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Evaluation of Australian cement reactivity in accelerated shotcrete

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Abstract

Accelerated shotcrete is a common method of ground support used in underground mines in Australia. Sufficient early strength gain relies upon the chemical composition of the shotcrete accelerator and the cement with which it reacts. The chemical composition of Ordinary Portland Cement used in shotcrete application varies significantly throughout Australia. Early strength development after the application of shotcrete is a determining factor for calculating the re-entry time during in-cycle underground mining. Due to the variance in the cement chemistry available in Australia, this article will show the effect of different cement on early strength development. Analysis of the most commonly used cements in Australia will be shown and how they can be classified. An overview of the cement chemistry of Australian cements and the impact of the cement chemistry on the early strength development using a set of standard shotcrete accelerators will be shown. The objective of this paper is to provide inside information to geotechnical engineers on the reaction time difference between different cements and standard shotcrete accelerators. This research is expected to provide greater confidence to geotechnical engineers in trouble shooting shotcrete early strength problems.

1 Introduction

Accelerated shotcrete is used as a method of ground support during the process of underground mining. A high performance concrete is pumped through a shotcrete rig and is conveyed by compressed air to the rock surface. The process of spraying involves the concrete passing through a mixing chamber and nozzle where the concrete is mixed with a shotcrete accelerator to react chemically with the concrete initiating the stiffening and setting reactions. The rate of stiffening and setting is determined by the chemistry of the two components, the cement and the shotcrete accelerator. Whilst the chemistry of the accelerator may be fixed, the chemistry of the Ordinary Portland Cement can vary considerably throughout Australia. This study begins to characterise some of the cements in Australia and the effect on the performance of accelerated shotcrete.

Currently, liquid alkali free accelerators have become the standard in high demanding shotcrete applications, worldwide, i.e. due to their beneficial properties regarding applicability and environment, health and safety (EH&S). These products which are based on aqueous solutions or suspensions of aluminium sulphate compounds are easy to handle, i.e. with respect to a constant dosing and secure a very good development of the early strength combined with optimal shotcrete properties (Schlumpf et al., 2011).

Alkali-free shotcrete accelerators act by reacting with the aluminate and silicate phases of the cement paste in the shotcrete matrix.

The initial stiffening in the first minutes is from the neutralisation reaction of the cement paste with the alkali-free accelerator. The pH of cement paste is approximately 12, whilst alkali-free accelerators are approx. 3. This reaction is very fast and produces an exotherm. The mixture gels reducing the viscosity of the shotcrete allowing for spray depths of up to 100 mm or more.

Subsequent to the initial neutralisation reaction, the aluminate reaction commences. The aluminate reaction produces ettringite which is exothermic. The aluminium sulphate present in the accelerator chemically combines with the calcium aluminate to produce ettringite which is an expansive reaction consuming significant proportion of water. This further dehydrates the mix increasing the stiffness of the shotcrete. Aluminium sulphate also combines with hydrated lime to produce ettringite and aluminium hydroxide, which is itself a cement accelerator.

The aluminate reaction produces up to approximately 1–1.5 MPa which is often taken as a target in the early age strength evaluation of shotcrete in the field. Some in-cycle shotcrete has a target of 1 MPa set in a specific time window.

Following the aluminate phase is the silicate reaction. This is the primary driver behind shotcrete gaining strength from 1.5 MPa and beyond. The silicate reaction occurs at a steady rate and will increase until all of the silicate phases are consumed which is typically measured at 28 days for practicality.

The ferrite phase reactions also contribute to the 28 days strength but for the early age strength of shotcrete are not significant.

Figure 1 shows the stiffening rate of the accelerated shotcrete, by directly measuring the shear modulus, showing the distinct aluminate and silicate reactions (Figure modified from Lootens et al., 2010b).

