The alkali-silica reaction — a model for predicting expansion in mortar

D. W. Hobbs

CEMENT AND CONCRETE ASSOCIATION : RESEARCH AND DEVELOPMENT DIVISION

SYNOPSIS

Data are presented which illustrate the influence that reactive aggregate content, mix proportions and cement alkali content have upon the time to cracking and upon the subsequent expansion of mortar specimens stored in water at 20 °C. It is shown that an assumption that the alkali-silica reaction is a two-stage process leads to predictions which are in general agreement with the observed expansion behaviour of mortars.

Introduction

Cracking in concrete can sometimes be caused by a reaction between the hydroxyl ions in the pore water of the concrete and reactive siliceous material which is present as a constituent in the aggregate. A few cases of damage due to this reaction have occurred in the UK⁽¹⁾. Such a reaction is termed an alkali-silica reaction and its product is a gel which imbibes water, expands and produces internal stresses which are sometimes sufficient to cause the concrete to crack. Silica can occur in a variety of forms in aggregate; quartz is the commonest form and is inert under normal conditions, whereas opaline silica is the most reactive⁽²⁻⁶⁾.

In concrete structures where cracking and excessive expansion have occurred as a result of the alkali-silica reaction, the aggregate is often found to contain opaline silica^(2, 7-13). Such material is frequently used in laboratory studies, since it may be found to occur as a constituent of chert, flint, shale, sandstone, limestone and other rocks^(4, 7, 13).

In the present paper, a model is presented which offers a possible explanation for the expansion observed in mortars which contain a reactive constituent accessible to hydroxyl ions and which are stored under water at 20 °C. The predictions arising from this model are compared with data obtained experimentally. Beltane opal, in the size fraction 150 to

300 μm , was used as the reactive constituent of the aggregate. A number of the chemical and physical properties of Beltane opal have been described by Gutteridge and Hobbs⁽¹⁴⁾, who concluded that it contained approximately 80% of reactive siliceous material, but that its reactivity at 20 °C was due principally to the presence of opal-A. The proportion of opal-A in Beltane opal was estimated to be 46% by weight. A comparison of the expansion of mortar bars containing a number of reactive aggregates is shown in Figures 1a and 1b. An examination of these Figures shows that when the different reactive aggregates, each containing opaline material, are used, expansion behaviour obtained is similar. As far as the author is aware, no natural aggregate containing opaline material, apart from pure opal, induces greater mortar bar expansion than that observed with Beltane opal.

Expansion tests are conventionally carried out on mortar bars and as a result very few data on concrete exist. Higher strain energies are necessary to cause cracking in concretes than in mortars and consequently the model is not directly applicable to concrete. However, it is shown that a simple modification of the model enables predictions to be made which are in general agreement with the limited experimental data obtained on concrete.

The model presented is not applicable to mortars or concretes containing a reactive constituent in the aggregate which is not readily accessible to hydroxyl ions.

Expansion induced by the reaction between opaline material and cement alkalis⁽¹⁸⁾

Figures 2a, 3a and 4a show how the expansion of mortar bars observed at 200 days is influenced by the content of reactive aggregate, the mix proportions and the alkali content, expressed as equivalent Na_2O , of the

Figure 1a: Comparison of expansion behaviour produced by four aggregates containing opaline material. (The acid-soluble alkali content is expressed as equivalent Na_2O .)

Figure 1b: Comparison of expansion behaviour produced by five aggregates containing opaline material. (The acid-soluble alkali content is expressed as equivalent Na_2O .)

(a) Observed

(b) Predicted

Figure 2: Relationship between expansion at 200 days and Beltane opal contents. $w/c = 0.41$, $a/c = 2$, $(\text{Na}_2\text{O})_{ew} = 0.8\%$, $(\text{Na}_2\text{O})_e = 1.04\%$. $(\text{Na}_2\text{O})_{ew}$ is the water-soluble alkali content of the cement.

