SUMMING UP

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It is quite impossible, in the time available, to sum up the contents of almost 40 papers and some very penetrating discussions on a paper by paper basis. I am therefore going to present, essentially in a general way, the most important points which emerged to me from each of the twelve sessions. I will then try and crystallize, in a simplified and brief form, ongoing action, first in respect of broad research objectives, and secondly in terms of what the engineer and/or user of suspect materials might do.

SESSION 1

OPENING

In his balanced and wide ranging keynote address, Dr Davis reviewed the incidence of, and background to, the alkali-aggregate reaction problem. He felt that we needed:

- a clearer understanding of the reaction mechanism;
- to develop a practical, rapid method of testing aggregate for reactivity;
- to make the optimum use of admixtures to control the problem; and
- to maintain a practical approach.

He compared the problem to that of shrinking aggregates and appealed for the use of sound engineering principles.

SESSION 2

ROLE OF ALKALIS IN CEMENT MANUFACTURING

Alkalis, generally as sulphates, profoundly influence the performance of cements in terms of their setting, strength and reaction with aggregate. We should be careful not to oversimplify the phenomenon, but important factors are the rate of reaction and the use of admixtures. While low alkali cement can be economically produced in dry process kilns using a precalciner and bypassing kiln gases, problems which arise are the need to handle more material, an imbalance of raw materials, a reduction in kiln and filter efficiency, possible strength reduction and increased energy consumption.

SESSION 3

ON THE INFLUENCE OF ALKALIS ON CEMENT AND CONCRETE

The influence of alkalis on cement is complex and not yet fully understood; until more is known, we should keep a balanced view. We do know that they increase the drying shrinkage, tend to result in undesirable gelatinous rather than crystalline hydrates, retard hydration and, with reactive aggregates, may result in the deterioration and cracking of concrete. The presence of alkalis is however, not entirely disadvantageous.

SESSION 4

THE ALKALI-AGGREGATE REACTION

The adverse affects of alkali-aggregate reaction can be reduced or eliminated by identifying and avoiding suspect aggregates or cements, or adding pulverised fuel ash or pozzolans. Existing tests are slow and do not necessarily reflect the performance of the aggregate or cements tested. Petrographic studies provide a useful basis for a further study of the materials concerned. While glasses of a wide range of compositions can react extensively with cements, even those with low alkali contents, a high alkali content or a porous structure enhances such reactivity. Glass-alkali reaction differs from that of the reactive, more porous aggregates and neither Pyrex glass nor Beltane opal model the behaviour of alkali-susceptible aggregates in concrete. Alkali-aggregate reaction in South Africa was confirmed in 1976 and its extent has been investigated, aggregates and cements have been evaluated and tentative criteria for their assessment and for the effectiveness of admixtures have been developed. Practical preventive and remedial measures to combat the problem have been made known and further studies of the phenomenon will be undertaken.

SESSION 5

ON THE TESTING FOR POTENTIAL REACTIVITY OF AGGREGATES AND CEMENTS

The diffusion controlled rate of expansion of cement bonded products is basically related to their ultimate expansion. The minimum rates of expansion above which materials cause deleterious effects have been established. The optimum test method depends on the type of aggregate, but is generally based on an appropriate accelerated prism test. The results of chemical tests, while promising, are difficult to interpret. Neither Pyrex glass nor Beltane opal prism tests are either reproducible or dependable criteria of the behaviour in practice of cements. For Malmesbury hornfels aggregates, the good relationship between expansion and the available alkali of cements is a promising criterion. The suitability of Tygerberg aggregates cannot be established by ASTM criteria and further work is needed. In New Zealand, it has been found that while petrographic methods and the ASTM method C 289 are useful, the ASTM C 586 test is not applicable to greywackes and expansion measurements

