Applications of Tremie Concrete in the Olmsted Dam

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ABSTRACT: Tremie concrete has been extensively used in challenging marine environments. Its recent application in the Olmsted Dam has provided one example of the advancement in the sophistication of the technology. In this paper, the complete placement procedures for tremie concrete in the Olmsted dam built by means of in-the-wet construction are presented together with the desired characteristics and corresponding mix designs. The use of Nonlinear Incremental Structural Analysis (NISA) for the determination of thermal effects in both the tremie concrete and its enveloping concrete shell is also reviewed. A mock-up test, which was used to test the constructability of the tremie concrete, is presented at the end. Several findings are included in this paper. During the initial tremie concrete placement, the formation of a seal of fresh concrete created by mounding concrete at the embedded end of the tremie pipe was identified as a key factor for a successful operation. Self-consolidation and good flowability were found to be other desired characteristics for the tremie concrete, which are proved to be achieved by the presented mix design. A high percentage of Ground Granulated Blast Furnace Slag (GGBFS) can significantly reduce the concrete heat of hydration. Proper admixture can enhance the performance of the tremie concrete. No potential major thermal cracks were identified through the use of NISA. The tremie concrete was confirmed by the tests to be able to fully infill the voids and have a high quality.

1 INTRODUCTION

The application of tremie concrete starts as early as Roman civilization (Netherlands Committee for Concrete Research, 1973). The term "Tremie Concrete" is classified by the unique construction methodology it employs; whereby concrete is placed underwater using tremie pipes and gravity feed. In the early stages of its development, it was generally used to seal the bases of cofferdams (Yao, Berner, and Gerwick, 1999). Its applications have since been extended to a large variety of different underwater projects. Tremie concrete was used to tie the precast waffle panels in the underwater reconstruction of the Intake Velocity Cap at the St. Lucie Power Plant (Hasan, Faerman, and Berner, 1993). In the Florida Keys Reef damage repair project, divers guided the placement of the tremie concrete into the interstitial space connecting the precast concrete panels and damaged reels.

Using tremie concrete eliminates the need for constructing a cofferdam to allow dewatering and therefore reduces the associated construction cost. It can also shorten the construction period by pouring a large amount of concrete within a relatively short time. Due to its special requirements, typically tremie concrete must be: self-consolidating; resistant to washout and workable in order to achieve high quality.

This paper presents one example of the use of special concrete mix designs, together with its pertinent construction practices. The example presents the use of tremie concrete in the construction of Olmsted Dam, on the Ohio River, as shown in Figure 1 using an "in-the-wet"
approach. The construction was conducted in several steps. First, large precast concrete shells were fabricated on the bank of the river near the dam site. Then the shells were transferred to the underwater construction location by a combination of gantry crane, marine skidway and catamaran crane barge (Figure 2). After the shells were lowered into the desired position, tremie concrete was used to infill the void underneath each shell, which connected the shell with the pre-driven foundation piles. Each shell serves as both the working surface of the dam and as a form for the fresh concrete. The mix designs for the Olmsted Dam are discussed in the following sections. Other pertinent aspects of the analyses and construction practices are also presented.

Figure 1 Rendering of Olmsted Locks and Dam (Courtesy of Louisville, USACE)

Figure 2 Representative Tainter Gate Stilling Basin Shell Ready for Load-out

2 PLACEMENT

Usually hoppers are installed at the top of the tremie pipes to serve as a supply buffer for the gravity feed process. Although some tremie placements are initiated with a wet tremie pipe and a suitable "pig" to separate the fresh concrete from the water in the pipe, for better quality control the Olmsted Dam placements were initiated using dry tremie pipes. Ridged watertight
end seals were applied to the bottom pipe-tips to prevent water from entering the tremie pipes. To equalize the internal and external hydraulic pressures, so that the bottom seals could be opened, the pipes were initially filled with tremie concrete to a certain height before the tremie pipes were lifted to break the end seal. Once the end seal was broken, the tremie concrete inside the tremie pipes flowed out to create a mound around the pipe tip, which served as a seal for the following concrete. The subsequent concrete needs to be placed underneath the initial concrete mound in a continuous and smooth manner. Therefore, it is continuously protected by the previously placed concrete from mixing/washout with the water. However, the initially placed concrete is subject to washout, which can produce laitance. In the case of Olmsted Dam the surface laitance was ejected from beneath the shells through multiple ports in order to improve the quality of the interfacial concrete.

