



From Passive to Active Thermal Control

California's transition to cooling pipes for high-performance mass concrete in bridges

BY RIC MAGGENTI

Several recent bridge projects in California have been built using high-strength, self-consolidating, low-permeability concrete, and one project included high-strength, low-density concrete. The heat of hydration produced by these high-performance concretes (HPC) made it necessary to control internal concrete temperatures, not only in large bridge components, but in some surprisingly small components as well. For these projects, embedded pipes carrying cold water proved to be effective thermal control measures (Fig. 1) and are becoming a common method for dealing with the increased heat produced by HPC.

ACTIVE OR PASSIVE CONTROL

ACI 116R-00 defines mass concrete 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.”¹ While this definition does not characterize mass concrete in terms of a specific dimension, the California Department of Transportation (Caltrans), as well as other agencies, has attempted to use minimum dimensions to identify mass concrete for the purpose of determining when thermal controls are needed.² This was effective when specified concrete compressive strengths for large concrete placements were low, but with higher strength concretes, minimum dimensions identifying mass concrete became less predictable.

The methods used to control concrete temperature can be either active or passive. Passive methods control temperature through actions taken before placement. These passive controls may include using supplementary cementitious materials that generate less heat or lowering the concrete temperature at placement by adding ice as part of the mixing



Fig. 1: PVC cooling pipes connected to main supply headers circulate cooling water to control the temperature of the concrete as it cures

water, chilling stockpiled ingredients prior to batching, or cooling the batched concrete with liquid nitrogen. Active methods control concrete temperatures after placement and during or after hardening. These active controls may include the installation of surface insulation or the use of cooling pipes that contain a flowing gas or liquid and act as a heat exchanger within the concrete element.

Before 1999, mass concrete temperatures in California bridges were easily controlled with passive methods because mass concrete was generally limited to large footings and columns that had traditional bridge concrete compressive strength requirements around 24 MPa (3500 psi) and seldom more than 28 MPa (4000 psi). In 1999, solely passive methods were found to be inadequate for designs incorporating higher-strength concretes in large components for three San Francisco, CA, area bridges. Active methods, particularly

cooling pipes, were found to be more appropriate and more efficient.

PRESCRIPTIVE SPECIFICATIONS

Although the dimensions identifying mass concrete in Caltrans bridges had changed through the years, the methods used to control temperatures had remained similar until the recent increase in the use of HPC. From 1978 to 1992, if designers had concerns about temperatures, California bridge specifications identified mass concrete as placements with a minimum dimension of 1.2 m (4 ft). Passive thermal controls were easily employed through prescriptive specifications. Initial placement temperatures were limited to 18 °C (65 °F) when the cementitious material was no more than 335 kg/m³ (564 lb/yd³) with the pozzolan being 15% of the cementitious material by weight. For each additional 4.5 kg (10 lb) of cement or 9 kg (20 lb) of pozzolan above this limit, the initial temperature was reduced by 0.6 °C (1 °F). Also,

the Type II cement's combined tricalcium silicate and tricalcium aluminate content was limited. Field experience showed that these specifications were conservative.

In 1992, the dimension identifying mass concrete was increased to a minimum of 2.1 m (7 ft). When the contractual unit of measure was changed in 1995, 2 m (6.6 ft) was used as a soft conversion to SI units along with a cementitious material content of 350 kg/m³ (590 lb/yd³) with 25% fly ash. Prescriptive specifications remained similar, reflecting common passive controls.³

With traditional bridge concrete strength requirements, control by mixture proportioning and initial temperature limits was relatively easy, and the prescriptive specifications were practical for both the owner and the builder. Temperature monitoring showed that these passive controls worked quite well.

EFFECTIVENESS OF PASSIVE CONTROL

During reconstruction of the Cypress Bridge structures on Route 880 in Oakland, CA, after the Loma Prieta Earthquake, six large footings and one column built between 1994 and 1996 were monitored for temperature. The footings were as large as 9.2 x 14 x 3.1 m (30 x 45 x 10 ft) and the column was 2.7 m (9 ft) square. The mixture proportions required 335 kg/m³ (564 lb/yd³) of cementitious material with 15% fly ash for the column and the first footings. Peak temperatures were no higher than 62 °C (144 °F). In 1996, fly ash percentages were increased to 30% and finally, 40%. The last footing was 3.1 m (10 ft) thick with 40% fly ash, reducing the peak temperature to 52 °C (126 °F) and temperature differentials to about 20 °C (36 °F).

