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How to make concrete that will not suffer deleterious alkali-silica reaction

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Abstract

Excessive expansion of concrete due to alkali-silica reaction will not occur if any one of the following circumstances exists: (1) the aggregate is insufficiently reactive; (2) the pH of the pore fluid is not too high; (3) the amount of reaction product formed is not sufficiently large or not sufficiently expansive so that its expansion can cause damage; or (4) there is not enough available water to cause the reaction to progress so as to develop the expansive product and to be available for imbibition by the product so as to cause it to swell and disrupt the concrete. Put the other way around, excessive expansion can occur only if there is enough potentially expansive alkali-silica reaction product and water so that, as the product takes up the water and swells, the concrete expands excessively. Hence, what is needed to avoid excessive expansion is to be able to predict the probable reactivity of the available aggregates, the probable mechanisms by which the pH of the pore fluid might get well above 13, and, when justified, select and implement appropriate precautions against the undesirable consequences of these eventualities.

Keywords: Aggregate; Alkali-aggregate reaction; Expansion; Petrography; Pozzolan

1. Introduction

In 1979, ACI published a paper I wrote called "Concrete Need Not Deteriorate," which included the essence of remarks I have made at quite a number of different places over the past 40 or more years [1]. It says, in effect, that concrete will provide the sort of performance desired, provided only that the specifications are correct and that they are followed. We know the relevant levels of properties needed by concrete to resist any reasonably anticipated set of environmental conditions. We know what sorts of quality-control procedures the contractor should use and what sorts of quality-assurance activities the owner should use to see to it that the standards of good practice in executing the work are followed.

Later I wrote a paper on how to make concrete that will be immune to the effects of freezing and thawing [2]. Still later I discussed at the Transportation Research Board what one needs to do to avoid premature deterioration and to obtain the desired performance of concrete in transportation [3]. Damage to concrete by freezing and thawing and damage caused by excessive expansion due to alkali-silica reaction (ASR) were the two principal issues relating to concrete durability that were selected for detailed research in the Strategic Highway Research Program. It seems appropriate now to try to do some technology transfer about preventing damage to concrete resulting from ASR.

Tom Stanton, of the California Department of Transportation, discovered ASR [4]. I went to work for the Concrete Laboratory of the Corps of Engineers in August 1941. Word of his discovery had already reached that laboratory, and one of the first bits of work I did was to look at his "siliceous magnesian limestone," which was described as the offending ingredient of the concrete that had deteriorated. At that point, the Corps of Engineers was quite concerned because, to us, "magnesian limestone" meant dolomite, and dolomite as crushed stone was very widely used as aggregate in concrete in Corps of Engineers structures. Our position had been that, whereas most limestones sold as aggregate were satisfactory, substantially all dolomites were. It turned out that the "siliceous magnesian limestone" that caused the trouble in California is a very unusual rock that contains a lot of opal. As far as I know, no other dolomite in the world contains enough opal to cause trouble due to ASR.

2. Assessing aggregate reactivity

Normally, the first issue confronting a person contemplating the use of concrete with regard to ASR is: "Are there some reactive aggregates out there among those that might get used in the work?" Hence, one usually thinks first of the

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procedures available for answering the question: "Is the material in this aggregate source potentially deleteriously reactive with alkalies?"

ASTM C 33-97 [5], the "Standard Specification for Concrete Aggregates," requires in Section 7.3 that: "Fine aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalies in the cement in an amount sufficient to cause excessive expansion of mortar or concrete, except that if such materials are present in injurious amounts, the fine aggregate may be used with a cement containing less than 0.60% alkalies calculated as sodium oxide equivalent ($Na_2O + 0.658\ K_2O$) or with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction," and in Section 11.2: "Coarse aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalies in the cement in an amount sufficient to cause excessive expansion of mortar or concrete except that if such materials are present in injurious amounts, the coarse aggregate may be used with a cement containing less than 0.60% alkalies calculated as sodium oxide equivalent ($Na_2O + 0.658\ K_2O$) or with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction."

An appendix to C 33 discusses the use of C 295, petrographic examination; C 289, the quick chemical test; C 227, the mortar-bar test; C 342, the Conrow test; and C 586, the rock cylinder method. In each case, some advice is given for interpreting the results in terms of the potential for excessive expansion due to ASR. Action to revise this appendix to cite more recently developed test methods is currently pending in ASTM. Reference to ASTM C 1260, which was approved in 1994, will be included. This procedure permits detection in 16 days of the potential of an aggregate for deleterious ASR and hence the need for additional evaluation.

