CAIT-UTC-006

# Supplement to the Bridge Resource Program:

## State-of-the-Art Practices of Mass Concrete – A Literature Review

Final Report

September 2013

Submitted by

Patrick Szary, Ph.D
Associate Director,
Principal Investigator, Bridge Resource Program

Andrés M. Roda, P.E.
Program Manager
Bridge Resource Program

Christopher Monopolis
Undergraduate Student
Rutgers School of Engineering

Center for Advanced Infrastructure and Transportation (CAIT)
Rutgers, the State University of New Jersey
100 Brett Road
Piscataway, NJ 08854

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16. Abstract
The mission of Rutgers University's Center for Advanced Infrastructure and Transportation (CAIT) Bridge Resource Program (BRP) is to provide bridge engineering support to the New Jersey Department of Transportation (NJDOT)'s Bridge Engineering and Infrastructure Management Unit. The program is a partnership between federal and state transportation agencies and Rutgers University, which provides technical and educational services to address infrastructure needs in New Jersey. CAIT supports the NJDOT by providing staff and resources to address the most pressing bridge engineering and training challenges in New Jersey (through advanced materials development, design enhancements, construction improvements, evaluation, monitoring, data mining, management enhancement and support, and bridge research).

The purpose of this grant is to supplement the Bridge Resource Program through the on-call investigation of mass concrete construction practices, which resulted in a report to NJDOT on state-of-the-art practices in mass concrete construction. The findings in the report were used to compare with the Thermal Control Plan for the Route 7 Wittpenn Bridge Pier 1W cap as well as the current mass concrete specifications included in the NJDOT 2007 Standard Specifications. The review focused on material composition, with description of each component's contribution to heat of hydration. The team observed that the literature focused on two areas of concern, maximum temperature reached during curing and thermal differentials between the core and surface of the mass concrete element.  The literature has extensively documented the urgency of maintaining the maximum curing temperature below 160°F. The adverse effects associated with exceeding the maximum temperature threshold are severe, but not visible for months or years after construction. This threshold should never be exceeded. The literature also documents damages resulting from exceeding temperature differential thresholds, which are more immediate and can be identified during construction. The thermal-induced cracking that results may be repaired through industry accepted means, from seals, coatings for hairline cracking, to more comprehensive repairs.  During early stages of curing, the concrete has not developed sufficient strength to resist excessive thermal gradients. Thus, form insulation and other methods to protect the concrete surface from dissipating heat greatly or reach excessively high peak temperatures reduces the likelihood of deleterious effects. The results of this literature review suggest that current research and industry agree that temperature thresholds are critical to mass concrete. Proper controls must be established in order to ensure well-performing concrete elements to be constructed.

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Mass concrete, delayed ettringite formation, thermal cracking, adiabatic temperature rise, thermal gradient

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# 1. Description Of The Problem

New Jersey Department of Transportation (NJDOT) is faced with significant challenges in addressing the state of good repair of their bridge asset system. Shrinking budgets and the need to "do more with less", has resulted in increasingly difficult decisions to repair or replace structurally deficient bridges. The state's current investing budget, $690 million in 2013 on bridge assets, follows a constrained model of asset management. With 6,452 bridges (over 20 feet long) in New Jersey, 2,584 state-owned bridges, and an average age of NJ bridges at 51 years, NJDOT is continually looking to innovate in order to meet their policy of maintaining an acceptability rate of 86% over the next 10 years. NJDOT was in need of a resource program that assists in advancing asset management practices, provides training in the use of advanced materials, technologies and construction techniques, identifies new technologies, and responds to unplanned, non-routine materials and construction issues.

NJDOT requested that Rutgers-CAIT perform a literature review on the state-of-the-art practice of mass concrete and use the findings to compare with the Thermal Control Plan for the Route 7 Wittpenn Bridge Pier 1W cap as well as the current mass concrete specifications included in the NJDOT 2007 Standard Specifications. The review focused on material composition, with description of each component's contribution to heat of hydration. The team observed that the literature focused on two areas of concern, maximum temperature reached during curing and thermal differentials between the core and surface of the mass concrete element.

