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# A WORKING APPRAISAL OF ALKALI-AGGREGATE REACTION IN CONCRETE

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## SYNOPSIS

The paper sets out to define a set of criteria for the recognition of potentially reactive materials and for the assessment of their soundness, volume stability and durability in new structures. Some guidelines are given for the evaluation of distress in existing buildings which are showing signs of the alkali-aggregate reaction.

## SAMEVATTING

Hierdie referaat poog om sekere kriteria vir die uitkenning van potensieel reaktiewe materiale te definieer sowel as om hul gaafheid, volume stabiliteit en duursaamheid vir nuwe strukture te bepaal. Riglyne word gegee vir die evaluering van verswakking in bestaande geboue wat tekens van alkali-aggregaatreaksie toon.

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## 1. SUMMARY

Deleterious alkali-aggregate reaction may occur in concrete when alkalis, derived from portland cement, react with aggregate which contains opal and acid volcanic glasses. As the reacted aggregate absorbs water and swells the concrete is expanded and disintegrated. Recognition of typical signs and symptoms will identify affected concrete and procedures are indicated for assessing the significance of the reaction, the extent of structural damage and the competence of the structure to perform its designed function.

In new construction the most effective means of ensuring freedom from alkali-aggregate reaction involves testing aggregates for potential reactivity prior to their use and where necessary seeking alternative, non-reactive materials. Although some reduction in the alkali content of cement can be achieved by modifying the clinkering process, a suitable choice of raw materials, especially of clay or shale which has a low alkali content, is a possible alternative economic option.

## 2. INTRODUCTION

Although alkali-aggregate reaction has been known and identifiable since Stanton's disclosure in 1940[1], there appears still to be some confusion about the terms 'aggregate reaction' and 'concrete expansion'. The two effects are connected but are not synonymous. Some aggregates or aggregate components may undergo chemical and physical changes without causing concrete expansion while concrete may undergo deleterious expansions for a variety of reasons which are not related to aggregate reaction. Deleterious expansion described by Vivian[2] becomes inevitable when a concrete is well compacted and contains aggregate which can react with alkalis derived from the cement and when an adequate amount of free water, which can be absorbed by the reacted aggregate is present in the concrete. The reaction of alkalis with opaline or acid volcanic glass components of aggregate produces a relatively small volume change and a negligible concrete expansion compared with the very large volume increase and the abnormally large concrete expansion which the reaction product, an alkali-silica complex, produces as it absorbs free water. The swelling alkali-silica complex, which at low water contents is a rigid gel, transmits expansive forces as it absorbs water to the surrounding concrete which distends, cracks and then expands as the cracks in it increase in length and width. The expanding concrete changes from a monolithic mass to a similarly shaped mass of composite fragments which have irregular shapes and sizes and are held together largely by frictional forces.

To ensure that new concrete structures are not affected by alkali-aggregate reaction, all aggregates should be tested for potential reactivity before construction begins. Such tests will indicate potentially reactive materials which can be discarded and replaced by proven sound, non-reactive aggregates. This procedure constitutes the simplest and most direct method of eliminating alkali-aggregate reaction from new construction. Its success depends on the correct assessment of test results and the further assurance that potentially reactive aggregates can not only be clearly distinguished but that non-reactive aggregates and those containing insignificant amounts of reactive components will not be condemned wrongly. The manufacture and use of low alkali cements to restrict the amount of alkali available for reaction with the aggregate, constitutes an alternative which may be adopted under some circumstances.

Criteria are needed to permit the recognition of alkali-aggregate reaction in ageing concrete and estimates should be made of the magnitude of the problem and the state currently reached in its development so that a fair assessment can be made of the extent of damage, its possible future extension and the competence of the structure to perform its designed function. It should be noted that under field exposure conditions the external symptoms of alkali-aggregate reaction are not always readily observable. In most instances affected concrete undergoes a long term expansion which progressively reduces its functional competence and the significance of expansion will vary in different structures or structural units. Consequently an estimate of the residual safety must be made and a decision taken on the need for drastic remedial action, which could involve demolition and reconstruction. The time when re-construction is deemed necessary will be determined largely on the basis of operational sufficiency, safety and various economic factors including those stemming from the possibility of a disastrous collapse which could involve life and property compensation claims.

