

# Variability of Compressive Strength of Shotcrete in a Tunnel-Lining Project

By Lihe (John) Zhang

**R**ecently, questions have been asked by the International Tunnelling and Underground Space Association (ITA) about what variability can be expected for compressive strength for shotcrete (sprayed concrete) in ground support projects. The compressive strength of concrete and shotcrete is mainly controlled by mixture design parameters, including the water-cementitious material ratio ( $w/cm$ ). With shotcrete, other factors, including the skill set of the nozzle man applying the shotcrete, can also affect compressive strength. The shotcrete method used—wet-versus dry-mix and accelerator addition at the nozzle—may also affect compressive strength and variability.

During recent shotcrete ground support projects, the author conducted routine quality control (QC) testing for compressive strength of shotcrete. Data from these projects showed that the compressive strength is dependent on the application method used. For one tunnel project, over 6500 yd<sup>3</sup> (5000 m<sup>3</sup>) of accelerated wet-mix shotcrete was applied and over 700 sets of cores (two cores for each set) were tested for compressive strength at 7 and 28 days of age. This paper provides a statistical analysis of the shotcrete compressive strength test data from a civil tunnel project in western Canada and shows that the variability in compressive strength is influenced by a number of factors.

## Introduction

During the construction of a tunnel project in western Canada, a total of over 6500 yd<sup>3</sup> (5000 m<sup>3</sup>) of shotcrete was applied as the final lining. The tunnel was lined with shotcrete reinforced with one or more types of reinforcement, including rock anchor bolts, steel mesh, steel sets, or ring beams, depending on the ground conditions. Wet-mix shotcrete with accelerator added at the nozzle was used for the project. The project design required shotcrete to be applied to an average thickness of 4 in. (100 mm), with a minimum 2 in. (50 mm) cover over steel sets or ring beams.

Performance requirements for the wet-mix shotcrete were as follows.

## Specifications

- Compressive strength: 1450 psi (10 MPa) at 3 days, 2900 psi (20 MPa) at 7 days, 5000 psi (35 MPa) at 28 days tested to ASTM C1604/C1604M;
- Boiled absorption: <8% tested to ASTM C642; and
- Volume of permeable voids: <17% tested to ASTM C642.

To meet the performance requirements, a wet-mix shotcrete with silica fume was designed, as shown in Table 1.

This mixture design used 10% silica fume by mass of cement to achieve the durability requirement. A hydration-controlling admixture was used to extend the plastic life of the shotcrete for up to 8 hours. To apply overhead shotcrete with minimal fallout, an alkali-free accelerator was added at the nozzle at dosages of 6% by mass of cement. The higher dosages of accelerator were used in wet ground conditions and where thicker shotcrete encapsulations were required.

## Shotcrete Quality Control Testing

The project required hand nozzling and all of the nozzle men were American Concrete Institute (ACI) Certified Nozzle men. Two levels of qualifications were required: Level I—each nozzle man was required to shoot a vertical test panel and an overhead test panel, and cores were extracted from each panel and tested for compressive strength, boiled absorption, and volume of permeable voids as required by the project specification; Level II—each nozzle man was qualified specifically to the underground reinforcement shooting, underground ring beams, steel girders, and wire mesh reinforcement.

During the construction stage, one QC testing panel was shot for each nozzle man for each day when shotcrete was applied. Four cores with diameters of 2.75 in. (70 mm) were extracted for