## Overview of mass concrete

Mass concrete is defined by the American Concrete Institute (ACI) as: *Any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking.* The practice dates back to the turn of the 20th century. The technologies employed today provide much greater quality control and capability to predict the material's performance. Recent research[1] has better defined the processes affecting mass concrete and provided guidance in the temperature thresholds that trigger deleterious effects such as Delayed Ettringite Formation (DEF). This study, as well as other state DOTs practice, provides a solid basis to provide recommendations for mass concrete operations in New Jersey.

The objective of using mass concrete is primarily for durability and workability and secondarily for strength. Mix designs and curing practice should be developed to provide the concrete with a

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[1] Folliard, K., et al., "Preventing ASR/DEF in New Concrete: Final Report", FHWA/TX-06/0-4085-5, June 2006

suitable environment to develop strength at a controlled pace, thereby maintaining controllable adiabatic temperature increases and protecting the concrete from sharp temperature contrasts between core and surface.

## Adiabatic Temperature Rise (ATR) and thermal cracking

In the early phases of curing, it is critical to prevent large temperature contrasts between the core and the surface. The combination of Adiabatic Temperature Rise (ATR) and low thermal conductivity results in high core temperatures. Heat escaping at the surface induces tensile stresses in the concrete. The material properties can resist this tension, but only in a limited capacity. Once tension exceeds the material's capacity to resist, thermal cracking ensues. In New Jersey, other concrete operations have been limited in their allowance for tension in concrete. Thus, the tolerance for this phenomenon should be considered in relation to the DOTs practice to limit tension in concrete elements.

## Concrete overheating Delayed Ettringite Formation (DEF)

As the exothermic reaction of concrete hydration develops, it is critical to prevent the concrete core from overheating in order to prevent longer-term deleterious effects. During hydration, the cement releases high amounts of heat. In mass concrete, the heat is maintained internally, creating adiabatic temperature increases. As temperatures rise, the chemical reactions in cement change, causing the entrapment of sulfates and aluminates in the cement paste (C-S-H gel). Over time, sulfates (and aluminates) diffuse from the hardened paste and react with monosulfate hydrates to form ettringite, an expansive material that induces stress in concrete, causing cracks. This phenomenon, referred to as Delayed Ettringite Formation or DEF, will continue over the years, reducing the concrete's life. In contrast, when temperatures are controlled, ettringite is allowed to form as part of the early formation of cement, thus accommodating expansion while concrete is still green.

Strength gain is considered secondary in mass concrete, however its development should be considered in relation to short and long-term. In mass concrete, strength develops at lower rates than conventional concrete, but can continue to grow significantly up to one year. The level of strength gain can be between 30% and 200%[2]. During this time, hydration of cement particles continues to churn out the exothermic reaction within the core of the concrete. The rate and magnitude of heat of the concrete depends on the cement mix and pozzolanic content, the compound composition and fineness of cement, the shape of the concrete element and its volume to surface ratio, the initial temperature of the concrete, the ambient temperature and the other

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[2] ACI 207.1R-96, November 1996

surrounding conditions[3]. The time for the core to reach ambient temperature is inversely proportional to the measure of the least dimension in the concrete element. Thus a 6 inch thick element can be thermally stable in a few hours, while a 50-foot thick dam wall would require two years. More common element, such as a 5-foot thick wall or pier cap would take approximately a week to reach comparable conditions.

## 2. Technical review of mass concrete composition

### Mix Design – Cement

Thermal cracking and Delayed Ettringite Formation (DEF), which will be discussed in greater detail further in this report, can be addressed to an extent by the composition of the cement used in the design. Temperature control is important here, as entrapment of sulfates ($SO_4$) in the CSH gel is triggered once the concrete reaches a temperature of 160°F or higher and thermal cracking occurs when the temperature gradient within the mass concrete causes sufficiently high tensile forces to exceed the concrete's stress limit, which develops over the curing period. The cement used in the mass concrete mix could be used as a means of controlling the temperature by specifying cement compositions that have a low heat of hydration or a longer set time to delay the hydration reaction and allow the heat generated in the reaction to develop over a more prolonged period. Figure 5.3.1 in ACI 207.1R-96 indicates ATR of mass concrete as a function of time, for each type of cement (Figure 1), given a content of 376 LB/CY.

