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Mass Concrete and Thermal Cracking,
a Joint ACI-JCI Seminar

Editors:
Melissa Harrison and Christopher C. Ferraro

SP-325



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Preface

Thermal cracking and damage from high internal temperatures during construction are concerns for the mass concrete of dams, bridges, buildings, and power plants. The design, planning and execution of placements which involve mass and thermally controlled concrete must consider hydration of cementitious materials within the concrete mixture to avoid thermal-related distress. Without such considerations, durability, and in some cases, structural integrity can be affected. This Special Publication is intended to help owners, designers, contractors, and concrete suppliers understand and address concerns with mass and thermally controlled concrete.

To highlight state-of-the-art developments in defining, designing, testing and modeling mass and thermally controlled concrete, American Concrete Institute (ACI) Committee 207 and the Japan Concrete Institute (JCI) held a full-day technical session at the ACI Fall Convention, Cincinnati, Ohio, October 16-20, 2011. This Special Publication (SP) contains eight of the papers presented at the technical session. The subjects of these papers include: (1) defining mass and thermally controlled concrete (2) design and planning considerations for mass concrete; (3) modeling and prediction of in-place concrete temperature development, and (4) physical testing of mass concrete.

On behalf of ACI Committee 207 and JCI, the editors sincerely thank all authors and presenters for their efforts and contributions to the technical session and this SP volume. Special thanks are given to the reviewers of the original manuscripts for their constructive comments and suggestions. The editors are also indebted to the ACI staff for their assistance in organizing this session and in preparing this SP. The editors earnestly hope that the information presented at the ACI session and in this SP will facilitate significant improvements in defining mass concrete, as well as the design, planning and control of mass concrete. This SP will serve as a valuable resource for researchers and engineers to make such improvements.

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TABLE OF CONTENTS

SP-325—1

Planning and Execution of a Mass Concrete Placement Utilizing Insulation Regimen

Author: Ufuk Dilek

SP-325—2

Shear Testing of RCC and Other Concrete Blocks

Authors: Stephen B. Tatro and James K. Hinds

SP-325—3

Temperature Predictions of a Ternary Mix Design for Mass Concrete Placements

Authors: Joseph W. Clendenen and Benn B Stutrud

SP-325—4

Design Considerations for Raising the Hinze Dam Mass Concrete Spillway

Authors: Scott Jones, David Hughes, and Orville R. Werner II

SP-325—5

Estimating Maximum Temperature Difference in Mass Concrete

Authors: Ronald Kozikowski and Bruce Suprenant

SP-325—6

Equivalent Age and Physical Properties of Mass Concrete

Authors: Christopher C. Ferraro, Mang Tia, and Adrian M. Lawrence

SP-325—7

Proposed Mass Concrete Definition Based on Concrete Constituents and Minimum Dimension

Authors: John Gajda, Jon Feld and Christopher C. Ferraro

SP-325—8

Planning and Execution of a Large Mass Concrete Placement with Different Insulation Levels

Authors: Boris Haranki, Harini Santhanam, and Ufuk Dilek

Planning and Execution of a Mass Concrete Placement utilizing Insulation Regimen

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Abstract

This paper summarizes the planning and execution stages of a critical mass concrete placement performed during summer months. The subject structure was a critical component of a large heavy industrial facility, consisting of large load bearing elevated flexural members. The planning and execution of this critical mass placement consisted of multiple tasks.

A laboratory study was performed for the purpose of making improvements to the mixture proportions existing and currently in use, admixture dosages and investigating placement temperature options. Adiabatic and semi adiabatic temperature rise was also measured during the laboratory study along with set times. Final proportions and admixture dosages were selected as a result of the laboratory phase. Primary outcome was increase in fly ash percentage from the existing mix design to control heat of hydration.

Based on the findings of the measured adiabatic temperature rise, a thermal control plan was developed adapting the new approach to structural mass concrete placements. A thermal protection/insulation regimen was developed using the mix parameters, expected ambient temperatures following placement, member dimensions and formwork/blanket insulation properties. The pre-placement modifications to the mixture proportions and the delivery temperature requirements protected the concrete against high internal temperatures and potential of Delayed Ettringite Formation (DEF), while the insulation regimen protected the concrete against rapid cooling and occurrence of thermal gradients between core and perimeter.

As part of the thermal control plan analysis, target placement temperatures were recommended to control maximum temperatures to prevent occurrence of DEF, in light of the heat rise of the modified mix. The placement temperature was accomplished by starting the placement at night and the use of ice to draw the temperature down. Upon completion of finishing, a curing compound was applied in lieu of water curing and the placement was insulated.

The thermal control plan simulation predicted a gradual reduction in the temperature of the placement, within limits of maximum internal temperatures and temperature gradients. The actual placement was monitored for core and perimeter temperatures using maturity probes. Monitoring enabled the team to react to abrupt changes in temperature if any was to occur. The placement was completed successfully with internal temperatures and gradients controlled within the desired ranges.

Keywords: mass concrete, adiabatic heat rise, thermal control plan, fly ash, thermal cracking, heat of hydration

Introduction

This paper summarizes the planning and execution stages of a critical mass concrete placement performed during summer months. The subject structure was a critical component of a large heavy industrial facility, consisting of large load bearing elevated flexural members, with minimum dimensions in the order of 2.1 meters (7 ft) [Figure 1]. The planning and execution of this critical mass placement consisted of multiple tasks.



Figure 1 Overview of beams showing reinforcement congestion.

Planning and execution consist of the following stages:

1. Laboratory Study
2. Development of the Thermal Control Plan and Batching Temperature
3. Post-Placement Thermal Monitoring
4. Curing, Insulation and Protection against Temperature Changes

Laboratory Study

Subject mass concrete placement was scheduled to occur during summer months. The existing concrete mixtures used on site were not utilized to date in a mass concrete placement of this significance and under the summer ambient conditions. Therefore the concrete mixture planned for use was reviewed in light of the placement specifics. A laboratory study was performed to revise the concrete mixture to achieve desirable performance objectives in the mass concrete placement under summer ambient conditions.

Existing concrete mixture utilized class F ASTM C 618 (ASTM, 2008) fly ash at a replacement rate of 25% of total cementitious material content. Existing concrete mixtures typically used type A (lignin based) water reducers meeting ASTM C 494

(ASTM, 2010). Lignin based water reducer also offered set control benefits in addition to reduction of water. In addition, as warranted by reinforcement congestion and consolidation challenges at the bottom of sizeable reinforced concrete members a type F superplasticizer meeting ASTM C 494 (ASTM, 2010) was utilized to achieve a maximum slump of 8 inches. Compressive strength of the concrete mixture (f'_c) was 4000 psi (27 Mpa) and specification required water-to-cementitious ratio maximum was 0.45 by weight.

Variables Used during Laboratory Study

During the laboratory study, concrete mixtures with a fly ash replacement rate of 25% and 35% of total cementitious material content were tested. In addition, the dosages of type A and type F water reducers were modified in coordination to yield the same slump value, while increasing the relative dosage of type A in the mixture and achieving an increase in the time of set.

Laboratory study also included concrete mixtures batched at varying temperatures. Temperature of water and aggregates was modified to achieve resulting batch temperatures ranging between 21 and 32 °C (70 and 90 °F) enabling evaluation of the changes with temperature, in time of set and retention or loss of slump. A total of 10 concrete trial batches were performed.

The laboratory study aimed to identify the combination of factors such as concrete placement temperature, admixture dosages, fly ash replacement rate prior to the placement. In addition to time of set and slump loss, adiabatic and semi-adiabatic heat rise of concrete mixtures was measured and the information gathered was used in the in-depth planning of the mass concrete placement.

Figure 2 shows semi adiabatic heat rise measurements performed using proprietary thermal measuring equipment by a national admixture manufacturer. This device mainly contains multiple insulated cylinder housing compartments for 4 x 8 in (10 cm x 20 cm) cylindrical specimens. The housing compartments are equipped with thermocouples feeding temperature data to the data acquisition hardware and associated software. The measurements are not fully adiabatic as is evident from the eventual decline in temperature. However, a time of set determination made based on the shape of the curve provides an estimate of the time of set, which can be compared or indexed to times of set determined per ASTM C 403 (ASTM 2008). For this study, the subject device was not used for an absolute determination of time of set but for comparisons between various trial batches with different attributes. In general, the comparisons between mixtures were made on the basis of

- maximum magnitude of temperature achieved,
- the occurrence time of this peak temperature, and
- occurrence of the flat portions of the curve with respect to admixture dosage and retardation effects as a result of the dosages used.

