Durability of Concrete in Highway Facilities

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In recent years TxDOT has discovered several concrete bridge structures with unusual levels of deterioration and distress. The deterioration and distress is considered unusual because all of the bridges are less than twenty years old and in some cases are only a few years old. The nature of the distress varies between bridges but several similarities have been noted. Many of the bridges have developed large longitudinal cracks in the bottom flanges of the prestressed concrete beams. These cracks at first were thought to be "splitting cracks" due to the development of the bond between the strand and the concrete. Further investigation reveals that these cracks start and stop and change locations at various points along the length of the beams indicating that splitting action is not the primary force driving the cracks. With prestressed concrete box beams, the distress also manifests itself as severe "map cracking" in the end block region of the beams with some longitudinal cracking near the bottom flange. Other bridges exhibit vertical cracking in the columns and "map cracking" in the abutment and bent caps. The vertical cracking in the columns is randomly spaced and is not associated with another mechanism such as corrosion of the underlying reinforcing steel. The map cracking in the caps does not follow the pattern normally associated with cracking in reinforced concrete. That is, the cracks are not oriented as they would be for flexure or shear stresses.

Preliminary investigations into the cause of this cracking have identified two separate material-based mechanisms, Alkali-Silica Reaction (ASR) and Delayed Ettringite Formation (DEF), as the most probable causes of this distress. Because of the controversy within the concrete industry as to the causes and responsibilities for these two mechanisms, and the fact that in many cases evidence of both mechanisms have been detected simultaneously, TxDOT has chosen to refer to this distress as Premature Concrete Deterioration.

An investigative team consisting of representatives of TxDOT's Materials and Test, Construction and Maintenance, and Design Divisions has been assembled to address this problem. The team has identified several key issues to be addressed during the course of this investigation. These issues are:

� Identification of structures and possibly other concrete in Texas with Premature Concrete Deterioration;
� Identification of the specific causes of distress in a given structure (ASR or DEF);
� Identification of sources of concrete components (cement, aggregates, admixtures, water) which result in the formation of ASR or DEF;
� Methods to prevent ASR/DEF in new concrete by revising concrete material and placement specifications;
� Determination of the loss of strength and the resulting reduction in service life of existing structures with Premature Concrete deterioration;
� Determination of the potential for further distress in existing deteriorating structures due to ASR/DEF (how much more can occur); and
� Repair and maintenance measures for structures with ASR/DEF deterioration.

A world wide literature search was conducted for information on the repair and maintenance of structures suffering from either Alkali-Silica Reaction (ASR) or Delayed Ettringite Formation (DEF). An electronic (Internet) search of journal articles, research reports and other studies pertaining to this subject found approximately 30 references offering potentially useful information. The reports and documents used came from the United States, Canada, Japan, Australia, England, France, Spain and Sweden. It should be noted that there is a wealth of information on the causes and prevention of ASR and DEF in new construction but relatively little information on maintenance and repair of in-service concrete structures with distress attributed to ASR or DEF.

Background on ASR and DEF

Alkali-Silica Reaction (ASR): Alkali-Silica Reaction is one of three main types of Alkali-Aggregate Reaction (AAR). AAR can result in concrete deterioration due to an expansive reaction between the active mineral constituents of some aggregates and the sodium and potassium alkali components in the concrete mix, which are usually derived from the cement. ASR is the result of the reaction between the alkalis in the cement and certain siliceous aggregates. This reaction can be harmful to the concrete in that it results in excessive expansion and cracking of concrete exposed to moisture. Cracking of structures suffering from ASR is usually observed within 10 years of construction. For excessive expansion of concrete due to ASR to occur, four requirements must be met: the aggregate must be sufficiently reactive; the pH of the pore fluid must be high (high alkalinity); the amount of reaction product formed must be large; and there must be sufficient water available in the concrete.

