CORRELATION BETWEEN MAP CRACKING AND DELAYED ETTRINGITE FORMATION IN FIELD SPECIMENS

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ABSTRACT

The study investigated the possible presence of Delayed Ettringite Formation (DEF) in the Maryland Bridge Inventory. Maryland is a state in the eastern part of the United States. The objective of the study included investigating the possible presence of DEF in cast-in-place concrete. Two nondestructive test (NDT) methods, potassium autoradiography and impact-echo, were utilized in the study. In addition, cores were taken for analysis with a scanning electron microscope and energy dispersive analysis x-ray, which identify DEF by crystal morphology and elemental composition. The focus of this study was on bridges exhibiting wet map cracking on the surface, which is regarded as a surrogate for DEF. The PONTIS bridge management database provided a means for selecting a sampling population. In order to identify potentially damaged bridges, the PONTIS database was queried for concrete elements with descriptions containing the phrase "map cracks". A representative number of bridges from this set were selected from each district in proportion to the total number of bridges in that district. The study found DEF throughout the sampled Maryland bridges, indicating that DEF is not simply a regional problem that affects only a few states like Texas. Of the twenty-nine cores taken, twenty-six exhibited DEF and two bridges without visible map cracking also contained DEF. Alkali-silica reaction (ASR) gel, which is commonly said to be associated with map cracking, was observed in only a limited number of bridges with map cracking. Therefore, map cracking is not necessarily a definitive indicator of ASR. The study also showed cases of coexistence of DEF and ASR in six of the ten bridges cored. In the bridges that were studied, DEF was found in cast in place bridge elements. This therefore refutes the theory that DEF happens only as a result of high temperature curing. Correlations between concrete surface conditions and four observed DEF morphologies are suggested.

1 INTRODUCTION

After the concrete has hardened, ettringite may form and expand in a process called Delayed Ettringite Formation (DEF, also called Secondary or Late Ettringite Formation). (Day [1], Taylor [2], Heinz et al [3]) have documented DEF and the deleterious effects on hardened concrete. Early studies focused on precast concrete members, which had high temperature heat treatments. Batic et al [4] indicate that DEF can occur at ambient temperatures. Field studies of cast-in-place concrete have shown DEF in deteriorated concrete (Larive et al [5], Schlorholtz [6]). Still it is difficult to directly correlate the potential for expansion with the deterioration occurring in the field, since the mechanism of DEF has not been established. Lawrence et al [7] document Texas Department of Transportation's (TxDOT) experience with DEF and premature concrete deterioration. They indicate in numerous cases that DEF caused microcracking leading to premature deterioration. Their results came from scanning electron microscope (SEM) analysis of corings. Other investigators have disputed this conclusion and put the blame on ASR.

The mechanism of DEF expansion is a highly debated issue. Ettringite Crystal Growth Theory and Uniform Paste Expansion Theory are the two predominant theories. Heinz et al [3], Lawrence et al [8] suggested the Ettringite Crystal Growth Theory, which attributes the expansion to pressure exerted by the growing ettringite crystals in the micro cracks between the cement paste and the aggregate. Scrivener et al [9], Johanson et al [10] proposed the Uniform Paste Expansion Theory, which suggests that the concrete expands and then the ettringite forms in the newly created gaps. Yang et al [11] found no evidence to support the Uniform Paste Theory concluding that the ettringite present in the mortar produced the expansion. Day [1] suggests that both mechanisms are possible and depending on the environmental condition one may be more prevalent.

2 OBJECTIVES AND SCOPE

The objectives of the investigation were:

- To perform a pilot field survey of Maryland bridges for delayed ettringite formation damage; and
- To evaluate two nondestructive test (NDT) methods that could provide indirect evidence of DEF damage. The ultrasonic impact-echo method was used to evaluate the extent of cracking and deterioration of the concrete; and potassium autoradiography was used to measure the level of potassium, which is believed to be important in the formation of ettringite.

This paper focuses on results obtained on cores taken from Maryland bridges. The cores were analyzed by scanning electron microscope (SEM) and energy dispersive analysis x-ray (EDAX).

3 BRIDGE SELECTION

MDSHA currently maintains two databases: PONTIS and Structural Inventory and Appraisal (SI&A). SI&A contains all information pertaining to the structure, such as age, materials, type, length, height, detour length, etc, and includes a general evaluation of the major components, such as the deck, superstructure, substructure, channel, etc. PONTIS concentrates on evaluating the elements and quantifies the condition level of various elements. The MDSHA PONTIS database gives the description for the condition state. Along with the quantifiable condition evaluation, the bridge inspector gives explanation of the defects. The comments given by the inspectors try to clarify the type of work that should be preformed.