These attributes can be observed in Figure 2.

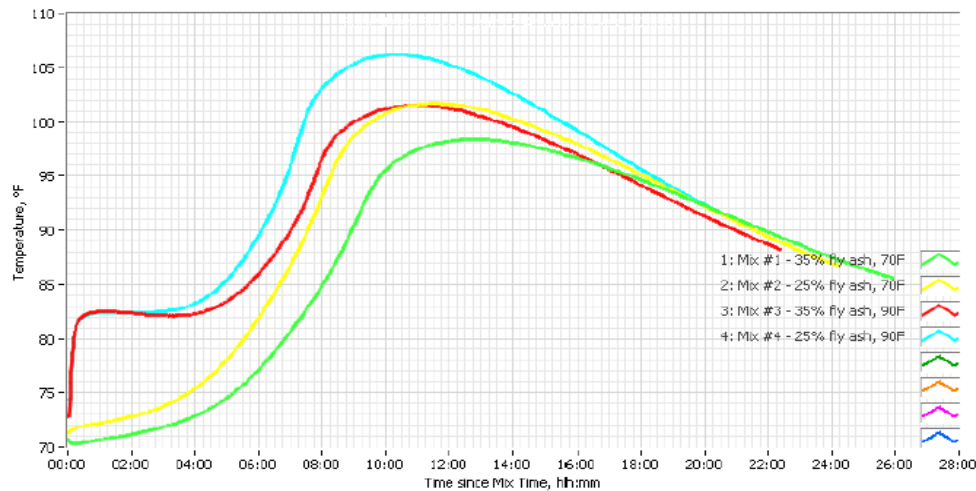


Figure 2 Thermal measurements using AdiaGraph.

Selected Mixture Proportions

Based on the findings of the study, the mixture proportions nominated for placement were determined. These proportions are provided in Table 1 below. It was decided to utilize an increase fly ash replacement rate of 35%. As a consequence of the increased fly ash usage, an ($f'c$) of 4000 psi (27 Mpa) determined at 56 days was utilized in lieu of the typical 28 day mixture design cycle. This increase in length of the design cycle aimed to reduce the earlier heat of hydration which would be more pronounced if the design cycle was kept at 28 days and a more aggressive water-to-cementitious ratio was used for the 28 day design.

Based on the behavior of mixtures and thermal measurement data, a likely upper limit for placement temperature was initially considered to be 80 °F (27 °C). Under standard operating measures, the supplying concrete plant was producing concrete just under 90 °F (32 °C) during the heat of the summer season. If this temperature limit of 80 °F (27 °C) was to be confirmed by the thermal control plan development, it would likely be necessary to use manually loaded ice as a replacement to batch water and that the placement be performed at nighttime.

Table 1 Selected Mixture Proportions.

Code	1435	1435
Strength	4000 psi	27.6 Mpa
	lb/CY	kg/m ³
Cement Type I/II	412 lb	245
Fly Ash	222 lb	132
Fine Aggregate	1112 lb	660
Coarse Agg. (67)	1852 lb	1100
Water	285 lb	169
W/(C+F)	0.45	0.45
Air (%)	3.5 - 6.5	3.5 - 6.5
Slump w/HRWR	5 to 8 in	12.5-20 cm

Subsequently, full adiabatic thermal measurements were performed on the final selected proportion. Figure 3 shows this measurement on the mixture containing 35% ash and a mix containing 25% ash for comparison, demonstrating the difference made with increasing the fly ash. An increase of 10% in fly ash results in a reduction of 3 °C (5 °F).

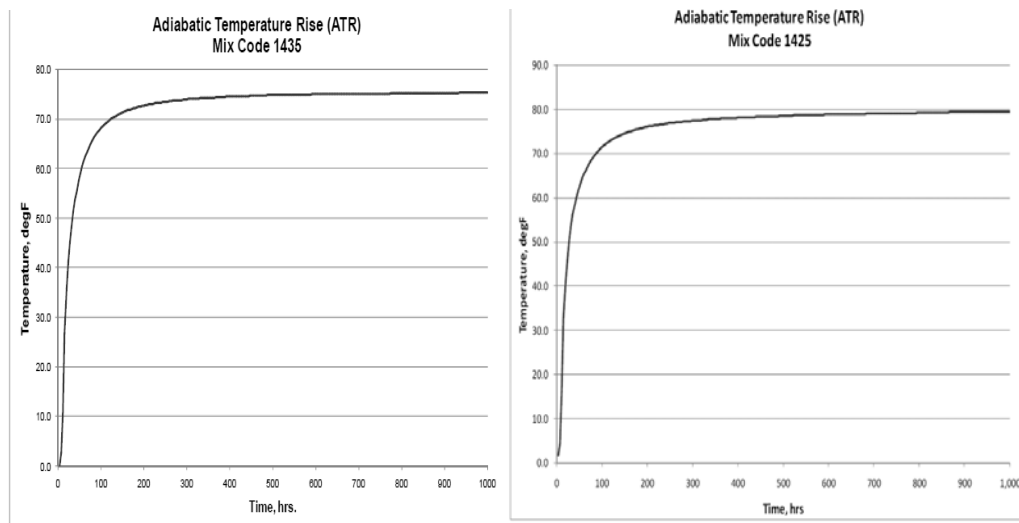


Figure 3 Adiabatic measurements, 35 % fly ash (left), 25% fly ash (right).

DEVELOPMENT OF THE THERMAL CONTROL PLAN

ACI 207 Mass Concrete Committee Report

In general, ACI 207 (ACI, 2005) committee report (Guide to Mass Concrete) concentrates on unreinforced, large mass structures, such as dams with typically lower strength requirements than reinforced structural concrete. The guidelines provided for mixture attributes (low heat, use of pozzolan, reduction of cement content etc) are appropriate. The recommended curing method is curing by water therefore aiming rapid removal of heat from the mass concrete structure.

ACI 207 committee is currently working on a committee report entitled “Guide to Reinforced Concrete Structures” that is geared towards reinforced mass concrete structures that are not sizeable as dams and possibly of a higher strength class. This report’s approach is generally inline with the mass concrete practice in ACI 301-10 (ACI, 2010). The fundamental difference in the new approach is in the curing regime.

The new approach states water curing cools the concrete surface rapidly and concentrates on prevention of thermal cracking that can occur due to thermal differences between a cooler perimeter and a hot core.

In general the new approach promotes use of pozzolans, reduction of cement content for control of heat of hydration, as well as controlling delivered concrete temperature by way of shading or evaporative cooling of aggregates and use of ice or liquid nitrogen, if warranted. The internal temperature of concrete is not recommended to exceed 71 °C (160 F) to eliminate the potential for the occurrence of a phenomenon called delayed ettringite formation (DEF).

In addition to the internal temperature limit, the second criteria is a temperature differential between core and perimeter. This value is typically 19 °C (35 °F) unless revised based on aggregate mineralogy and coefficient of thermal expansion (Bamforth). The recommended method of curing to prevent rapid drop of temperatures involves insulation of the concrete surface and use of moisture retentive barriers or curing compounds as a method of curing. The recommended method of curing with insulation is counter intuitive for mass concrete placements that generate heat, however, it is intended to control temperature drop of the surface, unlike the water curing method.

Development of the Thermal Control Plan

A commercially available system, Quadrel TM was used in development of the thermal control plan recommendations (CES, 2010). This system incorporates the adiabatic thermal measurement for the concrete mixture, concrete delivery temperature, member dimensions, expected ambient temperature ranges during and following placement, and insulating values of forms and blankets as input. The associated software aims to develop a simulation of thermal profiles for a given set of parameters in an effort to develop thermal control plan specifics such as duration of protection, extent of insulation etc. The simulation allows sensitivity analysis by modifying input parameters and observing the effects on the outcome, in an effort to identify a combination of parameters that are achievable and provide the desired outcome.

The thermal control plan aimed to protect the concrete against thermal cracking by an insulation regimen, over the prescribed protection period, under the given ambient conditions, while satisfying the two objectives of core temperature and temperature differential.

Upon completion of the thermal control plan the upper limit for placement temperature was determined to be 80 °F (27 °C). Under standard operating measures, the supplying concrete plant was producing concrete just under 90 °F (32 °C) during the heat of the summer season. It was therefore decided to use manually loaded ice as a replacement to batch water and that the placement be performed at nighttime.

