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ALKALI-AGGREGATE REACTION : PRACTICAL PREVENTIVE AND REMEDIAL MEASURES

by J C Flanagan*

SYNOPSIS

In the design of any new structure there are a number of factors that must be considered before it can be decided what preventive measures, if any, will be necessary to prevent alkali-aggregate reaction. These include the nature of the aggregate, the amount of alkali in the concrete, the conditions of exposure, the massiveness of the sections and the consequences of failure should there be an alkali-aggregate reaction.

In a case where no reaction can be tolerated, its occurrence must be positively prevented by using a nonreactive aggregate, a low alkali cement, incorporating a suitable pozzolan in the mix or by a combination of all three.

Measures aimed at arresting or retarding the reaction in existing structures must be applied with circumspection. Incorrect action may actually increase the rate of deterioration. Remedial measures must attempt not only to retard the reaction but also to combat the increased risk of corrosion which the cracking invariably creates.

SAMEVATTING

Alvorens 'n besluit geneem kan word oor die voorkomende maatreëls, indien enige, wat nodig sal wees om alkali-aggregaatreaksie te voorkom wanneer enige nuwe struktuur ontwerp word, moet 'n aantal faktore oorweeg word. Dit sluit in die aard van die aggregaat, die hoeveelheid alkali in die beton, die blootstellings-toestande, hoe massief die dele is en die gevolge van faling in die geval van 'n alkali-aggregaatreaksie.

In gevalle waar geen reaksie verdra kan word nie moet dit positief voorkom word deur gebruik te maak van 'n nie-reaktiewe aggregaat of 'n lae-alkalisement, of deur 'n geskikte possolaan in die mengsel in te sluit of deur al drie te kombineer.

Maatreëls wat daarop gemik is om die reaksie in bestaande strukture te stuit of te vertraag, moet met omsigtigheid toegepas word. Foutiewe optrede kan inderwaarheid die tempo van verswakking versnel. Herstelmaatreëls moet nie slegs die reaksie probeer vertraag nie, maar moet die vergrote risiko van korrosie, wat sonder uitsondering plaasvind wanneer die beton kraak, teenwerk.

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1. INTRODUCTION

There are three conditions which must all occur simultaneously before the alkali-aggregate reaction can take place. Preventive measures are directed at one or more of them as follows:

(i) Precluding the presence, in the aggregate, of any constituent that will react deleteriously with soluble alkalis.
(ii) Preventing a sufficient concentration of alkali to be capable of causing the reaction.
(iii) Avoiding environmental conditions in which the reaction can take place.

Very little can be done to stop the reaction once it has started. However there are measures which will help to control or retard it. In some cases action must be taken to counter corrosion damage to the reinforcing steel.

The phenomenon of alkali-aggregate reaction has been known for the past 40 years but has only become evident in South Africa comparatively recently. As sources of aggregate of proven quality have become depleted, new, unproven materials are being used. In addition, the alkali content of some cements has increased as a result of changes in manufacturing technique. These factors coupled with the complexity of many modern structures, have caused an increase in the incidence of the problem[1]. The extent of the damage can vary widely and in some instances it is serious.

Remedial measures are not very effective so if the danger exists, precautions should be taken to prevent its occurrence. The nature of these precautions will depend on prevailing circumstances. In many cases they may not be very onerous.

2. ASSESSMENT OF RISK

There are certain factors which may cause or contribute to the occurrence of deleterious alkali-aggregate reaction. Consideration of these factors will enable the potential risk to be evaluated and preventive measures to be formulated. Among the main factors to be considered are the following.

Environment: Cyclical changes in moisture and temperature appear to aggravate the reaction. Those portions of the structure which are exposed to the elements must be given special attention. Exposure to elevated temperatures accelerates the reaction[1, 2].

Presence of moisture: Damp earth or water on one face only is particularly deleterious. Migration of moisture in one direction can cause a concentration of alkali[3, 4].

Size of sections: Large, massive sections are particularly vulnerable. Large sections dissipate the heat of hydration slowly. As heat builds up the reaction is accelerated. Cracking can be caused by stresses induced by the temperature gradients and cracks permit the ingress of moisture. Because large sections take much longer to dry out, moisture is present for a longer period during which it is available for promoting the reaction or causing expansion[15].

