Mass Concrete Report

San Francisco-Oakland Bay Bridge East Spans Safety Project: Skyway Structure

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INTRODUCTION

Concrete structural elements of the replacement bridge for the East Span of the San Francisco-Oakland Bay Bridge, which include piles, pile cap in-fill concrete, pile cap structural concrete, pier columns, pier table diaphragms, and pier table soffits, meet the American Concrete Institute (ACI) definition of mass concrete. ACI defines mass concrete in part as "any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of cement." Elements such as the pier tables and pier columns are of special concern due to the high concrete compressive strength requirement of 8 ksi.

For construction of these elements of the bridge, thermal control plans to "cope with the generation of heat" will be required. Before proceeding with actual construction of the elements requiring high strength, the validity of the control plan is to be demonstrated by use of a mock-up of high strength mass concrete elements-- e.g. the pier tables and pier columns.

A control plan, and mock-up for the high strength mass concrete elements, is needed for the large concrete elements because heat can potentially compromise the durability of concrete due to temperature induced stresses and possible chemical alteration of cement paste. Induced stresses may cause thermal cracking, including micro cracking, as a result of uncontrolled volume change. Chemical alteration from too high of a peak curing temperature can allow for the potential for delayed or secondary ettringite formations that may occur years later. A high peak temperature can also restrict the hydration process due to self-desiccation. In general, ultimate strengths are lower as curing temperature rises.

For normal strength mass concrete of 4 ksi or less, Caltrans has historically specified the measures to be taken to control or mitigate heat generation of mass concrete. The measures have been primarily limited to the mix design and initial placement temperature. Typically, the mix design measures included keeping the cementitious content under 6 sacks per cubic yard, replacing up to 35% of the portland cement with fly ash, disallowing the use of high performance pozzolans such as silica fume and metakaolin, and using inch and a half aggregate. The initial placement temperature has been kept to either a maximum of 18.5°C (65° F), or 21 °C (70 °F) if all mix water was added as ice. Though these have been the practices used for mass concrete designed to be 4 ksi or less, these measures have also been adequate for concrete achieving actual strengths near 5 ksi.

However, since some elements on the planned new San Francisco-Oakland Bay Bridge structure require strengths of 8 ksi, some of these measures would not be adequate or even possible. Because of this high strength requirement, it is problematic to keep cementitious material content low or use aggregate larger than pea gravel, especially given the congestion of reinforcing steel. In general, high strength concrete is obtained typically by increasing cementitious material content, using high performance pozzolans such as silica fume or metakaolin, and, reducing the maximum aggregate size to that of pea gravel. These typical means for obtaining high strength concrete also increase heat generation.

SOURCE MATERIAL USEFUL FOR THERMAL CONTROL

Two established technical committees useful to the designer and the reviewer of thermal control plans are ACI Committee 207, and, the International Union of Testing and Research Laboratories for Material and Structures (RILEM) Technical Committee 119.

Information on mass concrete generated by Caltrans from mass concrete footings constructed for the new 580/680 interchange in Dublin included in this report may also be useful.

The ACI 207 Committee reports are published as guidelines for construction of mass concrete. The reports discuss the development of construction practices, properties of materials, and thermal behavior of mass concrete. The reports are updated periodically and are published annually in the ACI Manual of Concrete Practices.

RILEM is an international organization working in the field of construction sciences and practices regarding properties of materials and performance of structures. In 1989, RILEM established Technical Committee 119 and published, in 1998, RILEM Report 15 as a book titled <u>Prevention of Thermal Cracking in</u>

Concrete at Early Ages. It is a collection of technical reports edited by Rupert Springenschmid of the Technical University of Munich, Germany.

Of particular interest is Chapter 9 of the RILEM Report, written by Stig Bernander of Lulea University of Technology, Division of Structural Engineering, Sweden. In section 9.3.4,"Measures Related To the Construction Stage", the recommendations include: control of initial temperature, regulation of curing temperatures through the use of artificial cooling and/or insulation, mock-ups to verify hydration and thermal properties of concrete as well as efficiency of cooling systems, and numerical stress analysis. Section 9.5 concerns "medium mass concrete structures" which include large bridge elements having high performance (high strength concrete). The term medium mass is used to differentiate between dams as the traditional mass concrete structures and much smaller structures where thermal effects need to be addressed, especially because of the development towards higher strength and durability requirements. In 9.5.4.1 it says that artificial temperature control is "indispensable" and "internal cooling by pipe-borne water is technically the most effective".

