Mitigation of Thermal Cracking in Massive Foundations

Self-consolidating concrete mixture successfully used for thick slabs in wastewater pumping station

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Upon its completion, the North Jeddah Main Wastewater Pumping Station in Saudi Arabia became one of the deepest and largest such facility in the world. The project involved the construction of three cast-in-place reinforced concrete (RC) bottom slab foundations 70 m (230 ft) below ground level (Fig. 1). Slabs designated as B1 and B2 are located in pump shafts. Each has a diameter of 42.6 m (140 ft), a horizontal area of 1426 m^2 (15,350 ft^2), and a thickness of 5.5 m (18 ft), with an estimated volume of ready mixed concrete of about 7845 m^3 (10,260 yd^3). Slab B3 is the foundation for the screen shaft for the facility. It has a diameter of 44 m (144 ft), an area of 1521 m^2 (8440 ft^2), and a thickness of 4.5 m (15 ft). The volume of concrete needed for B3 was about 6846 m^3 (8950 yd^3).

Considering that the three slabs must be classified as mass concrete and that thermal cracking would be a serious risk, the original plans were to construct each in three layers, allowing time between subsequent layers for dissipation of heat of hydration before the placement of a new layer. This approach would have been quite problematic, however, because the slabs were at the bottom of very deep shafts and had very dense mats of top reinforcement—it would have been extremely difficult to consolidate the concrete in the bottom layers. Thus, it was decided to construct the massive slabs using a continuous placing process and self-consolidating concrete (SCC). The expected placement time for each of the three foundation slabs was 24 to 30 hours, at placement rates of 262 to 327 m^3/h (340 to 430 yd^3/h) for Slabs B1 and B2, and at placement rates of 229 to 286 m^3/h (300 to 375 yd^3/h) for Slab B3. No cold joints were allowed in this continuous casting process.

The 28-day design strength of the concrete was 37 MPa (5370 psi), based on cube tests. In addition to the need to address the potential for cracking due to volume change and thermal differentials, it was necessary to design the concrete mixtures for resistance to penetration of seawater and diffusion of harmful substances such as chloride and sulfate ions to ensure durability and mitigate corrosion of reinforcing steel. The mixture also needed to be capable of consolidating under self-weight without vibration and resistant to segregation and bleeding.

This article details the development of the SCC mixtures for the slabs, discusses the planning to mitigate thermal cracking, and outlines the decisions and actions that allowed the contractor to successfully place SCC for the foundation slabs.

Background

To provide a colloidal volume allowing greater cohesiveness and resistance to bleeding and segregation, SCC mixture designs often involve increased powder content. Furthermore, the coarse aggregate content and maximum particle size are often reduced to mitigate friction and blockage of SCC flow. Such measures are not conducive to developing SCC for mass concrete applications requiring reduced heat of hydration and enhanced resistance to thermal cracking. Hence, there is a dearth of information on using SCC in mass concrete applications.

Kaszyńska[1] explored the effects of temperature changes due to hydration heat of cement in massive concrete on the mechanical properties of early-age and mature SCC. To predict the early-age cracking of SCC, Kang et al.[2] explored the stress and crack-opening relationship of SCC over time. Kaszyńska[3] also presented results of analysis of hydration heat and mechanical properties (compressive strength, tensile strength, and modulus of elasticity) of high-performance concrete and SCC mixtures hardened inside massive structures. However, use of SCC in massive full-scale concrete structures is not well-documented in the open literature.

Cement hydration is an exothermic reaction. Hence, in massive concrete elements, the internal temperature can rise substantially. The differential between the internal temperature and surface temperature can induce nonuniform volume changes and subsequent tensile stresses. The higher the temperature gradient, the larger these tensile stresses would be. When the tensile stresses reach or exceed the tensile strength of concrete (which is typically about 7 to 10% of its compressive strength), the stresses will be relieved through thermal cracking. Such thermal cracks can be detrimental to the durability of concrete structures by forming paths for the ingress of hostile media such as chlorides and sulfate ions.

