Mass Shotcrete Wall Construction and Thermal Control Plan

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Wet-mix shotcrete has been used more and more for structural applications in the past few decades. Recently, wet-mix shotcrete was successfully used to construct a mass structural wall with congested reinforcement and minimum dimensions of 1. 0 m in a sewage treatment plant. A low-heat shotcrete mixture that included up to 40% slag was proposed for shotcrete application. A preconstruction mockup was shot to established proper work procedures for shotcrete application and qualify the shotcrete mixture and shotcrete nozzlemen. Extraction of cores and cut windows from the mockup confirmed proper consolidation around the congested reinforcement. A thermal control plan was developed, which included laboratory and field testing requirements, thermal analysis modeling with a three-dimensional (3-D) finite element program, and thermal control requirements, including installation of cooling pipes and thermal blankets.

Shotcrete proved to be an efficient means for mass concrete structural construction. Thermal control for mass shotcrete construction was studied, and the proposed thermal control plan was proved to function properly. The general guidance for mass shotcrete construction is provided.

Keywords: compaction; consolidation; encapsulation; mass concrete; mass shotcrete; nozzleman; shotcrete; temperature differential; thermal control plan.

INTRODUCTION

Shotcrete is the pneumatic conveyance of concrete materials at high velocity to a receiving surface to achieve in-place compaction.[1] While shotcrete has been used for over a century, the use of shotcrete instead of conventional cast-in-place concrete for new construction has greatly increased in the past several decades. Structural shotcrete refers to shotcrete application for structural elements, including structural walls, pilasters, and other structural components. Structural shotcrete has many advantages over cast-in-place concrete, including reducing or even eliminating formwork requirements. More and more structural shotcrete is being applied across North America. To determine if shotcrete is suitable for structural applications, configurations of the reinforcement and structural dimensions need to be considered. Besides the reinforcement configuration, a successful structural shotcrete application requires shotcrete materials to be:

- Pumpable (that is, good workability for delivery/ transport and pumping);
- Shootable (that is, work compatibly with the shotcrete pump, hose, and nozzle, and can be efficiently managed/ controlled by the nozzleman);
- Stackable (that is, shotcrete applied to the receiving surface must display suitable adhesive and cohesive properties that it can be stacked and built up to the full thickness and height without sagging or sloughing); and
- Finishable (that is, must be suitable for cutting, screeding, and finishing properly).

With the use of proper materials, equipment, and shooting techniques as recommended by ACI 506[1] and ACI C660,[2] shotcrete is able to fully consolidate around the reinforcement and other embedments.

During the past few decades, more and more wet-mix shotcrete is being used for concrete structures with minimum dimensions increasing from 200 mm (8 in.) thick to 500 mm (20 in.) thick. Recently, structures with thicker dimensionsthat is, over 500 mm (20 in.) to as much as 1.5 m (38 in.) have been successfully built with wet-mix shotcrete.

This paper provides details regarding wet-mix shotcrete used to construct a structural wall 1.0 m (3.3 ft) thick with two layers of 25M (#8) reinforcing bar in a sewage treatment plant. Due to constrictions on the site, constructing the wall using conventional form and pour with cast concrete would have been very difficult. The shotcrete method was proposed, and the wall was successfully constructed in a practical and cost-effective manner. Features of the shotcrete construction of the mass concrete wall using this method were as follows:

First, a shotcrete mixture with 40% slag replacement for portland cement was successfully used for the shotcrete construction. This mixture proved to be able to satisfactorily meet all the pumpability, shootability, stackbility, and finishing requirements for shotcrete.

The structural wall was built by experienced ACI-certified shotcrete nozzlemen using the hand application method. A mockup with the most heavily congested section of reinforcing bar was constructed and shot to qualify the mixture, the nozzleman, and the shotcrete application.

Second, structures with minimum dimensions of more than 0.9 m (3 ft) are categorized as mass concrete and require a thermal control plan (TCP) to minimize the potential for thermal cracking. The shotcrete mixture was tested and the heat of hydration was recorded. A three-dimensional (3-D) finite element model (FEM) was used to model the heat development and thermal behavior of the structure. Based on the TCP, installation of cooling pipes was selected as an option to meet the TCP requirements. One layer of cooling pipes spaced at 1.0 m intervals was installed to meet the TCP requirements.

