Impressions from the 10th Shotcrete Conference in Alpbach (Austria)

(Roland Heere, Wolfgang Kusterle, Rusty Morgan)

On 12 and 13 January 2012, Wolfgang Kusterle organised and directed the 10th Shotcrete Conference (*Spritzbeton-Tagung*) in Alpbach, Austria. Since its inception in 1985, these shotcrete conferences have become an institution mainly for German-speaking shotcrete professionals. The topics presented and discussed are however also highly relevant to shotcrete professionals outside of central Europe. This publication provides a selected summary of the Alpbach presentations. The reader should realise that the information provided here is by no means exhaustive of what the conference participants presented. We also do not attempt to provide, with this relatively brief glimpse, a well-balanced compilation of what was presented and discussed in approximately 12 hours of sessions. We rather hope to highlight issues we think may be of particular interest to the North American shotcrete industry. On the following pages, we summarise the presentations, ordered in chronological order. We focus on issues which may be less well known in North America. Note that we have not attempted to verify the accuracy of the original presentations.

Professor **Wolfgang Kusterle** introduced the topics to be presented. Thereafter, **Erich Erhard** (Torkret, Hamburg, Germany; co-author Christoph Hankers) talked about "*A New Method for Surface Design With Shotcrete*". He described the construction of deeply textured shotcrete surfaces. The method is as follows: After placing the bulk layer of shotcrete, attach a polystyrene template to the still fresh surface. Cover the surface with a finishing coat of shotcrete, which may even be pigmented differently from the bulk layer. After removing the template at the correct time (around initial set), a surface remains which for instance may mimic a natural stone wall. Figures 1 to 4 show examples of shotcrete surfaces produced with this technique.

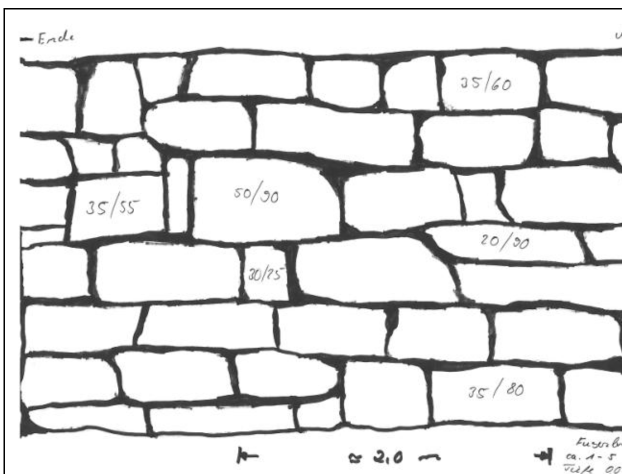


Figure 1: Drawing of template

Figure 2: Polystyrene template

Figure 3: Shotcrete application

Figure 4: Completed surface

Peter Ramge (BAM, Berlin, Germany; co-author Hans-Carsten Kühne) presented a paper on the "*Development and Modification of PCC and SPCC Mortars for Concrete Repair*". He reminded the audience that repair mortars, applied to mature substrate concrete, will undergo restrained shrinkage. If the product of shrinkage (ε_{sh}) and modulus of elasticity (E) of the repair mortar exceeds its tensile strength (f_T), i.e. $\varepsilon_{sh} * E > f_t$, then restrained shrinkage cracking may ensue. However, this relationship is complicated by the fact that shrinkage, tensile strain capacity and modulus of elasticity are dependent on the maturity of the shotcrete and curing conditions. Further, creep has a mitigating effect on the potential for restrained shrinkage cracking. Ramge et al. also observed that on low strength substrate concretes, mortars with a lower $\varepsilon_{sh} * E$ generally developed superior bond strength. Extensive data on various mortars, including polymer modified mortars, support this theory. The graph in Figure 5 below illustrates some important findings.

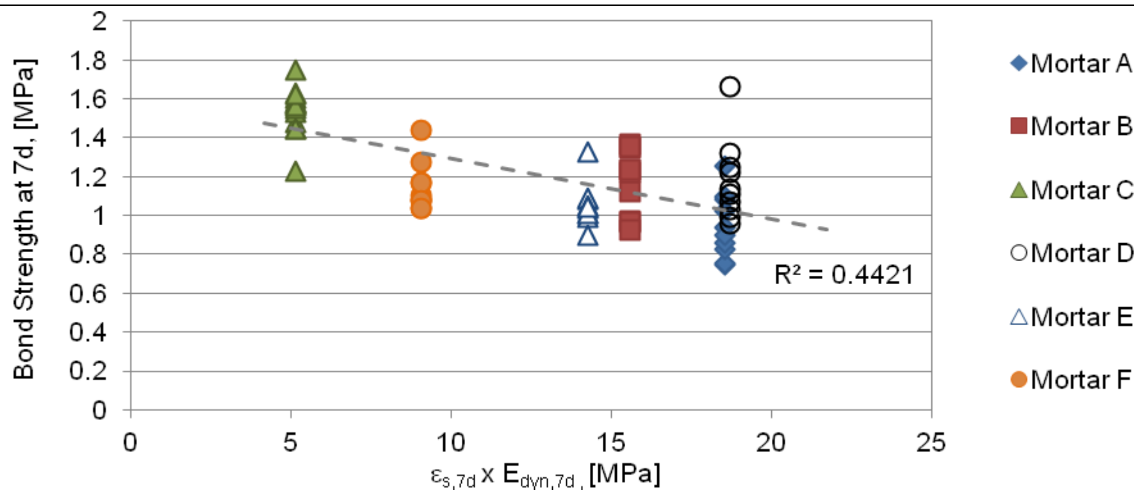


Figure 5: Relationship between achieved bond strength, and mortar strain capacity multiplied by the dynamic modulus of elasticity, at age 7 days

