ASSESSMENT OF PREMATURE CONCRETE DETERIORATION IN PRECAST CONCRETE BRIDGE BEAMS

Mark E. Williams, PhD, PE, SE Walter P. Moore and Associates, Inc, Houston, TX
Dilip Choudhuri, PE, Walter P. Moore and Associates, Inc, Houston, TX

ABSTRACT

In recent years concrete bridge structures have been experiencing varied levels of premature deterioration due to deleterious reactions within the concrete. Alkali silica reaction (ASR) and delayed ettringite formation (DEF) are two such causes of this premature concrete deterioration. Although their mechanisms are very different, both ASR and DEF cause expansion of concrete and thus extensive cracking. Both ASR and DEF also exhibit surface distress conditions that resemble incipient damage from other sources, such as dry shrinkage, thermal gradients, high anchorage stresses, and corrosion. Having a reliable methodology for bridge inspectors and bridge design professionals to distinguish between deleterious reactions and other damage mechanisms is imperative.

This paper presents a comprehensive methodology for assessing whether observed concrete deterioration in precast concrete bridge beams is attributable to ASR and/or DEF. The methodology presented combines visual observations with materials testing to study the extent of the deterioration. Visual observations discussed include documentation of crack patterns, locations, and widths as well as areas of discoloration. Materials testing methods covered include petrographic examination, UV fluorescence, expansion testing, alkalinity analysis, scanning electron microscopy, and energy dispersive X-ray analysis.

The information gathered from both observations and materials testing facilitates informed decisions as to the causes of the observed deterioration and a future course of action for repair if needed.

Keywords: Alkali-silica reaction (ASR), delayed ettringite formation (DEF), premature concrete deterioration, precast bridge

INTRODUCTION

The structural integrity of the aging highway infrastructures in the USA continues to be a subject of concern. Many concrete bridges experience distress due to growing traffic volumes, higher loads, and harsher environments. The distress generally manifests as cracking and subsequent spalling of concrete through various damage mechanisms throughout the service life of the bridge. There is a particular class of bridges, however, that is experiencing premature concrete deterioration due to deleterious reactions such as alkali-silica reaction or delayed ettringite formation within the concrete. These deleterious reactions also produce cracking and progressive deterioration in concrete. This paper presents the argument that it is often difficult to distinguish between deleterious reactions and other damage mechanisms, such as dry shrinkage, thermal gradients, and high anchorage stresses, in precast prestressed concrete bridge beams. The distress can visually appear quite similar to bridge inspectors or bridge design professionals. Laboratory testing of concrete materials is therefore generally required to establish the source of the concrete deterioration.

UNDERSTANDING ASR

Alkali-Silica Reaction (ASR) is an internal chemical reaction that causes premature deterioration in concrete. The chemical reaction is characterized by adverse interactions between alkali hydroxides (Na^+, K^+, OH^-) in the concrete pore fluid and reactive silica in the concrete fine or coarse aggregates. This reaction produces a gel-like substance that expands in the presence of water. In the continued presence of moisture, the gel expansion leads to concrete cracking, which can then lead to further deterioration by environmental factors.

The extent of the concrete deterioration resulting from ASR generally depends on factors such as the aggregate reactivity, high alkalinity in concrete, availability of moisture, temperature gradients, and structural restraint. ASR deterioration is prevalent in areas of high moisture, particularly on exterior beams exposed to temperature and wetting cycles. Deterioration caused by ASR is irreversible and must be repaired to extend the service life of the concrete.

UNDERSTANDING DEF

Delayed ettringite formation (DEF) is a chemical process that also causes premature deterioration in concrete. The process is characterized by an expansive ettringite crystalline growth within the cement paste due to an internal sulfate attack within the concrete. This crystalline growth leads to micro-cracking and separation of the paste from the aggregate. DEF generally only occurs in precast concrete members and is believed to be caused by improper heat curing of concrete.

Studies have found that in most cases, DEF is not found alone in concrete test specimens, but rather in conjunction with ASR, suggesting a possible relationship between the two deterioration mechanisms. It is not advisable to confirm DEF deterioration by field inspection only. Laboratory testing and a petrographic examination should be conducted to verify the nature and source of premature concrete deterioration.

