

THE MECHANISM OF ALKALI-AGGREGATE REACTION IN CONCRETE

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Alkali-Aggregate Reaction can be described briefly as a reaction between alkalis derived largely from Portland cement and a siliceous component in aggregate. In concrete reacted aggregate particles absorb free water from the surrounding concrete and commence swelling. The swelling particles exert a disruptive force on the surrounding concrete and produce many fine cracks in it. As the particles absorb more water these fine cracks are widened and the concrete is expanded abnormally.

INTRODUCTION

This contribution is a brief re-statement, based on studies and experiences covering some 50 years, of the basic mechanism of alkali-aggregate reaction and the consequent damaging effects which are produced in concrete. It is concerned therefore with the interaction of the three essential factors, alkalis, namely sodium and potassium hydroxides derived from hydrating cement, a reactive siliceous component in the aggregate and free water which is normally present in concrete. The resultant cracking and expansion of concrete is caused by the swelling forces exerted during the absorption of free water by reacted aggregate particles which are completely confined within a relatively inelastic, but permeable, hardened cement paste or concrete matrix. The effects of a number of other factors, notably reactant quantities, environmental conditions, concrete quality, action of pozzolans, on the expansion and disruption of concrete will also be discussed.

These basic studies constitute a suitable background for understanding and evaluating material test data and various operational problems in large structures. The significance of test procedures and interpretation of test results have caused many difficulties while variability of materials, cement, natural sands and gravels and in some instances aggregate taken from different places in one quarry has on occasions caused much confusion. On account of the presence of other potentially damaging actions, recognition of alkali-aggregate reaction as a major cause of deterioration of a concrete structure in the field is often difficult. Moreover evaluation of the contribution of alkali-aggregate reaction to observable damage

is not easy and assessment of the future performance of affected concrete and possible repair requires considerable judgement.

BASIC COMPONENTS AND REACTIONS

The essential requirements for alkali-aggregate reaction to occur are: (a) alkalis, sodium and potassium hydroxides derived principally from cement, (b) a component of the aggregate which can react with hydroxyl ions to produce a new reaction product which can absorb water and (c) free water which may be excess mixing water. As the reacted aggregate component absorbs water it swells initially as a non-deforming solid, exerting a disruptive force on the surrounding concrete and producing cracks which propagate and widen and thus cause the concrete to expand.

It is apparent that alkalis may be derived not only from cement but also from other sources such as surrounding soil solutions and some admixtures. The reactive aggregate component may be present in either the fine or coarse aggregate and is usually opaline silica, acid and intermediate glassy volcanic rocks or rocks which contain relatively large amounts of cryptocrystalline quartz. Crystobalite, tridymite, fused silica glass and high silica artificial glasses are also reactive while de-vitrified volcanic glasses are non-reactive. Water derived from foundations and soils and intermittent precipitation can augment the excess mixing water.

The quantities of alkalis present in cement and the quantity of the reactive component in the aggregate affect the magnitude of expansion. As the cement alkali content (expressed as $\text{Na}_2\text{O} + 0.658\text{K}_2\text{O}$) falls below 0.60% the reaction rate decreases progressively and the time required for expansion to become significant increases greatly. The quantities of reactive material in the aggregate, e.g. opal or volcanic glass, may be relatively low (1-5%) while the quantity of cryptocrystalline quartz is relatively high - approximately 35-40%. Absorption of free water is the critical factor which causes expansion. Consequently concrete that dries out and remains dry will not expand significantly and indeed will probably shrink while concrete exposed to external flow water is likely to lose alkalis by leaching and thus develop a reduced expansion. Low density rocks, e.g. pumice, scoria etc., low cement factor concrete and poorly compacted concrete are generally not usually expanded. It is only well compacted, good quality concrete that can be expanded abnormally.

WATER ABSORPTION AND EXPANSION

Radioactive tracer studies have shown that the positive sodium counter ion penetrates throughout and concentrates rapidly in reacting silica particles. It is considered that the hydroxyl ion, which is the critical reacting ion, penetrates with similar rapidity into and throughout the particle and produces large numbers of Si-OH bonds which completely change the properties of the original siliceous particle and increase its capacity to associate with large

numbers of water molecules. It should be noted in passing that the alkali-silica ratio in the reaction product may vary but generally approaches 1:4.

The swelling of the reacted particle is caused by it absorbing water. The distribution of absorbed water throughout the reacted particle is not uniform. The greatest amount of adsorbed water occurs initially at the external particle surface and diminishes with depth inside the particle. The swelling of the reacted particle as water is absorbed is therefore non-uniform and moreover the concomitant changes occurring in the physical properties of the reaction product are also non-uniform. Initial water absorption increases the volume of the reaction product which swells as a rigid, non-deformable solid. As more water is absorbed the reaction product continues to increase in volume but becomes increasingly deformable until at a sufficiently high absorbed water content it converts to a fluid sol. The swelling reaction product first forms several incipient cracks in the surrounding concrete. Some of these cracks are propagated and widened as the reaction product swells. Readily deformable gel and sol are forced into these cracks by the continued swelling of the non-deformable reaction product. However as reacted particles progress through the sequence of water absorption - non-deformable swelling - deformable gel - sol transformations concrete cracking and expansion will reach a maximum and then decrease because the residual swelling reaction product can be accommodated in the original particle sockets and space created by the expansion cracks.

