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Efficiency of accelerator atomisation in mechanised applications of sprayed concrete

Jonathan Lavallee [a,*], **Jakob Van de Sande** [a]

[a] *MacLean Engineering, Canada*

Abstract

Due to the numerous complexities involved with sprayed concrete operations, determining methods for savings and efficiencies that provide several benefits throughout the value chain can allow for product viability across a wider range of use cases. Mechanised sprayed concrete is essential for a wide range of construction activities, with the leading sectors being civil tunnelling, slope stabilisation, and mining.

The operational costs associated with sprayed concrete can become significant due to the wide range of requirements involved, including batched material components, admixture chemicals, re-entry or set times, rebound, etc. Therefore, finding solutions to provide savings and efficiencies while improving the final quality of the process is crucial to improving operations and making the process more technically economically viable to an expanded range of use cases. Additionally, solutions that allow for a reduction in the carbon footprint associated with sprayed concrete, as well as improving operations, make the prospect enormously more valuable. This paper discusses how a system designed to reduce the amount of set accelerator chemical consumed by using an efficient accelerant dispersal method can provide improved strength development characteristics while also providing savings and efficiencies throughout the process. Key areas addressed include how atomisation of aluminium–sulphate-based accelerator impacts initial early-age strength development while allowing for a reduction in dosage or consumption of accelerator, increased strength development at reduced time intervals that can allow for decreased re-entry times, and effectively optimising sprayed concrete mix designs.

Utilising a passive solution that does not require additional procedures or changes to the sprayed concrete process administers numerous benefits that impact initial and final strengths, as well as operational efficiencies and cost improvements, and adds value throughout the process, is a true leap forward for the sprayed concrete industry.

Keywords: *equipment technology, strength generation, low-carbon solutions, quality control, accelerator, savings, cost reduction*

1 Introduction

The dosage of set accelerator for sprayed concrete activities as well as the spraying equipment often does not attract the attention it deserves, and the scrutiny required to realise its far-reaching impacts on all facets of the sprayed concrete processes and final result. The prospect of reducing accelerator consumption for mechanised sprayed concrete operations is enticing as it has the potential to provide significant downstream benefits that can impact many parts of underground operations. This may be achieved by reducing times for re-entry and by installing stronger, more durable ground support. Furthermore, reducing the dosage of accelerator is a secondary benefit to the real transformation being studied, optimising the usage of your accelerator by making the real point that more can be achieved with less. Meaning, strength generation curves and properties can be improved and optimised while using less product and using it more effectively.

* Corresponding author. Email address: jlavallee@macleanengineering.com

The material cost of set accelerators is a significant contributor to the overall operational cost of sprayed concrete in underground operations. By using the accelerator more effectively, more opportunities arise where refining the complete process and its different inputs become more feasible. Reducing accelerator usage and consumption for the equivalent shot volume of material has the potential to allow for optimised mix designs, 'greener' sprayed concrete, the reduction of re-entry times during strength development, and material usage optimisation, in addition to the cost reduction alone of saving on chemical.

2 Set accelerator atomisation

The key to optimising the use of accelerator for sprayed concrete, and therefore reducing overall consumption, is how the chemical is dispersed at the nozzle. Effective dispersal for integration into the sprayed concrete is at the core of what needs to be accomplished to achieve the desired outcomes (Ginouse 2014). Accelerator is needed to speed up the hydration of the Portland cement components of the material (Wang et al. 2021). To understand how the traditional process can be improved and refined, it is critical to first grasp how the process works and what occurs at each stage; from pump to nozzle.

2.1 Dosing of set accelerator

It is critical to consider the cost of accelerator and how quickly its operational cost can accumulate. With prices ranging around USD 3,500 per 1,000 litre tote, over time, the excessive usage of chemical can have a significant impact on the bottom line of those utilising sprayed concrete. In addition, excessive use or overdosage of set accelerators can often lead to reduced final age strength. Providing a method for reducing this cost while maintaining and improving sprayed concrete material quality is an encouraging proposition for all stakeholders; where unlocking the full potential of leading accelerators on the market is possible to improve material performance, while reducing cost.

Traditionally, a wet process sprayed concrete liquified accelerator is pumped to the nozzle and only becomes dosed into the wet material by use of a constant flow rate pump dosing the liquid to a 'stream converter' or 'mixing ring' (Bérubé 2018). Figure 1 from Hanskat (2012) highlights how this device takes the independent flows of liquid accelerator and high-pressure high-volume air and introduces it into the sprayed concrete simultaneously.