Table 1: Wet-mix shotcrete mixture proportions

Material	Mass per 1.3 yd <sup>3</sup> (1 m <sup>3</sup> ), SSD aggregate
Cement type GU	900 lb (410 kg)
Silica fume	88 lb (40 kg)
Coarse aggregate (0.2 to 0.4 in. [5 to 10 mm], SSD)	1180 lb (535 kg)
Fine aggregate (SSD)	2480 lb (1125 kg)
Water	49 gal. (185 L)
Water-reducing admixture	0.142 gal. (0.538 L)
Hydration-controlling admixture	0.227 gal. (0.860 L)
Air content: at pump	3 to 6%
As shot, ±1.5	3.5%
Total	5072 lb (2301 kg)

every test panel. Two cores were tested for compressive strength at 7 days and two cores were tested at 28 days. Shotcrete construction included Stage I, when shotcrete was applied primarily on the upper walls and overhead parts of the tunnel, and Stage II, when shotcrete was applied primarily in the lower half of the tunnel. A total of over 1000 cores were extracted from QC test panels and tested during the whole construction stage of the project.

### 7-day Compressive Strength

A total of 566 cores were tested for 7-day compressive strength in Stage I of the project and 482 cores in Stage II. Test results are graphically shown in Fig. 1 and 2 for Stage I and Stage II, respectively.

Figures 1 and 2 show that the 7-day compressive strength for shotcrete cores extracted from the test panels ranged from 1450 to 7300 psi (10 to 50 MPa) with the majority of results meeting the specified minimum (7-day requirement of 2900 psi [20 MPa]). For Stage I shotcrete, the average compressive strength was 4400 psi (30.5 MPa) and there were 22 cores out of 556—that is,  $22/566 = 3.9\%$ —where the 7-day strength did not meet the specified 2900 psi (20 MPa) compressive strength requirement. For Stage II shotcrete, the average 7-day compressive strength was 4200 psi (28.7 MPa) and there were 30 cores out of 482—that is,  $30/482 = 6.2\%$ —where the 7-day strength did not meet the specified compressive strength requirement.

The standard deviation (SD) for shotcrete core 7-day compressive strength from both Stage I and Stage II shotcrete was less than 1300 psi (9 MPa), with 95% of them being less than 730 psi (5 MPa). The coefficient of variation (COV) for 7-day compressive strength was 21% for Stage I shotcrete and 20% for Stage II shotcrete. It should be noted that 95% (540/566) of the core strengths in Stage I had a COV of less than 15%, while 95% (460/482) of the core strengths in Stage II had a COV of less than 20%. This shows that the

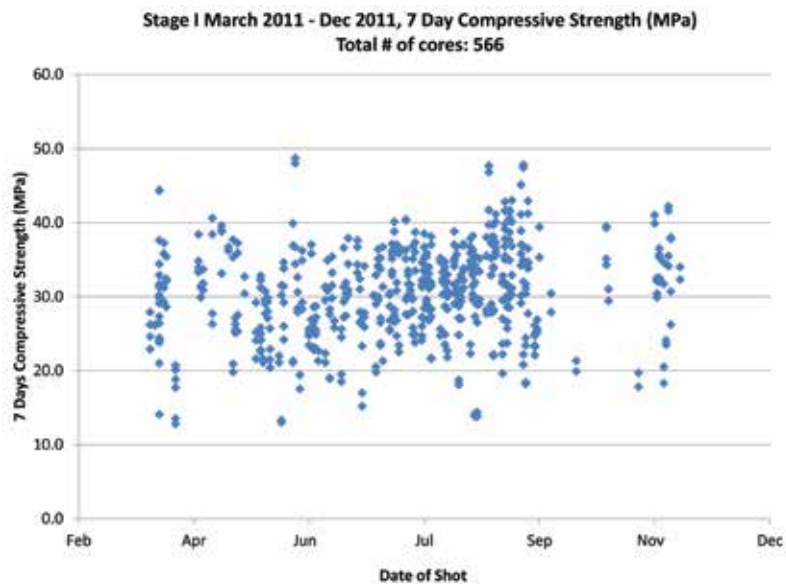


Fig. 1: 7-day compressive strength for shotcrete cores from test panels, March to December (Note: 1 MPa = 145 psi)

