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A novel approach to assessing the early age strength of fibrecrete, using shear wave velocity

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SUMMARY: Prior to backfilling, fibrecrete barricades (which for the purpose of this paper refers to both barricades and bulkheads utilised for Minefill purposes) are typically cured to achieve a target strength. However, due to sensitivity of early age fibrecrete strength caused by variations in mix properties, curing environments and spraying techniques, the rate of strength development can be quite varied. Challenges associated with conventional curing, coring transportation, and destructive strength testing methods and mine location generally prevent early age quality control testing of fibrecrete barricades and the consequence is often conservative cure periods leading to extended fill cycle times.

This paper further develops a novel technique where laboratory testing is used to develop a unique relationship between strength and the shear wave velocity (or small strain stiffness) of the fibrecrete. The investigation considers a range of different variables encountered during the manufacture of fibrecrete to illustrate the unique relationship.

The presented non-destructive test method provides a practical method to define the relevant barricade strength and shear wave velocity relationship. Implementation of improved quality control techniques such as that proposed can reduce fill cycle times without compromising safety.

Keywords: Fibrecrete, Shear Wave Velocity, Non-destructive testing, Early Age Fibrecrete Strength

1 INTRODUCTION

Advancement in technology has resulted in the use of fibrecrete (fibre reinforced shotcrete), often labelled as shotcrete, for ground support, to increase the rate of development in mines. The introduction of fibres to shotcrete has led to an increase in toughness and impact resistance (Morgan & Bernard, 2017). Fibrecrete has also formed an integral part of the backfilling process, whereby the fibrecrete is used for barricade construction.

To date, the industry standard is to ensure that the fibrecrete reaches a target strength by 28 days hydration. However, there is usually limited ongoing early age quality control testing of the fibrecrete and a ‘rule of thumb’ approach, which includes a significant factor of safety, is typically used to extrapolate longer term quality control testing. Ultimately, it is the ground control engineer who determines the compressive strength required to provide safe re-entry (Rispin et al., 2017) and adequate bulkhead capacity. This duration can have significant impact on mine development and stope backfilling rates.

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Numerous non-destructive test (NDT) methods are available for measuring the early age compressive strength of fibrecrete. These include the rebound hammer and ultrasonic pulse velocity (ISO 1920-7, 2004), penetration resistance (ASTM C403, 2016), needle penetrometer, Beam-End Tester and the Hilti gun-test method (AuSS, 2010). However, these all come with intrinsic issues and most do not measure accurately over the range required, which can significantly affect the relevance of results unless properly correlated (Moczko and Mockzo, 2018). The Australian Shotcrete Society (AuSS, 2010) suggest the only effective means of assessing direct compressive strength is using the Beam-End Tester. However, this only measures up to 8 MPa which is the highest of all . Due to the limiting range on these NDT methods. This strength is generally not suitable for the backfill process, which typically requires strength in the order of 10-30 MPa.

There is an abundance of data available on the early strength of fibrecrete and it is highly variable, as illustrated by Saw, Villaescusa & Windsor (2015). These variations are most likely a consequence of test method, variable mix designs, curing environment, application techniques, quality control measurements and fibrecrete design constituents. Therefore, it is imperative for any NDT method, that thorough and relevant correlations are made.

Stope backfilling typically involves placing a cemented slurry into an open stope, which is often contained using a sprayed fibrecrete bulkhead. The time at which backfilling can commence, post barricade construction, is based around the fibrecrete achieving a target strength, typically between 10-30 MPa, which is normally correlated to a curing period. This often leads to a conservative timeframe before backfilling can occur behind a fibrecrete barricade which can result in significant impacts to the mining schedule.

