Successful Design of Wet-Mix Shotcrete

Five common misconceptions and corresponding facts

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Since Carl Akeley introduced shotcrete to the construction industry in 1910, developments in materials, chemical admixtures, equipment, and techniques have led to significant advancements. Relative to conventional concrete, shotcrete is now capable of providing similar performance at a lower cost (made possible by reductions in labor and materials required for formwork), and it can be placed in challenging work areas where the application of conventional "poured" concrete is not convenient. Although shotcrete has proven to be an ideal alternative to conventional concrete in numerous applications, its further success is sometimes hindered by a few common misconceptions. The aim of this article is to discuss some of those misconceptions and emphasize the corresponding facts.

Misconception 1: Shotcrete is not concrete

Fact 1: Shotcrete IS concrete

One of the most common misconceptions is in regard to whether or not shotcrete should be considered concrete. The answer is YES—shotcrete is concrete! As a matter of fact, shotcrete is termed "sprayed concrete" in many parts of the world.

Shotcrete is composed of cement, water, aggregates, and chemical admixtures; therefore, from a materials perspective, shotcrete is certainly concrete. Similarly, it should be noted that other special concrete types such as pervious concrete, self-consolidating concrete, lightweight concrete, and ultra-high-performance concrete—regardless of their different mixture designs or application types—are all considered to be concrete, and shotcrete is not an exception.

Perhaps the confusion about how to categorize shotcrete comes from the facts that:

- Shotcrete has a different placement method than conventional "poured" concrete; and
- The spraying application requires mixture designs that are different than conventional concrete.

The mixture design has to be selected based on the desired fresh and hardened properties, which are determined in accordance with the intended use of the concrete structure, exposure conditions, the size and shape of the building elements, and the selected placement/spraying equipment.

Misconception 2: Strength is the most important parameter for shotcrete

Fact 2: Strength is important, but it is NOT the only parameter affecting performance

Although compressive strength is the most commonly specified material parameter for the acceptance of concrete, and although a minimum strength is generally required to ensure the structural performance of concrete, strength has little direct correlation with durability. In other words, meeting a 28-day compressive strength requirement does not necessarily ensure that a shotcrete mixture will meet expectations for durability.[1-4] Considering that durability is what determines the service life/longevity of a concrete structure, strength cannot be solely relied on to assess shotcrete performance. When specifiers put too much emphasis on strength as the only parameter to control the quality of concrete, durability becomes secondary. Consequently, it is not uncommon for a structure with an intended life span of 20 years to start deteriorating within the first couple of years, leading to early rehabilitation.

Figure 1 presents data from more than 60 shotcrete mixtures that were analyzed to determine the correlation between compressive strength and boiled absorption at 7 and 28 days. Boiled absorption is a commonly used indicator of durability—the higher the boiled absorption, the less durable the concrete. According to the stated misconception, one would expect mixtures to achieve similar absorption values for a given compressive strength. However, the data shown in Fig. 1 indicate that mixtures with nearly identical compressive strength (for example, 7000 psi [48 MPa]) could have a wide range of absorption values—as low as 1% and as high as 7%.

Therefore, data confirms that compressive strength is not sufficient to presume a mixture to have good durability characteristics, as the correlation between these two test methods is poor. In fact, durability is influenced by factors

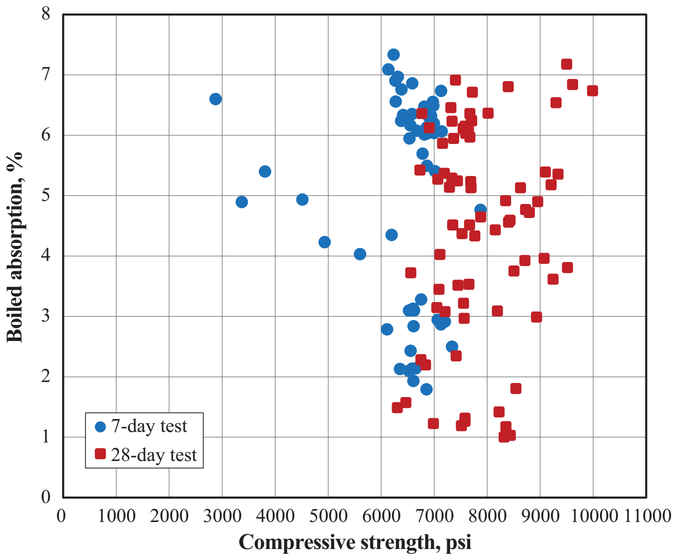

Fig. 1: Boiled absorption versus compressive strength for shotcrete mixtures (Note: 1 psi = 0.007 MPa)

