RECENT RESEARCH ON SHOTCRETE BY THE
US ARMY CORPS OF ENGINEERS

by

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INTRODUCTION

During the July 1973 Engineering Foundation Conference on the "Use of Shotcrete for Underground Structural Support," Mr. Thomas Reading of the Corps of Engineers' Missouri River Division Office presented a paper entitled "Corps of Engineers Studies of Shotcrete." Mr. Reading is the Corps of Engineers' expert in this field, and due to his efforts, much interest has been generated within the Corps of Engineers to develop a greater knowledge of the potentialities of shotcrete. The Corps has conducted research and plans to continue to conduct research on shotcrete, especially in the areas of materials, protective structures, tunnel support, repairing poorly consolidated ("honeycomb") areas in new construction, and rehabilitating older structures. The Corps of Engineers has found shotcrete to be a very versatile material. An unofficial inventory was recently made of the number and type of concrete structures being maintained by the Corps and these results are indicated below.


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Since shotcrete is such a good repair and maintenance material, one can readily see why the Corps is interested in knowing more about it. My first experience with shotcrete came in 1966, when the Huntington District of the Corps of Engineers decided to use shotcrete to rehabilitate Charles Mill Dam in Ohio, which was built during the early thirties. The project construction specifications were based on information found in the American Concrete Institute's Recommended Practice for Shotcreting (ACI 506-66). Results of tests on this shotcrete caused the Corps to become increasingly interested in shotcrete for repair work. A number of panels were fabricated for evaluating the compressive strength of the shotcrete but in addition, panels were shot and sawed into 3-1/2 x 4-1/2 x 16 in. (8.9 x 11.4 x 40.6 cm) beams and at 28 days, these beams were subjected to the Rapid Freezing and Thawing Test (ASTM C 666). The results of these tests indicated that the shotcrete continued to gain flexural strength and the relative dynamic modulus of elasticity actually increased while being subjected to 300 cycles of freezing and thawing. There were probably two significant reasons for these results:
1. Manufactured fine aggregate was used since natural fine aggregate meeting the grade requirements was not readily available.

2. The use of the manufactured fine aggregate resulted to an excessive amount of rebound (> 40%).

MATERIAL PROPERTIES

During 1974, Messrs. William Tynes and William McCleese of the Concrete Laboratory, US Army Engineer Waterways Experiment Station, investigated the two processes for producing shotcrete, the wet process and the dry process. The wet process consisted of adding all the ingredients of the mixture, including the water, and thoroughly mixing prior to application. The dry process consisted of thoroughly mixing all of the ingredients except the water in a mixing drum and then forcing the dry mixture through a hose where the water was added at the nozzle just prior to application. Specimens cored from panels of the shotcrete were tested to determine such physical properties as compressive strength, tensile strength, shear strength, permeability, bond pullout resistance of steel, density, absorption, and resistance to freezing and thawing. Significant results of this research program are:

1. Compressive strengths of shotcrete comparable to those of normal structural concrete were obtained for all four shotcretes evaluated (4000 to 8000 psi (27.58 to 55.16 MPa)).

2. The average shear strength percentages relative to the compressive strengths were 11.4 percent for the dry-mix, fine-aggregate shotcrete; 8.5 percent for the wet-mix, fine-aggregate shotcrete; 12.2 percent for the dry-mix, coarse-aggregate shotcrete; and 12.3 percent for the wet-mix, coarse-aggregate shotcrete. The
shear to compressive strength ratio of the shotcrete was approximately equal to a comparable ratio for normal structural concrete (8 to 12).

3. For the bonding of shotcretes to old shotcrete, the bond strength tests (shear and tensile) indicated approximately 100 percent bond efficiency. The bond efficiency for the shotcrete to old concrete was considerably lower than the bond efficiency of the shotcrete to old shotcrete.

4. The splitting tensile strength to compressive strength ratio of the shotcrete was approximately equal to the ratio of the shear strength to the compressive strength, i.e., 8 to 12. In general, this ratio is approximately equal to a comparable ratio for normal structural concrete.