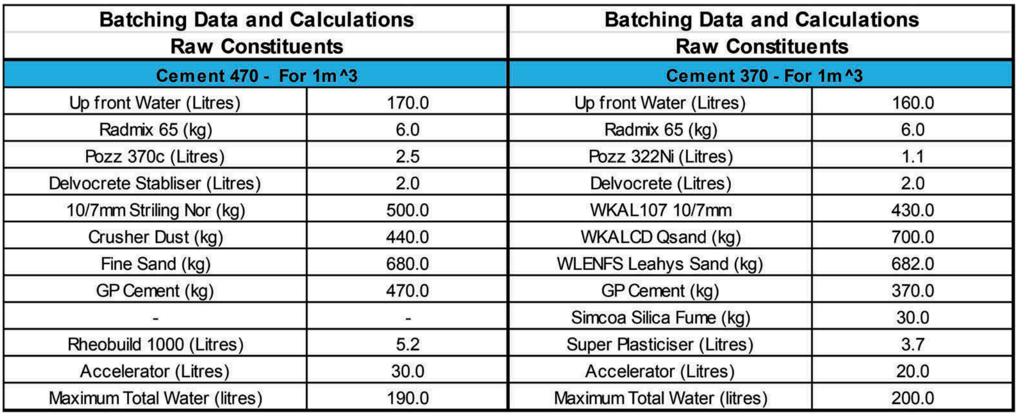
As illustrated by Helinski et al. (2011), for a given bulkhead geometry the aspect that most significantly influences the capacity of fibrecrete bulkheads is the fibrecrete strength. However, in order to accelerate stope cycle times and achieve economical benefits, it is often useful to begin filling behind minefill bulkheads as quickly as possible. The problem with loading fibrecrete bulkheads at early hydration periods is that even subtle variations in mix inputs or curing conditions, can have a significant impact on the rate of strength development. While this variability is widely recognised, due to the logistics of spraying and transporting quality control (QC) samples, it is difficult to regularly gather QC data at relevant hydration periods (1-3 days), which makes managing this risk challenging.

In addition to variations in fibrecrete mix properties and curing conditions, delays in heading availability, substantial transport distances from batch plant and changes to mine plans, can have a significant impact on the duration between batching and spraying of underground mine fibrecrete. This often results in the fibrecrete being discarded, or more water and/or chemicals being added to delay the cement hydration process. This can have a significant impact on the early age fibrecrete strength development.

This paper presents further development of a novel approach to assessing the fibrecrete strength using shear wave velocity across a range of different mix constituents to form a basis for future field research and implementation.

2 FIBRECRETE DESIGN AND SENSITIVITY STUDY

Fibrecrete is a designed material that comprises of cementitious binder, fine and coarse aggregates, fibres, water and often additional chemical and cementitious additives. It is usually mixed at an on-site batch plant and transported in an agitator bowl, where it continues to mix during transportation to the desired location. It is then pumped and sprayed to form a solid concrete layer on headings and barricades. The physical,



Batching Data and Calculations Raw Constituents		Batching Data and Calculations Raw Constituents	
Cement 470 - For 1m^3		**Cement 370 - For 1m^3**	
Up front Water (Litres)	170.0	Up front Water (Litres)	160.0
Radmix 65 (kg)	6.0	Radmix 65 (kg)	6.0
Pozz 370c (Litres)	2.5	Pozz 322Ni (Litres)	1.1
Delvocrete Stabliser (Litres)	2.0	Delvocrete (Litres)	2.0
10/7mm Striling Nor (kg)	500.0	WKAL107 10/7mm	430.0
Crusher Dust (kg)	440.0	WKALCD Qsand (kg)	700.0
Fine Sand (kg)	680.0	WLENFS Leahys Sand (kg)	682.0
GP Cement (kg)	470.0	GP Cement (kg)	370.0
-	-	Simcoa Silica Fume (kg)	30.0
Rheobuild 1000 (Litres)	5.2	Super Plasticiser (Litres)	3.7
Accelerator (Litres)	30.0	Accelerator (Litres)	20.0
Maximum Total Water (litres)	190.0	Maximum Total Water (litres)	200.0

Figure 1. Fibrecrete mix constituents for two different mine sites.

chemical and mechanical properties of fibrecrete effect the gelling, setting and hardening of the fibrecrete.

For this study, two different recipes from two different mine sites were investigated; Cement 470 and Cement 370, referring to 470 kg and 370 kg of GP cement per cubic meter of fibrecrete, respectively. The mix constituents are presented in Figure 1.

The mix constituents presented in Figure 1 are the "standard design" mix adopted for the laboratory testing. However, during the batching and transportation process, these constituents can vary. To investigate the impact of mix variations and curing conditions on strength, a sensitivity study was undertaken. This sensitivity study considered the following permutations:

1. Standard Fibrecrete Mix (Base Mix)
2. Base Mix, No Accelerator
3. Base Mix, –20% Cement
4. Base Mix, +20% Cement
5. Base Mix, +50% Water
6. Base Mix, +100% Water
7. Base Mix, Cured at ambient laboratory temperature
8. Base Mix, +20% or +50% Accelerator
9. Base Mix, +50% Water and –20% Cement
10. Base Mix, +50% Rheobuild

Each of these mixes were cast into 100 mm diameter × 200 mm long cylindrical moulds and a single sample was tested for strength (UCS) and seismic velocity (Vs) after hydration periods of 1, 2, 3, 7, 14 and 28 days. With the exception of Mix 7, all specimens were cured in a curing chamber that was set to achieve a temperature of 35°C ± 2°C and a relative humidity exceeding 95%. This is expected to be representative of underground conditions. Mix 7 was cured in ambient conditions where the temperature varied from 16-26°C.