Andreas Schaab (Hochtief, Frankfurt, Germany; co-author Michael Knecht) presented a paper on "*Shotcrete with Alkalifree Accelerator – Application Problems and Their Effects*". He reminded the audience that, in order to apply thick layers of shotcrete to tunnel surfaces, set accelerators are needed. The current generation of alkali-free accelerators poses fewer health hazards than earlier-generation accelerators, while allowing placement of fairly uniform quality shotcrete of high strength and low permeability. However, adverse reactions between alkali-free accelerators and cements have sometimes been observed. Schaab described several examples from construction projects, including the following:

- In spite of consistent as-batched shotcrete mix proportions, the accelerator addition rate to achieve the required early-age strength of a wet-mix shotcrete steadily increased over the course of several months. Detailed analysis revealed that concurrently the C_3A content of the cement had reduced from approximately 10.6% to 7.4%. In this particular shotcrete, the accelerator consumed approximately $^1/_3$ of the C_3A within the first 3 hours to form Ettringite (required for early-age strength development). As the C_3A content in the cement drops, more accelerator is needed to activate a larger portion of the diminishing C_3A supply. A modification to the firing process in the cement kiln corrected the problem.
- The early-age properties of an accelerated wet-mix shotcrete were erratic. At times, the initial set occurred virtually before the shotcrete impacted the substrate, leaving massive spray shadows around rebar. At other times, rebar encapsulation was excellent, but early-age strength development was lacking. Inconsistent mix proportions and operator error were not present. A closer analysis of the cement revealed that the sulphate carrier in the cement was of inconsistent quality. The cement manufacturer fed gypsum ($CaSO_4 * 2H_2O$) into the cement mill. However, during the grinding process, heat converted a portion of the gypsum into hemihydrate ($CaSO_4 * 0.5H_2O$). The ratio between the two sulphate carriers varied widely with time. As hemihydrate is much more readily soluble in the mixing water than gypsum, shotcrete batches containing cement with a high hemihydrate to gypsum ratio would form ettringite more rapidly than mixes with lower hemihydrate to gypsum ratios. To achieve more controlled setting times and early-age strength development, the cement manufacturer started using anhydrate ($CaS0_4$), which is not chemically affected by the grinding operation.
- In a case similar to the above, pumpability of the base shotcrete mix (before addition of the accelerator) gradually deteriorated. The reason was the occurrence of false set (oversaturation of the mix water with sulphates), caused by relatively small variations in the anhydrite-to-hemihydrate balance and the alkali content of the cement.

A uniform quality of cement and accelerator are therefore crucial to a successful shotcrete application in tunnels and elsewhere.

Luka Oblak (Sika, Zürich, Switzerland; co-authors Benedikt Lindlar, Didier Lootens) spoke about "*Continuous Monitoring of Strength Evolution of Shotcrete*". He first commented on the conventional test methods generally used to determine the strength of shotcrete as it matures. In particular, he focused on the shear modulus of shotcrete as a measure of strength. Immediately after shotcrete application, setting and early age strength development can be measured using penetration needles. The force required to press a needle with a defined cross-section to a certain depth into the shotcrete is related to shotcrete shear resistance, which in turn is related to compressive strength. When penetrometers cannot any longer return meaningful results from maturing shotcrete, its increasing shear modulus can be determined with powder-actuated pin setting tools. The penetration depth of a pin with a defined geometry, driven by a defined energy and impulse, will correlate well with the shear modulus (and indirectly with the compressive strength) of the substrate material. Finally, when the shotcrete has stiffened to an extent unsuitable for shear modulus measurements with powder charge driven pins, traditional core extraction and compressive strength testing can be employed. The Figure below illustrates the useful ranges of the various testing techniques:

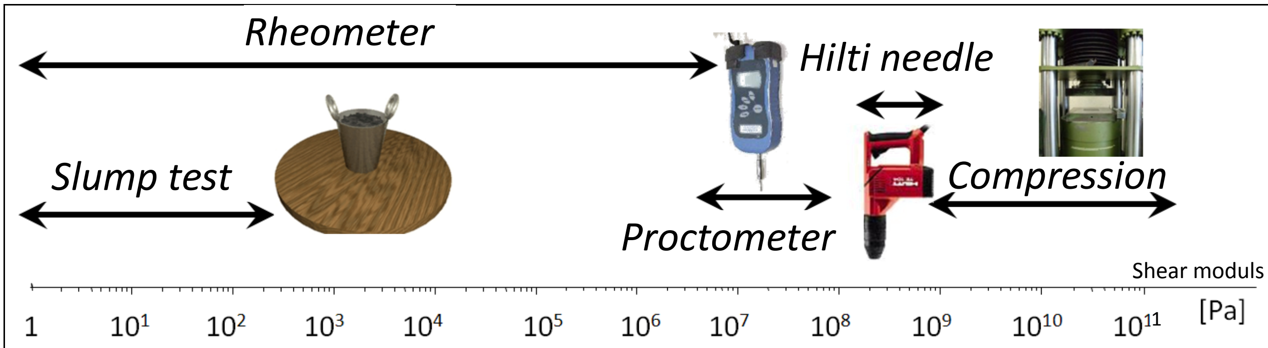


Figure 6: Methods to determine shear modulus and their ranges of application

Oblak et.al. also experimented with Ultrasound spectrometry. Using reflected shear and compression waves (in the 0.1 to 10 MHz range), they were able to determine Poisson ratios and shear moduli of cement pastes and concretes. Note that ultrasound spectroscopy determines amplitude reductions between incidental and reflected waves. Therefore the specimen needed to be instrumented on one side only. Figure 7 below shows the set-up:

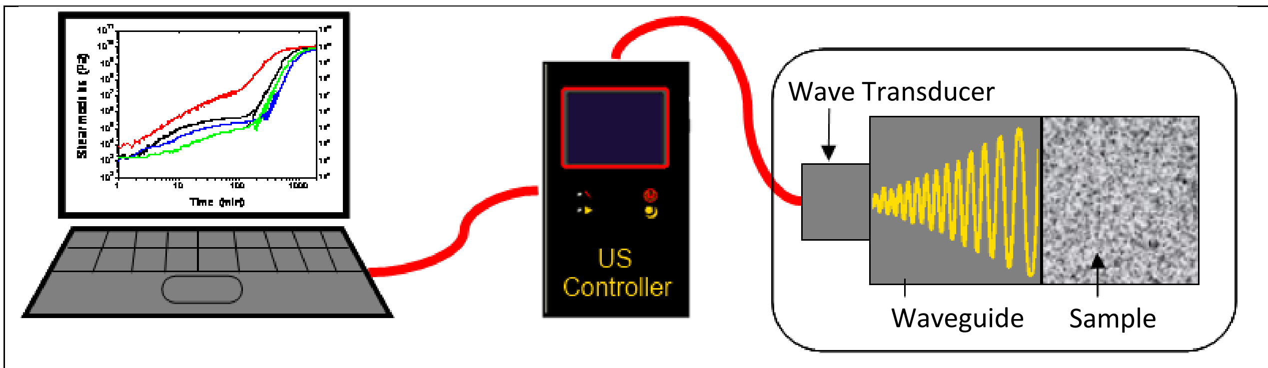


Figure 7: Schematics of ultrasonic spectroscopy

A comparison between ultrasonic spectroscopy and mechanical measurements of shear moduli showed good correlation, as demonstrated in Figure 8. This method could be very useful for testing early-age strength of shotcrete, allowing a reduction in testing effort.

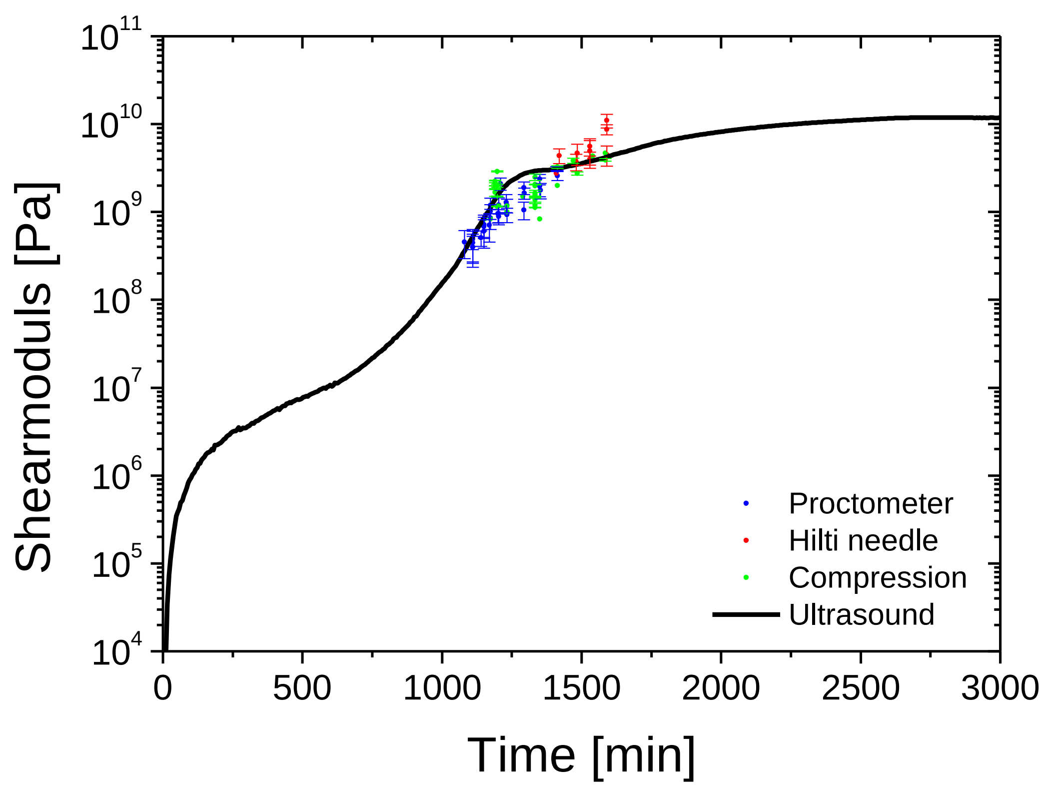


Figure 8: Correlation between acoustic and mechanical test results.

Veit Reinstadler (Mapei, Milano, Italy; first author Enrico Dal Negro, co-author Cristiano Maltese) talked about "*Using Advanced Admixtures to Enhance Accelerator Performance in Sprayed Concrete*". The presentation is published in English in the conference proceedings. Therefore only a brief synopsis is given here. Alkali-free accelerators generally contain aluminium sulphate complexes stabilised by either organic or inorganic acids. Combined with a wide range of cements, the performance of such accelerators is not always predictable. A new mineral powder based admixture (Accelerator Aid Agent – AAA) is used to substitute cement (at a ratio of typically 12.5% in the experiments published), thereby providing more uniform accelerator response at lower accelerator addition rates. In spite of slightly reduced accelerator dosage, the AAA modified mixture achieved greatly enhanced early-age performance for a wide range of cements, particularly benefitting speed of construction and tunnel safety during construction. The table below presents results of some of the early-age compressive strength tests.

Mortar Mix Design for Strength Determination		
Component	Mixture 3, kg/m^3 (lbs/yd^3)	Mixture 4, kg/m^3 (lbs/yd^3)
Cement IV/A-P 42.5 N	480 (810)	431 (727)
AAA	0	54 (91)
Superplasticiser	2 (3.4)	7 (12)
Accelerator	29 (49)	26 (44)
Aggregate (0 – 2.5 mm)	1449 (2443)	1454 (2605)
Water	217 (266)	194 (327)

Compressive strength development							
Mixture	Penetration Resistance (N) and Compressive Strength (MPa), at age						
	0.5 h	1 h	2 h	4 h	6 h	8 h	24 h
3	12 N	37 N	54 N	67 N	75 N	100 N	11.0 MPa
4	155 N	0.5 MPa	1.2 MPa	3.3 MPa	4.1 MPa	5.3 MPa	10.8 MPa

Figure 9: Example of mix proportions and early-age strength. The strength tests were first conducted with a penetration needle, then with a powder-actuated piston tool driving studs
Note: 1 N = 0.225 lbsf, 1 MPa = 145 psi