Aggregates: If aggregates have a satisfactory history they may be used with confidence[5, 6, 7, 8, 9]. If not, they should be assessed by someone competent to do so.

Alkalis: If aggregates are potentially reactive, the presence of alkali is important and their quantity will have to be limited[3, 10, 11, 12].

3. DEGREE OF VULNERABILITY

After considering the above and any other relevant factors, the risk of deleterious reaction can be assessed, and the extent of preventive measures that are required can be determined.

Three categories will be considered:

(i) Important structures where the risk is high.
(ii) Less important structures or those in which the risk of reaction is small.
(iii) Those structures in which the risk is negligible.

4. PREVENTIVE MEASURES

It is important in every case to use dense, high quality concrete[8]. Good concreting practices are therefore essential in all operations and this requires conscientious and intelligent supervision. If only portions of a structure are exposed to the elements then only those portions need receive special attention.

Consider first the case where the risk is high and the consequences of failure would be serious. There are three options, given in order of merit:

(i) Use of an alternative non-reactive aggregate.
(ii) Use of low alkali cement.
(iii) Use of a suitable admixture such as milled granulated slag or a proven pozzolan.

All three methods can be successful, but the final decision will usually be dictated by economics. Detailed discussion of these measures will be covered adequately by other papers being read at this conference.

When assessing an aggregate for reactivity, its service record when used in similar conditions is the best indication of its suitability[5, 6, 7, 8, 9]. If the aggregate has not been used previously or if doubt exists as to its suitability then it should be referred to an experienced petrographer.

Low alkali cements are available but may be more expensive than other cements. Although present knowledge does not enable us to prescribe admixtures with total confidence, the evidence shows that there is much to be gained by their use. In time the use of suitable admixtures may well become the most practical and economic means of preventing the reaction. However, admixtures such as pozzolans should not be used without thorough investigation as some of these have been known to increase the reaction[6,13,14]. It has been suggested that excluding the reactive aggregate is the most effective way of overcoming the alkali-aggregate reaction problem[15]. Nevertheless, there are many practical steps that can be taken to control the reaction, particularly where the risk and consequences are less serious. The three methods outlined above will still be relevant. Other methods that may be considered are reducing the total quantity of alkali in the concrete, improving the quality of the concrete and paying particular attention to relevant construction details.

Cement content: Many specifications and codes rate the durability and impermeability of concrete in terms of the cement content. This is valid provided the water content is held constant. Increasing the cement content then improves the water-cement ratio and thereby increases impermeability and durability. This concept is fully recognised by the American Concrete Institute and others[16,17].

Similarly, provided the water-cement ratio is not altered, it becomes possible by reducing the water content to reduce the cement content, and thus the total alkali, without affecting the quality of the concrete. This does not simply mean using a drier mix because full compaction is essential for impermeable concrete. Rather, means must be found of reducing the water without decreasing the workability.

Assuming that the cement is the sole source of alkali, then reducing the cement content will correspondingly reduce the quantity of alkali in the concrete.

It is the total quantity of alkali in the concrete that is more important than the percentage alkali in the cement[3,10,11,12]. There have been various estimates of the maximum alkali content that can be tolerated without causing deleterious reaction[12,18]. In South Africa the National Building Research Institute considers a mass of 2,1 kg/m^3 to be an acceptable limit with Malmesbury aggregate[8] (eg with 6 per cent alkali in the cement the maximum cement content would then be 350 kg/m^3).

Reducing the cement content: Where possible, concrete strengths should not be too high. The difference between 30 and 40 MPa concrete is about 75 kg cement per m^3 of concrete. Strengths below about 25 MPa are not recommended because the permeability of low strength concrete allows the easy penetration of moisture.

Sands of low water demand have low cement requirements. In the Cape Peninsula area the average quality sand has a water demand of about 195 ℓ/m^3 of concrete. However, there are sands from the Klipheuwel area with water demands as low as 170 ℓ/m^3. With 30 MPa concrete this represents a saving of about 48 kg cement.

The larger the size of the stone, the lower the water requirement of the mix. Stone of the largest practical size should therefore be used bearing in mind such other factors as corrosion of steel and flexural strength of concrete. The difference in cement content between a concrete mix using 20 mm and one using 40 mm nominal size stone, each with a minimum strength of 30 MPa, is about 38 kg/m^3.

