Enhancement of Shotcrete Performance with a Pozzolanic-Based Rheology Control Agent

By Ezgi Yurdakul and Klaus-Alexander Rieder

In underground applications such as mining and tunneling, shotcrete is widely used for structural support of permanent openings, linings, and rock stabilization. Considering the performance that shotcrete plays on the quality of these applications, the following properties are often assessed:

- Pumpability—the mixture should have an adequate flowability for the ease of pumping;
- Sprayability—viscosity, cohesiveness, and stickiness is desired for minimum rebound;
- Early-age strength—the mixture should have sufficient early-age strength to ensure required structural support is provided to the ground within the first few hours;
- Later-age strength—the mixture should meet the specified long-term strength to ensure no strength loss is occurring over time that may compromise the service life of the structure; and
- Durability—the mixture should be durable to ensure the longevity.

Because silica fume improves many of these properties, the use of silica fume became common in shotcrete in the last few decades.[1] However, due to various concerns about the health and safety, variation in quality, availability, and cost-efficiency of silica fume, there is a need to use alternative materials, which could provide equal or superior performance while eliminating any potential risks.

The Need for Replacing Silica Fume with Pozzolanic-Based Rheology Control Agent

What is pozzolanic-based rheology control agent?

Pozzolanic-based rheology control agents (for example, TYTRO® RC 430) are suspension of fine amorphous silica particles in a stable liquid form. It consists of nonporous, spherical, non-aggregated, nanometric particles dispersed in water free from chlorides and with low alkalinity.

Which Applications is Pozzolanic-Based Rheology Control Agent Used For?

A pozzolanic-based rheology control agent can be used in any shotcrete mixture to replace cementitious materials such as silica fume, metakaolin, fly ash, or slag cement within a certain limit. Typical applications include but are not limited to the following areas:

- Mining;
- Tunnel linings;
- Rock slope stabilization;
- Pools and recreational structures;
- Domes;
- Retaining walls;
- Water-retaining structures; and
- Repair and rehabilitation of concrete structures.

Reason 1—Health and Safety

There is a concern that silica fume is a potential hazard to workers who add the material to the concrete or shotcrete mixers. Any dust generation can be a nuisance; and the lifting and dumping of bags presents their own health and safety risks with respect to back injuries, pinching, and straining. Because the pozzolanic-based rheology control agent is a liquid product, it can be automatically dispensed, and thus problems associated with handling powder-based silica fume can be eliminated. The facilities required for storing and dispensing admixtures are less expensive than those for silica fume, and require less maintenance and attention.

Reason 2—Quality Assurance

In plants that are storing silica fume in silos, problems may arise when traditional silica fume cakes in the silo or when the absorbed moisture causes the formation of lumps. Due to its liquid form, pozzolanic-based rheology control agent can eliminate such deficiencies, which may cause variations in shotcrete performance. It is more effectively dispersed than silica fume, reducing the mixing time required and minimizing the risk of lump formation in concrete or shotcrete. In addition, rheology control agent is manufactured under stringent quality control in an industrial process using high-quality raw materials to obtain a material with high fineness and purity. The tolerances for the particle size distribution are very tight to ensure that the specific surface area remains the same from batch to batch, unlike for silica fume being a by-product, which can have batch-to-batch variations and can contain impurities causing variations in the shotcrete performance. From a physical point of view, differences between the two materials are shown in Table 1.

Reason 3—Dosage Efficiency

Silica fume is often used to replace ordinary portland cement within the range of 5 to 10% to improve the performance of shotcrete mixtures. However, the selected grade of pozzolanic-based rheology control agent only requires one-tenth of the silica fume dosage rate (for example, 3 kg/m^3 [5 lb/yd^3] of TYTRO RC 430 is needed to replace 30 kg/m^3 [50 lb/yd^3] of silica fume in shotcrete mixtures) to provide equivalent performance, which makes it a more economical and sustainable solution.