VISUAL ASSESSMENT OF DISTRESS

Concrete distress is generally apparent as either cracking or spalling at the surface of concrete bridge beams. When assessing precast bridge beams, crack patterns can be evaluated by using either aerial equipment to provide a direct means of access, or by using binoculars, depending on the actual access conditions at each particular bridge site. When identifying possible crack patterns, the width and length of cracks in the beams can be measured and documented by way of crack comparators. The general location of the cracking within the beam can also be documented. Information gathered during the visual review can be used to obtain a general idea of the nature and extent of concrete distress.

There are several recognizable cracking mechanisms in precast prestressed concrete beams. During the stressing process, precast prestressed beams are prone to cracking at the beam end zones. This cracking is due to high anchorage stresses and can be controlled by debonding some of the prestressing strands at the beam ends. Precast prestressed beams can also develop cracks from drying shrinkage and thermal gradients during initial curing. Beams can additionally develop cracks from on-going corrosion in the prestressing strands or mild reinforcement. Crack patterns similar to those described can also be observed in bridge beams undergoing premature concrete deterioration as discussed below.

BEAM END ZONE CRACKING

Longitudinal cracks, often called *end zone cracks*, at the ends of pretensioned concrete beams are commonly observed after prestressing strand detensioning. The use of relatively high concrete strength and high levels of prestress has made this cracking more prevalent in recent years [1]. Although vertical bursting steel is generally provided in beams, longitudinal cracks in the bottom beam flange and web can still occur if the level of stress from prestress transfer exceeds the tensile capacity of the concrete. Efflorescence (Fig. 1) or other staining (Fig. 2) is often observed along these cracks as water migrates into the cracks over time.

Premature concrete deterioration due to ASR or DEF is prevalent in areas of high moisture. This deterioration is commonly characterized by longitudinal cracking in concrete beams and in the case of ASR, the presence of surface discoloration at the crack locations. Depending on the severity of the cracking, it can be difficult to visually discern initial end zone cracking from anchorage stresses (Fig. 3) and long-term cracking due to expansion from ASR or DEF (Fig. 4). It is also likely that ASR or DEF is not the initiator of prestressed beam cracking, but rather the perpetuator of the cracking when there is an abundant source of water to drive the expansive reactions of ASR or DEF within the concrete [2]. Further evaluation is therefore needed to determine whether there is a potential for additional beam cracking.

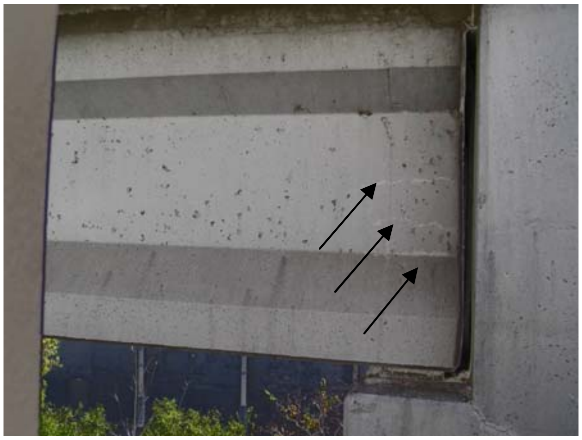
Fig. 1 End Zone Cracking in Exterior Beam


Fig. 2 End Zone Cracking in Interior Beam


Fig. 3 Longitudinal End Zone Cracking Due to Anchorage Stresses


Fig. 4 Longitudinal End Zone Cracking Due to ASR/DEF

Vertical cracking at the beam ends noted during a visual assessment also warrants further review. Cracking could be caused by corrosion of the reinforcing steel from an ingress of chlorides at open bridge joints or other damage mechanisms. Cracking at the beam ends could also be due to ASR or DEF, particularly where there is little or no reinforcement (i.e. in the concrete cover) to contain the expansion from deleterious reactions (Fig. 5 and Fig. 6).

It has been the authors' experience that while bridge inspectors and bridge design professionals are generally well trained to look for abnormalities in concrete bridges, deterioration can be mischaracterized or not documented in some cases. In some instances, beam end zone cracking had been notated as diagonal shear cracking or flexural cracking in bridge inspection reports, rather than being attributed to high anchorage stresses at the beam end. In other instances, web cracking at the beam ends has been attributed to corrosion of reinforcing steel. Such observations demonstrate that a visual review alone is often not sufficient to determine the cause of the concrete deterioration nor is the deterioration easily characterized in certain instances. Areas of deterioration should be notated for follow-up review by more experienced professionals, particularly where there is a documented geographic history of premature concrete deterioration in the bridges.

