PROPERTIES OF SHOTCRETE ON
CONSTRUCTION PROJECTS

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INTRODUCTION

The Author has been involved in the materials aspects of shotcrete construction since 1965. At that time there were no applicable codes or testing standards available on which to base conformance testing so it was necessary to develop appropriate in-house procedures.

This paper relates to shotcrete properties as determined from tests conducted on samples prepared at construction projects. The Author’s experiences relate to projects covering a range of shotcrete work in underground mining, restoration, channel lining, slope protection and foundation stabilization. However, in order to present shotcrete properties on a comparable basis, information here will be confined to those test results obtained from a series of ten foundation support projects recently constructed in the Vancouver area.

Test procedures referenced were developed by the Author in consultation with the staff of Dolmage, Mason and Stewart, who were the prime shotcrete consultants on the majority of the projects. The procedures have evolved since 1965 with periodic modifications to obtain evaluations of shotcrete properties in a form which would provide the quality control for the prime consultants supervision.

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functions. Readers will appreciate that this has been a unique opportunity to objectively develop testing procedures which directly provide the information required for engineering a system without the necessity of strict conformance to conventional codes.

SHOTCRETE PERFORMANCE REQUIRED

Foundation stabilization systems are often demanding on the performance of the support materials, in this case, shotcrete. There are close parallels with the support of unstable ground in underground excavations.

The shotcrete is required to:
- have high early strength gain to prevent soil sloughing or weather slaking;
- bond to the soil system to permit "membrane" action with the ground system (and, in some cases, the soil anchors);
- be sufficiently flexible to accommodate localized strains and provide load redistribution - again a "membrane" action;
- be sufficiently impermeable and/or set rapidly to arrest ground seepage.

Ideal properties are therefore rapid set, early strength gain, bond to the native soil and flexibility.

Experience indicates that these ideal properties can be achieved using dry mix shotcrete with the addition of accelerating admixtures and with mix proportioning optimizing rapid and high level flexural strength gain and high in-place density.
CONSTRUCTION SPECIFICATIONS

Following is an outline of the materials portion of construction specifications which have been evolved by Dolmage, Mason & Stewart for foundation stabilization shotcreting.

(a) Aggregates

Aggregates are required to be provided in two sizes, sand and 3/8 inch x No. 4 stone. They are blended to achieve the combined gradation limits shown in Figure 1.

Superimposed on Figure 1 is the Fuller theoretical maximum density curve which was used to develop the original specification. The Figure also shows the overall particle size distribution that would result from aggregates blended to the median of the specifications with a normal cement content added.

Aggregate particles are required to meet conventional ASTM C33 limits for concrete aggregate with the following additional criteria:

Maximum passing No. 200 screen -

<table>
<thead>
<tr>
<th></th>
<th>stone</th>
<th>sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit</td>
<td>0.25%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

The stone limit was imposed to provide maximum particle bond and therefore flexural strength. The sand limit was originally intended to assist in minimizing workmen hazards from airborne dust. (Not a major problem in open excavation.)
Figure 1 - Aggregate Gradation Chart
CONSTRUCTION PROJECTS

(b) Shotcrete Strength

Minimum performance required is:

<table>
<thead>
<tr>
<th></th>
<th>Compression (psi)</th>
<th>Flexure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>-</td>
<td>300</td>
</tr>
<tr>
<td>7 day</td>
<td>3000</td>
<td>450</td>
</tr>
<tr>
<td>28 day</td>
<td>4000</td>
<td>600</td>
</tr>
</tbody>
</table>

(c) Density

Properties required at 7 days:

- boiling absorption - 6-1/2% maximum
- volume permeable voids - 12% maximum

(d) Mix Design

A typical mix design used for the projects was:

- Cement, Type 10 700 lb
- Stone, 3/8" x No. 4 1350 lb
- Sand, No. 4 x dust 1820 lb
- Water, net through nozzle 245 - 275 lb
- Accelerator, powder type 3 - 4% of cement

TEST PROCEDURES

Shotcrete properties are evaluated by the following procedure:

1. Sampling

A panel is prepared on the site during shotcreting by using a 2 ft x 2 ft x 4 inch plywood-backed form supported vertically. The panel is protected by a plastic sheet cover.
until it can be transported to the laboratory.¹

Test samples are obtained by cutting with a diamond saw from the central portion of the panel. Normally, eight 3-inch cubes and three 3 inch x 3 inch section beams are obtained. Cubes are tested in pairs with the average constituting a test.

Two cubes are used for the density determinations and the remainder for:

2 at earliest possible test age, nominally one day;
2 at 7 days;
2 at 28 days

compressive strength determinations. For flexural strength, sufficient beam length is obtained (about 18 inch) to permit two tests on one sample. Test ages are as above.

2. Curing

Initial strength tests are conducted on samples as received (without any temperature or moisture conditioning). They therefore provide an appraisal of the in situ early age conditions. Samples are subsequently cured at 73 ± 3F in a fog room.