(a) Observed

(b) Predicted

Figure 3: Influence of mix proportions upon relationship between expansion at 200 days and Beltane opal content. $(Na_2O)_{cw} = 0.8\%$, $(Na_2O)_c = 1.04\%$.

mortars. It is found that, for a given mix and cement alkali content, the expansion of the mortar bars increases with 'reactive aggregate content' until a maximum expansion is reached; the observed expansion then decreases as the content of reactive

aggregate is increased further. The reactive aggregate content producing the maximum expansion is called a 'pessimum content'. In the case of mortars with a cement content of 550 kg/m^3 made with a cement of high alkali content, the pessimum Beltane opal content

(a) Observed

(b) Predicted

Figure 4: Influence of cement alkali content upon relationship between expansion at 200 days and Beltane opal content. $w/c = 0.41$, $a/c = 2$.

is approximately $4\frac{1}{2}\%$ and, since not all the Beltane opal is reactive, the actual pessimum opaline content will be less than $4\frac{1}{2}\%$, possibly as low as 2 to $2\frac{1}{2}\%$. In practice, the proportion of opaline material contained in a reactive aggregate will be significantly lower than in Beltane opal and a maximum expansion will consequently not be observed for such aggregate unless the proportion by weight of accessible opaline material in the reactive aggregate is greater than about $2\frac{1}{2}$ to 4% by weight; this figure could be higher if the cement content is greater than 550 kg/m^3 . Thus, when the proportion of the reactive constituent in the reactive aggregate is less than $2\frac{1}{2}$ to 4%, no pessimum reactive aggregate content will be observed and the greatest expansion will occur when 100% reactive aggregate is used.

Cracking and expansion of the mortar bars containing Beltane opal have only been observed when the ratio of the water-soluble alkali content to Beltane opal content exceeds approximately 0.02. At the peak expansion, this ratio is approximately 0.07. The ratio of alkali to Beltane opal associated with the peak expansion will be termed 'the most critical ratio'. The behaviour of concrete and mortar at this most critical ratio is of particular practical significance because, if such a concrete or a mortar does not crack at this critical condition, similar concretes or mortars with

the same alkali content, but with a higher or lower opal fraction, will not crack as a result of the alkali-silica reaction.

The influence of mix proportions and water-soluble cement alkali content upon the expansion behaviour of mortar (which contains an opaline constituent) and having an alkali-reactive silica ratio close to the most critical value is illustrated in Figures 5a, 6a and 7a. The data shown in Figure 5a were obtained by using a cement having a water-soluble alkali content of 0.8% by weight and the data given in Figures 6a and 7a were obtained by using mortars having mix proportions of

$$w/c = 0.41, a/c = 2$$

and

$$w/c = 0.53, a/c = 3.75$$

respectively. It can be seen that expansion occurs slowly at first and there then follows an abrupt increase in the rate of expansion. The increase in the rate of expansion occurs when the internal stress generated by the formation of the calcium-alkali-silicate gel can no longer be sustained by the mortar, which cracks*. The strain at which cracking occurs is generally less than 300×10^{-6} . Figures 5a, 6a and 7a show that time to cracking decreases, whereas the expansion produced after prolonged curing increases as the alkali content

*The earliest age at which cracking has been observed is 2 days.

(a) Observed

(b) Predicted

Figure 5: Influence of mix proportions upon expansion behaviour. $(Na_2O)_{cw} = 0.8\%$, $(Na_2O)_c = 1.04\%$.

Figure 6: Influence of cement alkali content upon expansion behaviour. $w/c = 0.41$, $a/c = 2$.

Figure 7: Influence of cement alkali content upon expansion behaviour. $w/c = 0.53$, $a/c = 3.75$.

of the cement is increased and as both the water/cement and the aggregate/cement ratios are reduced.

The model

The model presented here is based in part upon an earlier model⁽¹⁹⁾ in which it was assumed that, if the hydroxyl ion concentration was sufficient to maintain the alkali-silica reaction, the reaction rate was directly proportional to the quantity of reactive aggregate, y , remaining at time t thus

$$\frac{dy}{dt} = -k_1 y$$

However, examination and comparison of the data shown in Figures 4a, 6a and 7a showed that both the time to cracking and the magnitude of expansion are influenced by cement alkali content. These facts indicated that the earlier model was oversimplified. Attempts to describe the observed behaviour by assuming that the reaction rate was given by

$$\frac{dy}{dt} = f(y, A)$$

where A is the alkali concentration in the pore water, proved to be unsuccessful; consequently a revised model based on the following assumptions was developed.

