Developing Dust Reduced and Low Cracking Potential - Dry-Mix Shotcrete Mixes

By William Clements and Cody Fournier

Although dry-mix shotcrete has been used extensively in both mining, tunneling and concrete repair projects, it suffers from the reputation that it will produce more dust than other repair methods or even wet-mix shotcrete. Due to the fact that dry-mix shotcrete is most often applied using pre-packaged bagged material, the act of emptying the shotcrete itself into the shotcrete spraying equipment inherently generates dust. In contrast, the vast majority of wet-mix shotcrete is sprayed using shotcrete supplied via ready-mix trucks which introduces little to no dust generation at the jobsite itself. Dust is generated at the ready-mix plant during batching and controlled by the ready-mix shotcrete supplier via engineering controls such as dust collection. By the time the contractor receives the material it is fully mixed and does not emit any dust on-site. There are options available to reduce the amount of dust generated while spraying dry-mix shotcrete but using dust-reducing additives to the pre-packaged dry-mix shotcrete is still an area of interest for development. This article explores the results of testing several dust-reducing additives, how dust generation can be evaluated, and how the inclusion of these additives can affect the mechanical properties of dry-mix shotcrete

Previous work has shown that by modifying the mixture design of conventional dry-mix shotcrete, the cracking resistance can be greatly increased in laboratory conditions (Clements & Robertson, 2019). Although it was found that removing silica fume from the formulation greatly increased the cracking resistance, it also drastically increases the rebound observed during shotcrete placement. As a result, King - A Sika Company (KING) developed a testing program to evaluate four prototype mixture designs to select the mixture with the lowest cracking potential for further development. The selected candidate mixture was sprayed following an intensive testing protocol to characterize the desired mechanical and durability properties of the mixture. The initial results of the testing program and the preliminary results of the full characterization testing program are contained in this article.

DRY-MIX SHOTCRETE DUST GENERATION

Workplace dust is an unavoidable risk in many construction-related occupations and especially true for dry-mix shotcrete. Prolonged exposure of workers to elevated concentrations of silica dust can lead to irreversible physical damage such as silicosis. Currently, the only reliable, proactive defense is the use of proper engineering controls such as suitable ventilation, appropriate dust respirators and appropriate PPE. However, the best form of risk management is to eliminate or reduce the potential of the risk itself.

When observing dry-mix shotcrete placement, it is first important to identify the regions where dust can potentially be generated. Dust is generated at high concentrations in two specific regions: at the discharge from the nozzle; and feeding material into the dry-mix shotcrete machine (Figure 1 and 2).

Fig.1: Case 1-High concentration of dust emitted from the nozzle.

Fig. 2: Case 2: High concentration of dust emitted when pre-packaged dry-mix is emptied into the material hopper of a dry-mix shotcrete machine.

QUANTIFYING DUST

When it comes to quantifying dust levels at the hopper for dry-mix shotcrete, two methodologies can be proposed. These methodologies shall be referred to as the "static" and "dynamic" method of testing.

A static dust emission test involves measuring the dust levels with the DustView II from Palas based on the standard CIPAC MT 171. (CIPAC, 2015). This device functions by dropping a powder sample of 0.035 ounces (30g) down a cylindrical tube. As the powder descends, dust particles are measured through extinction measurement with a laser beam. The results are then summarized with an optical dust value, referred to as the "Dust Number". The Dust Number can be calculated using the software offered by the device and serves as a manner to interpret dust emission activity.

Dust Number = Maximum Dust Value + Dust Value 30-seconds after the Maximum Dust Value. (Palas, n.d)

As per CIPAC MT 171, and as seen in Figure 3, in the event where the Dust Number is lower than 25, it shall be considered as being "essential non dusty". An "essential non dusty" material is one where dust levels are lowered but can still be seen by the naked eye.

