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A Case Study on the Impact of Pozzolanic-Based Rheology Control Agent on Wet-Mix Shotcrete Performance in Underground Applications

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This paper presents the results of a case study conducted with a major mining operation to assess the impact of pozzolanic-based rheology control agent on the performance of a wet-mix having a specified mix design. The project had a minimum cement content requirement and a specified water-to-cement ratio (w/c). Therefore, the mix previously used in the mine that met the project specifications was selected as a reference, and the mix design of the proposed system was selected accordingly. The major difference between these two mixes is that the proposed mix incorporated pozzolanic-based rheology control agent.

Test matrix included air content, slump, rebound, early-age strength development using penetrometer needle and Hilti stud, bond strength, and compressive strength on cast cylinders and drilled core samples at various ages. The performance of the proposed system was compared with the reference mix as well as the target performance limits of the project. Test results showed that when compared to the reference mix, the proposed system incorporating pozzolanic-based rheology control agent improved the shotcrete performance by 1) improving sprayability through increased cohesion, stickiness, and higher build-up thickness; 2) reducing rebound from 20% to 6%; 3) increasing early-age and later-age strength as much as up to 60%; and 4) increasing bond strength. The impact of rheology control agent on performance has been verified when used as an “addition” and has been found suitable to replace a portion of the cementitious materials. Therefore, next step will be conducting trials where it will be used as a “replacement” to optimize the mix design by reducing cement content and avoid overdesign. After the assessment of test results, pozzolanic-based rheology control agent will be listed as a recommended material in shotcrete specifications.

1. INTRODUCTION

Shotcrete is widely used in mining applications to support permanent openings such as ramps, haulages, shaft stations, and crusher chambers. The quality of such applications is affected by the performance of shotcrete. Therefore, the following properties are often tested to evaluate the performance of shotcrete mixes: 1) early-age strength development rate which indicates the time requiring for re-entry; 2) adhesion strength between shotcrete and rock which indicates the bonding ability; 3) later-age strength; 4) permeability which indicates the longevity; 5) rebound; 6) energy absorption and toughness; and 7) slump or slump flow which indicates the pumpability characteristics. Since silica fume improves many of these listed properties, the use of silica fume as a supplementary cementing material has become quite common in the manufacture of shotcrete [1]. However, due to various concerns listed below, there is a need to find an alternative source to silica fume that could provide equal or superior performance in shotcrete while eliminating any potential risks. Although, silica fume was not used in this particular project, comparisons will be made in the following section between pozzolanic-based rheology control agent and silica fume to demonstrate the benefits associated with the differences between these two products.

The need for replacing silica fume with pozzolanic-based rheology control agent

What is pozzolanic-based rheology control agent?

Pozzolanic-based rheology control agent (TYTRO[®] RC 430), also known as colloidal silica, is a suspension of fine amorphous nanometric silica particles in a liquid form. As shown in Figure 1, it consists of non-porous, spherical, non-aggregated particles dispersed in water free from chlorides and with low alkalinity.



Figure 1. Pozzolanic-based rheology control agent.

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 created 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. Since 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 store silica fume in silos, problems may arise when traditional silica fume cakes in the silo or when absorbed moisture causes the formation of lumps. Pozzolanic-based rheology control agent can eliminate such deficiencies causing variations in product quality because due to its liquid form, it is more effectively dispersed than silica fume, reducing the mixing time required and minimizing the risk of lump formation in concrete. 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 whereas due to being a by-product, silica fume is known to have batch-to-batch variations as well as impurities causing variations in shotcrete performance. From a physical point of view, differences between the two materials are showed in Table 1.

Table 1. The comparison of properties between silica fume and rheology control agent

Silica fume	Rheology control agent
Powdered product	Liquid product
Variable particle size and distribution	Uniform particle size and distribution
Particle size: 200 to 1000 nm	Particle size: 7 nm
Specific surface: 15 to 30 m ² /g	Specific surface: 345 m ² /g

Reason 3 – Performance

The use of pozzolanic-based rheology control agent provides several performance benefits compared to silica fume. When added to the shotcrete mix, rheology control agent provides greater cohesiveness to the mix. Therefore, while also improving the sprayability and pumpability characteristics, it reduces rebound and increases maximum thickness build-up. Furthermore, as reported by Bergna and Roberts [2], in contrast to silica fume, the surface of the colloidal silica particles is fully hydroxylated, and has much higher specific surface area; therefore, its pozzolanic activity is higher than silica fume. As a result, rheology control agent accelerates the hydration process which reduces the time of setting and increases early age strength while having no detrimental impact on the long-term performance [3, 4].