By substituting pozzolans, pulverised fuel ash, milled granulated slag or some other suitable material for a portion of the cement, not only may the alkali content be reduced, but in many cases the reaction is suppressed.

The degree of control exercised on the job determines what average strength must be aimed at to ensure that not more than a certain number of results fall below the specified minimum strength. With 5 per cent of results permitted to fall below the minimum, a saving of about 10 kg of cement may be effected by improving the control from 'average' to 'good'.

As an example of the effects of the abovementioned measures, assume a 30 MPa concrete is needed. Average quality sand, 19 mm stone and no admixture will be used and control on site will be average. The cement content would be about 370 kg/m^3.

Then assume 30 MPa concrete using a very high quality sand with 38 mm stone. Pozzolan is to be substituted for 15 per cent of the cement and control is to be good. The cement content would be about 240 kg/m^3.

Assume the cement contained 0,7 per cent alkali. Total alkali in the first concrete would be 370 x 0,7 per cent = 2,6 kg/m^3.

Total alkali originating from the cement in the second concrete would be 240 x 0,7 per cent = 1,7 kg/m^3. The control measures have reduced the total alkali from 2,6 kg/m^3 to a modest 1,7 kg/m^3.

Other measures: Besides reducing the cement content to a minimum there are other practical measures that may be adopted to lessen the danger of deleterious reaction and to minimise the consequences of possible expansion.

Impervious concrete: Every endeavour must be made to manufacture high quality, impervious concrete. Aggregates with shrinking characteristics must be avoided. Good concreting techniques must be employed and after curing the concrete must be allowed to dry slowly. Precautions must be taken to control early thermal cracking and the structural design must aim at minimum crack widths.

Air-entraining agents, by breaking up and limiting the length of capillaries, make the concrete less pervious, and their use is therefore to be encouraged.

Heat: Heat must not be used to accelerate curing as it accelerates the reaction and may even induce reactions that would not occur at normal curing temperatures[15].

Drainage: Rain and ground water must be catered for by carefully designing drains that will shed and carry away water as efficiently as possible. Drains must be free flowing and have generous falls. Where structures have one exposed face, the surface which is in contact with the water or moisture should be protected by an impermeable membrane or layer[10].

Joints: Joints with adequate clearance should be provided. The force exerted by expanding concrete is large and if it is restrained, very high stresses can result.

Supervision during construction: During construction care must be taken to ensure that drains, weep holes, joints, etc are constructed strictly in accordance with the drawings, particularly where these will later become inaccessible.

Maintenance: After construction it is highly desirable that the structure be inspected periodically to ensure that drains are open and working, that joints are free and functioning and that jointing material is in good condition. Should any repairs be necessary they must be carried out promptly and intelligently.

5. REMEDIAL MEASURES

It has been stated that there is no known method of adequately preserving existing concrete which contains the elements that contribute to deleterious alkali aggregate reaction[6]. However, there are some measures that may be taken and others that should be taken.

Structural stability: It is of primary importance to secure the stability of structures. Any necessary action will be dictated by prevailing circumstances. If the structure is an old one, it could well be that expansion has stopped and that no further movement will take place[4]. Monitoring movement at selected positions would give valuable information on which decisions about remedial measures could be based.

Corrosion: The cracking of concrete always increases the risk of corrosion of the reinforcement. This is particularly so in the Cape where in addition to the moist coastal conditions, salt from the sea is blown in by prevailing onshore winds. Cracks allow easy ingress of this salt and corrosion of the steel is then a very real danger.

Sealing: If cracks must be sealed to prevent corrosion or for any other reason, this should be done by injecting epoxy or some other suitable material. Any covering to the outer face of concrete must be impervious to water to prevent it entering the concrete, but it must also allow the passage of water vapour to enable moisture to escape. Suitable materials would be cement based paints or acrylic PVA paint. Completely impervious coverings would be satisfactory if applied to dry concrete, but unless this state can be achieved they should not be used[2,10]. Because of the dangers of sealing moisture in, no decision to seal the surface of any affected concrete should be taken without full consideration of all the relevant facts[2,10].

