Development of a Wet-Mix Shotcrete for a Deep Mine

by Dan Millette and Michel Lessard

In 2002, an economic study and testing determined that application of wet-mix shotcrete by mechanized application methods permitted substantial gains in cost and in production levels. As is common in new developments, major problems needed to be overcome. Sending the shotcrete through the vertical piping system in the shaft literally put the mixture into a free-fall situation, attaining speeds of 197 mph (315 km/h) over a distance of 1.2 miles (1.9 km). The friction encountered during the fall raised the temperature of the shotcrete by 13 °F (10 °C), altering the properties of the shotcrete and rendering it unusable. In 2003, The Euclid Chemical Co. team, supported by St. Lawrence Cement, was able to put together a self-consolidating wet-mix shotcrete recipe to overcome these extreme conditions. Agnico-Eagle designed a system for receiving the mixture underground and reducing its speed at discharge into the transmixer unit at the bottom of the shaft to a normal flow rate. Because of these trials, the Laronde Division has shot over 45,000 yd^3 (34,500 m^3) of shotcrete and is currently studying the possibility of further increasing the shooting capacity.

The Laronde mine is owned and operated by Agnico-Eagle Mines and located in the Abittibi district of northwestern Quebec, Canada. Since the beginning of construction of the lower levels of the Penna Shaft, it became evident that the use of dry-mix shotcrete in 2200 lb (1000 kg) bags was going to be problematic. The weight constraints of the cage, imposed by the depth of the shaft (more than 1.2 miles [2 km]), and the restricted availability of the service cage limited the use of such shotcrete.

Table 1: Number of bags (2200 lb [1000 kg]) of shotcrete permitted with respect to the weight limits of the cage

	Depth		
Level	ft	m	Bags/trip
194	6365	1940	8
206	6760	2060	6
215	7053	2150	4

Therefore, to supply the daily demand (approximately 15 bags/work shift) of shotcrete for one shotcrete application team, it was necessary to make four cage trips to the level 215 and three trips to level 206. At this stage, the ramp system did not connect between levels 194, 206, and 215. What this represents is 2 hours of cage time for level 215 and 1 hour, 30 minutes for level 206. This meant that more than 25% of the available cage time would be used to lower the material underground for the shotcrete on one level only. It was a serious problem because the demand for shotcrete would only increase with the start of the production phase.

Few suggestions remedied the situation, and the majority of the suggestions only partially solved the supply problems. To resolve the supply problems to the lower levels, there needed to be a delivery system that did not depend on the service cage. Shotcrete using the wet-mix method was believed to be the only solution that could totally resolve the problem. A system of vertical piping installed in the shaft had already served to deliver concrete destined for use in the underground infrastructure construction (lunchroom, garage, and various floors). Using this system to convey shotcrete had the advantage of not only solving the problem of transporting shotcrete underground, but equally of liberating cage time. All that remained was to validate this wet-mix shotcrete supply option from an economical and operational point of view.

2002 Trial

The dry- and wet-mix processes both have their advantages and inconveniences. It cannot be said that one process is better than the other. Application by the dry-mix method uses a bagged shotcrete mixture that contains the cement, aggregates, and set accelerator. The mixture is dispersed into a gun that propels the dry-mix shotcrete using compressed air to the nozzle where the water is added just prior to projecting it onto the substrate. The quantity of water is adjusted by the nozzleman. This is the most commonly used method by mines in the Abitibi-Temiskaming region. The wet-mix process uses a mixed shotcrete that is discharged into a concrete pump to propel it to the nozzle. At the nozzle, compressed air and set accelerator are added prior to shooting.

To prove the viability of the wet-mix shotcrete, an economic study was completed. This study determined that to be viable, the wet-mix shotcrete needed to be applied by mechanical means to maintain productivity. Manual application of wet-mix shotcrete did not appear practical or profitable compared to manual application by the dry-mix method. Following this study, underground trials were planned.