Reason 4 – 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 mixes. However, pozzolanic-based rheology control agent only requires 1/10th of the the silica fume dosage (or any other cementitious materials that may be present) to provide equivalent performance which makes it a more economical and sustainable solution.

2. EXPERIMENTAL PROGRAM

2.1. Aggregates

Combined aggregate system with a nominal maximum size of 10 mm was used. The gradation was within the limits of the project specification as shown in Table 2.

Table 2. Combined aggregate gradation

Sieve size (inch, mm)	Reference mix	Proposed mix	EFNARC (min-max)
5/8" (16)	100	100	100
3/8" (10)	100	100	93-100
No 4 (4.75)	89	88	77-100
No 8 (2.40)	60	60	59-92
No 16 (1.20)	43	41	41-76
No 30 (0.60)	30	29	26-56
No 50 (0.30)	16	16	14-32
No 100 (0.15)	7	6	6-16

2.2. Mix design

The project had a minimum cement content requirement and specified water-to-cement ratio (w/c). Therefore, the mix previously used in the mine that met the project specifications was selected as reference, and the mix design of the proposed system was selected to match the design of the reference mix. Both mixes had identical cement type and content, w/c, and combined aggregate gradation. The reference mix contained the competitor products for polycarboxylate-based high-range water-reducer and alkali-free set accelerator; however, the dosage rate was kept constant in both mixes. The major difference between these two mixes is that the proposed mix incorporated pozzolanic-based rheology control agent. Due to its pozzolanic properties, rheology control agent is typically used as a replacement to cementitious materials such as ordinary portland cement, silica fume, or fly ash. However, in this particular project, it was used as an addition due to the specified minimum cement content requirement. The selected mix designs are summarized in Table 3.

Table 3. Mix design

Mix components	Reference mix	Proposed mix
Cement, kg/m ³	459	460
Water, kg/m ³	211	210
water-to-cement ratio (w/c)	0.46	0.46
Maximum aggregate size, mm	10	10
High-range water-reducing admixture, % of total cement content	Competitor product 1.2%	TYTRO [®] WR 130 1.2%
Alkali-free set accelerator, % of total cement content	Competitor product 6%	TYTRO [®] SA 528 6%
Pozzolanic-based rheology control agent, % of total cement content	0	TYTRO [®] RC 430 0.67%

2.3. Test matrix

The selected test matrix is presented in Table 4.

Table 4. Performance requirement for shotcrete mixes used in this project

Property	Target performance criteria	Age	Test method
Temperature	15 to 30, ideal 20 °C	N/A	ASTM C1064
Air content	Range of 7% to 10%	N/A	ASTM C231
Slump	Min 180 mm	N/A	ASTM C143
Rebound	Max 20%	N/A	N/A
Early-age strength development using needle penetrometer	1.5 MPa	3 hours	EN 14488-2
Early-age strength development using Hilti stud	3 to 20 MPa	6 to 24 hour	EN 14488-2
Compressive strength (cored)	10 to 100 MPa	1 to 28 day	EN 12504-1
Compressive strength (cylinders)	10 to 100 MPa	1 to 28 day	ASTM C39
Bond strength	0.5 MPa	28 day	EN 1542

3. RESULTS AND DISCUSSION

3.1. Temperature

Ambient temperature in underground affects the rate of hydration which in turn has an impact on the compressive and tensile strength as well as the development of bond strength between shotcrete and rock [5]. Furthermore, extreme ambient and concrete temperatures are detrimental to shotcrete performance. For example, high temperatures may cause rapid slump loss, thermal stresses, and the tendency for drying shrinkage cracking. On the other hand, chemical reactions are slower at lower temperatures which results in low strength development. Considering that time is critical for 1) supporting the underground structures as fast as possible for increased safety; and 2) re-entry to the mine, it is important to have the desired temperature to have an adequate strength development rate and achieve the target shotcrete performance. In most applications, the allowable temperature range of shotcrete is between 10 °C and 38 °C [6]. In this project, temperature was specified to range between 10 °C and 30 °C while the ideal temperature was listed as 20 °C. As shown in Figure 2, despite the variation in ambient temperature resulted in slightly higher variation of concrete temperature for the reference mix, both mixes were within the allowable range and the average temperatures were very close to the ideal temperature of 20 °C, as desired.