Fig. 1: The foundation slabs for the pumping station were constructed at the bottoms of 70 m (230 ft) deep shafts

Therefore, adequate temperature control is paramount in assuring the serviceability and long-term performance of mass concrete structures. The change in volume and induced thermal cracking can be minimized by such measures as reducing the cement content, replacing part of the cement with pozzolans, pre-cooling, post-cooling, insulating the concrete placement to control the rate of heat absorbed or lost, construction joints, and by other temperature control measures outlined in ACI 207.1R-05[4] and ACI 207.4R-05.[5] The measures that are eventually selected to control thermal cracking will depend to a large extent on the economies of the project and the seriousness of the possible cracking.

Mixture Design

Flowable concrete requires a relatively large volume of fines to reduce aggregate friction and blockage of flow. However, using portland cement alone to supply the needed volume of fines would lead to large temperature gradients, as heat generation is directly proportional to the quantity and type of cement in the concrete mixture. Pozzolanic materials, however, contribute much less to heat generation than cement. For instance, the early-age heat contribution of fly ash is estimated to range between 15 and 35% of the heat contribution from a similar weight of cement. There is also a large body of research and data demonstrating the superior durability of ternary cements incorporating silica fume and fly ash (for example, Nehdi et al.[6] and Thomas et al.[7]). So, to meet strength, flowability, and durability requirements, we developed a mixture with a ternary binder comprising ASTM C150 Type I/II cement, silica fume, and Class F fly ash in proportions of 270, 25, and 170 kg/m^3 (455, 42, and 286 lb/yd^3) of concrete, respectively (Table 1).

Table 1:
Concrete mixture proportions

Material or property	Quantities, kg/m^3 (lb/yd^3) or as noted
Type I/II portland cement	270 (457)
Silica fume	25 (42)
Class F fly ash	170 (288)
Coarse aggregate	865 (1907)
Fine aggregate (sand)	805 (1362)
Water	195 (330)
Polycarboxylate HRWRA	6 (10)
Retarding admixture	2 (3.4)
Polypropylene fiber	3 (5.0)
Entrapped air (pressure method)	<2.5%
Slump flow	670 ± 30 mm (26 ± 1 in.)
Fresh concrete temperature	<25°C (77°F)

The selected coarse aggregate was crushed granite having a 12.5 mm (1/2 in.) maximum particle size, absorption of 1.85%, apparent specific gravity of 2.74, and bulk density of 1561 kg/m^3 (97 lb/ft^3). The flakiness index of the coarse aggregate was 12.8% and its elongation index was 33.7%. The selected fine aggregate was a natural sand with a fineness modulus of 2.68 and apparent specific gravity of 2.65. Chilled water and crushed ice were used for mixing to reduce the fresh concrete temperature. A polycarboxylate high-range water-reducing admixture (HRWRA) was used along with a compatible retarding admixture. To further enhance crack resistance, the proposed mixture design incorporated synthetic polypropylene fiber reinforcement to

Fig. 2: The SCC mixture exhibited no segregation or bleeding, even after a high-energy drop chute placement in the 70 m (230 ft) deep shaft

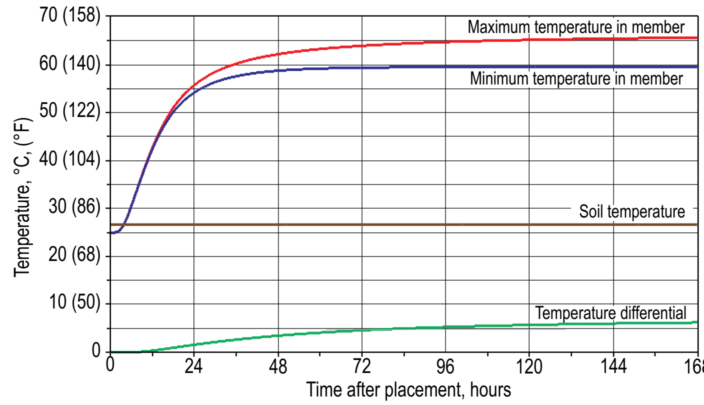

Fig. 3: Plot of finite difference model predictions for heat evolution in the massive foundation slab

