Rapid Strength Gain Dry-Mix Shotcrete: A Unique Solution for Highly Complex Projects

By Christine Poulin

As the construction industry faces new needs and challenges, shotcrete undergoes constant evolution through research and development in materials, equipment, and construction procedures. Widely employed in concrete repairs and underground applications, shotcrete offers numerous advantages over conventional form-and-pour concrete. Its distinctive pneumatic placement technique employs high-velocity spraying to place concrete conveyed by hose to the nozzle onto the receiving surface. Renowned for its convenience and cost-effectiveness, shotcrete often reduces or eliminates the need for formwork, enables access to difficult work areas, and allows for variable thicknesses and finishes within close tolerances. Due to its high compaction effect, shotcrete achieves excellent adhesion to the receiving surface and effectively encapsulates reinforcing bars, both of which are crucial design considerations for projects (ACI PRC-506-22, 2022).

1. SHOTCRETE PROCESSES

There are two distinct processes for shotcrete: Wet-mix and dry-mix. In the wet-mix process, the concrete mixture, thoroughly mixed with water, is introduced into a concrete pump and conveyed by hose to the nozzle. Compressed air is then added to the nozzle to achieve high velocity and ensure proper concrete compaction on the receiving surface. Fig. 1 illustrates the wet-mix shotcrete application.

In the dry-mix process, only dry pre-mixed components are used, without water, to feed a shotcrete gun. Compressed air is used to convey the dry concrete materials (or slightly damp if a predampener is used) through the hose to a nozzle body. The nozzle body includes a water ring through which pressurized water is introduced to be uniformly mixed with the concrete materials. Simultaneously, the concrete is projected through the nozzle at high velocity onto the receiving surface.

There are several industry-recognized variants to ensure homogeneous mixing and reduce dust emission with the dry-mix shotcrete, such as the use of a predampener or placing the water ring in the delivery hose up to 10 ft (3 m) before the nozzle, also known as hydromix nozzle. These two variants are distinguished by the point at which the water is introduced through the nozzle body before the concrete is sprayed. Fig. 2 illustrates dry-mix shotcrete application with the use of a predampener.

Either process can be suitable for various construction requirements. Their distinctive characteristics may make wet-mix or dry-mix process more suitable for a specific

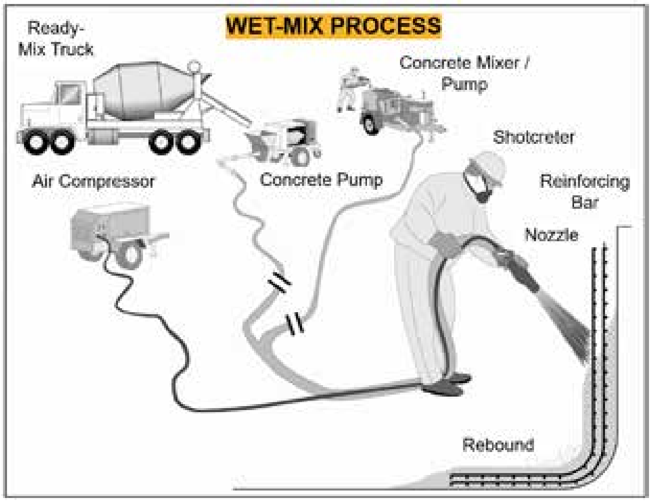

Fig. 1: Wet-mix shotcrete

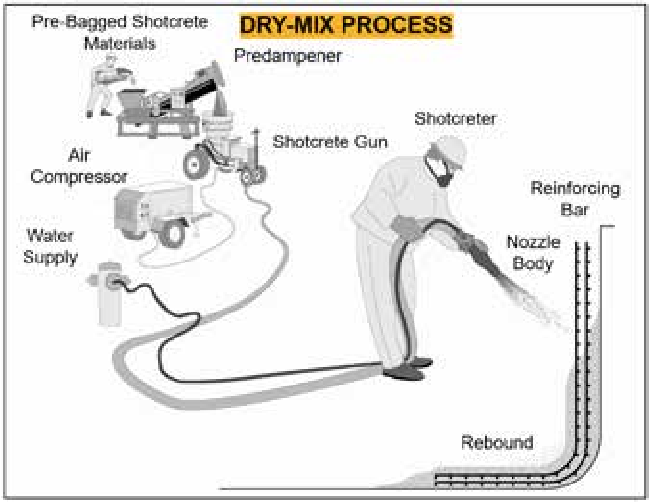

Fig. 2: Dry-mix shotcrete

application due to differences in equipment, operational features, availability of concrete materials, and placement characteristics. According to the American Concrete Institute (ACI) Shotcrete - Guide from Committee 506 (ACI PRC-506-22, 2022), Table 1 illustrates the significant differences and features offered by both shotcrete processes.