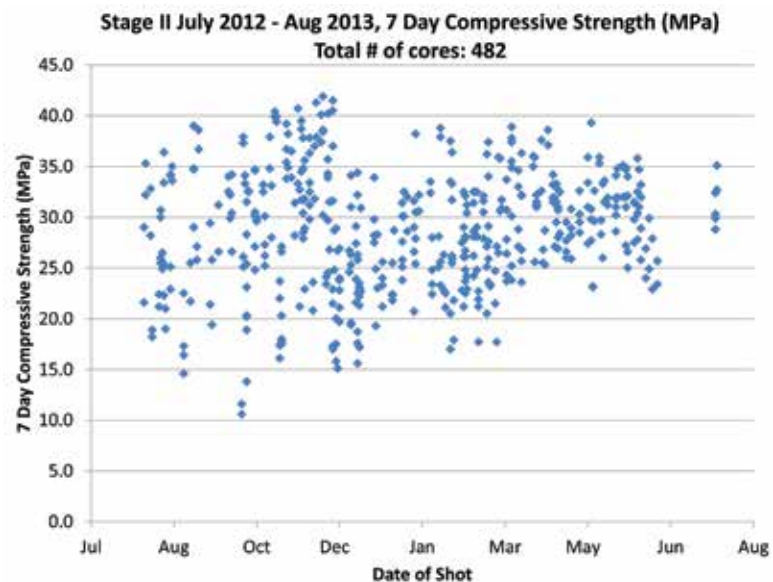


Fig. 2: 7-day compressive strength for shotcrete cores from test panels, July to August (Note: 1 MPa = 145 psi)

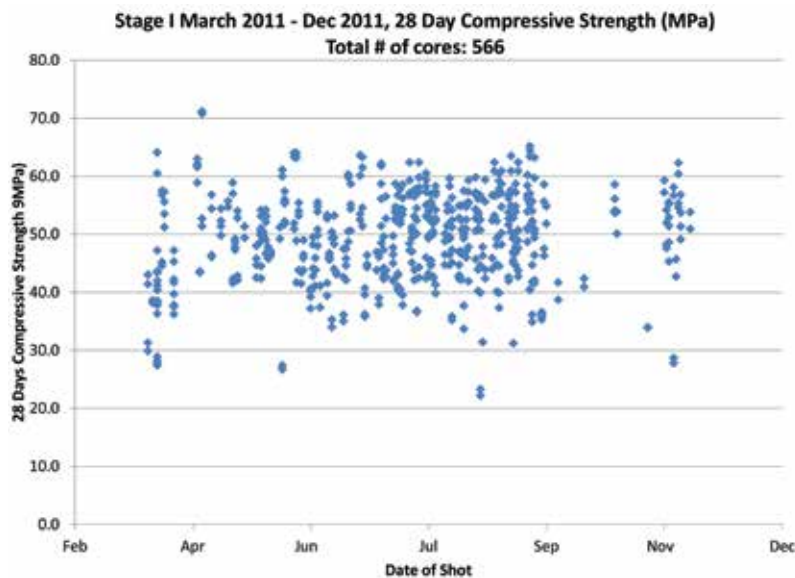


Fig. 3: 28-day compressive strength for shotcrete cores from test panels, March to December (Note: 1 MPa = 145 psi)