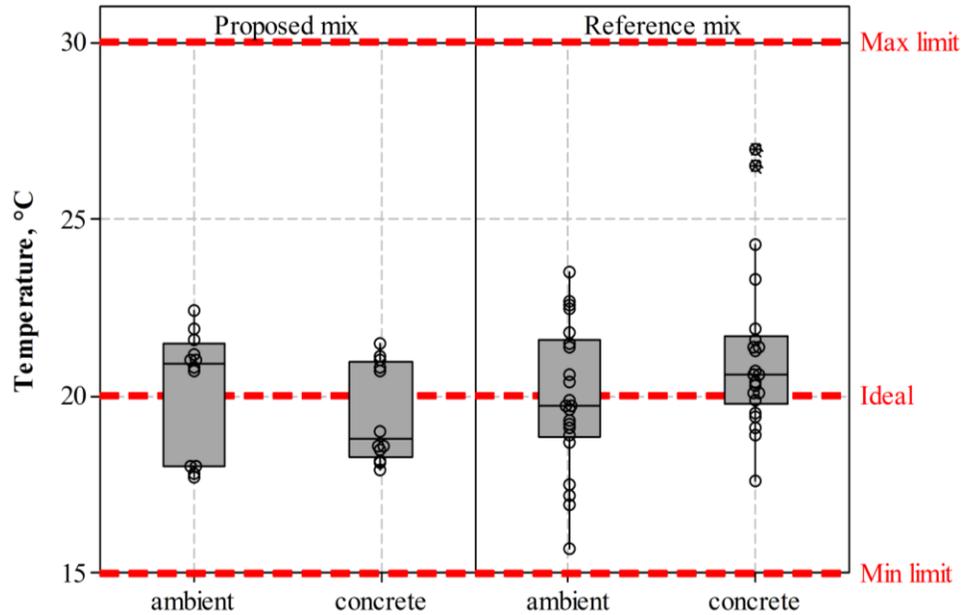


Figure 2.Temperature comparison between the reference and proposed mix.

3.2. Rheology

Workability is often assessed based on the slump test due to its ease of use. However, slump only indicates consistency (ease of flow) and does not evaluate cohesiveness (tendency to bleed and segregate) which is also a workability indicating parameter. One of these two parameters is often compromised due to the pumpability and sprayability of shotcrete mixes requiring conflicting workability properties. For pumpability, low viscosity (usually associated with high slump and suitable consistency) is desired. However, for sprayability characteristics, a stiff and sticky mix with low slump and high cohesiveness is desired to minimize rebound and increase build-up thickness [7]. Therefore, both consistency and cohesiveness should be considered when evaluating the rheology of the mix.

Slump

Slump indicates the flowability characteristics of a shotcrete mix; therefore, for enhanced pumpability, high slump values are generally desired depending on the project requirements. Figure 3 shows the comparison of slump between the reference and the proposed mix along with the specified project limit. According to the obtained test results, both mixes met the minimum slump requirement where the proposed mix with 0.67% of pozzolanic-based rheology control agent had slightly higher slump than the reference mix. The use of the rheology control agent as an addition didn't affect the slump at the selected dosage rate mainly because slump is affected by the paste content and in this study, the total cementitious materials content was kept constant for both mixes.

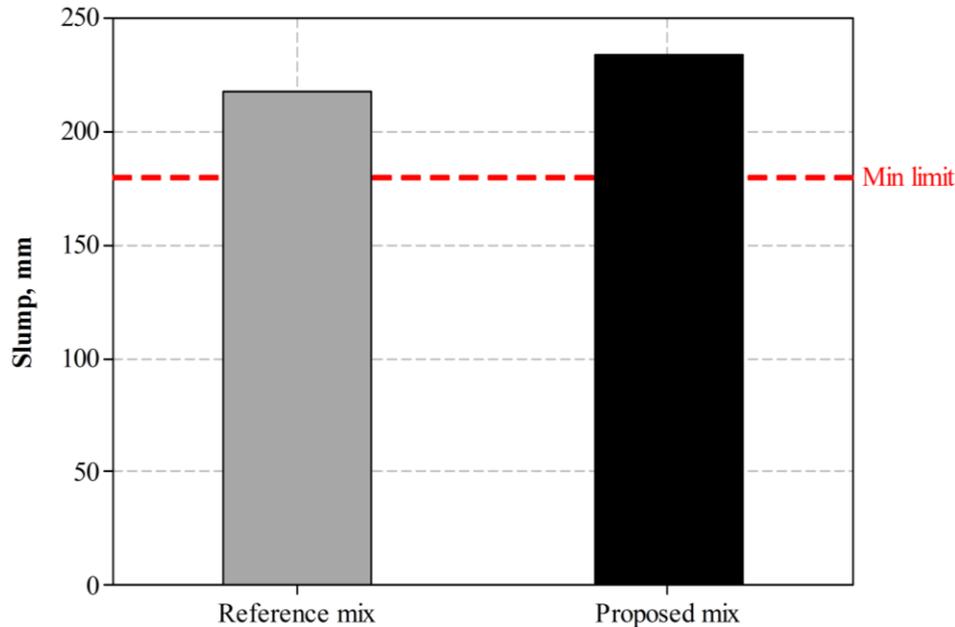


Figure 3. Slump comparison between the reference and proposed mix.