Rolf Breitenbuecher (Ruhr-Universität Bochum, Germany; co-authors Markus Thewes, Goetz Vollman, Heiko Rahm, Ingo Kaundinya) talked about "*Waterproof Shotcrete in Tunnel Construction*". While the double shell construction method (structural shotcrete for ground support, drain mat, waterproofing membrane, and inner tunnel lining) of long tunnels with constant cross-section is an economical proposition, short tunnel sections with non-standard geometries are expensive to construct in this traditional method. As an alternative, the single-shell construction method may be a viable alternative. (For background information: the single-shell method comprises a thick waterproofing membrane sprayed onto the shotcrete layer serving as structural ground support. A second layer of shotcrete, sprayed directly onto the waterproofing membrane, then serves as a protective layer and may even add structural load resistance to the system.) However, this system is prone to water leakage wherever the membrane is breached. Breitenbuecher et. al. presented methods to increase the resistance against water penetration of accelerated fibre reinforced shotcrete to reduce the possibility that cracks in the shotcrete, breaches in the membrane and porous shotcrete line up to provide a continuous path for water leakage. In an experimental program, a reference shotcrete mixture and multiple modified alternatives were tested. The table in Figure 10 documents the proportions of the reference mixture.

Constituent	Type	Addition Rate, kg/m^3 (lbs/yd^3)
Cement	CEM I 42,5R	430 (725)
Aggregate	0/2 mm: 43 % 2/4 mm: 23 % 4/8 mm: 34 %	1740 (2930)
Water		190 (320), w/cm = 0.41
Silica fume	Centrilit Fume SX	30 (51), 7% by mass of cement
Set accelerator	Rapid Centrament 650	9.0 % by mass of cement

Figure 10: Mixture proportions of reference concrete
Note 1 mm = 0.0394 inch

Noticeably the variations of the base mix with the addition of 50 kg/m^3 (84 lb/yd^3) steel fibres (l/d-ratio of 60), 60 kg/m^3 (101 lb/yd^3) fly ash, 30 kg/m^3 (51 lb/yd^3) metakaolin, 43 kg/m^3 (72 lb/yd^3) acrylate (0.1 – 0.3 μm particle size), or combinations of steel fibres and polymers improved the resistance against water penetration. The last variation provided the best performance, as the steel fibres controlled crack widths, while the polymer reduced water flow along the fibre-shotcrete interface. Figure 11 below shows a diagram with water penetration depths of different mixtures in a test according EN 12390-8.

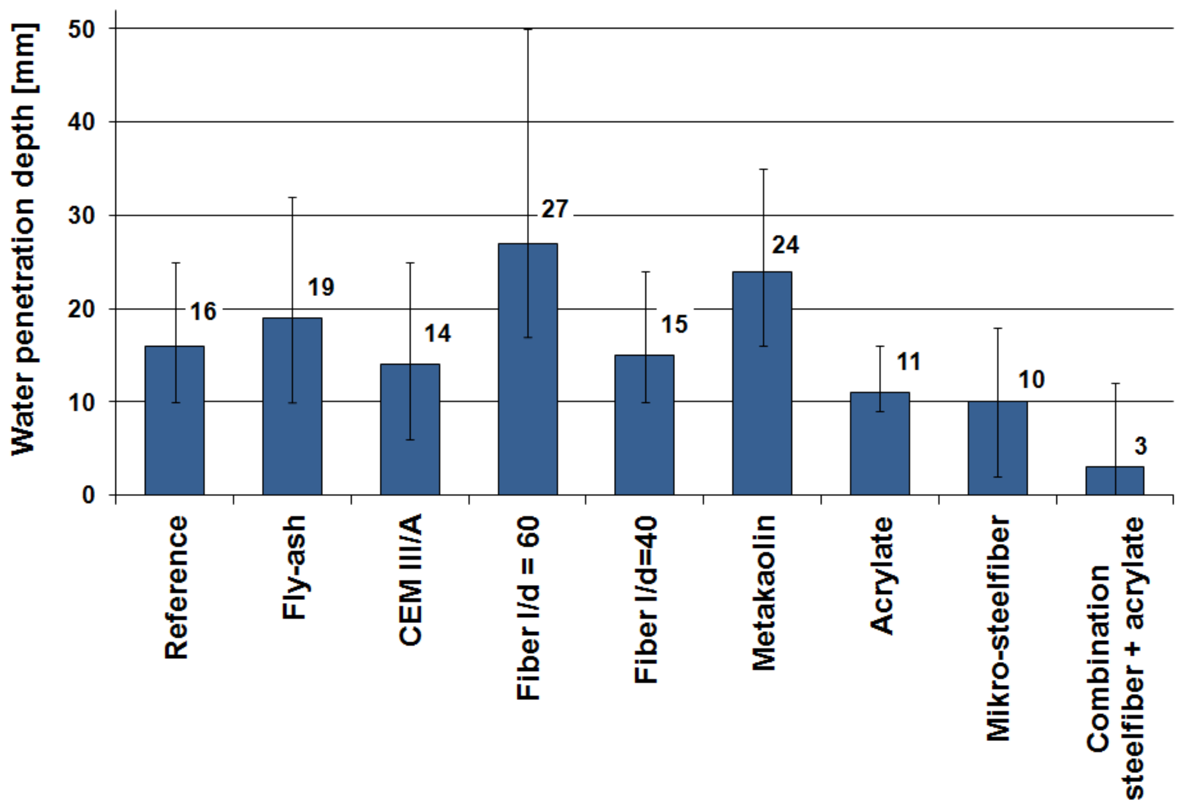
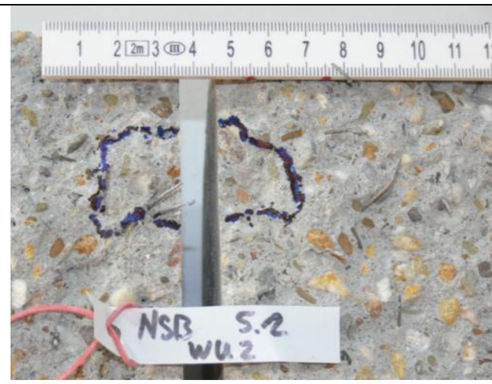
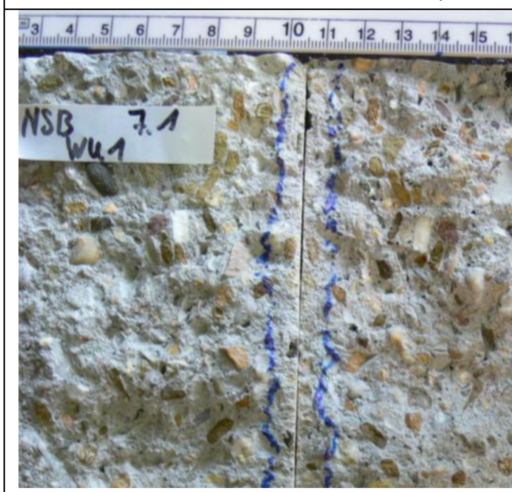
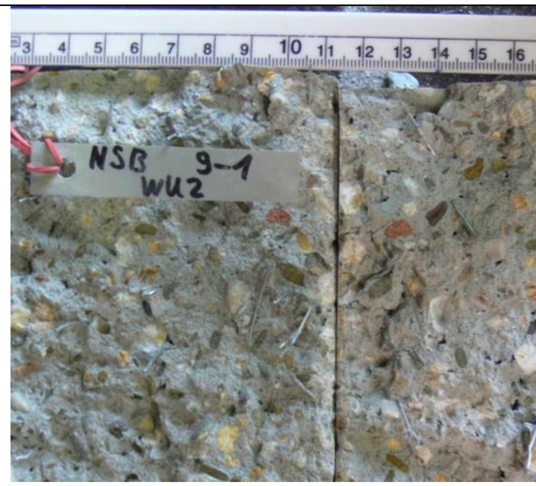