Figure 4 is an example of how DustView II records

Category	Range of results		Interpretation
	gravimetric "collected dust" [mg]	optical dust value	
1	0 - 12	0 - 10	nearly dust-free
2	> 12 - 30	> 10 - 25	essential non dusty
3	> 30	> 25	dusty

Fig. 3: CIPAC MT 171 table for evaluating the level of optical dust emissions for DustView II (CIPAC, 2015).

the activity of dust particles during static testing. The graph showcases how the dust activity peaks in the initial moments and then decreases gradually as the dust settles. The Dust Number for this particular test was 18.63 which would mean that the product falls in second category from Figure 3.

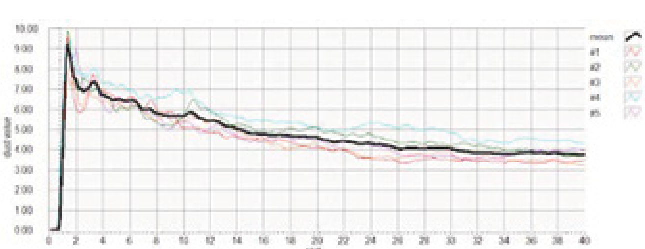

Fig. 4: An example of the results which can be obtained from the DustView II.

The dynamic method takes measurements during a live test with real equipment and external activities. During a real dry-mix shotcrete test, there are many variables which can generate additional dust: compressed air, ambient wind pressures and currents, movement from equipment and personnel, entrapped-air, etc. This manner of testing uses the DustTrak II Aerosol Monitor 8530 by TSI. The DustTrak II performs readings with gravimetric sampling. It is capable of measuring aerosol concentrations ranging from 0.001 to 400 mg/m^3. (TSI, n.d).

In KING's shotcrete laboratory, a series of tests were conducted to see where the dust should be measured. Three locations for the monitors were established for the testing (Figure 5):

- Location A – situated 1 ft (0.3 m) from the hopper of the dry-mix shotcrete machine;
- Location B – set 10 ft (3 m) from Location A and;
- Location C – located in the shotcrete shooting chamber.

The chamber was rectangular in shape and the entrance was sealed with rubber lathes to contain dust from the nozzle. Through trial and error, it was deemed too turbulent to take accurate readings when the DustTrak II was placed in the shooting chamber at Location C. For Location B the aerosol recordings did not depict any significant differences between shooting and not shooting. It was only at Location A when the monitor was placed 1 ft (0.3 m) from the dry-mix shotcrete machine , that significant fluctuations were recorded, and corresponded with the shotcreting activities.

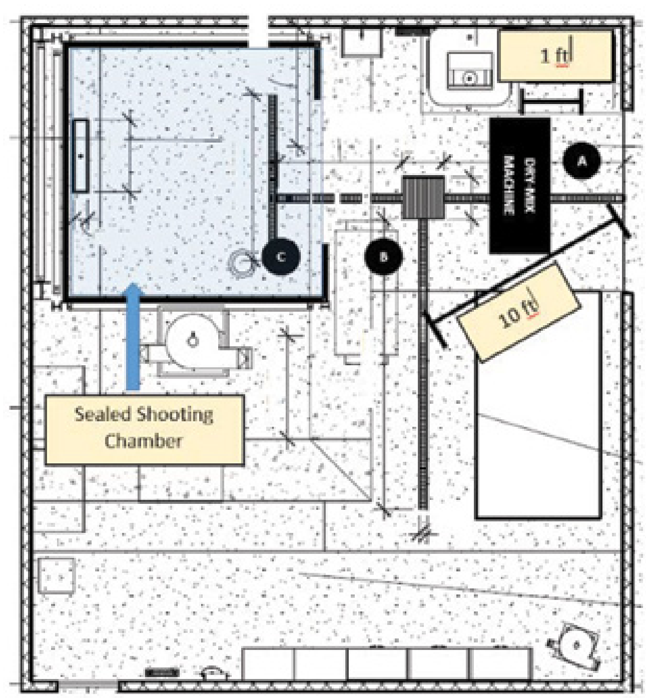

Fig. 5: Locations A, B & C for DustTrak II Aerosol Monitor 8530 dust level monitoring.