This paper therefore attempts to set out in simple terms the procedures which are involved in:

(a) A prior assessment of materials for new construction projects where a chosen aggregate may be potentially reactive, and

(b) A study of existing structures which show some signs of distress and estimates of the extent of their damage and their expected future behaviour.

## 3. PRIOR ASSESSMENT OF MATERIALS FOR NEW CONSTRUCTION

All materials proposed for use in large structures should be critically examined for soundness, volume stability and durability, in addition to their more usually measured functional characteristics. Materials for use in large constructional projects should be subjected to non-standard volume stability and durability tests under environmental conditions which are comparable with those to which the structure will be exposed.

Cements produced by selected manufacturing plants should be examined and tested for a range of properties including composition, fineness, strength, soundness and durability. The cement plants should be inspected to ensure that they have sufficient capacity in installed units to maintain the required supply of cement of the quality specified and an inspection of production records should reveal a satisfactory history of plant control, product quality and product uniformity. While it is desirable that the total alkali content of the cement should not be excessively high, it should not be regarded as being particularly significant unless the proposed aggregate shows some signs of potential reactivity or unless some additional limitation is placed on the performance of the concrete. Cements containing total alkalis less than 0,6 per cent (% $Na_20$ + 0,658 x % $K_20$) are generally regarded as having low alkali contents and are considered to be relatively safe for use with reactive aggregates. However, for structures which are designed for long projected lives or for volume stability only the lowest alkali cements available should be used. It can be mentioned that cements usually but not invariably contain more potassium than sodium and that both compounds are derived largely from the argillaceous component of the raw meal. The choice of a low alkali clay or shale therefore offers an effective means of producing low alkali cement while other available procedures are less effective, complicate plant operation and increase costs.

Aggregates constitute the bulk of concrete and may consist of a wide variety of rock types and minerals which may occur in different forms and which in sediments may be derived from different sources. Aggregates consist either of (a) natural coarse gravels and sands or (b) crushed massive stone and crusher fines. Natural gravels are merely washed, screened and recombined as required to yield a specified size grading. Oversize cobbles are either discarded or crushed depending on quantities and available crushing plant. Massive stone is crushed, screened and recombined as required. Natural sands may be washed to remove organic matter and clay and either screened to remove fine silt particles or stock-piled for direct use if they comply with the requisite fineness grading. Crusher fines are merely screened to remove the bulk of the fine dust particles. Aggregates may be used in mixtures with materials imported from other sources in order to correct size deficiencies.

Samples of aggregate from each potentially usable deposit or quarry should be taken for reactivity tests. Stone standing in quarries can be assessed visually for variability and different zones can be sampled and tested separately. Moreover drill cores can be obtained and tested to allow an assessment of stone quality and variation to be made. Similarly coarse gravels from proposed excavation sites can be sampled and tested and if necessary the different pebble types can be hand sorted and tested separately for reactivity. Crusher fines intended for use as fine aggregate should yield reactivity test data that are comparable with data obtained from the quarry stone. Natural sands, however, extracted from active riverine deposits must be treated with great caution on account of their capacity to undergo abrupt changes in behaviour. Sands derived from ancient dunes or deep loads can be more readily assessed because of their relative stability.

The composition of natural sand extracted from an active riverine deposit is generally not stable and consequently changes in time and position with each change in river-flow. These changes may be especially variable in rivers which have large catchments and carry sediments from a wide variety of different rock types. If only a portion of the catchment contains reactive materials, the reactivity of the riverine sediments can change dramatically depending on the most recent flooding history in the catchment area. Consequently a survey of the catchment rock types in such a river system is essential.