As illustrated, wet-mix and dry-mix shotcrete processes complement each other, offering to designers and contractors great versatility for use in various applications, ranging from concrete repairs to underground constructions like in tunneling and mining. While the wet-mix process provides greater volume capacity and relatively low material wastage due to reduced rebound, the dry-mix process uses lighter and smaller equipment, making it more suitable for specific applications. Dry-mix process also offers instant consistency control to adapt to field conditions. Typically, experienced industry professionals, such as experienced shotcrete contractors, are best positioned to determine which process is most suitable for specific applications and serve as excellent advisors to ensure successful shotcrete works.

In today's construction industry, there is an increasing demand for higher efficiency and speed to meet tight schedules while ensuring safe access. As a result, the industry is continuously enhancing shotcrete mixtures by integrating alternative binders and fibers, along with various admixtures. These ongoing research and development efforts enable the industry to meet rigorous quality standards, rendering shotcrete one of the premier construction techniques for ensuring both safety and performance.

Working underground comes with its own set of challenges, from demanding conditions to limited equipment access. Rapid strength gain shotcrete is often required in these environments, where suppliers and contractors must meet strict performance standards and tight deadlines. The need for quick equipment mobilization, immediate concrete availability, and the possibility of stop-and-go situations during application call for effective solutions. Sika Canada has therefore introduced various technologies in dry-mix shotcrete to consistently improve performance and meet the demands of these complex applications.

Wet-Mix Process	Dry-Mix Process
Mixture water is controlled at the mixing equipment and can be accurately measured	Instantaneous control over mixture water and consistency of the mixture at the nozzle to meet variable field conditions
Better assurance that the mixture water is thoroughly mixed with other ingredients	Better suited for placing mixtures containing lightweight aggregates or refractory materials
Less dust and cementitious materials lost during the shooting operation	Delivery hoses are easier to handle
Normally has less rebound, resulting in less waste	Well suited to conditions where the timing of placing the shotcrete cannot be predicted or is intermittent
Higher volume per hose size	Lower volume per hose size

Table 1. Comparison of wet-mix and dry-mix processes

2. CEMENT TECHNOLOGIES

There are a wide variety of cement options to produce high-quality shotcrete mixes tailored to project needs. One of the most commonly used in the industry is ordinary portland cement (OPC). When combined with a high-level of setting accelerator, OPC-based shotcrete achieves faster setting and early-age strength development.

OPC-based concrete comprises four primary phases: Calcium silicates (C_2S and C_3S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). The main product of OPC hydration, resulting from the reaction of C_2S and C_3S in solution, is calcium silicate hydrates (CSH), which contributes to the great rigidity of the system. In cement production, gypsum, serving as a source of calcium sulfate, is added to induce a period of low chemical activity, termed the dormant phase (a necessary step to avoid flash set). The dormant period ensures the requisite workability for proper concrete placement on site and can typically last up to 4 hours, depending on the temperature and environmental conditions. Once the calcium sulfates are depleted and the solution becomes saturated with ions, the initial setting of OPC-based shotcrete begins, followed by a strength gain of around 15 MPa (2200 psi) at 24 hours.

Setting accelerators are widely employed in shotcrete to rapidly accelerate the reaction rate of standard OPC systems. Sika Canada promotes only alkali-free setting accelerators, which are commonly used today to improve the performance and durability of shotcrete, unlike the highly alkaline setting accelerators previously used in the industry. These alkali-free setting accelerators, primarily composed of aluminum sulfates, impact the hydration kinetic by reducing the setting time of OPC-based shotcrete to around 5 to 10 minutes. They contribute to early strength development, with a gain of approximately 1 MPa (150 psi) per hour, allowing the shotcrete to reach a strength of around 21 MPa (3000 psi) within 24 hours when a high-level of setting accelerator is used.

However, this solution has limitations in terms of achieving early-age strength gain in this standard system. Excessive use of setting accelerator during shotcrete placement can also negatively impact the quality, strength and durability of the concrete in place

(Morgan & Jolin, 2022). As a result, alternative cements, such as calcium sulfoaluminate cements (CSA), are commercially available, and serve as an excellent alternative option to achieve very high early-age strengths.