5. The average resistance to freezing and thawing (DFE) values was 26 or below for all shotcretes tested. Since the shotcretes were not air-entrained, these low values were to be expected and were not lower than should be expected for nonair-entrained structural concrete.

6. The average bond pullout stress for the dry-mix, fine-aggregate shotcrete was 1200 psi (8.27 MPa); for the dry-mix, coarse-aggregate shotcrete, 1480 psi (10.20 MPa); for the wet-mix, fine-aggregate shotcrete, 790 psi (5.45 MPa); and for the wet-mix, coarse-aggregate shotcrete, 1050 psi (7.24 MPa).

7. The average permeability \(K_c\) values were \(10.25 \times 10^{-12}\) or less for all shotcretes tested. However, the dry process specimens were four times more permeable than the wet process specimens. These low permeability values indicate relatively impermeable shotcrete.
8. The addition of accelerators to the shotcrete did not result in any increase in the compressive strength at 7-days age; in fact, a slight decrease was noted.

9. In general, the epoxy-coated panels did not increase the bond strength of shotcrete to old shotcrete or old concrete.

10. The direct tensile test was the best test used in this investigation for evaluating the bond strength and uniformity of shotcrete. The shotcreting process results in a layering of the material as it is placed. Normally, placement of shotcrete is parallel to the direction in which test specimens are taken. In compressive testing, the layering effect does not significantly affect the test results. However, in the direct tensile tests, the layering effect is critical to the test results; hence, a better measure of the uniformity and quality of the shotcrete can be determined.

11. The percent rebound obtained on the dry-mix, fine-aggregate shotcrete was 36; on the dry-mix, coarse-aggregate shotcrete, 39; on the wet-mix, fine-aggregate shotcrete, 30; and on the wet-mix, coarse-aggregate shotcrete, 35.

12. The average water absorption values of 3.8 to 4.4 percent indicated normally dense shotcrete.

13. The average unit weights of the shotcretes were of magnitudes similar to those of conventional structural concrete (145 to 151 lb/ft$^3$ (2323 to 2419 kg/m$^3$)).

Reviewing these test results and by discussing application processes with the operators, the researchers preferred the wet
SHOTCRETE FOR GROUND SUPPORT

process over the dry process method due to more uniform results and slightly reduced rebound.

TUNNEL SUPPORT

In preparation for initiation of a research project to improve tunnel and rock cavity support systems, the Soils and Pavements Laboratory of the Waterways Experiment Station recently published Contract Report S76-4, which is a "State-of-the-Art Review on Shotcrete." It contains the results of four studies pertaining to shotcrete technology. The first part is an overview of American practices in shotcrete. The second is a discussion of the development and practice of shotcrete technology in Europe, including a description of the New Austrian Tunneling Method (NATM). The third describes the experiences of the US Bureau of Reclamation in using shotcrete for tunnel linings and their design and construction concepts. The fourth is a discussion of instrumentation currently employed for obtaining the data used in design of shotcreted tunnels being constructed by the NATM. The present research plans are to use a computer model, developed in 1975, together with actual documented failure cases, to create a geologic model of a typical tunnel failure and calibrate and verify the computer model. With the model calibrated to duplicate a field situation involving failures or impending failures, various tunnel support systems, i.e., steel sets, rock bolts, shotcrete, rockbolt-reinforced shotcrete, wire-mesh reinforced shotcrete, fiber-reinforced shotcrete, or various combinations will be evaluated for effectiveness in providing tunnel support. Additionally, using the calibrated computer model and a typical tunnel instrumentation plan, tunnel
instrumentation interpretative techniques will be investigated in an effort to assist the engineer in evaluating support requirements and anticipating possible failures.