CALTRANS MASS CONCRETE STUDY AT DUBLIN 580/680 INTERCHANGE

As an effort to gain some practical experience and as an aid and source of information for dealing with mass concrete, Caltrans has recently generated some regional information for both normal and high strength mass concrete. Six large footings meeting the definition of mass concrete as part of the current construction of the Dublin 580/680 interchange was used for the study.

Five footings, utilizing the conventional specified 6-sack concrete mix design, having dimensions approximately 10 feet thick and widths and lengths between 25 and 40 feet, were monitored for temperature. These 5 footings are located on the northeast connector at Bents 3, 4, 5, 6, and 10. The mix designs had 25% and 35% replacement of the portland cement with fly ash. The 35% replacement mix had 28-day compressive strength near 5 ksi although the contract requirement was only 3.25 ksi. Cementitious material was a little higher at 6.18 sacks per cubic yard.

For the sixth footing, Caltrans changed the normal strength concrete for construction to a high strength concrete. This footing is located on the southeast connector at Bent 18. This large bridge footing has comparable dimensions to pier tables planned for the new East Spans of San Francisco Oakland Bay Bridge. The dimensions of the footing are 38 feet by 38 feet by 12 feet.

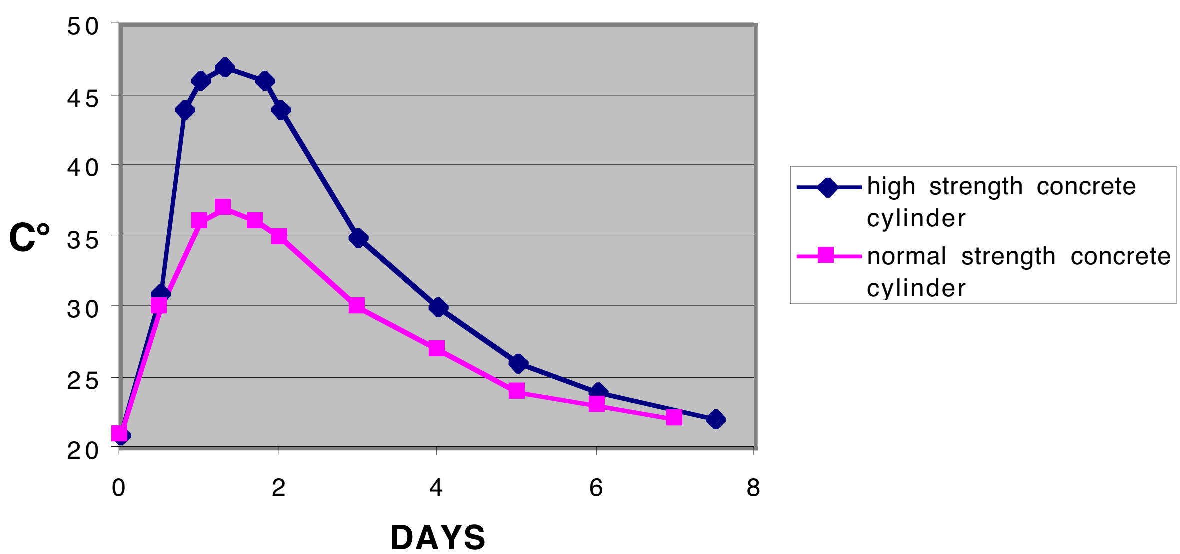
For this footing having the high strength concrete, an internal pipe borne water-cooling system was designed and operated. The design assumptions for the cooling system were based on the predicted temperatures of the mix using a finite element analysis submitted by the cement supplier, and a graphical solution method using the nomograph shown as Figure 5.4.2a as published by ACI 207 in the 1996 Manual of Concrete Practice. One-inch diameter steel schedule 40 pipe was used. The pipes were configured into 3 square coils at the site. The pipes were installed at the same time the reinforcing steel was placed and secured in the same manner as the horizontal rebar. The vertical distance between the three coils was 3 feet. The lateral distance between the longitudinal coil pipes was also spaced 3 feet. Fifteen gallons per minute of water was pumped through each coil. The water was chilled. The temperature of the water was gradually adjusted upward, manually setting a thermostat on the chiller usually at the end of the day, starting at around 40°F (4°C) and ending at around 70° F (21°C). The difference between inflow and outflow varied from a high of 15°F (8°C) during the first few days after placement to a low of 4°F (2°C) on the 8^{th} day.