CSA cement-based concrete consists of a predominant phase, ye'elimite ($C_4A_3\bar{S}$), which plays a pivotal role in the overall hydration of the system. This reaction is influenced by the proportions of calcium sulfates (generally hemihydrate and anhydrous) and hydrated lime. When placed in solution, the chemical reaction is almost instantaneous due to the formation of ettringite, the primary hydration product of CSA cement. This hydrate reacts very quickly due to its mineralogy, allowing for very high initial strengths. Compared to OPC, CSA cement-based shotcrete exhibits a strength gain of around 21 MPa at 3 hours, with a final setting time that is nearly instantaneous.

Fig. 3 illustrates the correlation between early-age compressive strength development for shotcrete mixes based on OPC, with and without a high-level of setting accelerator, and CSA cement.

CSA cement-based shotcrete exhibits outstanding performance in comparison to OPC-based shotcrete, whether with or without a high level of setting accelerator. While OPC-based shotcrete without setting accelerator has not yet achieved its final setting, the strength development of CSA cement-based shotcrete is four times higher than that of OPC-based shotcrete with a high-level of setting accelerator. For reference, the compressive strength result for OPC-based shotcrete without setting accelerator is only displayed at 24 hours. The OPC system is not meant for achieving early-age strength development and has insufficient strength for testing shortly after placement. It takes about 6 hours to reach its final setting time, whereas OPC-based shotcrete with a high-level of setting accelerator takes place within the first few minutes after spraying, and CSA cement-based sets almost instantaneously.

In addition to its rapid strength advantages, the unique hydration process of CSA cement offers shrinkage compensation properties. There are alternatives to OPC-based shotcrete mixtures to also provide volumetric stability along with rapid strength development. This was demonstrated by a research project at Laval University (Lemay, 2013), which utilized ternary mixtures comprising OPC, Calcium Aluminate Cement (CAC), and calcium sulfate. However, the proper dosage of calcium sulfate is fundamental for ensuring the volumetric stability of the system; otherwise, uncontrolled expansion may occur. This complex kinetic was effectively illustrated in Fig. 4, highlighting the interaction among these components

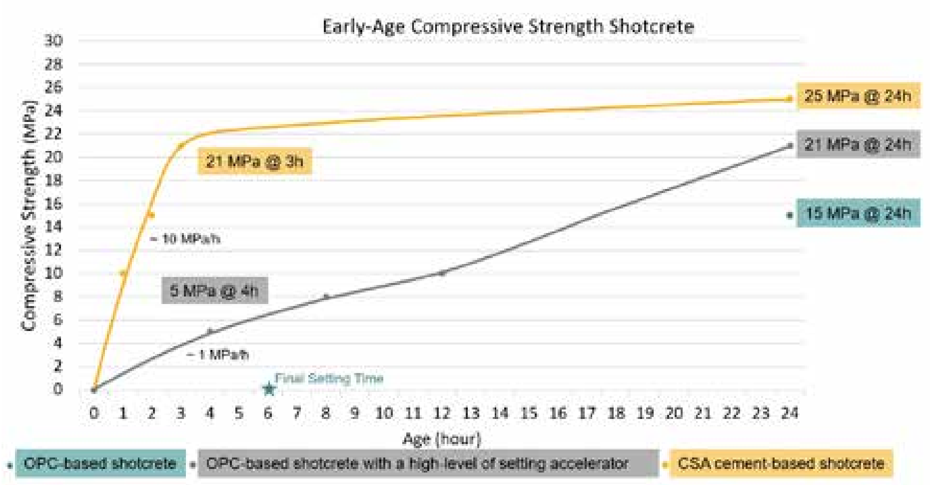

Fig. 3: Comparison between shotcrete of different binder systems and setting accelerator

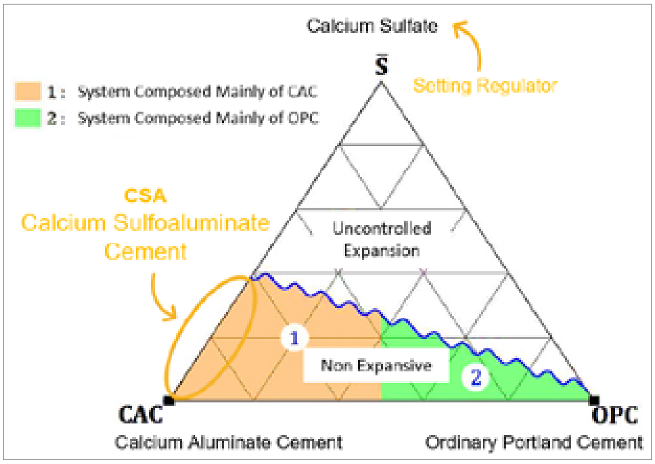

Fig. 4: Ternary diagram with expansive limits with OPC, CAC and Calcium Sulfate (Lemay, 2013)

upon the addition of calcium sulfate.