- (1) The alkali-silica reaction is a two-stage process.
- (2) In the first stage, the alkalis and accessible reactive siliceous material react rapidly until one or other of the reactants is depleted.
- (3) Provided there is an excess of alkalis, the reaction product imbibes water and hydroxyl ions to form an alkali-silica gel (the second reaction product) at a rate proportional both to the quantity of the first reaction product remaining at time t and to a simple power function of the alkali concentration in the pore water at the time the first reaction is complete. (The decline in alkali concentration with time is being ignored and, as a consequence of this, equilibrium will possibly be established more slowly in mortar bars than is predicted.)
- (4) Any gel (the second reaction product) formed while the mortar is setting and hardening is accommodated within the mortar without the development of significant internal stress. The earliest age at which specimens were observed to crack as a result of the alkali-silica reaction was 2 days; it is therefore assumed that internal stress, due to the formation of gel, is not induced until after $1\frac{1}{2}$ days.
- (5) Cracking is induced in the mortar bars only when the volume concentration of gel formed after the mortar has hardened exceeds a particular value.
- (6) Expansion is proportional to the volume of gel formed after cracking occurs. *Note that it is implicit in this assumption that the physical properties of the gel are independent of reactive aggregate content, mix proportions and cement alkali content and that expansion is not influenced by porosity of the mortar and rate of gel formation.*
- (7) The second reaction process goes to completion stoichiometrically when the alkali-Beltane-opal ratio is equal to a particular value which, from the data reported earlier, is calculated to be 0.067.

The above assumptions can be expressed analytically as follows.

Assumption 1. Since it has been observed that cracking due to the alkali-silica reaction does not occur when the alkali-Beltane-opal ratio is less than 0.02, the available alkali content from the cement when the first reaction is completed is taken to be

$$(\text{Na}_2\text{O})_{\text{ew}} \left[1 - \frac{0.02 R a/c}{(\text{Na}_2\text{O})_{\text{ew}}} \right]$$

where R is the Beltane opal content by weight of total aggregate and $(\text{Na}_2\text{O})_{\text{ew}}$ is the water-soluble alkali

content of the cement expressed as equivalent Na_2O . The alkali concentration in the pore water when the first reaction is complete is assumed to be given by

$$A = (\text{Na}_2\text{O})_{\text{ew}} \left[1 - \frac{0.02 R a/c}{(\text{Na}_2\text{O})_{\text{ew}}} \right] / w/c$$

Assumption 2. The rate at which the first reaction product is converted into gel is given by

$$\frac{dv}{dt} = -k_2 A^{k_3} v$$

where v is the volume concentration of the stage 1 reaction product remaining at time t and k_2 and k_3 are constants. This rate equation was chosen in part for mathematical convenience and in part because the plots of observed expansion against time for mortar bars were approximately exponential.

Assumptions 3, 4 and 5. The expansion of the mortar after cracking occurs is given by

$$k_4 \{ V_R [\exp(-1.5 k_2 A^{k_3}) - \exp(-k_2 A^{k_3} t)] - k_5 \}$$

provided the hydroxyl ion concentration is sufficient to maintain the reaction, where V_r is the volume concentration of Beltane opal in the mortar. The constants k_2 , k_3 and k_5 were determined numerically from the experimental data and found to be 1×10^6 , 5 and 0.004 respectively. The constant k_4 was taken to be equal to 0.715. A value for k_4 was chosen so that the model correctly predicts the expansion at 200 days of mortar specimens made a water/cement ratio of 0.41, an aggregate/cement ratio of 2, a reactive aggregate content, R , of 0.06 and a cement with a water-soluble alkali content expressed as equivalent Na_2O of 0.8%. The time to cracking is obtained from the above expression and is given by