Although water is not usually regarded as being a potent contributory factor in alkali-aggregate reaction, in some areas surface run off or more probably ground water contains large amounts (perhaps as high as $40 \times 10^3$ ppm) of dissolved salts consisting mainly of sodium chloride and sulphate but usually with some magnesium and calcium chlorides and sulphates. Such water contributes a large amount of undesirable alkali metal ion as well as unwanted chloride and sulphate to concrete and indicates the general ground water conditions to which concrete will be exposed. Protection of concrete from aggressive solution attack and the discovery of a more suitable water supply would be essential.

Partial replacements of portland cement by pozzolanic materials have been made for various reasons in mass concrete. It has been observed that large replacements of portland cement may reduce and in some instances inhibit concrete expansion caused by reactive aggregate. Replacement of portland cement by pozzolan generally decreases the alkali content of the concrete and simultaneously increases the quantity of siliceous material which is capable of reacting with the residual alkalis. The amount of alkali which reacts with finely divided pozzolan compared with that which reacts with reactive aggregate is roughly proportional to their reactive surface areas. Moreover the very small size of the individual pozzolan particles precludes the possibility of them undergoing large volume increases and causing concrete expansion. Since the extent of aggregate reaction is significantly reduced, concrete expansion is correspondingly restricted. Care must be exercised in the choice of a suitable pozzolan which should have a low alkali content, be very finely ground (particles $< 45\mu m$) and possess a high degree of reactivity with alkalis. Effective control of pozzolan characteristics is essential to ensure their satisfactory performance in concrete and their major use is in large mass structures such as dams where low rates of strength gain are acceptable, concomitant reductions in heat evolution are most desirable and where damaging drying shrinkages cannot occur.

Aggregates containing opal, cryptocrystalline silica and highly siliceous glasses found in acid and intermediate volcanic rocks such as obsidian, rhyolite and andesite react with alkalis. On the other hand, aggregates which contain quartz and coarsely crystalline silicates which are found in such rocks as granite, granodiorite, diorite and gabbro and in less coarsely crystalline rocks such as tuff, porphyry and dolerite do not react significantly with alkalis. The basic, low silica glasses found in basalts do not react significantly with alkalis and the reactivity of sedimentary rocks depends on the composition of the constituent particles

and the presence of secondary deposits of opaline silica. Devitrified siliceous glasses which may sometimes occur in acid and intermediate volcanic rocks are non-reactive while metamorphic rocks, which may possess many undesirable physical characteristics, are generally holo-crystalline and non-reactive. The more exotic reactive materials such as cristobalite and tridymite are unlikely to be encountered in significant quantities in naturally occurring rocks. Artificial reactive components such as fused silica and soda and pyrex glasses may sometimes be encountered in re-claimed materials and the latter two glasses have been used occasionally, with disastrous effect, for decorative architectural surface finishes in cladding panels.

When assessing the potential performance of an aggregate in concrete a number of structural factors should also be considered. These factors are:

(a) *The expected life of the structure.* Materials used for constructing massive structures such as dams, which are expected to have long, maintenance-free lives, should be subjected to extensive testing to prove their long term volume stability and for aggregates, inertness to attack by alkalis. The same stringent requirements are not necessary for non-load-bearing and temporary structures.

(b) *The expected duty of the structure.* Only non-reactive aggregates should be used in suspended concrete, in concrete subjected to heavy traffic and large intermittent live loads, in water-retaining structures and in blocks designed to function as stable bases for finely balanced and aligned equipment.

(c) *The exposure conditions to which concrete will be subjected.* When exposed to the elements, the presence of expansion cracks caused by the alkali-aggregate reaction tends to allow water and other aggressive solutions to penetrate and thus accelerates deterioration. On the other hand, relatively thin section cast-in-situ or precast concrete units, which are placed under cover, allowed to dry out and thereafter to remain dry, will attain a desiccated condition which inhibits aggregate reaction and expansion. Concrete pavements, foundations and pipelines, which can absorb ground water as well as intermittent flow water and precipitation, may be adversely affected by alkali-aggregate reaction as well as by aggressive solution attack and by various structural and operational problems. For economic reasons or in certain situations it is sometimes necessary to use available reactive aggregates for minor, non-load bearing functions such as batter stabilisation or temporary rock face protection.