3 SHEAR WAVE VELOCITY

Prior to testing each specimen in unconfined compression, the specimen's shear wave velocity was measured. The small strain shear stiffness was measured using piezo ceramic shear plates (Dyvik and Olsen, 1989, Baig *et al.* 1997, Fernandez and Santamarina, 2001). The shear plates are attached to opposite ends of the sample and for good results, the transmitter and receiver

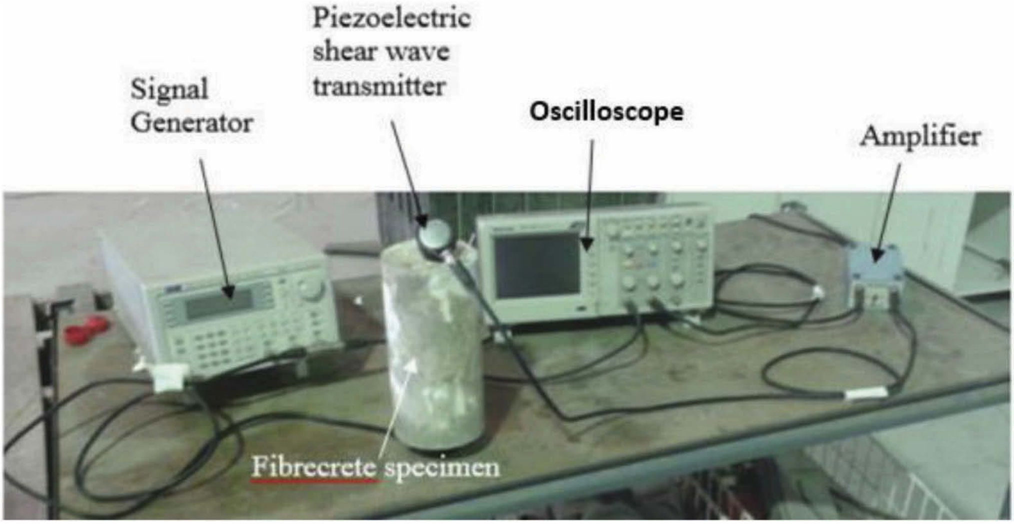


Figure 2. Photograph showing seismic testing apparatus of fibrecrete sample.

are properly coupled to the sample through a layer of viscous conductive gel (petroleum jelly). The shear plate at the top of the sample is used to generate a shear wave, which travels through the sample at a given frequency and are detected by the receiver element at the opposite end of the sample. A photograph of the experimental setup used in this testwork is presented in Figure 2.

The time taken for the shear wave to travel through the specimen is measured as time (Δt). Measuring the length of the specimen and using the time taken to travel from the sent transmitter to the received transmitter, the shear wave velocity, V_s, can be calculated. An example of a sent wave and received wave is presented in Figure 3, where the time taken to travel through the specimen is measured from peak to peak as illustrated.

Santamarina et al. (2001) provided an equation and reasoning for relating the shear wave velocity (V_s) to the small strain shear stiffness (G_0) and the mass density (ρ) through Equation (1):

$$V_s = \sqrt{\frac{G_0}{\rho}} \tag{1}$$

From the theory of continuum mechanics, the small strain shear stiffness is related to Young's modulus (E) and Poisson's ratio (v) in Equation 2:

$$G_0 = \frac{E}{2(1+v)} \tag{2}$$

Ciancio and Helinski (2010) showed there a clear relationship between the development of strength and Young's modulus with time. It was therefore expected that a similar relationship between compressive strength and shear modulus could be achieved and hence shear wave velocity and fibrecrete strength could be developed.