> *Wet-mix shotcrete was successfully used to construct a mass structural wall with congested reinforcement...*

RESEARCH SIGNIFICANCE

Although shotcrete is now being widely used for structural construction, relatively few projects have been reported to be mass concrete structures with minimum dimensions of 0.9 m. The thermal behavior for mass concrete construction needs to be controlled properly; however, there is little information in published literature regarding thermal control measures for mass shotcrete construction. This paper presents information regarding a wet-mix shotcrete mixture with 40% slag used to build a mass shotcrete wall 1.0 m (thick with two layers of 25M reinforcing bar. It also provides details regarding thermal analysis and modeling, and development of a thermal control plan for this mass shotcrete wall construction. The thermal control plan was executed by controlling the shotcrete placement temperature, installing cooling pipes to dissipate the heat generated by hydration of the shotcrete, and applying thermal blankets for thermal protection. Recorded temperatures during construction monitoring were very close to the modeled temperature development. Post-construction inspection found no thermal cracking in the structural shotcrete wall.

This paper provides general guidance for mass shotcrete construction including:

- Use of a low-heat mixture that is suitable for shotcrete batching, pumping, shooting, and finishing;
- Mass shotcrete structure construction to achieve proper consolidation around reinforcement; and
- Mass shotcrete thermal control plan to minimize the potential for thermal cracking.

FEASIBILITY STUDY

A major civil contractor in Western Canada is constructing a sewage waste treatment plant. The dimensions of the structural wall of interest are shown in Fig. 1.

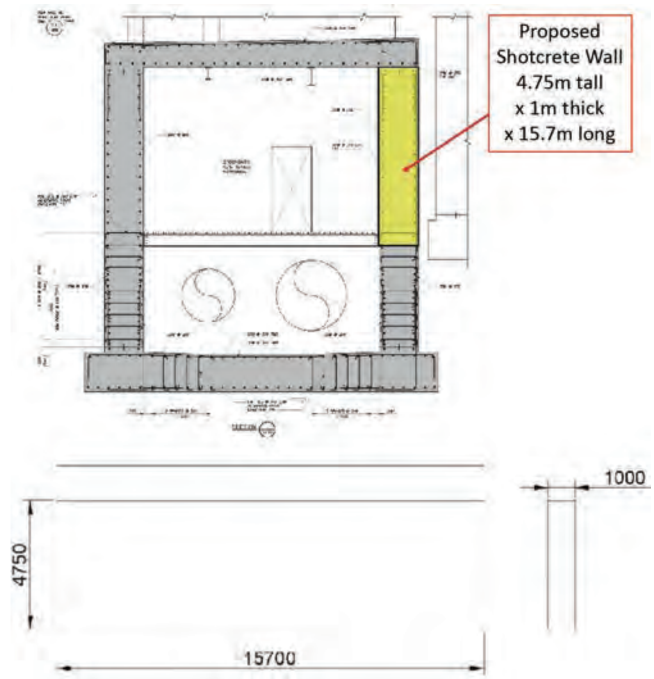

Fig. 1: Structural drawing and wall dimensions.

A method of using a shotcrete mixture with a high volume of slag and installation of cooling pipes in the structural wall was proposed. However, due to a lack of any previous project experience for mass shotcrete wall construction with proper measures to meet the thermal control requirements, questions were raised by the owner, design engineer, and contractor as follows:

1. Can shotcrete be successfully applied to a 1.0 m thick wall with two layers of 25M reinforcing bar spaced at 300 mm (12 in.)?
2. As the shotcrete process involves applying concrete at high velocity, will this process damage the cooling pipes during application?
3. Because shotcrete mixtures typically have a higher cement content than cast-in-place concrete, usually at least 400 kg/m^3 (670 lb/yd^3) cementitious material, this may result in higher temperatures. Will the heat of hydration increase the potential for thermally induced cracking?
4. What measures can be implemented to mitigate the potential for thermal cracking?

To address these questions and to prove that shotcrete was suitable to construct the 1.0 m thick structural wall with satisfactory consolidation around the multilayer reinforcement of 25M reinforcing bar and provide satisfactory thermal performance, a mockup trial shoot was proposed and conducted. The mockup panel was evaluated and the encapsulation of the reinforcing bar was visually inspected with extracted cores and cut open windows in the mockup wall. Subject to it being demonstrated that shotcrete could be applied to properly encapsulate the reinforcing bar, the contractor would then proceed with shotcrete construction of the wall. At the same time, a heat box test was conducted to obtain the adiabatic temperature rise of the mixture, based on which thermal control plan could be developed for the mass concrete structural wall.

MIXTURE DESIGN

The concrete supplier proposed a shotcrete mixture with a compressive strength of 35 MPa (5000 psi) at 28 days. This satisfied the compressive strength requirements for a structural element in this exposure environment. The mixture was designed with 60% Type GUL (Type 1L) cement and 40% slag replacement for portland limestone cement. Type GUL cement has approximately 15% limestone and has a lower heat ofhydration compared to a Type GU cement. With 40% slag replacement, heat generated during the cement hydration process is further reduced. Increasing the cement replacement with higher slags content will reduce the heat of hydration of shotcrete. However, increasing of the slag content too much can cause difficulties for the shotcrete process, which involves shotcrete pumping, shooting, and, in particular, stacking without sloughing. Prior to this project, slag was typically added at 25% replacement in the wet-mix shotcrete mixture design. Therefore, increasing the slag content to 40% was required to be tested and proven to be pumpable, shootable, and stackable.