In addition to the 27 °C (80 °F) placement temperature limit, an ambient daily temperature range of 16 – 38 °C (60 -100 °F), typical wind speeds, and insulating values of forms and blankets (R value 5 °F-ft²-h/Btu) were input into the simulation. Upon completion of the simulation, as shown in Table 2, under daily temperature range of 16 – 38 °C (60 -100 °F), concrete placed at 27 °C (80 °F) was predicted to reach a maximum internal temperature of 67 °C (152 °F). (CES, 2010)

The insulation was required to be kept on the structure for a minimum of 7 days to maintain temperature gradients within the established differential limit. This period was coincident with the specification required curing period which could occur concurrently with insulated protection.

Table 2. Maximum internal temperatures and required insulation period for 16 – 38 °C (60 -100 °F) daily temperature range.

Daily Ambient Temperature Range, °F	Concrete Placement Temperature, °F	Time to Reach Max Temp, hours	Max Temp, °F	Number of Insulation Blankets Required	Time to Remove Insulation, days
60-100	60	54	132	1	5
60-100	70	49	142	1	6
60-100	80	40	152	1	7
60-100	85	38	157	1	9
60-100	Greater than 85	Not Recommended			

Figure 4 shows results of one of the simulation runs. Based on the results of the analysis, insulation can be removed and the protection can be terminated after 7 days, when the temperature of the surface and core have reduced relatively and somewhat converged. The analysis suggests upon removal of the insulation, the temperature of the surface would start to demonstrate more pronounced fluctuations in response to the ambient temperature fluctuations, however this would not constitute a violation of the temperature differential limit since the core values have dropped as well. If the concrete was not insulated during the early age period, the exterior temperatures would rapidly drop and approach 16 – 38 °C (60 -100 °F) range. The rapid reduction of the external temperatures would constitute a large temperature gradient relative to the hot core at the time and impose thermal strains on the concrete that is of relatively young age and of lower strength.

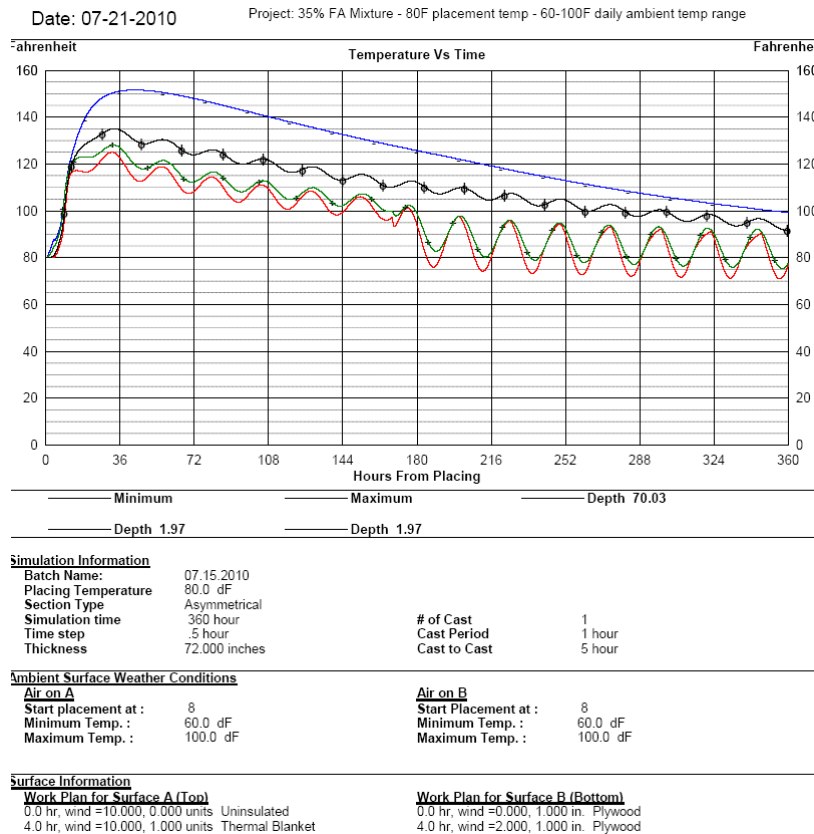


Figure 4 Simulation run for 16 – 38 °C (60 -100 °F) ambient temperature range and 7 day protection period and 80 F placement temperature

Temperature Monitoring Locations

In order to monitor temperatures following placement, the two largest beams were equipped with temperature sensors, typically used for maturity metering per ASTM 1074 (ASTM, 2010). Sensors were placed at perimeter and core locations (Figure 5), (CES, 2010). Figure 5 shows typical sections of beams with varying width and a minimum height of 2.1 meters (7 ft).

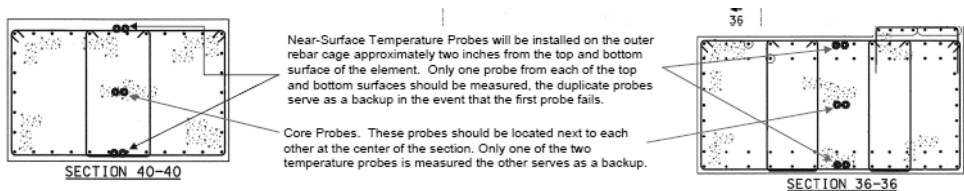


Figure 5 Monitoring Locations

EXECUTION OF CONCRETE PLACEMENT

Concrete Placement

The thermal control plan and the associated analysis required a placement temperature no higher than 27° C (80 °F) and that the placement be performed at night with use of ice to achieve this placement temperature. Figure 6 shows the placement during night time.



Figure 6 Nighttime Placement.

Due to the hot summer ambient conditions, the aggregate stockpiles were sprayed during the day to benefit from evaporative cooling. Up to 75 % of the batch water was replaced with ice during batching. Concrete temperatures were monitored both during the record testing as well as in-situ by the field crew using manual infrared thermometers. Figure 7 shows concrete in-situ temperature after running through the pump, measured at 25 °C (77 °F).



Figure 7 Concrete temperature in the form during nighttime placement.

After the concrete placement was complete, a curing compound was applied and the concrete finished surfaces as well as the vertical surfaces of the side forms were insulated for a period of 7 days per the requirements of the thermal control plan.

Monitoring

Sensors were placed at the pre-determined locations, fixed to the reinforcing steel cage, or supported on dedicated supports and activated prior to the placement. Sensor cables were extended to a central location for monitoring and a communication box fed the data to the dedicated computer at the job-site office over the cell phone network.



Figure 8 Maturity sensors and centralized monitoring junction box.

The measured data was monitored and reviewed periodically at half hour intervals. This real-time monitoring provided site crew the ability to react and modify the extent of insulation if temperatures were observed to exceed the prescribed limits.

The temperature data indicated that maximum temperatures did not exceed 71 °C (160 °F) which is the limit for prevention of occurrence of DEF. (Figure 9). The measured data was in general agreement with the simulated temperature values. It was noted that the measured perimeter temperatures exhibited fluctuations following ambient temperatures, as forecasted by the simulation. The measured data also indicated that the temperature differential between core and perimeter did not exceed (25 °F) and was generally controlled within the prescribed limit.

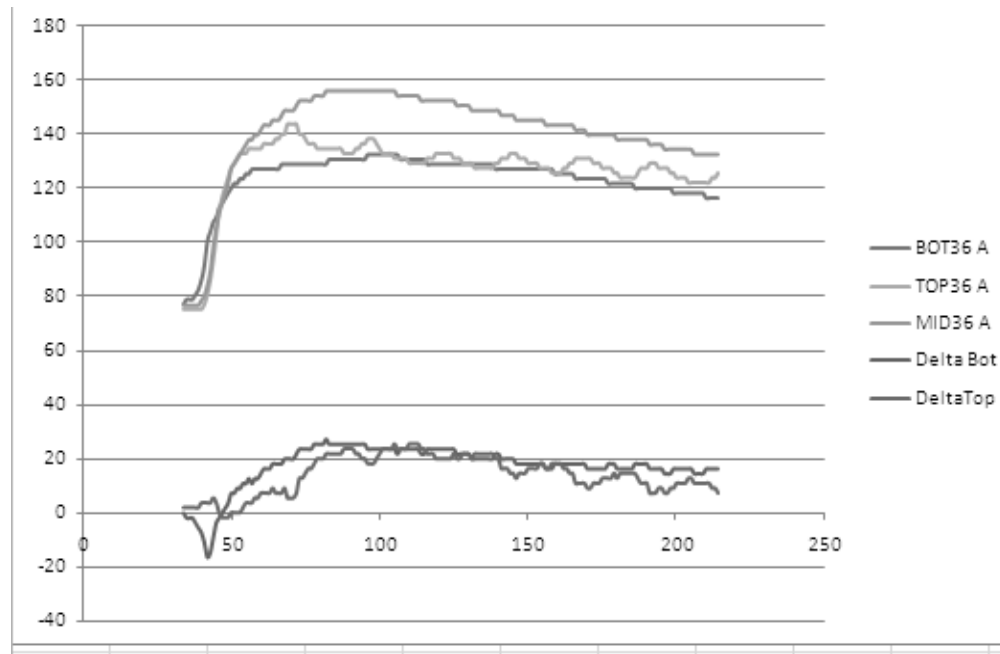


Figure 9 Measured temperatures.