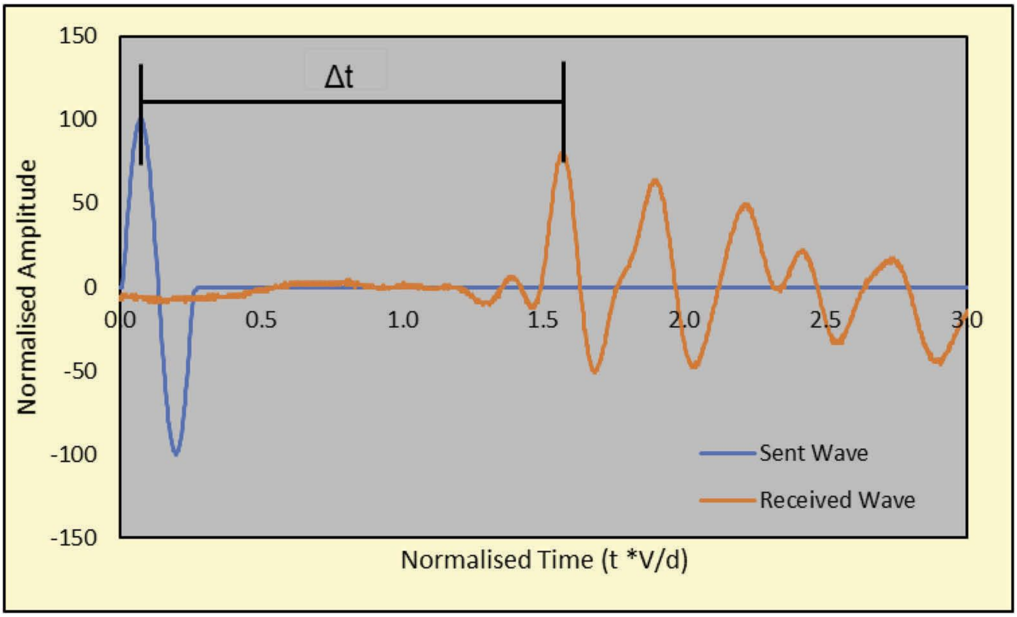


Figure 3. Sent seismic wave and the measured seismic wave of a fibrecrete specimen.

4 EXPERIMENTAL RESULTS

The measured unconfined compressive strength (UCS) and the shear wave velocity (V_s) for the range of different fibrecrete mixes is presented against hydration time for 'Cement 470' recipe in Figure 4a and b and for the 'Cement 370' recipe in Figure 5a and b. The results for both recipes show that the mix constituents and curing conditions can have a dramatic impact on the strength of early age fibrecrete. This strength variation is most significant in the first 1-3 days, which is the relevant cure period for ground support and bulkhead applications. As an example, this is the impact of curing conditions, where the results show a 40% variation in 3 day fibrecrete strength (and therefore bulkhead capacity) due to curing condition. Notably, these figures also show a similar trend exists between shear wave velocity and hydration time.