Rebound

Shotcrete tends to present material loss due to rebound since compressed air is pneumatically applied [8]. Although, a certain percentage of rebound is inevitable and even necessary since paste is needed to create a sticky surface for subsequent shotcrete material to become compacted into the surface, it is desirable to keep the rebound at minimum [9].

As shown in Figure 4, when compared with the reference mix which has the same mix design as the proposed mix, the addition of pozzolanic-based rheology control agent significantly reduced the rebound from 20% to 6%. Due to the smaller particle size associated with higher specific surface area of rheology control agent, it works as a nucleation site for the precipitation of calcium silica hydrate (CSH) gel, and it has stronger Van der Waals and electrostatic ionic forces between particles [10]. Considering that the main source of cohesion in cement paste is the calcium silicate hydrate (CSH) gel [11], it is expected for pozzolanic-based rheology control agent to increase cohesion due to 1) its impact on accelerating and forming additional CSH gels, and 2) its reactant surface particles exhibiting stronger tendency for adsorption of ions and increasing the surface adhesion between adjacent particles, and to other materials. Having a mix with high cohesiveness, viscosity, and stickiness is desired to maximize thickness build-up and minimize rebound of shotcrete which is prone to segregation under pressure.

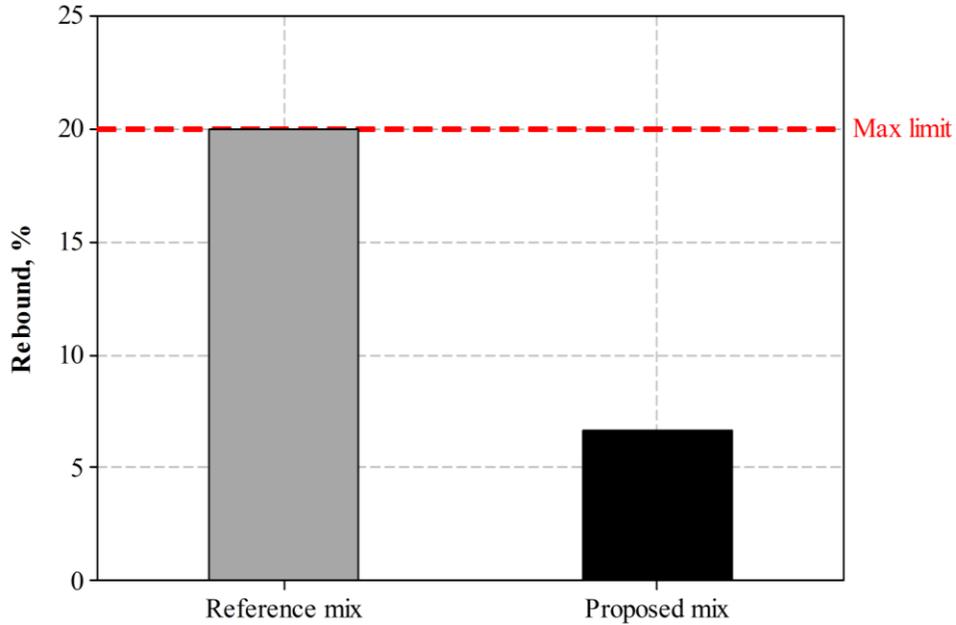


Figure 4. The effect of the pozzolanic-based rheology control agent on rebound.

To illustrate the cohesiveness and stickiness of the proposed mix, a horizontal beehive was shot which reached at depth of 350 mm as shown in Figure 5.



Figure 5. An illustration of the spraying process and cohesiveness of the proposed mix.

3.3. Air content

As initially suggested by Beaupré [12], shotcrete mixes are deliberately batched with high initial air content because high air content increases the paste volume which in turn improves the pumpability of the mix. However, these high initial air contents are temporary because during pumping and spraying, a large portion of the entrained and entrapped air (approximately 3% to 6%) is often lost due to the compaction process [13]. As a result, the ultimate air content of the sprayed mix is often reduced enough to meet the target air content while avoiding the detrimental effect of high air content on compressive strength.

Therefore, in this project, the target air content of the non-air-entrained shotcrete was specified to range between 7% and 10% before shooting. As shown in Figure 6, the mixtures batched according to the proposed mix design were within the target range throughout the trial which shows that the use of pozzolanic-based rheology control agent have neutral impact on air content.