From July to October 1999, five large footings for the 580/680 Interchange bridges in Dublin, CA, just southeast of Oakland, were monitored for temperatures. The footings were 8 to 11 m (26 to 36 ft) wide, 11 to 12 m (35 to 39 ft) long, and 3.1 to 3.7 m (10 to 12 ft) thick. Only the specified passive temperature controls were used. All mixtures had 350 kg/m³ (590 lb/yd³) of cementitious material with either 25 or 35% fly ash. The peak temperatures ranged between 57 and 60 °C (135 and 140 °F), and temperature differentials demonstrated that the passive controls were appropriate.

Other temperature measurements suggested that the 2 m (6.6 ft) minimum dimension criterion was adequate for identifying mass concrete. In October 1999, concrete placed in a 1.8 m (6 ft) diameter steel shell shaft rising to the surface of the Carquinez Straits was monitored for temperature. This new pile for the 1962 Benicia-Martinez Bridge was part of its seismic retrofit. The concrete in the pile had no thermal control and was instrumented with thermocouples. Peak temperature along its central axis at 6.7 and 1.8 m (22 and 6 ft) down from the surface was no more than 50 °C (122 °F). Temperature differentials

between concrete near the steel shell and concrete at the center axis of the pile were less than 8 °C (14 °F).

PRACTICAL EXPERIENCE DESIGNING AND OPERATING COOLING PIPES

In 1999, three upcoming bridge projects requiring higher concrete strengths in large concrete components led to concerns that existing prescriptive passive specifications would not work and that active controls, particularly cooling pipes, would be necessary. The unlimited combinations of pipe size and arrangement, water temperature and flow, and possible combination with other passive controls led to the use of a performance specification. To demonstrate to the contractors that cooling pipes were a viable option, Caltrans designed a heat exchanger made of steel pipes for another footing at the 580/680 Interchange project.⁴

In November 2000, concrete for the 580/680 Interchange footing was changed to a high-strength mixture with 475 kg/m³ (800 lb/yd³) of cementitious material of which 20% was fly ash and 5% was metakaolin. This concrete generated significantly more heat than the mixtures used on the other footings at this site that were of a similar size and had previously been monitored for temperature. Temperature control in this 11.6 x 11.6 x 3.7 m (38 x 38 x 12 ft) footing consisted of 25 mm (1 in.) diameter steel pipe cooling tubes that were installed at the same time as the reinforcing steel and configured into three square coils. A 180,000 kW (50 ton) chiller was used to cool water circulating through the pipes.

The peak temperature was comparable to the other footings on the project with only 350 kg/m³ (590 lb/yd³) of cementitious material and 35% fly ash. A report was written and included with the bid documents on other projects where active controls were expected.⁵

NOYO RIVER BRIDGE

The first Caltrans bridge requiring internal cooling systems was the new Noyo River Bridge located 225 km (140 miles) north of San Francisco. The specified concrete compressive strength ranged from 30 to 40 MPa (4300 to 5700 psi) with low permeability required for elements near brackish water. Bridge construction began in May 2002 and was completed in August 2005. The mass concrete elements included 12 x 33 x 2.5 m (39 x 108 x 8.2 ft) footings, 3.0 m (9.8 ft) diameter columns, 6.2 x 22 x 3.7 m (20 x 72 x 12 ft) bent caps, and 3.5 x 26 x 2.2 m (11 x 85 x 7.2 ft) abutments.

The contract required a thermal control plan that limited the peak temperature to 65 °C (149 °F) and the differential temperature between any two points within the placement to 20 °C (36 °F). Cooling pipes were required in the first placements of the footings, columns, and bent caps. If the contractor proposed a plan that did not use the cooling

pipes and proved that the plan was effective during the first placements with the cooling pipes in place only as a back-up system, the cooling pipes would not be required in subsequent placements.

The contractor chose to use 25 mm (1 in.) diameter steel cooling pipes and chilled water from a storage tank as part of the thermal control plan even at the abutments where it was not required in the first placement. The Caltrans design engineer for this project noted the ease of fabrication and operation of the system to control temperatures.