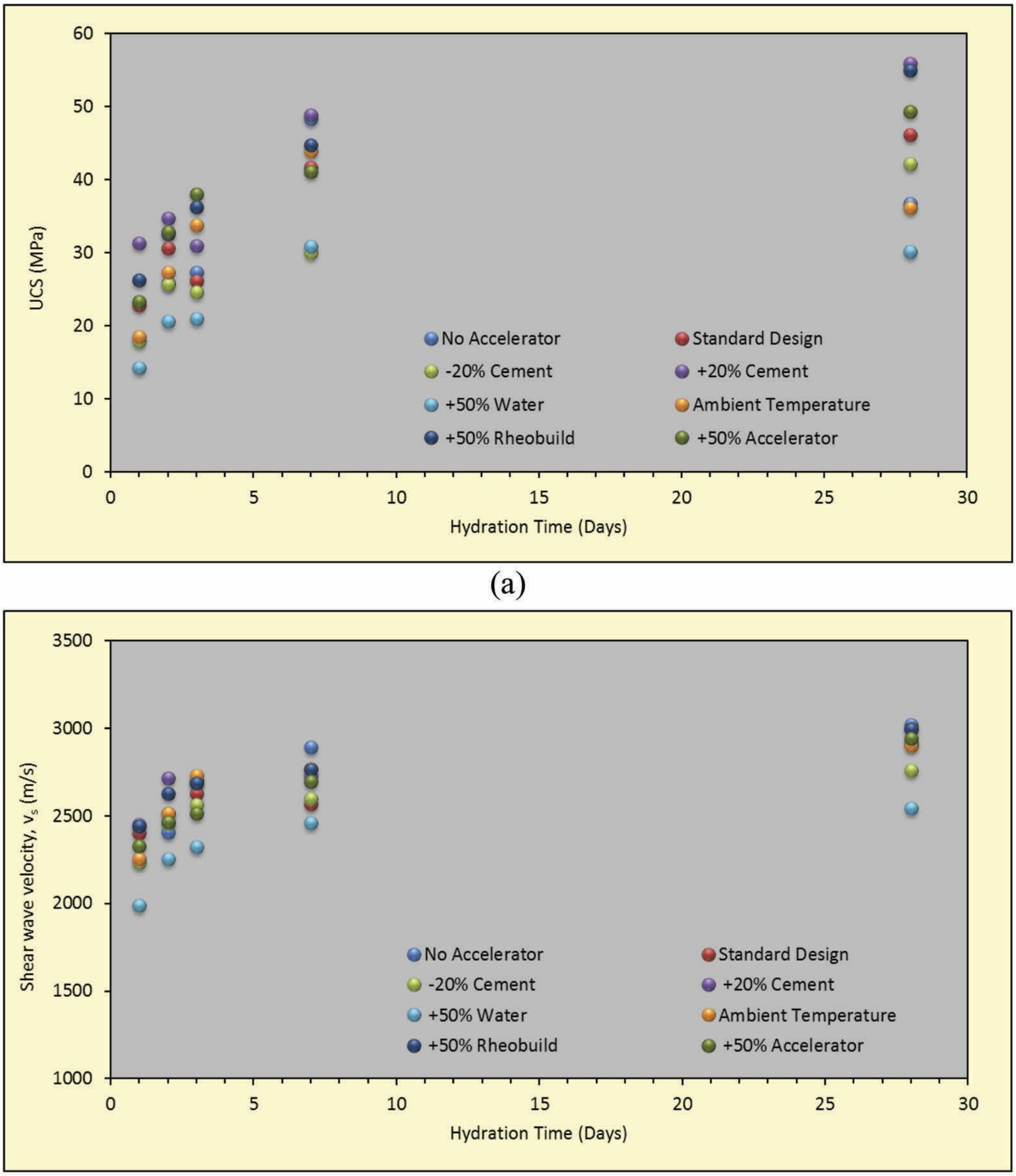
To illustrate the correlation between strength and shear wave velocity the fibrecrete UCS is plotted against shear wave velocity in Figure 6 and Figure 7, for the 'Cement 470' and 'Cement 370' mixes, respectively.

The results presented in Figure 6 and Figure 7 show a relatively unique exponential relationship between the fibrecrete strength and the shear wave velocity.

5 DISCUSSIONS

The test results presented in this paper show a clear correlation between shear wave velocity and the strength of fibrecrete for a given mix recipe.

Whilst the results do appear somewhat scattered, which is expected given the significant changes to the base mix design, within the range relevant to backfill bulkheads (10-30 MPa) a lower bound curve could be used for NDT quality control testing. An



(a)

(b)

Figure 4. ‘Cement 470’ fibrecrete recipe for (a) UCS and (b) shear wave velocity versus hydration.

example of this is presented in Figure 8, for the ‘Cement 470’ recipe, whereby, the ‘lower bound’ trend can be used as the minimum required shear wave to confirm exceedance of a fibrecrete strength target. The proposed method would allow a specimen to be continuously monitored until the time that the target wave velocity is exceeded. For the example in Figure 8, if the design strength was 20 MPa, a shear wave velocity of 2,710 m/s would form the target.