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[3] Chini, A., Parham, A., "Adiabatic Temperature Rise of Mass Concrete in Florida", BD 529, February 2005

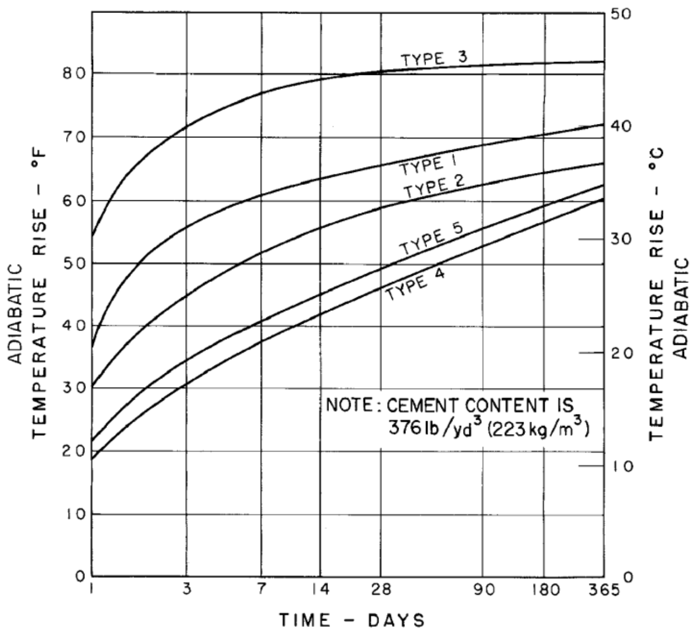

**Figure 1 - Temperature rise of mass concrete (ACI 207.1R-96 Fig. 5.3.1)**

Note that Type I and III cements generate the greatest ATR. Cements with low heat of hydration incorporate smaller percentages of tricalcium aluminate ($C_3A$) and tricalcium silicate ($C_3S$), since these components of cement contribute to a higher heat of hydration. In general, cement types II, IV and V provide reduced $C_3A$ and $C_3S$ content, making them suitable for mass concrete applications. NJDOT Qualified Products List (QPL) and Standard Specs only allow for the use of Type II cement.

In addition to the cement's heat of hydration, several studies have looked at Sulfite ($SO_3$) content in cement mixes in relation to DEF formation. A 2006 TXDOT study examined a Type V cement which had a $SO_3$ content of 1.9% (Types I and III tested alongside it ranged from 2.78% to 4.2%), which experienced DEF-induced expansions that were smaller than 0.1%, far less than the other types. The same TXDOT study also found that a type I cement with a lower percentage of $C_3A$ and $SO_3$ experienced substantially less DEF expansion.[4] In comparison, a Cement and Concrete Research Report, composed in 2003, also finds that low $SO_3$ content in cement is able to prevent DEF. For comparison purposes, the Essroc Type I cement used in NJDOT projects contains 3.9% $SO_3$.[5]

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[4] Folliard, K., et al., "Preventing ASR/DEF in New Concrete: Final Report", FHWA/TX-06/0-4085-5, June 2006

[5] Ramlochan, T., Zacarias, P., Thomas, M. D., & Hooton, R. D. (2003). *The effect of pozzolans and slag on the expansion of mortars cured at elevated temperature Part I: Expansive behaviour. Cement and Concrete Research*, 33(6), 807-814.

## Mix Design – SCMs

The Supplementary Cementitious Materials (SCMs) used in the concrete mix reduce the heat of hydration. Class-F fly ash and slag can be used for this purpose, although the percentage of replacement depends on several factors including environmental exposure and durability requirements.[6] This reduction in heat of hydration makes the possibility of DEF less likely by limiting the temperatures at the element core reach 160°F or greater during the curing period. A 2005 FLDOT study examined the effect of fly ash and slag on the peak temperature of concrete, and found that there were reductions of 0.1% to 26.1% over ordinary Portland cement (OPC), as detailed in Table 1 below.[7]