control early-age microcracking. The fresh concrete unit weight was 2410 kg/m^3 (150 lb/ft^3) with an entrapped air content of less than 2.5%. The slump flow of the SCC at the job site was 670 ± 30 mm (26 ± 1 in.). The difference between the slump flow and the J-ring flow was less than 25 mm (1 in.) with no observable blocking. The fresh concrete temperature at the job-site delivery was between 22 and 25°C (71 and 77°F).

Figure 2 illustrates the SCC flow from a full-scale placement of concrete at the bottom of the 70 m (230 ft) shaft delivered using a drop chute. No segregation or bleeding was observed despite the high-energy drop. Testing of SCC specimens per ASTM C1202-12, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," indicated a total charge passed of 650 coulombs at 56 days—indicative of very low chloride penetrability. Testing according to the water penetration test per DIN 1048-4[8] indicated 5.9 mm (0.23 in.) penetration after 72 hours of exposure to 5-bar water pressure. Testing per ASTM C157/C157M-08, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," indicated a shrinkage strain of 0.048% at test completion.

Numerical Modeling

A numerical model implemented using computer software was used for thermal analysis and prediction of temperature rise within the RC foundations. The software is based on the finite difference method. It accounts for the properties of the cement, pozzolanic materials, and chemical admixtures in the concrete mixture as well as the weather conditions, temperature of fresh concrete at placement, and the geometry and boundary conditions for the foundation.

A typical result of a thermal simulation is presented in Fig. 3. The predicted maximum temperature within the core of the foundation was about 65°C (149°F). The model boundary conditions included the soil at the base and sides of the slab as well as a layer of thermal insulation at the top. The insulation consisted of a blanket of 50 mm (2 in.) thick expanded polystyrene (EPS) with a material conductivity of 0.036 W/(m·K) (a resistivity [*R*-value] of 4.0 h·ft^2·°F/Btu/in.) used on the entire surface of the circular slab foundations. The maximum temperature difference in the foundations before removal of the insulation was only about 5°C (9°F), which was considered acceptable to mitigate thermal cracking.

Mockup and Model Validation

In addition to the finite difference model prediction of temperature rise (Fig. 3), a large-scale mockup (2.9 x 2.4 x 2.4 m [9.5 x 7.9 x 7.9 ft]) was constructed on the project site using the proposed concrete mixture. A general view and internal reinforcement details are shown in Fig. 4. The mockup was instrumented with temperature sensors near the bottom, at the center of mass, and near the top surface. Concrete and ambient temperatures were recorded using a data acquisition system. The results of the test mockup are illustrated in Fig. 5. It can be observed that the maximum core temperature reached was about 66°C (151°F) and the maximum thermal differential was about 22°C (40°F). The maximum core temperature obtained from the test mockup validated the finite difference model predictions, which gave a maximum core temperature of 65°C (149°F). However, the maximum temperature differential from the large-scale test mockup was higher than that from the numerical prediction due to the different boundary conditions between the mockup and the model of the full-scale foundation. Based on the predicted and observed peak temperatures, the observed temperature differential in the mockup, and the local weather conditions anticipated during the concrete placement, a thermal plan was outlined for the full-scale construction.