Steel corrosion: If there is evidence that reinforcing steel is corroding then the defective concrete and rust must be removed and repairs executed in the usual manner.

Water: The structure must be carefully examined with a view to excluding or controlling water. Defective or inoperative drains must be restored. If necessary new measures should be instituted either to prevent moisture reaching the structure or to conduct it away.

Even though existing structures may not exhibit any signs of distress, if it is felt that there is a risk of the reaction, then it will be worth taking precautions to control moisture and checking on the other factors described above.

6. SUMMARY

Deleterious alkali-aggregate reaction can occur only when three conditions are satisfied. They are:

(i) the aggregate is reactive;
(ii) sufficient alkalis are present, and
(iii) the environment is suitable.

The risk of expansive reaction increases with exposure to moisture and as the massiveness of the section increases.

Preventive measures include the following:

(i) use of non-reactive aggregate;
(ii) use of low alkali cement;
(iii) incorporating a suitable admixture such as slag or a proven pozzolan.

To reduce the seriousness of the reaction the alkali content can be reduced by keeping the cement to a minimum. Other measures include providing efficient drains and joints, avoiding shrinking aggregates, ensuring thorough curing, using an air entraining agent, insulating the structure against the ingress of moisture and improving the degree of control on the site during construction.

After construction there should be periodic inspections of drains and joints and repairs must be carried out promptly.

Remedial measures should include removal of moisture, prevention of steel corrosion, and where necessary the restoring of structural stability.

DISCUSSION

Dr G M Idorn (G M Idorn Consult Aps, Naerum, Denmark) said that in relation to the very concrete and valuable guidelines for designing preventive measures, he wanted to stress that in the evaluation of buildings, whether dealing with a high risk construction (from the point of view of consequences) or a low risk construction, the consultant should pay attention to Mr Flanagan's advice to have discussions with the builder before construction began, so as to involve the builder who had to take the final decision as to what the real risk analysis in building was. He had to be aware that it was unfortunately a law of nature that even a low risk building occasionally failed. It was necessary to establish this kind of communication more systematically than in the past, and he felt Mr Flanagan had given consulting engineers very good advice on how to approach that problem. He further mentioned that when one was casting in lifts, one was actually casting new concrete on old concrete, which had already cooled. The new concrete expanded over it and became glued to the old concrete during the early hydration. When the new concrete cooled it could not shrink back to the volume of the underlying concrete to which it was glued. Thus the cooling temperature stresses often created cracking in that situation, and one often saw cracking following the line of lifts which was evident in some of the pictures shown.

Mr Flanagan agreed that both comments were valid with any structure, and particularly with this problem, it was only right that not only the consultant and the builder but also the owner should consult each other. The more everybody realised the problem had to be brought into the open, the better. In regard to the thermal cracking, he felt this was far more prevalent than people liked to believe and it could only aggravate the position.

Mr E H J van Rensburg (Murray & Roberts, Cape Town) referred to Mr Flanagan's remarks in which he had stressed the importance of the cement content, which had to be reduced in order to attempt to control the alkali content. He had also briefly mentioned the use of water reducing admixtures. These had been used in the Cape for some time now, and researchers had occasionally succeeded in persuading certain consulting engineers that in fact the alkali content had been sufficiently reduced to prevent any manifestations of alkali-aggregate reaction. For example, with the high quality Klipheuwel sand which Mr Flanagan had mentioned and a certain water reducing admixture one could lower the cement content to approximately 270 kg per cubic metre, which was virtually what Mr Flanagan had quoted for cases where he had used pulverised fuel ash as an admixture. By using the water reducer and the lowest cement content one had not only a more economical concrete but also reduced the risk of any undesirable side effects or unknown effects that might be picked up with the pfa. Most of the water reducing admixtures were derivatives of either calcium or sodium salts. It was important to use one which was based on a calcium salt as opposed to a sodium salt because one was attempting to remove the alkalis from the concrete. This could be one reason why super plasticisers should not be used because the majority of them were sodium salts. The water reducing admixtures people claimed increased drying shrinkage, but when one considered the reduction in water content when the water reducing admixtures were used, the increase in drying shrinkage was in fact negated.