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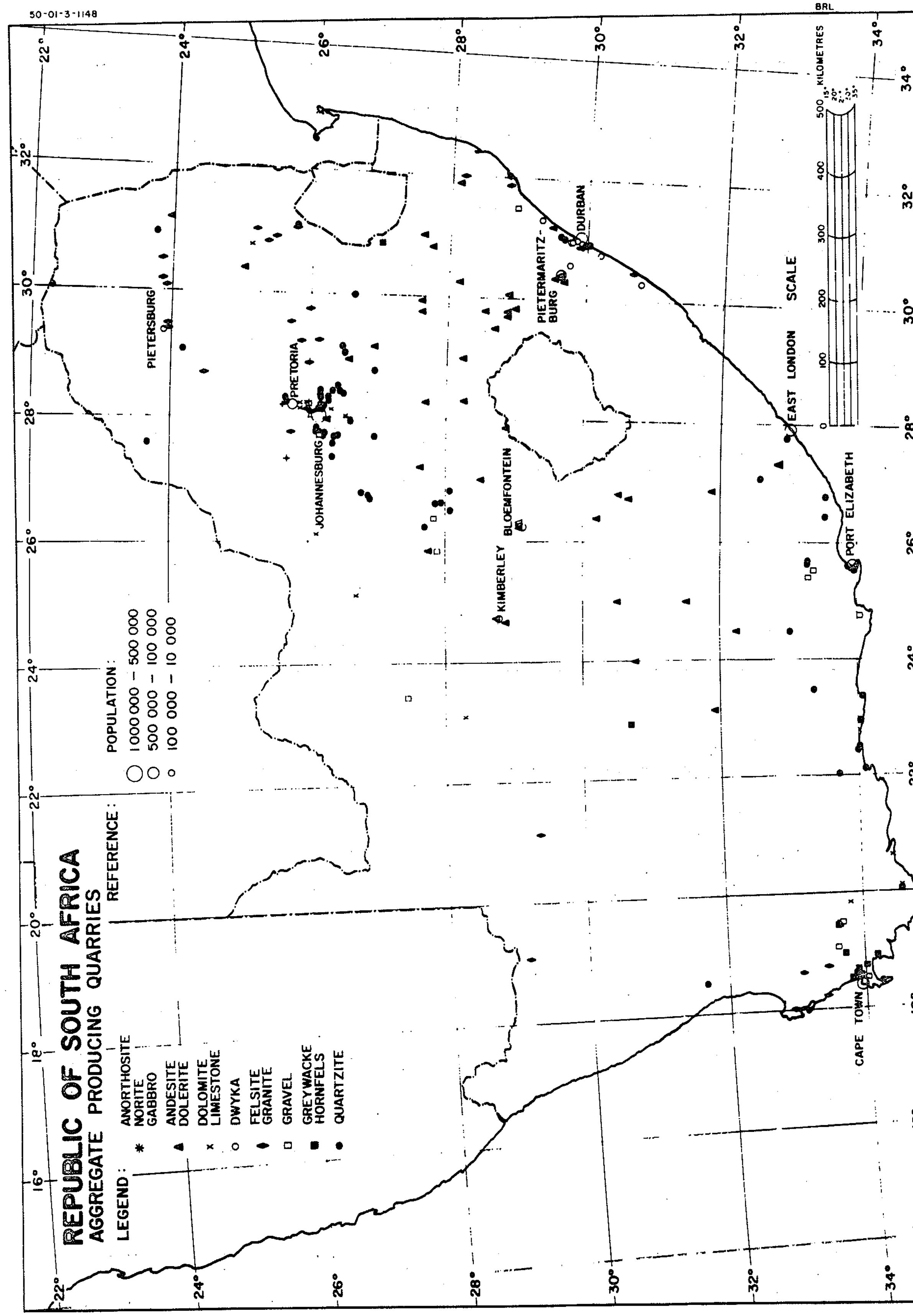

appear to be the only method of directly determining the effects of alkali-aggregate reaction. While the extra cost of manufacturing only low alkali cements may have been justified in the past, current energy conservation needs and economics now make this doubtful. Petrographic and gel pat tests are useful. The use of low alkali cements is not always appropriate. The effectiveness of mineral admixtures and of presently common remedial measures is uncertain and more research on them is needed.

SESSION 6

TECHNICAL EXCURSION

The very useful technical excursion to the Steenbras Dam, the Somerset West Freeway and bridge, the Landsdowne Road bridge and the dolosse (tetrapods) at the harbour container terminal, offering as they did a balanced cross section of the consequences of alkali-aggregate reaction, showed that:-

- the problem is insidious, takes time to manifest itself, and then takes various forms;
- the damage appears to be progressive;
- the extent of the problem ranges from mere disfigurement to significant structural damage;
- moisture and moisture content play an important but as yet incompletely understood role;
- the problem is sufficiently serious to justify ongoing attention and research and the application of the results of the research.