(d) *Thickness of concrete section.* In contrast to the relatively thin expanding surface zone of a large concrete mass which is undergoing reaction and expansion, the entire thickness of relatively thin section structural units, pavements and concrete products tends to be adversely affected. The inertial effect of size restrains the expansion of the interior zone of a large mass and cores removed from the centre of such a mass will expand abnormally if kept moist. Although the expansion of the surface zone can have damaging effects on the performance of mass structures, its effect on the overall behaviour of the mass and its safety is generally less significant than the systemic expansion which occurs in thin section, plain or reinforced water-retaining structures, load-bearing members and pavements.

(e) *Damage to working surfaces.* Working surfaces of pavements, spillways and training walls can be damaged by pop-outs, spalls, cracks, displacements, excessive dusting and joint failures. Warping may also develop in pavements and cladding panels.

(f) *Concrete mixes.* The mode of occurrence of the reactive component in the aggregate and its distribution in aggregate particles may sometimes be significant. In general the proportion of the total reactive component in coarse aggregate, which is exposed and capable of being attacked by alkalis, is smaller than in fine aggregate. A reduction in the reactive component of the coarse aggregate has the same ultimate effect on the reaction as an increase in the cement alkali content. Although the reduced amount of reactive material tends to produce a reduced overall expansion, a sufficiently large amount of reaction and expansion may occur in localized areas over long periods of time and, even when the alkali content of the cement is low, to cause damaging pop-outs, spalls and a few expansion cracks.

Concretes which contain large volumes of void space resulting from the use of lean mixes, low mix water contents or expanded or light-weight aggregates, are incapable of expanding significantly even when the aggregate is very reactive. In the same way light-weight aggregate concrete made with reactive pumice or with non-reactive basaltic scoria will not expand abnormally because they contain very large amounts of void space.

## 4. EXAMINATION OF AGGREGATES AND TESTS

An initial visual inspection of aggregate will indicate whether it is igneous, sedimentary or metamorphic, coarse or fine-grained, and crystalline or amorphous. Depending on the examiner's geological experience, the rock can be roughly classified to indicate whether it could contain potentially reactive volcanic glasses or amorphous silica. These initial observations indicate the possibility of potential reactivity and the amounts of sampling and testing that will be desirable.

Microscopic examination of thin sections of aggregate by a petrologist is necessary to determine the mineral content and to estimate the amount of any suspect mineral in it. This examination will also distinguish opal from quartz in chalcedonic and other siliceous rocks such as flints, cherts, and jaspers, and allow distinctions to be made between cryptocrystalline and other fine-grained quartzose components and between fresh (active) and devitrified glasses in volcanic rocks. Moreover when a rock sample is finely ground and suspended in a heavy liquid such as a bromoform-benzol mixture (RD 2,35) the float material can be separated, weighed and examined microscopically to determine its refractive index and to yield confirmatory evidence about the quantity and composition of the potentially reactive component.

Many different performance tests have been proposed for detecting reactive aggregates. While most of these tests yield only qualitative data, two which yield quantitative data have become very widely accepted. These tests are:

(a) The rapid chemical reactivity test devised by Mielenz et al[3] and now designated as ASTM C289, and

(b) The Mortar bar expansion test which was described initially by T E Stanton[1] and which has since been designated as ASTM C227.