Mr Flanagan referred to his mention of mineral admixtures and water reducing admixtures: he stressed that he did not give his blanket approval to the use of these because he had seen concrete that after 2 days he could put his finger into, and this had been attributed to the admixtures. He felt that unless one really knew what one was doing and what the full effect was going to be on all the properties of concrete, one should be very circumspect about using them; but they certainly did have their uses.

Mr T Nemeth (Murray & Roberts, Johannesburg) raised three points. It had been mentioned that one should use the best aggregate available. He asked how one could make a selection since the Malmesbury aggregate, which had for years been regarded as an excellent aggregate, had now been proved to be alkali reactive. Secondly, he asked which proven mineral admixtures had been referred to. Finally, he inquired how one could design for medium strength, if 65 MPa concrete was required for a bridge 400 metres long and 235 metres above ground level.

Mr Flanagan explained that in respect to the best aggregates, he had been referring to physical properties. In particular when he said aggregate he was not necessarily talking about stone: for example sand was a fine aggregate. He had been talking about the precautions which should be taken if possible. The sand certainly did not seem to be contributing to the problem and yet it made the biggest contribution towards reducing the cement content. As far as mineral admixtures were concerned he had been referring to the work which had been and would be discussed during the conference. In answer to the last question he suggested that for a bridge of that size one should aim at high strength and use either a non-reactive aggregate or a cement with the lowest possible alkali content.

Mr A Hemp (Murray & Roberts Quarries, Eersterivier, South Africa) asked why the use of an alternative aggregate was ranked higher than the use of a low alkali cement in the listing of preventive measures.

Mr Flanagan stressed that he had mentioned three conditions which all had to occur simultaneously before the alkali-aggregate reaction could take place. As long as any one of these three was eliminated the reaction would be prevented from taking place.

Dr I Sims (Messrs Sandberg, London, England) commented that the often suggested preventive measure of using low alkali cement was not always appropriate in all parts of the

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ALKALI-SILICA REACTION IN GREAT BRITAIN - A REVIEW

by R T L Allen*

SYNOPSIS

Since 1971 when the first case of alkali-aggregate reaction was reported in the British Isles a number of other cases have been identified. The history of some of these is examined and proposed future research work outlined.

SAMEVATTING

Sedert 1971 toe die eerste geval van alkali-aggregaatreaksie in die Britse Eilande aangemeld is, is 'n aantal ander gevalle ook geïndentifiseer. Die geskiedenis van enkele hiervan word ondersoek en voorgestelde toekomstige navorsingswerk word aangedui.

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world. Many British engineers were operating in the Middle East where this was usually not possible. The supply of cement in the Middle East was unpredictable and one could not specify the use of a low alkali cement; at times it was not even possible to specify the use of an ordinary Portland cement. One got cement in all sorts of bags and from all sorts of places and this could vary day by day. The second reason was that one of the biggest problems in the Middle East was that the aggregates often contained quite a high proportion of sodium chloride, and even if the proportion of sodium chloride present was reckoned to be tolerable from a reinforced concrete point of view, this could still add sufficient sodium to the system to negate the benefit of using a low alkali cement. So although this was often a possible preventive measure, in some areas of important construction activity it could not always be implemented.

Prof U Ludwig (RWTH, Aachen, West Germany) referred to the situation in Germany, where it had been found that when using ready mixed concrete difficulties could be encountered with placing the concrete, because there were great variations in the workability of the concrete with the same cement, and sometimes one had to break off concreting when building bridges, to change the mix-design. The variation in the workability of the same cement occasionally led to the fear that the cover over steel reinforcement would be unsatisfactory. They had therefore started discussions on changes in workability with the same cement. He therefore asked, what, when changing the water/cement ratio and reducing the cement content, was being referred to, was the role of the cement itself.

Mr Flanagan said that he personally had not come across this phenomenon, although he had read about it in the literature. Here in the Cape there were 3 different cements, and in the normal work they did they had not been able to pick up any difference even in cement from different factories. There were, of course, many other factors, for example temperature and the method of measuring workability, which exerted such a big influence that he thought they would probably mask any effects that occurred unless they were really dramatic. Depending on whether the concrete was made early in the morning or in the heat of the day, there would be differences, and he thought these were far larger than those produced by a change in the cement.