Conclusions and Recommendations

The measures developed as a result of the thermal control plan and the associated analysis enabled a controlled reduction of the concrete temperature. If insulation regime was not adapted, temperature differentials between core and exterior could have exceeded the prescribed limit. In general maximum internal temperature and the temperature differential was kept within the prescribed limits. Temperature levels were monitored during the protection period and following the protection period using maturity sensors. Real-time monitoring provided the capability to react and modify the extent of insulation if temperatures were observed to exceed the prescribed limits. The placement and protection period was completed successfully with no apparent thermal cracking and without exceeding the limits on temperature magnitude and differential.

The planning leading up to the placement contained several stages. During the laboratory phase, the heat of hydration was reduced based on the modifications made to the concrete mixture particularly in pozzolan replacement rate. Subsequently, measures such as evaporative cooling of the aggregates, use of ice, nighttime placement enabled reduction of the placement temperature. These measures were effective in preventing the concrete from reaching detrimental temperature levels which could lead to formation of DEF. The thermal simulation utilizing, adiabatic heat rise, member sizes, insulation properties, ambient conditions as input provided estimates of the expected core temperatures and temperature gradients. While the core temperatures were kept under control with mixture modifications and delivery temperature reduction, the temperature gradients were controlled with the insulation regimen following placement. The laboratory study contained two replacement rates of Class F fly ash. The laboratory findings presented herein can be confirmed and expanded with higher replacement rates or other supplementary cementitious materials.

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SHEAR TESTING OF RCC AND OTHER CONCRETE BLOCKS

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ABSTRACT

Shear testing using large concrete or RCC specimens is not commonly done. The equipment and manpower required to produce the required concrete volume and the apparatus required to restrain and apply loads can be quite substantial. All are beyond the market capability of most testing organizations. However, large projects may realize significant benefits if properties of concrete from testing of large specimens can be determined.

This paper will provide general guidelines for when large specimen testing may be advantageous and specific examples of shear testing of large specimens. It will also provide recommendations on practical measures to implement when organizing such testing. The presentation is illustrated with an example of a project where production and testing of large shear specimens has been done. The example is from an RCC project where biaxial shear and direct tensile testing has been done. This is not intended to be a case study but a guidance document that may be applied to future projects.

INTRODUCTION

Concrete testing may be performed for many reasons. Often, testing is performed in order to assess workability or to confirm strength performance. Testing may be conducted as part of a program to assess or optimize the locally available aggregates or cementitious materials for a specific project or it may be performed in an effort to characterize properties for use in design. Testing is normally performed using standardized test methods developed by organizations such as ASTM and AASHTO in the United States and numerous other standardization organizations in other countries (see references). Use of these standard methods provides confidence that effects from external variables such as testing equipment, sample size, curing conditions and testing procedures are controlled in a manner that assures that the test is performed consistently and that results are the same regardless of where or by whom the test is performed.

The vast majority of concrete testing is done on relatively small specimens such as 6-inch by 12-inch (150mm by 300mm) cylinders, 6-inch (150mm) cubes, and 4-inch by 4-inch (100mm x 100mm) beams. Since aggregate size in most concretes is often less than 1-

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inch (25mm) maximum size, even smaller test specimens are used. The most commonly performed tests on hardened concrete include unit weight, compressive strength, splitting tensile strength, flexural strength, and Young's Modulus. Some of these tests, including direct tension, are performed on concrete cores that typically range up to 6-inch (150mm) diameter in size.

There can be conditions where the properties of specimens fabricated on a small scale can be significantly different than properties measured on a larger scale. This is loosely analogous to the difference between rock properties and rock mass properties. However, in the rock mechanics field, it is usually impractical to perform tests on a rock mass thus requiring the use of empirical relationships to relate rock properties to rock mass properties. However, the fabrication and testing of large-scale concrete specimens is not impractical and thus provides a means to determine more realistic "concrete mass" properties rather than relying on empirical approaches that are not necessarily reliable for concrete applications and that can ultimately lead to overly conservative and more costly designs.

In general, testing of larger specimens should be considered when one of several conditions exists:

1. If concrete is to be produced that has an aggregate size larger than 2-inch (50mm) and the effect of screening the concrete sample to reduce the maximum aggregate size is not desired, then larger specimens are required to meet the aggregate size to specimen dimension ratios. However, there are many mass concrete applications where aggregate size is 2-inch (50mm) or smaller where large scale testing must be done. See items 2 and 3 below.
2. Related to aggregate size are specimen mold edge effects. The presence of an edge results in the alignment of the aggregate along the edge and thus changes the performance of the concrete in that location. Coring is one way to reduce the edge effect; the fabrication of larger specimens is another. It should be noted that using larger specimens does not completely eliminate the edge effects, but it can significantly reduce the effect by simply reducing the ratio of surface area to specimen volume.
3. If construction processes are believed to affect the properties of the concrete, a larger sample that allows the construction process to be simulated is necessary. This can also be considered a scale effect. The size of the construction process may change how a sample performs compared to its fabrication in a laboratory environment. Scale effect will be discussed in more detail in subsequent paragraphs.

Large-scale concrete testing should be performed whenever the specimen or test placement size matters. When the properties of the concrete are critical to the performance of the structure and conservative estimation of the property may have an adverse effect on another property, then large-scale testing should be considered. For

example, in a concrete dam raising project, when placing a new concrete mass on top of and against an existing concrete mass, it is critical to determine the properties of concrete at the bond interface. However simply increasing the cement content to increase strength well beyond what is required has the adverse effect of creating a mass that will generate excessive heat due to cement hydration, disparity in Modulus of Elasticity, and creep rate changes that create adverse cracking through the structure and along the bond interface.

Due to concerns regarding edge and scale effects, the evaluation of shear strength is more appropriately performed on large size samples – usually large sawn blocks with a shear failure plane area ranging in size up to 12 inches by 12 inches (300mm by 300mm). Shear strength is a critical design consideration for dams and other large massive structures, especially when evaluating bond strength between old and new concretes, bond between successive concrete placements, bond between successive RCC lifts, or bond between differing concretes. Large shear specimens are commonly sawn from laboratory fabricated test panels, full-scale test sections, existing structures, or in the case where tests are performed to confirm in-situ properties samples can be sawn from newly completed construction.

Other examples of large-scale concrete testing may include:

- Large sized beams and cylinders – For projects with aggregate larger than 2 inches (50mm), fabricating larger cylinders has been done. Cylinder sizes of 9 inches by 18 inches (225mm by 450mm), 12 inches by 24 inches (300mm by 600mm), 18 inches by 36 inches (450mm by 900mm), and 24 inches by 48 inches (600mm by 1200mm) have been done on a number of projects. Typically cylinders are tested for unconfined compressive strength and for creep. In addition, triaxial testing of some specimens has been done. Casting large beams is done for large projects to determine tensile strain capacity. Beams measuring 12 inches by 12 inches by 72 inches (300mm by 300mm by 1800mm) are most common.
- Tremie concrete – Testing to determine flow and other characteristics of tremie placed underwater concrete requires large-scale equipment to properly simulate actual field conditions. Unless the testing is performed in the field under actual job conditions, testing can be performed in a laboratory or test area using suitably large sized tanks, tremie pipes and the means for concrete delivery. Testing may include evaluation of flow, density, strength, setting time, bond strength to foundation rock, thermal characteristics, etc.
- RCC test sections – RCC test sections and special test pads can vary in size from 2-5 lifts up to 20 lifts in thickness; and they are sufficiently sized to accommodate full size equipment that is planned for use in the construction. Generally, test sections are initially constructed as part of a construction project in order to demonstrate the suitability of the Contractor's equipment and methods and to assure that specified construction methods are achieved. However, test sections can also be constructed as part of a testing program to evaluate new or proposed construction methods, concrete mixtures or other materials. Following construction of the test section, cores ranging

to 10 inches (250mm) in diameter or sawn block samples are removed and tested to confirm performance under field placement conditions. Tests on these samples can include shear and direct tension, density, compressive and flexural strength tests.