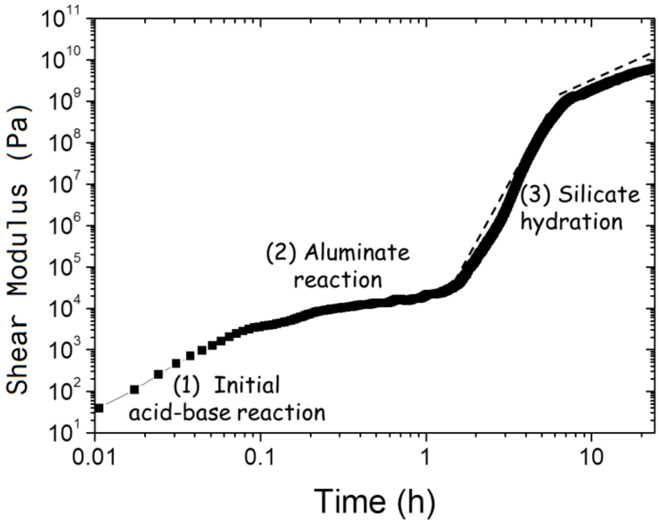

Figure 1 Schematic diagram of the initial reactions in accelerated shotcrete

2 Hypothesis

Due to the different composition of cement and the fact that the accelerators only react with certain components of the cement, there may be a way to identify a link between cement composition and the reactivity of shotcrete. Previous studies have been attempted using calorimetry which attempts to correlate the chemical exotherm with the physical properties of the stiffening shotcrete (DiNioa and Sandberg, 2004). This approach can lead to erroneous interpretation since there is no correlation between calorimetry and the strength of the shotcrete.

It is expected that by using different cements there will be a different shotcrete reactivity. By analysing and grouping the components of the cement and conducting shotcrete trials it may be possible to predict the strength performance of a cement in shotcrete at early ages, 0–2 hours.

3 Methodology

A series of cements from across Australia commonly used in the mining industry for shotcrete were chosen for testing. Each cement was analysed by Rietveld XRD analysis to show the individual phase composition for the cements along with the specific surface. The cement analysis may give an indication of the reactivity by quantifying the phases and showing the quantity of gypsum and dehydrates present.

The application technique used in this paper was a miniaturised shotcrete machine, shown in Figure 2, designed to produce a fine spray of cement paste which is the reacting chemical component of shotcrete. The effect of aggregates and sand has been taken care of by compensating for the water requirement of the mix. The resultant mix is sprayed through a piston driven machine and is mixed with air and accelerator in the spray nozzle. The shotcrete is then propelled onto the surface where it is immediately tested by ultrasound attenuation. The chemical reactions resulting in stiffening and then cement hydration are measured directly as the ultrasound attenuation gives the shear modulus.

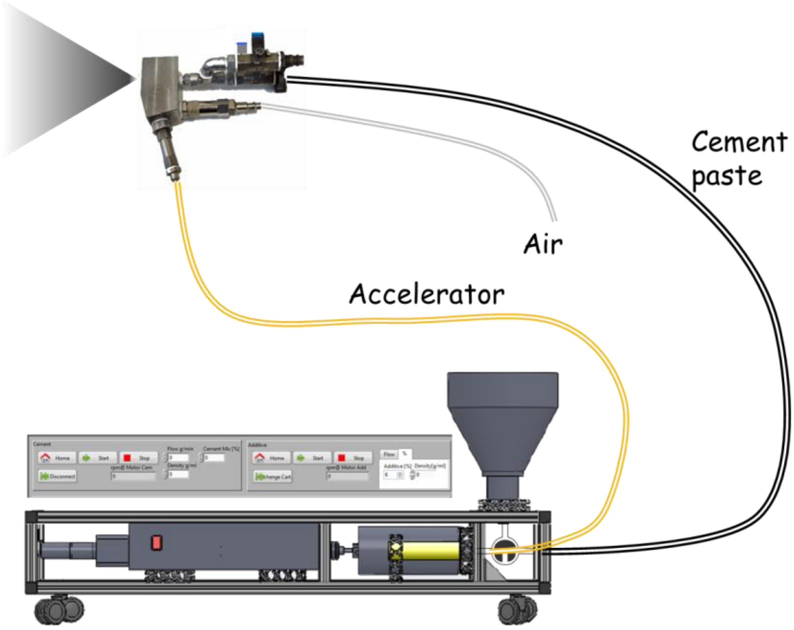

Figure 2 Diagram of the miniaturised shotcrete spray machine (Lootens et al., 2010b)

The test involved preparing a cement paste mix with the respective cement and spraying the mix through a spray machine and recording the resulting increase in stiffness over time.

The testing device for this series is a patented invention utilising the characterisation of hydrating cement crystals by reflecting ultrasound waves from the interface between the test device and the hydrating cement shown in Figure 3. The difference in amplitude and phase gives information to directly measure the shear modulus of the cement paste. The shear modulus is a direct measurement of the mechanical properties of the hydrating cement which will be used as a direct comparison between various cements. This test methodology parallels the methods used in the field where a needle is penetrated into the shotcrete, which measures shear modulus and the results are converted into MPa.

