Reaching 20 MPa (2900 psi) in 2 Hours is Possible

By Simon Reny and William Clements

In the mining and tunneling industries, time is critical; and as the mining/tunneling cycle becomes shorter, production increases. Shotcrete is often used for ground support when using the drill and blast method or other tunneling methods. But before reopening access for the next phase of the underground heading, the applied shotcrete must reach a minimum compressive strength to ensure the safety of the workers going into the heading. To speed up the mining and tunneling process, King Packaged Materials Company has been continually investigating different approaches to obtain the minimum required compressive strength as fast as possible. By using high-early-strength cement (Type III or Type HE) and a high accelerator dosage, it is possible to provide a shotcrete mixture design capable of reaching early-age compressive strengths of up to 7 MPa (1000 psi) in 4 hours. But to go over this previous limit, the cement technology needed to be reviewed. Working with calcium sulfo-aluminate cement (CSA), a Rapidset Cement technology from CTS Cement, King has developed a research program to bring early-age compressive strength gain to another level. One of the challenges in shotcreting with Rapidset Cement, as its name implies, is that it sets almost instantly. This can prove difficult when casting test specimens. Combining the use of the Rapidset Cement technology with the dry-mix shotcrete process provides a solution for reducing the mining and tunneling cycle.

Fig. 1: Shooting test panels above ground in winter conditions

Fig. 2: Shooting test panels and end beams on surface in summer conditions

The testing program included a first phase where the cement paste was optimized with the use of different pozzolans. Following this initial testing, the target final set time was established to be 10 minutes after shooting. The rapid-strength-gain dry-mix shotcrete went through several levels of testing prior to its availability for commercial use. Initially, the rapid-strength-gain dry-mix shotcrete was tested internally by King in both winter and summer conditions above ground (refer to Fig. 1 and 2). Following that, the rapid-strength-gain dry-mix shotcrete was tested in both a mine training facility (to observe the effect of underground conditions) and at Laval University (Quebec City, QC, Canada), where all parameters of the shotcrete application could be controlled. The final portion of the testing protocol involved testing the rapid-strength-gain dry-mix shotcrete underground at a mining facility in Northern Ontario under a cemented sand-fill section.

Results

Shooting operations were conducted using both the Aliva 246 and Aliva 252 dry-mix shotcrete machines. Regular shooting procedures were followed as described in ACI 506, "Guide to Shotcrete."[1] During the first two phases of testing, a standard mining shotcrete (produced by King) was used as a control mixture to make sure all of

Fig. 3: End beams in a steel mold after shooting underground

the different parameters were typical to normal shotcrete operations. The control mixture results met the usual standard; therefore, these results are not presented in the article as they are not relevant to the topic. Setting time was determined using a hand-held penetrometer in accordance with ASTM C1117, "Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance (Withdrawn 2003)." Early-age compressive strength was determined using the end-beam test method, adapted from ASTM C116, "Test Method for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure (Withdrawn 1999)"[2] (refer to Fig. 3). Later, age compressive strength was determined in accordance with ASTM C1604, "Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete." The boiled absorption and volume of permeable voids was determined in accordance with ASTM C642, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." Also, the shotcrete nozzleman was asked to provide comments regarding the evaluation of the material (including rebound) based on his experience. The rapid-strength-gain dry-mix shotcrete was tested for all of the properties listed above at different material and ambient temperatures in order to observe the effects of temperature on the shotcrete mixture. Setting-time results are provided in Table 1. Early-age compressive strength and later-age compressive strength development curves with relation to material temperature are shown respectively in Graphs 1 and 2. The target compressive strengths in both graphs are typical for a mining shotcrete specification. The flexural strength results are presented in Table 2. The volume of permeable voids and boiled absorption results are given in Table 3.