Fig. 2: Mockup for mass concrete wall with two layers of 25M reinforcing bar and cooling pipes.

Fig. 3: Casting shotcrete into 1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft) box to calibrate adiabatic temperature rise (ATR).

Fig. 4: Shotcrete construction of mockup wall.

Fig. 5: Cores extracted from mockup wall section.

Fig. 6: Cutout block showing thorough shotcrete consolidation around reinforcing bar and cooling pipes.

The combined coarse aggregate (10 mm maximum size) and fine aggregates used for the shotcrete mixture were designed to meet the ACI 506R gradation No. 2 requirements.

The water-cementitious materials ratio (w/cm) was a maximum 0.40.

The slump was designed to be 70 ± 20 mm (2.8 ± 0.8 in.) for structural shotcrete application. This has been proven to work properly with the pumping and shooting for structural shotcrete application. Slump is critical for nozzleman to successfully apply shotcrete to structural components. Lower slump helps shotcrete to stack in thick sections to greater heights without sloughing. However, if the slump is too low, the shotcrete will not properly flow around and encase reinforcing bar and embedments. With 40% slag replacement, the wet-mix shotcrete tends to slough at higher slump. Therefore, special consideration and shooting techniques are required when working with high-volume supplementary cementitious material (SCM); shotcrete and nozzlemen prefer to work with lower slump for structural application. High-range water reducer was used to reach the required slump. No hydration control admixture or retarder was required. The mixture was designed to be placed within 90 minutes, beyond which the mixture started to stiffent and could not be pumped and shot properly. Slump in the range of 70 ± 20 mm was found to be suitable for this mixture.

The shotcrete mixture was air entrained with an as-batched air content of 5 to 8% satisfying the CSA C-1 Exposure Class for freezing-and-thawing durability requirement. The addition of entrained air into shotcrete helps shotcrete to be pumpable and shootable after exiting from the nozzle. An airentrained shotcrete will have a higher as-batched air content, and reduced as-shot air content. The higher as-batched air content facilitates the pumping process while the lower as-shot air content help the stackability. This is a unique benefit of entraining air into shotcrete and is referred as the "slump killing effect".[1,3,4]

A preliminary thermal analysis based on assumed thermal values was conducted and shotcrete construction of the wall was considered to be acceptable subject to implementation of the following measures:

1. Use a 40% slag mixture, with cooling pipes and installation of thermal blankets for thermal control.
2. Use an experienced structural shotcrete contractor, with rigorous inspection and quality control testing to ensure conformance to the project specifications.

MOCKUP SHOOTING

A mockup shooting was conducted with details summarized as follows:

- Reinforcement was installed as per the structural wall drawings (Fig. 1).
- During the mockup construction, a layer of cooling pipes (polyvinyl chloride [PVC] pipe with 25 mm [1 in.] diameter) was installed at 1.0 m spacing to test if it would cause any consolidation issues (Fig. 2).
- Samples were cast to test the heat of hydration required by the 3-D FEM model.
- A block with dimensions of 1 x 1 x 1 m with 150 mm (6 in.) thick extruded polystyrene (EPS) board insulation on each of the six sides was constructed. The temperature development for both a 150 mm (6 in.) diameter cylinder and the 1 m^3 (35.3 ft^3) block was used to calculate the adiabatic temperature rise (ATR) for the shotcrete mixture (Fig. 3).

The structural wall mockup shotcrete application was conducted successfully. An experienced nozzleman (ACI certified nozzleman in wet-mix process) was able to successfully bench shoot the wall to the full height, in combination with the use of a vibrator and blow pipe (Fig. 4).

Fig. 5 shows cores extracted from the mockup wall and Fig. 6 shows the cutout block. They clearly show that both the 25M reinforcing bar and 25 mm diameter cooling pipe are properly wrapped with shotcrete and the mockup is free of voids or any other defects.

The mockup trial shoot results were considered satisfactory and met industrial best practices.[1] It was agreed by the owner and the design engineers that wet-mix shotcrete could be used to construct the structural wall with proper consolidation around reinforcement and cooling pipes.