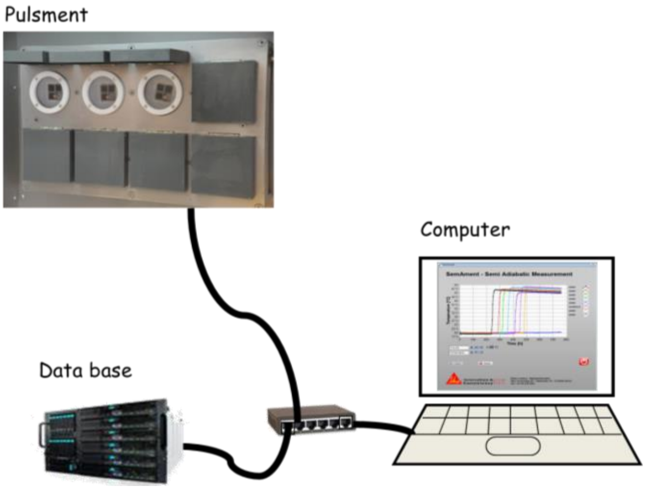

Figure 3 Diagram of the ultrasound testing device used to continuously measure the strength gain (Lootens et al., 2010a)

In the test series the water/cement ratio was kept constant whilst the type of cement was changed. The mix used is detailed in Table 1 and the cements used are listed in Table 2. Superplasticiser dosage was adjusted to maintain a constant workability. The effect of the superplasticiser upon the hydrating shotcrete is very small when compared to the reaction between the accelerator and the cement and water matrix.

The accelerator used was an aluminium hydroxysulphate type dosed at 4, 6 and 8% based on cement content.

Table 1 Mix design used in the test

		Weight (%)
Cement	As per Table 2	40.42
Filler	Limestone powder	6.55
Water	Potable tap water	51.91
Superplasticiser	Viscocrete 10	0.55
	Water/cement ratio	0.41

Table 2 Cements used in the test

Supplier	Cement Name/Type
Adelaide Brighton	Adelaide Brighton GP
Boral Cement	Berrima SL
BGC	BGC GP
Cement Australia	Bulwer Island GP
Cockburn Cement	Cockburn GP
Cement Australia	Gladstone GP
Wagners	Wagners GP

Dry material was mixed in a planetary mixer for 30 s, the water and superplasticiser was added and mixed until homogenous.

After mixing, the cement paste was poured into the spray machine and loaded into the piston. The mix was conveyed by compressed air with the addition of accelerator in the mixing chamber, spraying the cement paste directly onto the test device, replicating the actual shotcrete sprayed on the job site.

The results are recorded as soon as the cement paste is sprayed onto the ultrasound cell, testing is recorded continuously and the data recorded until the test is completed.

The test results will be presented as a plot of shear modulus over time. From this analysis we can compare the shotcrete performance of the different cements with different accelerator doses.

4 Results and discussion

The cement analysis in Table 3 shows a broad range of C_3A contents from 4.4 to 8.2% in total. The average C_3A content in the test series was 6.5% with 3.9% of the cubic form and 2.5% of the orthorhombic form. Ettringite formation during the early shotcrete reactions happens with the available C_3A phase, but it is clear from the shotcrete performance data in Figures 4, 5 and 6, that the content of C_3A from the Rietveld analysis does not determine the rate of strength gain.