REHABILITATION OF OLDER STRUCTURES

As mentioned in the introduction, the Corps of Engineers is very interested in economic procedures for rehabilitating older structures. Shotcrete is one of the most practical materials available since it does not require expensive forming. Very good laboratory results have been obtained with the use of short (1-in.) (25-mm) steel fibers in the shotcrete; the steel fibers increase spall resistance and since shotcrete has been shown to be relatively impervious, corrosion becomes a relatively insignificant problem. Shotcrete construction at the Dresden Island Lock and Dam, on the Illinois Waterway, has been one of the Corps' best experiences; the shotcrete was applied in 1953, and Figure 1 shows the appearance in 1976. Figure 2 is a picture of a 6-in. (15-cm) core taken from the lock wall during the summer of 1976. This shotcrete has been exposed to continuous wetting and drying, as well as freezing and thawing for the past 23 years. If research could assure such quality on all newly rehabilitated projects, there would be no question as to ability of shotcrete.

Three (3) representative shotcrete cores from the Dresden Island Project have been evaluated microscopically to determine the air-void content (ASTM C 457). The results of the evaluation are shown in Table 1.
Table 1
Micromatic Air Data\(^{(a)}\) for Shotcrete Cores from
Dresden Island Lock, Illinois Waterway

<table>
<thead>
<tr>
<th>Component</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North Wall</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Entrained Air, (%)(^{(b)})</td>
<td>2.3</td>
</tr>
<tr>
<td>Entrapped Air, (%)</td>
<td>1.5</td>
</tr>
<tr>
<td>Total Air, (%)</td>
<td>(3.8)</td>
</tr>
<tr>
<td>Paste, (%)</td>
<td>43.1</td>
</tr>
<tr>
<td>Aggregate, (%)</td>
<td>52.5</td>
</tr>
<tr>
<td>Wire Mesh, (%)</td>
<td>0.6</td>
</tr>
<tr>
<td>Totals</td>
<td>100.0</td>
</tr>
<tr>
<td>Air Void Spacing Factor (in.)</td>
<td>0.013</td>
</tr>
</tbody>
</table>

\(^{(a)}\) ASTM C 457, examined at 125X
\(^{(b)}\) Air voids 1 mm or less in diameter

Figure 1. Dresden Island Lock and Dam
Figure 2. Dresden Island Lock and Dam Core

Figure 3. Fiber-Reinforced Shotcrete Domes
Prior to Placement
Whether the air was intended to be entrained or not, I do not know, but the resulting 2 percent average entrained air along with the relatively high strength has certainly provided the project with a relatively maintenance free surface.

**PROTECTIVE STRUCTURES**

The US Army Corps of Engineers' Construction Engineering Research Laboratory has been investigating various systems to develop field operational systems for constructing hardened shelters for use in theaters of operation. Their requirements are for a system that is rapid, economical, and of course requiring low skill to construct.

Fiber reinforced cellular shotcrete has been found to meet these requirements and domes measuring to 28 ft in diameter have been successfully constructed on the laboratory grounds in Champaign, Illinois. Figure 3 reflects the appearance of the placement prior to shotcreting. Figure 4 shows the completed 28-ft diameter by 14-ft-high dome with entrance. Figure 5 shows dome number 4, 18 ft in diameter by 10 ft high, being lifted from the construction platform by a truck mounted crane. This dome is 2-1/2 to 3 in. thick and weighs approximately 20,000 pounds. It is reinforced with 1 percent by volume of steel fibers; no other reinforcement was used. Only four lift points were required to successfully move the dome 75 ft into position for testing. This dome has been subjected to a simulated 4-ft underground burial by covering with 70 tons of sand. Dial gages monitor long-term deformations. As
Figure 4. Completed 28-ft Diameter Fiber-Reinforced Shotcrete Dome

Figure 5. 18-ft Diameter Dome Being Lifted
of this time, no increased deformation over that experienced at the time of applying the load has occurred. The dome has been under load for 16 months.

SUMMARY

As you can see, the Corps of Engineers is very much interested in the use of shotcrete and envisions many economical and desirable uses of the system. We are very interested in the physical properties of shotcrete as well as its ability to be used in rapid construction, as a repair material, for tunnel supports, and for protective structures.

References

1. ACI Standard "Recommended Practice for Shotcreting (ACI 506-66)," American Concrete Institute, Detroit, MI, 1966.