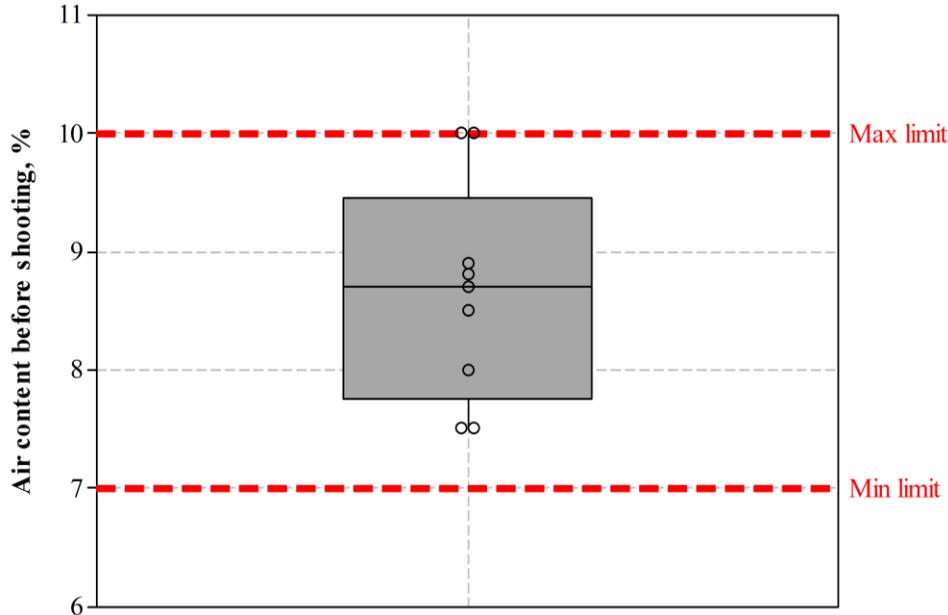


Figure 6. The air content of the proposed mix prior to shooting.

3.4. Strength development at early-ages

The compressive strength test results of the proposed mix based on the penetrometer needle up to 2 hours followed by Hilti stud up to 3 hours are shown in Figure 7 and Figure 8, respectively. As shown in these two figures, the strength development rate during the first couple readings is relatively low whereas starting from two hours, rapid strength gain has been observed. This behavior can be explained with the hydration process as shown in Figure 9. Cement hydration is an exothermal reaction, therefore higher the heat evolution, the faster the cement hydration thereby faster the strength gain rate. In stage I, the reaction occurs immediately after contact with water because ions dissolved in water react with C3A and gypsum. However, the formation of ettringite significantly reduces the hydration rate in the latter part of stage I; therefore, this stage has marginal effect on concrete strength. In stage II, there is also no strength development given the stable heat of hydration trend. In stage III, the alite (C3S) and belite (C2S) in the cement start to hydrate and release heat. In this stage, the silicate reaches a high rate of hydration where heat generation is rapidly accelerated followed by faster strength gain [14].

As shown in Figure 7, cement hydration seems to be relatively slow between 15 minutes to 2 hours, which indicates that the strength gain up to 2 hours is most likely provided by the accelerator since no strength development through cement hydration is expected within the first two stages, as described above. On the other hand, Figure 8 shows that since the rate of hydration increases after the dormancy period, faster strength development is obtained between 2 to 3 hours as a result of the accelerated cement hydration which is contributed by the pozzolanic-based rheology control agent. This is mainly because the rheology control agent 1) has high pozzolanic activity as a result of the ultrafine size of rheology control agent having high specific surface area; 2) reacts with the calcium hydroxide released by the cement hydration and forming additional calcium silicate hydrate (CSH) gel; 3) serves as nucleation sites to CSH gel; and 4) accelerates the primary CSH gel formation. In addition, it is noted that the proposed

mix significantly exceeded the strength requirements of 1.5 MPa at 3 hours due to the minimum cement content requirement leading a deliberate overdesign and required the rheology control agent to be used as an addition instead of as a replacement where approximately 6% to 10% of cement content reduction would be expected.