Table 3 Cement analysis (units in wt% unless specified) Gallucci, 2013

				Alite	Belite	Calcium Aluminate Cubic	Calcium Aluminate Orthor.	Calcium Alumino Ferrite	Lime	Periclase	Quartz	Calcite	Gypsum	Bassanite	Anhydrite	Density g-cm	Specific Surface
	Type	SO_3	SO_3/C_3A	C_3S	C_2S	C_3A-c	C_3A-o	C_4AF	C	M	S	$C\hat{C}$	$C\hat{S}.2H$	$C\hat{S}.½H$	$C\hat{S}$		$m^2.g$-1
Adelaide Brighton	GP	2.57	0.44	54.9	16	1.5	4.3	11.9	0	0.1	0.2	6.9	2	2.3	0	3.11	1.07
Gladstone	GP	2.30	0.35	57.7	13.1	2.7	3.8	11	0.1	0.1	0	6.6	0.6	4.1	0	3.13	0.91
Berrima	SL	3.01	0.68	59.4	14.2	3.1	1.3	11.5	0.3	0.1	0.3	4.9	1.3	3.6	0	3.12	1.12
Cockburn	GP	2.39	0.3	61.1	17.4	7.1	0.9	8	0.2	0.2	0.4	1.1	0.4	3.1	0	3.14	0.94
Wagners	GP	2.16	0.43	64.1	14	3.3	1.7	11.4	0.3	0	0.1	0.9	1.2	2.9	0	3.093	1.02
Bulwer Island	GP	2.27	0.27	55.7	12.5	2.9	5.3	10.4	0.3	0.2	0.2	8.3	1	3.3	0	3.117	0.95
BGC	GP	1.47	0.19	57.8	16.7	7	0.5	9.8	0.3	0.3	1	3.9	0.6	2.2	0	3.149	0.67