In developing a population of bridges, several statistical models and method were investigated. The purpose of the research involves investigating the existence of ettringite in concrete elements of MDSHA bridges, and because the objective only required investigating and not quantifying the existence of ettringite, a reduced population with a high probability was investigated. From this "sick patient" population, a spatial distribution was chosen to be representative of the distribution of MDSHA bridges. In order to reduce the total population to the "sick" population, the PONTIS database queried for concrete elements with descriptions containing the phrase "map crack". From the query, a possible bridge element list was started with the basic bridge information, type of element with map cracking, and inspector's comments about that element. In order to have all information available in the project bridge list, the data from the SI&A database was added to provide the bridge demographics that are not included in the PONTIS database. Once the SI&A data was added, the project bridge list could be used to determine the breakdown by type and location throughout the state.

Of the 2463 bridges owned by the MDSHA, 905 bridges have at least one element with map cracks as noted by bridge inspectors in the PONTIS database. But map cracking alone was found to be too general as a description, since map cracking is often associated with several possible causes including: overstress, improper stripping of formwork, ASR, and DEF. Additional refinement of the list was needed to increase the probability of incidence in the selected bridges.

DEF often appears as map cracking with moisture surrounding the cracks (Livingston [12]), so bridges were selected from the project database based on the inspectors' verbiage matching this description. A representative number of bridges from this set were selected from each district in proportion to the total number of bridges in that district. Two bridges were also selected that did not exhibit map cracking to provide control samples for the project.

4 EXPERIMENTAL PROGRAM

Scanning electron microscopy (SEM) was utilized on this project to examine samples of concrete taken from bridges throughout the Maryland State Bridge Inventory. The SEM provides images of the cement paste for microcracking and alkali-silica reaction (ASR) gel, the voids for crystal formations contained inside, and aggregate pullouts for cracking along the aggregate / paste interface and crystal formations. The intent of the core sampling was to develop a better understanding of concrete deterioration that exhibits map cracking on the surface of a concrete element. Ten bridges were cored during the project in order to verify the presence of ettringite. Ettringite is identified visually using the scanning electron microscope (SEM) and elemental analysis of the crystals was preformed using energy dispersive analysis x-ray (EDAX). Two nondestructive test (NDT) methods, potassium autoradiography and impact-echo, were also utilized in the study but the results are not included in this paper.

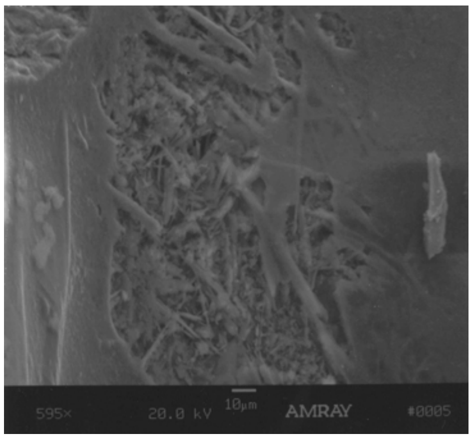
A total of 29 cores, 2 inches in diameter and 3 inches deep, were taken from ten bridges throughout the state. In order to analyze the concrete, smaller samples of concrete are needed. Each core is broken into small pieces with a 5 pound sledge hammer, and a sample is selected which has a relatively flat side to allow mounting. After carbon coating, the sample assembly is placed into the SEM with the top surface at an approximately 30 degree angle to produce the maximum possible signal for the EDAX. The sample is searched in an across-down-across-down pattern for possible locations of DEF and ASR gel.

A separate test was also performed to search for the presence of ASR using AASHTO T299-93 which defines the procedure for identifying ASR in the field (AASHTO [13]). Since all of the tests were conducted in a laboratory, several simplifications were made, but the basic procedure was followed. The procedure requires fresh concrete surface to test, and a large fragment was selected after the cores were fractured. The sample is then washed with clean water and a solution of dilute uranyl acetate is applied. After the sample has dried for at least 3 minutes, the sample is placed under a short wave ultra-violet (UV) light (~250 nm). When viewed under the UV light, ASR appears yellow-green and tends to be found in cracks or around aggregates.

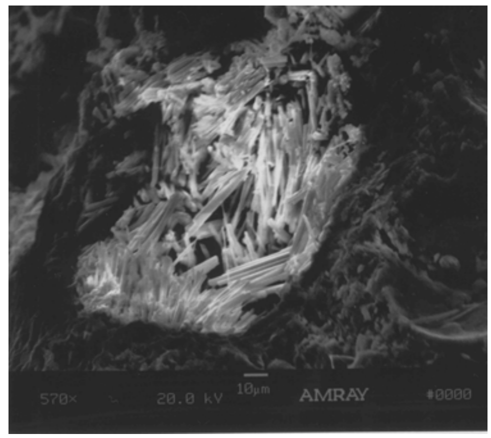
5 RESULTS

Twenty-six of the twenty-nine cores that were examined contained delayed ettringite formation (DEF), and of the 10 bridges, 6 bridges were found to have alkali-silica reaction (ASR) gel. Four different types of ettringite formations were observed: needle-like crystals, hexagonal prismatic crystals, a tightly packed, and an amorphous material, see Figure 1. Some researchers have suggested the possibility of ettringite existing in different forms.

