

Ultra Rapid Strength Development in Dry-Mix Shotcrete for Ultra Rapid Support in Challenging Mining Conditions

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Recent developments in the field of cementing materials have brought forward many non-traditional binder systems. Engineers involved in the fields of emergency repairs and rapid ground support have been on the lookout for materials that allow rapid production, placement, and, most of all, very rapid strength development kinetics. One binder system that fits the description is composed of ordinary portland cement (OPC), calcium aluminate cement (CAC), and calcium sulfate (CS). However, this type of binder also sometimes exhibits difficult workability that severely limits its use in regular cast-in-place concrete. This limitation is overcome when using dry-mix shotcrete as a placement method. Since the contact between water and cement occurs in the nozzle immediately before placement, workability problems are avoided.

As a part of a graduate project at Laval University, 49 different mixtures, including simple, binary, and (mainly) ternary blends, were tested. Two major parameters were studied, the development of compressive strength and the volumetric stability. The numerous binder compositions tested allowed the selection of a stable optimized formulation in regard to early compressive strength and volumetric stability. Finally, the selected formulation was successfully tested with industrial dry-mix shotcrete equipment to verify the large-scale placement feasibility of such a product.

Introduction

Transport and placement methods for concrete have evolved tremendously throughout history. Although cast-in place concrete is still the most common placement method, other processes have been developed; let us simply think of the first concrete pump, self-leveling concrete, or roller compacter concretes. There is also another con-

crete placement process developed at the beginning of the last century that has gained global acceptance. First presented to the construction industry in 1910 by Carl Akeley (American Concrete Institute [ACI] 2005), shotcrete is now present everywhere, particularly in the mining and tunneling businesses.

Shotcrete (also known as sprayed concrete in many parts of the world) is a placement method for concrete. Shotcrete is defined as a mortar or concrete pneumatically projected at high velocity onto a surface (ACI 2005). The high velocity is essential to the process as it ensures an adequate compaction or consolidation and allows the material to stick to the sprayed surface. Without the proper compaction, quality shotcrete cannot be produced (ACI 2009).

As with all placement methods, different advantages of shotcrete make it more appropriate in certain situations. With its capacity to stick to vertical and overhead surfaces, shotcrete need only minimum, if any, formworks. To take full advantage of this specificity, shotcrete is best used in ground supports (tunnel, mine, slope stabilization, etc.), overhead civil work reparation (bridge deck and parking lower surface, etc.), and where complex formworks make cast-in place concrete very expensive (arc type bridge, circular column repairs, etc.).

Shotcrete can be produced using two different processes, the wet-mix and the dry-mix. The major differences between these processes are the conveying method of the material through the hose and the location where the water is added to the mixture.

Wet-Mix Shotcrete

In the wet-mix process, all the ingredients are mixed together before being pumped through the