During the months of June and July 2002, a trial campaign was realized jointly with Beton Fournier and one of the big three North American admixture companies. A mechanized shotcrete applicator and a transmixer were rented for 3 months to verify different variables in operational techniques. It is important to mention that the trials served not only to test the wet-mix shotcrete process, but also to verify the capacities and efficiencies of the equipment.

These initial trials permitted the demonstration of all aspects of the feasibility of this project. The wet-mix shotcrete application surprised the mine's personnel by its performance and ease of operation. The numbers speak for themselves:

- 8 yd^3 (6 m^3) of shotcrete (equivalent to 15 to 20 bags) were applied in an average of 35 to 45 minutes
- Dust was nonexistent and verified by dust tests
- Rebound, on average, was less than 5%
- Record production of 39 yd^3 (30 m^3) in a 10-hour shift was equivalent to 75 to 100 bags (productivity at the time was limited by the availability of the shotcrete mixture—with a second transmixer, the production doubles)

The achieved productivity naturally affects the suitability of applying shotcrete by the wet-mix method. Table 2 summarizes the economic study made partially from the results of the campaign of the summer of 2002.

It was at the technical level that most of the problems had to be overcome. Transport of the shotcrete via the vertical piping system in the shaft induced important changes in the quality of the shotcrete. In the course of its descent in the piping, the mixture was subject to friction that resulted in heating of the shotcrete. The longer the drop distance, the more the shotcrete heated up. At a drop distance of 5440 ft (1660 m) of depth, the mixture gained approximately 13 °F (10 °C). The heating of the shotcrete greatly affected its set time and strength. The set time was significantly reduced, such that on certain occasions water needed to be added to the mixture to ensure that it did not set in the transmixer. Also, the employees that were in charge of transportation of the mixture needed to add water at different levels to enable flow and prevent line blockage. The properties of the mixture were therefore altered, rendering the mixture unusable. Several trials were done to try to keep the temperature of the shotcrete within reasonable limits, but without success. This resulted in the compressive strength of the shotcrete never attaining the specifications of the mine engineers, which was 4350 psi (30 MPa) at 28 days. There needed to be a shotcrete recipe that was able to sustain the effects of the friction and the heating of the mixture for the wet-mix shotcrete process to be viable.

Fig. 1: Shotcrete applicator

Fig. 2: Transmixer

*Table 2: Summary of comparative study**

	Dry-mix method	**Wet-mix method**
Coverage	27 ft^2 (2.5 m^2)/bag	74 ft^2/yd^3 (9 m^2/m^3)
Rebound	10 to 20%	<5%
Productivity	43 ft^2 (4 m^2)/hour	193 ft^2 (18 m^2)/hour
Maximum productivity	20 bags/shift	39 yd^3 (30 m^3)/shift
Average productivity	15 bags/shift	23.5 yd^3 (18 m^3)/shift
Cost, %	100	64

* The numbers furnished in this table were a function of an application of a 3-in. (76 mm) thickness of shotcrete.

2003 Trial

In the late summer of 2002, the Laronde mine asked The Euclid Chemical Co. to try to design a self-consolidating shotcrete. The objective of the mine at this time was to obtain a self-consolidating shotcrete having a slump-spread in the order of 25 to 28 in. (635 to 710 mm) at the surface, which would not necessitate the addition of water during its descent over a 1.2 mile (1.9 km) distance, would not block the pipe, and could be shot underground such that it could build a thickness of 4 in. (100 mm) in a single pass.

The major issue was to be able to accelerate the self-consolidating shotcrete at the nozzle to enable the application of the thickness demanded by the engineers, always avoiding blockage of the pipe during transport. In effect, given that a self-consolidating shotcrete contains much more superplasticizer than conventional shotcrete and, in an actual application, a set-stabilizing admixture was necessary to facilitate the transport of the mixture, acceleration of the mixture underground seemed like a difficult task. Consequently, under these conditions, those involved were skeptical as to whether a self-consolidating shotcrete could be transported this distance with the ability to accelerate it and shoot it at a thickness of 3 to 4 in. (75 to 100 mm).