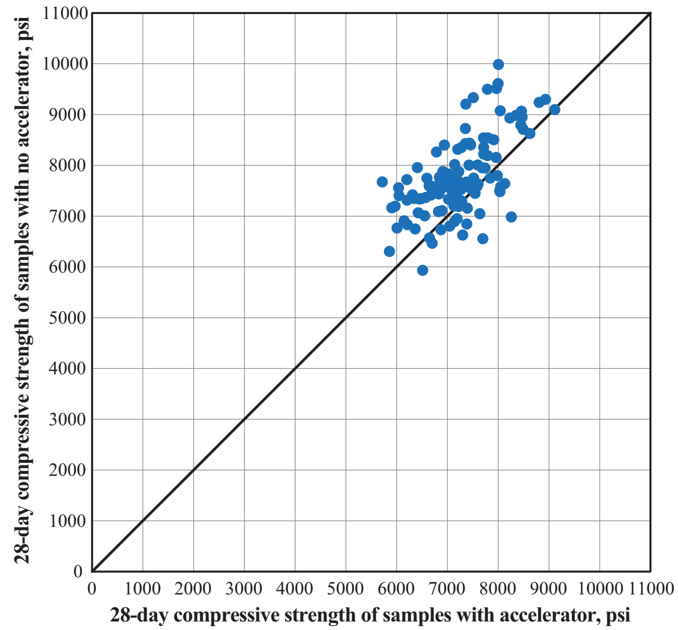

Fig. 2: The impact of alkali-free accelerator on 28-day compressive strength (Note: 1 psi = 0.007 MPa)

such as water-cementitious materials ratio (*w/cm*), total binder content, type and amount of supplementary cementitious materials (SCMs), aggregates, consolidation, curing, and external environmental conditions. With such a wide array of factors affecting durability, it's clear that each mixture must be evaluated using a test that correlates with durability. A strength test is not an appropriate test for that outcome.

Misconception 3: Alkali-free accelerators reduce the 28-day strength

Fact 3: Alkali-free accelerators have a minor impact on the 28-day strength

In shotcrete applications, it is not uncommon for mixtures containing accelerators to have lower 28-day strengths than similar mixtures containing no accelerator; however, this does not necessarily mean that such behavior is caused by the presence of accelerators. There are many factors that affect the performance of concrete. For shotcrete applications, strength is affected by the mixture design, the constituent materials, and the quality of the spraying. Because these factors affect each other as well as the "finished product," it can be difficult to isolate the primary cause of compromised performance. A placement issue, such as inadequate compaction resulting in high voids content, probably will have a more detrimental effect on compressive strength than the presence of an accelerator. Therefore, if strength test results obtained from cores (with an accelerator) are significantly different than strength test results from cylinders (without an accelerator), cross-sectional disks of specimens should be examined to determine the quality of the spraying.

Figure 2 presents data from more than 130 shotcrete mixtures. Samples were taken before and after the addition of an alkali-free accelerator at various dosage rates (all within the manufacturer's recommended dosage range). The 28-day compressive strengths of samples produced before the addition of the accelerator tend to be about 500 psi (3.45 MPa) greater than the strengths of samples produced after the addition of the accelerator. Although the trend is statistically significant and would lead one to expect a slight reduction in compressive strength when using an alkali-free accelerator, the magnitude of the difference is small enough to be tolerated. For example, ASTM C39/C39M, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," indicates that the within-test precision is 10.6% for strength tests using three 4 x 8 in. (100 x 200 mm) cylinders made under laboratory conditions. Within the strength range of 6000 to 10,000 psi (41 to 69 MPa) shown in Fig. 2, this means that the strength of samples could be expected to vary by 640 to 1060 psi (4 to 7 MPa).

Other researchers have shown that the impact of alkali-free accelerators on later-age strength is relatively minor.[5-7] According to De Belie et al.,[5] for example, the decrease in compressive strength associated with the addition of an alkali-free accelerator is not statistically significant.

Misconception 4: Concrete slump dictates the rebound rate

Fact 4: While slump does provide an indication of the ease of flow, rebound rate is determined using more complex rheological properties

A leading (and misleading) myth contends that a low slump is ideal for reducing the rebound rate of shotcrete mixtures. However, while the slump test is a simple test method for evaluating the yield stress (ease of flow) of concrete, it is not a reliable indicator of the overall quality or suitability of shotcrete mixtures. First of all, there is no direct correlation between a mixture's slump and its thixotropic properties. Furthermore, modern chemical admixtures make it possible to have two mixtures with the exact same slump values but with completely different rheological properties. Slump test results actually provide limited guidance despite the commonly held misconception that they can be used to judge the sprayability, placeability, finishability, and rebound rate of shotcrete mixtures.