The rapid chemical reactivity test, which can be carried out in less than 3 days, involves treating the aggregate with a normal solution of sodium hydroxide at 80 °C for 24 hours. It yields data on the reduction in the alkalinity of the solution assumed to result from the alkali reacting with aggregate and on the amount of silica dissolved from the aggregate and found dispersed in the solution. The test conditions are rather severe and the reaction criteria are somewhat confused and may be modified by various factors. The significance of the chemical test data has been amply confirmed by positive correlations with the performance of aggregate in test concrete and in structures but can be interpreted correctly only by a broadly experienced concrete test operator. The significant figure obtained from this test is the amount of dissolved silica even though the reaction between alkalis and silica and the dispersion of the reaction product in the solution are both slow and very incomplete processes. Reduction in the amount of soluble alkali metal ions may also occur for reasons other than their function as the positive counter ion for reacted by undispersed silica-hydroxide complex which remains attached to the aggregate. It should be recognized that, for aggregate to be considered capable of causing concrete expansion, a large quantity of dissolved silica must be found in solution. Thus when the amount of silica in solution exceeds 100 millimoles per litre, the aggregate can be considered to contain a sufficiently large amount of reactive component to cause significant concrete expansion. When test results show less than 100 millimoles/litre dissolved silica, the aggregate will not cause significant concrete expansion even though a low alkalinity reduction test result and high dissolved silica/alkalinity reduction ratio indicate that the aggregate is potentially deleterious. The added criterion that dissolved silica must exceed 100 millimoles/litre has been found to correlate satisfactorily with mortar and concrete test specimen measurements and with the performance of aggregates in concrete structures.

The mortar bar test reveals the potential behaviour of a cement-aggregate combination and is therefore a very practical performance test. Although it possesses the disadvantage of requiring a long elapsed time (up to 1 year) before a reliable estimate of aggregate reactivity can be obtained, the test is non-destructive and has such advantages as the specimen may be measured and examined visually at regular time intervals and progressive changes can be observed during the entire test period. The usual signs of developing reaction such as the appearance of numerous wet surface reaction spots, surface pop-outs, gel exudations and an increasingly large number of expansion cracks which become progressively wider can be observed simultaneously with the measured changes in the overall length of the specimen. Moreover specimens can be made from any specified fraction of crushed and sieved coarse aggregates as well as from unsieved sands and cement produced by any designated plant. The specimens should contain water, cement and aggregate in the proportions 0,5:1:2 by mass to ensure suitable compaction and may be cured and stored in moisture-saturated air at atmospheric temperature or at elevated temperatures if accelerated test results are required. ASTM test requirements specify that, when stored at 37,8 °C, the expansions of specimens containing non-reactive aggregate should not exceed 0,05 per cent in 3 months or 0,10 per cent in 6 months. In Australia it has been observed that the expansion of specimens made with non-reactive aggregates and stored at ambient atmospheric temperature have never exceeded 0,05 per cent in 1 year. If specimens expand abnormally but do not develop the typical reaction symptoms and the random crack pattern some cause other than alkali-aggregate reaction should be suspected.

In the field, aggregates do not react rapidly and concrete structures do not develop reaction symptoms and expand significantly in very short periods of time. For this reason the possibility of alkali-aggregate reaction can be discounted as a cause of rapid and early concrete expansion and deterioration.

## 5. STRUCTURES AFFECTED BY ALKALI-AGGREGATE REACTION

The occurrence of alkali-aggregate reaction in a structure can be suspected if some of the positive symptoms are observed. Significant microscopic signs are surface pop-outs and a fairly widely-spaced random crack pattern on concrete surfaces. Wet reaction spots and gel exudations may be present on external surfaces in moist, protected locations but are unlikely to be readily apparant on surfaces exposed to ambient weathering. The random crack pattern should not be confused with the fine, closely-spaced craze pattern usually found on concrete surfaces exposed to ambient weathering or with cracks caused by drying shrinkage and other differential movements and displacements. Since aggregates generally react and expand slowly, the first clear signs of distress will be detectable about one or two years after the concrete has been placed and any damage which develops prior to this time is probably not caused by reactive aggregate expansion.

Concrete spalls or cores should be taken from an affected structure and examined microscopically to confirm the presence of reacted aggregate as the cause of concrete damage. Examination of broken surfaces of concrete with a low power (approximately 30 x magnification) stereoscopic microscope will reveal the condition of the aggregate

particles and of the concrete. Some aggregate particles will exhibit surface reactions and somewhat softened surfaces, other particles will be more completely softened and will undergo a brittle-type failure when pressed while still other particles will have been completely softened and may even be tending to become wet. In the early stages of reaction and expansion, reacting particles are neither typically gelatinous nor wet and since they are beginning to expand very fine, short cracks will be observed in the surrounding concrete. At a more advanced stage of reaction and expansion the reactive particles may be completely softened in some instances quite wet or even converted to a fluid consistency. Deformable gelatinous or fluid reaction product will also be observable in adjacent voids or in open cracks associated with the reacting particles.