$$t_c = \frac{-\ln[\exp(-1.5 k_2 A^5) - 0.004/V_R]}{k_2 A^5}$$

Comparison between predicted and observed expansion behaviour

INFLUENCE OF MIX PROPORTIONS AND REACTIVE AGGREGATE CONTENT

Values of the predicted expansion at 200 days obtained by using this model are shown plotted against reactive aggregate content for specimens having various mix proportions in Figures 2b and 3b. In Figure 5b expansion has been plotted against age for those specimens which produce the largest observed expansion. Comparing these Figures with Figures 2a, 3a and 5a indicates reasonable agreement between predicted and observed behaviour. The model predicts correctly that expansion may increase or decrease as both the water/cement and the aggregate/cement ratios are increased, depending upon the proportion of

opaline material present in the aggregate. At the lower values of water/cement and aggregate/cement, the model predicts a greater dependence of expansion upon mix proportions than was observed.

CEMENT ALKALI CONTENT

The predicted influence of cement alkali content upon expansion behaviour is shown in Figures 4b, 6b and 7b. In Figure 4b the expansion observed at 200 days is shown plotted against reactive aggregate content, whereas in Figures 6b and 7b expansion has been plotted against age for those specimens which produced the maximum observed expansion. There is reasonable agreement between the data given in these Figures and Figures 4a, 6a and 7a.

TIME TO CRACKING

In Figure 8 the predicted time to cracking is shown plotted against the observed time to cracking, whilst in Figures 9a and 9b the observed and predicted times to cracking (see Appendix) are shown plotted against water-soluble alkali content for specimens with alkali-Beltane-opal ratios of approximately 0.07. The same lower-bound curve is shown plotted in both Figures 9a and 9b. General agreement exists between the observed and predicted times to cracking.

Figure 8: Comparison between predicted and observed time to cracking. $0.26 \leq (Na_2O)_{ew} \leq 1.25\%$, $0.45 \leq (Na_2O)_e \leq 1.49\%$.

Figure 9: Variation of observed and predicted times to cracking with water-soluble alkali content of the mortars (see Figure 8 for key).

Figure 10: Comparison between predicted and observed expansion at 200 days (see Figure 8 for key).

EXPANSION

The predicted and observed expansions at 200 days are compared in Figure 10 and in Figures 11a and 11b for specimens with alkali-Beltane-opal ratios of approximately 0.07. The same lower-bound curve is shown in both Figures 11a and 11b. It can be seen from Figure 10 that there is a wide spread in the plotted results.

PARTICLE SIZE OF REACTIVE AGGREGATE

It is known that reactive particle size can have a major influence upon the extent of the observed expansion induced in mortar bars by the alkali-silica reaction^(3, 16, 20). This is illustrated in Figure 12 where observed expansion is shown plotted against age for specimens containing Beltane opal particles in the size ranges 150 to 300 μm and 1.18 to 2.36 mm. Note that times to cracking are similar although the expansions are very different. The model proposed in the current paper is unable to account for the influence of reactive particle size upon expansion behaviour. However, it is possible, since the times to cracking are independent of particle size, that the expansion behaviour of mortar bars containing Beltane opal particles in the size range 300 μm to 2.36 mm can be predicted simply by adjusting the value of the constant k_4 .

(a) Observed

(b) Predicted

Figure 11: Variation of observed and predicted expansion at 200 days with water-soluble alkali content of the mortars (see Figure 8 for key).

Figure 12: Influence of reactive particle size upon expansion behaviour. $w/c = 0.47$, $a/c = 3$, $R = 0.02$, $(Na_2O)_c = 1.04\%$, $(Na_2O)_{cw} = 0.8\%$.

Figure 14: Influence of a/c ratio upon the relationship between predicted expansion at 200 days and Beltane opal content. $w/c = 0.47$, $(Na_2O)_{cw} = 0.8\%$.