To better demonstrate the reason slump cannot dictate the rebound rate, it's important to understand the basics of rebound. During the spraying process, larger aggregate particles tend to segregate from the mixture after hitting and bouncing off the receiving surface. Thus, a high volume of rebound material primarily consists of aggregate particles. If the quantity of paste is sufficient to fill the voids between the aggregates, paste quality and aggregate gradation play more important roles in rebound reduction than the amount of cementitious materials. In other words, for evaluating the rebound characteristics, the quality of the paste is more important than the quantity of the paste.

The quality of the paste is affected by the mixture's rheological characteristics, such as:

- Stickiness (adhesion to substrate surface—allowing large thickness buildup);
- Cohesiveness (adhesion to itself—providing resistance to segregation under pressure); and
- Viscosity (resistance to gradual deformation—reducing sagging on vertical walls).

Therefore, instead of relying solely on the slump, which informs the users only about the ease of flow and thus is limited to being one indicator for the pumpability of a mixture, those three rheological parameters should be evaluated and optimized to reduce the rebound rate. Until a sufficiently thick paste layer accumulates on the substrate, thus creating a "sticky" viscoplastic surface, rebound of the aggregate particles is inevitable. This is especially true at very early stages of spraying, when the concrete is sprayed directly onto hard walls or rock surfaces. When a soft, cushion-like cement paste encapsulates aggregates, the rebound rate becomes lower during the placement of subsequent layers. Therefore, although it is not feasible to completely eliminate rebound, it is possible to reduce the rebound rate by changing the mixture's rheological characteristics. However, the ideal mixture for a given project should draw a delicate balance between these rheological characteristics, as they also influence other aspects of shotcrete quality such as compaction, consolidation, and encasement.

Pumpability and sprayability are two other key properties that need to be taken into account when shotcreting, and it is important to understand the differences between these two parameters. Pumpability characterizes the stability and mobility of a mixture under pressure.[9,10] For pumpability, it is desirable to have a mixture with low viscosity and high flowability (usually associated with high slump). Sprayability characterizes the efficiency of a mixture to stick to the applied surface (adhesion) and to itself (cohesion). For sprayability, a stiff and sticky mixture with low slump and high cohesiveness is desired to minimize rebound and increase thickness buildup.[10]

Fig. 3: Poor coating on the surface of reinforcing bar resulting from use of a mixture with inadequate rheology

Adequate rheological properties are also essential for proper placement, consolidation, and compaction. Because shotcrete is consolidated by high-velocity placement rather than mechanical vibration, mixtures should provide sufficient fluid properties to accomplish consolidation around reinforcing bars. If mixtures lack cohesion and are not fluid enough, voids will occur within the shadow areas behind the bars (Fig. 3). This is especially significant because shotcrete is not subjected to a post-placement mechanical vibration process, and further consolidation will not occur. This can negatively affect the in-place properties, as poor consolidation results in poor coating of reinforcement and high porosity of the concrete, impairing strength and durability.

However, while satisfying the needs for consolidation, users should note that highly flowable mixtures are prone to sagging if they do not possess a certain degree of viscosity, allowing the material to remain on the applied surface and resist the effect of gravity. Therefore, mixture components should be selected to provide adequate viscosity and yield stress for minimizing sagging while not increasing the pump pressure.

Unlike cast-in-place concrete, shotcrete must stick or adhere to a surface, as there is no formwork. Therefore, "sticky" mixtures are desirable for the shotcrete process, as they allow larger buildup thicknesses on walls and overhead applications. "Stickiness" also contributes to enhancing safety, productivity, and cost-efficiency, as materials that do not stick or adhere cause fallouts that raise a safety concern and become costly waste.

As explained previously, there are many factors contributing to the quality of shotcreting. Slump is only one parameter, and the rheological behavior of shotcrete is too complex to be oversimplified with one test. Rather, selecting a shotcrete mixture requires a delicate balance between flowability, cohesiveness, viscosity, and "stickiness". Considering that different phases of shotcreting require conflicting rheological properties, it is ideal to maintain the highest possible fluidity (lowest yield stress) while providing the desired viscosity, cohesiveness, and "stickiness" to satisfy all needs.

Misconception 5: Prescriptive-based specifications are necessary to control quality

Fact 5: Prescriptive-based specifications can result in mixture overdesign, and they do not assure performance

Currently, many concrete mixtures are proportioned based on recipes that have been used before or on prescriptive-based specifications. While prescriptive specifications may appear to conservatively define limits on the type, amount, and proportions of the mixture components, they do not necessarily ensure that performance requirements are met. They also typically put constraints on the minimum compressive strength, maximum *w/cm*, maximum cement replacement level for SCMs, and minimum cementitious material content. In effect, these constraints promote overdesign of mixtures by forcing the producer to use cement content as a safety factor. Even so, mixtures designed using prescriptive specifications do not always provide the desired end results.

