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PREVENTIVE MEASURES TO COUNTERACT EXPANSION OF

CONCRETE CONTAINING ALKALI—REACTIVE AGGREGATES

by P.E. Grattan-Bellew

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RÉSUMÉ

La réaction entre des alcalis et des agrégats se traduit
par l'expansion et la fissuration des ouvrages de béton en
milieu très humide. La dégradation est d'autant plus
forte lorsqu'on applique des sels de déglaçage sur le
béton. L'expansion, causée par la réaction entre la
solution alcaline dans les pores et certains minéraux dans
l'agrégat, peut être évitée ou minimisée par différentes
méthodes. La meilleure consiste à utiliser un agrégat non
réactif. L'amélioration de l'agrégat par extraction
sélective est souvent efficace comme méthode d'élimination
des matières réactives, notamment dans les carrières de
carbonate en couches horizontales. Une autre méthode qui
peut être efficace pour empêcher la détérioration précoce
du béton contenant des agrégats réactifs consiste à
limiter la teneur en alcali du béton en utilisant soit un
ciment à faible teneur en alcali, soit un mélange à faible
teneur en ciment, soit les deux. La substitution d'une
partie du ciment par du pouzzolane d'efficacité éprouvée
est une autre méthode permettant d'empêcher l'expansion
délétère. Les grands ouvrages en béton contenant des
agrégats réactifs devraient être conçus de façon que l'eau
ne s'y accumule pas. Il est aussi important de mettre sur
pied un programme permanent d'entretien consistant à
étanchéifier les joints et à colmater les fissures de
façon à empêcher l'eau de s'infiltrer dans l'ouvrage.
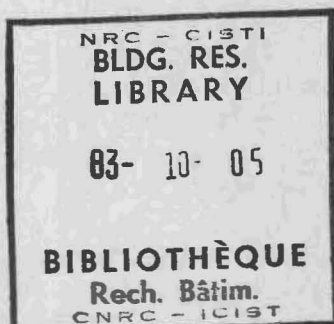
PREVENTIVE MEASURES TO COUNTERACT EXPANSION OF CONCRETE CONTAINING ALKALI-REACTIVE AGGREGATES

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ABSTRACT

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Alkali—aggregate reaction causes expansion and cracking of concrete structures exposed to high humidity. Deterioration is much exacerbated if de-icing salts are used on the concrete. The expansion, caused by reaction between the alkaline pore solution and certain minerals in the aggregate, can be prevented or minimized by a number of methods. The best solution is to use an alternative, non-reactive aggregate. Beneficiation of the aggregate by selective quarrying is often effective in eliminating reactive material, particularly in horizontally layered carbonate quarries. Limiting the alkali content of the concrete, by using either a low-alkali cement or a mix with a low cement content, or both, may also be effective in preventing premature deterioration of concrete containing reactive aggregates. Replacement of part of the cement with a pozzolan of proven effectiveness is an alternative method of preventing deleterious expansion. Major structures made with concrete containing reactive aggregate should be designed so as to prevent water from ponding on them. It is also important to establish an ongoing maintenance programme to keep joints sealed and cracks grouted, to prevent water from entering the structure.

INTRODUCTION

Alkali—aggregate reaction, causing expansion and cracking of concrete exposed to high humidity, is due to reaction between some minerals in the aggregate and the alkaline pore solution of the concrete. The alkalies in the pore solution are derived largely from the cement, but may be augmented by soluble alkalies in some aggregates or by alkaline salts from the environment. The alkali content of many Type 1 cements (ANSI/ASTM C150-78a, 1979) currently available in eastern Canada is around 1%, expressed as Na_2O equivalent (per cent acid-soluble Na_2O + 0.658 per cent acid-soluble K_2O). These are classed as high-alkali cements. Cements with an alkali content less than

0.60% are classed as low-alkali cements (ANSI/ASTM C150-78a, 1979). Use of a low-alkali cement is, however, no guarantee that deterioration of concrete made with reactive aggregate will not occur; tests must be made for confirmation.

Traditionally, the so-called classical alkali—silica reaction occurs when aggregates containing opal, chert and volcanic glass are used. Alkali carbonate reactivity occurs with some argillaceous dolomitic limestones. The presence of fine-grained reactive quartz in any rock can cause reactivity. Cases of alkali—aggregate reactivity involving quartzite, argillite, rhyolite, hornfels, greywacke, phyllite, gneiss, andesite, limestone and granite have been recorded. Man-made glass has also been known to cause expansion.