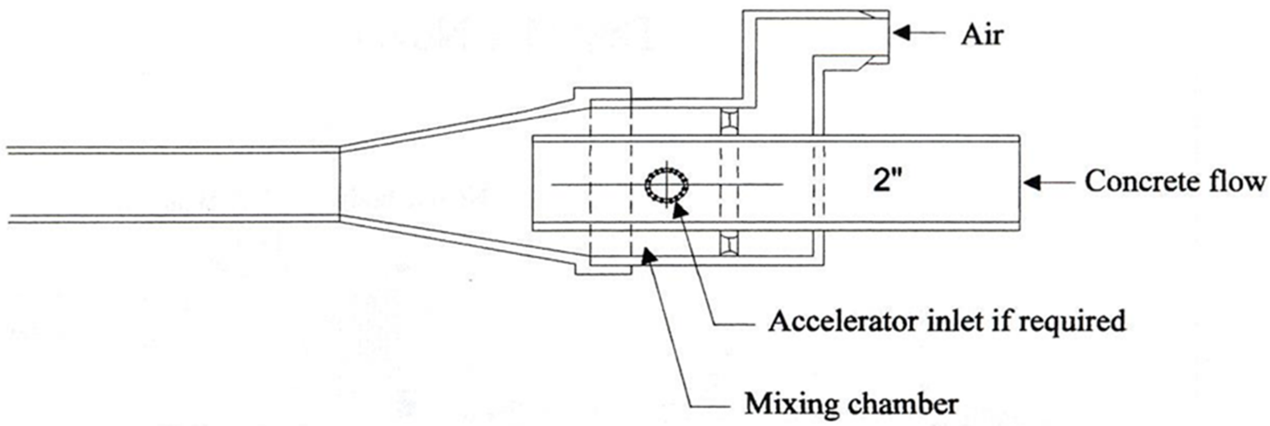


Figure 1 Typical wet process sprayed concrete nozzle arrangement (Hanskat 2012)

As seen in Figure 1, this process has inherent flaws as it relies on the turbulent flow of the sprayed concrete itself and air to adequately distribute the chemical throughout the material at the stream converter in its flowing liquid state. With no additional mechanism to blend the three components before exiting the nozzle (Burns 2008). To provide a more efficient manner of utilising the accelerator, an additional process is required to formulate a more effective accelerant–air mixture prior to reaching the stream converter. With a traditional setup, one way to comprehend how the accelerator and high-velocity air mix with the sprayed concrete could be thought of as 'injecting and coating' as the method of dispersal. Typically meaning that the accelerator is pumped through an inlet into the material stream without much consideration, where the liquid chemical can bond with cementitious material at the molecular level in a more limited manner due to the particle size of the liquid accelerator. To provide a more effective and efficient method, a fully atomised gaseous mixture should be obtained that allows for a reduction in droplet particle size allowing more thorough mixing and bonding.

2.2 Atomisation of set accelerator

Atomisation of the chemical requires an additional device to the traditional system. Various methods exist for the atomisation of fluid into the flow of air. By atomising the accelerator, the smaller particles in the air mixture provide the desired effect of superior and thorough molecular bonding to the cementitious material. An airblast atomiser provides a method of atomising accelerator as it is more conducive to varying viscosities of liquids (Methven 2004). According to Lefebvre & McDonell (2017), drop sizes produced by airblast nozzles tend to be less sensitive to variations in liquid viscosity. This can allow for more effective bonding with the cementitious particles in the sprayed concrete at a molecular level.

By decreasing the size of accelerator particles into the gaseous state versus the liquid state, a superior mixing effect can be obtained.

> *'The airblast concept lends itself to a wide variety of design configurations. However, in all cases the basic objective is the same, namely, to deploy the available air in the most effective manner to achieve the best possible level of atomisation'* (Lefebvre & McDonell 2017).

To obtain the mixture in such a state, the liquid accelerator chemical must be atomised to allow it to become more comprehensively distributed in the gaseous mixture, using high-velocity air (Ashgriz 2011).

To incorporate these principles and adapt them to a mechanised sprayed concrete application that achieves the objectives of a well distributed accelerator, research and development have been undertaken to explore and develop systems utilising different methods for atomisation to promote better distribution of chemical droplets that enhance underground mechanised sprayed concrete applications. Improving processes and creating efficiencies are all part of delivering an improved ground support product that brings an assortment of downstream benefits.

3 Early-age strength development of accelerator atomised sprayed concrete

Ensuring that required material properties are obtained is essential when reducing the dosage of accelerator of sprayed concrete. A reduction in dosed chemical without verification of the desired material properties is a dangerous proposition. When atomised accelerator is introduced in the spraying system, the impact the revised method of dispersal has on the sprayed concrete is significant. As the atomised accelerator has a large influence on the strength development of the material, dosages must always be reconsidered to evaluate for adequate observed material properties. Table 1 describes the sprayed concrete J-curve representation for early-age compressive strength development, from EN 14487-1 Sprayed Concrete (Austrian Standards International 2024). J3 represents rapid strength development in a brief period and would be the desired outcome for mining applications where re-entry set times to 2–4 MPa are preferred to be as short as possible, typically within 1–4 hours, to maximise in-cycle sprayed concrete productivity. Curve J2 is better suited to represent what would be desired in the civil construction industry, where quick set times are less imperative.