The U.S. Army Corps of Engineers' Manual [6] includes guidance to field offices in preparing specifications for concrete. It is assumed that a survey of potential aggregate sources will be made and data on samples from them will be obtained. The project specifications will contain a list of the sources that are regarded as containing adequate amounts of material of satisfactory quality to provide aggregate for the project. The evaluation of reactivity will include examination and tests by C 227, C 289, and C 586. The manual states: "If aggregates containing reactive constituents are to be used, the problem then becomes one of identifying the reactive constituents and determining the conditions under which the available aggregates may be used. Where the reactive constituents can be positively determined to occur in such small proportions as to be innocuous, an aggregate, if otherwise of suitable quality, may be used without special precautions. Where the reactive constituents occur in such proportions that they are potentially deleteriously reactive, it will be necessary to use low-alkali cement or an effective pozzolan, or both, with the aggregate. If the requirement of low-alkali cement would impose serious difficulties of cement procurement or excessive increase in cost, consideration should be given to the use of portland blast-furnace slag cement (a blend of portland cement and slag), portland-pozzolan cement, cement with GGBF slag, or cement with a pozzolan, or both, that will prevent excessive reaction even when high-alkali cement is used. When consideration is given to the use of any of these materials in lieu of low-alkali cement, mortar-bar tests should be conducted to verify that the potentially deleterious expansion will be reduced to meet the criteria in Appendix D or E in [6]. If petrographic examination determines the presence of potentially reactive materials in excess of the limits given in Appendix D, mortar-bar tests, ASTM C 227 shall be performed. If the petrographic examination determines the presence of strained quartz in excess of the limit given in Appendix D, the high-temperature mortar-bar test shall be performed."

3. Precautions to take to avoid excessive expansion due to ASR

As noted in the Corps of Engineers' Manual, in some cases, no specific precautions are needed to preclude excessive expansion due to ASR. These cases include the following:

1. The aggregates have been shown not to be potentially deleteriously reactive, i.e., innocuous with respect to ASR.
2. The cementitious medium to be used has been shown to be of sufficiently low alkali content and the possibility of alkali from any other source is sufficiently remote to be disregarded; hence, it can be confidently expected that the pH of the pore fluid will not get too high.
3. The cementitious medium to be used includes a sufficient amount of satisfactory ground slag or pozzolan, so excessive expansion will not occur with this composition, which was selected for reasons of temperature control or economy or both, unrelated to ASR.
4. The concrete to be produced will all be in an environment in which it will rapidly get dry (internal relative humidity well below 80%) and remain so during its service life.

In some cases where the aggregate is classed as potentially deleteriously reactive, the level of such reactivity is sufficiently low so that the only precaution that is needed is to specify that the cement be "low alkali." In others, one should preselect one or more aggregate sources that have a good service record when used in similar work with the local cement or cements. In still others, there should be a study of other constituents that might be included in the concrete such as ground granulated blast-furnace slag or a pozzolan. Natural pozzolans (volcanic ash, diatomaceous earth, etc.), fly ash, and silica fume have all been shown to be able to prevent excessive expansion of potentially deleteriously reactive cement-aggregate combinations.

4. Process and mechanism

While we talk about ASR, in every case of damage to concrete in service I know of caused by it, it was the presence of alkali (sodium ion or potassium ion or both in solution) that caused the pH of the pore fluid to rise to levels where it became aggressive to the thermodynamically metastable silica in the aggregate. It is not the alkali that does the reacting; it is the hydroxyl ions. Vivian [7] demonstrated that: “The hydroxyl ion must be considered to be the reacting ion.” He based this conclusion on the observation that tetramethyl ammonium hydroxide produced a similar reaction product to that formed from sodium hydroxide. He found that a mortar bar made with low-alkali cement to which sufficient tetramethyl ammonium hydroxide had been added to provide 0.85% hydroxyl ion by mass of the cement expanded 0.85% at 10 months. A control with low-alkali cement did not expand.

The alkalies that end up in concrete, from the cement or elsewhere, are almost never NaOH or KOH unless we are doing research in the laboratory; they are often potassium sulfate from the cement, or sodium chloride from sea water, etc. Solutions of such salts are pH neutral, not above the value of 12.6 of a saturated calcium hydroxide solution. The reason alkalies get a chance to mobilize hydroxide ions, raise the pH, and allow the pore fluid to become aggressive to the reactive constituents of aggregate when such are present is that the chloride or sulfate ions react and precipitate out of the solution, usually to form calcium sulfoaluminate or calcium chloroaluminate or gypsum. I suggest that some attention might be given to the use of a cement with either little or no aluminate as a means of reducing the likelihood of an undesirably high pH developing in the pore fluid in concrete. “Zero C3A” cements exist.