The concrete mix design was for a 56-day strength of 8 ksi, the design strength of the planned pier table. The design used 8.5 sacks of cementitious material per cubic yard, a high range water reducer, metakaolin as a high performance pozzolan, half-inch maximum size aggregate (pea gravel), and flyash. The actual compression value of samples taken at the time of construction were 6.3 ksi and 6.8 ksi @ 28days, and, 7.4 ksi and 7.8 ksi @ 56 days. The concrete was high slump and retarded so steel forms were used instead of the wood that was used on the other footings monitored. The slump may have been higher then the trial batches causing the strengths to be just under the 8 ksi target.

At the time of the placement of the footing having the cooling system, a sample of the concrete was poured into a 1-meter cube and its curing temperature profile was recorded. It was left exposed to outside environment at the batch plant located about 3 miles from the bridge.

Temperature profiles of 2 concrete cylinders, one high strength having the 8.5 sack mix design and one normal strength having a 6 -sack mix design with 25% of the portland cement replaced with fly ash, are shown in Figure 1. The cylinders were cured and temperatures monitored while in individual curing boxes insulated with polyurethane foam. The high strength mix had a peak temperature of 48° C at about 30 hours while the 6-sack mix with 25% flyash peaked at 37 °C at about 30 hours. By 7 days both samples were back to the room temperature at 22 °C. Though the insulation was not adequate to be near an adiabatic condition,

FIGURE 1: Comparison a High and a Normal strength concrete cylinder cured under same condition



comparisons can be made between the two mixes since the curing condition was the same for both. The high strength mix resulted in a 30% increase in peak temperature when compared to the normal strength mix.

CONCLUSIONS FROM DUBLIN 580/680

A report on the mass concrete work done on footings for the Dublin 580/680 Interchange is attached as an appendix. The report is from the Instrumentation Services Branch of the Division of Materials Engineering and Testing. The report is a record of all the data collected. It includes an overall description of the project, photos, locations and number of the temperature sensors in each footing, tables showing data collected, concrete mix designs used, presentation of the data in graphical form, description of the cooling system used in the high strength concrete footing, and discussion of the equipment and techniques used to collect the data. A future report with more analysis is planned under the general direction of the Division of New Technologies & Research.

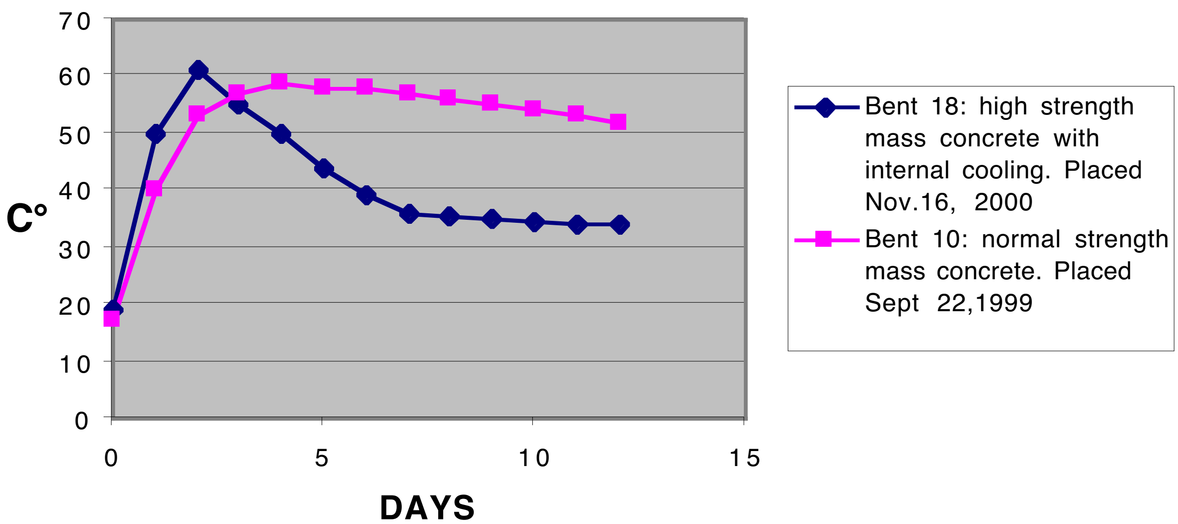
Though no two footings were identical in terms of geometry, form work, or ambient temperature, observations from the temperature time graphs shown in full in the report attached as an appendix give indications as to how the cooling system performed.