There has been a marked upsurge in research on alkali—aggregate reactivity (AAR) during the past 15 years (Ramachandran et al., 1981). This is related to the increased number of cases reported worldwide. Damage to concrete due to AAR has been reported from more than 20 countries. The cost of renovation of structures affected by AAR may often exceed the original cost of construction and, where major structures such as dams or bridges are involved, the loss may run into millions of dollars. In areas such as the Cape Town region of South Africa, it is estimated that 50% of the concrete structures built in the past 15 years show some deterioration due to the use of alkali-reactive aggregates and a moderately high-alkali cement (Semmelink 1981). This underlines the need for more research into methods of detecting, and then preventing, damage due to AAR. The methods of detecting potentially reactive aggregates have been covered in a previous publication (Grattan-Bellew 1981).

The reasons for the increased incidence of AAR during the past 15 years or so are not well understood but it is probable that a number of factors are involved. The increased alkali content of some cements is due to recycling of flue-gas-containing alkalies or to a change from oil- to coal-fired kilns. The sulphides in the coal convert to sulphates in the clinker; these sulphates are the main source of alkalies in cement. In some instances, the $C_3S:C_2S$ (standard cement chemistry notation: C_3S = tricalcium silicate, C_2S = dicalcium silicate) ratio may have increased. This leads to a higher $Ca(OH)_2$ content in the concrete. The addition of $Ca(OH)_2$ to mortar containing reactive aggregate has been shown to increase expansion (Ming-Shu and Su-fen 1980).

Exhaustion of good aggregate sources and replacement by marginal material may, in some cases, increase the risk of damage due to AAR. The use of higher cement contents, hence higher alkali contents, in some modern high-strength concrete increases the probability of damage if reactive or marginally reactive aggregates are used. In Canada and other countries where sub-freezing temperatures occur, damage due to AAR is likely to be aggravated by cycles of freezing and thawing.

MATERIAL ASPECTS

The following methods have traditionally been employed for preventing, or at least minimizing, expansion due to AAR:

(a) use of an alternative source of aggregate;

(b) beneficiation of aggregate;

(c) dilution of aggregate with non-reactive rock;

(d) use of low-alkali cement ($\leqslant 0.6\%$ Na_2O equivalent) or blended high- and low-alkali cement;

(e) replacement of part of the cement by pozzolan (calcined shale, diatomite, fly ash or pulverized blast-furnace slag).

Some other preventive measures have been proposed but have not been used in practice. Many additives have been tested for effectiveness in reducing expansion of mortar containing reactive silica aggregate (McCoy and Caldwell 1951). Lithium salts were found to be the most effective. The addition of 0.72% Li_2CO_3 caused a marked reduction in the expansion of test bars but, because of the high cost, it has not been used in practice. More recently, the addition of $FeCl_3$ has been proposed as a method of reducing expansion due to alkali carbonate reactivity (Pagano and Cady 1982a). Reduced expansions were observed but, in the case of the most expansive aggregate, 11% $FeCl_3$ would have to be added to reduce expansion to a safe level (Pagano and Cady 1982b). This quantity might affect the setting of the concrete and cause corrosion of reinforcing steel.

It has been suggested, based on field observations, that concrete made with some reactive siliceous aggregates and a moderately high-alkali cement does not expand when immersed in either fresh or sea water (Oberholster 1981). Laboratory evidence of expansion of mortar and concrete made with reactive aggregates does not support the above hypothesis (Smith 1964, Chatterji 1979). Field evidence of concrete made with reactive carbonate aggregate from Ontario also indicates that expansion and cracking can occur under water.

(a) Use of an alternative source of aggregate

Owing to the high cost of transporation, this may not be feasible unless the alternative source is close to the concrete plant. The cost of a truckload of aggregate in Ottawa, Ontario, in 1983 doubles for every 50 km it must be transported. In some instances, however, such as bridge construction, where the cost of the aggregate is only a small fraction of the total, even a doubling in this factor would have a negligible effect on the overall cost, and the use of the alternative should be recommended. In some cases, socio-political reasons may make the use of an alternative aggregate undesirable. For example, this might force the closure of a pit or quarry.