Figure 11: Water penetration depths for different mixtures in a test according to EN 12390-8
Note: 1 mm = 0.0394 inch

Figure 12 below shows the split specimens after the water penetration test. Note the water ingress around steel fibres. The voids and porous matrix around steel fibres may serve as a conduit for moisture; therefore short fibres and a matrix with reduced water permeability are desirable.

<table>
<tr><td></td><td></td></tr>
<tr><td>12A: Shotcrete with Steel Fibres, l/d = 60</td><td>12B: Shotcrete with Steel Fibres, l/d = 40</td></tr>
<tr><td></td><td></td></tr>
<tr><td>12C: Shotcrete with Acrylate</td><td>12D: Shotcrete with Acrylate and Steel Fibres, l/d = 40</td></tr>
<tr><td colspan="2">Figures 12A-D: Water penetration into steel fibre reinforced shotcrete. (Each image shows both fracture faces of a specimen.)
Note: units on scale are in cm. 1 cm = 0.394 inch</td></tr>
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Also of note was that in spite of the high steel fibre content and a high dosage of shotcrete accelerator, the shotcrete was able to encapsulate reinforcing steel without significant spray shadows.

Klaus Bonin (Wacker Chemie AG, Burghausen, Germany) talked about "*Waterproofing with Sprayed Single Shell Construction*". The single-shell construction (typically comprising a structural shotcrete layer supporting the rock, a sprayed polymer waterproofing layer and an inner shotcrete tunnel liner which may contribute structural strength) requires good crack control in the shotcrete. Cracking is a function of many parameters, including temperature effects, restraint from reinforcing steel and substrate, bond with the substrate and other properties. The table in Figure 13 shows EFNARC and DIN requirements for minimum bond strengths for shotcrete and repair mortars, both for non-structural and structural purposes.

Structural Role of Repair	Minimum Bond Strength to Concrete Substrate, MPa	Minimum Bond Strength to Rock Substrate, MPa
EFNARC Table 9.5.1		
Non-load bearing	0.5	0.1
Load bearing	1.0	0.5
EN1504-3 Table 3		
Not structurally relevant	0.8	Not available
Structurally relevant	2.0 – 1.5	Not available

Figure 13: Comparison of bond strength requirements for shotcrete and repair mortars on substrate concrete and substrate rock
Note: 1 MPa = 145 psi

In order to reduce cracking in shotcrete and improve bond strength, adding vinylacetate-ethylene copolymer on the order of 5% by mass of cement produced good results. A large-scale test was started in a salt mine tunnel near Stetten (Germany). The tunnel was lined with 200 – 300 mm (8 to 12 inch) thick accelerated wet-mix shotcrete but no waterproofing membrane. Some sections of the tunnel were constructed with polymer modified wet-mix shotcrete, while other sections were constructed with a control shotcrete containing no polymers. Pressurised mine water was able to leak through cracks, depositing calcium hydroxide on the tunnel walls. However, as demonstrated in the three photographs in Figures 14A to 14C, the polymer-modified tunnel liner significantly reduced leakage rates compared to the traditional shotcrete liner.

Figures 14A-C: Tunnel walls with regular (above) and polymer-modified (middle and below) wet-mix shotcrete liner. Note the significantly reduced incidence of leaking cracks in the polymer-modified shotcrete shown in the two lower Figures (14B and C). The bottom Figure 14C shows the same area as the middle Figure 14B, but after 2 years of service life.

A second example described the successful lining of leaking sections of a headrace tunnel in Hintermur, Austria with polymer modified dry-mix shotcrete. A site visit 2 years after installation showed well-bonded crack-free shotcrete. It is thought that in both examples the polymer imparted more flexibility to the otherwise rigid shotcrete matrix, reducing cracking from shrinkage and ground movements.