Table 1 Sprayed concrete J-curve representation for early-age compressive strength development, from EN 14487-1 Sprayed Concrete

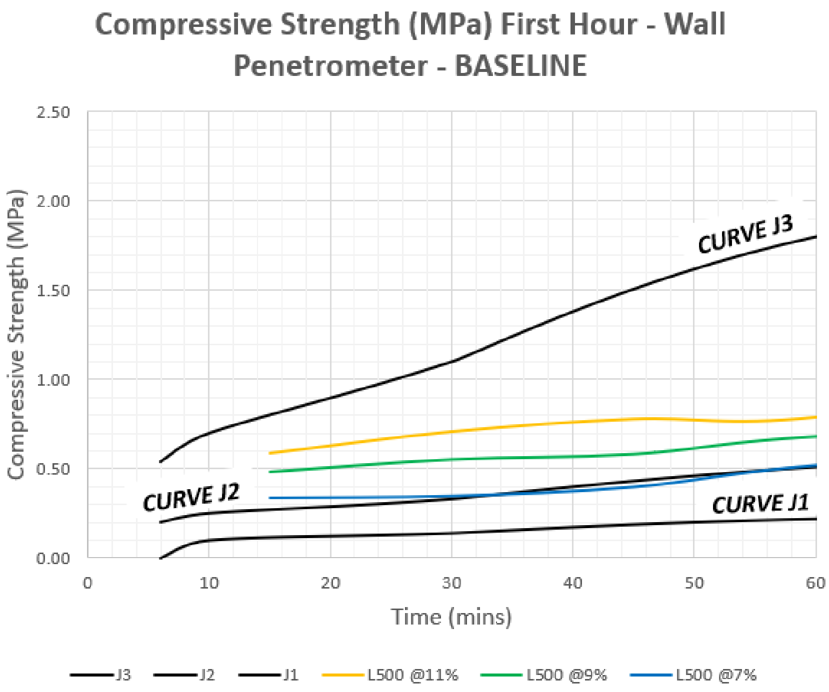
Time/age (minutes)	J1 (MPa)	J2 (MPa)	J3 (MPa)
6	0.00	0.20	0.54
10	0.10	0.25	0.70
30	0.14	0.33	1.10
60	0.22	0.51	1.80
360	0.60	1.75	6.00
720	1.00	2.50	8.50
1,440	2.00	5.00	18.50

3.1 Baseline strength development for common sprayed concrete mix

Before conducting any quality control testing for sprayed concrete applied using a system for accelerator atomisation, baseline results are needed for comparison. All field data collected was from testing conducted using Sika® KING MS-W1UG sprayed concrete material for wet process applications using Sika Sigunit® L-500 AFI liquid alkali-free sprayed concrete accelerator. Results obtained from field data for testing using a conventional mechanised equipment setup, suggest that accelerator dosage ranges between 7–11% to achieve 2 MPa in 3.5–4 hours. Observed field data is seen in Table 2 and plotted in Figure 2.

Table 2 Field test results for MS-W1UG using L-500 accelerator

Time/age (minutes)	Compressive strength over time at varying dosages (MPa)		
	11%	9%	7%
15	0.59	0.48	0.34
30	0.71	0.55	0.35
45	0.78	0.58	0.40
60	0.79	0.68	0.52
90	1.09	0.76	0.66
120	1.32	0.91	0.67
150	1.44	0.96	0.90
1,320	16.5	16.0	16.3



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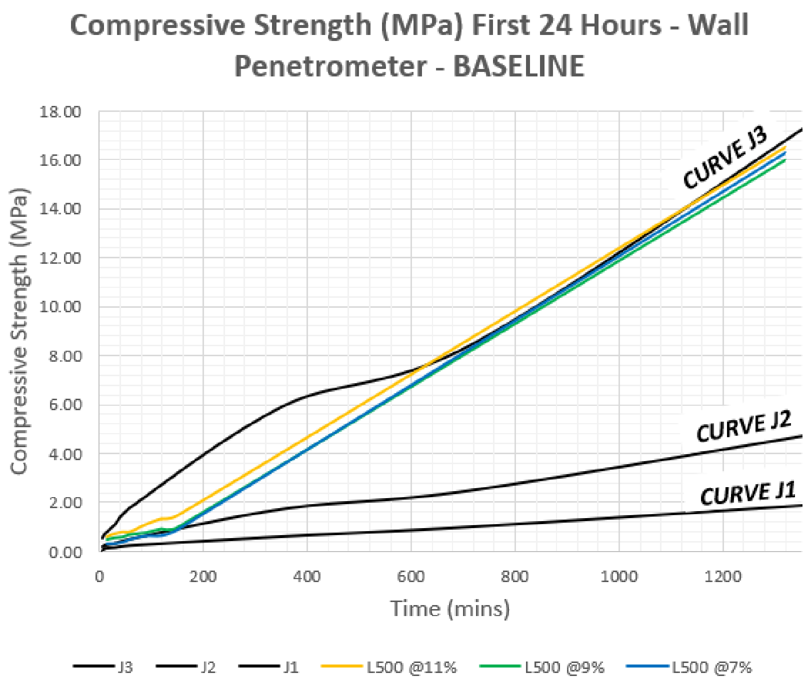


(b)

Figure 2 Field data for compressive strength for (a) first hour and (b) first 24-hour strength of MS-W1UG product using Sigunit L-500 accelerator