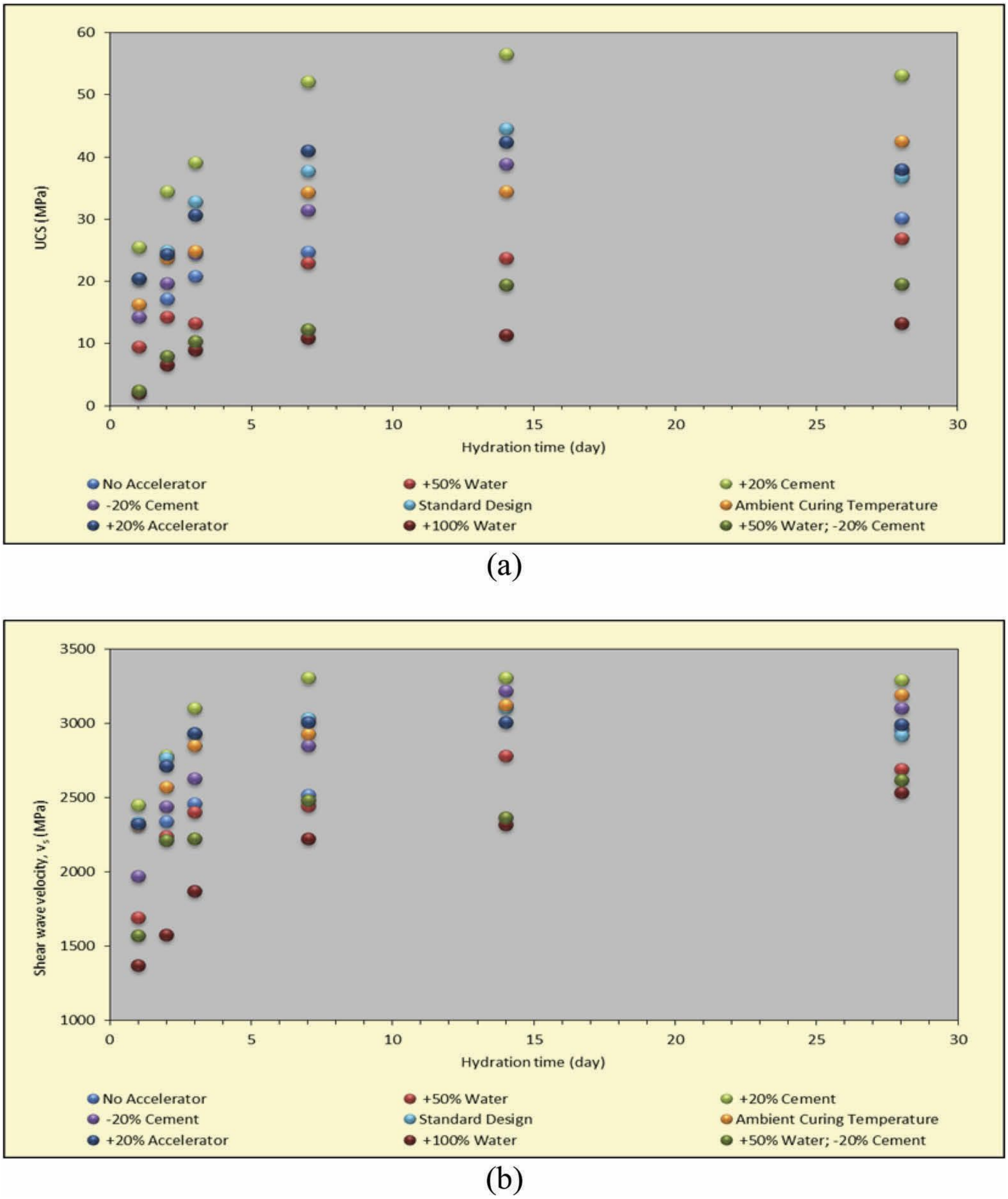


Figure 5. ‘Cement 370’ fibrecrete recipe for (a) UCS and (b) shear wave velocity versus hydration.

6 CONCLUSION

The results presented in this paper show a relatively unique relationship between shear wave velocity and the strength of fibrecrete for two different fibrecrete mixes. Given a suitable relationship, the shear plate method for measuring the shear wave velocity of fibrecrete could be used as a NDT to confirm fibrecrete strength. The approach provides a practical method to confirm suitability of early age fibrecrete strength.