**Table 1 - Effect of Pozzolans on the Peak Temperature of Concrete (Chini & Parham, 2005)**

| **Cement Source** | **Placing Temperature** | **% Reduction in Peak Temperature after 14 days** | | | |
|---|---|---|---|---|---|
| | | 25% Fly Ash | 35% Fly Ash | 50% Slag | 70% Slag |
| A | 73°F | 12.7 | 17.2 | 8.2 | 21.2 |
| B | 73°F | 8.5 | 26.1 | 14.1 | 24.1 |
| *Average for Cements A & B* | | *10.6* | *21.7* | *11.2* | *22.7* |
| A | 95°F | 1.9 | 8.0 | 0.1 | 23.4 |
| B | 95°F | 9.7 | 18.6 | 4.6 | 7.0 |
| *Average for Cements A & B* | | *5.8* | *13.3* | *2.4* | *15.2* |

By lowering the peak temperature, the concrete core temperatures are less likely to reach the 160°F temperature threshold during the critical period of curing, and less likely to have an extreme core-surface temperature difference. In addition, when cements are placed at lower temperatures, the peak temperature drops, thus colder placing temperatures significantly help thermal control of the curing concrete. In the *Materials and Structures* article, Breitenbücher advocates a lower placing temperature for fresh concrete, as it makes it less likely to experience thermal cracking.[8]

A similar FLDOT report, performed in 2003 investigated the effects of high curing temperatures on the phenomena of DEF by testing multiple cement mixes with varying levels of SCMs[9]. The study found that DEF did not occur in any samples cured at room temperature (73°F). However,

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[6] Gajda, J., "Mass Concrete: How do you handle the heat?", PCA

[7] Chini, A., Parham, A., "Adiabatic Temperature Rise of Mass Concrete in Florida", BD 529, February 2005

[8] Breitenbücher, R. (1990). Investigation of thermal cracking within the cracking frame. *Materials and Structures*, (23), 172-177

[9] Chini, A. R., Muszynski, L. C., Acquaye, L., & Tarkhan, S. (2003, February). *Determination of the maximum placement and curing temperatures in mass concrete to avoid durability problems and DEF*

once concrete samples were cured at temperatures at or above 160°F, DEF began to occur in all mixes. The OPC mix exhibited greater presence of DEF in comparison to mixes that incorporate SCMs. These mixes experienced a smaller decrease in compressive strength than the OPC mix, which lost 34% of its compressive strength (in comparison to the samples cured at room temperature, or 73°F) at the 28 day mark. A mix that incorporated an 18% fly ash replacement (by weight) only lost 8% of its compressive strength at 28 days when cured at 160°F. Similarly, a mix using a 50% weight replacement of ground granulated blast furnace slag, experienced a 7% reduction in its compressive strength[10]. Similar effects are reported by multiple studies[11]. Thus, using SCMs in the mix design lowers the incidence of DEF, and mitigates the cracking associated with the condition.

Slag is divided into three classifications based on its activity index, grade 80, 100 and 120. The grade reflects the strength of a mortar mix made with 50% slag and 50% Portland cement, and is reported as a percentage of the strength of mortar made with reference cement alone. NJDOT has approved grade 100 (medium activity) and grade 120 slag (high activity). Grade 80 slag has a low activity index thus generating less heat than Portland cement concrete, making it ideal for use in mass concrete applications. FHWA recommends avoiding the use of grade 80 slag unless warranted in special circumstances.

ASTM C989 indicates that the use of slag cement will decrease the $C_3A$ content of the cementing materials, reducing concrete reactivity, and will decrease the permeability and calcium hydroxide content of concrete.

It should be noted that some SCMs are not suitable for use in mass concrete. The 2006 TXDOT report examined DEF and the impact of silica fume on related expansion, in addition to the effects of fly ash and slag replacements[12]. It was determined that at 10% replacement (by weight), silica fume was unable to successfully mitigate expansions caused by DEF, which lead to cracking. It did manage to delay the onset of DEF, which caused reduced expansions in the concrete as compared to a pure cement mix, however not within acceptable limits. Fly ash (20% and 40% replacements) and ground granulated blast furnace slag (35% and 50% replacements) on the other hand were able to reduce DEF-induced expansion to the point where extremely minor cracks occurred, or even none at all. Silica fume causes the concrete's heat of hydration to increase; increasing the risk that concrete reaches temperatures above 160°F, and the likelihood of DEF occurring. This also increases the risk of temperature differences between the core and surface to exceed the 35°F threshold, which could lead to thermally induced cracking. Other

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[10] Chini, A. R., Muszynski, L. C., Acquaye, L., & Tarkhan, S. (2003, February). *Determination of the maximum placement and curing temperatures in mass concrete to avoid durability problems and DEF*

[11] Siler, P., Kratky, J., & De Belie, N. (2011). Isothermal and solution calorimetry to assess the effect of superplasticizers and mineral admixtures on cement hydration. *Journal of Thermal Analysis and Calorimetry*.