Reason 4—Enhancement of Shotcrete Performance

The use of a pozzolanic-based rheology control agent provides several performance benefits compared to silica fume (designated as "SF") and ordinary portland cement (designated as "OPC") as presented in the following, based on the results obtained from the following case studies:

Case study A—0.67% TYTRO RC 430 was used to replace 5% SF in a binary mixture

- Mix with 5% SF (water-cementitious materials ratio [*w/cm*] of 0.40; total cementitious materials content: 473 kg/m^3 [29.5 lb/ft^3])
- Mix with 0.67% TYTRO RC 430 (*w/cm*: 0.40; total cementitious content: 450 kg/m^3 [28.1 lb/ft^3])

Case study B—0.67% TYTRO RC 430 was used as an addition (due to minimum cementitious materials content requirement) in a plain mixture where OPC was used

- Mix with 100% OPC (*w/cm*: 0.46; total cement content: 459 kg/m^3 [29.7 lb/ft^3])
- Mix with 0.67% TYTRO RC 430 (*w/cm*: 0.46; total cement content: 459 kg/m^3 [29.7 lb/ft^3])

Case study C—0.67% TYTRO RC 430 was used to replace 6% SF in a ternary mixture

- Mix with 6% SF (*w/cm*: 0.35; fly ash designated as "FA": 23%; total cementitious materials content: 521 kg/m^3 [32.5 lb/ft^3])
- Mix with 0.67% TYTRO RC 430 (*w/cm*: 0.37; FA: 23%; total cementitious materials content: 489 kg/m^3 [30.5 lb/ft^3])

Note: Test methods were selected based on the project requirements. Because the specified performance characteristics varied based on the case study, the following section presents results from the selected case studies where testing was conducted.

a. Enhanced sprayability and reduced rebound

For sprayability, a viscous and sticky mixture with high cohesiveness is desired as shotcrete mixtures for reduced rebound. In addition, segregation of the shotcrete mixture under pressure is reduced. However, for pumpability reasons, the viscosity of the shotcrete mixture needs to be limited due to the maximum allowable pump pressure.

When added to the shotcrete mixture, rheology control agents provide greater cohesiveness of the shotcrete mixture, lower rebound, and higher thickness buildup (Fig. 1). A possible explanation for these effects could be related to the smaller particle size associated with the higher specific surface area of the rheology control agent working as a nucleation site for the precipitation of calcium silica hydrate (CSH) gel, and having stronger Van der Waals and electrostatic ionic forces between particles.[2] Considering that the main source of cohesion in cement paste is the calcium silicate hydrate (CSH) gel,[3] it is expected for pozzolanic-based rheology control agent to increase cohesion due to its impact on accelerating

Table 1. Comparison of Properties between Silica Fume and Rheology Control Agents

Silica fume	Rheology control agents
By-product	Engineered material
Contains impurities	High purity
Powder	Liquid
Difficult to handle	Easy to use
Variable particle size and distribution	Uniform particle size and distribution

Fig. 1: The effect of pozzolanic-based rheology control agent on thickness buildup

and forming additional CSH gels, and its reactant surface particles exhibiting stronger tendency for adsorption of ions and increasing the surface adhesion between adjacent particles, and to other materials. Studies are currently being carried out to determine the exact mechanisms of the pozzolanic-based rheology control agent leading to the observed enhanced sprayability and reduced rebound characteristics.

As shown in Fig. 2, in Case Study A, mixtures containing 5% SF and 0.67% TYTRO RC 430 were both efficient in reducing rebound to as low as 5 to 6%. The reference mixture containing SF was already optimized. Because the rebound loss of the baseline mixture is already considered to be very low, the impact of the rheology control agents in achieving similar low rebound loss at much lower dosage rates is a significant improvement. However, Case Study B shows that the addition of the pozzolanic-based rheology control agent significantly reduced the rebound from 20 to 6%. Results show that the degree of improvement on rebound loss is related with the mixture design and mixture constituents. When the performance of the rheology control agents on rebound is compared with those of mixtures containing portland cement only, or mixtures containing silica fume with rebound losses higher than the one obtained in this study, the decrease in rebound may be more dramatic.