Andrew Pickett (Mott MacDonald Budapest, Hungary; first author Alun Thomas) presented a study on "*Composite Shell Linings*". The conference proceedings provide this paper in English. Thomas et.al. also published a similar paper in the North American Tunnelling Journal, April/May 2012, pp 30-39, under the title of "*Where are we now with sprayed concrete lining in Tunnels?*" Therefore we present a brief synopsis only. Traditional tunnelling methods rely on ground support comprised of temporary rock support (say, a shotcrete liner), followed by a waterproofing system and a permanent structural inner shell. Single-liner shotcrete shells comprising structural shotcrete and a waterproofing film (either sprayed onto the substrate surface or sandwiched between two shotcrete layers) promise more economical ground support in some tunnels, as such designs may use all the concrete sprayed for permanent ground support. In order to ensure composite action, the minimum tensile bond and shear strengths anywhere in the system must be a minimum 1 and 2 MPa (approximately 150 to 300 psi), respectively, as shown in Figure 15 below.

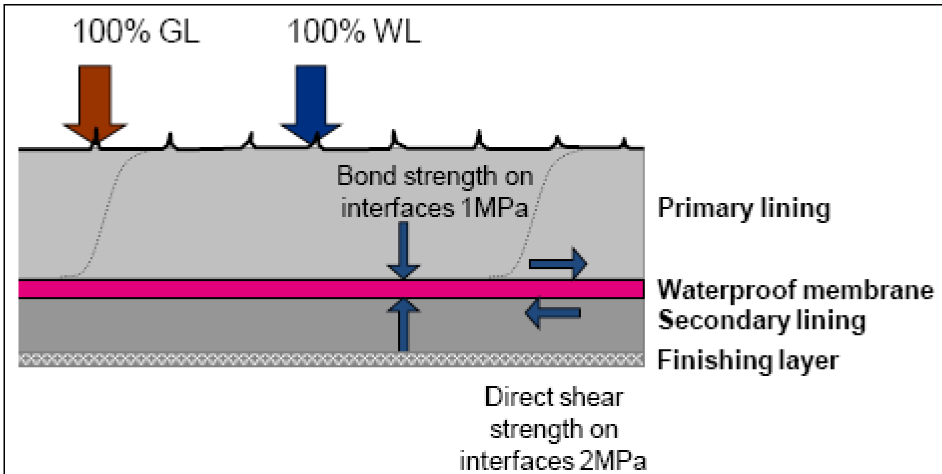


Figure 15: Minimum bond and shear strengths to ensure composite action in multi-layer shell linings

Currently Thomas and Pickett are not aware of a lining with a spray-applied membrane that has been designed as a full composite, even though testing shows that the required strengths at the interface are achievable. However, successful examples of single-layer systems (without spray applied membranes) in dry ground can be found, for instance in Norway and Great Britain. The following Figures 16 and 17 illustrate the difference between the current design concepts for traditional and composite shell tunnel liners.