This expansive threshold observed in systems primarily composed of OPC and CAC demonstrates how an excessive dosage of calcium sulfate can lead to undesired expansion of concrete. The exact boundary between the expansion of each system, although is not entirely clear due to variability in the sources of these components, thus requiring further investigation for a better understanding of these ternary systems (Lemay, Jolin & Gagné, 2014). Therefore, the use of CSA cement sourced from the industry, already pre-blended, ensures stable concrete when employing this technology, thus benefiting from rapid strength development and shrinkage compensation properties. Indeed, CSA cement, typically positioned to the left of the diagram, containing calcium aluminate phases, remains below the threshold for uncontrolled expansion.

From an ecological standpoint, it is relevant to mention that CSA cement is more environmentally friendly. Its production efficiency is improved compared to OPC, resulting in lower CO_2 emissions per ton of cement. These advantages are particularly valuable considering the current challenges confronting the industry (Juenger et al., 2011).

In traditional form-and-pour concrete, setting retarders are commonly used to ensure the necessary workability of CSA-based concrete. However, with dry-mix shotcrete, no retarding admixture is required because mixing occurs at the nozzle just before the concrete is sprayed. This exceptional combination enables the deployment of an ultra-performing technology that no other concrete method can match.

3. CASE STUDY

An excellent case study showcasing the effectiveness of CSA-based dry-mix shotcrete is the construction of tunnels and underground structures within the Eglinton Crosstown project in Toronto, Canada.

The Eglinton Crosstown project stands as Canada's largest infrastructure endeavor, initially estimated at $8.4 billion CAD in 2011, but now valued at $12.5 billion CAD. This project entails the construction of a light rail transit system (LRT) designed to transport commuters from east to west within the city of Toronto. Commencing in 2011, the project was originally slated for completion in 2021 but has encountered delays, leading to a revised completion target of late 2024. Spanning a 19 km (12 mi) corridor, the project includes a 10 km (6.2 mi) underground section and incorporates 25 stations along with 2 connections to the existing Toronto Transit Commission subway line, illustrated by the stars in Fig. 5 (KPMB, 2024). The Cedarvale station is located at the Eglinton West intersection, and the Yonge station at the Eglinton intersection.

The technical challenges faced at these intersections of the existing subway lines and the future LRT line, where a new tunnel had to be constructed under the operational subway tunnel, necessitated the use of underpinning techniques. While the contractor used dry-mix shotcrete with a high-level of setting accelerator at the Cedarvale station, CSA-based dry-mix shotcrete was used at the Yonge station, as shown in the figures 6 and 7.

CSA-based dry-mix shotcrete played an important role at the Yonge station for ensuring rapid and safe excavation. The project demanded specific early-strength development that highly accelerated shotcrete could not achieve. The contractor met these requirements with the CSA-based mixture, ensuring timely and durable completion of tunnel linings and support structures. Moreover, the versatility and adaptability of dry-mix shotcrete has been advantageous in navigating the complex underground terrain and meeting the stringent project requirements. The results obtained with CSA-based dry-mix shotcrete on the project were around 10 MPa (1500 psi) at 1 hour and 20 MPa (2900 psi) at 2 hours. The strengths were measured on-site at the time required to meet project requirements.

For testing at such an early age, strength measurements were carried out on-site using the beam-test method with a manual hydraulic pump and a calibrated pressure gauge, following the ASTM C116 (withdrawn) test standard (ASTM, 1999), as shown in Fig. 8.