Fig. 5 Cracking in Beam Web Due to ASR/DEF

Fig. 6 Cracking in Beam Top Flange Due to ASR/DEF

BEAM MAP CRACKING

Map cracking is generally characterized by intersecting cracks that extend below the surface of hardened concrete. Map cracking can be caused by shrinkage of the drying surface concrete, which is restrained by concrete at greater depths where either little or no shrinkage occurs (Fig. 7). Map cracking can also be caused by early age thermal gradients that develop when the interior concrete increases in temperature and expands while the surface concrete cools and contracts. Map cracking caused by shrinkage or thermal gradients can vary in width from fine and barely visible to open and well-defined depending on the physical properties of the concrete and reinforcing steel. Map cracking is also a common indicator of ASR (Fig. 8). With ASR, cracking is usually characterized as random and on a fairly large scale, and in severe instances the cracks may reach a width of 0.50 in. Although there are several prominent causes of map cracking, the exact cause is generally not visually apparent and requires a determination by further examination of the concrete.

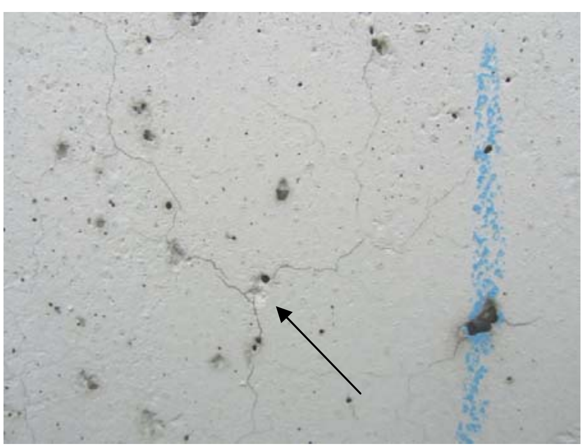

Fig. 7 Map Cracking Due to Shrinkage

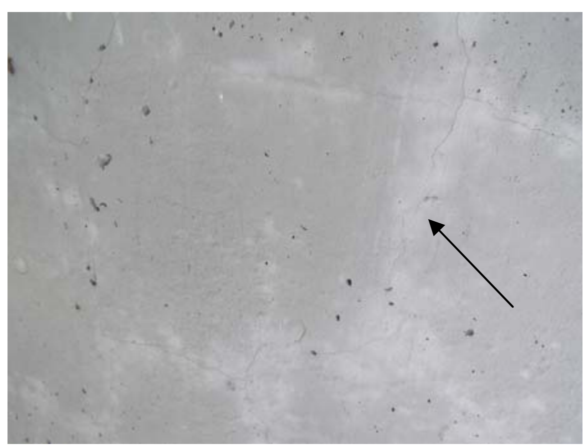

Fig. 8 Map Cracking Due to ASR, Staining Around Cracks

It has been the authors' experience that map cracking deterioration can be also mischaracterized or not documented in some cases. In some instances, ASR gel exuding from cracks had been notated as efflorescence during previous bridge inspections. In other instances, map cracking was not documented despite being present through the bridge structure, likely because there was no visible staining at the cracks at that time. Such observations demonstrate that a visual review alone may not be sufficient to characterize premature concrete deterioration due to ASR or DEF. In such instances, areas of deterioration should be reviewed by more experienced professionals, particularly where there is a documented geographic history of premature concrete deterioration in the bridges.

DETECTING ASR AND DEF

Despite the characteristic visual signs of ASR such as map cracking and surface discoloration, the presence of ASR must be confirmed by laboratory testing of excised concrete samples. A similar methodology applies for detecting DEF in concrete beams suspected of undergoing premature concrete deterioration. As part of the testing protocol, separate cores should be excised from deteriorated concrete members at the location of the crack being investigated and at the location of sound concrete away from the cracked area. By doing so, comparisons can be made between sound and deteriorated samples to study the progression of premature concrete deterioration or identify other damage mechanisms. It is advisable to excise numerous cores, as laboratory investigations can produce inconclusive or contradictory results with limited core sampling. A discussion of general laboratory testing procedures used to identify deterioration and the implications of deterioration in excised samples follows.