DEVELOPMENT OF A DUST REDUCED SHOTCRETE

Trials to date for reducing the amount of dust generated during dry-mix shotcreting for Case 2 are still in the preliminary stages. General findings have been positive for reducing emissions. However, dust reducing additives used thus far were shown to influence two major components of dry-mix shotcreting: 1) The amount of water required at the nozzle to properly hydrate the mix; and 2) A reduction in early and later-age strength gain.

In Figure 6, there is an example of how DustTrak II records the activity of dust particles during dynamic testing. The orange curve is the control mixture and the green and yellow are with two different types of dust reducing admixtures. Everything in gray represents dust generated by other equipment.

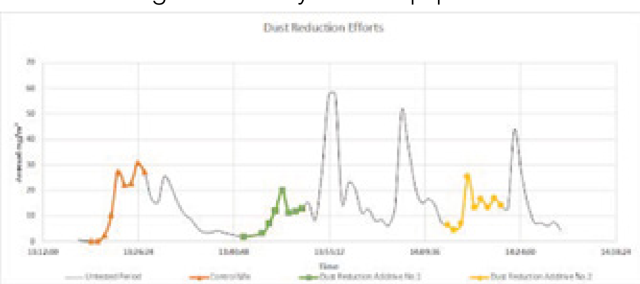

Fig. 6: Dynamic test results for dry-mix shotcretes with and without dust reducing additives.

Dust reducing additives have been effective at lowering dust emissions by up to 43% in dry-mix shotcrete mixes when using the dynamic method. When comparing the compressive strengths for the different formulations as seen in Figure 7, the strength development is slower. However, the differences in strength can be associated with the fact that more water was required at the nozzle to produce a cohesive spray. When observing results from the Rapid Chloride Ion Penetration (RCP) ASTM C 1202, the relationship between additional water can be seen. Referring to Table 1, the early RCP values are elevated for one of the dust additives but at 28 days all formulations reach relatively low coulomb ratings. Figures 8, 9 and 10 show the visible reduction of dust at the hopper when using the dust reduction additives.

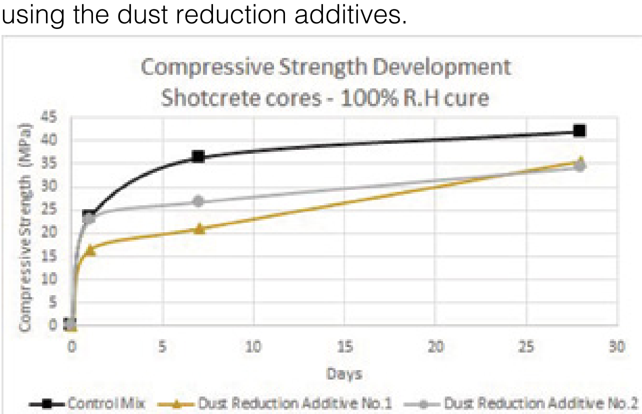

Fig. 7: Compressive Strength development for dry-mix shotcretes with and without dust reducing additives.

Mix Design	Chloride Ion Penetration (7 Days)s	Chloride Ion Penetration (28 Days)
Control	1500 coulombs	650 coulombs
Dust Reduction Additive No. 1	3600 coulombs	750 coulombs
Dust Reduction Additive No. 1	1400 coulombs	500 coulombs

Table 1: Chloride Ion Penetration results for dry-mix shotcretes with and without dust reducing additives.

Fig. 8: Dry-mix shotcrete without any additives.

Fig. 9: Dust Reduction Additive No.1.

Fig. 10: Dust Reduction Additive No.2.

