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Project Summary Report 0-4085-S
Project 0-4085: Preventing Premature Concrete Deterioration Due to ASR/DEF In New Concrete

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PROJECT SUMMARY REPORT

Preventing Alkali-Silica Reaction and Delayed Ettringite Formation in New Concrete

Introduction...

The state of Texas has been widely impacted by materials-related distress in various transportation structures. This distress has been mainly attributed to alkali-silica reaction (ASR) and delayed ettringite formation (DEF) and has been commonly referred to by the Texas Department of Transportation (TxDOT) as "premature concrete deterioration." In response to these problems, TxDOT has aggressively sought to prevent cases of this distress in new concrete structures by implementing new ASR specifications (initially as TxDOT Special Provision to Item 421). This specification, and updates since, requires contractors to address ASR through prescriptive options (e.g., 20-35 percent Class F fly ash) or performance testing. The research detailed in this summary report was performed in support of this new specification, with the intention of improving upon the initial specification efforts and increasing the service life of transportation applications.

This summary report briefly summarizes the overall findings of TxDOT Project 0-4085, Preventing ASR and DEF in New Concrete. This research project, conducted at the Concrete Durability Center (CDC) at The University of Texas at Austin, took 4 ½ years, with an emphasis on both laboratory and field evaluations. A more detailed description of this study can be found in the report 0-4085-5.

What We Did...

Project Objectives

The main objectives and goals of this project can be summarized as follows:

1. Understand the underlying mechanisms behind ASR and/or DEF
2. Review available test methods for aggregate reactivity and for preventive measures and recommend test method(s) to prevent ASR and/or DEF in new concrete
3. Develop specification and guidelines to prevent ASR and/or DEF in new concrete
4. Identify and implement strategies for preventing ASR and/or DEF, with emphasis on prudent use of supplementary cementing materials (SCMs)
5. Develop protocol for evaluating the cause, extent, and future potential for damage caused by ASR and/or DEF in existing concrete structures
6. Transfer knowledge and experience gained from this project to TxDOT practice to increase the service life of transportation structures

Figure 1 – Outdoor Exposure Site at the Concrete Durability Center (CDC)

What We Found...

Laboratory Testing Program

Alkali-Silica Reaction

A wide range of materials were evaluated in this project, including seventeen different reactive aggregates from Texas (and some from other parts of the U.S. and Canada), and a range of portland cements, supplementary cementing materials (SCMs), and lithium nitrate. A variety of laboratory test methods were performed, including the American Society for Testing and Materials (ASTM) C 1260 (accelerated mortar bar test) and ASTM C 1293 (concrete prism test). In addition, an outdoor exposure site, shown in Figure 1, was developed under this project to evaluate real-world behavior of concrete blocks exposed to climatic conditions in Austin, Texas.

Some of the main conclusions regarding **ASR test methods** include the following:

- The concrete prism test (ASTM C 1293) is, in general, the most appropriate laboratory test method for predicting field performance. The test should be run for 1 year for testing aggregates and 2 years for testing SCMs or lithium compounds, with an expansion limit of 0.04 percent.