If the spall or core samples of affected concrete are stored in a moisture saturated atmosphere subsequent examinations will reveal the progress of reaction and expansion which can be compared with the changes occurring in the concrete structure. With the passage of time the whole reactive particle will react and the alkali-silica reaction product will absorb uncombined water from the concrete. The alkali-silica reaction product which has a variable alkali:silica molecular ratio generally close to 1:2-4, changes from a hard, rigid, low water content gel to a less rigid, high water content gel which becomes increasingly deformable as it absorbs water and if it absorbs a sufficiently large amount of water it will convert to a sol. As the reaction product absorbs water its volume increases and the expanding gel transmits its swelling pressure to the surrounding concrete which is expanded as the cracks in it increase in length and width. These cracks form a three dimensional random pattern throughout the affected concrete. Expanding gel which can be deformed or fluid sol can be observed in these open cracks as well as in adventitious voids in the concrete and may sometimes be present as fluid exudations issuing from cracks and seeping on to external concrete surfaces. At very late ages and after long reaction times, the gel or sol in cracks and voids or on external surfaces may become white and opaque due to reaction with lime or to desiccation. At the same time the sites occupied originally by reactive aggregate particles may be observed as voids which are only partially filled with clear or in some instances white, opaque gel.

In addition to the typical surface, random crack pattern some structures may exhibit modified or additional crack patterns which are due to restraints imposed by reinforcement or other factors on expansion movements. Massive structures may exhibit an additional system of long, open vertical cracks which are spaced at regular distances. These vertical cracks indicate that a deep-seated expansion is occurring and that as a result of horizontal and vertical structural restraints, is causing a type of surface exfoliation.

Microscopic examination of aged concrete generally reveals evidence of many different deleterious reactions. The extent of most of these is minor and they should not be assumed to have caused significant damage. Where reactive aggregate is the cause of deterioration, the particles showing signs of the reaction will be readily visible, together with the gelatinous reaction products in every microscopic field examined. A significantly large number of the exposed aggregate particles will have been altered by the reaction. It should be noted that damaging concrete expansion may be caused by the reaction of a relatively small proportion (as little as 1 per cent) of the total aggregate and that expansion may be enhanced when the reactive component is widely distributed in numerous small particles. The presence of a few reactive particles in aggregates is fairly common and may cause an occasional reaction spot or pop-out but will not cause significant concrete expansion or damage.

## 6. ESTIMATES OF THE EXTENT OF DAMAGE IN CONCRETE

The extent and significance of damage, which should be considered in relation to the particular structure and its designed function, can be estimated in various ways. Visual inspection of the structure should be combined with microscopic examination and mechanical and chemical tests on cores drilled from the structure. This will indicate material changes, the position and extent of cracked and expanding zones, the condition of joints and any adverse changes induced by other causes. Expansion movement in structures or structural units can be measured and monitored by installing fixed measuring points or by overall measurements made from an external stable base.

Visual inspection may be hampered by the surface condition of the structure. Surfaces may by obscured or contaminated by earth fill while exposed surfaces may be weathered or in the case of submerged concrete heavily leached or covered with aquatic growth. Although all the usual surface symptoms may not be apparent, microscopic examination of the state of the internal concrete will readily reveal any adverse changes in its condition. Desiccation also reduces the extent of apparent damage by restricting aggregate reaction and expansion. The potentially reactive alkali-aggregate system can remain dormant in concrete which is maintained in a dry condition. If such concrete is subjected to wet, damp or even dry wet cycling conditions, the reaction will become active and expansion and disintegration of the concrete will proceed when uncombined water is available for absorption by the reacted aggregate.