NEW BENICIA BRIDGE

The new 2.2 km (1.4 mile) long Benicia/Martinez Bridge on Route 680, about 24 km (15 miles) northeast of Oakland, CA, has spans up to 200 m (660 ft). It was designed as a lifeline structure that will be serviceable after a major seismic event. The portion over water was constructed from 335 cast-in-place single-cell box segments made of high-strength, lightweight concrete. The segments were cantilevered from 11 piers, 10 of which were marine piers rising out of the strait.

Substructure

The substructure had thermal control requirements similar to those for the Noyo River Bridge. The large 2.5 to 2.8 m (8.2 to 9.1 ft) diameter piles and massive piers were made of normalweight HPC with a maximum water-cementitious material ratio (w/cm) of 0.40 to limit the permeability of the concrete and protect the reinforcing steel. The specified compressive strength was 35 MPa (5000 psi) for the pier footings, pile caps, and pier walls/columns and 45 MPa (6500 psi) for the pier tables.

Two mixtures with cementitious material contents of 470 and 400 kg/m³ (792 and 674 lb/yd³) and 25% fly ash were used to construct the mass concrete piles. The pile placements

went well until a 2.8 m (9.1 ft) diameter pile was placed without embedded cooling pipes. This pile, made using concrete with the higher cementitious material content, reached a peak temperature of 74 °C (165 °F), which was the highest peak recorded for normalweight concrete on the bridge. When subsequent piles were cast with cooling pipes, however, only one pile with intermittent water flow through the pipes exceeded the specification limit of 65 °C (149 °F) reaching 72 °C (162 °F). None of the over 100 remaining piles placed after this pile exceeded the specified limit.

The piers used seven different mixtures with cementitious material contents ranging from 390 to 470 kg/m³

(657 to 792 lb/yd³) and 25 to 35% fly ash. Some of the piers consisted of four 1.75 m (5.7 ft) diameter corner columns connected by walls up to 1.25 m (4.1 ft) thick. The other piers were up to 2.5 m (8.2 ft) diameter without connecting walls. The pier walls and columns varied from 19 to 41 m (62 to 135 ft) in height, were placed in one to three lifts, and included cooling pipes. Between August 2002 and August 2005, there were 47 separate mass concrete placements. Only three of these placements exceeded the specified limit and reached maximum temperatures of 69 to 72 °C (156 to 162 °F).

The pier tables atop the walls and columns were divided into three placements for the soffit, the stem



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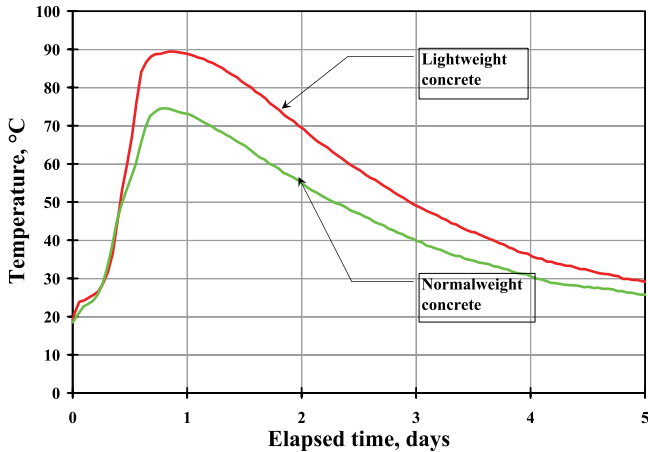


Fig. 2: Comparison of core temperature readings for 1.0 m (3.3 ft) noninsulated cubes of normalweight and lightweight concrete. Both mixtures contain identical fine aggregate, cement, and mineral admixture and have the same w/cm ($^{\circ}F = ^{\circ}C \times 9/5 + 32$)

and diaphragm, and the deck, which was not considered mass concrete. The pier table soffit ranged from 0.5 to 1.8 m (1.6 to 6 ft) in thickness at different piers. The diaphragms were up to 6 m (20 ft) tall with the least dimension at the top at about 6 m (20 ft). The pier table mixture contained 475 kg/m^3 (800 lb/yd^3) of cementitious material with 25% fly ash. All pier table soffits and diaphragms contained cooling pipes. Of the 26 mass concrete placements, only one reached as high as $66 \text{ }^{\circ}\text{C}$ ($151 \text{ }^{\circ}\text{F}$).