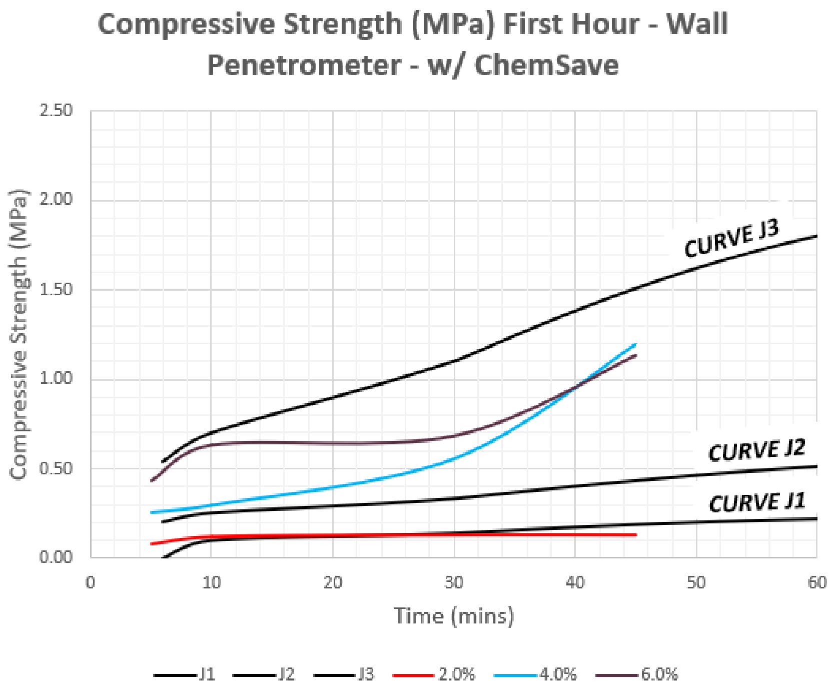
As seen in Figure 2, early strength development within the first hour is limited. Development accelerates later within the first 24 hours to reach 14 MPa within 1,200 minutes (20 hours). Furthermore, it is observed that even an increase in dosage from 7–11% accelerator has a limited effect on accelerating the early strength development of sprayed concrete. This is seen by the closely correlating curves for each of the three test trials. Early strength development for these trials most closely resembled a result that aligns with curve J2, meaning that early-age strength development can be improved to reach the 2 MPa threshold far quicker and potentially with reduced accelerator dosages.

3.2 Testing and verification of early-age strength development

To verify first hour early-age strength development properties of shot material using an accelerator atomisation system, early-age strength testing was undertaken on sprayed concrete from a MacLean SS5 sprayed concrete sprayer equipped with the ChemSave accelerator efficiency and atomisation system. Testing was conducted by MacLean Engineering in partnership with Sika Canada, using a Mecmesin needle-style penetrometer for first hour strengths for tests expected under 1.5 MPa. The results observed provided impressive data that outlined how reducing accelerator dosage while maintaining impressive strength generation is feasible. The materials upon which testing was conducted consisted of Sika MS-W1UG material for wet process applications using Sika Sigunit L-500 AFI liquid alkali-free accelerator. The material and accelerator are controlled and considered to be the same quality and from the same manufacturing process as the baseline. Testing conducted for early-age strengths was conducted without the use of any synthetic fibres. As seen in Figure 3, it is observed that the early-age strength achieved results trending towards 1.5 MPa within the first hour for dosages at 4–6%. The dosage at 2% does not achieve significant strength in the first hour. In comparison to the curves observed in Figure 3, material shot at 4 and 6% experience significantly more strength development than the material at much higher dosage levels without the use of accelerator atomisation. The results for tests at 4 and 6% in Figure 3 are approaching 1.5–2 MPa within one hour, which is a compelling increase in strength development, proving that no variability between the materials, besides the utilisation of an accelerator atomisation system at decreased dosage levels, can provide impressive, reduced re-entry time for in-cycle operations. In Table 3, compressive strength results for three varying accelerator dosages are outlined all time intervals tested.

Table 3 ChemSave trial test results for MS-W1UG using L-500 accelerator

Time/age (minutes)	Compressive strength over time at varying dosages (MPa)		
	6%	4%	2%
5	0.43	0.26	0.08
10	0.63	0.30	0.12
30	0.68	0.56	0.13
45	1.13	1.20	0.13
1,290	16.5	15.5	13



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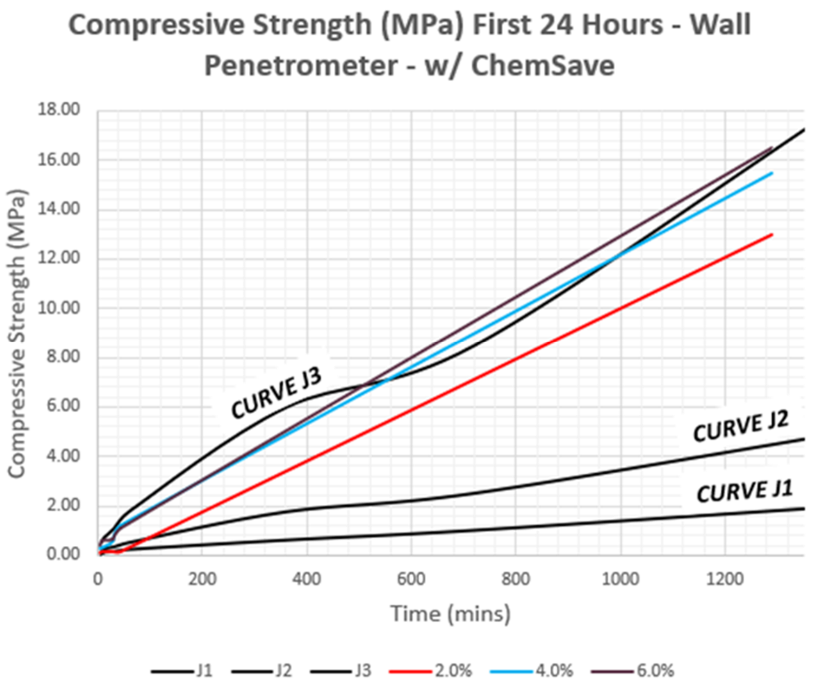