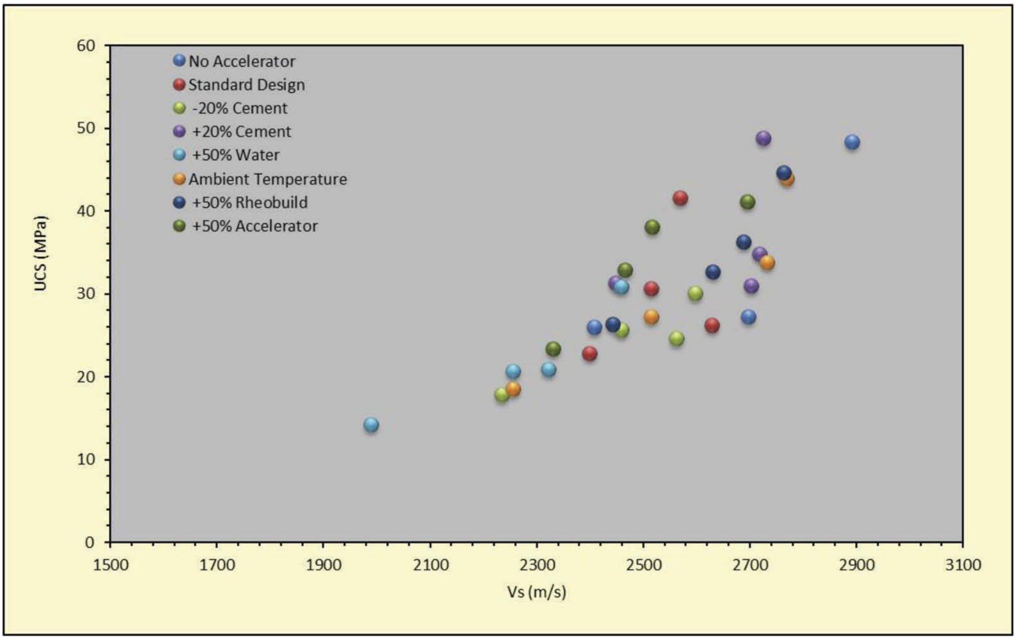


Figure 6. UCS versus shear wave velocity for 'Cement 470' fibrecrete recipe.

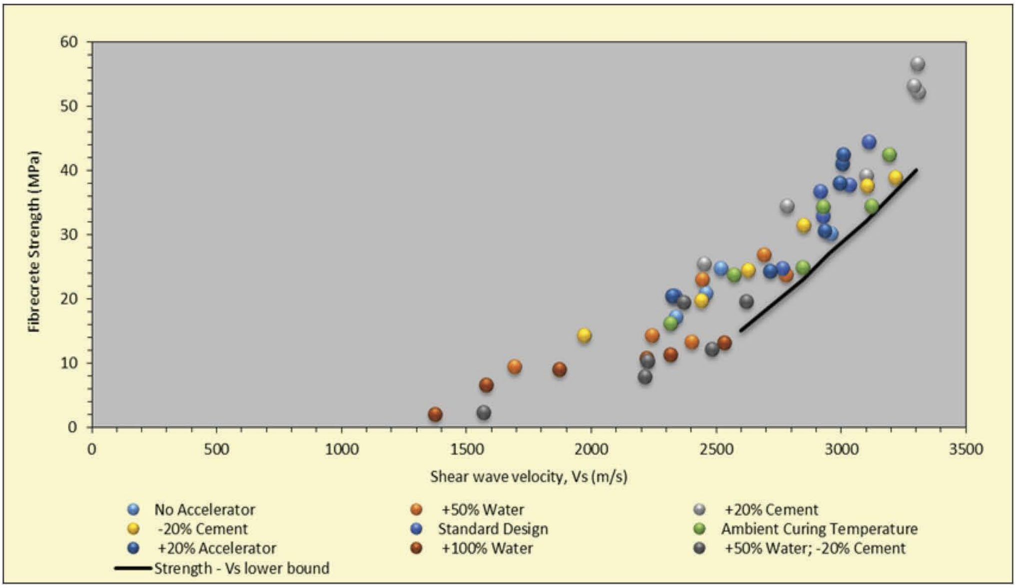


Figure 7. UCS versus shear wave velocity for 'Cement 370' fibrecrete recipe.

Implementation of improved quality control techniques such as that proposed can reduce development and fill cycle times where appropriate and also identify lower strength material, leading to increased mining efficiencies and reduced risk.