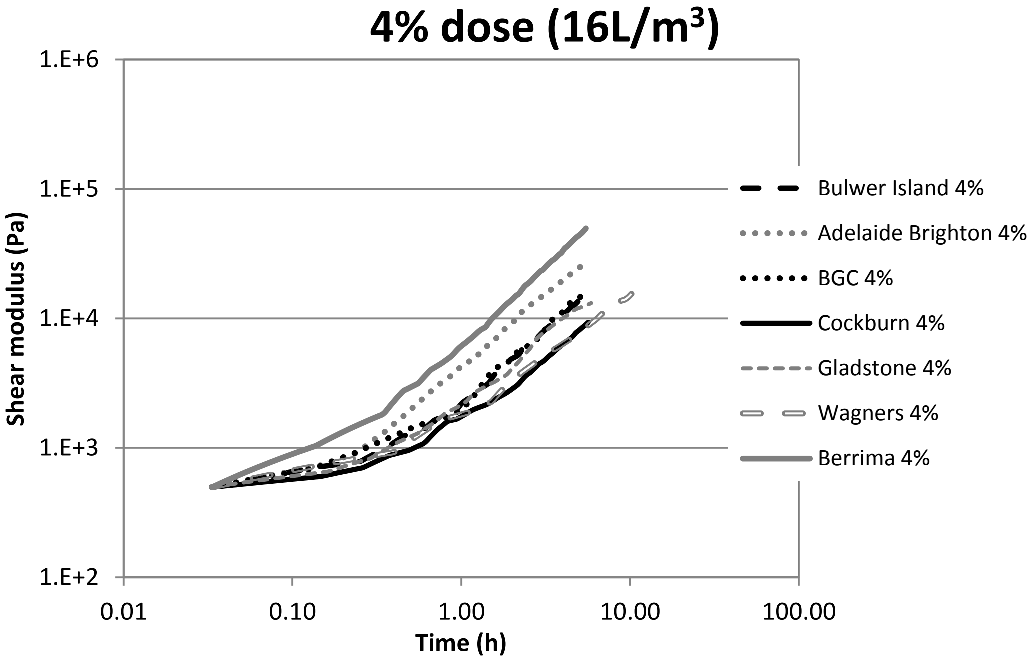

Figure 4 Shotcrete performance at 4% dose rate

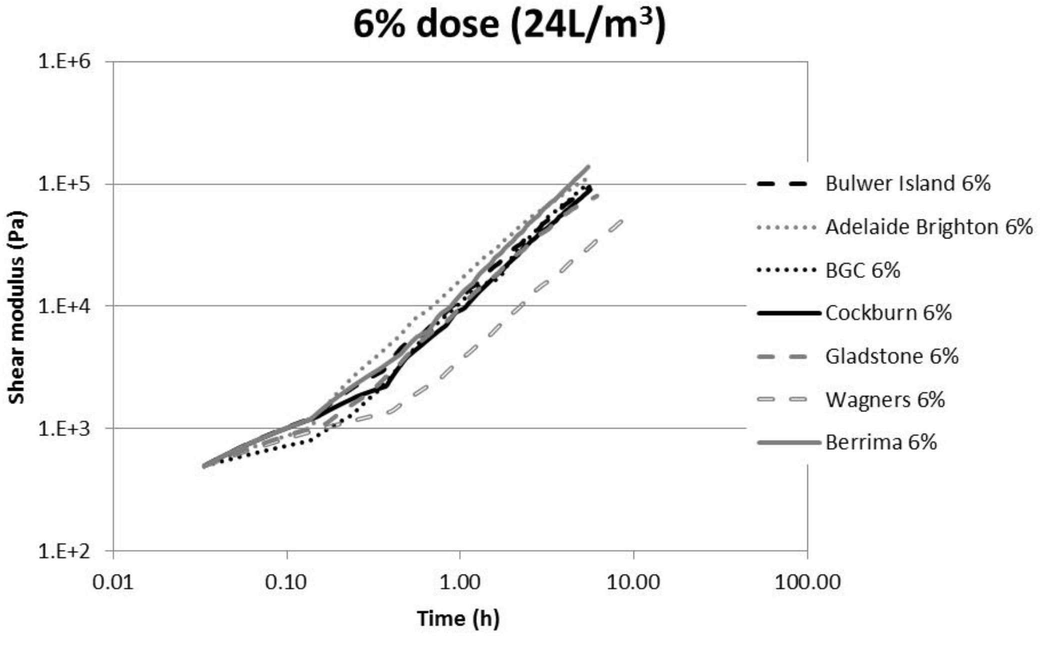

Figure 5 Shotcrete performance at 6% dose rate

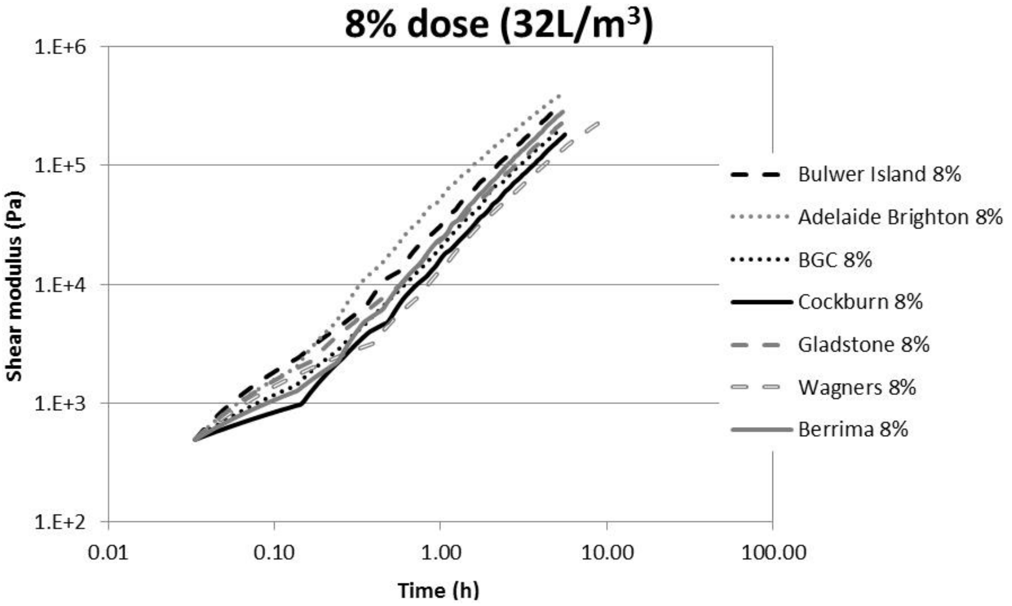

Figure 6 Shotcrete performance at 8% dose rate

It can be shown that different cements around Australia have a different behaviour when used with the same shotcrete accelerator at the same dose rate. Some of the cements are very reactive giving a very fast initial and final set, while some cements are much less reactive giving much slower initial strength gain.

From the results, the cements with the lowest C_3S contents achieved more rapid rates of strength gain compared to cements with the highest C_3S contents. At 4% of accelerator Berrima SL reaches approximately three times and Adelaide Brighton GP approximately two times the average strength of the remaining five other cements. By the time 5 hours have elapsed, the gap has broadened for Berrima SL to approximately five times and Adelaide Brighton GP three times the strength of the two cements with the lowest strength gain.

At 6% of accelerator, Figure 6, a similar trend emerges with the same top two performers and also the bottom two cements being the same as in the 4% trials.

The performance results at 8% show that the top three performing cements change somewhat but the bottom two cements remain the same throughout the trial series.