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Figure 3 Compressive strength for (a) first hour and (b) first 24-hour strength of Sika MS-W1UG product using Sigunit L-500 accelerator at varying dosages using ChemSave system

Tests conducted beyond the initial first hour of strength development, and the 1.5 MPa threshold, were conducted with the use of a HILTI DX 460 nail gun with a 72 mm nail. This test provided a result for the 24-hour strength development. Where we can observe the trends in comparison to the J2 and J3 curves that identify the rate and magnitude of strength development in this region. When considering 24-hour compressive strength development, it is observed in Figure 3 that all data trends towards following the J3 curve. Highlighting that even at incredibly low dosages, appropriate strength development for a 24-hour period is observed utilising an accelerator atomisation system. Furthermore, these results show that an accelerator system utilising atomisation as a method for more thoroughly mixing the chemical into the shot material can yield results in line with the representation for strength development by curves J3 and J2. Overall, the testing conducted provided a result that points towards an initial conclusion that an accelerator atomisation system can provide results for early first hour strength development that are consistently within the bounds of all three curves, and first 24-hour strength all trends towards the targets set by J3, while drastically reducing dosage levels of accelerator in comparison to baseline data.

4 Strength development of accelerator atomised fibre-reinforced sprayed concrete for permanent linings

Sprayed concrete designed for permanent linings with a composition of synthetic fibres, commonly known as 'fibrecrete', was tested using the ChemSave accelerator atomisation system to determine strength development properties over a period of 30 days. Testing intervals ranged from as early as 8 hours up to 28-day strengths to provide data on strength development for mix designs, using MS-W1UG product with 5 kg and 7 kg per cubic metre of SikaForce Fibre-48, respectively. These tests were conducted to provide insight into the impact on strength development of utilising an accelerator atomisation system for sprayed concrete designed for permanent linings. All tests were conducted utilising the ChemSave system to determine its specific impact on the performance of the sprayed material, where final strength development is crucial when service life must exceed several decades.

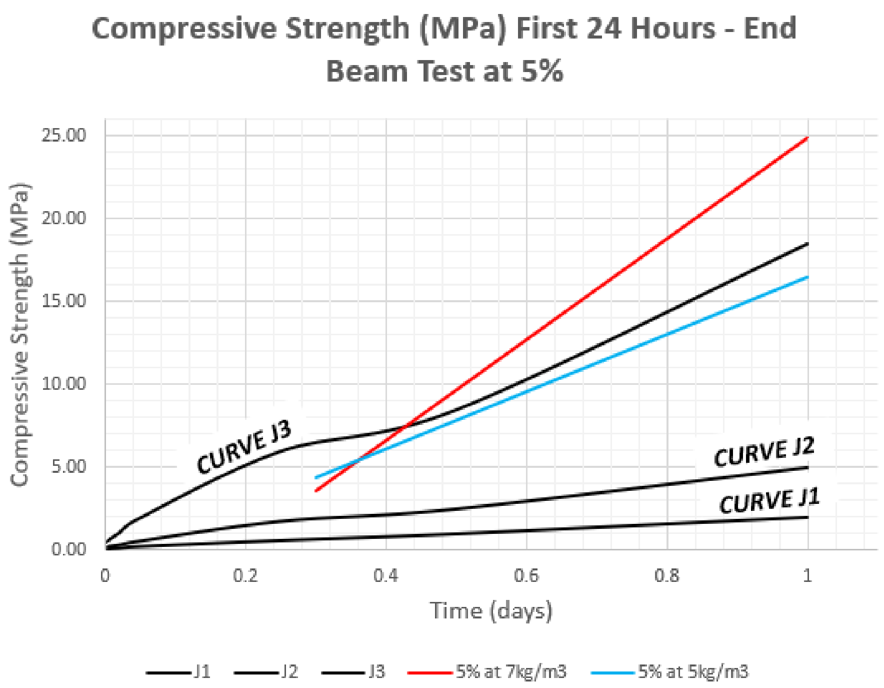
4.1 Early-age strength development utilising end-beam test

First 24-hour strengths were determined with the use of the end-beam test, which is commonly used in North America and Australia. Tests were conducted at 8-hour and 24-hour intervals to test for compressive strength development at dosages of 3 and 5% accelerator content per kilogram of cement per cubic metre. Variations also included tests with different fibre content, 5 and 7 kg of fibres, respectively, both tested at accelerator dosages of 3 and 5%. Results from this test were crucial to determine the strength development versus time relationship for these fibrous mix designs for permanent sprayed linings to assist with determining re-entry times for in-cycle sprayed concrete. Mix design, accelerator content, and re-entry time are all key factors in optimising operational performance and cost for sprayed concrete.