Additional predictions of the model

WATER/CEMENT RATIO, AGGREGATE/CEMENT RATIO AND CEMENT ALKALI CONTENT

It has been shown that the predictions of the model are in approximate agreement with the limited data obtained on mortar bars containing Beltane opal. It is therefore probable that the model can correctly predict the general effect of changing water/cement ratio, aggregate/cement ratio and cement alkali content upon the expansion behaviour of mortar bars

Figure 13: Influence of water/cement ratio upon the relationship between the predicted expansion at 200 days and Beltane opal content. $a/c = 4$, $(Na_2O)_{cw} = 0.8\%$.

containing Beltane opal. The predicted influence of water/cement ratio and aggregate/cement ratio upon the expansion of mortar bars is shown in Figures 13 and 14, whilst in Figure 15 the predicted expansion is shown plotted against the water-soluble alkali content of the cement for specimens tested at their most critical

Figure 15: Predicted influence of cement alkali content upon expansion at 200 days and some observed results. (V17 opaline rock was used with a particle size of 300 to 900 μm ; the cement had an acid-soluble alkali content of 0.59% and additional alkalis were added as NaOH.)

alkali-Beltane-opal ratio.* Figure 15 includes some experimental data obtained on Beltane opal and data obtained by Vivian⁽²²⁾ on V17 opaline rock.

From Figures 13 and 14 it can be seen that the predicted expansion of mortars bars may increase or decrease as the water/cement ratio and the aggregate/cement ratio are increased, depending upon the proportion of opaline material present in the aggregate. The model predicts that, at the critical alkali-Beltane-opal ratio, the expansion is a maximum when the water/cement ratio is between 0.41 and 0.47 (see Figure 13); this prediction is in agreement with the experimental observations of Jones and Tarleton⁽²¹⁾ obtained when they used a siliceous magnesium limestone containing an opaline constituent.

It has been suggested⁽¹²⁾ that the partial replacement of an aggregate containing a reactive constituent by an inert aggregate can reduce expansion caused by the alkali-silica reaction. It can be seen from Figure 14 that this is only so if the content of the reactive constituent before partial replacement is below that necessary to produce a peak expansion.

An examination of Figure 15 shows that the model predicts that the expansion of mortar bars of given proportions increases with the alkali content of the cement until a maximum is reached; the predicted expansion then decreases as the alkali content of the cement is increased further. The expansion data obtained by Vivian using V17 opaline rock show a dependence upon the alkali content of the cement similar to that predicted.

CONCRETE

It has been shown that more energy is required to propagate a crack in concrete than in mortar⁽²³⁾. It is therefore probable that greater reaction due to the alkali-silica reaction will be necessary to initiate cracking in concretes than is the case for mortars. Thus the predictions of the model are unlikely to be in agreement with results obtained on both mortars and concretes containing Beltane opal unless a higher value for the constant k_5 is chosen for concrete than for mortars. This is illustrated in Figures 16a, b and c where the expansion predicted by the model when k_5 is equal to 0.004 and 0.010 is compared with the observed expansion of concretes stored at 20 °C. When k_5 is equal to 0.004 the actual times to cracking are greater and the expansions less than those predicted, but when k_5 is equal to 0.010 closer agreement is obtained with the few results illustrated in Figure 16a. In tests on concretes so far carried out by the author, no concretes with acid-soluble alkali contents below 4.0 kg/m³ or with water-soluble alkali contents below 3.0 kg/m³

(a) Observed

(b) Predicted, $k_5 = 0.004$

(c) Predicted, $k_5 = 0.010$

*Since Figure 15 refers to specimens tested at their most critical alkali-Beltane-opal ratio, the predicted expansion could equally well have been plotted against the alkali content of the mortar or alternatively the Beltane opal content.

Figure 16: Influence of mix proportions upon expansion behaviour of concrete.

have cracked as a result of the alkali-silica reaction. The comparable figures for mortars are 3.5 kg/m³ and 2.6 kg/m³ respectively.

Dahms and Sprung in 1973 reached similar conclusions from tests on concretes⁽²⁴⁾ and mortars⁽²⁵⁾ containing an opaline sandstone from North Germany and stored at 40 °C. Dahms observed that no cracking due to the alkali-silica reaction occurred in concrete cubes and prisms when the cement content was less than 400 kg/m³ (i.e. when the acid-soluble alkali content was less than about 4 kg/m³) and that cracking when the cement content was 600 kg/m³ only occurred when a high-alkali-content cement was used. In the case of mortars, Sprung concluded that cracking due to the alkali-silica reaction would not occur if the acid-soluble content was less than 3.0 kg/m³.