Fig. 3: Slump-spread of shotcrete mixture of September 4

Fig. 4: Old system of receiving concrete

Preliminary trials began immediately in The Euclid Chemical Co. laboratory at St. Hubert. The skepticism at the beginning quickly disappeared when the first trials demonstrated that it was possible to accelerate self-consolidating shotcrete that had significant quantities of superplasticizer and set stabilizer, using relatively low dosages of accelerator.

The self-consolidating shotcrete formula was refined at the Euclid Canada laboratory in St. Hubert. This formula contains ternary cement with Class C fly ash and silica fume called TerC3 from St. Lawrence Cement and Grade 1 sand with no large aggregate. At the admixture level, the polycarboxylate-based superplasticizer PLASTOL 341, the conventional water-reducer EUCON WR-75, the set-stabilizer, EUCOSHOT S, and the air entrainer AIREXTRA were used. A polycarboxylate-based superplasticizer was used rather than a conventional naphthalene-based superplasticizer to facilitate the acceleration of the self-consolidating concrete mixture. In addition to these admixtures, the alkali-free shotcrete accelerator EUCON SURESHOT AF was added at the nozzle. Finally, the water-cement ratio of this formulation was 0.42.

Once the initial laboratory formulation of the self-consolidating shotcrete mixture was completed, surface trials took place at the mine in June 2003 to optimize this formula. The results obtained from these trials demonstrated that it was possible to reproduce the laboratory results at the mine plant. The slump-spread attained was also more than 28 in. (710 mm). This only left a trial to reproduce the self-consolidating shotcrete with a greater slump-spread, transport it 1.2 miles (1.9 km) underground without blocking the 6 in. (150 mm) diameter pipe, and to evaluate the shotcrete characteristics both on surface and underground.

The trials were delayed until September 2003 for the transmixer and applicator equipment to be taken underground, reassembled, and made functional. The first pour with the self-consolidating shotcrete recipe took place on September 4, 2003. In the first trial, the mixture became unusable for shooting because of residual water that had been left in the piping system (refer to Fig. 3).

Confident of having resolved the residual water problem, the trials resumed the following day. Up until then, no one had really doubted the efficiency of the transport/delivery system that dispensed the mixture. The system in question had served up until then for all underground concrete pours in this shaft. The velocity attained by the concrete had never been calculated, though it was evidently arriving at high velocities.

On September 5, 2003, the receiving system for concrete could not resist the pressure or impact of the shotcrete material descending the piping system. Approximately 5 seconds after receiving the first quantities of shotcrete mixture, the system broke. Three people were standing on the transmixer to observe the arrival of the mixture. One person was thrown from the transmixer by the impact of the shotcrete flow, and some dislodged piping and two others were pushed off the carrier by the force of the shotcrete flow. Fortunately, no one was severely injured. The person who was thrown had several minor cuts and the other two had light cement burns. Nonetheless, this accident gave a severe warning. The trials were suspended as well as all other underground pours. The pours would only resume once a new reception system had been designed and constructed underground.

In retrospect, it was determined that the shotcrete mixture attained a maximum velocity of 197 mph (315 km/hour). It only took 47 seconds for the 4 yd^3 (3 m^3) of shotcrete to travel the distance of 6760 ft (2060 m). The shotcrete is literally in a free-fall situation in the piping. Therefore, a system needed to be designed that could resist the impact and the pressure of the shotcrete as it arrived at the shaft station. To do this required a simple system based on the principles of physics and was designed to dissipate the impact energy and pressure. The Victaulic couplings were replaced with flange type couplings and the safety factors were augmented to overcome unknowns (refer to Fig. 5). To add to the safety of personnel, a shotcrete/concrete receiving procedure was written. As a result, no person is authorized to be in the shotcrete reception area during delivery.

On October 2, 2003, with the new reception system in place, the trials resumed and the first trial was to be a test not only for the shotcrete mixture but of the new reception system as well.

The reception system worked better than expected. The velocity of the mixture at the outlet of the system bore no comparison to the old system. The shotcrete was slowed by the system and the pressure reduced to a minimum. All that remained was to test the shotcrete itself.