(b) Beneficiation of aggregate

This can be done in various ways, depending on the type of rock and the deposit in which it occurs. Selective quarrying is the most common method, particularly in horizontally bedded carbonate rocks (Smith 1974), but it has also been used in quarries in igneous rocks, where dykes or veins of reactive

material occur. The second method, density separation, can only be used when there is a significant difference in density between the reactive component and good aggregate. An example of this was the removal of opaline from gravel by heavy media separation for the construction of the South Saskatchewan River Dam (Price 1961). The main drawbacks of this method are the expense and the need for a marked density difference between the reactive and non-reactive aggregate.

(c) Dilution of reactive aggregate

Such dilution with a non-reactive rock would seldom be practicable due to the cost of transport and blending of the aggregates. Furthermore, tests would have to be done to determine the optimum blend for reducing expansion due to AAR. This method has been applied mainly to carbonate aggregates in the U.S.A., where it was found that dilution of reactive aggregate by more than 50% was required to reduce the expansion to an acceptable level (Newlon and Sherwood 1963).

(d) Use of low-alkali cement

This has been the most commonly applied method of preventing deleterious expansion due to AAR. However, several authors have shown that this method is not always successful (Woolf 1952; Swenson and Gillott 1964; Stark 1978). There are at least four reasons why using a low alkali cement may not be effective:

(i) Highly reactive rocks may cause expansion of concrete even when very low-alkali cements are used. For example, concrete containing the reactive carbonate rock from Kingston, Ontario, and a cement having an alkali content of 0.36% expanded by 0.048% in two years (Swenson and Gillott 1964). The Canadian Standard A23.1-M77 Appendix B3.5 (Canadian Standards Association 1977) specifies that "linear expansions of about 0.03% or more indicate potentially deleterious reactivity".

(ii) The addition of alkaline-earth salts to concrete from the groundwater or through the use of de-icing salts, or by solution of alkalies from the aggregate, increases expansion of concrete containing reactive aggregates (Stark 1978). Laboratory experiments have shown that expansion is much increased when mortar or concrete is immersed in $NaOH$, $NaCl$ or Na_2SO_4 solutions (Ming-Shu and Su-fen 1980, Chatterji 1978). The reaction between alkali-metal salts and hydrated cement is complex and is not readily expressed in chemical equations. Hydrated Portland cement consists mainly of the C—S—H phase, lime and calcium aluminum sulphate hydrates. For example, if $NaCl$ is added to concrete, the chloride will form a complex with the sulphate phase, ettringite or monosulphoaluminate, excess Na^+ ions will pick up OH^- from the pore solution to form $NaOH$, which will enhance expansion due to AAR. Some of the observed expansion

could be due to the formation of an expansive chlorosulphoaluminate complex, although this possibility apparently has not been investigated. (iii) The alkali content of the pore solution of concrete may be raised by using a higher cement content that that used for the test sample. For example, a 25 MPa test mix (showing no expansion), when made with a marginal aggregate and a cement containing 0.81% alkalies, would contain 2.7 kg alkalies/m^3 concrete (Fig. 1, mix A). Suppose the job required 61 MPa concrete and the same cement was used, then from Fig. 1, mix B, the alkali content of the concrete would be 4.0 kg/m^3. The proposed limit for alkali in concrete in Britain and Germany is 3.0 kg/m^3 (Hobbs 1982; Krogh 1975). Thus, although a cement with a medium alkali content was used for the 61 MPa concrete, if the aggregate was reactive, expansion would probably occur.