- The major drawback to ASTM C 1293 is its long duration (1 or 2 years). Efforts were made to accelerate this test by increasing the storage temperature from 100 °F to 140 °F. However, it has been shown that expansions at the higher temperatures are significantly reduced because of increased leaching, increased specimen drying, and potential changes in pore solution chemistry. In addition, the effects of non-reactive aggregates in this test were found to be dramatic in some cases. Specifically, some fine aggregates will yield vastly different expansions when tested under the two different temperature regimes, even though these aggregates meet the requirements for non-reactive under ASTM C 1293. Significant work is in progress to elucidate the underlying mechanisms behind this confounding behavior.
- One technical deficiency of ASTM C 1293 is that it is not well-suited for determining the effects of cement alkalinity on expansion, most likely because of leaching of alkalies during the course of the test. This downside of the test was highlighted when comparing concrete prism test data to exposure block data, where it was observed that concrete containing a highly-reactive aggregate from El Paso, Texas, and approximately 3.5 lbs/yd^3 of Na_2O_e expanded and cracked in exposure blocks but showed essentially no expansion after 2 years of testing in ASTM C 1293.
- The accelerated mortar bar test (ASTM C 1260), in most cases, is a reasonable indicator of aggregate reactivity or a reasonable means of assessing various mitigation measures. A 14-day expansion limit of 0.10 percent is recommended as it best relates to concrete prism data (1 year for aggregates, 2 years for SCMs).
- One downside of ASTM C 1260 is that it tends to be overly severe when testing some aggregates, resulting in expansions exceeding the failure limit, even though these aggregates pass the concrete prism test and perform well in field applications. This trend has been well documented over the years, and for this reason, it is not recommended that the results of ASTM C 1260 be used by themselves alone to deem an aggregate as being reactive. If an aggregate fails this test, the results should be confirmed using the concrete prism test.
- Several coarse aggregates in this study showed a trend opposite that just discussed. Specifically, these aggregates passed ASTM C 1260 but failed ASTM C 1293 and showed expansion and cracking in exposure blocks. This behavior is much less often documented in literature and is actually more relevant and important for this TxDOT-funded project. The reason for this enhanced relevance and importance is that the new TxDOT specification for ASR allows an aggregate to be deemed non-reactive based solely on ASTM C 1260 results. Work is in progress at the Concrete Durability Center (CDC) to better understand the mechanisms responsible for this behavior. One possibility is that the processing (crushing, grinding, washing) required to test coarse aggregates in ASTM C 1260 may, in effect, wash away the reactive phases or alter the aggregate textural characteristics, thereby producing a test material that will show reduced expansion characteristics. Work is now in progress, using the so-called Chinese Mortar Bar test, to determine if modifications to the ASTM C 1260 can be used to better identify reactive aggregates in a short-term testing regime.
- The outdoor exposure site at the CDC has proved to be the best indicator of field performance of aggregates, SCMs, and lithium compounds. Although it is not practical to propose exposure block testing as a standard test method, it has been shown that real concrete in real exposure conditions helps to shine light on available standard laboratory tests, and information gained from these blocks can ultimately be used to improve laboratory-based test methods.

Various methods of preventing ASR in new concrete were evaluated in this project, and a range of viable options have been identified that serve this purpose. Some of the key findings regarding **mitigation options for ASR** are as follows:

- All of the fly ashes studied and evaluated in this project were shown to be effective in controlling expansion caused by ASR, provided that sufficient dosages were used. Class F fly ashes, with CaO less than about 20 percent, tend to be more effective than higher CaO ashes, requiring less fly ash to suppress expansion. However, even fly ashes with CaO contents in excess of 25 percent were found to be effective in suppressing expansion, but higher dosages were needed, in some cases up to 40 percent (by mass of total cement). To reduce the required fly ash dosage, ternary blends containing fly ash plus either silica fume or ultra-fine fly ash, are quite effective.
- Other SCMs, such as slag and metakaolin, were also found to be quite effective in suppressing ASR, again provided that sufficient dosages are used. The required amount of any SCM (or SCMs for ternary blends) will depend on the aggregate reactivity, total alkali loading, and exposure conditions.
- Reducing the alkali loading in plain concrete (without SCMs) can be an effective method of preventing ASR-induced expansion and cracking, but it has been shown that for highly-reactive aggregates, even low alkali loadings (e.g., 3.5 lbs/yd^3) resulted in significant cracking in exposure blocks. This is a key issue because standard laboratory tests, such as ASTM C 1293, were not able to identify this mixture as being reactive, and mixtures with such low alkali loadings meet the requirements of the current TxDOT ASR specification.
- Lithium nitrate can be used to control expansion in new concrete, but it was found that some aggregates require substantially more lithium nitrate than the typical 100 percent dosage (based on manufacturer's recommended dosage of 0.55 gallons of 30-percent lithium nitrate solution per pound of Na_2O_e in mixture). Thus, a major finding of this project, as well as related research at the CDC, is that it is not possible to prescriptively select the amount of lithium needed to control ASR. Rather, one should rely on 2-year concrete prism data for determining the dosage of lithium needed for a given reactive aggregate.

Delayed Ettringite Formation

Delayed ettringite formation is a less common, but potentially more damaging, cause of distress than ASR. There have been far fewer documented cases of DEF than of ASR, and prior to this project, there were no published cases in which DEF was the sole culprit in causing deterioration in an actual field structure. Significant progress was made in understanding how best to evaluate the potential for DEF in laboratory testing regimes and identifying means of preventing DEF through optimizing materials, mixture proportions, and curing regimes. Some of the main findings related to DEF are highlighted below.

A comprehensive evaluation was performed within this project that focused on testing methodologies for DEF. Most of the testing was performed using tests developed by either Kelham or Fu. These mortar tests were found to be effective in generating DEF through high-temperature curing regimes, followed by subsequent storage conditions that promoted alkali leaching and accelerated expansion. The tests tended to produce similar ultimate expansions, but the Fu test produced earlier expansions, most likely because of microcracking caused by the early severe drying cycles. Both tests were effective in evaluating critical temperature thresholds for triggering DEF and in identifying and evaluating methods of preventing expansion, even when excessive temperatures are encountered.