SESSION 7

ON APPRAISAL, PREVENTION AND REHABILITATION

Alkali-aggregate reaction forms a complex gel which absorbs water, expands and cracks the concrete to an extent where it can no longer perform its functions. There is no satisfactory cure and affected structures should be investigated in depth. In new construction the problem can be avoided by using non-reactive materials, identified as such by means of existing tests. In mass concrete the problem can be alleviated by replacing some of the cement by a suitable pozzolan. Severe deterioration of concrete made using Witwatersrand quartzite aggregate and which appears to occur only in conditions of cyclic wetting and drying and becomes apparent after 10 - 15 years, is compatible with alkali-aggregate reaction. Compressive strength is typically halved and tensile strength probably reduced to zero. A system of inspection and testing for monitoring deterioration was proposed.

Disproportionate attention to construction and design at the expense of good concrete technology has, during the last 30 - 40 years, resulted in severe concrete deterioration problems, including alkali-aggregate reaction, which can perhaps be better described as alkali-silica hydration. The cause and effects of this phenomenon on concrete structures are unpredictable. Future essential research should be rationalised by research workers and engineers working together to identify the most relevant problems and the best approach to solving them effectively and economically and should be based largely on existing knowledge. Expansive reaction increases with exposure to moisture and the massiveness of the sections. Its seriousness can be reduced by keeping the cement content to a minimum, providing drainage, avoiding dimensionally unstable aggregates, ensuring good curing, using air entrainment, preventing the entry of moisture and improving site control. Suspect structures should be regularly inspected and appropriate remedial measures taken. Alkali-aggregate-reaction-based problems in the South West United Kingdom involve sea dredged reactive sand, now no longer used. Ongoing research envisaged in the United Kingdom will include studies on the migration of alkalis, on aggregates, water and gel distribution and crack propagation, on various structural aspects and on the effectiveness of coatings and resin impregnation as remedial measures. Extensive field surveys in the South Western Cape in 1978 have indicated that alkali-aggregate reaction depends on moisture, temperature, cyclical water content changes and mix composition. While cracking of superstructures is more severe than in foundations, serious damage is considered unlikely. The 'present worth' value of the bridges and concrete roads showing definite signs of reaction is in the order of R40 million. The systematic recording of relevant data is recommended as an aid to the researcher.

SESSION 8

ON ALKALI-AGGREGATE REACTION IN CONCRETE PAVEMENTS

Alkali-aggregate reaction can result in the deterioration of a ten-year-old pavement to an extent where extensive and costly rehabilitation will be required within the next ten years. Overloading will seriously aggrevate the situation. Rehabilitation measures based on a computer model and heavy vehicle simulator studies, and involving the consideration of various alternatives, are being worked out.

SESSION 9

PANEL DISCUSSION

This panel discussion on the application of research was useful and stimulating but the many-faceted complexity of the matter and the lack of hard and generally applicable knowledge prevented any definitive conclusions. What did emerge was that:-

- factors such as wetting and drying, the role of water and temperature and the nature of the reaction actually involved should be taken into account;
- you have to depend on judgement rather than numbers;
- there is a risk of over reaction leading to an excessively conservative approach based on insistance on the too general use of low alkali cements and non-reactive aggregates;
- it is unlikely that the reaction can be completely suppressed or so modified as to be harmless;
- while the effectiveness of mineral admixtures has in principle been demonstrated and may also have cost advantages, no generally valid procedure can be prescribed with confidence at this stage;
- detailed appropriate and in depth petrographic studies are a powerful tool which should be fully used;
- vacuum processing of concrete is unlikely to remove soluble alkalis completely;
- since early microcracking plays a role, its reduction is advantageous;
- the use of coatings to reduce moisture content changes may be promising but is still unproven;
- the complicated and multi-disciplinary nature of the problem make the full and continuous involvement of all relevant disciplines and close and effective collaboration between them essential;
- a code of practice spelling out practical guidelines and a check list type procedure for the investigation of suspect materials is urgently needed.