Three noteworthy observations and conclusions from the Dublin Study are:

1) ***Degradation of the concrete due to excess temperature did not take place.*** No thermal cracking was observed in any of the footings, and, concrete peak temperatures were kept under 70°C, the temperature that potentially could result in delayed or secondary ettringite formations. The footing having high strength concrete was stripped of its forms on the 8th day after placement. The only cracks observed in this footing were settlement cracks around the top mat of steel. These cracks were observed the first morning after placement, before any significant heat rise in the mass. (These types of cracks are typical on large footings. The cracks are believed to be due to the settlement of the soil under the heavy weight of the concrete, or settlement of the concrete itself due to consolidation. Because the piles support the reinforcing steel, it is prevented from settling with the mass of concrete that is going from a semi-fluid state to a solid state. Revibrating the concrete just before its initial set is called for to mitigate such cracks. However since this mix was retarded the initial set did not take place until much after the shift. There was a fear that there would be a possibility of a vibrator breaking the instrument wires in the concrete because it was dark and late and thus easy to lose track of the wire locations.) There were no cracks in the vertical walls.

2) ***The cooling system effectively removed heat from the mass***. This is demonstrated by two observations of the curves, obtained from sensors near the center of mass, shown in Figure 2. The first observation is a comparison of the relatively steep negative slope of the curve after peak temperature of the internally cooled footing, to the more gradual slope after peak temperature of the normal strength mass concrete footing. Bent 10 was chosen for comparison since it was constructed during the same season of the year. The second observation is that the curve of the water-cooled footing has a steep negative slope after peak and then flattens when the cooling water pump was shut off on the 8th day. The sensor used in Bent 18 curve

FIGURE 2: Comparison of High Strength Concrete with internal cooling to Normal Strength Concrete without internal cooling . Footings Dublin 580/680 Interchange