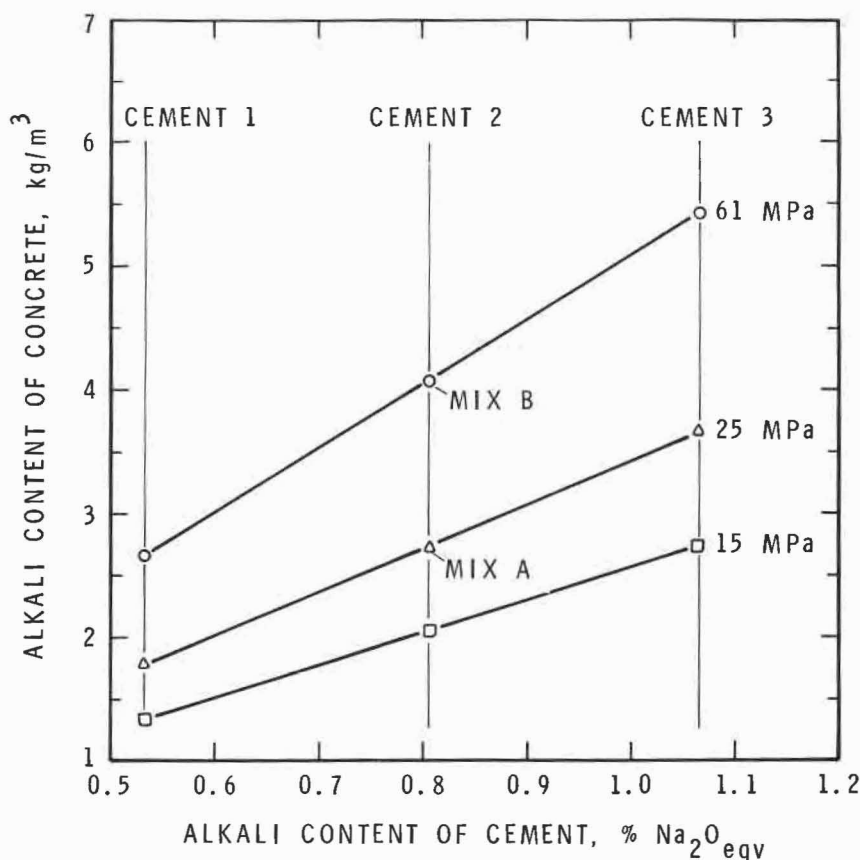Fig. 1. Graph showing variation in alkali content of concretes of different design strengths with change in alkali content of cement. Mix designs from Canadian Portland Cement Association (1978) and Freedman (1971). 61 MPa — cement, 505 kg/m^3; water, 190 l/m^3; w/c, 0.38; PFA, 45 kg/m^3. 25 MPa — cement, 340 kg/m^3; water, 180 l/m^3; w/c, 0.53. 15 MPa — cement, 255 kg/m^3; water, 180 l/m^3; w/c, 0.71.

(iv) The pessimum alkali:silica ratio (French 1980; Hobbs 1978) may inadvertently be obtained when a particular low-alkali cement is used with an alkali–silica reactive aggregate. In one instance, the pessimum was observed with a cement containing 0.4% $Na_2O_{eqv.}$ (Woolf 1952).

It has recently been pointed out that it is important to limit the alkali content of concrete (instead of using cement as a base) for controlling expansion when concrete is made with a reactive aggregate (Smith 1964, Krogh 1975, Deutschen Ausschusses für Stahlbeton 1974). In New Zealand, the proposed limit is 3.5 kg/m^3 concrete (Kennerley et al. 1981), while in the Cape Province of South Africa this limit is 2.1 kg/m^3 (Oberholster 1981). The differences between the various limits presumably reflect differences in the reactivities of the respective aggregates. Owing to the wide variation in the expansivity of aggregates, there can be no universally applicable safe level for the alkali content of concrete. However, limits of regional applicability have also been established in Northern Germany.

The establishment of safe alkali limits for concrete made with a reactive aggregate is further complicated by the effect of changes in water/cement ratio (w/c) on expansion due to AAR. In one case, the author's unpublished results show that reducing the w/c from 0.57 to 0.46 increased the rate of expansion from 8×10^{-3} day$^{-\frac{1}{2}}$ to 12×10^{-3} day$^{-\frac{1}{2}}$. Thus, in Fig. 1, even if the cement contents of mixes A and B were the same, greater expansion might be expected from mix B with a w/c of 0.38, compared to a w/c of 0.53 for mix A. Increased expansion is observed at low w/c ratios because reducing the water content of the mix increases the concentration of alkalies in the pore solution.

Other factors may affect the expansion of concrete containing reactive aggregate and ordinary Portland cement (OPC) about which little is known. These include $C_3S:C_2S$ ratio, which determines the amount of $Ca(OH)_2$ in the concrete, and the Blaine fineness, which determines the rate and amount of hydration of the clinker. The effects of individual factors have not, so far, been isolated because it has not been possible to obtain a series of cements containing only one variable. There is usually a premium price for low-alkali cements, except in areas where the normal Type 1 cement has a low alkali content as, for example, in western Canada. This is because it takes about 15% more energy to produce a low-alkali cement than it does to produce high-alkali cement. This, coupled with the increased transport costs if the low-alkali cement has to be transported for a long distance, makes the use of these cements, in many areas, economically unattractive. Provided the safe alkali limit for concrete is not too low, it may be possible to find a locally available cement with an intermediate alkali content which would meet the requirements. For example, if 25 MPa concrete must be made with a reactive aggregate, for which a safe alkali limit of 3.0 kg/m^3 concrete has been established, Fig. 1 shows that by using cement no. 2 with an alkali content of 0.81% $Na_2O_{eqv.}$ instead of cement no. 3 containing 1.07% alkalies, the alkali content of the concrete would be about 2.7 kg/m^3, considerably

below the 3.0 kg limit. In this way, the financial penalty for using a low-alkali cement could be avoided.