5. Remediation

Suppose someday you get the news that your structure (or one of your structures) that you had been counting on for another half century or more of service has been declared to contain ASR product, or worse, found to have typical pattern of cracking and, on investigation, found to have both ASR product and remaining unreacted reactive aggregate constituents. What are the chances that deterioration will progress to an unacceptable level? This is not an easy question to answer. As one philosopher put it, “Making predictions isn’t easy, especially about the future.” What we did years ago was to store cores with length-change measuring inserts in the fog room [8]. What was found was that a core from a dry area showed twice as much expansion as any of the others, all of which came from areas that were wet or damp. This suggested that there was a limited amount of expansion to be expected, much of which had already taken place in the wet or damp portions of the structure.

Tuscaloosa Lock in Alabama, the Corps of Engineers’ best-studied ASR-affected structure [9,10], is a classic example of how a structure that when first examined was declared to be “so badly cracked that the natural impression would be that it is about to collapse” [11] and 30 years later [10] was be found to be “of generally good quality.”

Another structure, also in Alabama, from which cores were studied in detail at our laboratory is Martin Dam [12]. From that study, it was concluded that “the condition of the concrete . . . can be considered acceptable” after 50 years of service. ASR evidence was found in all the concrete cores examined. The reactive constituent was metamorphosed quartz and quartzite that had undulatory extinction. The reaction product was typical of ASR. The concrete had less reaction product than seen in other structures still in good condition after 10 or 24 years of service. One photomicrograph of Martin Dam concrete was so illustrative of ASR phenomena that it was used as the frontispiece in the Proceedings of the 1978 Fourth International Conference on the Effects of Alkalies in Cement and Concrete [13].

A somewhat similar story is that of Stewart Mountain Dam in Arizona, where major expansions were observed, then they ceased, and 30 years later the concrete was in as good as or better condition than it had been previously.

ACI Committee 221 on Aggregates has prepared an extensive report on ASR in which remediation will be addressed.

6. Conclusions

Procedures are available to reach a probably accurate answer to the question: “Is the aggregate from this source reactive?” In some cases, it is not necessary to take any particular precautions to avoid excessive expansion due to ASR even if the answer is “yes.” These cases include (1) when there is a “nonreactive” aggregate available at comparable cost; (2) when the cement is low alkali and that is all that is needed; and (3) when the intent is to use ground slag or a pozzolan in adequate amounts for other reasons. However, if specific precautions are needed, they can be taken. Pozzolans and ground slag are widely available.

It is better to take the steps to avoid excessive expansion before the structure is built, but even if this is not successfully accomplished and severe cracking due to internal expansion caused by ASR occurs, one does not necessarily need to “run for the hills.” Tuscaloosa Lock, Stewart Mountain Dam, and others with severe internal expansion have gone on for 30 or more years giving adequate service despite having manifested a lot of internal expansion.

Meanwhile, all of us who are interested in ASR should keep up with the state of the art. In 1994 ASTM published a new edition of STP 169 with excellent papers by Stark [14] and Ozol [15]. As previously noted, ACI 221 on Aggregates has completed a review. The 10th International Conference was held in Melbourne, Australia, in 1996, and the proceedings are available [16]. There is a wealth of information in the compiled proceedings of the preceding conferences.

7. Postscript

A reviewer of this manuscript suggested that I should also address the question of why is it that, since the principles of ASR have been known for more than half a century, examples of distress due to ASR are still being found in structures much less than 50 years old and how current actual practice agrees with the concepts I outlined to avoid excessive expansion due to ASR.

There are many situations in which it was assumed none of the aggregate sources in a region were potentially deleteriously alkali reactive, because no distress had ever been observed that was proven to have been caused by ASR. Then there was an abrupt change upward from about 0.4% Na_2O_e to about 1.2% Na_2O_e in the alkali content of the available commercial cement. In one case there was severe distress from the use of crushed stone containing substantial amounts of opal, the presence of which was well known to geologists in the area but not to any concrete people who were prepared to realize its significance.

There have been strong efforts to dissuade users from specifying low-alkali cement “when it is not needed,” because in many locations it is difficult or impossible for some or all the cement producers to make it. The methods for establishing the fact of reactivity or nonreactivity of materials from aggregate sources without a service record have often been somewhat capricious, and the procedures for evaluating the effectiveness and needed dosage of a mitigating material—slag, pozzolan, lithium salts—are likewise less precise and straightforward than would be preferred.

In my view, current practice in the Corps of Engineers is more effective than most and close to being as good as the state of the art allows. I believe that if all constructions were carried out with the approach outlined in the Corps Manual, there would be few, if any, structures showing distress due to ASR.

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