For the Olmsted Dam project, the rate of rise of the tremie concrete was limited to the range of 0.15-0.46 m per hour, and the tip of the tremie was periodically raised to match the rate of rise of the concrete. Care was taken to ensure that the tremie pipe tip was kept embedded at least 0.61 m in the tremie concrete at all times. This was essential in order to ensure the quality of the tremie concrete.

After the concrete placement was completed at one location, the pipe was raised to the surface, re-fitted with a plate seal and re-located to the next placement location to continue the operation. The end seal needed to be installed every time the pipe was lowered into the water.

To increase the productivity and efficiency, multiple tremie pipes were utilized to place concrete at different locations at the same time. The distances between the tremie pipes are usually 4.57 m or 2-3 times the depth of the tremie concrete. This methodology is logistically demanding because concrete needs to be constantly batched and fed to the hoppers in order to keep the operation continuous. If placement were to be disrupted, cold joint may form. For such projects, that need large amounts of tremie concrete to be placed in a short time period, it is recommended that the transport distance for moving the fresh concrete be kept as short as practicable.

The slump-loss of tremie concrete can be retarded, thus permitting the batched concrete to be transported to the construction site by transit mixers and barges. The final logistics need to be carefully planned. Contingency plans usually need to be developed in order to reduce the risks of disruptions to the continuous supply of tremie concrete.

Because tremie concrete typically cannot be mechanically consolidated, the concrete needs to rely on its own buoyant weight, and low fresh shear strength, to be self-consolidating. Obstructions such as rebar cages, or piles, further impede the flow of tremie concrete and require high-flowability for the concrete. Low flowability may prevent the tremie concrete from fully encasing the rebar cages, and/or piles.

Factors such as those cited previously also present challenges into proper tremie concrete placement. If the tremie does not flow well or sets up early, voids or honeycomb may be created in some areas. Excessive laitance may be created at the edges and top surface of a tremie concrete placement, if the mix design is not well formulated, or if the placement is not executed properly. Large placements of tremie concrete must be designed to avoid high rates of heat generation, which may cause significant thermal stress/cracking in the hardened concrete. The water temperature also needs to be both monitored and addressed, in order to avoid large temperature differences between the curing concrete and the surrounding water. Large temperature differences induce large temperature gradients, which can crack the concrete.

The placement of tremie concrete for the Olmsted Dam is divided into four stages (Figure 3) to match the locations of the tremie pipes, and to avoid high stresses in the shells. In the first two stages, the tremie concrete partially filled the voids underneath the precast concrete tainter gate shell through tremie pipes along the lifting frame. The third pour filled the voids between the
sheet pile cut off wall and the precast concrete shell. In the fourth stage, the rest of the voids were completely filled.

Figure 3 Tremie Concrete Placement Sequence

3 CHARACTERISTICS

Flowability is one of the most important considerations for tremie concrete placements. It is usually measured by two indices: slump and slump flow. For the Olmsted case, slump needed to be within the range of 15 to 20 cm. Slump flow diameter was limited to being between 46 and 51 cm. The slope of the final formed surface was found to be between 5% and 10%.

Retardation of concrete setting time is also desirable when the concrete needs to be transported from an off-site batch plant, as was the case for the Olmsted project. The initial time of set was between 6 and 24 hours. Final time of set was within 30 hours.