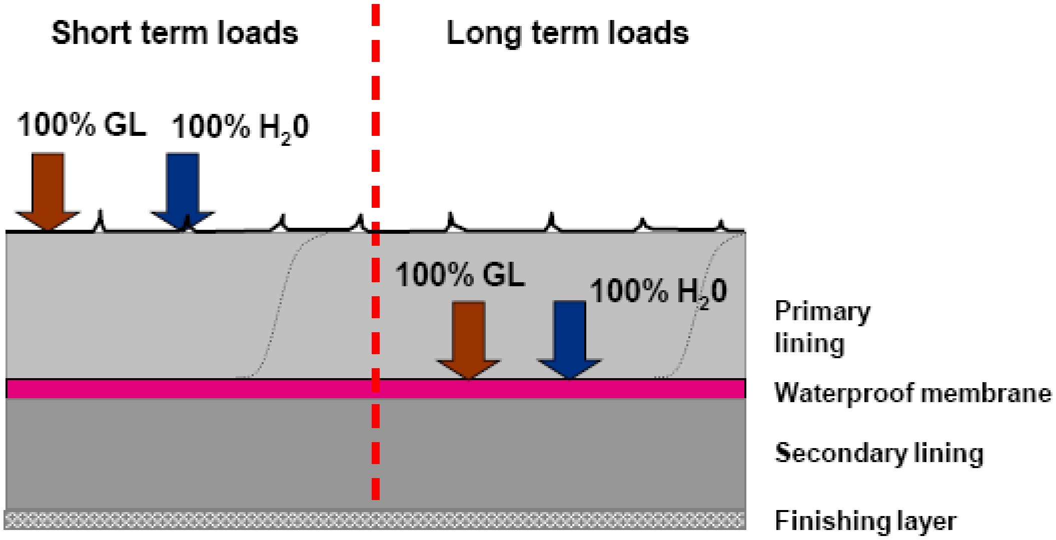


Figure 16: Double-shell Lining: short-term vs. long-term function

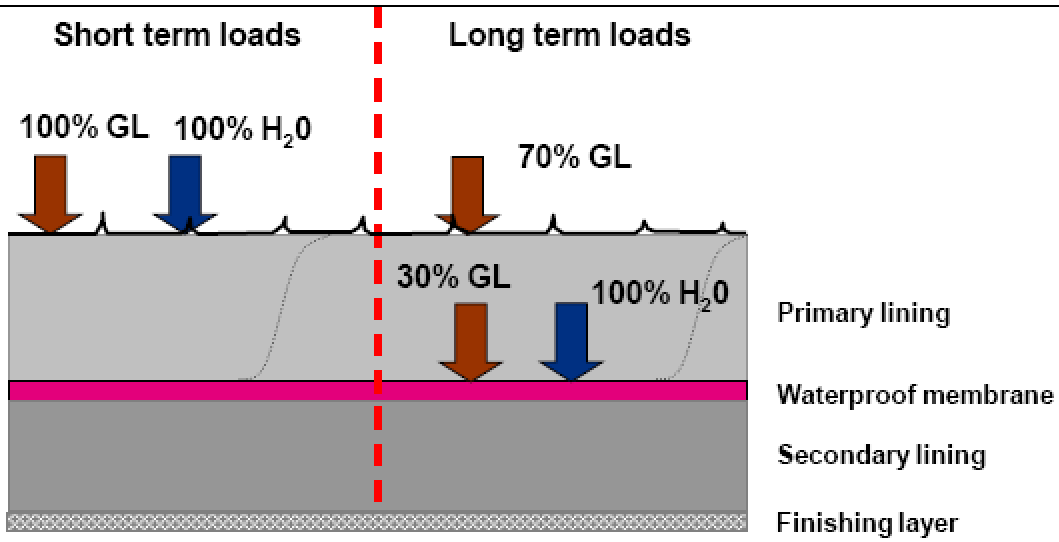


Figure 17: Composite (single) Shell Lining: short-term vs. long-term function

Thomas and Pickett then discussed detailed design assumptions, materials options and properties, construction sequences, testing programs and results. They suggested that a 650 mm (26 inch) thick fully bonded composite liner of permanent shotcrete with a spray-applied membrane may be capable of replacing a 750 mm (30 inch) thick double shell liner with a sheet membrane and cast in-situ secondary liner in large-bore tunnels. The saving in materials may be small but the saving in time and cost of formwork is significant since the whole liner can be sprayed.

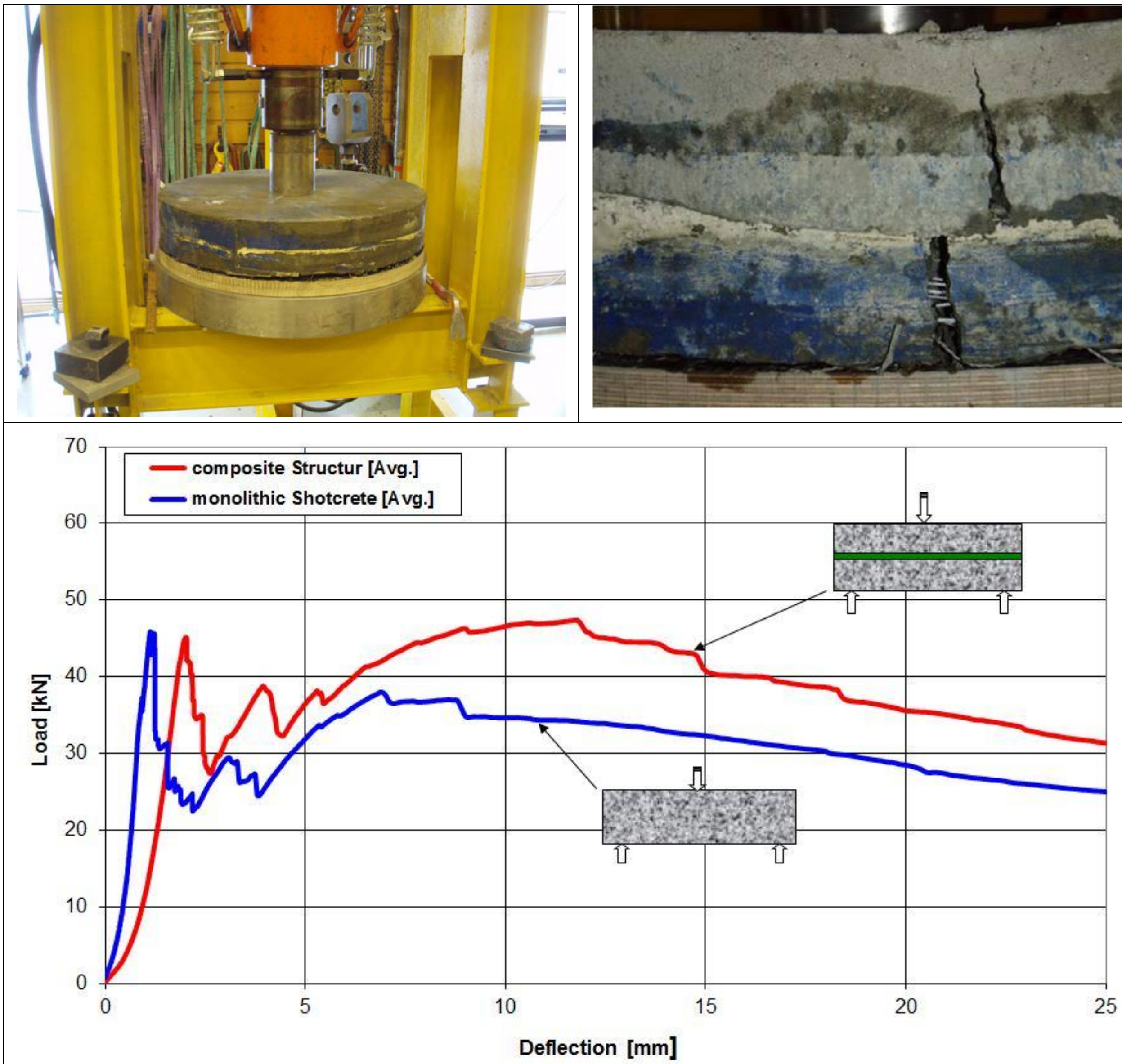
Roland Mayr (BASF, Krieglach, Austria) presented a paper on "*Single Shell Linings with Sprayed Membrane – Experiences and New Findings Regarding Composite Action and Frost Resistance*". He reported on recent single-shell projects in Austria, England and Norway. In all projects, a spray-on polymer membrane (generally suitable are methyl-metacrylate, polyurethane, ethylene-vinylacetate or styrene acetate copolymers) applied to the seal coat shotcrete lining provides waterproofing, while a steel fibre shotcrete liner supports the ground. In his examples, dry-mix shotcrete equipment was used to spray a 2 to 4 mm (approximately 0.1 to 0.2 inch) thick layer of vinyl acetate ethylene powder, mixed with water. The table in Figure 18 provides typical physical properties of such a membrane.