[12] Folliard, K., et al., "Preventing ASR/DEF in New Concrete: Final Report", FHWA/TX-06/0-4085-5, June 2006

studies have reported similar issues with silica fume[13]. These results indicate that silica fume is less suited for use with mass concrete than fly ash or ground granulated blast furnace slag.

## Mix Design – Admixtures

The ACI 207.1R-13 guide for Mass Concrete states that admixtures do not have an effect on heat of hydration after the first few hours after mixing. Thus, their effects can be neglected in preliminary computations. However, when a design incorporates several million cubic yards of concrete, adiabatic temperature rise should be determined for the exact mixture used and compared with the proposed placing temperature to arrive at a proposed peak temperature.

Some admixtures may not be suited to use with mass concrete. An accelerating admixture will contribute to undesirable heat development, so it should not be used. Superplasticizers still require more research on their effects, as studies offer conflicting results on peak heat and total heat generated.

## Mix Design – Aggregates

The aggregates incorporated in mass concrete will impact temperature control during curing. The aggregate's co-efficient of thermal expansion, and thermal conductivity determine the concrete's ability to manage temperature changes and maximum temperature achieved during curing. Table 2 shows typical coefficient of thermal expansion ranges for several widely used aggregates. Using aggregates with low coefficients of thermal expansion causes the aggregates to expand less as they increase in temperature, which reduces the risk of cracking due to thermally induced volume expansion. In addition to this, having a low thermal conductivity reduces the risk of thermal cracking, as the concrete on the outside will not cool off as quickly, decreasing the temperature differential between the outer portion and the core of the concrete.[14]

**Table 2 – Typical thermal expansion ranges for common aggregates (FHWA)**

| | **Coefficient of Thermal Expansion** | |
|---|---|---|
| | **$10^{-6}$/°C** | **$10^{-6}$/°F** |
| **Aggregate** | | |
| Granite | 7-9 | 4-5 |
| Basalt | 6-8 | 3.3-4.4 |
| Limestone | 6 | 3.3 |
| Dolomite | 7-10 | 4-5.5 |

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[13] Ramlochan, T., Zacarias, P., Thomas, M. D., & Hooton, R. D. (2003). *The effect of pozzolans and slag on the expansion of mortars cured at elevated temperature Part I: Expansive behavior. Cement and Concrete Research*, 33(6), 807-814.

[14] Choktaweekarn, P.; Somnuk, T. (2010) Effect of aggregate type, casting, thickness and curing condition on restrained strain of mass concrete. *Songklanakarin Journal Of Science & Technology*, *32*(4), 391.

| | | |
|---|---|---|
| Sandstone | 11-12 | 6.1-6.7 |
| Quartzite | 11-13 | 6.1-7.2 |
| Marble | 4-7 | 2.2-4 |

In addition to their thermal characteristics, the size of the aggregates, the volume used and the manner of their preparation prior to use all have impacts on the concrete's temperature.  It is recommended that the largest aggregates compatible with the mix be used, in the largest volume possible.  Prior to their usage, aggregates should be kept in a shaded area, in addition to being chilled or wetted to reduce the placing temperature of the concrete.

# 3.  Technical review of typical mass concrete symptoms

## Initial symptoms caused by thermal gradients

Thermal gradients in concrete lead to the development of tensile stresses. Large gradients during concrete curing can lead to early age cracking of mass concrete elements. Following initial placement of mass concrete, the ATR at the core of the mass reaches its peak and begins to diffuse its heat to the surface. If the surface is allowed to release the heat quickly, surface temperatures may drop beyond a threshold, allowing unacceptable tensile stress to develop at the surface. Ultimately, this gradient will act as a restraint, causing the surface to crack under the tensile stress.