b. Higher early-age strength

The compressive strength test results based on the penetrometer needle up to 3 hours followed by Hilti stud[4] are shown in Fig. 3. The rate of strength development during the first couple of readings is relatively low in both mixtures. However, starting from 2 hours, rapid strength gain has been observed, especially for the mixture containing TYTRO RC 430 compared to the silica fume mixture. This could be due to the following properties of the pozzolanic-based rheology control agent[4]:

- It has high pozzolanic activity because its ultrafine particles have high specific surface area and they are fully hydroxylated;
- It reacts with the calcium hydroxide released by the cement hydration and forming additional calcium silicate hydrate (CSH) gel;
- It serves as nucleation sites to CSH gel; and
- It accelerates the primary CSH gel formation.

Figure 4 shows the compressive strength[5] tested 1 day after spraying. As expected, mixtures with pozzolanic-based rheology control agent outperformed their corresponding reference mixtures.

c. Equal or higher long-term strength

Figure 5 shows the impact of the rheology control agent on the compressive strength[5] at 28 days. As desired, while accelerating the hydration process, which increased the early-age strength of the shotcrete, the pozzolanic-based rheology control agent provided equal (compared to mixtures with silica fume) or higher (compared to the mixture containing portland cement only) later-age strength based on three case studies incorporating various mixture designs. This trend shows that the impact of the rheology control agent on the compressive strength is more prominent at early ages, and most importantly, unlike other rapid setting materials, it is not harming the later-age strength. This makes it ideal for underground applications, where minimal time for re-entry to the mine or tunnel is desired.[7-9]

d. Similar durability

Figure 6 shows that the water penetration depth[10] of the mixture containing TYTRO RC 430 was slightly lower than that of the silica fume mixture.

Figure 7 shows the boiled absorption and the volume of permeable voids test results[11] from

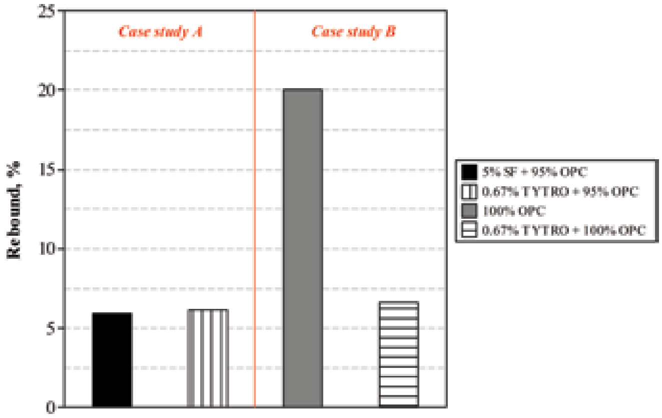

Fig. 2: The effect of pozzolanic-based rheology control agent on rebound

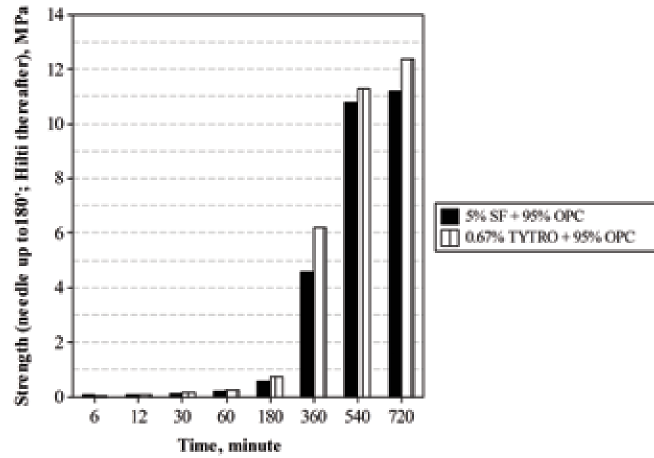

Fig. 3: The effect of pozzolanic-based rheology control agent on early-age strength