Wet-mix shotcrete test results for the mockup were as follows:

- Slump: 55 mm (2.2 in.)
- Temperature: 17.8°C (64.0°F)
- As-batched air content: 6.2%
- As-shot air content: 2.5%

Cores were extracted from a shotcrete test panel and tested for compressive strength at 7 and 28 days, and boiled absorption and volume of permeable voids at 7 days and test results were as follows:

- Compressive strength at 7 days: 23.6 MPa (3420 psi)
- Compressive strength at 28 days: 36.1 MPa (5235 psi)
- Boiled absorption: 5.4%
- Volume of permeable voids: 12.0%

The mockup shotcrete application demonstrated that shotcrete could be successfully applied to consolidate the large-diameter reinforcing bar and multi-layer reinforcement. In particular, it was demonstrated that the most congested section of reinforcing bar could be consolidated properly with proper shooting. In addition, shotcrete could also be fully consolidated around the cooling pipes without any damage to the pipes. Compressive strength results for shotcrete cores met the specified 35 MPa (5000 psi) at 28 days. The boiled absorption was less than 8% and volume of permeable voids was less than 17%, which met the specified performance requirements and indicates a good quality of shotcrete.[3] The thermal behavior of the shotcrete mixture was obtained by both laboratory and field testing.

THERMAL MODELING AND EFFECT OF COOLING PIPES ON TEMPERATURE DEVELOPMENT

Adiabatic temperature rise (Fig. 7) was developed by laboratory testing with the 150 mm diameter cylinders and the field test with the 1 x 1 x 1 m block insulated with 150 mm EPS board (R = 15).

A 3-D finite element computer program was used to model the temperature development for the structural wall. The effect of cooling pipes was studied and the concrete block was modeled with and without cooling pipes. Results are plotted in Fig. 7. The concrete placement temperature was 15°C (59°F) for both scenarios. When cooling pipe was used, the peak temperature was reduced from 58 to 53°C (136 to 127°F). The time to reach the peak temperature was also reduced from 48 to 50 hours to 35 to 38 hours. After reaching the peak temperature, the cooling pipe was very effective in reducing the center temperature during the descendant portion of the temperature. This resulted in a lower temperature differential between the center and surface. Without cooling pipes, the temperature differential was approximately 15°C when the thermal blankets were kept in place, and then exceeded 20°C (68°F) after 168 hours or 7 days when the thermal blankets were removed. With cooling pipes, the temperature differential was 10°C (50°F) and less with the thermal blankets in place, and stayed under 10°C after 168 hours or 7 days when the thermal blankets were removed.

This demonstrates that cooling pipes can effectively reduce the peak temperature as well as the temperature differentials between the center and the surface.

Cooling pipes also provide great flexibility for the construction schedule. During construction, it is common that the construction schedule changes due to various reasons. Cooling pipes provide an alternative option for construction activities to proceed to accommodate challenges from factors, such as higher concrete placement temperatures and sudden changes in ambient temperature.

THERMAL CONTROL PLAN

A thermal control plan (TCP) was prepared for the construction of the wall to meet the specified mass concrete thermal requirements of:

1. Peak temperature to be ≤ 60°C (140°F) to avoid delayed ettringite formation (DEF)
2. Temperature differential between center and surface to be ≤ 20°C (35°F)
3. In a situation where the temperature differential exceeded 20°C, a stress analysis should be conducted and the calculated thermal stress versus tensile strength ratio should not exceed 75%.

Thermal modeling results are included in Table 1 with scenarios No. 1 and 2 as follows:

Scenario No. 1: Shotcrete placement temperature of 15°C, no cooling pipes, thermal blanket covers the finished shotcrete surface from the time of placement for 10 days. This scenario controlled the placement temperature, which may be the most effective way to reduce the peak temperature. However, this may be challenging for mass concrete batching during warm weather in the summer or early fall.

Scenario No. 2: Shotcrete placement temperature of 20°C, one layer of cooling pipes at 1.0 m spacing, with cooling water temperature of 13.7°C (56.7°F), thermal blanket covers the finished shotcrete surface from the time of placement for 7 days. This scenario requires less effort of controlling of placement temperature, but more effort on controlling temperature during construction-that is, by installing and maintain the cooling water during the curing period.

Model results from both scenarios are plotted in Fig. 8 when concrete is placed at 15°C.

Selection of the scenario is dependent on the construction schedule and effort to control the placement temperature, installation, and maintaining of the cooling pipe, which requires coordination between the design engineers and construction teams.

The construction of the shotcrete wall was scheduled to for early September, when controlling the shotcrete temperature to be 15°C and less was found to be challenging. Therefore, Scenario No. 2 was selected and cooling pipes were installed at a spacing of 1.0 m as shown in Fig. 9.