Concrete prisms and outdoor exposure blocks were also tested as part of this study, and it was shown that DEF can be triggered in similar fashions, specifically by exposing specimens to high early temperatures, then storing them in conditions that either promote leaching or that trigger ASR, which then activates DEF as the pore solution pH drops. More work is needed to refine and ultimately develop standardized DEF tests, but it is hoped that the extensive work performed under this project will serve as the basis for such tests.

This project evaluated which parameters have the most profound impact on DEF-induced expansion and what means are available for preventing such distress in new concrete. Some of the key findings are briefly summarized below.

- Preventing internal concrete temperatures from exceeding 158 °F is effective in preventing DEF. No mixtures suffered from excessive expansion or cracking when temperatures were kept below this threshold value.
- When mortar or concrete mixtures were subjected to temperatures in excess of 158 °F, the incorporation of various SCMs was found to be effective in preventing subsequent DEF-induced expansion. Fly ash (Class F or Class C), slag, metakaolin, and ultra-fine fly ash were all found to be effective when used in sufficient quantities. Silica fume, however, was not found to be effective in the dosages evaluated in this project. A lithium nitrate-based admixture, typically used for protection against ASR, was also found to be effective in suppressing DEF-induced expansion in heat-cured mortars.

The Researchers Recommend...

Implementation of Key Findings in TxDOT Specifications

Much of the work done under TxDOT Project 0-4085 was in support of Special Provision to Item 421, which was the first major effort to implement prescriptive and performance-based specifications for ASR (and to a lesser extent, DEF). The bulk of the research has shown that these specifications are both warranted and effective. Further, the findings of TxDOT Project 0-4085, coupled with ongoing research efforts within TxDOT, have helped to improve the initial Special Provision to Item 421 approach. As with any research, this project has also highlighted some aspects of the specifications that deserve further attention and improvement. Some of the main findings related to the previous and current **TxDOT specifications** include the following:

- Some aggregates that pass ASTM C 1260 and are thus deemed non-reactive may actually be reactive in concrete, and more work is needed to determine how many aggregates fall into to this classification. Research underway using the Chinese mortar bar test may prove to be quite useful in addressing this concern. Conversely, another option might be to require that ASTM C 1293 be performed on all aggregate sources in the state to determine which sources the mortar bar test provides incorrect results. These aggregates could then ultimately be tested for specification compliance using different regimes (e.g., Chinese mortar bar test or ASTM C 1293), or they could be dealt with using strictly prescriptive guidance (that is, assume they are reactive and mitigate using SCMs, etc.).
- The new ASR specification has been improved from a testing perspective by requiring that coarse and fine aggregates be tested separately, which is now in agreement with most other national and international specifications. Combining aggregates in an accelerated mortar bar test, as was required in the previous TxDOT specification, may result in unwanted side effects and may lead to issues related to pessimum effects, etc. This approach of testing fine and coarse aggregates separately also will provide a better long-term database for aggregates in our state and will help to isolate these results from data obtained testing combinations of various materials.
- Some highly reactive aggregates were found to result in substantial cracking in exposure blocks, even though the total alkali loading met the TxDOT maximum alkali loading requirement for plain concrete of 4 pcy of alkalies. More work is needed to determine how many aggregates in the state respond at such low alkali contents, and thought should be given to reducing the allowable alkali loading for such aggregates. Lowering the maximum allowable alkali loading for plain concrete in Texas would also help to spur the use of SCMs, which have other major benefits, such as reduced heat of hydration, better sulfate resistance, and enhanced sustainability.
- Prior to the initiation of this research project, there were no TxDOT specifications aimed at preventing DEF in new concrete structures. However, the findings of this project were directly responsible for the implementation of new specifications intended to prevent DEF through prudent limits placed on internal concrete temperatures. Examples of these new specifications include:
  - ➢ Temperature limits have been placed on precast girder fabrication, with a maximum temperature of plain concrete set at 150 °F and SCM-containing concrete set at 170 °F.
  - ➢ Temperature limits were placed on mass concrete placements, with a maximum temperature limit of 160 °F.

For More Details...

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The research is documented in the following reports:

0-4085-1, *Alkili-Silica Reaction and Delayed Ettringite Formation in Concrete: A Literature Review*

0-4085-5, *Preventing ASR/DEF in New Concrete: Final Report*

To obtain copies of a report: CTR Library, Center for Transportation Research, (512) 232-3126, email: ctrlib@uts.cc.utexas.edu

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