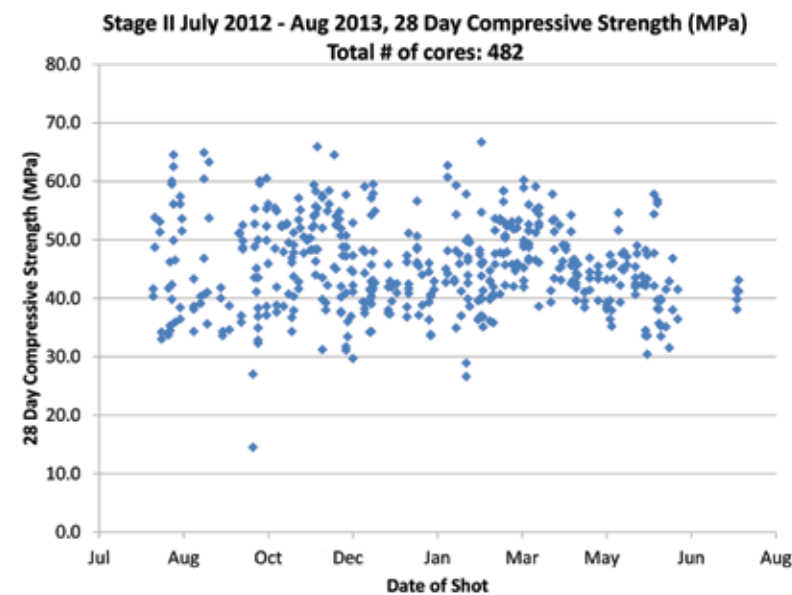


Fig. 4: 28-day compressive strength for shotcrete cores from test panels, July to August (Note: 1 MPa = 145 psi)

strength variation of Stage II shotcrete cores is higher than in the Stage I shotcrete cores.

## 28-day Compressive Strength

Figure 3 shows the compressive strength development at 28 days for Stage I shotcrete. It ranged from 4400 to 10,300 psi (30 to 71 MPa) with an average compressive strength of 7140 psi (49.2 MPa). For Stage I shotcrete, there were 15 cores that have strengths lower than the specified 5000 psi (35 MPa), which means that 97% (551/566) of the shotcrete cores met the specified compressive strength of 5000 psi (35 MPa) at 28 days.

For Stage II shotcrete, except for one core which had a compressive strength of 2000 psi (14 MPa), the 28-day compressive strengths ranged from 3900 to 9700 psi (27 to 67 MPa) with an average compressive strength of 6600 psi (45.4 MPa). Figure 4 shows there were 16 cores with strengths lower than the specified minimum 5000 psi (35 MPa). This means that 97% (464/482) of the shotcrete cores met the specified compressive strength of 5000 psi (35 MPa) at 28 days.

The SD and COV of the 28-day compressive strength for Stage I and Stage II were calculated and are summarized in Table 2. The SD of 28-day compressive strength for Stage I shotcrete is 1100 psi (7.8 MPa) and the COV is 16%. Except for three cores that show higher SD and COV, the SD for Stage I shotcrete 28 days core strength is less than 870 psi (6 MPa). This shows that 99.5% (553/556) of the Stage I shotcrete cores had a SD of less than 870 psi (6 MPa) and a COV of less than 15% at 28 days.

The SD of 28-day compressive strength for Stage II shotcrete is 1100 psi (7.5 MPa) and the COV is 17%. Except for four cores, the SD for Stage II shotcrete core strength is lower than 1450 psi (10 MPa). This means that 99.4% (479/482) of the Stage II shotcrete cores had a SD of less than 1450 psi (10 MPa) and a COV of less

Table 2: Summary of average strengths, standard deviation, and coefficient of variation at 7 and 28 days

Variation	Stage I shotcrete compressive strength		Stage II shotcrete compressive strength	
	7 days	28 days	7 days	28 days
Specified, psi (MPa)	2900 (20)	5000 (35)	2900 (20)	5000 (35)
Average, psi (MPa)	4420 (30.5)	7140 (49.2)	4160 (28.7)	6580 (45.4)
SD, psi (MPa)	910 (6.3)	1130 (7.8)	840 (5.8)	1090 (7.5)
COV, %	21	16	20	17
CSA required average strength, psi (MPa)	4580 (31.6)	7280 (50.2)	4410 (30.4)	7180(49.5)

than 28%. This shows that the 28-day compressive strength for Stage II shotcrete cores is higher than that in Stage I shotcrete.