As explained by Heere & Morgan (2002), within roughly 24 hours after initial spraying, the compressive strength of shotcrete is typically insufficient for using core extraction and conventional testing procedures. Therefore, the

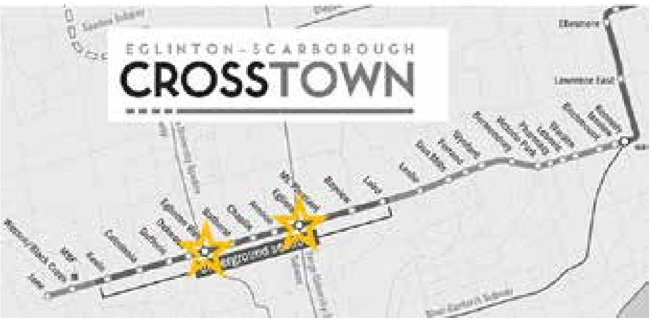

Fig. 5: Eglinton Crosstown Underground Line

Fig. 6: Cedarvale Station, Eglinton West Intersection, courtesy of HC Matcon Inc.

Fig. 7: Yonge Station, Eglinton Intersection

beam-test method has been developed, where each side of the flexural beam serves as modified cubes for loading. This test method is considered best suited for testing shotcrete at an early age and has the advantage over other indirect, early-age shotcrete test methods (such as penetrating probes or pins, and pullout tests) of directly measuring compressive strength.

The specifics of the CSA-based dry-mix shotcrete chosen, and the test methods employed, offer valuable insights into the properties and performance of the dry-mix shotcrete in this critical application. This case study highlights how Sika Canada, with this technology, contributed to the success of the Eglinton Crosstown project, underscoring its effectiveness in large-scale infrastructure developments.

4. Conclusion

The construction industry must embrace new technologies and innovations to address today's challenges. With its unique features, shotcrete stands out as a placement solution, meeting the most stringent project standards and offering unmatched benefits compared to traditional form-and-pour concrete.

By combining the advantages of shotcrete with alternative cements, CSA cement-based dry-mix shotcrete offers high-performance results under complex site conditions. This unique solution achieves a compressive strength gain of approximately 21 MPa (3000 psi) within 3 hours, whereas OPC-based shotcrete with a high-level of setting accelerator requires 24 hours to reach similar strength. As a result, CSA cement-based dry-mix shotcrete allows higher efficiency and speed to meet demanding project timelines.

The Eglinton Crosstown project is an excellent example of how Sika Canada, working closely with contractors and designers, successfully tackles these challenges by implementing cutting-edge solutions in tunneling and mining industries.

Christine Poulin, P. Eng., M. Sc., *is the Key Technical Engineer for shotcrete and tunneling at Sika Canada Inc. She studied civil engineering at Université Laval in Quebec City, where she received her master's degree in civil engineering in shotcrete in 2019, supported by a Mitacs Accelerate Research Grant with the American Shotcrete Association. Following her work experiences in research and materials consulting, Christine joined Sika's Shotcrete, Tunneling, and Mining division in 2021, where she focuses on the shotcrete and tunneling market.*

Fig. 8: Beam-test method

References

1. ACI PRC-506-22. (2022). Shotcrete - Guide. Farmington Hills, MI: American Concrete Institute Committee 506.
2. Morgan, D. R., & Jolin, M. (2022). Shotcrete Materials, Performance and Use. Taylor & Francis Group, UK, 500 p.
3. Lemay, Jean-Daniel. (2013). Développement de béton projeté à ultra-haute résistance initiale. Département de Génie Civil. Québec, Université Laval. M.Sc., p. 127.
4. Lemay, J.-D., Jolin, M., & Gagné, R. (2014). Ultra Rapid Strength Development in Dry-Mix Shotcrete for Ultra Rapid Support in Challenging Mining Conditions. American Shotcrete Association magazine, Fall 2014, p. 14-19.
5. Juenger, M. C. G., F. Winnefeld, J. L. Provis et J. H. Ideker (2011). Advances in alternative cementitious binders. Cement and Concrete Research, Vol.41, No.12, p. 1232-1243.
6. KPMB. (2024). Eglinton Crosstown makes infrastructure exciting again: Marianne McKenna sitting on Metrolinx board. Retrieved from https://www.kpmb.com/news/eglinton-crosstown-makes-infrastructure-exciting-again-marianne-mckenna-sitting-on-metrolinx-board/
7. ASTM. (1999). ASTM C116-90 (withdrawn): Standard Test Method for Compressive Strength of Concrete using Portions of Beams Broken in Flexure. ASTM, West Conshohocken, PA: ASTM International.
8. Heere, R. & Morgan, D.R. (2002). Determination of Early-Age Compressive Strength of Shotcrete, American Shotcrete Association magazine, Vol.4, No.2, p. 28-31.