In its simplest form, ASR can be visualized as a two-step process:

1) Alkali + Reactive Silica + Moisture = Reaction Product (ASR gel)
2) Reaction Product + Additional Moisture = Expansion

Alkalis present in Portland cement are released during normal hydration. The pore-water present in concrete, although saturated with calcium hydroxide, is largely a mixture of sodium and potassium hydroxides, which account for the alkalinity being higher than that of a saturated solution of calcium hydroxide. A total concrete alkalinity of 3 to 4 kg/m3 seems to represent a threshold alkalinity. Typically, the alkali-silica reaction occurs immediately following the initial set of the concrete and can continue over a prolonged period of time. The amount of water needed for damaging levels of ASR to form is surprisingly low. A Relative Humidity (RH) of 80% or greater provides sufficient moisture for absorption by ASR gel resulting in expansion and cracking of the concrete.

Delayed Ettringite Formation (DEF): Delayed ettringite formation is also known as secondary ettringite formation (SEF) or late ettringite formation (LEF). For the purposes of this paper, "DEF" will be used to describe the phenomenon by which concrete is damaged by the gradual formation of ettringite within the microstructure of the hardened material. Delayed ettringite formation is also more simply defined as an "internal sulfate attack" on the concrete. That is, the source of the sulfates is internal to the concrete rather than from an external source such as ground water.

Ettringite is a crystalline mineral formed due to the reaction between sulfates, calcium aluminates and water. The aluminates are in the form of tricalcium aluminate (C3A), one of the four primary compounds that make up Portland cement. Sulfates, in the form of gypsum, are added to the clinker during the grinding process. The purpose of gypsum is to slow the hydration of aluminates and thus prevent a "flash set" of the concrete. Sulfates may also be present in the clinker from the raw materials used to make the clinker and from recycled kiln dust during the burning of the raw materials. The initial or primary ettringite formation occurs shortly after the water has been added to the cement but before the concrete reaches its initial set.

It is the delayed ettringite formation that causes the damage to the concrete. There are two main schools of thought on the mechanisms that result in DEF. The first school holds that the initial ettringite decomposes into monosulfoaluminate with the increasing temperature due to hydration and/or elevated curing temperatures (such as from steam curing). There is some disagreement as to the temperature required for this decomposition to occur but the generally accepted threshold is 148oF. This decomposition is accelerated by the presence of alkalis. The monosulfoaluminate, when later exposed to moisture at lower temperatures, can then reform into delayed or late ettringite. The other school holds that sulfates locked in the clinker or excess unreacted gypsum react with moisture and previously unreacted aluminates over time resulting in a delayed formation of ettringite. There is a third, but smaller, group of researchers that believe that the primary ettringite never forms due to the high early hydration temperatures in the concrete but this requires certain conditions to occur. In reality, it is very likely that both mechanisms occur to some degree in concrete and the type of member (precast vs. cast-in-place), type of cement used, temperature of the concrete in its early stages, and the member's exposure to moisture determine which of the two mechanisms will dominate. The subject is very controversial and there is little consensus as to the exact mechanisms involved in the formation of ettringite.

There are also two schools of thought on the expansion mechanism associated with DEF: crystal growth and swelling. In the "crystal growth" school expansion is caused by the formation of ettringite at the surface of reactant grains. The growth of this inner layer pushes other particles out and thus causes expansion. The ettringite crystals do not re-orient when formed and are more likely to exert pressure. The "swelling" school holds that the crystals are initially very small and swell or enlarge in the presence of water.

The bottom line is that ettringite formation in a confined space is capable of producing very high forces. The most important fact is that the volume that ettringite forms per unit volume of C3A is 8:1; the exact mechanism of its formation and expansion is irrelevant.