Calcium hydroxide, which is a large component of hydrated cement, is sparingly soluble and in solution produces a very small concentration of hydroxyl ions. Consequently it is not a significant factor in promoting aggregate reaction. Some alkali-silica reaction product (gel or sol) may come into contact and react with calcium hydroxide to produce a white, opaque, non-swelling alkali metal-calcium-silica complex. This complex product may be observed in cracks, voids and sometimes in protected areas on surfaces of concrete structures usually after alkali-aggregate reaction has been proceeding for a long time.

The behaviour of a pozzolan presents an interesting example of a reactive material which restricts the extent of or inhibits aggregate reaction while, although it reacts readily, it does not cause concrete cracking and expansion. Pozzolan particles must be very fine (i.e. they have small individual volumes and large exposed surface areas) and they must replace a relatively large amount of cement. These requirements ensure that the major proportion of the alkalis reacts with pozzolan rather than with large aggregate particles which have relatively small exposed surface areas. The pozzolan reaction product absorbs water and rapidly passes through the gel to the sol condition. There is sufficient space in the hydrated cement in contact with the pozzolan particles to accommodate the reaction product. The sol can react with calcium hydroxide to form the non-swelling alkali-calcium-silica product. On account of its small size the capacity of pozzolan to cause a disruptive expansion is limited by its deficiency in residual potentially

swelling material. Reaction and expansion of aggregate is therefore suspended indefinitely.

SOME PRACTICAL CONSIDERATIONS

Many procedures have been proposed for testing the reactivity of aggregates. Those most widely used are (1) the mortar bar test and (2) the rapid chemical test. Both have been criticised on various grounds and major difficulties occur in assessing whether an aggregate can be used safely when test results fall in the doubtful reactivity area. The mortar bar test can be quite definitive but it takes a long time, several months up to a year, to produce results. The chemical test yields test results rapidly (within days) but these require expert evaluation. Mortar bar expansions should exceed 0.05-0.10% within a year and the test specimens should contain large numbers of reacting particles and associated cracks. The critical measurement produced by the chemical test involves the quantity of dissolved silica, which must exceed 100 millimoles/litre, because a determination of this magnitude is necessary to indicate the presence of a significant amount of reactive material in the aggregate. Elevated temperatures may be employed to accelerate reaction rates and produce early test results. Such results should be interpreted with caution because elevated temperatures may promote reactions which either do not occur or which proceed at very low rates at atmospheric temperature.

Diagnosis of alkali-aggregate reaction in structures may be obscured and confused by various additional factors such as changes induced by environmental cycling conditions, cement unsoundness, drying shrinkage and the dimension of the structure, its design details, restraints and construction defects. In common with other deteriorating agents, the actual damaging agent, in this instance reacting aggregate particles, must be present in large numbers and readily observable. Reacted particles must be softened, centres of water absorption and associated with cracks which may contain gel. In addition clear gel or the white, opaque, non-swelling alkali-calcium-silica product may also be observed in significant quantities in the voids which are present adventitiously in the concrete.

Prior testing of aggregate is the most effective method of eliminating alkali-aggregate reaction. However in some areas all available aggregates may be reactive. Under these circumstances it is essential to evaluate the expected life and working duty of the structure and to select suitable materials. For example use of a very low alkali cement will significantly reduce the rate of aggregate attack and further restriction of the rate of reaction can be achieved by replacing a portion of the cement with a pozzolan. Under these circumstances aggregate reaction and serious concrete deterioration can be delayed for a time approaching that of the useful life of the structure.

Concrete that is placed under cover dries out and remains permanently dry. It will not undergo further change. Concrete placed on or under ground may continue reacting while concrete exposed to environmental changes will continue reacting, expanding and deteriorating intermittently. Expansion cracks tend to expose the interior of the concrete mass to further

changes including carbonation and reinforcement corrosion. Apart from displacements caused by expansion, reinforcement corrosion and loss of bond especially in pre-tensioned, prestressed units can lead to calamitous failures.

Repair of damaged concrete is not generally or readily achievable. In some limited areas and for relatively small units complete encasing with steel plates held on the surface by stressed steel bars may be effective in maintaining the working capacity of the units.

CONCLUDING REMARKS

A great deal is now known about the mechanism of alkali-aggregate reaction and the deterioration of affected concrete. The simple expansion mechanism involves the swelling of reacted siliceous aggregate particles as they absorb water and the disruptive expansion cracking of the concrete. Although the swelling forces are not excessively large they are sufficiently great to exceed the cohesive strength of hardened cement paste and concrete.

In practice test results obtained from variable and borderline aggregates are sometimes difficult to evaluate and experience and judgement are needed to achieve a reasonable assessment. Similar judgement must be exercised when choosing materials for specific projects and when assessing the condition of deteriorating structures.