According to ACI 207.1R-96, concrete tensile strength can be expressed as a relationship to its compressive strength as follows: $f_t = 1.7\, f_c^{2/3}$ (psi). Within a time-dependent analysis, the critical thermal gradient threshold can be determined. Various studies referred to in this report, as well as industry standards, indicate that a 35°F gradient threshold is sufficient to avoid thermal-induced cracking on the surface of mass concrete. Through additional modeling, it is anticipated that temperature differential thresholds can be tabulated as a function of curing period in order to provide a more stringent criteria for thermal control.

## Symptoms of concrete overheating – Delayed Ettringite Formation

Delayed ettringite formation is a deleterious phenomenon that may occur in mass concrete resulting from elevated concrete curing temperatures. Although less common than other similar phenomena such as Alkali-Silica Reaction, it may be equally damaging to concrete elements.  the phenomenon is directly linked to cement curing at temperatures exceeding  158$^{o}$F threshold. Normally forming ettringite ($C_3A\cdot 3CaSO_4\cdot 32H_2O$) in curing concrete is delayed at these higher temperatures due to a change in the hydration of the cement paste. Sulfates and aluminates in the cement become trapped in the Calcium Silicate Hydrate (C-S-H) paste and other hydrates produced during hydration.   Once the hydration process is complete and the concrete is exposed to moisture at ambient temperature for extended periods, these trapped sulfates and aluminates slowly diffuse through the C-S-H paste and react with monosulfate hydrates, forming ettringite. A material that normally expands in a cement paste expands in a hardened concrete. Expansive tensile forces cause cracking in the concrete. Sufficiently high sulfate and aluminate concentrations in mass concrete result in reduced durability and strength loss in concrete elements.

Ettringite may also fill in in pre-existing cracks, exacerbating the condition. The 2006 TXDOT report documents a 1993 investigation by Fu on delayed ettringite formation, incorporating fracture mechanics and thermodynamic considerations.[15] It was determined that ettringite nuclei will form near the tips of the cracks. After this nucleation, the ettringite crystals can grow, expanding the crack and further weakening the concrete.

## 4. Ettringite Formation in well-performing concrete

Despite the problems associated with DEF, ettringite presence in concrete is typically expected. Often, ettringite is found in mature concrete, especially in areas such as voids or air bubbles which give it necessary space to expand. If ettringite forms prior to concrete hardening, the material may expand within the "green" concrete, without creating tensile stresses. It is ultimately the time at which ettringite forms that determines whether it has a negative effect.

## 5. Wittpenn review and comparisons

### Concrete mix design

According to the Thermal Control Plan (TCP) prepared by CTL Group, dated October 1, 2012, the Wittpenn Bridge pier cap design mix consisted of a Class P concrete consisting of 537 Lb/CY of Essroc Type I cement and 178 LB/CY Holcim Grade 100 Slag. Mill certs from local suppliers indicate that Essroc Type I cement consists of a 71.48% $C_3S$ + $C_3A$ composition[16]. Using Table 3, the mix closely aligns with a 30% slag replacement, reducing heat of hydration.

**Table 3 – Summary of concrete mixes tested by semi-adiabatic calorimetry (converted to cal/g)[17]**

| No. | Cement Type | Heat of Hydration at 100% Hydration (cal/g) |
|---|---|---|
| 1 | Type I Cement | 114 |
| 2 | Type I Cement + 15% Class C Fly Ash | 113 |

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[15] Folliard, K., et al., "Preventing ASR/DEF in New Concrete: Final Report", FHWA/TX-06/0-4085-5, June 2006

[16] Quality Assurance Sample, Essroc Cement Co. Plant #1 – Nazareth, PA, dated October 18, 2011

[17] Schindler, A, Folliard, J., "Heat of Hydration Models for Cementitious Materials", ACI Materials Journal, Title no. 102-M04

| | | |
|---|---|---|
| 3 | Type I Cement + 25% Class C Fly Ash | 112 |
| 4 | Type I Cement + 35% Class C Fly Ash | 111 |
| 5 | Type I Cement + 45% Class C Fly Ash | 110 |
| 6 | Type I Cement + 15% Class F Fly Ash | 106 |
| 7 | Type I Cement + 25% Class F Fly Ash | 101 |
| 8 | Type I Cement + 35% Class F Fly Ash | 95 |
| 9 | Type I Cement + 45% Class F Fly Ash | 88 |
| 10 | Type I Cement + 30% Ground Granulated Blast Furnace Slag | 113 |
| 11 | Type I Cement + 50% Ground Granulated Blast Furnace Slag | 112 |

ACI recommends limiting the use of cement to as small an amount as possible. Other optional recommendations include limiting the $C_3S + C_3A$ composition to 58% or limiting the heat of hydration to 70 cal/g at 7 days (ACI 207.1R-13, section 2.2).