Density samples are cured similar to strength samples. They are normally tested at about 7 days although experience indicates that there is no major improvement in void and absorption characteristics after three days.

¹If the panel is shot early in the day, it can be moved without damage later the same day, otherwise it is transported early the next day.
3. Strength Tests

Compression - ASTM C42 with the direction of loading perpendicular to the direction of shooting

Flexure - ASTM C78 (One-Third Point Loading) with the direction of loading parallel to the direction of shooting

Loading directions have been selected to simulate the field conditions.

One-Third Point flexural loading has been found to give a better overall evaluation of shotcrete quality since the constant mid-span moment, to a degree, avoids testing the inevitable localized shotcrete structure variations.

4. Density Tests

Procedures of ASTM C642 are used.¹

PROJECT PARAMETERS

It was indicated above that a group of projects had been selected in order to provide comparable information. These projects span a three-year period and all involved the use of shotcrete to stabilize deep excavation walls (shotcrete shoring system). Construction was by a single shotcrete contractor and supply of the material from a single central mix plant. Following are the common elements:

¹Concrete technologists will appreciate that this test procedure does not provide an evaluation that directly correlates with concrete durability or permeability. However, experience indicates that it is a realistic evaluation of the density of the shotcrete structure.
SHOTCRETE FOR GROUND SUPPORT

- Shotcrete sprayed by dry mix method using a Mayco Gun.
- All mixes had powdered accelerators added at the mixing pot.
- Single type of aggregate - 3/8 inch maximum size, glacio fluvial origin consisting of hard sound particles predominantly granitic.
- Mix transported in ready-mix trucks.

Foundation wall areas shotcreted ranged from 6,000 to 70,000 sq ft.

TYPICAL SHOTCRETE PROPERTIES

Figures 2 and 3 present the age-strength curves for flexural and compression tests from the projects. A best fit line and 20% dispersion limit are shown. It is apparent that there is almost a linear relationship between both strengths and the log of the curing time - this indicates that the shotcrete is performing in accordance with the Plowman Maturity Principle for conventional concrete.

It will also be evident from Figures 2 and 3 that the specified strength levels have readily been met. Twenty-eight day compressive strengths in the order of 7000 psi and flexural strengths of 1000 psi were achieved.

Curves in Figures 2 and 3 have been extrapolated backwards to an approximate "zero" strength age as determined by previous tests.

Figure 4 provides more interesting information. It shows that flexural strength of shotcrete is a far higher percentage of compressive strength at early rather than later age.\(^1\) It is thought that

\(^1\)After about 3 days the compressive : flexural ratio is about the same as would be expected from conventional concrete produced from the same aggregate and cement as used here.
Figure 2 - Compressive Strength versus Curing Time
Figure 4 - Strength Ratio versus Curing Time
this phenomena is related to a combination of:

- the action of the accelerator;
- the high aggregate bond strength resulting from coating of stone particles in dry mix shotcrete;
- the lower stone content of an as-shot mix compared with conventional concrete.

Test results provide an interesting relationship between flexural and compressive strength. Figure 5 shows results obtained from the best fit curves of Figures 2 and 3 and indicates that the relationship can be generally represented by:

\[ f_{mr} = 0.74 f_c^{0.82} \]

where \( f_{mr} \) = flexural strength (modulus of rupture)

\( f_c \) = compressive strength

as determined by test procedures here.

Tests on the shotcrete showed values of voids and boiled absorption generally within the 12 and 6-1/2% limits respectively of the specifications. Figures 6 and 7 show the correlation of these values with both forms of strength test. There is a general relationship between the absorption and strength, as represented by the best fit lines on the Figure, although the scatter for absorption versus flexural strength is appreciable.

High quality conventional concrete, in the order of 5,000 psi compressive strength and 0.45 water : cement ratio, would have voids and absorption values in the same order of magnitude as these results.

The fact that strength is generally a function of density is not surprising and not inconsistent with conventional concrete technology.
Figure 5 - Log Modulus of Rupture versus $f_c$
Figure 6 - Compressive versus Absorption and Voids
This paper describes shotcrete test procedures which have been developed to provide materials quality control for foundation stabilization programs. Typical test results are presented.

The test procedures have been developed to specifically provide engineers with the type of information required to complement their design systems. Necessary information primarily includes evaluations of early age flexural strength and shotcrete density. Experience indicates that the procedures are practical, effective and economical.

Test results show that shotcrete has properties such as:
- age : strength relationships;
- strength : density relationships similar to conventional concrete. It is capable of being produced to high strength and density levels. A unique feature of shotcrete, and one that partially accounts for its effectiveness in early ground stabilization, is its high early age flexural strength.

There are no present generally referenced test procedures for shotcrete. It therefore presents a unique opportunity for engineers to develop procedures that will directly complement their design systems.

The Author suggests that more emphasis in this direction is preferable to expenditures of technical time and energy in debating refinements of test procedures.
Figure 7 - Flexural versus Absorption and Voids