The effectiveness of reduced alkali content for decreasing expansion due to AAR requires that no alkali be introduced to the concrete from external sources. However, alkalies may be derived from the aggregate, either because it contains soluble alkalies such as andesite, or because the aggregate is contaminated by alkaline salts (Sims and Poole 1978). Stark (1978) has documented a case where concrete made with low-alkali cement and andesite expanded due to the alkalies derived from the aggregate. Although this is a rather uncommon occurrence, alkaline salts are frequently introduced into concrete in the form of de-icing salts applied to roads and bridges. Increased expansion of concrete made with reactive aggregate occurs when salts are added to the concrete (Fig. 2), possibly due in part to the reaction of the salt and the cement.
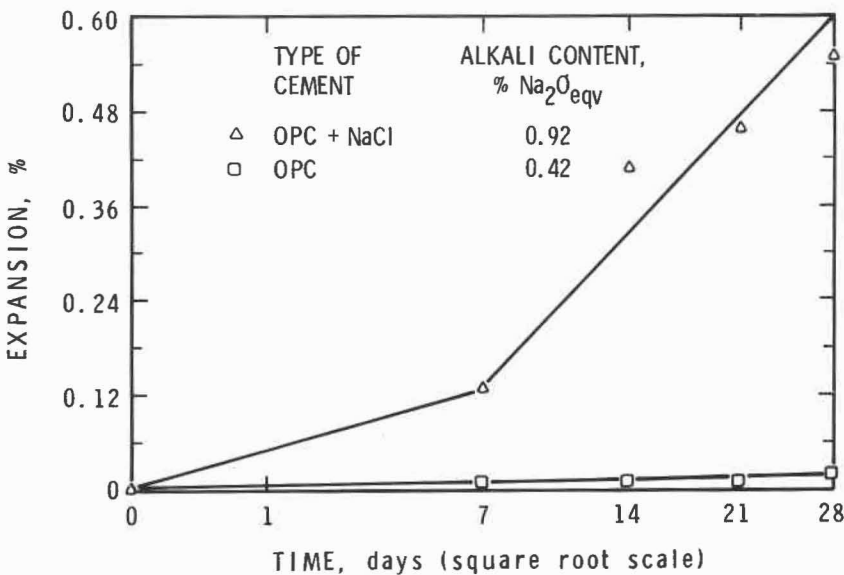

Fig. 2. Expansion of mortar bars made with sand to which 5% opal (by weight of cement) was added: curve (1) — ordinary Portland cement containing 0.42% alkalies ($Na_2O_{eqv.}$); curve (2) — ordinary Portland cement 0.42% $Na_2O_{eqv.}$ + NaCl to give a total $Na_2O_{eqv.}$ of 0.92%. After Mehta (1978).

In the construction of bridges, guard rails, medians and other concrete structures that will be subject to heavy salt applications in winter, it would probably not be possible to reduce the alkali level of the concrete low enough to prevent deleterious expansion if the aggregate is reactive. In such cases, either a non-reactive aggregate should be used or the reaction should be prevented by use of a good-quality pozzolan.

(e) Effect of pozzolans on expansion due to alkali—aggregate reactivity

The effect of pozzolans in reducing expansion due to AAR has been known for over 30 years (Stanton 1949) but the mechanism by which this occurs is still not completely understood. At present, fly ash (PFA) and pulverized blast furnace slag (PBFS) are the most widely used pozzolans, but silica fume, a by-product of the production of silicon, has recently become available in some areas. Silica fume is faster reacting than either PFA or PBFS but, so far, little information is available on the optimum addition to concrete. Problems with mixing are also encountered due to the fineness of the silica fume. When part of the cement is replaced by PFA or PBFS, care is required to ensure that the concrete still meets the design strength development. Mehta and Gjørv (1982) have shown that by mixing silica fume with PFA, the slow strength development characteristic of concrete containing PFA can be overcome.