KEY ELEMENTS

If shear and other large-scale shear testing can benefit the design and execution of a project, consideration of the following general elements and specific issues is recommended.

In general, there are four key elements to performing a successful test program where large-scale testing of concrete is to be done. Not surprising is that these elements are common to most any concrete testing program.

1. **The Plan.** A good plan is integral to a successful project. Large-scale testing is often much greater in scope and complexity than normal day-to-day testing, requiring different equipment, personnel, and processes. All require specific consideration, validation, and confirmation that the operation will be properly executed. An often-missing part of a good plan is the contingency considerations regarding what should be done if any element fails to perform as required.
2. **Materials Expertise.** Testing large-scale samples requires the talents of a number of disciplines. Of particular note is the concrete materials specialist. Typically, most laboratory staff is expert in the performance of specific tests. However, they generally do not have expert knowledge in the performance of materials nor are they expert in construction equipment and methodology. Since large-scale testing is outside the scope of most normal testing, the contribution of a concrete materials specialist should be considered a critical element in the large-scale testing program. The concrete materials specialist should provide assistance in development of the testing program plan and should also provide assistance and oversight in fabrication and construction of test sections or large-scale samples and in the testing of the large-scale samples.
3. **Parameter selection and evaluation.** When designing a test program, a careful evaluation of all test parameters and influencing variables must be performed. Conditions must be controlled so the influence of unwanted variables are eliminated or minimized and that only those variables or characteristics under consideration are evaluated. Although it may seem obvious, the test must provide the information for which the test is being performed! Equipment used to fabricate specimens must be of an appropriate size to produce representative samples. Consider for example a large test section constructed using equipment that does not adequately consolidate the RCC. In this case can you be certain that shear or direct tension tests on lifts joints are representative? In addition, a sufficient number of tests are necessary to yield reliable results. For example, is a single test sufficient or should two or three tests be performed? In the case of a full biaxial (normal and confining load) shear test with at least 3 confining loads, this can mean 3, 6 or 9 specimens should be tested to evaluate

the shear strength for the range of confining loads. Lastly, key parameters should not be assumed. For *example*, it should not be assumed that samples would be properly fabricated, cored, sawn or transported. These are all aspects of the test program that require careful consideration and oversight during the testing program because they can all have significant detrimental effects to test results.

4. Laboratory equipment and staff. It is unlikely that a large-scale test program can be conducted with the same equipment used for normal testing. The program may require a larger mixer, small loaders to handle and batch materials, and more use of forklifts. Similarly, more manpower will be required to perform the work. It is not good practice to utilize unskilled labor for this function. Even though the scale is larger, the use of good laboratory practice and consistent processes is necessary as in any laboratory program.

SOME KEY CONSIDERATIONS

The following specific issues are discussed in more detail since they can have an appreciable impact on implementing the test program and may significantly impact test results.

Select Appropriate Lab Scale

The scale of testing generally refers to the size or quantity of concrete batches required, the size and number of concrete specimens to be fabricated, or both. A large-scale of either concrete quantity or number of specimens can overwhelm the normal laboratory staff. The most obvious question when considering large-scale testing is how big to design the scale of the testing. It is critical that equipment and personnel be appropriate for the scale of the program. Underequipped and understaffed operations will almost always result in poor performance. Schedule delays, poor uniformity and consistency of results, and non-timeliness of reports are common symptoms of a laboratory operation that is overwhelmed.

It is always necessary to evaluate the available equipment and staff and determine what scale of testing program is suitable. Consideration should be given to determine what additions could be made to increase the scale of the testing. Simply adding or replacing the mixer with a second or a larger mixer may provide the additional required capacity along with additional manpower to deal with the mixed product and specimen fabrication. Further scale increases may require modification to the entire material handling process utilizing greater reliance on mechanized systems.

Not all evaluations are appropriate at every scale of testing. Detailed evaluation of the effect of materials, proportions, and temperature conditions should be done in a controlled environment where many of the other variables are carefully controlled. Such evaluations are suitable for the laboratory using batch sizes that allow for good control of processes and elapsed time. When the scale increases and the specimens are fabricated outdoors or using production grade equipment, the control of many variables is more

difficult and the ability to evaluate subtle differences in materials and proportions may not be possible.

Control the Testing Variables

Regardless of the scale of the testing, the control and evaluation of variables is critical. The general approach that should always be used is to change one variable at a time and assess the effect of that change on the particular set of tests performed. It is rarely a good idea to change more than one variable since it is difficult to isolate which variable was dominant.

In order to evaluate variables singularly, a wide range of external variables must be controlled during the testing process. External material variables could include material type such as crushed or rounded aggregates, aggregate quality and gradations, aggregate moisture content, cement and pozzolan type and content, water quality, and temperature. External process variables might include mixer type and size, batch size, batching sequence, mixing time, discharge process, transport and placement of concrete, specimen acquisition (sawing, coring), and curing.

Mixing the Concrete

Many operations converge to create a mixed concrete product. One of the key operations is the mixing process with its many inherent factors. Mixer size, shape, blade configuration, rotation speed, drum angle, surface texture are a few of the factors for drum mixers. Incomplete mixing has surely been the cause of variable performance of mixtures in testing programs.

Mixer experience is one primary method of validating the performance of a mixer. If past testing programs have shown good performance and results show good uniformity, it may be concluded the mixer is performing adequately. This conclusion requires that future uses of that mixer utilize the same or better processes to batch and mix materials for subsequent testing and that batch sizes are consistent with what has worked well in the past. Absent good experience with laboratory or trial mixer uniformity, uniformity testing should be part of the validation process.

At times, it may be necessary to quantify the uniformity of the mixing process. Mixer uniformity testing has been standardized and can be used to evaluate mixer performance. It is a less than ideal test but to-date is the only practical test for most applications. Mixer uniformity testing can be performed on either batch or continuous mixers. The uniformity test consists of evaluating various portion of a batch or various samples from a continuous mixer to assess concrete uniformity based on properties such as slump or vebe consistency, density, air content, and compressive strength.

Internal shaft mixtures are more appropriate for mixing no-slump concrete and RCC than drum mixers. This is because drum mixing is a plunging flow process that is a mechanism that does not occur in RCC or no-slump concrete because of the less fluid

consistency of the material. However, drum mixers have been used extensively and continue to be used for mixing RCC and no-slump concretes in laboratory settings with some accommodation such as using a reduced mixer capacity, scraping mixer sidewalls periodically during the mixing cycle, and manually remixing the concrete after discharging from the mixer.

Fabricating Specimens

The uniform and timely fabrication of test specimens is a key component in achieving good results. Specimens, especially large specimens, require a very uniform process so the materials in the specimen are consistent from top to bottom. When using tampers, hammers and rollers to consolidate samples, molds or containers must be sufficiently rigid to assure complete consolidation. Testing standards generally require specimens be fabricated in layers and with large specimens more time and effort are required to fabricate each layer. It is critical that process be the same for each layer and the same from specimen to specimen. In addition each specimen must be consolidated in a timely manner and ideally each specimen should be consolidated at about the same time after mixing. Time limits to complete the fabrication of specimens are established because of the increasing difficulty to consolidate specimens as the concrete mixtures begins to set. This is difficult to accomplish when numerous large specimens are required but is very important in order to obtain consistent results. It may be advantageous to reduce the sample size and increase the number of samples to match a longer duration of sample fabrication. As a general rule, better results are achieved if specimens are fabricated more quickly.

Density testing of large specimens after initial fabrication is difficult to check and is more commonly done on the hardened specimen at or near the time of testing. Similarly, the density of sawn blocks or core specimens is normally done at the time of testing.

Moist curing of any specimen starts immediately after fabrication of the specimen. It may be as simple as placing a plastic cover, a wet towel, or wet burlap over the specimen. Large specimens are often immediately placed on a pallet so subsequent movement can be done by forklift. Movement into the cure room by forklift is often done immediately allowing the specimen to be undisturbed until the time of testing.

Sawcutting, Handling, and Protection

It is common for large-scale testing to utilize sawn block or core specimens from test slabs, test sections or from existing structures. Each presents challenges. The primary caution is to use care, care, and more care. The large specimens are heavy and awkward to handle. They normally require a forklift to raise, lower and transport specimens. Extreme care must be used to avoid tipping, dropping and banging specimens. Specimens are often banded with banding material to both hold and lift specimens in a manner that minimizes damage to blocks and lift joints.