It was determined that for sprayed concrete sprayed at a dosage of 5% accelerator, results between 3.5–4.5 MPa were achievable within 8 hours, with later-age strengths ranging between 17–25 MPa, depending on fibre content. As seen in Figure 4, for mixes with higher fibre content, later strengths are significantly higher where accelerator dosage does not present itself as a major factor at the tested reduced dosages. These results are in line with expectations for the behaviour of these materials and provide data points to compare when plotted against the same sprayed material at varying accelerator dosages.

Table 4 ChemSave end-beam and core test results for MS-W1UG with Fibre48 using L-500 accelerator

Panel/test	End-beams 8 h (MPa)	End-beams 24 h (MPa)	3D cores (MPa)	7D cores (MPa)	28D cores (MPa)
7 kg/m^3 at 3%	3.3	23.9	31.1	43.5	59.5
7 kg/m^3 at 5%	3.6	24.9	24.8	33.3	58.3
5 kg/m^3 at 3%	6.2	12.8	N/A	27.2	41.9
5 kg/m^3 at 5%	4.4	16.5	N/A	34.6	50.2



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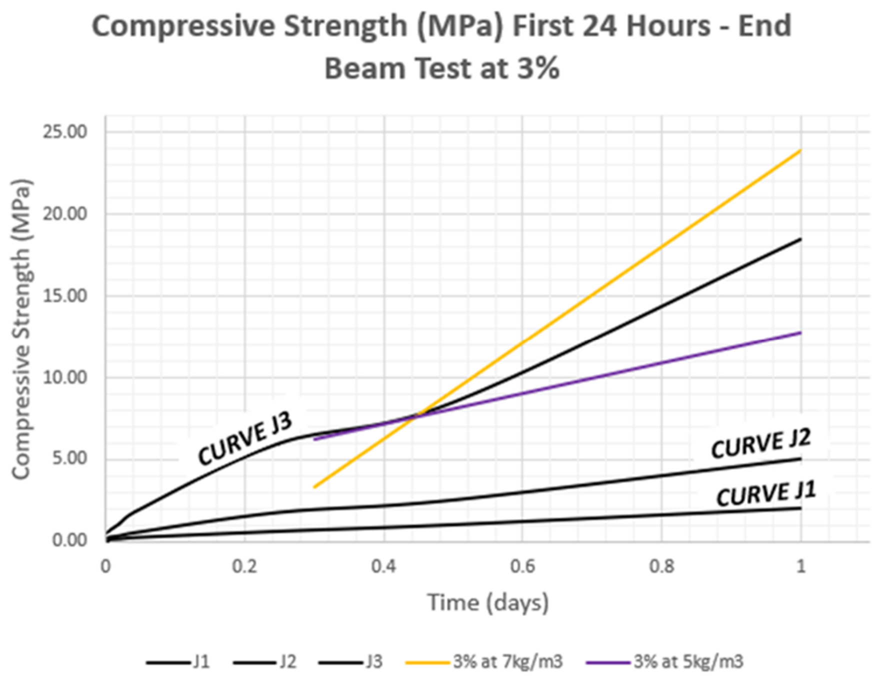

(b)

Figure 4 End-beam test results for first 24-Hour compressive strength for fibrecrete material at (a) 5% accelerator and (b) 3% accelerator

For sprayed concrete sprayed at a dosage of 3% accelerator, results between 3–6 MPa were achievable within 8 hours, while later-age strengths ranged between 13–24 MPa, depending on fibre content. The results from the reduced accelerator dosage test provided encouraging results, and evidence that reducing accelerator dosages with no changes to mix design can achieve comparable strength development levels when using a method of accelerator atomisation. The test results show the effect of an accelerator atomisation system on the final performance of the sprayed material, and how it can be used to achieve required strength targets while providing the ability to reduce operating cost. For permanent linings, the first 24-hour strength development is crucial for assessing re-entry criterion and strength development. The end-beam test provides a thorough, accurate result upon which to draw further conclusions and provides insight for direction on further research.

4.2 Later-age strength development core testing

To be able to provide a full understanding of the strength development of a specimen of sprayed concrete, further testing are required in addition to the tests discussed earlier. Determining observed later-age strength development characteristics was conducted using core samples tested at intervals of 3, 7, and 28 days. For all core samples considered, panels were shot on the wall of the substrate and were continuous onwards from the end-beam specimens to provide as similar a shot product as possible. The primary focus of the core sample tests was to provide data on the utility of an accelerator atomisation system for achieving the required final material strengths within 28 days. Out of the tests conducted, it was expected to see a relationship between fibre content and accelerator dosage, where a 5 kg/m^3 composition would achieve approximately 45 MPa and 7 kg/m^3 at over 50 MPa, where accelerator dosages would have an impact on early-age strength generation but have a limited impact of final strengths due to the reduced dosages tested that used a method for chemical atomisation. As seen in Figure 5, the same relationship between mixes at varying fibre content at varying time intervals applies. Figure 5 highlights the results of all four examined variations of core samples and plots them against each other over a 28-day period to identify the durations for achieving prominent levels of compressive strength.