## Compressive strength at 28 days versus 7 days

Generally, concrete develops about 70 to 75% of its 28-day compressive strength at 7 days. For shotcrete cores, similar compressive strength development is expected, provided the cores are cured properly. Figures 5 and 6 show the increases of the compressive strength from 7 days to 28 days. The compressive strength ratio is defined as the ratio of compressive strength at 28 days versus the compressive strength at 7 days. The ratio ranges from 1.5 to 2.5 for both Stage I and Stage II shotcrete. This variability could be attributed to the following reasons:

- 1. Curing of the testing panels:** The shotcrete QC test panels were typically shot in the tunnel, and left there for 2 days before being transported to the surface and then to the testing laboratory. The moisture content in the tunnel was generally above 80%, and was considered to provide natural curing as defined in ACI 506.5R-09, "Guide for Specifying Underground Shotcrete." But the temperature in the tunnel was generally in the 40 to 50°F (5 to 10°C) range. In addition, Sets 541 and 542 had greater increases in compressive strength from 7 to 28 days due to the fact that the cores were left on site without proper curing (the weather was cold during February when cores were extracted), and were only delivered to the lab at 7 days of age. Therefore, these cooler temperatures caused a slower rate of strength development in the 7-day test results, compared to cores with standard laboratory curing at 73°F (23°C) from 2 days of age.
- 2. Handling the QC test panels:** Due to the challenges in shotcrete QC panel handling, some panels, when moved to the surface, were found to have been left outside for a few days without proper curing before cores were extracted for testing. In a few cases, the shotcrete cores were extracted at 7 days and then sent to the laboratory for testing without even being stored in the laboratory curing tank.
- 3. Addition of accelerator:** An alkali-free accelerator was added to the shotcrete. The dosage of the accelerator was found to not be consistent during shotcrete production. This was largely due to the challenges of properly operating the accelerator dosing pump in the underground environment. The author worked with the contractor to accurately calibrate the accelerator dosing pump, establish operational procedures, and train the shotcrete crew.<sup>3</sup>

However, it was found that the accelerator dosing pump was not always operated properly. Excessive accelerator addition occurred at times and was found to be detrimental to the 7- and 28-day compressive strength.<sup>4</sup> This influenced the variability of compressive strength test results.

- 4. Nozzlemen shooting technique:** Shotcrete is a method of placing concrete, and the quality of the shotcrete is dependent on the nozzlemans skills. Hand nozzling requires proficient operation of the nozzle, prompt adjustment of

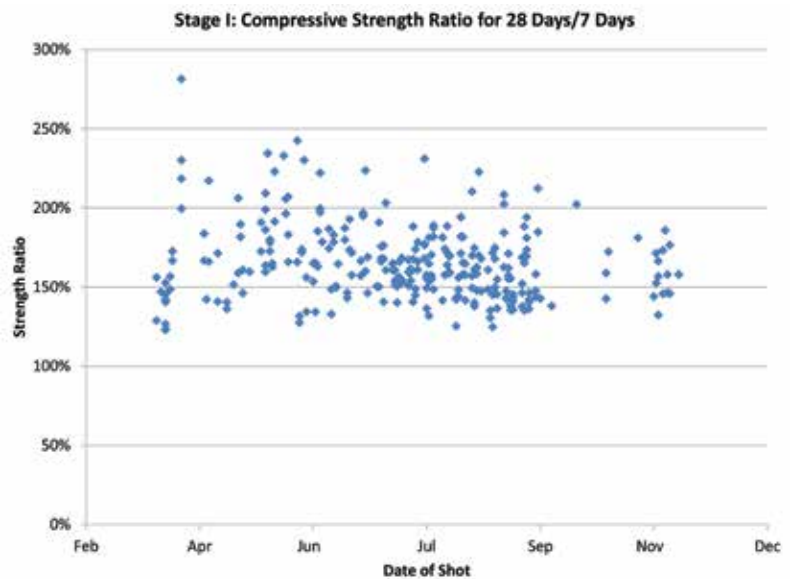


Fig. 5: Compressive strength of concrete at 28 days versus 7 days for Stage I shotcrete