Specimens are normally sawn or cored from test sections at 28 days of age or greater. The compressive strength of these specimens may be quite low depending on the type of mixture. The specimens can be easily damaged, edges (for blocks) dinged, and if dropped or tipped, the specimen can fracture.

Again it is necessary to avoid drying. The specimens should be kept covered continuously with a wet towel or burlap in order to maintain proper moisture conditions. Failure to do so can have potentially adverse impacts to tensile strength and related parameters.

Know the Stress Environment; Control the Load

Testing large specimens may require the design and fabrication of specialized test equipment. This can include load frames, hydraulic systems, and instrumentation systems. Load systems can be static or dynamic and load application can be either constant stress or constant strain or some other variation. Each has application for a specific type and range of tests and the load system should be compatible with the type of test to be performed.

Large specimens, by virtue of being large, often require large loads during testing. These large loads can release significant energy when the specimen ultimately fails. The system should include features to prevent catastrophic effects upon failure. Stiffness of the system may provide the necessary protection of the load frame by limiting deflection but more active protection measures such as guards or shields may be necessary.

The rate that load is applied to the specimen can significantly affect test results. Shock loading can result in premature failure of the specimen or erroneous results. The slow application of load allows for seating of the specimen and uniform restraint of the specimen. Test methods often provide a range for the rate of loading. It is advisable to operate in the low end of this range during the early stages of the test.

Collect Enough Data

Different tests require different approaches to data collection. The testing of large specimens usually includes the use of transducers and data collection systems. Many systems exist. Analog systems are where data is recorded from a dial gage readout where peak readings are annunciated on the gage. This is suitable for single-point peak reading type measurements. They include compressive strength, tensile strength, and shear strength.

Digital data collection systems are commonly used in applications where numerous data points are required such as when load rate application and load deflection relationships must be recorded or where multiple readings and a frequent reading interval are required.

Load cells and pressure transducers are capable of collecting load data as slowly as 1 reading every few seconds to many thousands of readings per second. Data acquisition systems can be matched to these devices that very precisely display the data.

It is necessary to properly match the data frequency with the property being measured. If clear definition at the time preceding and following failure is necessary high frequency of data recording is necessary. Conversely, it may be necessary to select a sampling interval or program a filter whereby data is collected at a much-reduced frequency. It is very easy to collect more data that can be easily processed.

Content of the Report

Typically the testing standard will provide the requirements for report content. Where a standard does not exist, similar standards exist that provide an example of report content. Guidance suggested by some organizations regarding testing documentation is to prepare documentation and reports with enough detail that a third party can repeat the test and achieve the same results. Others suggest that testing reports should provide at least enough definition and explanation to instill understanding to the reader on how work was done.

At a minimum, the report should include the following information:

- Purpose of the test
- Equipment used
- Methodology of test
- Sample conditioning
- Test results
- Required computations

CONCLUSIONS

This paper provides guidelines for when large specimen testing may be advantageous and recommendations on practical measures to implement when organizing such testing. It is important to recognize that large-scale testing should be considered when concrete properties are critical to performance and where conservative estimates may have adverse effects on other key properties or cost - there are certainly conditions where the properties of specimens fabricated on a small scale can be significantly different than properties measured on a larger scale. Key elements of a successful evaluation and testing program include developing a comprehensive plan, including the appropriate concrete materials expertise, evaluation of influencing variables, selection of test parameters, and performing the work in a properly equipped and staffed laboratory facility. Good laboratory practice and consistency of testing cannot be overstressed since mixing, fabrication, moisture conditioning, handling, saw cutting, and testing methodology can significantly effect test results. Schrader (2003) provides an example of shear testing for Dam applications. The following example is a project where production and testing of

large specimens has been done. It can be used as a guidance document that may be applied to future projects.

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Schrader (2003), Schrader, E.K, and Rizzo, P. C., Extensive Shear Testing for Saluda Dam Roller Compacted Concrete, Roller Compacted Concrete Dams, pp. 1045-1056, Swets and Zeitlinger, Netherlands, Lisse, ISBN, 90 5809 594 9.

EXAMPLE OF A LARGE-SCALE SHEAR TEST PROGRAM

A large-scale testing program, USACE (2006) and Bombich (2006) was conducted for the design of Portugues Dam, a Corps of Engineers gravity arch dam near Ponce, Puerto Rico. The purpose of the testing program was to evaluate effects of fly ash, retardation, joint maturity, and fines content on RCC lift joint performance. Lift joint performance was quantified by testing RCC across lift joints in direct tension, splitting tension, and biaxial shear.

Each variable was evaluated by constructing a test panel measuring 46 inches by 72 inches by 12 inches (1.2m by 1.8m by 300mm) thick. Each panel was constructed in two 6-inch (150mm) lifts using varying lift joint treatments. RCC was consolidated using a small single-drum vibratory roller. Samples were removed from the panels by drilling 6-inch diameter cores and sawing 10-inch (250mm) square block samples. Photographs of the test panel construction and testing and charts of typical test results follow.



Figure 1 – Forms and bracing for RCC test panel



Figure 2 – First lift of RCC placed in test panel form



Figure 3 – Compacting RCC lift with single drum vibratory roller



Figure 4 – Applying bedding mortar joint treatment after joint surface has been exposed for required time at designated temperature



Figure 5 – Continuous wet curing of complete test panel



Figure 6 – Sawcutting test panel into test blocks and elements for core drilling



Figure 7 – Core locations for tensile testing specimens



Figure 8 – Prepared specimens for direct tensile testing

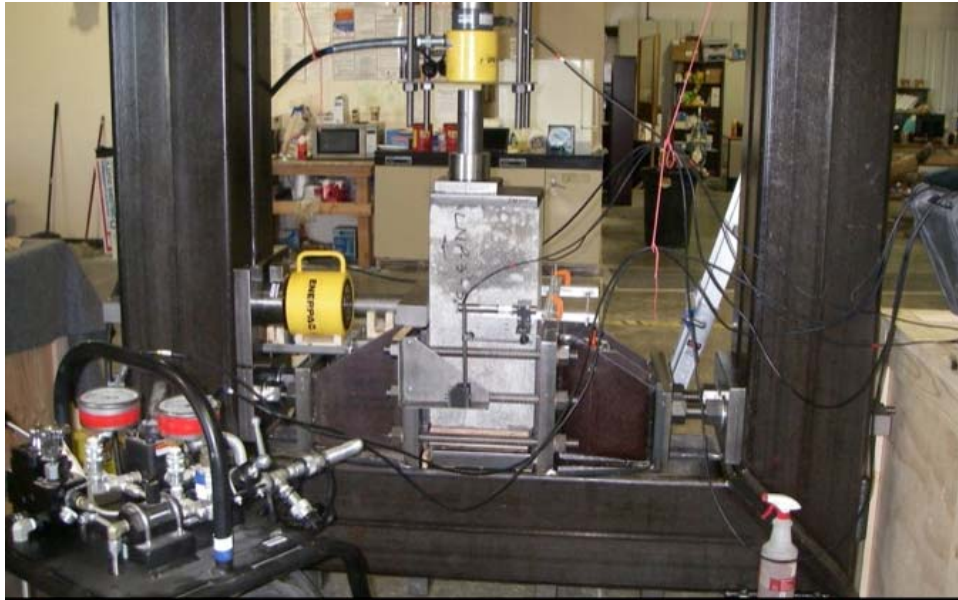


Figure 9 – Biaxial shear testing configuration



Figure 10 – RCC block after completion of shear test at a lateral displacement of 0.5 inches (12mm)