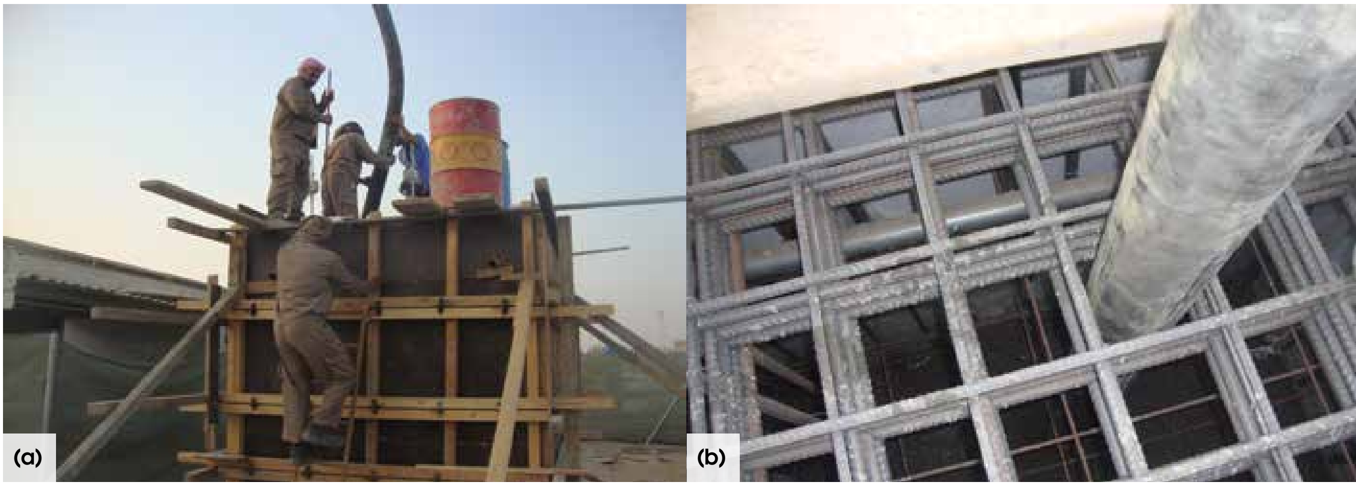

Fig. 4: Placement of concrete in test mockup: (a) overall view; and (b) pump hose extended through top layers of reinforcing bars

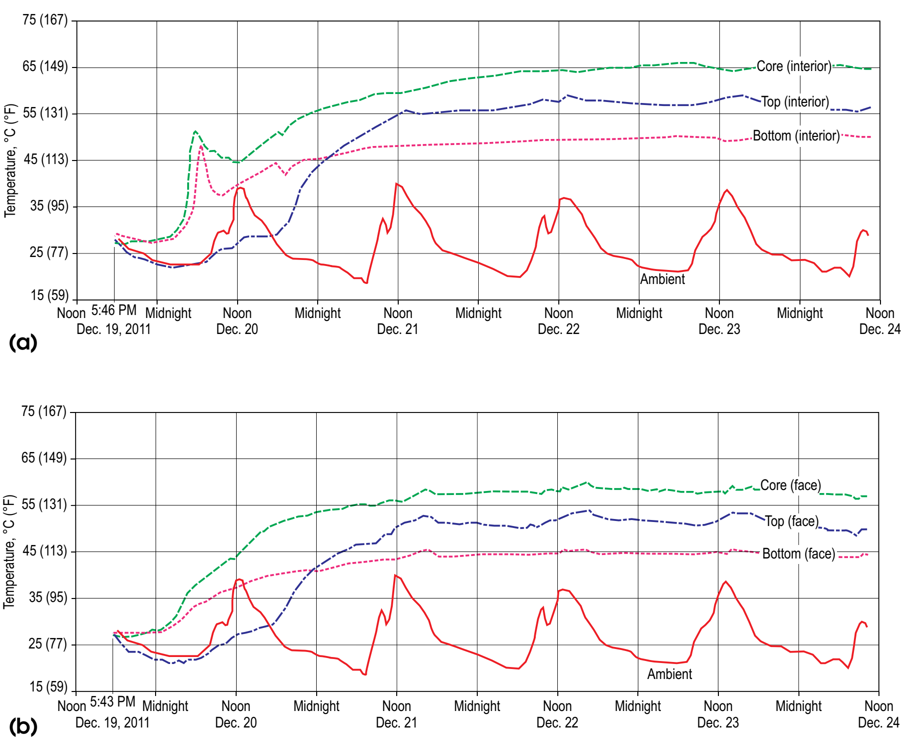

Fig. 5: Temperature data acquired from the instrumented mockup after filling with 17 m^3 (22 yd^3) of the proposed SCC mixture: (a) readings taken by sensors mounted along the vertical centerline of the mockup (interior); and (b) readings taken by sensors mounted near the form face (face)