The reactive component in pozzolans consists mainly of finely divided silicates which react with $Ca(OH)_2$, in concrete, to produce a C—S—H gel, allied to that formed by the hydration of cement paste. Pozzolans are usually used in amounts of 35 to 75% by weight of cement. The extra gel formed by the pozzolanic reaction, coupled with the removal of porous $Ca(OH)_2$ (Mills 1981), reduced the porosity and permeability in the cement paste Bakker 1981). The reduction in the expansion of mortar bars containing Pyrex, when OPC is replaced by blast furnace slag cement (BFC) (65% pulverized blast furnace slag + OPC), is shown in Fig. 3. Even when the $Na_2O_{eqv.}$ of the BFC is increased to 1.49% by the addition of $Na_2SO_4 \cdot 10H_2O$, expansion is almost eliminated.
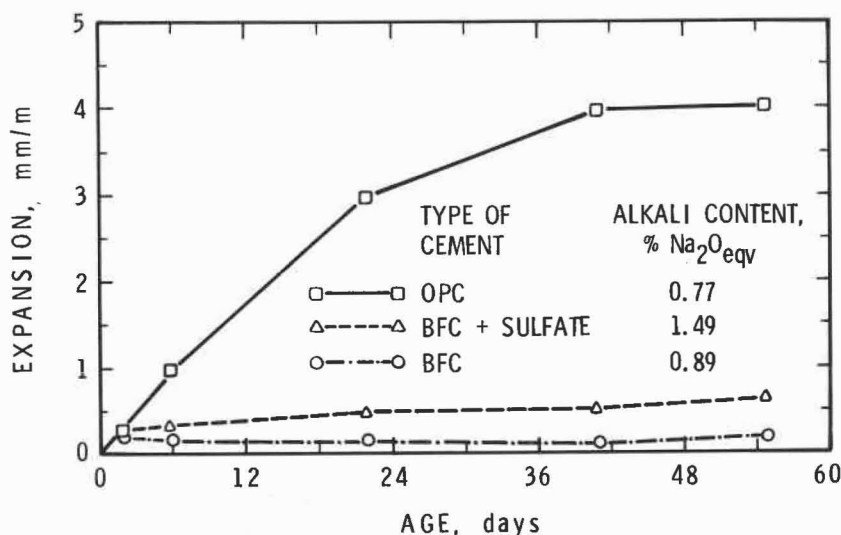

Fig. 3. Expansion of mortar bars containing pyrex aggregate and made with ordinary Portland cement (0.77% $Na_2O_{eqv.}$), blast furnace slag cement (0.89% $Na_2O_{eqv.}$) and BFC plus 3% $Na_2SO_4 \cdot 10H_2O$ by weight. After Bakker (1981).
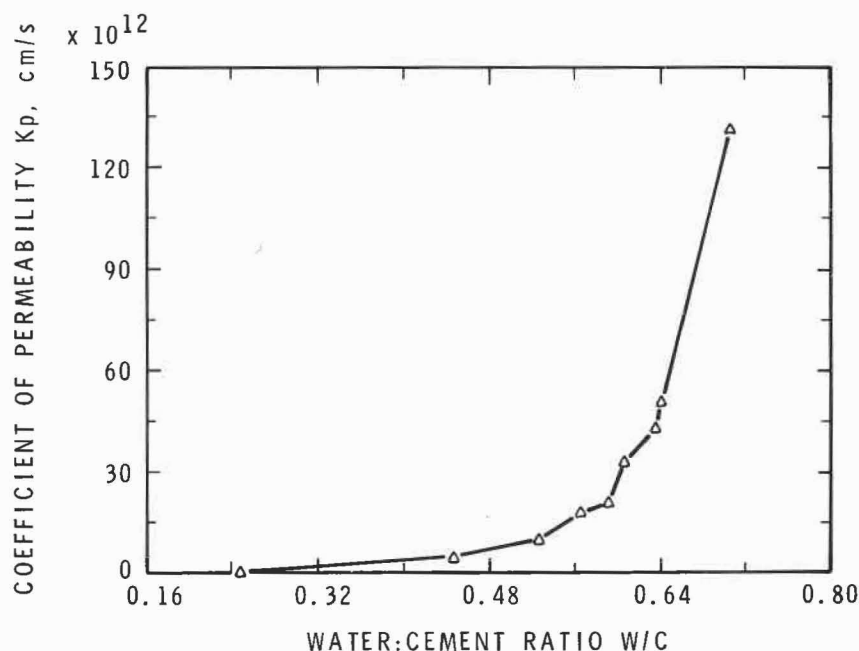
Fig. 4. Change in permeability of mature cement with w/c ratio. After Powers et al. (1954).