## Thermal Control Plan

The thermal control plan indicates that the specified 35°F temperature gradient may not prevent thermal cracking at early ages and can be too conservative at later ages because it does not consider the properties of the actual concrete mix design.[18] The concrete's ability to resist the temperature gradient is proportional to the strength gain during curing. It is a time-dependent behavior that may be best described by tabulating temperature thresholds as a function of time, which can be calculated through Finite Element Analysis of the element.

The TCP outlines the methods to be used to maintain both thresholds. Table A in the document indicates that only the final, 7 ¼-FT thick pier cap segment would require cooling pipes. The document also includes a graph that outlines temperatures as the concrete cures.

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[18] Letter dated October 1, 2012 – titled "Thermal Control Plan for the mass concrete fill within the precast cofferdam at Pier 1W Wittpenn Bridge, Route 7 over the Hackensack River, Kearny NJ, CTLGroup Project No. 051622, TCP 1", Feld, J., Gajda, J., Smith, S., CTLGroup

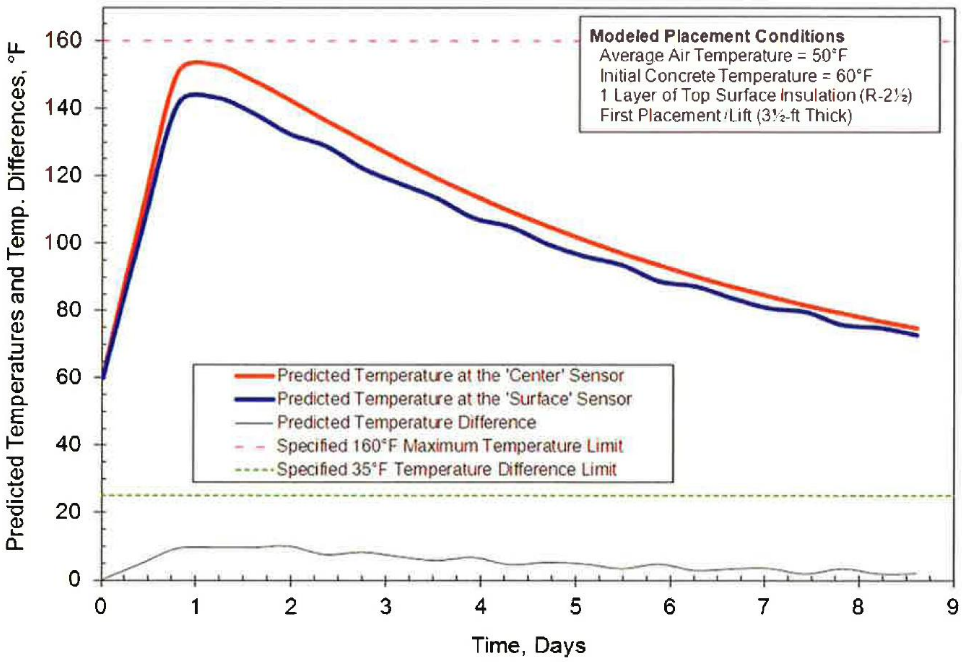

**Figure 2 - Detailed Results of Thermal Modeling for the First Placement**

As can be seen from the graph, the model predicted that both maximum temperature and temperature difference thresholds would be maintained. Further, the temperature differences would be maintained no higher than 10-15°F, which is well within the limits.

## 6. Comparison with NJDOT 2007 Standard Specifications

The NJDOT 2007 Standard Specifications provide explicit direction to contractors about the required documentation and plans that must be submitted at least 30 days before placing concrete. The following is a point-by-point discussion of each requirement a contractor must include in the Thermal Control Plan:

1. Concrete mix design, including pozzolanic materials to control concrete temperature.

As described in the previous sections, it is critical for each concrete component to be accounted for in terms of heat of hydration. The contractor should be aware of materials that should be explicitly avoided, such as silica fume and accelerating agents.