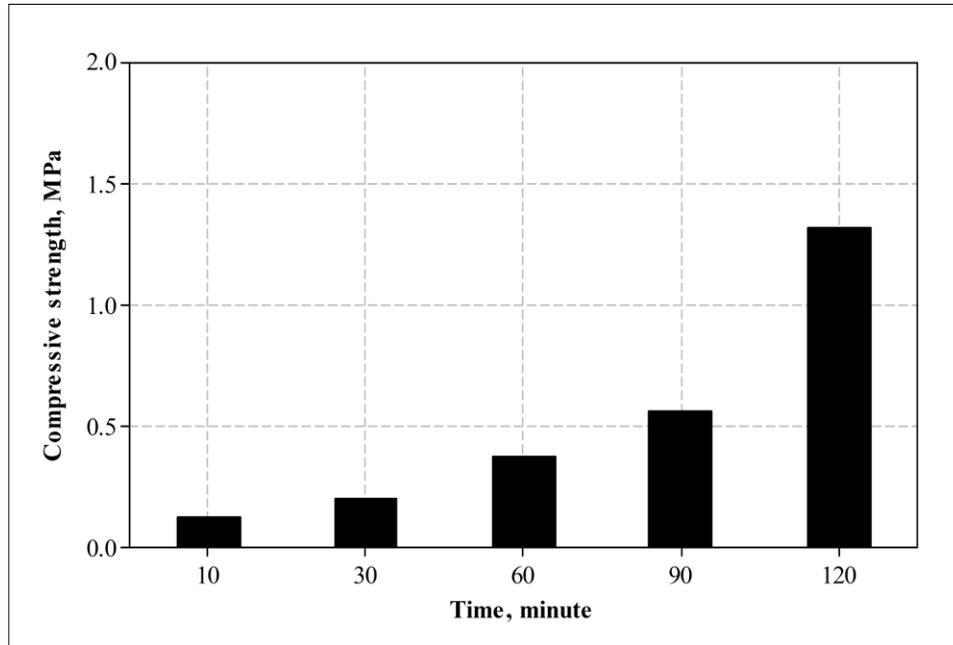


Figure 7. Compressive strength results based on the penetrometer needle.

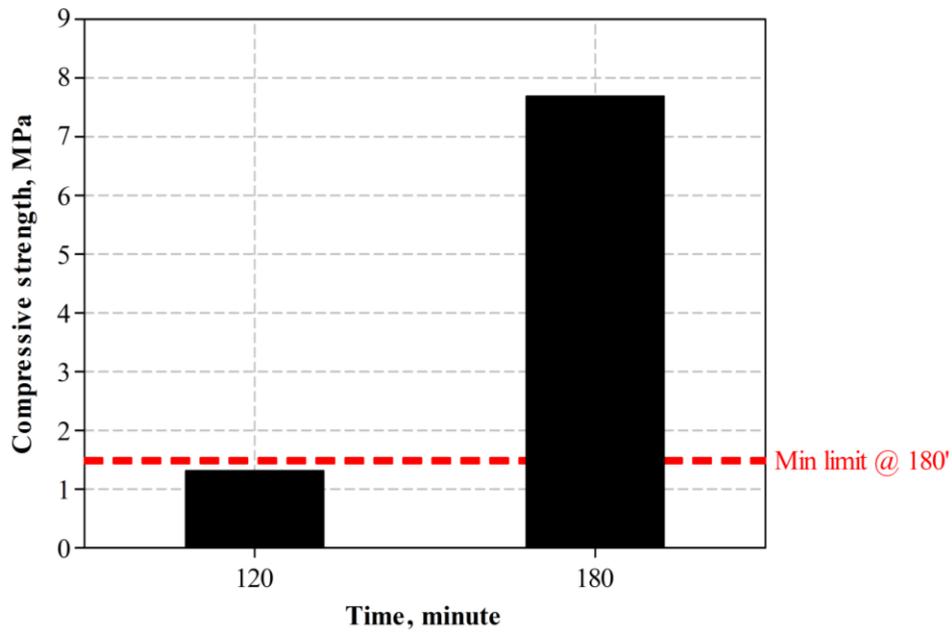


Figure 8. Compressive strength results based on the Hilti stud.

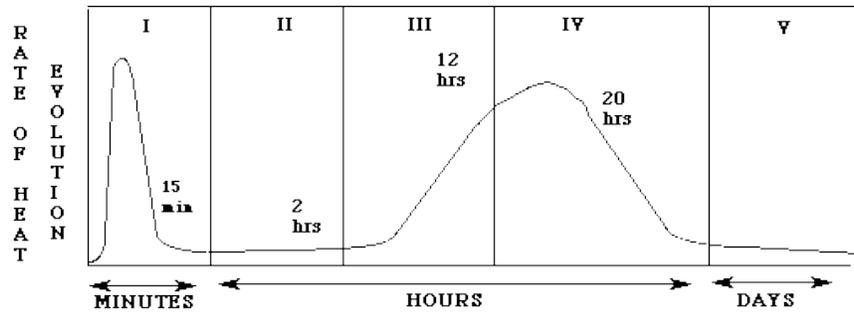


Figure 9. Rate of heat evolution during hydration [15].