The time interval between the concrete batching and placement was limited to be within one hour. Three hours was the maximum time window achieved without causing significant stiffening of concrete. For time intervals exceeding three hours, a complete halt of construction was required on the Olmsted Dam project.

4 MIX DESIGN

The proportions of the structural tremie concrete mix are listed in Table 1. To achieve high flowability, natural round gravel was used as coarse aggregate instead of crushed stone, which has sharp angles. The maximum aggregate size was 1.91 cm, due to the close spacing of the embedded reinforcing steel.

The requirements for the fine aggregate included that 10% pass the 50-mesh sieve and that more than 2% pass the 100-mesh sieve. Within limits, increasing the fine aggregate content, can lead to reduced segregation and washout.

Type II Portland cement was used in this case. Compared to Type I Portland cement, Type II cement has higher sulfate resistance and less heat of hydration. By controlling the maximum amount of hydraulic cement in the cementitious material, low heat concrete was obtained. Frequently, the cement content in tremie concrete can range between 297 and 386 kg/m³. For the Olmsted Dam project this was significantly modified to reduce the temperature of concrete during curing. In the tremie concrete mix design used in the Olmsted Dam, the Portland cement
content only composed 14% of the total cementitious material. By using other cementitious materials such as GGBFS, fly ash, limestone powder, and silica fume, which have slower rates of heat generation, the peak temperature in the tremie concrete was significantly reduced.

Table 1: Tremie Concrete Mix Design

<table>
<thead>
<tr>
<th>Materials</th>
<th>Weight (kg) per Cubic Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse Aggregate</td>
<td>890</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>755</td>
</tr>
<tr>
<td>GGBFS</td>
<td>260</td>
</tr>
<tr>
<td>Limestone Powder</td>
<td>120</td>
</tr>
<tr>
<td>Cement</td>
<td>76</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>51</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>22</td>
</tr>
<tr>
<td>HRWR (Admixture)</td>
<td>1.63 liter</td>
</tr>
<tr>
<td>WR (Admixture)</td>
<td>0.42 liter</td>
</tr>
<tr>
<td>AWA (Admixture)</td>
<td>2.84 liter</td>
</tr>
</tbody>
</table>

In this mix design, GGBFS composes 49% of the cementitious material. This large percentage of usage of GGBFS improved the concrete workability and also prolonged the set time.

Fly ash was also used to reduce the heat of hydration and to reduce the rate of slump loss. Fly ash can improve concrete pumpability. Because the size of fly ash particles is smaller than that of cement particles, fly ash can result in a finer microstructure of the hardened paste, which in-turn can reduce the concrete permeability.

When the cement paste is mixed with limestone powder, ettringite is typically produced with a coarse crystallization that can increase the density of hardened paste. As a result, the use of limestone powder can enhance the cohesion of, and reduce the bleeding of, fresh tremie concrete.

Silica fume particles are typically much finer than the particles of the other cementitious materials. The small particles of silica fume can result in a denser microstructure of the paste. The filler effect of silica fume can also reduce both segregation, and bleeding, of tremie concrete. Low addition rates (2-5%) of silica fume typically produces a denser structure in the transition zone, which increases microhardness and fracture toughness.

Three types of admixture have been used in the Olmsted Dam tremie concrete mix design. A High-Range Water-Reducer, HRWR, was used to reduce the water/cementitious material ratio in order to achieve the required high strengths. A Water-Reducing Admixture, WRA, was used to increase fresh concrete’s slump-life and to decrease its shear strength. Also, an Anti-Washout Admixture, AWA, was used to reduce cement washout and concrete bleeding and it also served to extend the slump-life of the tremie concrete.