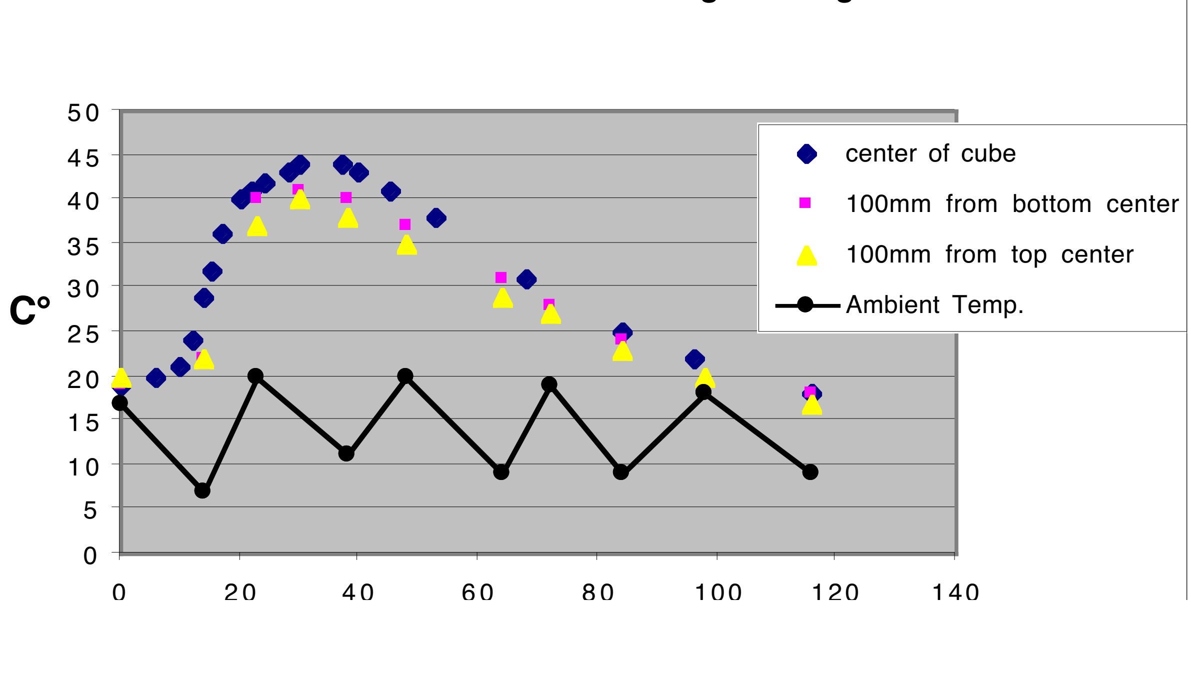


shown in Figure 2 was one near the center of mass, just above the vertical centerline. It nearly split the distance between the 4 closest pipes. It is thermocouple #11 that is found in the Appendix. Thermocouple #10 had a similar location with respect to the center of mass and its surrounding pipes but just below the vertical centerline. Its curve is almost identical to #11. Thermocouples #12 and # 9 were nearer to the top and bottom, respectively, and those curves show the same tendency although not as pronounced. Curves for Bents 3, 4, 5 and 6 are similar to the Bent 10 curve shown in Figure 2. The complete set of curves can be seen in the Appendix.

The slope of the line of Bent 18 in Figure 2 between day 2 and day 6 is approximately –6°C per day. Assuming this to be nearly the temperature removed by the pipes per day based on the observatons of the flat slopes without cooling described above, then the peak temperature for this curve would have been just above 70°C, the critical temperature for delayed ettringite formation. Assuming an 11° C difference in peak between the normal and high strength as shown in Figure 1, then the peak for this Bent 18 curve would be right at the critical temperature of 70°C by adding 11° to the Bent 10 peak of 59°. Also since the curves of the normal strength footings of time-temperature near the center of mass show a slow rate of heat loss, and, the time-temperature curves of the high strength showed the same tendency after the cooling system was shut down, it is reasonable to assume that a much greater temperature differential woud have occurred in the high strength mass concrete footing had there been no internal cooling. Therefore, with no internal cooling internal stresses would have been higher, and thermal cracking likely. Insulating to slow the heat loss on the outside perimeter to mitagate the temperature differential would not have addressed the unacceptable 70°C peak temperature, and at worst increased it.

3) ***The temperature profile of the high strength 1 cubic meter sample suggests that a 1 meter dimension is to small to require any special methods to cope with the heat of hydration.*** Time vs. temperature of the 1M x 1Mx 1M sample of the high strength concrete is shown in the Figure 3. The peak temperature was about 20 °C (36°F) cooler than the peak temperature of the footing even though the footing was artificially cooled internally. Also, the maximum differential

FIGURE 3: One meter cube of high strength concrete



SUMMARY

To ensure the desirable strength, appearance, and durability qualities of concrete are achieved in the mass concrete elements of the new East Span of the San Francisco-Oakland Bay Bridge (as well as the new Benicia Martinez Bridge), attention needs to be directed to the build–up of heat during curing. The exothermic reaction of cement requires the dissipation of heat if the heat is to be kept from affecting the designers' anticipated quality of the concrete element. Practices for coping with excess heat were first developed during construction of large concrete dams requiring relatively low concrete strengths. Recent bridge designing practices now mean the concerns regarding heat in the construction of dams are now also concerns for the construction of bridges. The design for the new bridges incorporate large volume concrete piles, piers, pier columns, pier tables, and footings. The pier tables and columns also require a high compressive strength. Literature sources such as those published by ACI, PCA, or RILEM and Caltrans data are available for information useful in developing thermal control plans for mass concrete.

For normal strength concrete a more or less passive approach can be used. The dissipation of heat can be controlled by slowing the rate of strength gain by replacing cement with normal quality mineral admixture (fly ash); having low initial temperatures so the rock, sand and water can absorb heat; and lowering the cement content to reduce the amount of heat produced. For high strength concrete, as demonstrated by the high strength mass concrete footing at Bent 18 of the 580/680 Interchange, a more active practice such as an internal pipe cooling system during curing appears to be needed.

For Appendix open file "Concrete-Appendix.pdf"