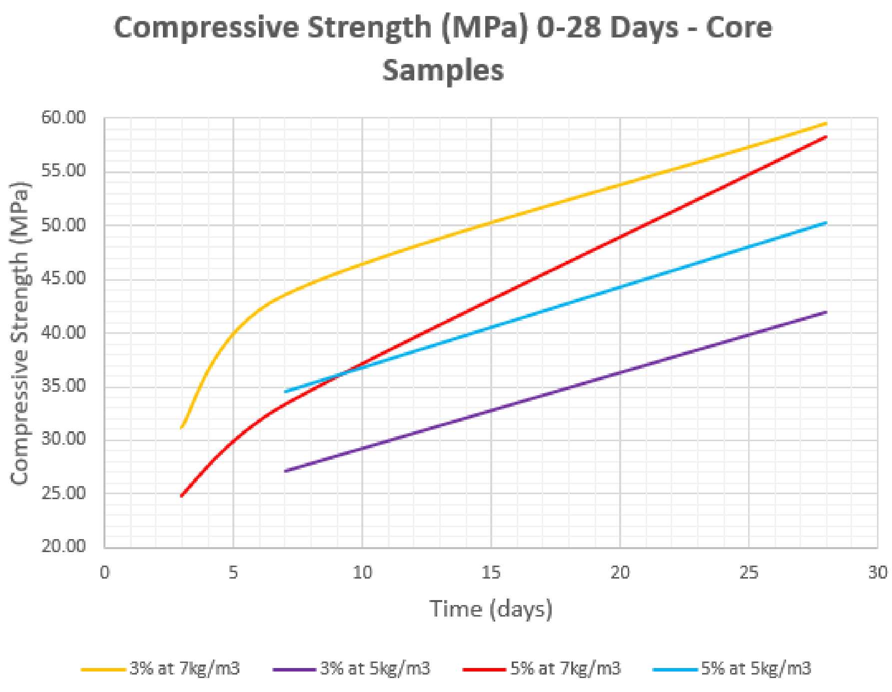

Figure 5 Core sample test results for 28-day compressive strength development of a fibrecrete material

As shown, the results achieved were in line with initial expectations, except for the result for the material shot at 3% with 7 kg/m^3 of synthetic fibres. All materials shot achieved a maximum compressive strength of 40 MPa to 60 MPa within 28 days. These results would satisfy many of the requirements for most projects utilising a similar mix design. However, for the results that achieved the highest maximum strength development, we observe that some of these specimens are of a sprayed concrete that is over-engineered for its application, meaning that final strengths far exceed the technical requirement for most applications leading to an opportunity for the mix to be redesigned to modify the composition and weights of the subcomponents of the mix design to optimise for performance, cost, and carbon intensity. This ultimately leads to a 'greener' material, but also one designed specifically for required performance and strength that does not overcompensate on mix subcomponents to ensure needed strength development targets are achieved.

Figure 6 shows the results of the end-beam and core test results overlayed to illustrate the strength development of each sampling variation. It is observed that all test samples achieved excellent results, even the samples that were sprayed at an accelerator dosage of 3% which had a maximum compressive strength of almost 60 MPa when batched with 7 kg/m^3 of fibres, and over 40 MPa with 5 kg/m^3 of fibres. This is a result that provides evidence that the accelerator atomisation system was able to hydrate the mix more effectively and therefore achieve a result higher than what would typically be expected for the final 28-day strength of the same design, where peak compressive strength normally is tested for around 50 MPa, when shot using a conventional mechanised sprayed concrete piece of equipment.