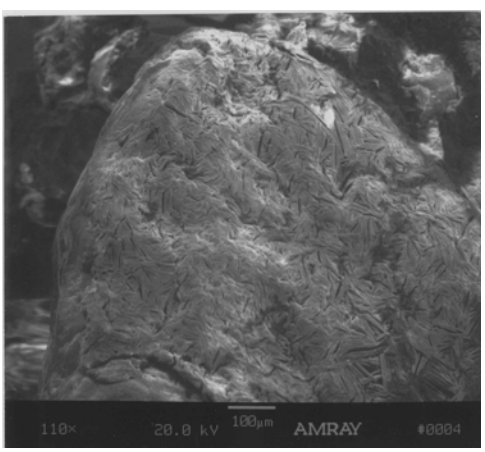
The study confirms that Maryland State Highway Administration bridges exhibit DEF in the bridge population throughout the state. No statistical values can be derived from this study since the population was deliberately skewed towards bridges with suspect symptoms. Alkali-silica reaction (ASR) gel, which is commonly said to be associated with map cracking, was observed in only a limited number of bridges with map cracking. Therefore, map cracking is not necessarily a definitive indicator of ASR. In the bridges that were studied, DEF was found in cast in place bridge elements. This therefore refutes the theory that DEF happens only as a result of high temperature curing.



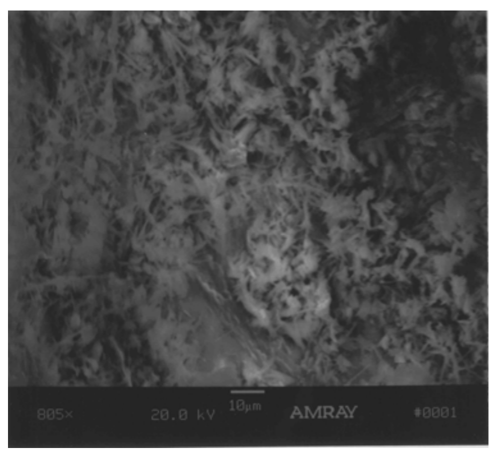
(a) Needle-like Ettringite Crystals



(b) Hexagonal Prismatic Ettringite Crystals



(c) Tightly-Packed Ettringite



(d) Amorphous Ettringite

Figure 1: Ettringite Morphology

The study compared the SEM results to the surface conditions, and several trends were observed including, the significance of DEF in concrete micro cracks, and the quantity of tightly packed DEF. Both are believed to be correlated with map cracking on the concrete surface. The results suggest a link between map cracking with associated moisture on the surface, extensive amounts of DEF in micro cracks inside the concrete element, and ASR. Diamond [14] suggests that ASR works to develop the initial micro cracks and DEF propagates the cracks. The correlations between concrete surface conditions and observed DEF morphologies are summarized in Table 1.

Table 1: DEF Morphology versus Crack Type

	No Map Cracking	Local Map Cracking	Local Map Cracking With ASR	Extensive Map Cracking With ASR
Crystal Formations in Voids	**X**	**X**	**X**	**X**
Crystal Formations in Cracks		**X**	**X**	**X**
Tightly-Packed Formations in Voids			**X**	**X**
Tightly-Packed Formations in Cracks				**X**

6 CONCLUSIONS

The study confirms that Maryland State Highway Administration bridges exhibit DEF in the bridge population throughout the state. No statistical values can be derived from this study since the population was deliberately skewed towards bridges with suspect symptoms. Twenty six of the twenty nine cores that were examined contained delayed ettringite formation (DEF), and of the 10 bridges, 6 bridges were found to have alkali-silica reaction (ASR) gel. Four different types of ettringite formations were observed: needle-like crystals, hexagonal prismatic crystals, a tightly packed, and an amorphous material. The study compared the SEM results to the surface conditions, and several trends were observed including, the significance of DEF in concrete micro cracks, and the quantity of tightly packed DEF. The results suggest a link between map cracking with associated moisture on the surface, extensive amounts of DEF in micro cracks inside the concrete element, and ASR. Correlations between concrete surface conditions and observed DEF morphologies are suggested. Alkali-silica reaction (ASR) gel, which is commonly said to be associated with map cracking, was observed in only a limited number of bridges with map cracking. Therefore, map cracking is not necessarily a definitive indicator of ASR. In the bridges that were studied, DEF was found in cast in place bridge elements. This therefore refutes the theory that DEF happens only as a result of high temperature curing.

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