LOW CRACKING POTENTIAL DRY-MIX SHOTCRETE

When repairing concrete structures, best practice is replacing any deteriorated concrete, with a material that closely matches the mechanical properties of the substrate when possible. Even though shotcrete can be very similar to cast-in-place concrete when shot, the shotcrete process and mixture design can invariably lead to increased shrinkage and volume change. This volume change becomes very important for a shotcreted concrete repair, as the substrate restrains the shotcrete from shrinking after placement. If the tensile stress developed in the patch or resurfaced area exceeds the tensile strength of the shotcrete it will lead to cracking or de-bonding.

To characterize the volume change of shotcrete AASHTO T 344 standard test method (ring test) was adapted to the shotcrete process at Laval University (Girard, Jolin, Bissonnette & Lemay, 2017). Using this method, KING was able to screen several prototype mixture designs for a low cracking potential dry-mix shotcrete. During this testing program the ring specimens (Figure 11) were wet cured for a period of 3 days, followed by being placed in a controlled environment at 50% (±5%) relative humidity and a temperature of 70 ± 2°F (21 ± 1°C). The results of this testing program are presented in Table 2.

Mix No.	Compressive Strength ASTM C 1604 (7 Days)	Compressive Strength ASTM C 1604 (28 Days)	Age of Cracking AASHTO T 344 (Days)
1	5800 psi (40 MPa)	7100 psi (49 MPa)	15
2	6235 psi (43 MPa)	6815 psi (47 MPa)	25
3	6380 psi (44 MPa)	6525 psi (45 MPa)	45
4	4640 psi (32 MPa)	5510 psi (38 MPa)	38

Table 2: Age of cracking for different prototype dry-mix shotcrete formulas.

Based on the results of the initial screening tests Mix No. 3 was selected for the next phase, which included a testing program to assess many mechanical and durability properties. This testing program also included the spraying of AASHTO T 344 rings which were then cured using three different curing regimes. The three curing regimes included exposure to 50% (±5%) relative humidity for the entire age of the specimen (Dry), three days of wet curing followed by exposure to 50% (±5%) relative humidity (Wet) and curing compound being applied to the exposed surfaces of the ring after spraying and demoulding then exposure to 50% (±5%) relative humidity for the entire age of the specimen (Curing Compound). All the ring specimens in each curing regime were maintained at a temperature of 70 ± 2°F (21 ± 1°C). The preliminary results of the ring tests performed in the second phase of the testing program for the candidate low cracking potential dry-mix shotcrete are presented in Table 3.

Curing Regime for Rings	Age of Cracking AASHTO T 344 (Days)
Dry (50% RH)	20
Wet (3 Days Wet, 50% RH)	42+*
Curing Compound (50% RH)	42+*
4640 psi (32 MPa)	5510 psi (38 MPa)

*Table 3: Age of cracking for low cracking potential dry-mix shotcrete using different curing methods. *Rings had not cracked at the time of publishing this article.*

It can be seen that exposing the rings of this candidate mixture to 50% (±5%) relative humidity without any curing, can still perform better than typical silica fume enhanced dry-mix shotcrete with three days of wet curing which would normally crack near six to seven days (Menu, Pépin Beaudet, Jolin, Bissonnette & Molez, 2018). However, in comparison to exposing the rings to either three days of wet curing or using curing compound has extended the age of cracking, to such an extent that the rings had not cracked prior to the publication this article and continue to be monitored.

Conclusions

Dust reduction technology for shotcrete is an area that needs further research. Improving the health and safety of the workers who are exposed to dust daily will benefit these individuals and the entire shotcrete industry. Dry-mix shotcrete with reduced dust emissions are currently achievable, but the effect of the additives on the physical properties and durability of shotcrete must be explored further.

It has been shown that by modifying the mixture design of dry-mix shotcrete, the cracking potential can be greatly reduced. Upon selecting the best performing mix design, it can also be seen that using no curing with the low cracking potential dry-mix shotcrete is better than current dry-mix shotcrete technology with three days of wet curing. In a laboratory environment it was observed that the use of three days of wet curing or the use of curing compound with this new technology can drastically reduce the potential for cracking. Low cracking potential dry-mix shotcrete continues to be evaluated to assess the appropriate durability parameters.

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