Overall, thermal control in the substructure was adequate even though a few placements did exceed the $65 \text{ }^{\circ}\text{C}$ ($149 \text{ }^{\circ}\text{F}$) specified limit. Cooling pipes were effective, if not indispensable, in these normalweight mass concrete elements.

Lightweight concrete segments

The new Benicia/Martinez Bridge construction brought to light the very special thermal properties of high-strength lightweight concrete. With a high cementitious material content of 581 kg/m^3 (980 lb/yd^3) coupled with a low fly ash percentage of 5%, the 70 MPa (10,000 psi) lightweight concrete used in the segments generated more heat than the normalweight concrete used in the substructure. Based on past experience, it was not anticipated that the decks, which were as thin as 0.25 m (0.83 ft), or the 0.55 m (1.8 ft) thick stems would require thermal control. Only soffits near 1 m (3.3 ft) and greater in thickness were anticipated to require thermal control.

After the first placements and continued thermal analyses, however, it became apparent that the temperature rise would be an issue with elements much smaller than 1 m

(3.3 ft). It was determined shortly after construction of the first few segments that all of the high-strength lightweight concrete making up the box cell segments needed thermal control. This led to designating the entire high-strength lightweight concrete to be under thermal control with a peak temperature limit of $71 \text{ }^{\circ}\text{C}$ ($160 \text{ }^{\circ}\text{F}$).

The first segment was cast December 31, 2004, and the last was cast October 23, 2006. Of the first 20 segments cast, 16 had elements exceeding $71 \text{ }^{\circ}\text{C}$ ($160 \text{ }^{\circ}\text{F}$), with four elements over $80 \text{ }^{\circ}\text{C}$ ($176 \text{ }^{\circ}\text{F}$). Additional temperature measurements at more locations within the segments were taken as construction proceeded. In February 2005, the only segment cast without any cooling pipes reached $91 \text{ }^{\circ}\text{C}$ ($196 \text{ }^{\circ}\text{F}$), even though all of the concrete was pre-cooled with ice and liquid nitrogen prior to placement. This was the tenth segment cast, and it became apparent that all segments needed cooling pipes spaced per thermal analyses in addition to precooling to as low as $7 \text{ }^{\circ}\text{C}$ ($45 \text{ }^{\circ}\text{F}$).

After the active controls were implemented, a few element temperatures exceeded $71 \text{ }^{\circ}\text{C}$ ($160 \text{ }^{\circ}\text{F}$) due to occasional problems with the pumping system, but most peaked below $55 \text{ }^{\circ}\text{C}$ ($131 \text{ }^{\circ}\text{F}$). Precooling with liquid nitrogen and post-cooling with water pumped from the strait flowing through PVC pipes performed quite well, and the cooling pipes appeared to be indispensable for this mixture.

The effect of the lightweight aggregate can be seen in Fig. 2, which depicts the temperature profiles of two 1 m (3.3 ft) concrete cubes. The only difference between the cubes is that lightweight coarse aggregate in one block was substituted with normalweight aggregate on an equal volume basis. All other ingredients were the same (the water and air in the lightweight coarse aggregate were assumed to be part of the coarse aggregate).

The normalweight concrete, with a density of 2400 kg/m^3 (150 lb/ft^3), produced a maximum temperature rise of $55 \text{ }^{\circ}\text{C}$ ($99 \text{ }^{\circ}\text{F}$), while the lightweight concrete, with a density of 2000 kg/m^3 (125 lb/ft^3), produced a higher maximum temperature rise of $71 \text{ }^{\circ}\text{C}$ ($128 \text{ }^{\circ}\text{F}$). The higher temperature rise in the lightweight concrete can be explained by the fact that the normalweight and lightweight concretes have nearly the same value of specific heat,⁶ which is the energy required to cause a unit temperature rise in a unit mass of a material. Because the same amount of cement was hydrated in each block, the amount of energy input was the same for each 1 m (3.3 ft) cube. Therefore, the product of the temperature rise and the mass for one block must be the same as in the other block. As illustrated in Fig. 3, the larger mass of the normalweight concrete block required a smaller temperature rise to equal the higher temperature rise, but lower mass, in the lightweight concrete block. This is an important factor to keep