SESSION 10

ON ALKALI-AGGREGATE REACTION MECHANISMS

It is possible to follow the kinetics in such reactions by measuring the rate at which alkalis are withdrawn from the pore solutions. The reaction velocity increases with temperature, and equilibrium can be reached after only 3 days. Expansion is not dependent on external water and typically lags behind the chemical reaction, indicating that they are separate processes. Variable expansions were found for synthetic soda-silica gels without any consistent relationship to the soda/silica ratio. Gels showing large expansions did not necessarily develop high swelling pressures. Scanning electron microscopy is a useful tool in this work.

Silica gel-sodium hydroxide model systems suggest that silicates or silica as such in alkali and hydroxyl ions from the pore fluid loosen the structure. Sodium ions diffusing in, lead to polyelectrolytes exerting imbibition pressure, with swelling and further disintegration.

The reaction is influenced by the type of material, particle size, the nature of the cement, the humidity and the temperature. Stronger concrete will expand more and for a longer period. Reacting particles can be made visible and an estimate of their number provides a means of evaluating the residual hazard.

No general agreement exists as to the precise nature of the expansive mechanism. The crystallinity of opaline material is reduced by reaction with sodium hydroxide. Osmotic effects are important in the basic reactions and while osmotic flow becomes almost negligible in time, continuing volume changes take place.

Mixing water content, in having an effect on porosity and concentrations in the pore solution, influences the reaction and thus the rate of deterioration.

Ionic plasticisers which release alkalis, influence the reaction, initially accelerating it. Expansion is accompanied by a decrease in the material's resonance frequency, followed by an apparent rehealing. Further studies are necessary especially with higher water cement ratios. In studies on popouts in concrete, changes in moisture content appear to be a basic factor. Such popouts are difficult to reproduce and their incidence is correlated to the amount of gel formation. Dimensional changes due to cement hydrates are small in relation to those resulting from reacting aggregate particles. The latter changes are also less reversible. Reaction products change from a rigid gel which causes deterioration to a sol which cannot cause expansion.

SESSION 11

ON MINERAL ADMIXTURES TO PREVENT ALKALI-AGGREGATE REACTION

Blastfurnace cements containing more than 65 per cent of slag demonstrate an increased resistance to both sulphate attack and alkali-aggregate reaction. While the reasons for this are not fully understood, their low permeability to ions and water, typically 5 to 20 times lower than in the case of comparable Portland cement mixes, is an important factor. Accelerated laboratory tests have shown that the addition of pulverised fuel ash can prevent the destructive effects of alkali-silica reaction, but this does not always apply in practice.

Cracking due to alkali-silica reactions, for a range of Portland cement concretes, only occurs if the water soluble alkali content expressed as equivalent Na_2O is greater than 2,5 kg per cubic meter. Reductions in the expansion of mortar prisms resulting from the addition of various mineral admixtures is significantly greater than the dilution effect. The reasons might be a lower alkali content, surface area and pozzolanic reactivity. In the evaluation of admixtures it must be ensured that the aggregate does not show a pessimum effect. With Pyrex glass and chert rock aggregates, both pulverised fuel ash and granulated blastfurnace slags at 30 to 50 per cent levels, reduce the expansion of mortar bars containing a high alkali cement to a value comparable to that of a low alkali Portland cement. Differences in the performance of different pulverised fuel ashes correlate with their pozzolanic activity but insufficient data are available to give full guidance. A suitable pulverised fuel ash improves concrete workability, bleeding, durability and density, reduces the heat of hydration and has only minor effects on most other properties. It is being used in about 10 per cent of ready mixed concrete in Cape Town.

SESSION 12

ON PETROGRAPHIC AND ELECTRON MICROSCOPIC EXAMINATION

Certain carbonate aggregates react with alkalis in concrete and can cause deleterious expansion. Electron probe microanalysis studies have indicated that dedolomitisation is involved and that additional alkali increases the reaction rate. Dedolomitisation does not in itself cause deterioration, which is attributed to clay particles in the reactive zone exposed by the dedolomitisation. Other studies on concrete containing glass aggregates have shown the formation of a gel, which under heat and pressure crystallises to yield silicates similar to tobermorite but containing alkalis in solid solution. Progressive structuring of the gels in silicate crystals is promoted by increased temperatures. Etteringite and calcium hydroxide reinforce alkali-aggregate type reactions.