Concrete Petrography

Concrete petrography provides an effective means of characterizing concrete deterioration mechanisms. Concrete petrography is generally conducted in accordance with ASTM C856 [3] to visually study the cause of the concrete deterioration on a microscopic level. Petrography can identify an expansive gel in the presence of ASR as well as microcracking and coarse aggregate cracking resulting from the expansive gel formation (Fig. 9 and Fig. 10). Petrography can also be used to identify expansive gaps around the aggregate, a feature consistent with DEF (Fig. 11). Unlike cracking due to ASR or DEF, shrinkage or thermal gradient cracks are generally found passing around the course aggregate during petrographic review. Concrete petrography can therefore be used as a valuable method to distinguish between concrete cracking mechanisms. As a cautionary note, concrete petrography may not always identify deleterious reactions in concrete due to ASR or DEF despite the visual evidence of deterioration at the bridge site. Therefore, other laboratory testing methods should be employed in the diagnosis of concrete deterioration.

Fig. 9 Review of Excised Concrete Core, Noting Cracking Through the Course Aggregate

Fig. 10 Petrographic Analysis Showing ASR Gel

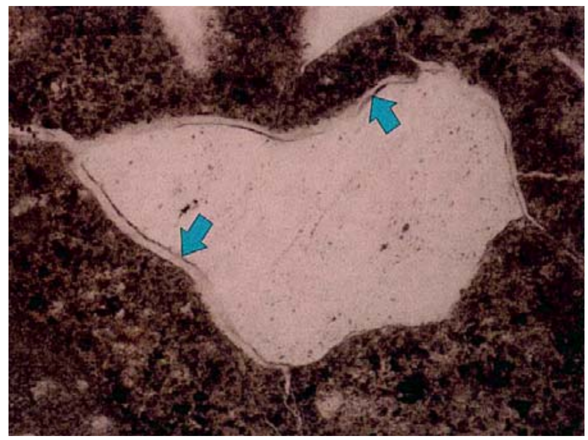

Fig. 11 Petrographic Analysis Showing Gaps Around a Sand Grain, A Feature Consistent with DEF

UV Florescence

For rapid detection of ASR gel, samples can be treated with uranyl-acetate and then observed under short-wave ultraviolet light per the procedure outlined in ASTM C856. A uranyl-acetate solution will fluoresce under UV light in the presence of ASR products (Fig. 12). Although this procedure can be performed in the field, it is generally performed in a testing laboratory in controlled environmental conditions. Contaminants are prone to florescence under UV light, so the presence of ASR gel should be confirmed by additional testing.

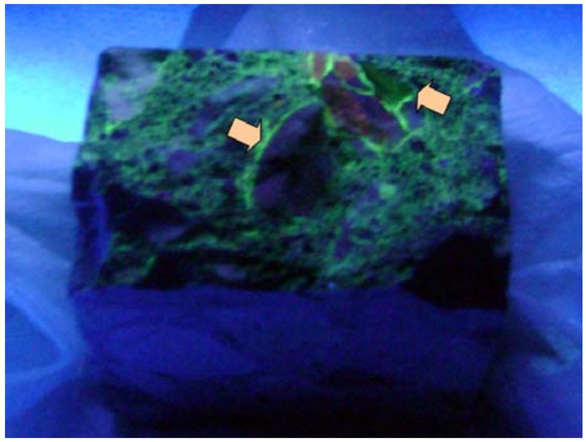

Fig. 12 ASR Gel Fluoresce Around Aggregate Particles After Being Treated With a Uranyl-Acetate Solution and Viewed Under UV Light

Accelerated Expansion Tests

Accelerated expansion tests can also be conducted to study potential expansion of concrete due to ASR in a short time frame of weeks to months rather than years. During the test, periodic volumetric measurements are taken to monitor expansion potential while subjecting the test specimen to elevated temperature and moisture (Fig. 13). In more severe cases of ASR, gel has been observed on the surface of the test specimen as it is exuded through microcracks.

Fig. 13 Accelerated Expansion Testing Measurement

Alkali Content

The alkali concentration in the pore solution can be tested by means of chemical analysis and used as an indicator of residual alkali reaction potential. The alkali concentration tends to progressively decrease with time as it becomes incorporated into the ASR gel. Alkali concentration threshold levels have been observed below which no significant long term expansion has occurred in laboratory testing of concrete with highly reactive aggregates [4].

Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) can be utilized to evaluate the mineralogy and microstructure of concrete as well as to identify deleterious reactions. SEM can identify microcracks around aggregate particles and ettringite deposits within these cracks. Furthermore, complete separations around aggregate particles can be identified, which are symptomatic of DEF (Fig. 14). Scanning electron microscopy is typically more costly than concrete petrography and should therefore be used for a confirmatory evaluation if needed.

Energy Dispersive X-ray Spectroscopy

Energy Dispersive X-ray Spectroscopy (EDX) can be performed in combination with SEM to confirm the chemical composition of the deposits noted in microcracks and separations around aggregates. EDX can identify the chemical composition of the deposits of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) (Fig. 13) found in concrete undergoing DEF.

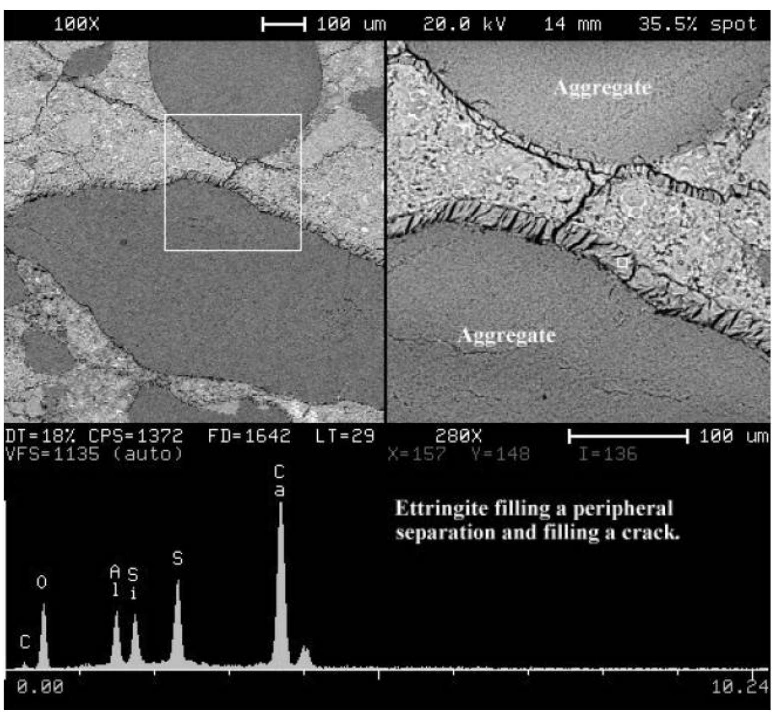

Fig. 14 Scanning Electron Micrograph of Ettringite Filling Gaps Around Aggregate Particles

CONCLUSIONS

This paper discusses methods for differentiating deterioration in precast prestressed concrete beam due to premature concrete deterioration and other damage mechanisms. Since ASR and DEF are not the most common concrete deterioration mechanisms, a visual assessment of concrete beams will likely not suspect deleterious reactions in the concrete. More common damage mechanisms such as shrinkage, thermal cracking, high anchorage stresses, and corrosion will likely be suspected first. These more common deterioration mechanisms can also be mischaracterized by an inexperienced reviewer. The visual appearance of the cracking should however prompt further inquiry by the bridge inspector or design professionals as to the cause of the cracking and related deterioration. Laboratory testing can then be used as a basis for determining the cause of the deterioration. The information gathered from both visual observations and laboratory materials testing will facilitate an informed decision as to the causes of the deterioration and a future course of action for repair if needed.

REFERENCES

1. NCHRP Report 654, “Evaluation and Repair Procedures for Precast/Prestressed Concrete Girders with Longitudinal Cracking in the Web.” Transportation Research Board, ISBN 978-0-309-11835-4, 2010.
2. Nikola P. and Arezki T., (2004), “Is Microcracking Really a Precursor to Delayed Ettringite Formation and Consequent Expansion?” ACI Materials Journal, Vol. 101, No. 6, pp. 442-447.
3. ASTM C 856, “Standard Practice for Petrographic Examination of Hardened Concrete”, American Society for Testing Materials.
4. Diamond, S. et al. “On the Physics and Chemistry of Alkali-Silica Reactions.” Proc. 5th Conf. Alkali- Aggregate Reaction in Concrete. S 252/22, 1-11, 1981.