To ensure that the 37 MPa (5370 psi) cube design compressive strength was reachable, cores were taken from the test mockup at 7 days as per ASTM C42/C42M-12, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." The measured core compressive strength was 38.2 MPa (5540 psi), corresponding to a cube strength of about 44 MPa (6400 psi), which is adequate.

Full-Scale Construction and Evaluation

The SCC for the foundation slabs was produced at and transported from four different stationary batch plants using transit mixer trucks. No additional mixing water was allowed on-site, but mixer trucks that arrived after 45 minutes of transit were allowed to be dosed with a maximum HRWRA dosage of 0.5 L/m^3 (0.2 gal./yd^3) of concrete. Transit trucks that did not deliver concrete within 60 minutes were rejected. SCC was cast 70 m (230 ft) below ground level using a central pump boom or drop chutes (Fig. 6). Full-scale trials for placing SCC using a drop chute showed that the kinetics of the 70 m (230 ft) free fall of concrete in a 200 mm (8 in.) diameter pipe were excessive, so it was decided to include a 130 mm (5 in.) diameter reducer near the bottom. The 5.5 m (18 ft) thick and 42.6 to 44.0 m (140 to 144 ft) diameter bottom slabs were cast using continuous concreting without vibration. A total of 24,000 m^3 (31,400 yd^3) of SCC was used. No surface finishing was needed. After casting, the slabs were covered with EPS insulation with total *R*-value of 8.0 h·ft^2·°F/Btu/in. (1.40 m^2·K/W).

The foundation slabs were instrumented using thermocouples at five locations along the diameter (Fig. 7). Thermal data was automatically recorded every 30 minutes. An example plot is shown in Fig. 8. The temperature reached a peak of about 68°C (154°F) at around 5 days after the start of concrete casting. This peak temperature agrees reasonably well with the numerical model prediction of 65°C (149°F) and the mockup data of 66°C (151°F). The first few hours showed relatively uniform temperatures due to the continuous placing of concrete. While the temperature at the bottom of the slab initially rose sharply as the upper layers of SCC were cast, the temperature plateaued at around 45°C (113°F) due to heat transfer to the underlying soil.

After a time lag reflecting the period of casting, the temperature at the core of the slab started to rise sharply, followed by temperature rise at the top of the slab. Due to the presence of the top insulation, the temperature in the top layer of the slab increased beyond the temperature at the bottom of the slab. The highest temperature differential between the core and top surface of the slab was about 25°C (45°F), reached at about 3 days after casting. The differential tended to decrease thereafter, reaching about 15°C (27°F) 2 days later. This behavior can be explained by the time lag during placement. The core was cast several hours before the top layer of the slab, so the top of the slab was still relatively cool when the core was generating much of the hydration heat. Once hydration in the top layer was more advanced, the temperature differential narrowed. The EPS insulation at the top of the slab also helped to minimize losses and differentials. This trend is advantageous because the concrete kept gaining higher tensile strength, while the thermal differential decreased gradually. It is noted that the numerical model predicted lower temperature differential because it did not account for the difference in age of the concrete through the slab thickness.

The EPS insulation was removed 14 days after placing, when temperature data and tensile strength measurements indicated that thermal cracking was no longer a significant risk. Indeed, the thermal gradient was in a safe range (less than 20°C [36°F]) at the time of EPS removal. After removal of the insulation, inspections of the exposed surface and careful examination of cores taken from various locations on the exposed surface provided no indication of cracking.