On another note, although more than 60% of shotcrete volume is composed of aggregates, many prescriptive-based specifications for shotcrete neglect to provide information regarding aggregates. It is not ideal to specify cementitious materials content without considering aggregates, as the required paste content is heavily dependent on the size, type, and gradation of aggregates. According to a study conducted by Dhir et al.,[8] aggregate properties have a greater impact on many aspects of performance than changing cement content at a given *w/cm*. This is especially true for shotcrete mixtures because a high volume of rebound material consists of mainly aggregate particles, and as long as there is a sufficient amount of paste to fill the voids between the aggregate particles, paste "stickiness" and aggregate gradation play more important roles in rebound reduction than the amount of cementitious materials.

Every application is subject to different environmental conditions, locally available materials, and performance

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requirements. Therefore, for high-performance shotcrete mixtures, mixture designs should be selected based on the project requirements instead of simply following an existing recipe that was found to be successful on a previous job. Rather than setting limits on the type and amount of materials in a shotcrete mixture, attention should be paid to the end result. The required performance can be best ensured by evaluating the fresh and hardened properties.

Conclusions

Shotcrete has advanced significantly over the years; however, the discussed misconceptions often limit many benefits it offers to the construction industry. To broaden the area of shotcrete applications and to improve its performance, it is essential to understand shotcrete as a material and its demands as a placement method. There is a very delicate balance between the mixture constituents and their impact on shotcrete performance. This is especially true considering that pumping, spraying, and placement require conflicting rheological requirements that may cause sacrificing one property while improving another. Consequently, underestimating rheological behavior with a simple slump test or overdesigning a mixture to meet prescriptive-based specifications might do more harm than good. Therefore, for successful shotcreting, it is ideal to consider all the desired performance criteria and find an optimum that could satisfy all the project needs.

References

1. Al-Amoudi, O.S.B.; Al-Kutti, W.A.; Ahmad, S.; and Maslehuddin, M., "Correlation between compressive strength and certain durability indices of plain and blended cement concretes," *Cement and Concrete Composites*, V. 31, No. 9, 2009, pp. 672-676.
2. Taylor, P.C.; Yurdakul, E.; and Ceylan, H., "Performance Engineered Mixtures for Concrete Pavements in the U.S.," *12th International Symposium on Concrete Roads 2014*, Prague, Czech Republic, Sept. 23-26, 2014.
3. Taylor, P.; Yurdakul, E.; Wang, X.; and Wang, X., "Concrete Pavement Mixture Design and Analysis (MDA): An Innovative Approach to Proportioning Concrete Mixtures," *TPF-5(205)*, CP Tech Center, Ames, IA, 2015, 50 pp.
4. Taylor, P.C., "Long-Life Concrete: How Long Will My Concrete Last?" *Supplement to TPF-5(159)*, CP Tech Center, Ames, IA, 2013, 46 pp.
5. De Belie, N.; Grosse, C.U.; Kurz, J.; and Reinhardt, H.W., "Ultrasound monitoring of the influence of different accelerating admixtures and cement types for shotcrete on setting and hardening behavior," *Cement and Concrete Research*, V. 35, No. 11, Nov. 2005, pp. 2087-2094.
6. Garshol, K.F., "New Admixtures for High-Performance Shotcrete," *Sprayed Concrete Technology: The Proceedings of the ACI/SCA International Conference on Sprayed Concrete/Shotcrete*, S.A. Austin, ed., Chapman & Hall, London, England, 1996, pp. 26-38.
7. Prudêncio, Jr., L.R., "Accelerating admixtures for shotcrete," *Cement and Concrete Composites*, V. 20, No. 2-3, 1998, pp. 213-219.
8. Dhir, R.K.; McCarthy, M.J.; Zhou, S.; and Tittle, P.A.J., "Role of cement content in specifications for concrete durability: Aggregate type influences," Proceedings of the Institution of Civil Engineers, *Structures and Buildings*, V. 159, No. 4, 2006, pp. 229-242.
9. Beaupré, D., "Shootability of Fresh Shotcrete," *Proceedings of the International RILEM Conference on Production Methods and Workability of Concrete*," P.J.M. Bartos, D.J. Cleland, and D.L. Marrs, eds., E&FN Spon, Oxford, UK, 1996, pp. 95-108.
10. Jolin, M.; Burns, D.; Bissonnette, B.; Gagnon, F.; and Bolduc, L.S., "Understanding the Pumpability of Concrete," *Proceedings: Shotcrete for Underground Support XI*, 2009, 13 pp.

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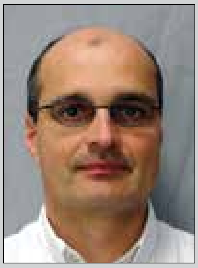

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