Dry-Mix Process

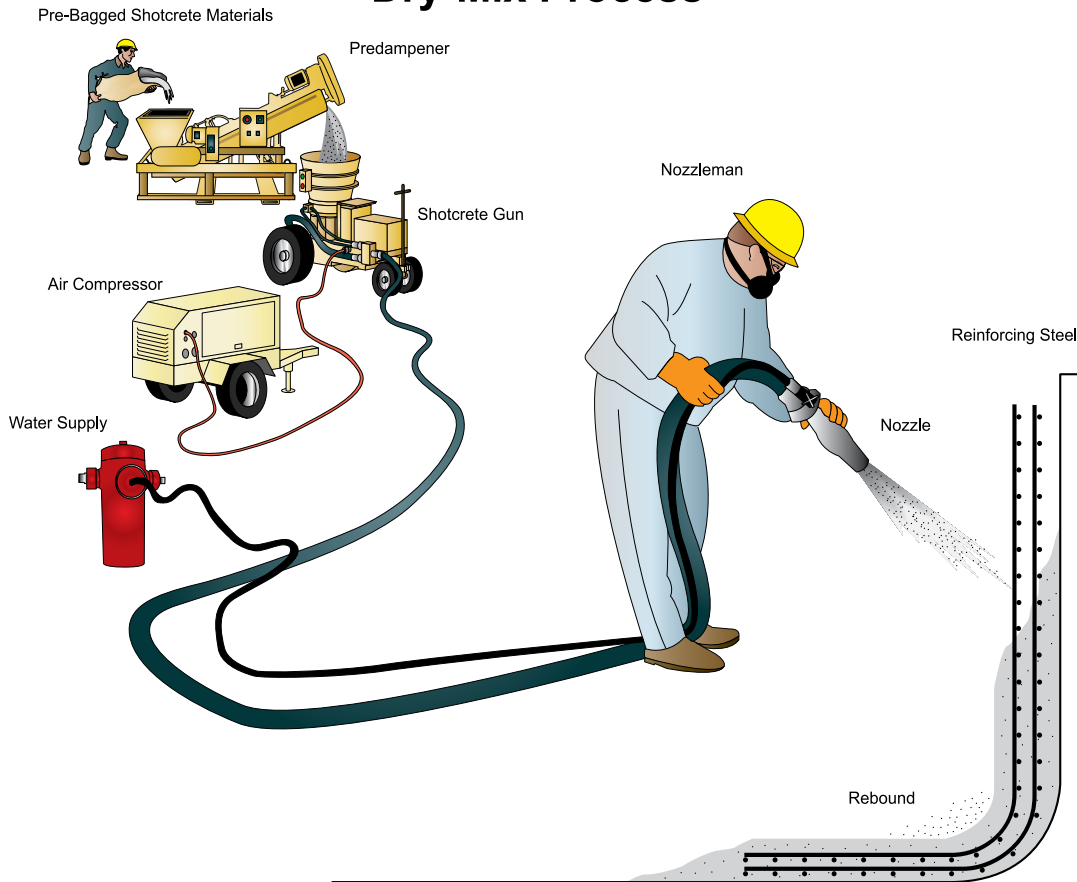


Fig. 1: Typical setup for dry-mix shotcrete operations

Table 1: Difference between dry-mix and wet-mix process

Dry-mix process	Wet-mix process
Pros	
Instantaneous adjustment of shooting consistency	Known w/cm
Delivery hose lighter to move	Rebound and dust are lower
Start-stop operations simple	High volume output
Cons	
Higher rebound	High volume output sometimes difficult to manage
Low volume output	Use (and dosage) of accelerator on site

hose. Air is added at the nozzle, through an airing, to propel the material at high velocity onto the surface ensuring sufficient compaction. As all components are mixed together prior to pumping, wet-mix concrete is usually delivered on site by a standard ready-mix truck and is fed directly into the pump.

With the exception of the set-accelerator, all admixtures are blended before pumping. When needed, the set-accelerator is added at the nozzle through a separate valve by using a special admixture pump. Normal dosage of accelerator usually ranges from 2.5 to 6%, but a dosage of >10% of

binder content is sometimes used (Prudêncio Jr. 1998). Accelerator dosage has to be carefully planned as it reduces long-term resistance and durability of concrete (Neville 2008).

Dry-Mix Shotcrete

Dry-mix shotcrete is fundamentally different from its wet-mix counterpart. In this process, all the solid materials (gravel, sand, cement, additives, fibers, admixtures) are transported through the hose using compressed air. Water is added through a water ring at the nozzle or shortly before depending on the type of nozzle used. No matter the

type of equipment used, the water-binder contact comes only a fraction of a second before placement. This particularity enables this process to bypass workability issues usually associated with the mixing and pumping of regular concrete. Figure 1 shows a schematic of a typical dry-mix shotcrete setup.

Since materials are introduced in the dry state in the hose, production of dry-mix shotcrete usually takes advantage of pre-bagged material. This enables easier quality control of the material as the production of such bags is done in a controlled environment.