Table 1: Set time results

Date	Jan-12	Jun-13	Dec-13	Feb-13
Final set time	4 minutes	4 minutes	6 minutes	n/a

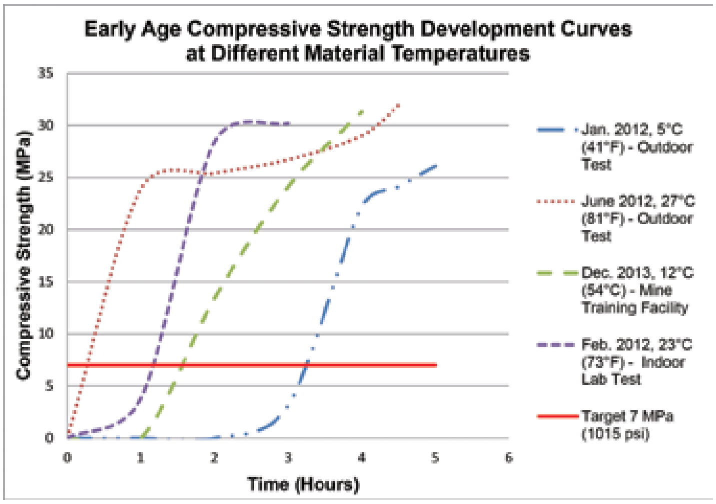
Table 2: Flexural strength results

Date	Jan-12
Initial material temperature	5°C (41°F)
7 days	5.6 MPa (810 psi)
28 days	6 MPa (870 psi)

Table 3: Volume of permeable voids and boiled absorption results

Date	Jan-12	Jun-12	Feb-13
Initial mix temperature	5°C (41°F)	27°C (81°F)	23°C (73°F)
Volume of permeable voids, %	15.8	15.0	15.9
Boiled absorption, %	7.1	7.0	7.1

Graph 1: Early-age compressive strength of end beam specimens



Graph 2: Later-age compressive strength of shotcrete cores

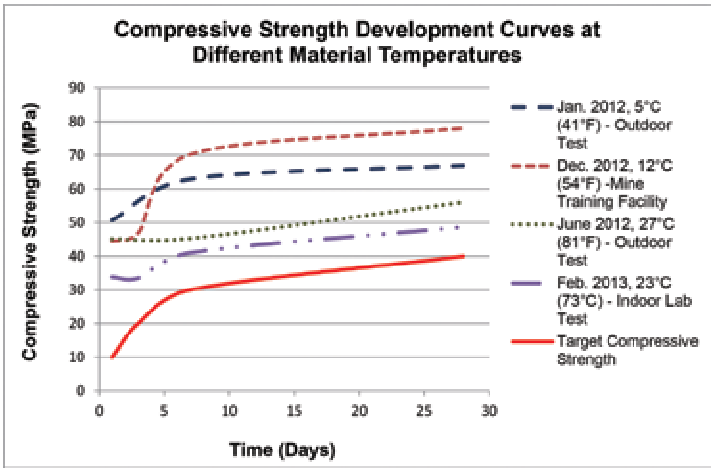


Fig. 4: King representative working with mining personnel to perform maintenance on a dry-mix shotcrete machine

Table 4: In-place test results from underground testing

Date	Mar-13	Jun-13
Temperature	20°C (68°F)	23°C (73°F)
Set time	10 minutes	N/A
Compressive strength at 1 hour	0.7 MPa (101 psi)	12.4 MPa (1798 psi)
Compressive strength at 1.5 hours	9.6 MPa (1392 psi)	N/A
Compressive strength at 2 hours	15.6 MPa (2263 psi)	14 MPa (2031 psi)
Compressive strength at 3 days	30.1 MPa (4366 psi)	41.3 MPa (5990 psi)
Compressive strength at 7 days	45.4 MPa (6584 psi)	42.4 MPa (6150 psi)
Compressive strength at 28 days	47.5 MPa (6889 psi)	51.2 MPa (7426 psi)
Volume of permeable voids, %	19.0	19.3
Boiled absorption, %	8.7	9.0

Various nozzlemen who shot the material in the lab or on the surface commented that the rebound levels were as low as or even lower than silica-fume-enhanced dry-mix shotcrete. They also added that the water was easier to adjust for the proper consistency and the rapid-strength-gain dry-mix shotcrete seemed to be less sensitive to water fluctuation than the control mixture.

The in-place underground testing brought minor daily challenges that a good product should be able to overcome. In this case, when the test was conducted in March 2013, the equipment was in poor condition and required maintenance prior to shooting (refer to Fig. 4). Even after emergency maintenance was performed on the equipment, the material feeding rate was not as consistent as usually expected.

Results from the in-place underground testing program with respect to set time, early-age compressive strength, later-age compressive strength, ambient temperature, volume of permeable voids, and boiled absorption are shown in Table 4.

Nozzlemen who shot the material underground provided the same comments as the nozzlemen who shot the material in lab/surface conditions, which were that the rebound levels were as low as or even lower than silica fume-enhanced dry-mix shotcrete.