Damage and loss of function vary considerably for different types of structure and structural component. Expansion cracks permit water and aggressive solutions to penetrate deeply and cause accelerated leaching, adverse cement hydration reactions, reinforcement corrosion and ultimately extensive failures in relatively thin-section, reinforced-concrete units, such as piles, pipes and cladding. Expansion movement closes the construction joints of roads, inducing edge spalling as well as pavement warping and arching, and leading to mechanical failure and operational malfunction. Cracking and expansion in airport hardstand concrete can cause joint spalling, surface scaling and the formation of damaging grit.

Massive structures such as large dams generally suffer surface damage. The crest parapets, roadway, downstream face and internal gallery surfaces may exhibit the typical symptoms of reaction and expansion. Although expansion cracks may extend for distances of up to several feet into the surface concrete, the expansion of the heart concrete will be negligible on account of the inertial resistance to expansion of the mass. Expansion movement may also be revealed by an increasing difficulty in maintaining tight gate closures and by the misalignment of equipment

It is clear that different structures may be affected by the alkali-aggregate reaction in different ways and to varying extent. Damaging expansion and the structural deterioration that follows are caused by the gelatinous reaction product absorbing free water, swelling and producing cracks and differential movements which reduce the coherence and strength of the concrete. The extent of damage sustained may affect both the operational sufficiency and the safety of the structure.

## 7. COMPETENCE OF AFFECTED STRUCTURES

Structures that exhibit obvious signs of distress are a continuing cause for concern. The condition of an affected structure should be assessed not only for alkali-aggregate reaction damage but also for additional damage by frost, aggressive solutions, reinforcement corrosion and failure and mechanical actions of various kinds. In addition, the future operational capacity and competence of the structure should be estimated.

The competence of structures or structural units which have relatively slender cross-sectional areas is more liable to be prematurely diminished than that of massive structures. Different structures should, therefore, be examined in relation to their designed characteristics and function and special attention should be given to safety, operational efficiency and to damaging effects caused by structural malfunction on surrounding areas. Since structures are extremely variable and are subjected to different environmental conditions, it is possible to make only a few general comments here.

The cracked and expanded zone of a structure or unit should be considered to be non-load bearing. Consequently the reduction in thickness of the concrete section will indicate the potential load-bearing capacity and stability of the structure or unit under its expected operating conditions. Reductions in total mass and strength of massive structures such as gravity dams are minimal under normal operating conditions and the safety of such structures will not be adversely affected. More significant problems may be induced by cracks opening in the upstream face and permitting water under pressure to penetrate into open horizontal joints.

The adverse effects of the expansion of pavements has already been mentioned briefly. Other thin section concrete structures such as water reservoirs, pipe-lines, sewer-outfalls and aqueducts may develop excessive leaks which reduce their efficiency and adversely affect their surroundings while cladding panels which may expand, warp and spall are unacceptable architecturally and constitute a dangerous injury hazard. Expanding reinforced units such as beams constitute a greater risk than post-tensioned, pre-stressed units because the large applied stresses in the latter oppose aggregate expansion. Although some minor surface pop-outs and spalls may occur in these latter units, adequate protection of pre-stressed tendons by grout and maintenance of the designed concrete section will ensure an effective performance.

When all the essential reactants, alkalis, reactive aggregate and free water are present together in concrete it is impossible to prevent the onset and development of some deterioration. Reaction and expansion proceed slowly and deterioration affects progressively deeper surface zones of the concrete. In some instances mechanical aids and minor repairs may be applied as temporary measures to maintain the functional capacity of some structures. It is more usual however to inspect affected structures regularly in order to check the progress of deterioration and to monitor their continued safety. When deterioration has reached a level that is considered to be critical, the affected structure should be demolished and re-constructed with sound materials. No effective overall repair treatment is possible for massive structures which, on account of their very great mass, will continue to operate satisfactorily for their projected lives

## 8. CONCLUSIONS

(a) Alkali-aggregate reaction involves a chemical reaction between alkalis derived from cement and a reactive, siliceous component in aggregate. The product of this reaction is an alkali-silica complex gel which absorbs free water and swells. As the gel swells it cracks and expands the concrete.