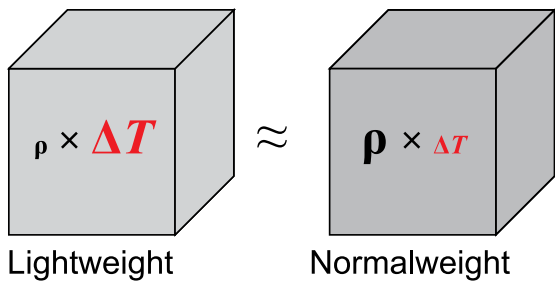


Fig. 3: When the specific heat of concrete doesn't vary with density, the product of temperature increase (ΔT) and density (ρ) will be about the same for equal volumes of lightweight and normalweight concrete containing the same amount and type of cementitious material



Fig. 4: The San Francisco-Oakland Bay Bridge Skyway



Fig. 5: One of two 19 x 19 x 10 m (63 x 63 x 33 ft) footing blocks for the self-anchored suspension structure

in mind when identifying concrete elements where mass concrete considerations may be a concern.

SAN FRANCISCO-OAKLAND BAY BRIDGE

The seismically vulnerable east span of the San Francisco-Oakland Bay Bridge connecting Yerba Buena Island to Oakland is being replaced with a new 3.6 km (2.2 mile) long bridge. Two of the major structures are the 2.4 km (1.5 mile) skyway (Fig. 4) and the 0.7 km (0.43 mile) self-anchored suspension (SAS) structure. The skyway had large mass concrete elements with required strengths of up to 70 MPa (10,000 psi). Although the specified compressive strength for two of the large footing blocks for the SAS structure was 35 MPa (5000 psi), the low permeability requirement resulted in an actual compressive strength that was over 63 MPa (9000 psi). Except for the two 19 x 19 x 10 m (63 x 63 x 33 ft) footing blocks (Fig. 5) that help balance the forces in the unequal spans of the signature SAS structure, all of the concrete was limited to a maximum temperature of 65 °C (149 °F). The two footing blocks were limited to 50 °C (122 °F).

The specifications for the mass concrete differed slightly from those of the Benicia and Noyo Bridges. To validate the contractor's thermal control plans, scaled-down mock-ups were required rather than mandatory cooling pipes in the first placement. As anticipated, the contractor chose to use bay water circulated through PVC cooling pipes (Fig. 6) as an integral part of the



Fig. 6: PVC cooling pipe system for one of the footings supporting a pier for the San Francisco-Oakland Bay Bridge

thermal control plan in addition to using liquid nitrogen to cool placement temperatures to 5 °C (41 °F) and lower. Numerous mixtures, including self-consolidating concrete, were used for the various cast-in-place bridge elements. Thermal control for these structures benefited greatly from experience gained at Benicia and was highly successful.

ACCEPTANCE OF ACTIVE CONTROLS

Given the many factors influencing the characteristics of mass concrete, the methods used to cope with heat are a matter of economics as well as expertise.⁷ As they become more adept at using cooling pipes to control temperatures in large or high-performance concrete bridge

elements, contractors are selecting this control method on many other Caltrans bridge projects, including some having traditional compressive strength requirements.

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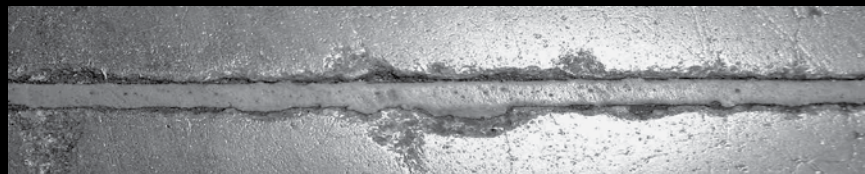
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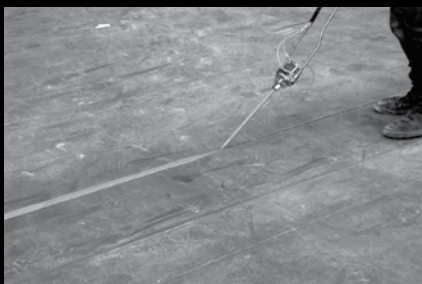
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