3.5. Compressive strength

Figure 10 shows the comparison of the compressive strength test results between the reference and proposed mix. Although both mixes performed within the project limits, the proposed mix outperformed the reference mix due to the presence of the pozzolanic-based rheology control agent. The compressive strength was 60%, 50%, and 45% higher than the reference mix at 1, 7, and 28 days, respectively. The obtained values for improvement are also supported in the literature. For example, the research study conducted by Wagner and Hauk [16] showed that colloidal silica with a particle size of 15 nm mixed with cement paste increased early age strength (at 1 to 7 days) by 36% compared with a reference mixture without colloidal silica. In our trial, pozzolanic-based rheology control agent consists of colloidal silica with a particle size of 7 nm. The slight difference in the percent of improvement is likely due to the particle size used in this study being much smaller than the one in the cited study (smaller the particle size, higher the pozzolanic reactivity). This trend shows that the impact of rheology control agent on compressive strength is more prominent at early ages, and most importantly, unlike other rapid setting materials, it does not harm the later-age strength which is ideal for underground applications where minimal time to re-entry to the mine is desired. As discussed above, the obtained results of 65 MPa at 28 days is an indicator of overdesign which will be eliminated in the next trial by optimizing the mix through the use of rheology control agent as a replacement of cement content.

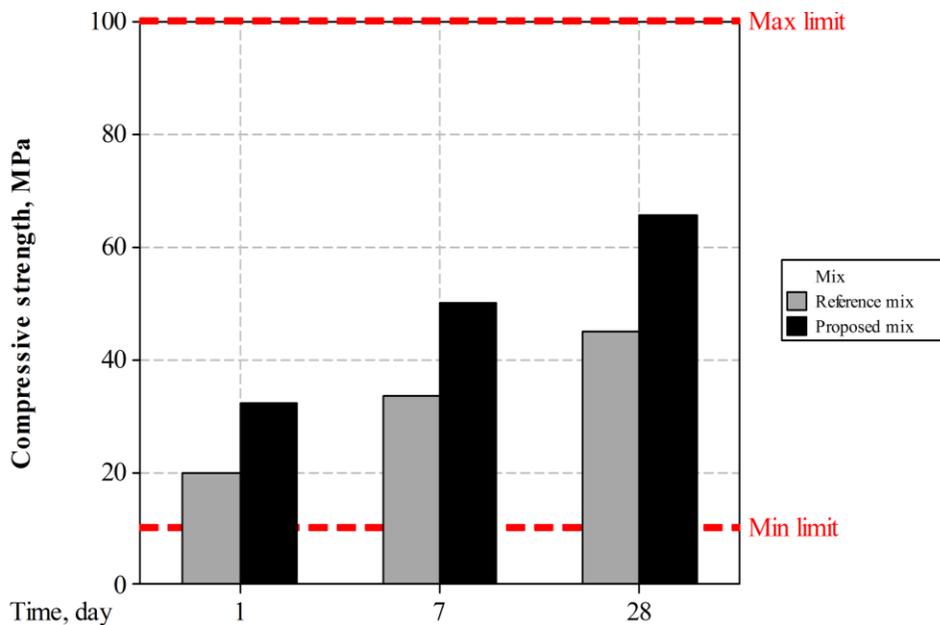


Figure 10. Comparison of compressive strength between the reference and proposed mix.

3.6. Cast cylinders versus drilled cores

Figure 11 shows the comparison of compressive strength test results between the cast cylinders and drilled core samples of the proposed mix at 1, 7, and 28 days. Test results show that the average compressive strength obtained from cast cylinders and cores from panels correlated very well.