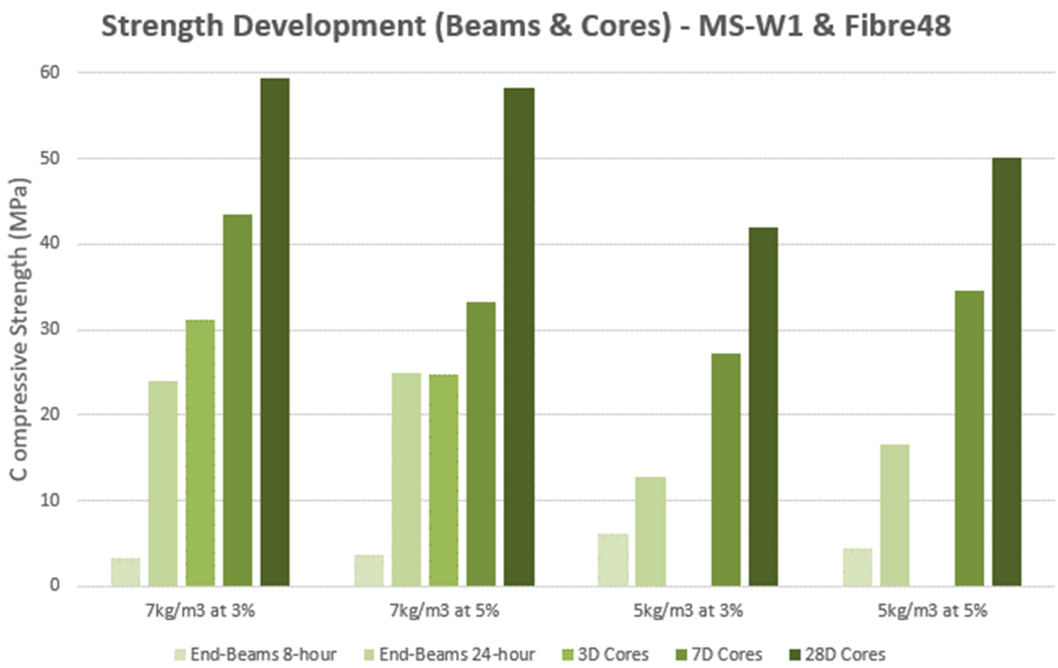

Figure 6 Strength development results for end-beam and core sample tests

5 Optimising mix design

Mix design optimisation is the process of looking into the parameters of the mix in question, ensuring that proper requirements are followed to ensure the fully engineered quality of the product. With the optimisation of cementitious properties through accelerator atomisation, a 'leaner' product can be achieved without sacrificing the final strength prerequisites (Rodrigues 2018) supported by the trial test results conducted on a standard sprayed concrete mix. Efficiently dosing and dispersing accelerant into wet sprayed concrete at the nozzle is one of the biggest steps that can easily be taken to fully optimise the sprayed concrete mix downstream. As described by Jarast & Bakhshi (2023), 90% of the CO_2 intensity of concrete used for linings is based upon the type of cement and its supplementary cementitious components. Therefore, if the composition of the mix design can be altered without sacrificing strength properties by utilising a method for more effectively hydrating a limited quantity of cementitious materials, the carbon intensity of the material can be safely reduced. Efficient use of accelerator can aid in ensuring that final strengths are not degraded by 'cooking' the sprayed concrete, having a high heat of hydration over a longer period (Salvador et al. 2016), but also by hydrating the comparatively limited amounts cementitious materials more effectively through better dispersal.

5.1 Low-carbon sprayed concrete

Optimisation of mixes increases the amount of savings over both the short-term and long-term, reducing the need for excessive quantities of cement and additional admixtures. Reduction of cement allows for the engineering of proper mix designs that can remove excessive safety nets for final strength development and ensure that the final product does not become too brittle over time, especially if fibre reinforcement is required. Low-carbon sprayed concrete is a material that can follow more stringent carbon reduction guidelines by reducing the amount of Portland cement and effectively reducing the need for additional onsite storage, additional logistical and transportation efforts. Efficient reductions in accelerator utilisation have a clear correlation to cement reduction and improved bonding which in turn has slight effects on rebound reduction. The efforts to optimise mix design for strength development targets when using methods for accelerator atomisation, along with the drive to achieve a 'greener' sprayed concrete, can be combined towards a holistic effort to design and build a sprayed concrete specialised for specific applications.

As described by Aldrian et al. (2022), cement has a significant impact on the total CO_2 intensity of sprayed concrete, as high as 91%, due to the excessive amounts of chemically bound CO_2 released during the burning process used to produce clinker. Therefore, ways that reduce the usage of clinker-heavy cement in the final mix design is the key path towards cleaner concrete. The methods described by Aldrian et al. (2022) to use clinker-efficient composite cement is one way to modify how clinker-based cements can be modified to reduce carbon intensity. Introducing a more effective method of using the cement component of your existing mix designs through accelerator atomisation opens the door to further optimisations and allows for a rethink of how carbon-reduced sprayed concrete can be approached.

6 Reducing re-entry times for in-cycle sprayed concrete

Time is an important commodity for underground mining operations. For sprayed concrete operations, the applied product must have sufficient time after being applied for strength development. This is even more critical when sprayed concrete is used as a method of primary ground support, rather than as a secondary or architectural method, as is common with many underground operations utilising high-amounts of sprayed concrete. Allowing the material to set and undergo strength development demands that sufficient time pass before re-entering the space supported by the young material. This delay prevents further work from taking place while the material is given time to set. Finding ways to reduce this waiting period is imperative to increasing the overall productivity of in-cycle sprayed concrete.

Considering the impacts of more efficient accelerator dispersal into the sprayed concrete and therefore enhanced material properties allows the mix design to be formulated in such a way that improvements can be found to provide better early strength development, as mentioned earlier. This is done concurrently with ensuring the final compressive strength is acceptable. Providing more rapid early-age strength development without sacrificing older-age compressive strength allows for a reduction in the re-entry time (time required to allow for sufficient strength development) required. Meaning a high rate of productivity can be achieved with the same resources.

7 Conclusion

The possibility of improving the performance of sprayed concrete by more effectively utilising set accelerators while simultaneously reducing the consumption holds the potential to create extraordinary amounts of value for mechanised sprayed concrete applications where a reduction in consumption limited to 30% can result in savings of over 100,000 litres per annum when spraying approximately 30 m^3 per day. The ability to reduce operating costs due to lower consumption of chemical alone is significant, but when downstream effects are taken into consideration, the advantages are compelling. By providing a method of more consistently and effectively adding accelerator to the sprayed concrete, the ability to make more optimised mix designs and 'greener' sprayed concrete is gained in a greater capacity than it would without. Downstream of that effect is the ability to create mix designs that can allow for faster strength development that still satisfies all other required material parameters.

The core component to achieving these objectives is to alter the way the accelerator is introduced into the material and to encourage thorough mixing. Atomisation of the chemical provides a way of combining the processes of mixing sprayed concrete with an accelerator and physically shooting the material with high-velocity air. This allows for the implementation of the ‘do more with less’ philosophy. With the global shift towards a greener economy and finding new efficiencies in the industry, underground operators utilising sprayed concrete have the potential to further corporate goals while improving operational processes.

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