Comparison of Both Processes

Each process has its own advantages and disadvantages. Wet-mix shotcrete is usually used only when high volumes of shotcrete are needed due to the important mobilization needs. On the other hand, while the dry-mix process cannot reach the production rates of the wet-mix process, its mobilization costs, preparation time, and flexibility are key factors in its selection.

Table 1 presents the major differences between both processes.

Development of New Shotcrete

The development of a new and alternative binder to Portland cement has opened the field of cementitious binders to a whole new variety of binder. One of those binders exhibiting very promising properties is a binder composed of OPC, CAC, and CS (Lamberet 2005). This type of mixture shows very rapid hardening behavior but is unfortunately often accompanied with important workability issues. With a pot life of less than 10 minutes, regular cast-in place application of this type of concrete is impossible without the use of numerous chemical admixtures to control set and fluidity. A means to avoid this type of problem was sought and this is where dry-mix shotcrete becomes a very interesting process since water is added only a fraction of a second before impact onto the receiving surface, avoiding workability issues. The validity of such a hypothesis was part of a research project at Laval University (Lemay 2013).

Research Program

The research program was divided in two phases. The first part focused on the mixture composition and the second on an actual life-size equipment testing.

Phase 1

Ternary binder made of OPC, CAC, and CS can present expansion if the mixture design is not properly done. The expansion can be such as to ruin the concrete (or shotcrete) and so, must be correctly assessed.

Based on work previously conducted by Lamberet (2005), numerous mixture formulations were tested. The stability was evaluated using standard 2 in. (50 mm) cubes incorporating only fine aggregate (sand). Each mixture had the same proportions and the same water-cementitious material ratio (w/cm). To ensure sufficient workability for casting, a polycarboxylate high-range water-reducer-superplasticizer was used. The admixture dosage varied based on the formulation as the efficiency was influenced by the major component of the binder (OPC or CAC). Table 2 presents the mixture design proportions (by weight) used in Phase 1.

The difference between each mixture was the proportion of OPC, CAC, and CS of the paste. All cubes were cured in a 100% relative humidity room at $82.4 \pm 1.8^\circ F$ ($21 \pm 1^\circ C$). Forms were removed as soon as possible and depending of the setting of the mixture could be as soon as 2 hours.

Phase 2

The main objective of the project consisted in realizing a conventional dry-mix shooting session of a special mixture based on a ternary binder using standard dry-mix equipment and techniques (ACI 2005, 2009). To ensure consistent shotcreting and adequate quality control, the shotcreting took place at Laval University's shotcrete laboratory. The laboratory is equipped with full-scale shotcreting equipment in an indoor environment that is temperature controlled. The shotcrete was sprayed using a rotating barrel ALIVA 246 with a 1.5 in. (38.1 mm) interior diameter hose with the water ring placed 10 ft (3 m) upstream from the outlet of the nozzle—also known as the hydromix nozzle (Fig. 2).

The mixture was shot indoors at an average temperature of $70^\circ F$ ($21^\circ C$). The shotcrete laboratory's equipment includes an electronic air flow meter, a water flow meter, and a set of electronic scales; the data acquisition system records the airflow, the water flow, and the material used during the spraying operations (Fig. 3). The targeted airflow is $180 \text{ ft}^3/\text{min}$ ($4.25 \text{ m}^3/\text{min}$) at a working air pressure of 100 psi (700 kPa). The water flow was adjusted (by the operator holding the nozzle) to what is referred to in the industry as the wettest stable consistency. The evolution of the water and material flows are used as a quality control point. Irregular or non-uniform flows lead to the rejection of a mixture.

Prior to the shotcreting operation, 1200 lb (780 kg) of dry shotcrete material was pre-weighted and pre-blended to allow for the production of the various panels and samples needed for testing. Table 3 shows the dry proportion of the pre-blended material.