Conclusions

- (1) Cracking and expansion of mortar bars containing Beltane opal are only observed when the ratio of the water-soluble alkali content to the Beltane opal content exceeds approximately 0.02.
- (2) The strain at which cracking occurs is generally less than 300×10^{-6} .
- (3) The ratio of the water-soluble alkali content to the Beltane opal content at the peak expansion after prolonged moist curing is approximately 0.07.
- (4) It is deduced from the experimental results that the alkali-silica reaction is a two-stage process.
- (5) A model is presented which predicts that the time to cracking is given by

$$-\ln \left[\frac{\exp(-1.5k_2A^{k_3}) - k_5/V_R}{k_2A^{k_3}} \right]$$

and the expansion by

$$k_4 \{ V_R [\exp(-1.5k_2A^{k_3}) - \exp(-k_2A^{k_3}t)] - k_5 \}$$

where V_r is the volume concentration of Beltane opal in the mortar, A is the alkali concentration in the pore water when the first reaction is complete and k_3, k_4, k_5 are constants.

(6) It is shown that, if $k_2 = 1 \times 10^6$, $k_3 = 5$, $k_4 = 0.715$, $k_5 = 0.004$ and the 'reactive aggregate' particle size is between 150 and 300 μm , the predictions of the model are in general agreement with the observed expansion behaviour of mortar bars containing an accessible opaline constituent and which are stored under water at 20 °C.

ACKNOWLEDGEMENTS

The author is grateful to Mr N. Swinton for his assistance with many of the calculations and to Dr C. D. Pomeroy and Mr W. A. Gutteridge for helpful discussions.

REFERENCES

1. PALMER, D. Alkali-aggregate reaction in Great Britain - the present position. *Concrete*. Vol. 5, No. 3. March 1981. pp. 24-27.
2. BREDSORFF, P. et al. Chemical reactions involving aggregates. *Chemistry of Cement: Proceedings of the Fourth International Symposium, Washington, 1980*. Washington, D.C., National Bureau of Standards, 1982. Monograph 43, Vol. II. pp. 748-806.
3. DIAMOND, S. and THAULOW, N. A study of expansion due to alkali-silica reaction as conditioned by the grain size of the reactive aggregate. *Cement and Concrete Research*. Vol. 4, No. 41. July 1974. pp. 591-607.
4. DIAMOND, S. *Mechanisms of alkali-silica reaction - a review and reassessment*. pp. 71 + 5 Figures. (Unpublished).
5. LOCHER, F. W. and SPRUNG, S. Ursache und Wirkungsweise der Alkali-reaktion. (Causes and mechanism of alkali-silica aggregate reaction.) *Beton: Herstellung, Verwendung*. Vol. 23. No. 7. July 1973. pp. 303-306. No. 8. August 1973. pp. 349-353.
6. GASKIN, A. J., JONES, P. H. and VIVIAN, H. E. Studies in cement-aggregate reaction. XXI: The reaction of various forms of silica in relation to the expansion of mortar bars. *Australian Journal of Applied Science*. Vol. 6. 1955. pp. 78-87.
7. STANTON, T. E. The expansion of concrete through reaction between cement and aggregate. *Proceedings of the American Society for Civil Engineers*. Vol. 66. December 1940. pp. 1781-1811.
8. STANTON, T. E., PORTER, O. J., MEDER, L. C. and NICOL, A. California experience with the expansion of concrete through the reaction between cement and aggregate. *Journal of the American Concrete Institute. Proceedings* Vol. 38, No. 3. January 1942. pp. 209-236.
9. KELLY, T. M., SCHUMAN, L. and HORNIBROOK, F. B. A study of alkali-aggregate reactivity by means of mortar bar expansions. *Journal of the American Concrete Institute. Proceedings* Vol. 45, No. 1. September 1948. pp. 57-80.
10. MEISSNER, H. S. Cracking in concrete due to expansive reaction between aggregate and high alkali cement as evidenced in Parker Dam. *Journal of the American Concrete Institute. Proceedings* Vol. 37, No. 5. April 1941. pp. 549-568.
11. TREMPER, B. Evidence in Washington of deterioration of concrete through reactions between aggregates and high-alkali cements. *Journal of the American Concrete Institute. Proceedings* Vol. 37, No. 6. June 1941. pp. 673-686.
12. HADLEY, D. W. Field and laboratory studies on the reactivity of sand-gravel aggregates. *Journal of the PCA Research and Development Laboratories*. Vol. 10, No. 1. January 1968. pp. 17-33.
13. DAHMS, J. Influence on the alkali-aggregate reaction under field conditions. *Proceedings of a Symposium on the Effect of Alkalies on the Properties of Concrete, London, September 1976*. Wexham Springs, Cement and Concrete Association, 1976. pp. 277-289.
14. GUTTERIDGE, W. A. and HOBBS, D. W. Some chemical and physical properties of Beltane opal rock and its gelatinous alkali-silica reaction product. *Cement and Concrete Research*. Vol. 10, No. 2. March 1980. pp. 183-193.
15. VIVIAN, H. E. Studies in cement-aggregate reaction. X: The effect on mortar expansion of amount of reactive component in the aggregate. Melbourne, CSIRO, Australia, 1950. Bulletin No. 256. pp. 13-20.
16. VIVIAN, H. E. Studies in cement-aggregate reaction. XIX: The effect on mortar expansion of the particle size of the reactive component in the aggregate. *Australian Journal of Applied Science*. Vol. 2. 1951. pp. 488-494.