When OPC was replaced by BFC, the reduction in the rate of diffusion of water in 34-day-old mortar was 94%, and of Na^+ ions in 14-day-old mortar, 96%, calculated from the data of Bakker (1981). These results suggest that the decrease observed in expansion of mortar containing reactive aggregate by a partial replacement of OPC with BFC may be partly attributed to the reduced permeability of the mortar. Permeability of mortar may also be reduced by decreasing the w/c ratio. From Fig. 4 it can be seen that reducing the w/c below about 0.40 reduced permeability to a very low level. However, the expansion of mortar bars containing reactive aggregate is increased as the w/c is decreased. From this observation, it is evident that factors other than, or in addition to, reduced permeability must be responsible for the observed decrease in expansion of mortar to which a pozzolan has been added. It is probable that the gel formed by the reaction of pozzolan and $Ca(OH)_2$ incorporates Na^+ and K^+ ions in its lattice, thereby reducing the concentration of these ions in the pore solution and, hence, expansion due to AAR. The concept that the beneficial effect of pozzolans is due to replacing part of the cement, thus diluting the alkalinity of the pore solution, is incorrect. Bakker (1981) has shown that even when Na^+ is added to mix in the form of $Na_2SO_4 \cdot 10H_2O$, reduction in the expansion of mortar occurs (Fig. 3). Normally, the addition of $Na_2SO_4 \cdot 10H_2O$ increases expansion of mortar containing reactive aggregates. Furthermore, the pozzolans themselves frequently contain more soluble akalies than the cement which they

replace. A brief survey of the literature has shown that the total or acid-soluble alkali contents of pozzolans varies between 0.48% for a silica fume to 3.78% for a PFA.

A wide variety of pozzolans are effective in reducing expansion due to AAR. These include: calcined shale, pulverized fly ash or blast furnace slag, silica fume, kieselguhr and volcanic ash (Oberholster and Westra 1981). The optimum addition of pozzolan for this purpose varies, but is about 30% by weight of cement for fly ash and 60% for blast furnace slag. The optimum addition of any pozzolan for use with a given reactive aggregate must be determined by experiment, as not only do the quality and composition of pozzolans vary but also their effectiveness, in combination with different types of aggregate. For example, Swenson and Gillott (1964) found that pozzolans were not effective for the long-term reduction of expansion due to alkali—carbonate reaction of the type found in the Kingston area of Ontario. The reason for this is not clear. It may be that poor-quality pozzolans were used, or that the pozzolanic reaction, particularly with fly ash, was too slow to prevent de-dolomitization.

EXPOSURE CONDITIONS

It has been found that, under laboratory conditions, the critical humidity above which expansion occurs in mortar is 85% RH (Ludwig 1981). If concrete can be kept dry, therefore, no damage should occur even though reactive aggregates are used with high-alkali cement. In practice, this is not easy to accomplish. Concrete in small structures, such as walls of buildings where drying after rain would be rapid, generally does not undergo deleterious expansion or cracking. There are, however, exceptions to this. For example, in Reykjavik, Iceland, where many houses have concrete walls, cracking due to AAR is a serious problem (Idorn 1981). In this case, expansion may be due to sea spray, carrying inland salts which would enhance the alkali—aggregate reaction. Exceptions have also been found where highly expansive aggregates were used, for example, in Kingston, Ontario.

The concept that expansion only occurs where moisture has access to the concrete is supported by observations on the access bridge over the N2 Freeway, Cape Province, South Africa (Oberholster et al. 1978). Cracking occurred along the parapet of the bridge and on the exterior concrete columns supporting it, but no cracking was observed on the underside of the bridge away from the edges nor on the supporting columns in the centre.

Damage due to AAR is most frequently observed in dams, bridges, retaining walls and concrete foundations where there is a constant supply of moisture to one side and evaporation from the other, possibly leading to a concentration of alkalies at the exposed side. This may cause differential expansion between the two sides of the structure, leading to severe damage. A typical example is shown in Fig. 5.