Table 1—Thermal modeling results

Maximum allowable temperature, °C	Specified, °C	Analysis (no cooling pipes), °C	Analysis (one layer cooling pipes), °C
Center temperature	60	58.7	58.5
Placement temperature	25	15.0	20.0
Differential center to surface temperature	20	14.0	11.4
Center temperature after blanket removal	60	25.3	24.0
Differential center to surface temperature (after blanket removal)	20	10.6	9.6

Table 2—QC test results summary for shotcrete construction

8 m³ per truck	Shotcrete temperature, °C	Slump, mm	As-batched air content, %	As-shot air content, %	As-batched density, kg/m³
Trucks 1-9, a total of 72 m³ shotcrete was applied in 10 hours	22.6 to 25	60 to 85	7.7 to 9.0	4.8 to 5.6	2197 to 2217

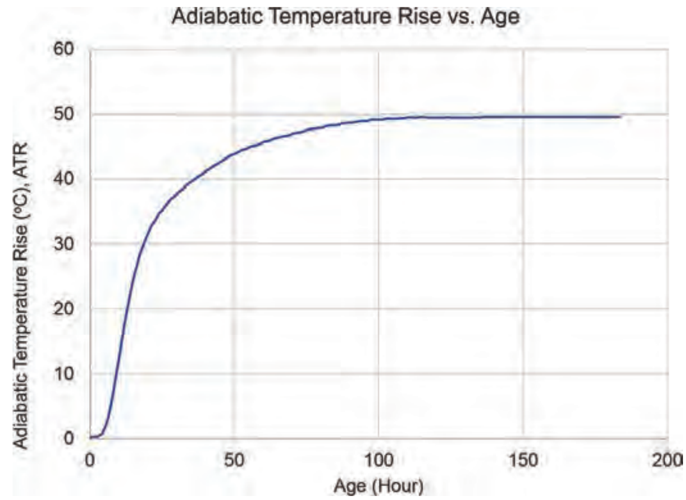

Fig. 7: ATR of shotctete mixture calculated based on results from both laboratory and field tests.

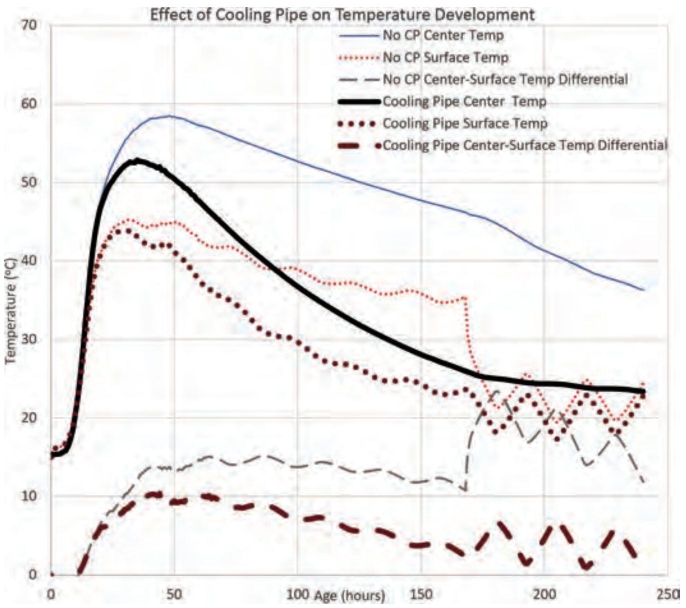

Fig. 8: Modeled temperature developments with and without cooling pipe.

STRUCTURAL WALL CONSTRUCTION

In early September, the structural wall was constructed using the wet-mix shotcrete application method. Rigorous construction monitoring and inspection and quality control testing was conducted by the author throughout the whole application process. QC test results are included in Table 2. Shotcrete application commenced at 7:00 am and finished at 4:30 pm. In brief, this large structural wall took only 9.5 hours to construct using ready-mixed supplied wet-mix shotcrete. A total of over 70 m^3 (92 yd^3) of shotcrete was applied using the bench-gun shooting method. Details of shotcrete application are included in Fig. 10 through 21.

SHOTCRETE QC TEST RESULTS

- Compressive strength at 9 days: 38.5 to 46.6 MPa; (5600 to 6800 psi) exceeds the specified 35 MPa at 28 days
- Boiled absorption: 6.5 to 7.0%, meets the specified maximum 8.0%
- Volume of permeable voids: 14.5 to 15.4%, meets the specified maximum 17.0%

PRODUCTIVITY OF MASS SHOTCRETE WALL CONSTRUCTION

Prior to construction of the wall, backside formwork and reinforcement was installed and inspected by the engineer. During the mass shotcrete wall construction, a total of nine 8 m^3 (10.5 yd^3) concrete truckloads of shotcrete, for a total of 72 m^3 (92 yd^3) shotcrete was applied. Shotcrete application started at 7:00 am with continuous shooting throughout the day. Shotcrete shooting finished at 3:55 pm, and finishing was completed by 5:30 pm. Therefore, it took a total of 9 hours to complete shooting and 10.5 hours to complete all the shotcrete work, including finishing. This resulted in a mass structural shotcrete wall construction production rate average of one truckload of 8 m^3/h for shotcrete application, with a total of over 72 m^3 being applied in a 10.5-hour shift. This production rate is typical for structural shotcrete application, with a crew of two to three nozzlemen, four finishers, and four helpers.

