical reactions taking into account the diffusion law, probabilities of random gradients of alkali and reactive silica sites, and formation of AAR gel. The mechanical effects of the reactions, i.e. expansion in an anisotropic three-dimensional distribution in concrete, are modelled on the basis of (1) capillary pressure arising form the excess volume of expansive gels, (2) linear fracture mechanics applied to crack propagations, and (3) proportionality between confinement, temperature, R.H. and reactivity. The model closely predicted the experimental results for the pessimum content of reactive silica, and development of expansion as a function of consumed alkali. The model predicted that an isotropic confinement was beneficial in reducing the AAR expansion. Therefore, the model has enabled expansion to be predicted form chemical effects in an anisotropic medium such as concrete.

Papers presented at the conference show that other approaches to modelling AAR in concrete are being explored; some taking the chemical reactions into account in their constitutive model, and deriving the expansion from them, whereas another approach is to start from a predetermined free expansion and model the behaviour of concrete at the given free expansion, based on the theory of incremental plasticity.

In both cases, there seems to be a reasonable agreement between experimental and predicted data. Nevertheless, each makes a number of assumptions, and further work would be needed to evaluate the validity of the assumptions. When refined, they would be excellent tools to demonstrate the mechanical effects of AAR in concrete, and to use the results in maintenance strategies for affected structures.

## CONCLUDING REMARKS

The author hopes to have provided a very broad overview of the state of knowledge about the various aspects of AAR research as presented at the 10th IAARC in Melbourne last August. The conference has raised issues to which we do not have satisfactory answers, and clearly, further research is needed to clarify them. The author has provided a small example in relation to some accelerated test parameters, but much more is needed for other areas. We are obviously not at the end of AAR research and management. Much more work is needed in the area of assessment, rehabilitation and management of AAR-damaged structures. Lets hope that we will be closer to it by the end of the 11th IAARC to be held in Canada in the year 2000.

Further Reading: Keynote Lectures — Proceedings of the 10th International AAR Conference, Melbourne, Australia, 1996, pp. 3–83.

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