(b) There is no cure for concrete affected by the alkali-aggregate reaction.

(c) An expert assessment of the extent of the damage to a structure and its safety should be obtained, and a decision made as to if and when the structure should be replaced.

(d) The development of cracks reduces the competency of concrete to perform its designed functions and may accelerate the failure of some units.

(e) The damage sustained by, and the condition of, different structures should be assessed in relation to their specific characteristics and functions.

(f) The failure of some structures could involve claims for compensation.

(g) In new construction projects alkali-aggregate reaction can be most readily avoided by testing available aggregates and using only those which prove to be non-reactive. Suitable tests are available for this purpose.

(h) In certain areas where all aggregates are reactive it is essential that they should be used in combination only with low alkali cements. Although procedures are available for reducing the alkali content of cement during its manufacture, they are costly and could increase environmental and atmospheric pollution. The most effective means of producing low alkali cement is to use low alkali raw materials, particularly clay or shale.

(i) In mass concrete structures some alleviation of the alkali-aggregate reaction may be achieved by replacing a portion of the cement by a reactive, siliceous pozzolan.

(j) Alkalis in cement influence other properties of concrete such as drying shrinkage and the tendency to effloresce. Although these effects may not be considered as being unduly deleterious, they can induce unwanted defects in concrete.

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## DISCUSSION

Dr L Dent-Glasser (Aberdeen University, Scotland) referred to the rapid chemical test. She suggested that much of the problem with the so-called reduction of alkalinity was because phenolphthalein was recommended as an indicator. This tended to give erratic results because if phenolphthalein was used as an indicator, an indefinite amount of the dissolved silicate was titrated along with the hydroxyl. If there was any considerable quantity of silicate in solution, the result was an extremely poor end point and this result depended on just what the particular operator decided was the proper end point. However, if methyl orange were used as an indicator, all the silica or silicate was titrated and then the result would correspond to the sum of silicate plus hydroxyl ion and this would indicate the amount of dissolved sodium in the solution. The use of phenolphthalein gave a quite useless quantity which did not indicate anything and she felt that using methyl orange might lead to more useful results.

Prof U Ludwig (RWTH, Aachen, West Germany) did not agree about the non-formation of an osmotic cell. He referred to his paper and said that on the question of the repair of a structure, he felt it would be difficult to repair affected concrete: there were some possible actions but they were expensive. In particular cases where the reaction was complete and it was possible to prove that it was finished or that the reactive aggregate had all been used up, the concrete could be repaired. He gave as an example a German case where it had been possible to say that the reactive material had all been converted to calcium alkali silicate hydrate or something similar. He mentioned that if the reaction stopped, the strength would again improve for the alkali silica gels which reacted with lime might be as hard or harder than the cement itself.

Mr Vivian stressed that it was very difficult to be confident that the reaction had worked itself right out. If one of the reactants was taken out of this system it came to a halt; therefore if the aggregate had reacted completely, there could not be any more to go on. However, his observation was that while this could happen with some particles it did not necessarily happen with all particles. He referred to Dr Ludwig's comment about the interaction between the reacted material and lime which undoubtedly occurred. It was important to know what happened to the alkali; and he thought that in many cases it might be released and go back into the reacting system. The end result would be somewhat like the normal cementing calcium silicate compounds and this could have a useful effect in filling up holes and so on in the concrete. However, if the alkali went back into the system and reacted with opal or whatever reactive aggregate was present there, then the problems would continue.

Dr Ludwig claimed that the reacting material had been used up. The situation might be different in the case of the fine hornfels of the South Western Cape but in his case they could say that there had been no more reaction. They had proved this over about 7 years in concrete cores, and found that in some cases there was no more reaction and that the wet cube strengths were only increasing.

Mr Vivian suggested that Dr Ludwig had been fortunate, because in the bridge that he had looked at on the previous day, where repairs had been attempted, the reaction was clearly still continuing and the cracks were still opening.