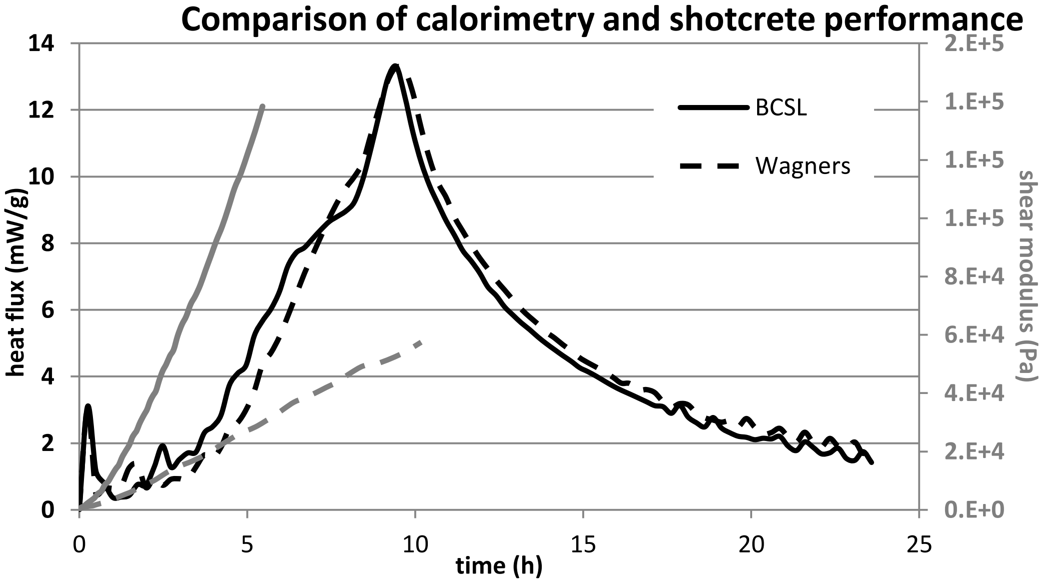

Figure 7 Shotcrete performance versus semi-adiabatic calorimetry

Additionally, two of the cements were analysed using semi-adiabatic calorimetry to determine the total heat flux over time of the hydrating phases. Calorimetry is a tool for determining the total heat of all of the reacting species (Lootens et al., 2012) and from this test we have shown that the shotcrete performance is not related to the calorimetry data. In Figure 7 above, two types of cement are shown with very similar calorimetry curves but very different rates of strength gain when sprayed.

5 Conclusions

At a given shotcrete accelerator dose rate, the performance of accelerated shotcrete varies depending on the cement used due to the different cement composition. It could be concluded that the lower the C_3S content of a GP cement the faster the strength gain in shotcrete; however, more data points are required to give a statistically valid correlation. It is advisable for geotechnical engineers to have knowledge of the cement composition used on a mine site and monitor any variation with time in order to have more consistent early strength performance of the shotcrete.

It is a high risk practice to rely on calorimetry data as a predictor for the early strength of shotcrete. This test series shows no correlation between semi-adiabatic calorimetry and shotcrete performance.

It is recommended that further research should be engaged to investigate the role of the C_3S content in the cement with respect to lower rates of strength gain in accelerated shotcrete.

Acknowledgement

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References

DiNioa, T.P. and Sandberg, P.J. (2004) Alkali-free shotcrete accelerator interactions with cement and admixtures, in Proceedings Shotcrete: More Engineering Developments, E.S. Bernard (ed), Second International Conference on Engineering Developments in Shotcrete, 4 October 2004, Cairns, Australia, Taylor & Francis Group.

Gallucci, E. (2013) Cement Analysis, Internal Report, CAS-2012-1426, Sika Technology.

Lootens, D., Pavcnik, L., Srabotic, M. and Oblak, L. (2012) Calorimetry for cement, gypsum, mortar and concrete. Comparison between semi-adiabatic and isothermal calorimetry, Project no. 10.210.1471, Report no. 5072, Internal Report, Sika Technology.

Lootens, D., Bourquin, R. and Kuhn, P. (2010a) Strength development measurements from ultrasonic attenuation, Project no. 08.210.1314, Report no. 4664, Internal Report, Sika Technology.

Lootens, D., Bourquin, R., Kuhn, P. and Oblak, O. (2010b) Scaling of shotcrete. Concepts, constructions and results, Project no. 10.210.1471, Report no. 4779, Internal Report, Sika Technology.

Schlumpf, J., Höfler, J. and Jahn, M. (2011) Sika Sprayed Concrete Handbook, Sika Services AG, Putzmeister AG.