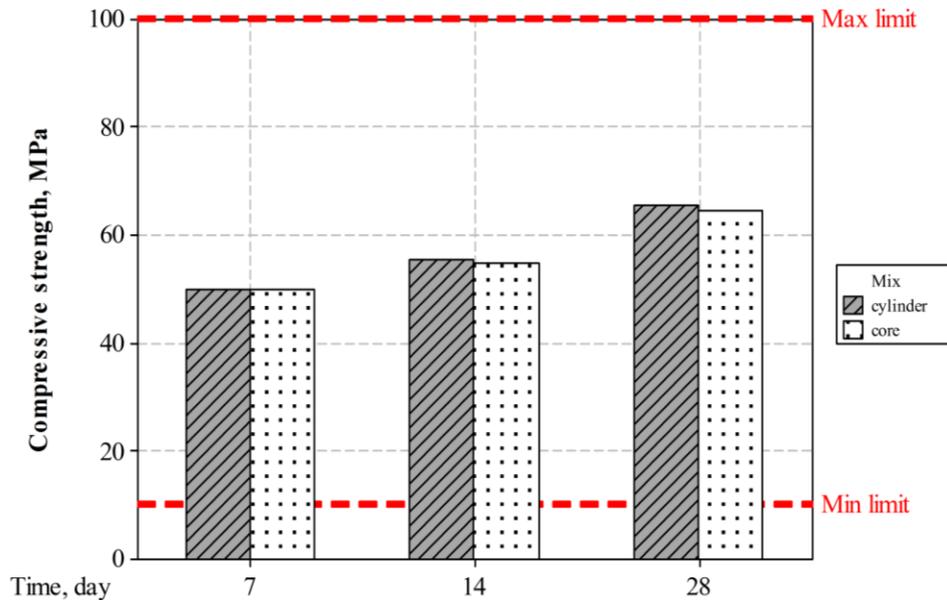


Figure 11. Strength comparison between the cored samples and cylinders cast from the proposed mix.

3.7. Adhesion strength

The bond strength between shotcrete and rock is one of the most important properties as it determines the longevity of the structure as well as the safety of the work area. Specification required 0.5 MPa of bond strength at 28 days. According to the pullout test results shown in Figure 12, proposed mix achieved higher than 1 MPa in 40 days whereas similar adhesion was achieved in 338 days for the reference mix. Although, both mixes met the project limits, the proposed mix achieved the equivalent bond strength as reference mix at much earlier ages. Considering that the bond between rock and shotcrete depend on the set accelerator and the micro structure [17], the obtained results are likely due to the influence of the pozzolanic-based rheology control agent providing a much denser structure as a result of its filler effect as well as the TYTRO[®] set accelerator outperforming the competitor accelerator at the same dosage rate.

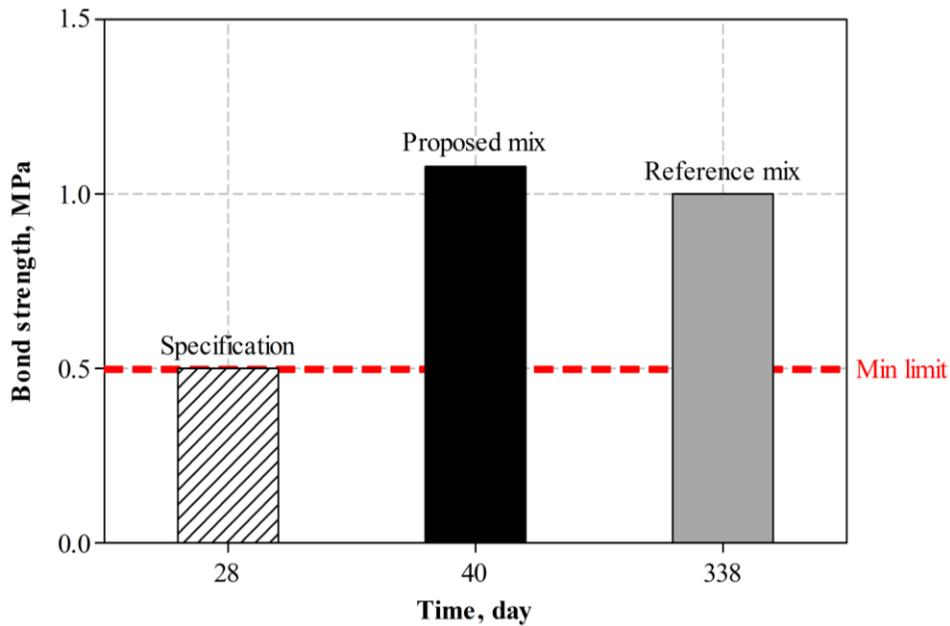


Figure 12. The effect of pozzolanic-based rheology control agent on bond strength.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the obtained test results, the following conclusions are drawn in regards with the use of pozzolanic-based rheology control agent in shotcrete mixes:

- neutral impact on air content
- slightly increased slump
- improved cohesion and viscosity allowing higher build-up thickness and enhanced sprayability
- significantly reduced rebound from 20% to 6%
- increased early strength development due to the accelerated CSH formation and contribution to the pozzolanic reaction with no detrimental impact on the later-age performance (increased later-age compressive strength within the range of 40% to 60%)
- increased adhesion

The impact of rheology control agent on performance has been verified when used as an “addition”. Next step will be conducting trials where it will be used as a “replacement” to cementitious materials to optimize the mix design by reducing cement content. After the assessment of test results, pozzolanic-based rheology control agent will be listed as a recommended material in shotcrete specifications.

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