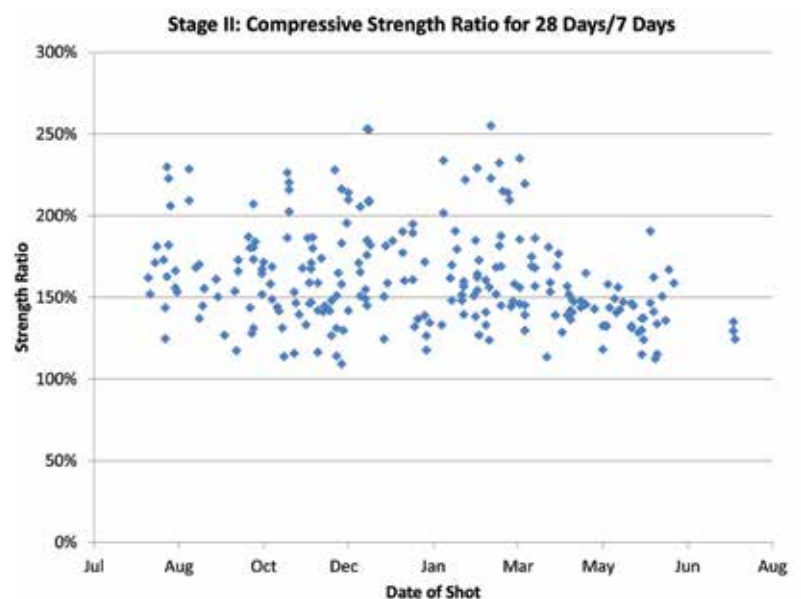


Fig. 6: Compressive strength of concrete at 28 days versus 7 days for Stage II shotcrete



the accelerator dosage to meet the ground condition requirements, and instant communication with other crew members, including the pump operator, to operate safely. During shotcrete construction, two items which influenced compressive strength were observed and found to be related to the nozzleman's shooting technique. First, a variation in strength between two cores extracted from the same test panel was shot by one nozzleman. One set (Set 282) had a core with 28-day compressive strength of 7140 psi (49.2 MPa), and the strength of the other core was only 3550 psi (24.5 MPa). Another set (Set 323) had one core with a compressive strength of 4680 psi (32.3 MPa) and the other core had a compressive strength of 7250 psi (50.0 MPa). Second, core strength variations were found between different nozzlemen. During QC testing, it was found that the shotcrete core strength from one particular nozzleman was typically 725 to 1450 psi (5 to 10 MPa) lower than the other nozzlemen. Shotcrete cores were examined prior to and after testing and it was found that there was typically a layer of overspray in the middle of the cores (Fig. 7). This nozzleman was then trained by the author to properly operate the nozzle and improve nozzling skills.

## Variability of Shotcrete Core Compressive Strength

1. Table 2 summarizes the SD and COV for 7- and 28-day compressive strength for both Stage I and Stage II shotcrete. It shows that the COV



Fig. 7: Low-strength shotcrete cores from one nozzleman, with overspray in the middle

for 7-day strength is 20 to 21%, and 15 to 17% for 28-day strength. This shows that the 7-day strength tends to have higher variation than the 28-day strength. The reasons have been discussed in the previous sections. Those include curing, panel handling, and core extraction.

2. The Canadian Standard Association (CSA) A23.1/23.2-2009<sup>4</sup> requirements for cores drilled from a concrete structure are: "... for standard-cured concrete specimens, the strength can be accepted if concrete has an average strength of (1) 1.4 times the SD above the specified strength when the SD is not more than 3.5 MPa (500 psi); and (2) 2.4 times the SD minus 3.5 MPa ( $2.4 \times \text{SD} - 3.5 \text{ MPa}$ ) above the specified strength when the SD is more than 3.5 MPa (500 psi). The SD should be based on at least 30 consecutive strength tests, representing concrete made from a single mix design." The CSA-required strength is calculated and listed in Table 2. It appears that the actual average strength for 7 days and 28 days for Stage I and Stage II are slightly lower than the CSA-required average strength. This is due to the fact that several compressive strength tests did not meet the specified compressive strength of 2900 psi (20 MPa) at 7 days and 5000 psi (35 MPa) at 28 days.