The undulatory extinction angle, itself a measure of imperfection in the crystal lattice, is widely used as a method of identifying alkali reactive quartz. Anomalous findings have however emerged and for good results data are required on the amount and nature of quartz present and the intensity of the undulatory extinction. Suspect South African aggregates include rock types such as quartzite, sandstone, granite, adesite and hornfels, all of which may react adversely with alkalis in cement. Petrographic studies have shown the presence of strained quartz in such materials. The likely performance and selection of aggregates should not be judged solely on the presence of potentially reactive minerals but largely on the past performance of the aggregate.

RESEARCH OBJECTIVES AND PHILOSOPHY

The following general impressions about ongoing research and some principles and specific action which might be considered, emerged:-

1. In applying our very limited research resources and manpower, we must accept that we cannot examine all those aspects of the problem in the depth and detail we would like, and that we must look critically at our priorities; we must do this in close collaboration with overseas and local research colleagues, engineers and the local construction and quarrying industry.

2. A systematic international inter-laboratory test series comparing results obtained on identical samples provided by one participating laboratory, using similar experimental conditions and making the results generally available, would be a most valuable liaison activity and serve as a basis for validly comparing techniques and findings.

3. In our research and in the application of the results of the research, there is a strong case for more generally and explicitly recognising the fact that cement and aggregates are engineering raw materials and not chemical products.

4. Specific and high priority research activities should be aimed at:-

   - the development of reproducible, rapid, simple and meaningful assessment tests to identify and characterise potentially reactive aggregates and cements;
   - obtaining a deeper understanding of the role of water in its various forms in the alkali-aggregate reaction;
   - the identification and characterisation of each of the obviously different but presently undefined types of alkali-aggregate reaction, and an understanding of the mechanism.
   - the development of economic and practical preventive and remedial measures.

5. A specific research based objective should be the development of a set of published guidelines in the form of a checklist type procedure which will enable the engineer to establish as simply and as unequivocally as possible:-

   - exactly what type of reaction might be involved and how serious it is likely to be;
   - what the broad alternative approaches are;
   - precisely, and in detail, what further steps the engineer should consider to arrive at the best solution or solutions to the problem; and
   - the cost implications of each alternative.

6. The results of research should be written up and published in a form which is fully meaningful to all users, especially engineers.

7. Research workers, again in collaboration with the industry and engineers, should work out a uniform, preferably international and very specific set of definitions and nomenclature. It should be meaningful to all disciplines concerned such as engineers, chemists, physicists and geologists. Similarly, there is a need for an internationally accepted set of standard conditions in respect of factors such as temperature and humidity. This would facilitate communication and consequently lead to more meaningful collaboration.

ENGINEER / USER ACTION

In closing this summing up, it seems appropriate to express a few comments and ideas of possible interest to engineers, contractors and the users of concrete.

1. This conference has been unique in the width of interests of the participants, ranging from specialists to practicing engineers. The research has led to a good deal of specialised discussion and we should not confuse the apparent incompatibility or even conflict of many of the research findings with the fact that generally valid information based on proven experience is already available as a basis for useful action, until a more final picture emerges from further research.

2. There is a need to plan the testing and selection of aggregates and cements on a longer term basis, especially in the case of large or critical structures or where there is reason to suspect the presence of the alkali-aggregate reaction. In this complex matter such tests take time and early testing can save a good deal of money by making possible more economical solutions.

3. In much the same way that research workers should make their findings known to engineers in more meaningful terms, so should more engineers make fuller and more discriminating use of research findings rather than overreact by taking blanket decisions such as prescribing low alkali cement and nonreactive aggregates. Such decisions could well be based on full in-depth cost benefit studies of the various alternative courses of action.

4. New knowledge and techniques regarding alkali-aggregate reaction and its control should be taught to civil engineering students and might also profitably form the subject of on-going and continuing education in the form of short courses for experienced engineers.

5. Judgement, which is not always easy to exercise, should be used when addressing an alkali-aggregate reaction problem: the numbers are not yet available and will only emerge when research has progressed a good deal further.