17. LENZNER, D. and LUDWIG, U. Alkali-aggregate reaction with opaline sandstone from Schleswig-Holstein. *Proceedings of the Fourth International Conference on the Effect of Alkalies in Cement and Concrete, Purdue University, June 1978*. West Lafayette, Purdue University, 1978. Publication No. CE-MAT-1-78. pp. 11–34.
18. HOBBS, D. W. *Influence of mix proportions and cement alkali content upon expansion due to the alkali-silica reaction*. Wexham Springs, Cement and Concrete Association, 1980. pp. 31. Technical Report 534 (publication 42.534).
19. HOBBS, D. W. Expansion of concrete due to the alkali-silica reaction: an explanation. *Magazine of Concrete Research*. Vol. 30, No. 105. December 1978. pp. 215–220.
20. HOBBS, D. W. and GUTTERIDGE, W. A. Particle size of aggregate and its influence upon the expansion caused by the alkali-silica reaction. *Magazine of Concrete Research*. Vol. 31, No. 109. December 1979. pp. 235–242.
21. JONES, F. E. and TARLETON, R. D. *Reactions between aggregates and cements. Parts I to VI*. London, H.M. Stationery Office, 1958. pp. 61. DSIR National Building Studies Research Paper No. 25.
22. VIVIAN, H. E. *Studies in cement-aggregate reaction. XII: The effect of amount of added alkalis on mortar expansion*. Melbourne, CSIRO, Australia, 1950. Bulletin No. 256. pp. 31–47.
23. MOAVENZADEH, F. and KUGEL, R. Fracture of concrete. *Journal of Materials*. Vol. 3, No. 4. September 1969. pp. 497–519.
24. DAHMS, J. Betonversuch zur Alkali-reaktion. (Tests on concrete for studying the alkali reaction). *Verbeugende Massnahmen gegen Alkali-reaktion im Beton*. (Preventive measures against alkali-aggregate reaction in concrete.) Dusseldorf, Beton-Verlag GmbH, 1973. Schriftenreihe der Zementindustrie, Heft 40. pp. 79–90.
25. SPRUNG, S. Einfluss von Zement und Zusätzen auf die Alkali-reaktion. (Effect of cement and admixtures on the alkali reaction.) *Verbeugende Massnahmen gegen Alkali-reaktion im Beton*. (Preventive measures against alkali-aggregate reaction in concrete.) Dusseldorf, Beton-Verlag GmbH, 1973. Schriftenreihe der Zementindustrie, Heft 40. pp. 69–78.

Contributions discussing the above paper should be in the hands of the Editor not later than 30 June 1982.

For Appendix, please see overleaf.

