realistic attempt to formulate and solve this problem.

I agree that there are important points needing clarification and explanation in the biaxial region. It is my view that this clarification is not impossible, although it has not yet been achieved. It is also evident that strain failure theories have not received adequate attention.

Finally I am unable to accept the statement by Dr Kotsovos and Dr Newman that “no evidence has been found to support the hypothesis of constant ultimate tensile strain”. I believe that there is *some* evidence, though I would agree that more is needed before drawing too many conclusions or becoming too committed to a strain-criterion viewpoint.

REFERENCES

1. KOTSOVOS, M. D. *Mathematical description of deformational behaviour of concrete under generalised stress states*. London, Imperial College of Science and Technology, 1978. pp. 242. Interim Report, Civil Engineering Department.
2. KOTSOVOS, M. D. and NEWMAN, J. B. Generalised stress-strain relations for concrete. *Proceedings of the American Society of Civil Engineers*. Vol. 104, No. EM4. August 1978. pp. 845–856.
3. KOTSOVOS, M. D. and NEWMAN, J. B. A mathematical description of deformational behaviour of concrete under complex loading. *Magazine of Concrete Research*. Vol. 31, No. 107. June 1979. pp. 77–90.
4. KUPFER, H., HILSDORF, H. K. and RÜSCH, H. Behavior of concrete under biaxial stresses. *Journal of the American Concrete Institute. Proceedings* Vol. 66, No. 8. August 1969. pp. 656–666.
5. GERSTLE, K. H. et al. Strength of concrete under multiaxial stress states. *Douglas McHenry International Symposium on Concrete and Concrete Structures*. Detroit, American Concrete Institute, 1978. ACI Publication SP-55. pp. 103–131.
6. KOTSOVOS, M. D. and NEWMAN, J. B. Behavior of concrete under multiaxial stress. *Journal of the American Concrete Institute. Proceedings* Vol. 74, No. 9. September 1977. pp. 443–446.
7. BRIDGMAN, P. W. Breaking tests under hydrostatic pressure and conditions of rupture. *Philosophical Magazine*. Vol. 24. 1912. pp. 63–80.

Expansion of concrete due to alkali-silica reaction: an explanation*

D. W. Hobbs

Contribution by G. M. Idorn

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Dr Hobbs's paper is a valuable contribution to the clarification of the pessimum-proportion concept regarding alkali-silica reactions in mortar bars. An early approach by Poulsen⁽¹⁾ and a recent one by Ozol⁽²⁾ to supplementary aspects of this problem should be kept in mind, because there is still a long way to go before the jigsaw puzzle of quantified knowledge on alkali-silica reactions can be made into an effective system for practical control. In order to achieve this, we must learn whether the particular pessimum proportion for any single particle-size fraction of the reactive aggregates adds up over the whole range of granulometry to a 'composite' pessimum for each type of reactive rock. Moreover, in this picture there are at least two more variables to consider: the ratio of the alkali content to reactive material by weight and the temperature development throughout the period of reaction. The latter parameter may be kept reasonably constant in small bars, but this may,

on the other hand, be misleading by interpretation, owing to the thermal sensitivity of the entire complex of hydration reactions to which, basically, the alkali-silica reactions also belong.

In general the continuity of the system cannot be taken for granted, either mechanically or chemically, because our knowledge is so fragmented. Thus a long period of patient compilation of fragmentary knowledge seems still necessary before we reach the stage at which we can say that certain peak regions of alkali-lime-silica-water compositions are expansively reacting in concrete, whilst the major regions – also with alkalies and reacting silica – are innocuous, in fact even useful.

A word of caution: the title of the paper refers to concrete, but it deals with mortar. In concrete, one has mortar between the coarse aggregate particles. If they comprise reactive materials, the 'reaction picture' is very different from that studied laboratory-wise by most researchers, and direct transfer of theoretical or empirical models is not justified or helpful as guidance for practice.

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Contribution by G. S. Dhillon, BSc, PhD, FIE

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Dr Hobbs must be congratulated for attempting a description of the influence of reactive aggregates in reinforced concrete structures. This has given us a very good paper, but he has not explained why the pattern cracking of the tank-trap structure built on

the Suffolk coast (Figure 1 of the paper) is attributed to alkali-silica reaction. A structure can experience this type of distress as the result of sulphate action instead. Will Dr Hobbs elucidate this point further?