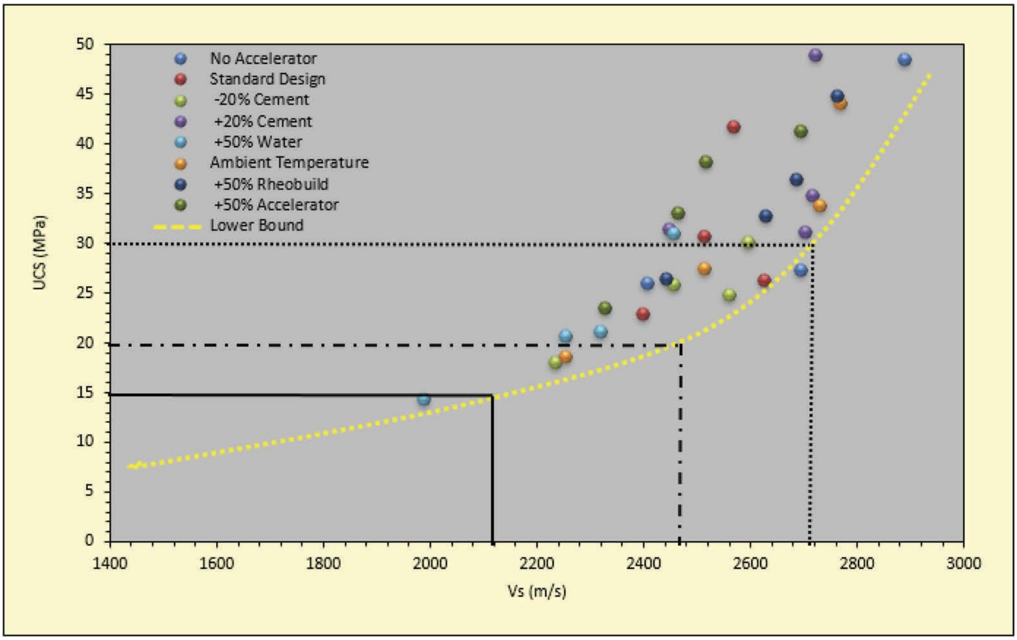


Figure 8. UCS versus shear wave velocity where the shear wave velocity is used to measure the strength of the fibrecrete for the Cement 470 recipe.

This theory and application would benefit from a detailed field investigation, where the method is applied in an operating mine environment to define appropriate casting techniques and methods to develop a field testing procedure.

BIBLIOGRAPHY

ASTM C403/C403M. 2016. *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*, ASTM International, West Conshohocken, PA, 2016, www.astm.org

AuSS 2010. *Recommended practice: Shotcreting in Australia: Second Edition*. Concrete Institute of Australia and Australian Shotcrete Society, pp. 72–81.

Baig, S., Picornell, M. and Nazarian, S. 1997. Low strain shear moduli of cemented sands. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE. Vol. 123, No. 6, pp. 540–545.

Ciancio, D. and Helinski, M. 2010. The use of shear wave velocity for assessing strength development in Fibre Reinforced Shotcrete. [In:] Bernard, E.S. *Shotcrete: Elements of a system: Proceedings of the 3rd International Conference Engineering developments ins shotcrete*. Queenstown, New Zealand, 15–17 March 2010. London: Taylor & Francis, pp. 65–70.

Dyvik, R. and Olsen, T.S. 1989. G_{max} measured in oedometer and DSS tests using bender elements. *Proceedings of the 12th International Conference on SMFE*, Rio de Janeiro, Balkema, Rotterdam, Vol. 1, pp. 39–42.

Fernandez, A. and Santamarina, J.C. 2001. Effect of cementation on the small strain parameters of sand. *Canadian Geotechnical Journal*, 38, pp. 191–199.

Helinski, M, Wines, D, Revell, M & Sainsbury, D 2011, 'Critical factors influencing the capacity of arched fibrecrete bulkheads and waste rock barricades', in HJ Ilgner (ed.), Proceedings of the 10th International Symposium on Mining with Backfill, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 293–304.

International Organization for Standardization. 2004. *Testing of Concrete —Part 7: Non-destructive tests on hardened concrete* (ISO 1920-7:2004(en). https://www.iso.org/home.html

Moczko, A. And Moczko, M. 2018. In-situ examintation of the concrete quality European standard approach. MATEC Web of Conferences 196, 02045 (2018). https://doi.org/10.1051/matecconf/201819602045

Morgan, D.R and Bernard, E.S. A brief history of shotcrete in the underground industry. *Shotcrete: 20th Anniversary Addition 19(4)*, pp. 24–29.

Rispin, M., Kleven, OB., Dimmock, R. and Myrdal, R. 2017. Shotcrete: early strength and re-entry revisited – practices and technology. [In:] M Hudyma & Y Potvin (eds), *Proceedings of the First International Conference on Underground Mining Technology*, Australian Centre for Geomechanics, Perth, pp. 55–70.

Saw, H.A., Villaescusa, E. And Windsor, C. 2015. Safe re-entry time for in-cycle shotcrete in underground mine excavations. [In:] Lu. M et.al. eds. *International Conference on Shotcrete for Underground Support XII*. Singapore, 11–13 October 2015. Engineering Conferences International: New York, pp. 173–192.

Santamarina, J.C., Klein, K.A., and Fam, M.A. (2001). Soils and waves: Particulate materials behavior, characterization and process monitoring. *Journal of Soils and Sediments*. 1. 130–130. 10.1007/BF02987719.