The best method of preventing deleterious expansion of concrete retaining walls and similar structures made with reactive or marginally reactive aggre-
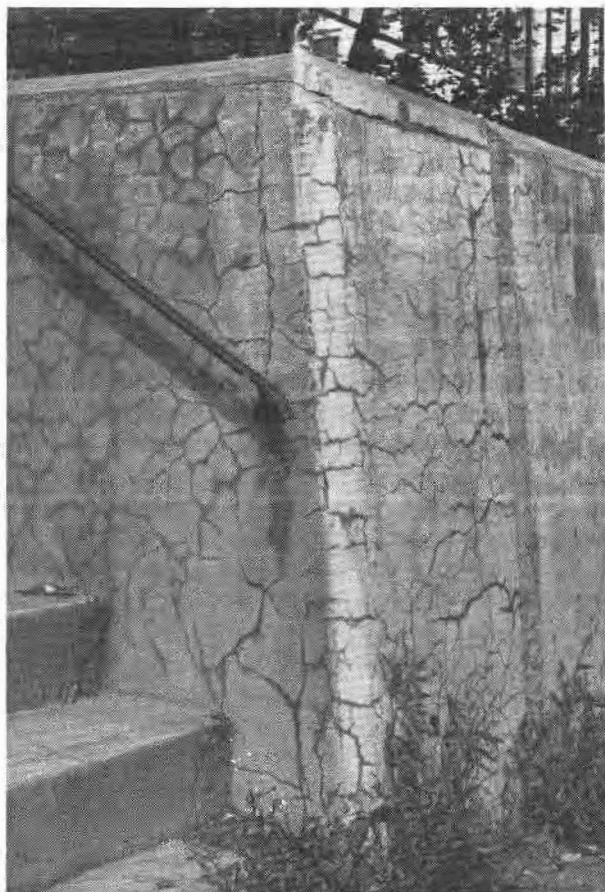
Fig. 5. Retaining wall showing advanced state of deterioration due to alkali—carbonate reaction of argillaceous dolomitic limestone.

gates is to use a good-quality pozzolan so as to make the concrete as impervious to water as possible and to reduce the risk of reaction between the aggregate and the alkaline pore solution. If this is not feasible, or if there is doubt about the effectiveness of the measures taken to prevent expansion, care should be exercised in the design and construction to seal the face in contact with the moisture to prevent water being drawn through the concrete by evaporation from the dry side.

STRUCTURAL ASPECTS

Deleterious expansion and cracking of concrete made with reactive aggregates can be minimized by designing the structure to shed water readily. Adequate drainage and weep holes should be provided for the removal of any water which might pond on the structure. The provision of adequate expansion joints is also of importance, as these would allow some expansion to occur without damaging the structure. A good, ongoing maintenance pro-

gramme should also be established to make sure that drain holes remain open and expansion joints filled so that water does not gain access to the interior of the concrete through them (Flanagan 1981).

PREVENTIVE MEASURES TO MINIMIZE DETERIORATION WHEN CRACKING HAS OCCURED

Once expansion and cracking have occurred, the damage is irreversible; subsequent measures must be aimed at minimizing further damage to the structure. The first priority should be monitoring the amount of distress in the structure for assessing the rate of deterioration. The complexity of the monitoring system may vary from simple visual observations to careful measurements of length change and joint movements. In some instances, where the strength and structural integrity of the concrete are critical, as for example, in dams, sonic testing at regular intervals may be desirable (Coombes 1976).

Preventive measures depend on a number of factors: the age of the concrete, the size and importance of the structure, the extent of the damage, whether the deterioration is continuing, and the possibility that continuing deterioration would render the concrete inadequate to fulfil its designed function. If the concrete is old and still fulfils its planned function, expansion may have tapered off and no action may be required. In minor structures such as sidewalks, where the damage is not severe enough to present a hazard to pedestrians, the only repair warranted may be the cutting of some additional expansion joints so that continuing increase in length does not damage adjacent structures such as curbs, light poles and manholes.

In large structures, such as bridges, where expansion and cracking are found to be continuing, two alternatives exist: allow the structure to deteriorate for eventual replacement; or carry out preventive maintenance to minimize further damage. The aim of preventive maintenance should be to exclude water from the structure. However, a satisfactory method of drying and sealing concrete structures has not yet been developed. Attempts at excluding water by the use of various coatings have generally been unsuccessful. As sealing the concrete is impracticable, the next best thing is to grout all cracks and seal expansion joints so that access for water to the interior of the concrete structure is minimized. Once remedial measures have been taken, a regular maintenance schedule should be established to ensure that cracks and joints remain sealed and that drainage channels and weep holes are unobstructed. Monitoring of expansion should also be continued so that warning can be obtained in case further action becomes necessary.

ACKNOWLEDGEMENT

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