Reply by the author

I appreciate the interest in my paper shown by Dr Idorn and Dr Dhillon. In reply, I would like to offer the following comments.

A number of the points raised by Dr Idorn are discussed in a paper published in this issue⁽³⁾ and in two papers in the process of publication^(4, 5).

The volume concentration of the gel product resulting from the alkali-silica reaction appears to be a function of the following parameters⁽³⁻⁵⁾: the proportion of reactive opaline-type material in the aggregate, reactive particle size, water-soluble alkali content of the cement, water/cement ratio, aggregate/cement ratio, temperature and age. If the volume concentration of the gel formed after the concrete has hardened is sufficient to disrupt the concrete, the final level of expansion is dependent upon the alkali content per unit volume of the concrete if the alkali-reactive silica ratio lies below its most critical value but upon the volume concentration of the opaline material in the concrete if the alkali-reactive silica ratio lies above its most critical value. In my view, neither the time to cracking nor the level of expansion should be expressed as a function of the alkali-reactive silica ratio.

In the case of aggregates containing an opaline constituent readily accessible to hydroxyl ions, it has been shown that the most critical alkali-reactive silica ratio is independent of reactive-aggregate particle size for particles in the range 20 μm to 2.4 mm⁽³⁾. Since the most critical alkali-reactive silica ratio will be independent of aggregate/cement ratio, it is possible to predict the expansion behaviour of concretes from mortar bar tests, provided the particle size of the reactive aggregate is known and lies within this range and provided the opaline material is accessible to hydroxyl ions. As an example, the predicted influence of aggregate/cement ratio upon the expansion of concretes having a water/cement ratio of 0.41, a cement with a water-soluble alkali content (expressed as Na_2O) of 0.8% and reactive aggregate particles in the size range 600 μm to 1.18 mm is shown in Figure I. To obtain the expansion, it was assumed that the peak expansion for a concrete having a water/cement ratio

Figure I: Predicted influence of aggregate/cement ratio upon expansion.

of 0.41 and an aggregate/cement ratio of 2 occurs at a reactive aggregate content by weight of total aggregate of 5% (see Figure 4a of my paper).

With regard to Dr Dhillon's question relating to Figure 1 of my paper, the concrete between the cracks in the tank traps is of high strength and the product exuding onto the surfaces of the tank traps is calcium carbonate. A petrological examination of a thin section cut from the interior of a tank trap showed that: a number of cracks in several aggregate particles were filled with a gel typical of the alkali-silica reaction; that some aggregate particles had partially dissolved; that ettringite (or thaumasite), was present in low concentrations – in our experience 'ettringite' is often detected in air voids in thin sections of hardened concrete; that the aggregate contained an opaline constituent; and that no dissolution of the cement paste has occurred. We therefore concluded that the map-cracking on the tank traps had probably been caused by the alkali-silica reaction, supplemented by weathering for some thirty years. Temperate sea waters rarely produce deterioration in concrete structures which is characteristic of sulphate attack.

REFERENCES

1. POULSEN, E. Part of discussion of the two-part paper by T. C. POWERS and H. H. STEINOUR. An interpretation of some published researches on the alkali-aggregate reaction. *Journal of the American Concrete Institute. Proceedings* Vol. 51. December 1955. Part 2. pp. 812-1 to 812-20.
2. OZOL, M. A. The pessimum proportion as a reference point in modulating alkali-silica reaction. *Symposium on Alkali-Aggregate Reaction - Preventive Measures, Reykjavik, August 1975*. Reykjavik, Icelandic Building Research Institute and State Cement Works, 1975. Rannsóknastofun byggingaridnadarins 16. pp. 113-130.
3. HOBBS, D. W. and GUTTERIDGE, W. A. Particle size of aggregate and its influence on the expansion caused by the alkali-silica reaction. *Magazine of Concrete Research*. Vol. 31, No. 109. December 1979. pp. 235-242.
4. GUTTERIDGE, W. A. and HOBBS, D. W. Some chemical and physical properties of Beltane opal rock and its gelatinous alkali-silica reaction product. (To be submitted to *Cement and Concrete Research*.)
5. HOBBS, D. W. *Influence of water/cement ratio and cement alkali content upon expansion due to the alkali-silica reaction*. Wexham Springs, Cement and Concrete Association. Technical Report to be published.