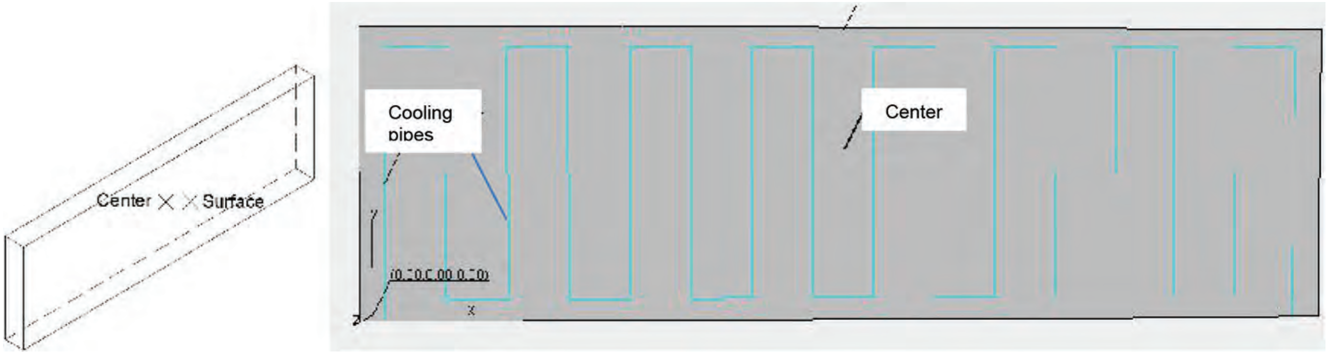

Fig. 9: Sensor locations with points of concern and cooling pipe layout (in blue).

Fig. 10: View of scaffold (three-deck platform), shotcrete crew, and finishing crew with tarp on top to protect wall from rain.

Fig. 11: Two layers of 25M reinforcement with cooling pipes (fixed using tire wire with auxiliary 10 m stirrups) erected in middle thickness of wall.

Fig. 14: Thermal sensors placed at surface of back wall (at formwork face), mid-thickness of wall, and surface of wall. All three locations are in center face of wall and at middle between cooling pipes. One additional thermal sensor was installed to measure ambient temperature.

Fig. 16: For each lift, shotcrete was applied to approximately 45-deg. slope. Prior to application of next lift, rebound and overspray were removed by blow pipe.

Fig. 15-Nozzleman moved nozzle into 300 x 300 mm reinforcing bar grid to fill up back layer of reinforcement. Note that nozzle angle was kept at approximately 90 deg. to receiving surface. Note that guide wires were used to control thickness of wall, and were cut and removed after finishing.

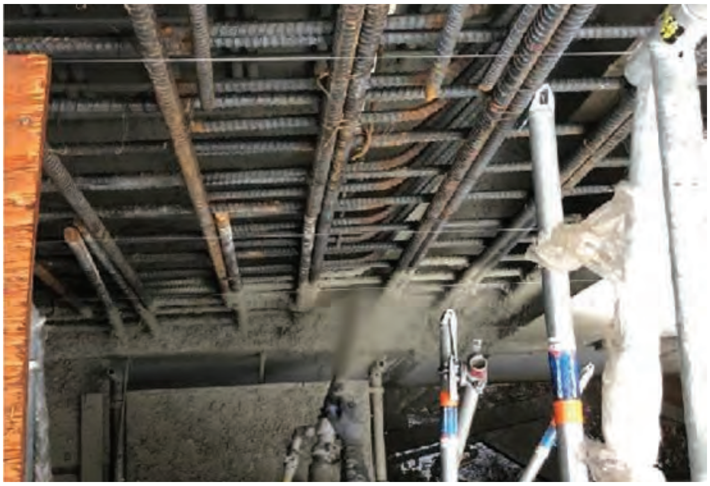

Fig. 12: Guide wires installed to control wall thickness and finishing. View from top deck. Shooting started at corner of wall.

Fig. 13: Cooling pipe installed at 1.0 m spacing with four inlets.

Fig. 17: Shooting, blow pipe operation, and light touch with pencil vibrator to enhance final consolidation.

Fig. 18: Shooting.finish coat.

Fig. 19: Screeding.finish coat to guide wires.