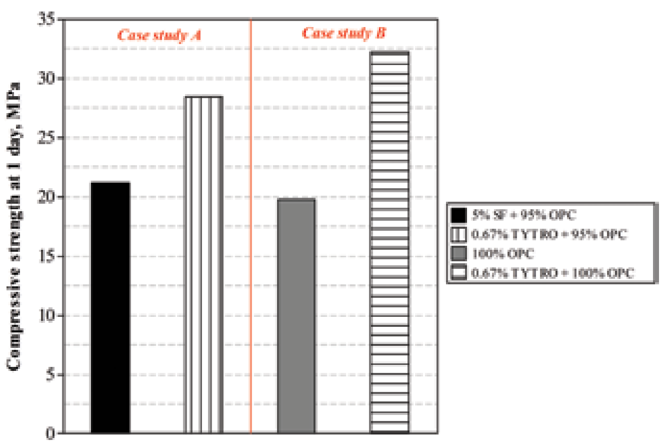

Fig. 4: Compressive strength at 1 day after spraying

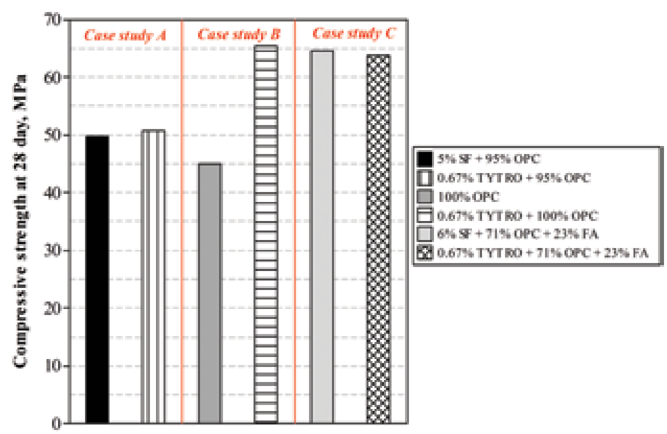

Fig. 5: Compressive strength at 28 days

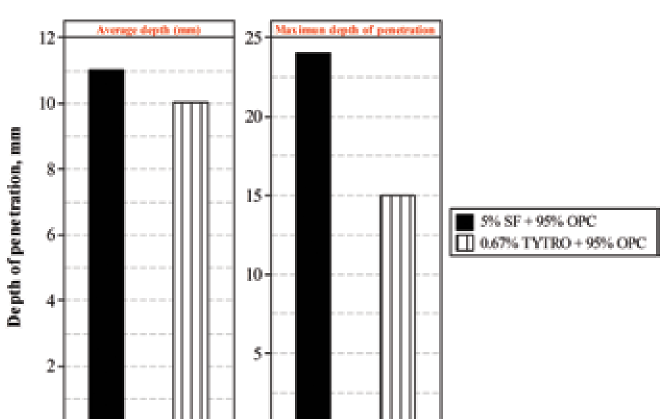

Fig. 6: Water penetration depth at 28 days

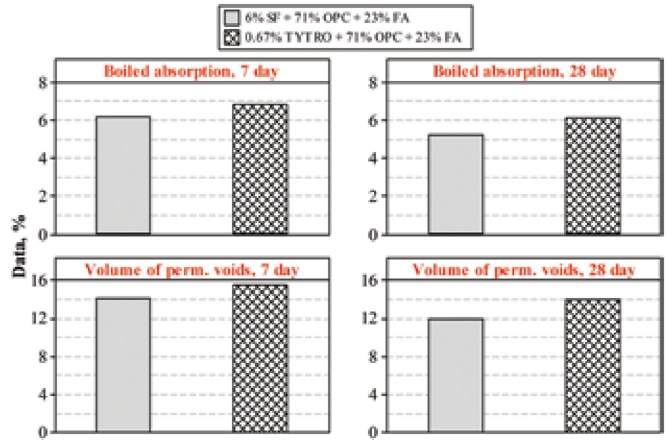

Fig. 7: Boiled absorption and volume of permeable voids tested at 28 days

Case Study C. Both mixtures performed in a similar manner, as the differences in boiled absorption were within 1 and 2% for the volume of permeable voids.

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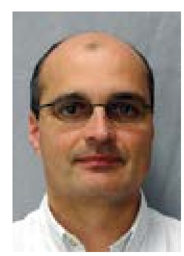

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