Self-Consolidating Shotcrete

The self-consolidating shotcrete is produced in a concrete plant in use by Beton Fournier at Cadillac. This plant is situated approximately 1/3 mile (500 m) from the discharge hopper at the shaft.

At the first underground trials, the percentage of EUCO SURESHOT AF accelerator was fixed at 8% by mass of cement, as in the trials of the 2002. This dosage of 8% of accelerator allowed the build-up of 16 in. (406 mm) on the wall and up to 12 in. (305 mm) on the roof, though the minimum application thickness required by the engineers was 4 in. (100 mm). Figure 9 shows the application thickness that we were able to build on the wall. Therefore, we were convinced that this dosage of EUCON SURESHOT AF was higher than needed because the shotcrete began to build up in the base of the nozzle tip as is shown in Fig. 10. Because we could build shotcrete thicknesses far exceeding the requirements of the engineers for the mine, the dosage of accelerator

Fig. 5: New reception system

Fig. 6: Loading self-consolidating shotcrete into the transmixer

Fig. 7: Concrete plant in use by Beton Fournier at Cadillac

Fig. 8: Application of shotcrete in one stope

Fig. 9: Thickness of fresh shotcrete on the wall

was reduced. Through trials, it was found that the optimum dosage to not cause build-up in the nozzle was between 5 and 6% by mass of cement, depending on variations of the slump-spread of the shotcrete mixture. What is even more important is that this dosage range permitted the build-up of this shooting thickness in a single pass, thus increasing the speed of shotcreting operations.

Table 3 provides the results of tests on the fresh shotcrete obtained during the trials in October. Notice an elevation in temperature between the surface and underground of more than 18 °F (8 °C), caused by friction during the free-fall of the self-consolidating shotcrete over a distance of 1.2 miles (1.9 km). It can be concluded that there is a loss of slump-spread due to the free-fall in the order of 8 in. (200 mm). Figure 11 shows the slump-spread obtained underground. Concerning the air entrainment, an air loss of less than 1% after the free-fall was measured. This demonstrates the quality and the level of stability of the self-consolidating shotcrete and of the entrained air. It is noted that it is not necessary, in this environment, to entrain air into the mixture for durability reasons due to this material not being submitted to freezing-and-thawing cycles or to deicing salts. It was decided, however, to add an air-entraining agent to enhance the consistency of the mixture to minimize the risk of blocking the pipe. The initial set was measured using a pocket penetrometer at 2 minutes, 5 seconds, demonstrating the efficiency of the EUCON SURESHOT AF accelerator.

Table 4 provides the results of the compressive strength tests obtained from the trials in October. The values of the compressive strength testing were from samples taken on surface directly from the mixer truck and cast in 4 x 8 in. (100 x 200 mm) cylinders. For the compressive strength values measured underground, 4 x 8 in. (100 x 200 mm) cylinders were cast with the shotcrete that was discharged from the transmixer or from 3.7 in. (94 mm) diameter cores that were drilled from shot panels like those shown in Fig. 13.

The compressive strengths obtained at 28 days on the 4 x 8 in. (100 x 200 mm) cylinders at the surface and underground always significantly surpassed the strength of 4350 psi (30 MPa) required by the mine. As well, the strengths obtained on the 4 x 8 in. (100 x 200 mm) cylinders underground were significantly higher than the ones from the surface. This difference can be explained by the fact that the self-consolidating shotcrete loses part of its water during the free-fall. This, together with the rise in temperature in such a short time, translates to the loss of slump-spread and the increase in compressive strengths observed. This cannot in itself fully explain the phenomenon of the increased

Table 3: Results attained on fresh shotcrete mixture

		Shotcrete temperature		Slump/spread		Air content, %	Initial set time
		ºF	ºC	in.	mm		
Trial 1	Surface	54	12	28	750	5.5	—
	Underground	79	36	16.5	420	4.6	2 minutes, 5 seconds
Trial 2	Surface	55	13	26	655	6.0	—
	Underground	79	26	20	500	5.3	—

Fig. 10: Accumulation of shotcrete in the nozzle

Fig. 11: Slump-spread of shotcrete mixture of 16.5 in. (419 mm) underground

strengths underground. There is also a loss of entrained air due to the free-fall that causes an increase in density, resulting in the higher compressive strengths.