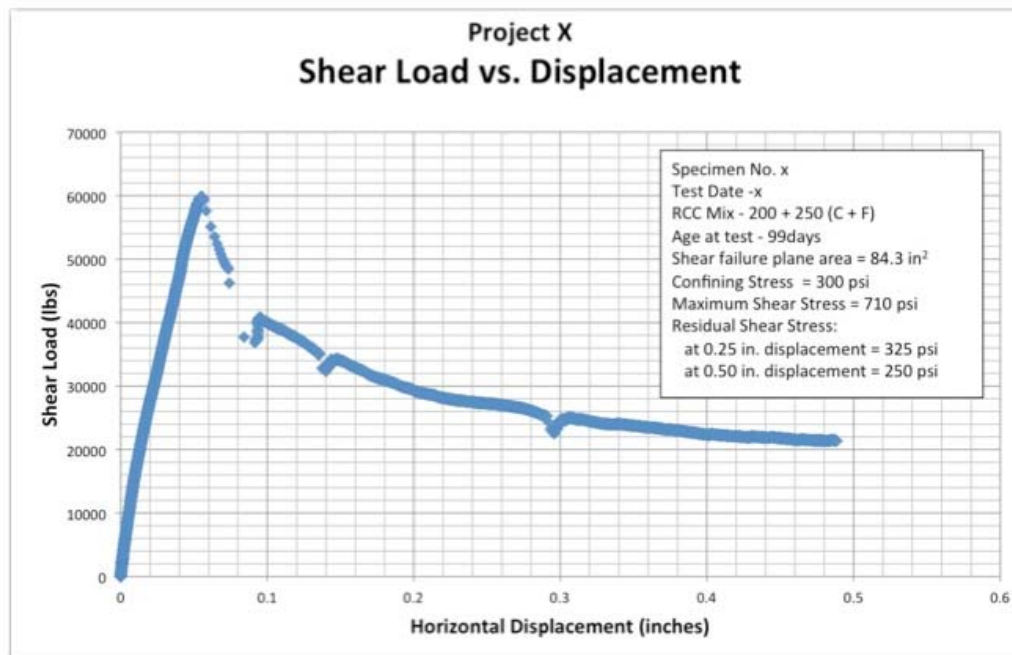


Figure 11 – Biaxial shear test results for RCC lift joint

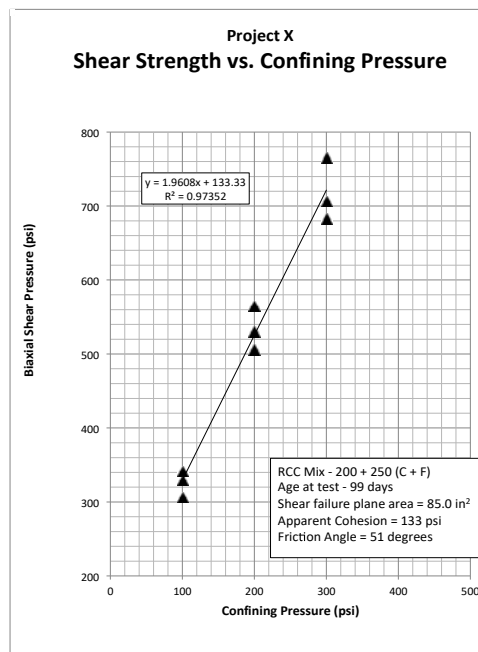


Figure 12 – Example of results of a full series of shear tests

Temperature Predictions of a Ternary Mix Design for Mass Concrete Placements

Joseph W. Clendenen and Benn B Stutrud

INTRODUCTION

The exothermic reaction of the heat of hydration in concrete can lead to problematic temperature differences between the surface and the core of mass concrete elements, which can lead to thermal cracking. This problem has led many engineers to create maximum temperature differential specifications, as well as maximum temperature specifications in response to concerns over producing conditions which may lead to delayed ettringite formation (DEF). In general, there are two solutions to meet this specification: design a mix that has low or an extended heat of hydration or cool the mass element internally as it cures. Regardless of the method, many engineers require that the mass elements' temperatures be predicted for the mix design, dimensions of placement, day of placement, placing temperature, and construction methods including the use of insulation. Therefore, mass concrete mix designs are tested experimentally for heat of hydration and thermal properties, and those values are used in a mathematical model. The following is a description of using Isothermal calorimetry to generate information about a mix design, which was used to input into the thermal modeling.

Isothermal Calorimetry Background

Calorimetry in the evaluation of hydraulic cementitious products is the monitoring of heat generation from the hydration process over time. Isothermal calorimetry, also referred to as isocalorimetry, is a form of calorimetry where the amount of energy required to maintain the sample at a constant temperature is monitored. One of the benefits of this type of system is that it will generally show important, but minor, nuances in the hydration curves, such as sulfate depletion marks and C3A reactions in the first few minutes, that would not otherwise generally show up as well with other thermal profile testing methods, such as the historically named “semi-adiabatic calorimetry”, where the varying temperature of the sample is monitored (see example comparison below on the same cement sample). In addition, isocalorimeter systems typical provide much more controlled and accurate information on the hydration heat production rate and quantity (ASTM C1679 2009).

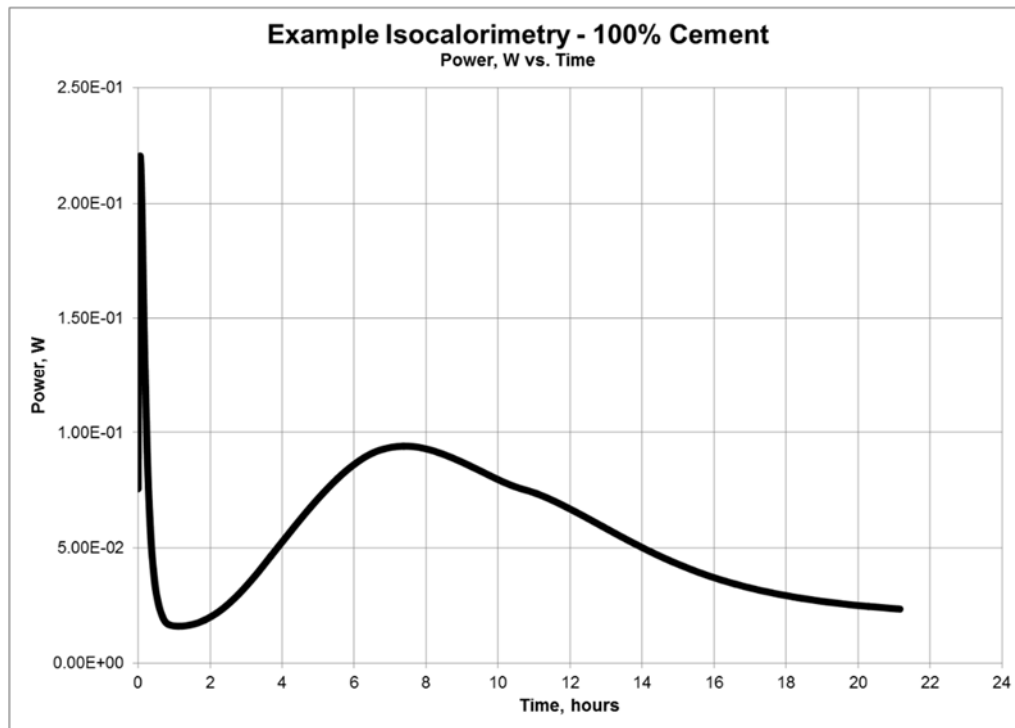


Fig. 1 – Isocalorimetry example, performed on a 100% portland cement sample

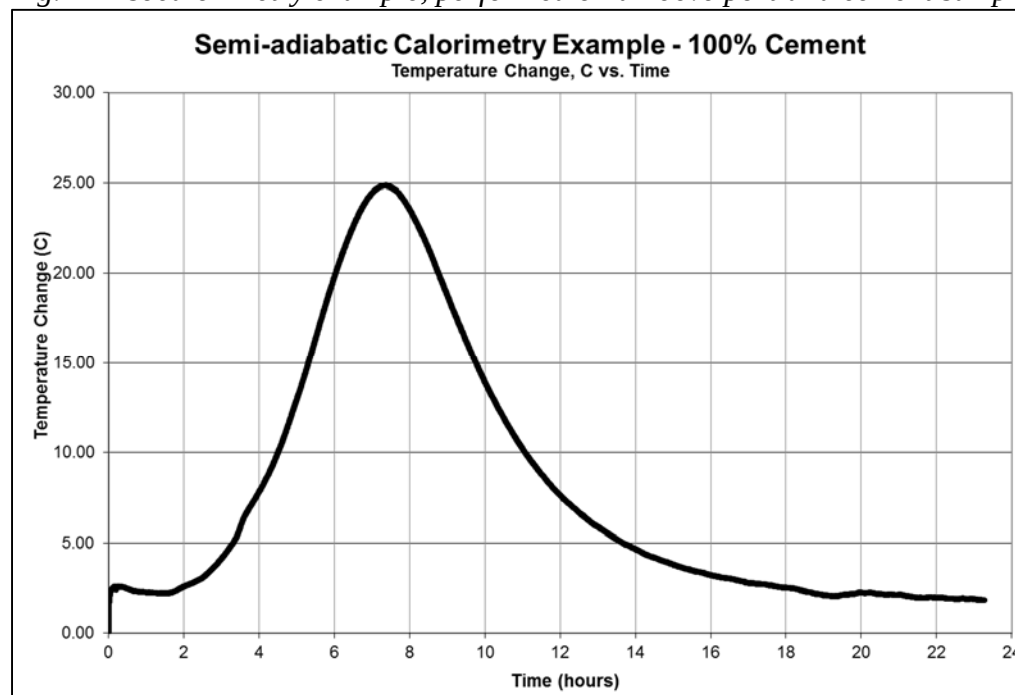


Fig. 2 – Semi-adiabatic calorimetry example, performed on same 100% portland cement sample as Fig. 1

Heat transfer basics

Fourier's heat equation, as shown in Equation (1), describes the flow of thermal energy down the temperature gradient (Maloney 2008). The heat equation is a partial differential equation in three dimensions. For those not performing mathematical modeling, the importance is not the equation itself but the constants associated with the equation.