Table 2: Mixture design for Phase 1 mixture

Water, %	Paste, %	Aggregate, %
7.7	17.5	74.4

To correctly assess the strength development of the ternary mixture, compressive strength tests were conducted. Early-age compressive strength tests (up to 3 hours) were conducted using beam specimens. These beam specimens are sprayed in steel mold to realize end beam test (Heere and Morgan 2002), which is a common test in the mining industry. Figure 4 shows the setup used to perform the test and an actual specimen tested.

To evaluate compressive strength after 3 hours, 3 in. (75 mm) diameter cores were extracted from test panels (ASTM International 2003, 2005). Figure 5 shows the different test panels ready for shotcreting in the rebound chamber in the shotcrete laboratory.

Results

Phase 1—Results

To obtain an accurate representation of the expansion pattern of these types of ternary binder, over 49 different mixtures were tested. The fast-setting nature of the OPC-CAC-CS binder ended up requiring the assistance of three persons to cast the cubes. Doing otherwise resulted in the setting of the mixture prior to proper placement. Initial setting of less than 5 minutes has been observed on some mixtures. Figure 6 presents all the mixtures tested in Phase 1. Figure 7 presents the wide range of expansion observed for the unstable mixtures.

The line leading to expansion is not a straight line because of the variability in the OPC, CAC, and CS oxide in the binders. Because of this difference and the very sensitive nature of the expansion, a straight and clear expansion limit cannot be identified. This means that with any composition change in any of the three components of the binder, this limit must be investigated again. Doing otherwise may lead to catastrophic expansion of the mixture.

It should be noted that the limit observed is very similar to what was observed by Lamberet (Lamberet 2005) with a minor difference in the CS content leading to expansion on the CAC side of the line. This is most likely due to the difference between the material used in Europe and Canada. For instance, a minor change in sulphate contents (SO_3) can have an important change in the mixture stability.

Based on the results from Phase 1, a non-expansive mixture was chosen for the shotcreting operations. The results and discussion on this selection can be found in previous work (Lemay et al. 2014).

Phase 2—Placement and Adhesion

The first goal of this shotcreting session was to establish whether the new type of binder allows for proper shooting and placement of dry-mix shotcrete. Using the standard equipment described above, the shotcreting was a success. Indeed, the use of the hydromix nozzle was efficient in reducing dust emission and no plugging was observed; dust and rebound were similar to those obtained with traditional dry-mix shotcrete mix-

ture design. Later coring of the test panels confirms the homogeneity of the in-place material.

Overall, the material shot very well and allowed placement on vertical surfaces without the need of accelerator; the in-place mixture showed sufficient cohesion and adhesion to stay in place with more than 5 in. (125 mm) thickness while presenting rebound losses of approximately 20%.