2. Adjustments to form removal and loading times for slower strength gains for high pozzolan mixes.

Mass concrete will cure at a slower rate than other concrete methods. It is critical for the contractor to understand concrete maturation. This may be monitored through NDE evaluations such as Ultrasonic Surface Wave. The contractor should outline the steps taken to ensure timing of form removal. In addition, mass concrete pours may be “staged” to further control thermal effects. The contractor should identify the timing between form removal and placement of the subsequent mass concrete segment.

3. An analysis of the anticipated thermal developments within placements using proposed materials and casting methods.

This analysis can be accomplished via Finite Element Analysis. The contractor’s engineer should be experienced in mass concrete modeling and be able to develop a proper analysis of the element being constructed.

4. A plan outlining specific measures to be taken to control the temperature differential within the limits.

This typically includes insulation, cooling pipes, and other methods to mitigate the tendency for concrete to dissipate heat from the surface. By maintaining a constant temperature throughout the element and minimizing ATR at the core, the contractor can best control temperature differentials. Modeling the mass concrete element prior to construction is critical to identifying the number and location of cooling pipes needed to maintain a consistent, acceptable temperature gradient through the element cross section.

5. The proposed monitoring system

The system should include temperature readings at the element’s central core and surface. It should also include maturation data to determine strength as a function of the element’s curing time. This could play a pivotal role in developing a more stringent threshold for temperature gradient, which relates concrete strength development with tensile resistance during curing.

6. Outline of corrective actions to control the temperature differential and maximum internal temperature.

In addition to precautionary steps outlined in item #4, the contractor should take necessary steps to maintain the differential below the 35°F threshold. Curing operations should take this into consideration, especially when wet curing. While water is the best option for mass concrete, the thermal control plan should account for this via maintaining an acceptable gradient through the element cross-section.

7. Proposed methods of repairs or corrective actions if the mass concrete member is not accepted.

The literature has extensively documented the urgency of maintaining the maximum curing temperature below 160°F. The adverse effects associated with exceeding the maximum temperature threshold are severe, but not visible for months or years after construction. This threshold should never be exceeded.

The literature also documents damages resulting from exceeding temperature differential thresholds, which are more immediate and can be identified during construction. The thermal-induced cracking that results may be repaired through industry accepted means, from seals, coatings for hairline cracking, to more comprehensive repairs.

It should also be noted that the standard specifications indicate that temperature control must be maintained for 15 days. This limit may not be sufficient to control the high core temperature that persists for significant periods beyond the 15 day limit. It is recommended that this limit be replaced with a requirement that the contractor's engineer submit an analysis indicating equilibrium between core and air temperatures that will result in temperature differences not exceeding the 35°F threshold.

In addition to the 15 day limit, the department should also consider the effects of thermal differentials on early age strength of mass concrete. Relying on tensile stresses is typically not acceptable by NJDOT. In considering other concrete placement practices such as prestressed concrete, in which no tensile stress is allowed, limiting tensile stresses in mass concrete should be a top priority. Thus, at minimum, maintaining the 35$^{o}$F temperature differential and 160$^{o}$F maximum should be continued. The team recommends considering that a table be developed outlining temperature thresholds as a function of time after placement. This table should be mix design-specific, and account for the strength development and its ability to resist tensile forces developed through thermal effects.

## 7. Recommendations and conclusion

The information provided in this review is considered a synthesis of current research and practice, and guidance and recommendations are based on the literature reviewed. For more information on the publications reviewed for this study, please refer to the references section of this document.

Mass concrete placement requires strict thermal controls in order to ensure proper concrete performance. Thermal Control Plans that outline how the contractor will achieve a low temperature during concrete placing, limit ATR, maintain peak temperatures below 160$^{o}$F and insulate the curing concrete from exceeding the 35$^{o}$F temperature threshold are critical.

During early stages of curing, the concrete has not developed sufficient strength to resist excessive thermal gradients. Thus, form insulation and other methods to protect the concrete surface from dissipating heat greatly or reach excessively high peak temperatures reduces the likelihood of deleterious effects. The results of this literature review suggest that current research and industry agree that temperature thresholds are critical to mass concrete. Proper controls must be established in order to ensure well-performing concrete elements to be constructed.

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