Discussion

The early-age compressive strength curves presented in Graph 1 indicate that the material temperature had the largest effect on the time taken to reach compressive strengths in excess of 20 MPa (2900 psi). It should be noted that, even with an initial material temperature of 5°C (41°F), it was possible to reach compressive strengths in excess of 20 MPa (2900 psi) within 4 hours after shooting. The later-age compressive strength curves presented in Graph 2 indicate that the material temperature did not have a major impact on later-age compressive strengths, and all of the samples tested were shown to exceed the target compressive strengths of 10 MPa (1450 psi) at 24 hours, 20 MPa (2900 psi) at 3 days, 30 MPa (4350 psi) at 7 days, and 40 MPa (5800 psi) at 28 days. It should be noted that the lower compressive strength results for the "Indoor Lab Test" (tested Feb. 2013) in Graph 2, can be attributed to the fact that the material was shot at the wettest possible consistency without sloughing. The flexural strength results presented in Table 2 are very similar to results that would be expected from a normal portland cement-based, silica fume-enhanced dry-mix shotcrete. When comparing the early-age compressive strength results between values obtained in lab/surface conditions to underground conditions, it is apparent that the same level of strength development has not been shown to be present in underground conditions. It is possible that this could have been caused by a higher water-cement ratio (*w/c*) being used underground, as it can be more difficult to visually attain the proper consistency in underground conditions.

It is also possible that sand lenses could have been present in end-beam samples due to the poor condition of the shotcrete equipment used underground. Future testing will help provide values that can be expected for early-age compressive strength in underground conditions.

Temperature has a big impact on early-age compressive strength (same as with portland cement), but since the goal of the testing program was to show it is possible to reopen the heading when compressive strengths reach at least 7 MPa (1000 psi) (approximately 1 or 2 hours), the slight reduction in early-age compressive strength in underground conditions was not considered an issue. Therefore, ambient temperature and temperatures of the dry material and water must be controlled and monitored to ensure safety. The set-time results were found to meet the requirements of the testing program and were, therefore, satisfactory.

The absorption values are higher than usual, but the commonly used guidelines that are proposed in literature and generally accepted in the industry[3] were all obtained using portland cement-based shotcrete, so the values available in this test program must be taken as data to be collected for further development. These higher values could possibly be related to shooting with too high of a *w/c* or poor compaction/consolidation which could also explain the lower compressive strength results.

The acceptable or lower rebound level can be explained by the combination of the different pozzolans and the fineness of the calcium sulfoaluminate cement (CSA). CSA cements are usually finer than normal portland cement, causing increased adhesion and compaction. All nozzleman pointed out the fact that the water was easier to adjust and seemed to fluctuate less than conventional portland cement-based dry-mix shotcrete.

Conclusions

1. It is possible to obtain 20 MPa (2900 psi) or even higher compressive strengths at 2 hours in the right conditions using dry-mix shotcrete with CSA for mining applications.
2. The rapid-strength-gain dry-mix shotcrete should be considered a very robust product that is suitable for regular mining and tunneling operations.
3. Early-age strength development seems to be sensitive to ambient temperatures.
4. Absorption results are higher than usual portland cement-based, silica fume-enhanced shotcrete mixtures.
5. In-place testing provided sufficient confidence to the mine to include this new product in the mining cycle. Since being introduced into the mining process, the mine requested that a pigment be added for safety reasons to differentiate where this mixture is used instead of their regular dry-mix shotcrete (refer to Fig. 5).

Fig. 5: Rapid-strength-gain dry-mix shotcrete modified with red pigment

Looking forward, the next steps are:

- To improve the formulation for higher strengths at earlier ages, since the technology provides sufficient evidence to believe it is possible;
- To develop a formulation with different steel fiber dosages and run the appropriate testing; and
- The boiled absorption level must be monitored and investigated, to evaluate if the lower results are the nature of the new technology or result from poor compaction.

References

1. ACI Committee 506, "Guide to Shotcrete (ACI 506R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 40 pp.

2. Heere, R., Morgan, D. R., "Determination of Early-Age Compressive Strength of Shotcrete," *Shotcrete* magazine, V. 4, No. 2, 2002, pp. 28-31.

3. Austin, S. A., Robins, P. J., "Sprayed Concrete : Properties, Design and Application," Department of Civil & Building Engineering, Loughborough University of Technology, Loughborough, UK, 1995, 382 pp.

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