Based on the testing data from this project, it appears that the COV of shotcrete core strength should be less than 20%. The least variation can be achieved by proper mixture design, rigorous quality control, proper curing and handling of test panels and shotcrete core samples, proper shooting skills, and most importantly, rigorous implementation of a QC testing program to test compressive strength for daily shotcrete production.

## Low Compressive Strength

When shotcrete cores show low compressive strength results, the owner will question the quality of the shotcrete being applied, and the contractor will then be required to pay attention to shotcrete production, transportation, and application, as well as the handling and curing of the shotcrete test panels. One example is a test result from January and February. Shotcrete core strength results (Sets 500 to 600) showed that the strengths at 7 days were lower than 2900 psi (20 MPa), and then increased greatly to about 5800 psi (40 MPa) at 28 days; later on, March shotcrete core strength test results (Sets 600 to 630) showed that the strength increased by about 4350 psi (30 MPa) from 7 to 28 days.

The low test results from Sets 500 to 600 (January and February) was attributed to the test panels being kept in the tunnel for a few days due

to logistic challenges, and then were moved to above ground and left uncured. Considering the cold weather conditions in the tunnel site, which were normally 32 to 50°F (0 to 10°C) during that time, the strength gain at early age under low temperature conditions was not sufficient. Most of these sets were delivered to the QC lab at about 6 or 7 days, and then put into the curing tank for standard moist curing. The 7-day compressive strength was thus tested when cores had not been properly cured. Consequently, the 28-day strength increased dramatically, and even doubled or tripled compared to 7-day compressive strength, as shown in Fig. 5 and 6.

Once core compressive strength was found to be lower than the specified strength, the shotcrete was ruled to be nonconforming. Contractors were then required to extract in-place cores from the tunnel and test these in-place cores for compressive strength. Test results for in-place cores override the strength of cores from the test panels and these cores were referred to as quality assurance (QA) cores. Normally, three shotcrete cores were extracted from one area and tested for compressive strength. Compressive strengths from QA cores ranged from 5440 to 8380 psi (37.5 to 57.8 MPa). Although the testing age exceeded 28 days, the strength met the 5000 psi (35 MPa) requirements and therefore, the project owner accepted the shotcrete represented by them.

## Summary

Underground shotcrete QC core strength is dependent on the mixture design, nozzleman skills, equipment, curing conditions, and test panel handling.

Variation in compressive strength of shotcrete cores at 28 days was found to be less than that found at 7 days.

When accelerator was used, the variation of the core strength tended to increase.

With a proper QC program, a minimum of 96% of the shotcrete cores tested met the specified minimum compressive strength of 2900 psi (20 MPa) at 7 days and a minimum of 96% of the shotcrete cores met the specified compressive strength of 5000 psi (35 MPa) at 28 days.

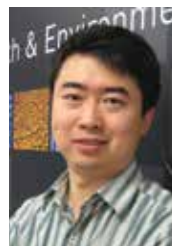
Tunnel shotcrete cores show an SD of 870 to 1160 psi (6 to 8 MPa) for compressive strength,

and COV of 16 to 21%. The variation can be minimized by proper mixture design, rigorous quality control, proper curing and handling of test panels and shotcrete core samples, proper shooting skills, and most importantly, implementation of a rigorous QC testing program to test compressive strength for daily shotcrete production.

Shotcrete cores from test panels with strengths lower than the specified compressive strength were rejected as nonconforming. In such cases, in-place cores can be extracted from the tunnel lining and tested for compressive strength, with these results overriding test panel results.

## References

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