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + S \quad (1)$$

where

ρ = density, kg/m³;

c = specific heat, J/kg-°C;

k = thermal conductivity, W/K-m²;

T = temperature, °C;

S = heat of hydration per volume, W/m³; and

t = time, s.

Density or unit weight, heat capacity, thermal conductivity, and heat of hydration are inputs that can be experimentally measured for a mix design. For concrete, there are a variety of probes for purchase that measure thermal conductivity. Heat capacity can be measured by varying boundary conditions on a concrete sample. Lastly, heat of hydration of the cement is typically measured by a variety of calorimetry methods.

Lafayette Bridge

In the spring of 2011, construction began on the Lafayette Bridge in St. Paul, MN. The owner, Minnesota Department of Transportation (MnDOT), required that all mass concrete elements have maximum curing temperature of 160°F and maximum temperature differentials of 45°F, 50°F, and 60°F in the first 48 hours, next 2 to 7 days, and next 8 to 14 days, respectively (MnDOT 2010). The reasons for these requirements were the prevention of delayed ettringite formation (DEF) and thermal cracking, respectively. To fulfill these requirements, a high pozzolan, ternary mixture was selected to lower the heat of hydration. American Engineering Testing, Inc. (AET) was responsible for the testing and thermal modeling of the mix designs.

The bridge's mix design for the pier had 55% Grade 100 slag cement and 20% Class F fly ash replacements. The two largest piers were placed in the Mississippi river and each required over 900 yards of concrete. Figure 1 shows the cross-section of these two piers. These stems were assumed to be cured with two thermal blankets and under average ambient conditions for the day of placement. Data was obtained by direct testing for thermal conductivity, thermal diffusivity, isothermal calorimetry, thermal profile testing (formerly called semi-adiabatic calorimetry), and unit weight. The data were then used in a finite element analysis to simulate the mass element's heat generation and dissipation.

temperatures while curing; however, the price paid for these mixes is low initial strengths. Therefore, it is important to understand the maturity development of the concrete, to insure optimal temperatures at a steady hydration rate. Additionally, the mathematical prediction of temperatures for mass concrete placements is becoming a widely accepted requirement. This paper presents on such process of predicting temperatures for two bridge piers and comparing the results to field measurements. Understanding reaction rate is essential for these high pozzolan mixes.

TEMPERATURE MODELING

Isothermal calorimetry procedure

All isothermal calorimetry work was performed at the Holcim (US) Inc. Concrete Laboratory at the St. Genevieve facility, which is located in Bloomsdale, MO. The isothermal calorimetry system used in this study, the Adiacal TC, has the capability of holding constant preset temperatures other than ambient. The Adiacal TC device has 8-channels and is capable of evaluating ~20-50 g of paste samples, ~100 g of mortar samples, and small concrete samples as well (enough to fill a 125 mL chamber cup).



Fig. 4 - Adiacal TC Isothermal Calorimeter.

The standard proportions used for calorimetry work at the Holcim (US) Inc. laboratory is 700 g of cementitious materials at a 0.49 w/cm with any admixtures added to the water ahead of mixing. This is mixed with a hand mixer in a bowl for one minute, whereupon, for isocalorimetry, a 25-50 g sample is taken, placed in a specimen cup, weighed, and placed into the isocalorimeter chamber. The sample weight and the time that the water and cementitious material were placed together is then entered into the system and the sample is analyzed.

In this study, the proportions were modified to model the pier mix used in the mass concrete thermal prediction. An Adiacal TC device was used to monitor the amount of energy required to maintain the mass concrete pier mix evaluated in this study at 4 temperatures (60, 80, 100, and 120°F), and the results are shown in Figure 2.

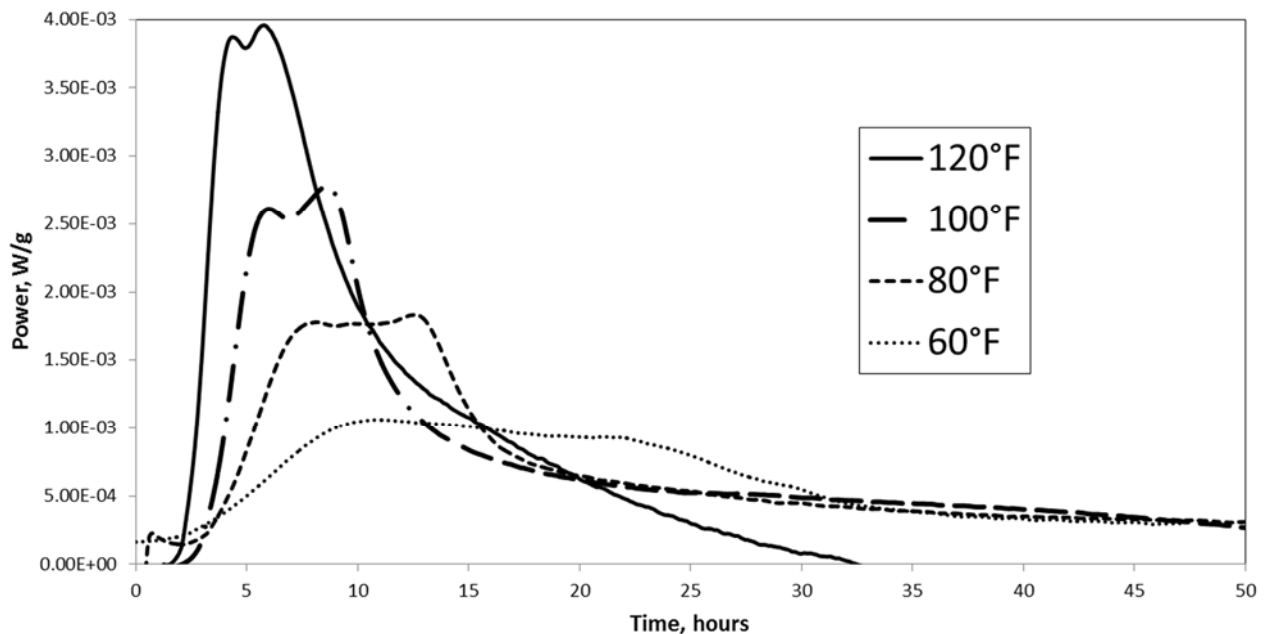


Fig. 5 – Isothermal power results for temperatures of 60, 80, 100, and 120°F.

Degree of hydration and activation energy

To analyze the raw calorimetry data, it is beneficial to convert from power to cumulative energy. Using equation (3), this conversion is simply the integration of power over time. Also, the result of cumulative energy can be converted to adiabatic temperature rise of the concrete, as seen in equation (4) (Tia 2010). The term adiabatic implies that no heat is lost or gained by the system of concrete, which is helpful when considering the maximum temperature rise of the placement. The results of the 80°F isothermal power signature are shown in Figure 3.

$$\int_{t=0}^t P \, dt \quad (3)$$

where

P = power, W/g.

$$\Delta Q \cdot \rho_{cem} = \rho_{con} \cdot C_p \cdot \Delta T \quad \text{or} \quad \Delta T = \frac{\Delta Q \cdot \rho_{cem}}{\rho_{con} \cdot C_p} \quad (4)$$

where

ΔQ = change in energy per gram cementitious, J/g;

ρ_{cem} = density of cementitious in concrete, g/m³;

ρ_{con} = density of concrete, kg/m³;

C_p = specific heat capacity, J/kg-°C; and

ΔT = change of adiabatic temperature, °C.