Summary

Three massive 5.5 m (18 ft) thick and 42.6 to 44 m (140 to 144 ft) diameter slab foundations were cast at 70 m (230 ft) below ground level for the North Jeddah Wastewater Pumping Station. A ternary SCC mixture with high levels of cement replacement was used to allow continuous placement yet minimize hydration heat. Chilled water and crushed ice were also used for mixing to reduce the temperature of the fresh concrete. Finally, surface insulation was installed to reduce the differential between the core and surface temperatures. In total, 24,000 m^3 (31,400 ft^3) of SCC were continuously placed without vibration for the construction of the foundation slabs.

A finite difference numerical model was used to predict the temperature rise in the foundations, and the model was validated using an instrumented mockup. The actual foundation slabs were also instrumented to acquire thermal data. While the peak temperatures obtained from the numerical model, mockup, and foundation slabs showed good agreement, it is recommended that modeling of mass concrete that is cast over extended periods of time should reflect the sequence of casting (the actual age of

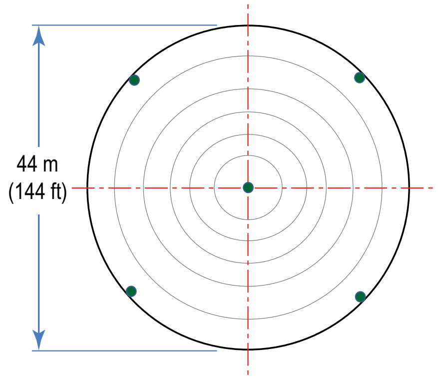

Fig. 6: SCC was placed at five locations in each slab. At the central point, concrete was discharged from a pump boom at a fixed location. At each of the four locations on the periphery of the slab, a flexible drop chute allowed concrete to be delivered over an entire quadrant of the circular cross-section

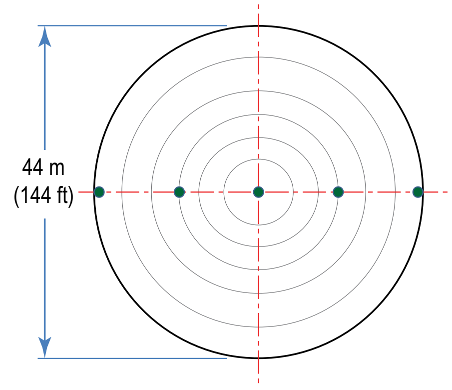

Fig. 7: Temperature sensors were installed at five locations across the width of each slab. At each location, temperature measurements were taken at the bottom, middepth, and top of the 5.5 m (18 ft) thick foundation slabs

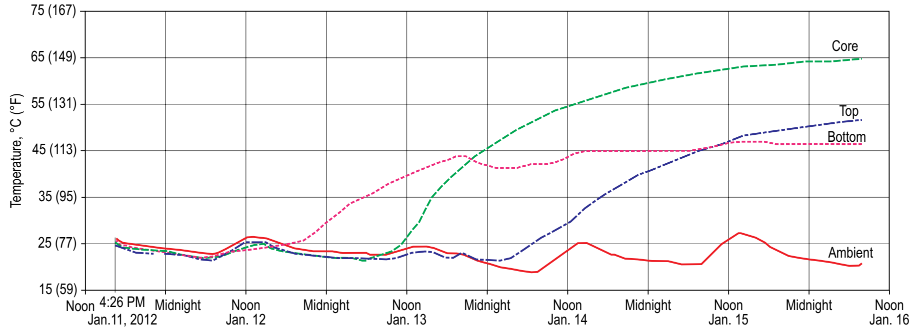

Fig. 8: Example of temperature data acquired from one of the slab foundations

concrete in each layer) to achieve more accurate predictions of temperature gradients at early age.

It was demonstrated that SCC can be used successfully for the construction of massive concrete elements. However, local materials and environmental conditions, as well as specific geometry and boundary conditions, must be taken into consideration before transposing the findings of this study to other structures.

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

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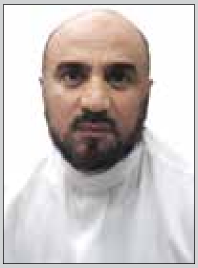

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