APPENDIX Predicted and observed times to cracking

R* (%)	Acid- soluble alkalis† (kg/m³)	Water- soluble alkalis‡ (kg/m³)	Time to cracking (days)	
			Observed§	Predicted
w/c = 0.29, a/c = 0.5				
23	12.9	9.9	2.1	1.8
15.8	8.7	6.0	4	2.6
14.2	7.7	4.2	15	72
8.1	6.5	3.2	77	220
11.8	6.5	3.2	54	460
11.5	6.3	4.6	14	27
14.2	5.7	4.2	14, 25	72
10.2	5.6	4.1	20, 29	52
8.1	4.5	3.0	70	390
6.0	4.1	1.6	u	33 000
7.5	4.1	1.6	u	86 000
w/c = 0.35, a/c = 1				
2	9.75	7.5	7	8.8
4			4	2.9
8			3.9	2.3
12			2.2	2.4
16			2	2.8
26			2	13
w/c = 0.41, a/c = 1.5				
5.3	7.9	6.1	7	3.5
8.0			4	3.8
13.3			u	8.3
w/c = 0.41, a/c = 2				
8.0	9.9	8.3	3	1.9
6.7	8.2	6.6	4	2.3
6.5	6.9	5.3	u	∞
0.75	6.9	5.3	u	∞
1	6.9	5.3	u	13.4
1.5	6.9	5.3	9	6.2
2	6.9	5.3	88	4.8
4	6.9	5.3	4.5 to 5	3.8
6	6.9	5.3	4.5	4.2
8	6.9	5.3	4	5.6
10	6.9	5.3	4	9.5
12	6.9	5.3	3	21
16	6.9	5.3	2	480
2	6.0	4.6	22	7.9
4	6.0	4.6	10	6.9
6	6.0	4.6	8.5	9.1
10	6.0	4.6	8	41
4.5	5.4	4.0	33	16
1.5	5.3	3.8	u	22.5
3	5.3	3.8	u	18
4.5	5.3	3.8	19, 36	22
6	5.3	3.8	u	37
10	5.3	3.8	u	570
3	4.7	3.2	u	50
3.75	4.7	3.2	u	60
4.5	4.7	3.2	u	78
3	3.7	1.9	u	2050
3	3.5	1.1	u	5400

* R = Beltane opal content (% by weight of total aggregate)

† (Na₂O)_a = acid-soluble alkali content of cement expressed as equivalent Na₂O‡ (Na₂O)_w = water-soluble alkali content of cement expressed as equivalent Na₂O

§ u = uncracked (some of these tests have now been in progress for 750 days)

R* (%)	Acid-soluble alkalis† (kg/m³)	Water-soluble alkalis‡ (kg/m³)	Time to cracking (days)	
			Observed§	Predicted
w/c = 0.41, a/c = 2 continued				
1	3.1	2.2	u	530
2			u	400
3			u	570
4			u	1100
5			u	3100
w/c = 0.41, a/c = 2.75				
2.9	5.7	4.4	6.5	4.3
4.4			5.5	4.7
5			5	5.3
7.3			5	11
w/c = 0.47, a/c = 3				
1	5.3	4.1	u	13
2			26	7.6
3			10	7.2
4.5			11	9.3
6			11	16
8			u	53
w/c = 0.53, a/c = 2.75				
4.4	5.4	4.15	11	13.5
w/c = 0.53, a/c = 3.5				
3.4	4.7	3.6	12	15
w/c = 0.53, a/c = 3.75				
3.1	6.3	5.4	12	2.7
1.5	4.4	3.4	78	14
2.2	4.4	3.4	69	14
2.25	4.4	3.4	34	14
3	4.4	3.4	58	15
4.5	4.4	3.4	u	27
2.75	3.9	3.0	156	37
2.41	3.5	2.6	147, 240	85
w/c = 0.53, a/c = 4.25				
2.8	4.2	3.2	33	18
w/c = 0.59, a/c = 4.5				
0.75	4.0	3.1	u	46
1.5			56	26
2.25			56	27
3			48	35
4			45	63
5			u	150
w/c = 0.65, a/c = 5				
2.25	3.5	2.7	101	50
1.8	3.1	2.4	u	120
1.8	2.8	2.0	u	300
2.4	2.8	2.0	u	470
1.8	2.8	1.9	u	440
2.4	2.8	1.9	u	720