Fig. 2: (a) Spraying gun; and (b) hydromix nozzle

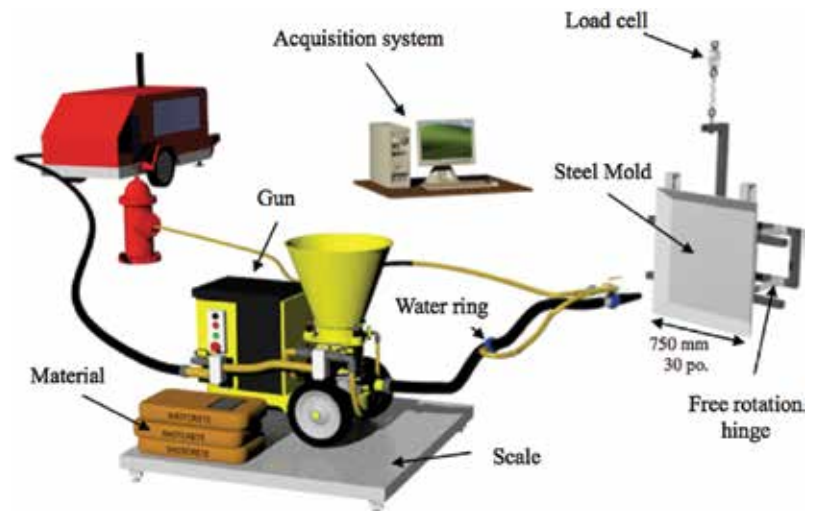


Fig. 3: Schematic of the electronic acquisition system

Table 3: Dry proportion of sprayed mixture

Ternary binder, %	Aggregate, %	
	Sand	Rock
19.0	52.7	28.3



Fig. 4: End beam test apparatus



Fig. 5: Rebound chamber before spraying

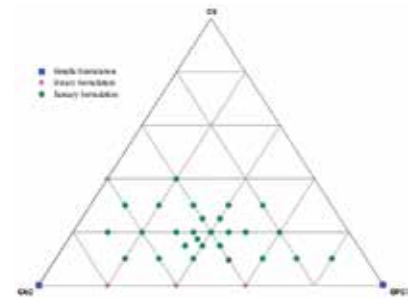


Fig. 6: All mixtures tested in this study



Fig. 7: (a) Expansion of a mixture close to the expansion line; and (b) expansive mixture compare to a stable mixture

Table 4: Average compressive strength

Specimens	Compressive strength, MPa						
	1 h	2 h	3 h	6 h	1 d	7 d	28 d
Prisms	12.9	24.9	29.6	—	—	—	—
Cores	—	—	35.6	47.6	54.6	51.9	52.1

Note: 1 MPa = 145 psi.

Phase 2—Compressive Strength

The spraying was successful using standard dry-mix shotcrete equipment. Particularly, the use of a hydromix nozzle where water is introduced 10 ft (3 m) prior to its delivery through the nozzle allowed the production of homogeneous good quality shotcrete with no clogging in the equipment. Table 3 presents the average compressive strength obtained using the end beam test (Fig. 4) and the average compressive strength using three cores taken from panels.

The results presented in Table 4 are actually quite impressive and are deemed a success for the mining and tunneling industry; indeed, typical early-age and compressive strength obtained with ordinary Portland cements based mixture design and set accelerators are usually around 435 to 580 psi (3 to 4 MPa). Compressive strengths over 4350 psi (30 MPa) at 3 hours with 28-day compressive strengths of some 7250 psi (50 MPa) are extremely promising. On the other hand, the 1-hour results also show very interesting potential for emergency

response. Structural damages caused by fire in tunnels or by natural disasters (e.g. flooding or earthquakes) on essential structures could very rapidly be alleviated using such a mix design in combination with the dry-mix shotcrete application method. In fact, although not measured because of its rapid onset, the setting time of the mixture used is very short (<10 minutes) which translates most probably to a few megapascals of compressive strength with minutes of its placement.

Obviously, the use of dry-mix shotcrete represents an extremely well-adapted method for placing such potent mixtures. Indeed, the fact that all of the dry materials are conveyed with air through the hose to the nozzle where water is added gives a very short contact time between the water and the cementing materials before it is sprayed onto the surface. By using pre-blended bulk bags that can be stored for long periods of time, it becomes easy to have concrete material ready in case of emergency. Combined with the very simple mobilization of dry-mix shotcrete and

absence of a need for formwork, a fast and reliable system could be obtained.

Conclusion

The objective of this research project was to produce a dry-mix shotcrete material offering a very rapid strength development. This was successfully achieved using standard shotcreting equipment.

While normal non-accelerated shotcrete usually needs a couple of hours before showing any compressive strength, it was possible to walk on the shotcrete developed after 10 minutes. The very rapid hardening provides extremely high early compressive strength (1740 psi [12 MPa] at 1 hour), showing very interesting potential for emergency response. Structural damages caused by fire in tunnels or by natural disasters on essential structures could be very rapidly alleviated using such a mixture design in combination with the dry-mix shotcrete application method. Along with pre-blended bulk bags and combined with the ease of mobilization of dry-mix shotcrete equipment, a fast and reliable system could be obtained for rapid structural emergency response.

The next step toward the acceptance of this new kind of binder is field testing. While showing a traditional comportment in the laboratory, extensive testing on the field must be done before it is used on a large scale.

Acknowledgments

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