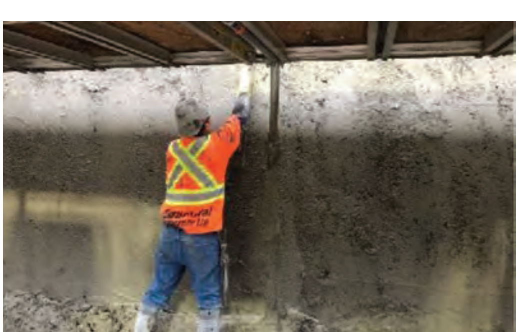

Fig. 20: Float finishing with darby.

Fig. 21: Final steel-trowel. finishing.

TEMPERATURE DEVELOPMENT OF MASS SHOTCRETE WALL

Right after installation of the shotcrete wall was completed, cooling water was passed through the cooling pipes for approximately 10 days. The thermal blankets were, however, not installed until 53 hours later due to site construction schedule issues. Temperature data was downloaded for approximately 4 days (90 hours), after which the temperature recording device was damaged.

Detailed temperature development data for the shotcrete wall is included in Fig. 22.

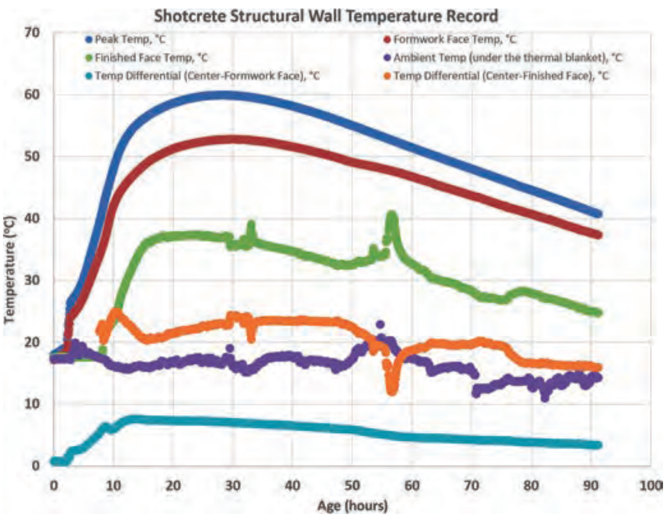

Fig. 22-Recorded temperature development.

The peak temperature at the center of the wall was 60°C and meets the specified allowable maximum temperature of 60°C. The temperature differential between the center and formwork face was less than 20°C. The ambient temperature ranged between 15 and 20°C for the first 50 hours. The temperature differential between the center and the finished face of the wall, however, was measured to range between 20 and 25°C (45°F) for the first 50 hours and then dropped back to be below 20°C (25°F). This is attributed to the fact that the thermal blankets were not installed until 53 hours in contravention of the thermal control plan. Typically, when the temperature differential exceeds 20°C (35°F), a stress analysis is required to be conducted to determine if the thermal stress exceeds 75% of the tensile strength.

Fig. 23: View of shotcrete wall surface from second deck; no thermal cracking was observed.

The post-pour remodeling and stress analysis was conducted with the 3-D FEM model and results are included in Table 3.

It should be noted that due to the construction schedule, tests for tensile strength and creep were not conducted to obtain the parameters for stress analysis. Parameters from a mixture with similar compressive strength, elastic modulus, and creep were used for thermal stress analysis. The stress analysis results show that the thermal stress versus tensile strength ratio is 59%, which is less than 75%, at which the potential for thermal cracking is considered high.

Although there was no temperature data recorded after 90 hours, the temperature trend at the peak, formwork face, and finished face are all descending to be below 20°C after 90 hours. With the ambient temperature of 10 to 25°C, the temperature differential was within 20°C until 10 days after the thermal blankets were installed, when the thermal blankets were removed and the TCP was terminated.

Table 3—Comparison of model and recorded temperatures

Maximum allowable temperature	Spec	Analysis with thermal blanket installed after completion of placement	Actual with thermal blanket installed after 53 hours	Conforms
Placement temperature, °C	25	24.5	24.5*	Yes
Maximum center temperature, °C	60	59	60	Yes, only 1°C difference
Maximum differential center to surface temperature, °C	20	11.4	24	Exceed spec, thermal stress analysis required
Thermal stress versus tensile strength ratio	<75%	Tensile strength = 1.55 MPa	Maximum tensile stress = 0.91 MPa	Yes, stress versus strength ratio = 59%

*Placement temperature was recorded as temperature when shotcrete contacted thermal sensor.

Fig. 24: View of finished wall surface from bottom deck; no thermal cracking was observed

A post-construction inspection was conducted after the thermal blankets were removed. The surface condition of the finished face is shown in Fig. 23 and 24. No thermal cracking was observed.