<u>Comparison of DEF and ASR</u>: Although DEF and ASR are the result of completely different mechanisms, some similarities exist with respect to their effect on concrete and on their primary causative ingredients. The common chemical designation for both ASR and DEF is C-A-S-H. For ASR these are Calcium-Alkali-Silica-Hydrate while for DEF the are Calcium-Aluminate-Sulfate-Hydrate. The common ingredient for the formation or development of both ASR and DEF is the availability of moisture. Without this moisture, the expansive processes of both ASR and DEF cannot occur. The structural effects of both ASR and DEF are also very similar. Both can reduce the service life of concrete members or entire structures by causing deleterious expansion, potential loss of structural stiffness due to excessive cracking, and an increase in permeability with resulting increases in the rate of deterioration due to other factors including sulfate attack or corrosion of reinforcing steel. ASR gel and DEF crystals can also fill air voids, reducing freeze-thaw resistance. In many cases, significant levels of both ASR and DEF are present in samples of deteriorated

concrete and it becomes very difficult to determine which was the causative agent and which was opportunistic. As mentioned earlier, high alkalinity can accelerate the decomposition of primary ettringite increasing the potential for DEF. Identification of DEF crystals and ASR gel is very difficult and usually requires the use of a scanning electron microscope with a microprobe for elemental analysis.

Studies on concrete samples with premature concrete deterioration have been performed by TxDOT and outside consultants using optical petrography techniques and scanning electron microscopes/microprobes. In most cases, they have found evidence of both ASR and DEF present in the concrete. Occasionally, only ASR gel will be found but DEF has not been found without the presence of ASR. This suggests that there is some relationship between ASR and DEF. It is well known that many of the Type I and Type III cements recently produced in Texas have both a high alkali and sulfate contents. It is also interesting to note that the alkalis and the clinker sulfates come from the same source: alkali sulfates (Na2SO4 and K2SO4) from impurities in the raw materials or fuel sources used to make the clinker. The alkali and sulfate levels are usually within the specification limits but are often very near the maximum allowable levels.

A recent journal article theorizes that microcracks initially form due to shrinkage, thermal stresses, ASR, flexural or shear stresses, or strand development (splitting cracks previously mentioned). Once formed, these cracks (except those due to ASR) tend to remain stable - that is, they do not continue to grow without an increase in applied stress. However, if the potential for DEF exists in the concrete (late sulfate release from cement clinker or other sources and exposure to wetting-drying cycles), ettringite can deposit in these cracks and cause further crack growth (both in width and length) due to ettringite swelling or crystal growth. It is also possible for ASR gel to infill cracks if these initial cracks form close enough to reactive aggregates.

Mitigation of ASR and DEF: For existing structures with distress attributed to ASR, DEF or both, one mitigating measure is to prevent the further intrusion of moisture into the concrete. This can be achieved by application of a waterproofing membrane. It is important to note that the waterproofing membrane should not be a vapor barrier. The concrete should be allowed to "breathe" and let moisture out. Other measures, such as controlling drainage can help keep the water out. Large cracks should also be sealed at the surface with a flexible sealant such as caulk. This sealant should not completely fill the cracks so that further growth or swelling of the ASR gel or DEF crystals will not cause further cracking. The Strategic Highway Research Program (SHRP) studied several mitigating measures for ASR in existing structures. One promising treatment is the use of Lithium compounds (LiOH and LiNO3) but further testing may be needed to determine their effectiveness on in-place concrete members. Another possible mitigating technique identified is triaxial restraint (of bridge columns, for example).

For new concrete placements, the mitigating measures recommended for ASR when a potentially reactive aggregate is to be used are as follows: use of a low-alkali cement (<0.6%), Class F Flyash, using LiOH and LiNO3 as an admixture, and controlling or limiting the concrete temperature at time of placement. For DEF, the mitigating measures for new concrete placements include: use of a Type II (moderate sulfate resistant) cement; strict controls on clinker sulfate and total sulfate content of cements; and, controlling or limiting the concrete temperature at time of placement and during curing through direct controls or mix design.

If you have any questions, please contact **Dr. C.Vipulanandan**