When the compressive strength values obtained from the 3.7 in. (94 mm) diameter cores were examined, a significantly lower strength compared with the values obtained from the cylinders was noted. The act of considerably accelerating the set time of the self-consolidating shotcrete when it is shot certainly reduces compressive strength. This phenomenon of strength reduction when accelerator is added to the mixture is well known. Also, shooting panels can cause a variation in the compressive strength by means of variable compaction caused by a change in the shooting angle. It must also be remembered that coring of the samples may cause micro-fissures that would also partially explain the drop in compressive strengths. So it is normal to measure lower strength in shotcrete cores, compared with cylinders made without an accelerator.

Finally, an increase in compressive strength between 28 and 91 days is noted. This is attributed in part to the nature of the cement, which contains fly ash. The fly ash contributes significantly to strength development after 28 days.

Fig. 12: Initial set time measurement

Table 4: Results of hardened shotcrete compressive strength tests

			Average compressive strength			
			Trial 1		Trial 2	
			psi	MPa	psi	MPa
3 days	Surface	Cylinder*	2610	18.0	2565	17.7
	Underground	Cylinder*	3525	24.3	3495	24.1
		Core†	2725	18.8	2350	16.2
7 days	Surface	Cylinder*	4350	30.0	3655	25.2
	Underground	Cylinder*	4975	34.3	4830	33.3
		Core†	3625	25.0	2640	18.2
28 days	Surface	Cylinder*	7005	48.3	6875	47.4
	Underground	Cylinder*	7820	53.9	7265	50.1
		Core†	4745	32.7	4670	32.2
91 days	Surface	Cylinder*	8050	55.5	8600	59.3
	Underground	Cylinder*	9295	64.1	8790	60.6
		Core†	6150	42.4	5005	34.5

*4 x 8 in. (100 x 200 mm) cylinders
†3.7 in. (94 mm) diameter cores

Future Developments

In conclusion, Agnico-Eagle Mines Ltd. has signed a long-term contract for the supply of the shotcrete mixture, the admixtures, and the cementing agents with the partners who contributed to bringing the wet-mix shotcrete project to term. By the language of this contract, the partners are expected to form a group for development of the shotcrete, the cemented rock fill and the paste fill.

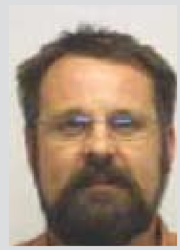
Fig. 13: Shotcrete panel for determining the compressive strength

Fig. 14: Concrete plant (at left) and concrete laboratory (at right)

Concerning the shotcrete, research will bring optimization to the existing mixture recipes, including the use of fiber in the shotcrete and a range of products will be developed for specific needs. To increase the efficiency of the group, Beton Fornier has set up a laboratory on the Laronde Division site to respond to the needs of Agnico-Eagle Mines. A technician has been assigned full-time for the demands of Agnico-Eagle. This type of partnership will no doubt improve the knowledge of the shotcrete and concrete needs for the conditions of use at the Laronde Division of Agnico-Eagle.

St. Lawrence Cement, The Euclid Chemical Co., Beton Fournier, and Agnico-Eagle Mines now have new facilities to enhance the existing operations and planned projects.

***Dan Millette**, Director, Mining and Tunneling Division for The Euclid Chemical Co., based in Cleveland, Ohio, is responsible for mining markets, tunneling projects, and shotcreting applications throughout the Americas. Millette is a mining engineer with 20 years of experience in shotcreting in underground applications. He is a member of the American Shotcrete Association, the American Concrete Institute, SME, CIM, and the American Underground Construction Association.*



***Michel Lessard**, Director of Technical Services for Euclid Canada in St. Hubert, QC, Canada, is responsible for mixture design, troubleshooting, and product development for all concrete and shotcrete products in the Canadian market. He has an MASc in civil engineering and has been involved in the concrete industry for 19 years.*