Conclusions

- Wet-mix shotcrete with 40% slag was successfully applied for construction of a reinforced mass shotcrete wall 1.0 m thick using the bench-gun shooting method. Proper encapsulation of the reinforcement of up to 25M in size and parallel spliced was achieved.
- Shotcrete encased the cooling pipes without any damage.
- Shotcrete was an efficient way to construct the mass structural wall.
- A thermal control plan was implemented. The peak temperature met the specified requirement for a mass concrete structure. The temperature differential between the center and the finished surface exceeded the specification requirements for up to 50 hours, but the post-pour inspection confirmed that no thermal cracking was observed.
- The recorded temperature and the modeled temperature, adjusted with the actual construction conditions, were very close, with less than 1° C (1.8°F) difference in peak temperature. This shows that the 3-D FEM model used in the project is capable of accurately modeling the temperature development of the mixture and shotcrete construction process.

In summary, shotcrete was successfully applied to the structural wall, met the specified project performance requirements of compressive strength, boiled absorption and volume of permeable voids, and the quality of mass shotcrete wall was satisfactory with no thermal cracking observed.

Recommendations

Looking forward, sophisticated complex concrete structures with complicated reinforcement details are now being constructed with shotcrete. This includes thick walls, beams, pilasters, and other structural components that can be classified as mass concrete. Most recently, ACI 308 has included shotcrete into the building code.[6] Implementation of thermal control plans for these mass shotcrete structures will be critical for meeting the structural design requirements and meeting service life requirements. This paper provides general principles and a detailed methodology for design engineers to consider for construction of mass shotcrete structural components. It involves structural design, mixture design, a thermal control plan, mockup and qualification, construction QC testing and inspection, and post-pour inspection. With appropriate efforts of the structural engineers, concrete/shotcrete engineers, contractor and supplier, mass shotcrete structural components are able to be built to properly meet the project specification and service life requirements.[5] Further research work is being carried out by the authors, including testing thermal behavior of shotcrete materials and modeling of massive shotcrete structures with optimized thermal control measures.

To design mass shotcrete structures, the following design principles are recommended:

- Specify shotcrete mechanical properties, including compressive strength, elastic modulus, flexural strength, shear strength and with fibers, residual tensile strength.
- Constructability with shotcrete. A properly designed shotcrete mixture should be trial shot and tested. The adiabatic temperature rise should be developed based on testing of the mixture.
- Thermal modeling should be conducted, based on which thermal control plan should be developed. The thermal control plan should specify the maximum allowable temperature in the structure, which is normally less than 60°C, and maximum allowable temperature differential between the center and the surface which is normally required to be less than 20°C. If the temperature differentials exceeds 20°C, a thermal stress analysis should be conducted to determine whether the stress versus strength ratio exceeds 75%. If it does, there is high potential for thermal cracking. The means and methods for proper measures to minimize the risk of thermal cracking include but are not limited to reducing the shotcrete application temperature and using thermal blankets with an extended installation period if needed. Use insulated formwork, cooling pipes, and other suitable measures if needed. The shotcrete specialist, contractor, and design engineer should work together to come up with the most efficient and cost-effective options to implement the thermal control plan.
- Pre-construction qualification for the nozzleman, shotcrete equipment, and mixture should be tested. The shotcrete nozzlemen should be ACI-certified nozzleman. During the mockup trial shoot, the structural component with the most congested section of reinforcing bar should be selected. Cores and/or cutout windows should be visually inspected by an experienced shotcrete specialist as to ACI requirements and project specification requirements. At the same time, thermal control measures should be implemented during the mockup phase. The purpose is to calibrate the thermal models and adjust the thermal control plan if necessary.

- Upon satisfactory inspection and testing of the mockup structural component, the mass shotcrete structure can then be constructed with the same materials, equipment, nozzlemen, and crew. The thermal control plan should be executed by installing sufficient thermal sensors to monitor the temperature development of the structure. Temperatures should be recorded and reviewed on a timely basis by the engineer and, if required, additional thermal control measures should be implemented, such as additional thermal blankets installation, reducing the cooling water temperature, increasing the water flow in the cooling pipes, or other suitable measures.
- Post-pour inspection should be conducted by a concrete specialist to establish whether there is any thermal cracking. Should there be any evidence of thermal cracking, the field thermal control plan should be reviewed and remodeled based on the actual curing and protection conditions of the structure. A post-pour comparison of recorded temperature versus modeled temperature is always encouraged.

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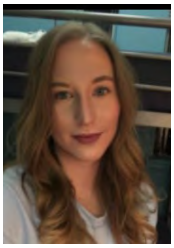

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