5 NONLINEAR INCREMENTAL STRUCTURAL ANALYSIS (NISA)

The purpose of the Nonlinear Incremental Structural Analysis, NISA, conducted for the Olmsted Dam was to determine the thermal influence on the precast shell and tremie concrete by the heat of hydration of the tremie concrete and ambient temperature regime. Typical sections of the dam were simulated in 2D numerical models. The analyses were conducted in two steps. In the first step, thermal analyses, using diffusion elements and thermal boundary
conditions, were performed. The predicted temperature distribution through a representative tainter gate monolith section, over a period of 48.25 days, is shown in Figure 4. While tremie concrete is still being placed, but 1.25 days after the initiation of the placement, the maximum temperature peaks at the lower portion of the tremie concrete. Within several days after the completion of the tremie placement, the peripheral regions of the section cool first, while the warmer core subsequently cools and contracts, thus introducing thermal stresses throughout the section.

The time-history of the temperature distributions were calculated in the first step; in the second step of the NISA analysis, the thermal deformation distributions and associated thermal stresses and cracking distributions were predicted. The boundary conditions were progressively modified as the tremie concrete gained strength and stiffness according to nonlinear constitutive material models. No potential major cracks were identified through the analysis.

![Figure 4 Thermal Stress Redistribution after Tremie Concrete Placement](image)

6 TESTS

A variety of tests have been conducted to verify that the designed tremie concrete would meet the specified requirements, which include washout tests and two mock-up tests.

The washout tests were conducted in several steps in accordance with CRD C61 (US Army Experiment Station Handbook, 1989). First, a 2 m high water tube was filled with water to a depth of 1.7m. Then, a sample of fresh concrete was loaded into a perforated receiving container, which was let fall freely through the water to the bottom of the water tube three times. The mass difference between before and after the test was measured and calculated to be the washout percentage. The washout tube has an inside diameter of 190 mm ± 2 mm and an outside diameter of 200 mm ± 2 mm. The average basket inside diameter is 127 mm and average outside diameter is 129 mm. Two sets of experimental data are listed in Table 2. It can be seen that all the washout ratios are less than 5%. During construction the washout testing was conducted for every first batch of each shift and at a frequency of one test for every 458.7 cubic meters of tremie concrete produced afterwards.
Two mock-up tests were also performed, simulating placement beneath the stilling basin shells, such as that shown in Figure 5. These tests were used to refine the placement techniques, and to verify that the tremie concrete could be placed in two stages, and could successfully infill against the underside of the concrete shells.

Table 2 Washout Test Results

<table>
<thead>
<tr>
<th>Sequences</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (g)</td>
<td>Mass Loss Ratio</td>
</tr>
<tr>
<td>Before Drop</td>
<td>2143.2</td>
<td>N/A</td>
</tr>
<tr>
<td>Drop 1</td>
<td>2103.9</td>
<td>1.8%</td>
</tr>
<tr>
<td>Drop 2</td>
<td>2074.6</td>
<td>3.2%</td>
</tr>
<tr>
<td>Drop 3</td>
<td>2048.5</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

The tests were conducted in the following orders. First the test concrete basin shell was cast in a basin. Then the other formwork simulating the surrounding conditions in the actual construction was set up together with rebar cages underneath the test basin shell. Next, river water was pumped into the basin. When the test shell was completely submerged, the tremie concrete was placed by infilling through the vents on the top of the shell (Figure 6). The tremie concrete was found to be able to fully infill the voids, encase the rebar cages, and have a high quality. This was verified through concrete cores taken from test basin shell, which showed a sound aggregate distribution (Figure 7).
7 CONCLUSIONS

Tremie concrete is a special concrete that can substantially reduce construction cost and shorten construction time. Both placement techniques and mix design are keys for a successful operation. The end of tremie pipe must be constantly embedded under the initial mound to avoid washout and segregation of concrete. A high GGBFS content can reduce the concrete heat generated by tremie concrete, which can be important in mass placements; while NISA can be used to predict the thermal effects of such mass placements. Mock-up tests are valuable for refining tremie concrete placement techniques and/or mix formulae.

8 REFERENCE

Netherlands Committee for Concrete Research. (1973) “Underwater concrete”, HERON 19(3)