Properties of polymer membrane	Value
Minimum layer thickness	3 mm (0.12")
Elongation at -20°C / +20°C	80% / 140%
Shear Strength on smooth surface, 2 mm thickness	1.1 MPa (160 psi)
Shear Strength on gun finished surface, 5 mm thickness	1.7 MPa (250 psi)
Tensile bond strength on concrete substrate	1 MPa (145 psi)
Tensile strength of membrane (dependent on moisture condition)	1 – 4 MPa (145 – 480 psi)

Figure 18: Physical properties of spray-on membrane

Important for the single-shell construction are a competent smooth substrate to ensure the integrity of the spray-on waterproofing liner, good seepage water control, good thickness control for the waterproofing liner, and adequate curing so that the polymer can harden and become resistant to the impact and abrasion caused by the shotcrete application. While the shotcrete for the tram crossover tunnels in Linz, Austria was shot with steel fibre reinforced accelerated wet-mix shotcrete, the underground hospital archive in Zams required only a 20 to 30 mm (1 inch) thick dry-mix shotcrete layer for protection. The English Hindhead tunnel received a 150 mm (6 inch) thick (steel and polymer) fibre reinforced shotcrete layer onto a spray-on polymer membrane in all areas more than 4 m (13 ft.) above the tunnel invert. This greatly accelerated the construction schedule compared to the initially planned double-shell construction. Note that in the Hindhead tunnel, a contact-less surveying station aided the shotcrete robot, ensuring a proper tunnel profile. The Gevingas railway tunnel near Trondheim, Norway is exposed to long cold winters. Therefore it was decided to install a dual-shell system with traditional drainage mats (thermally insulated towards the inside of the tunnel to avoid formation of ice) near the tunnel portals. Small-scale experiments with single layer shells exposed to harsh environments are still in progress. Therefore only the centre-section of the Gevingas tunnel was constructed with a single-shell liner. It was noted that, apart from more rapid construction, single-shell liners are more maintenance-friendly, as leakage or localised structural failures tend to telegraph to the surface at the exact location where they occur. Consequently, maintenance and repair can be much simpler than in a dual-liner system.

Toughness tests on round panels were conducted to evaluate load resistance. The tests compared composite panels to monolithic shotcrete panels of identical gross geometry, i.e. 100 mm (4 inch) thick and 600 mm (2 ft.) diameter. All shotcretes were reinforced with 5 kg/m^3 (8 lbs/yd^3) synthetic macro-fibres. Of note is that the composite panels (shotcrete-membrane-shotcrete) cracked at twice the deflection compared to the monolithic panels. Further, total energy absorption and post-crack load resistance of the composite panel was substantially higher than for the monolithic panels. The following Figures 19 to 21 show the test arrangement, a cross-section of a cracked composite panel, and averaged load-deflection curves for monolithic and composite panels.



Figures 19 to 21: Toughness testing of monolithic and composite panels
Note: 1 kN = 225 lbsf; 1 mm = 0.394 inch

An experimental program to study the performance of composite shells under ice-forming conditions is still under way. Preliminary results indicate that the Scandinavian codes are conservative, and the effect of freezing temperatures and ice formation may not induce stresses as high as indicated by the applicable codes.

Peter Paulini (University Innsbruck, Austria) gave a presentation on the *Evaluation of Shotcrete Hardening and Stiffening*. The properties of fresh and early-age shotcrete dictate shotcrete construction methods and schedules. Variables related to cementitious materials, admixtures, mix proportions and temperature affect these properties. In order to measure them, an array of test methods is available.

Paulini models construction materials from the perspective that their stress resistance is a function of the bond energy of the constituents, thus using an energy equilibrium approach. For instance, Paulini observes that a shotcrete's capacity to absorb deformation energy (in the linear-elastic range) is a function of the energy of its chemical bond. The bond energy is related to the degree of hydration of the cement paste. Calorimetric or volumetric reaction data give rise to cement hydration kinetics. Cement paste shrinks as it hydrates as a result of binding forces. Therefore a function ought to exist which describes stress resistance as a function of volume shrinkage and time.

Paulini points out that linear-elastic behaviour of a material is characterised by:

- E, modulus of elasticity
- G, shear modulus
- K, compression modulus
- M, p-wave modulus
- ν, Poisson ratio
- λ, Lame's First Parameter.

Paulini then demonstrates that all six of the above properties are related, and that only two properties need to be determined in order to calculate the remaining four. As M and G can readily be determined by measuring a materials density, and longitudinal or transverse sound velocities, respectively, the remaining properties can be calculated. The sound velocities can be readily measured on test panels, using appropriate transducers. Differences between dynamic and static moduli must be considered using a creep coefficient. (Note that the equation numbers provided here are directly quoted from Paulini's original paper.)

Young´s modulus
$$E = \lambda \cdot \frac{(1+\nu)\cdot(1-2\cdot\nu)}{\nu} \quad (6)$$

Shear modulus
$$G = \lambda \cdot \frac{1-2\cdot\nu}{2\cdot\nu} \quad (7)$$

Bulk modulus
$$K = \lambda \cdot \frac{1+\nu}{3\cdot\nu} \quad (8)$$

P-Wave modulus
$$M = \lambda \cdot \frac{1-\nu}{\nu} \quad (9)$$

P-Wave modulus
$$M = c_L{}^2 \cdot \rho \quad (10)$$

Shear modulus
$$G = c_T{}^2 \cdot \rho \quad (11)$$

Note the following definitions:

c_L = compression wave velocity

c_T = shear wave velocity

ρ = density.

In the final part of his presentation, Paulini discusses the indirect determination of compressive strength of shotcrete. Rebound hammers have been long used to estimate compressive strength of hardened shotcrete after it exceeds approximately 10 MPa (~1500 psi). However, early-age shotcretes with lower strengths undergo substantial plastic deformation when impacted by the rebound hammer. More than 90% of the impact energy causes plastic deformation, while less than 10% results in elastic deformation causing measurable rebound. This renders the rebound hammer useless for measuring low compressive strengths. However, if fitted with a suitable conical tip (120° tip angle), the impact will result in a measurable deformation. The compressive strength of the shotcrete can then be calculated from the impact energy W_i and the diameter (d) of the indentation left by the conical tip:

$$f_c = \frac{2 \cdot W_i \cdot \sqrt{3}}{d^3 \cdot \pi} \approx \frac{W_i}{d^3} \qquad (16)$$

This relation is shown in Figure 22 for conventional rebound hammer spring energy of 2.207 J.

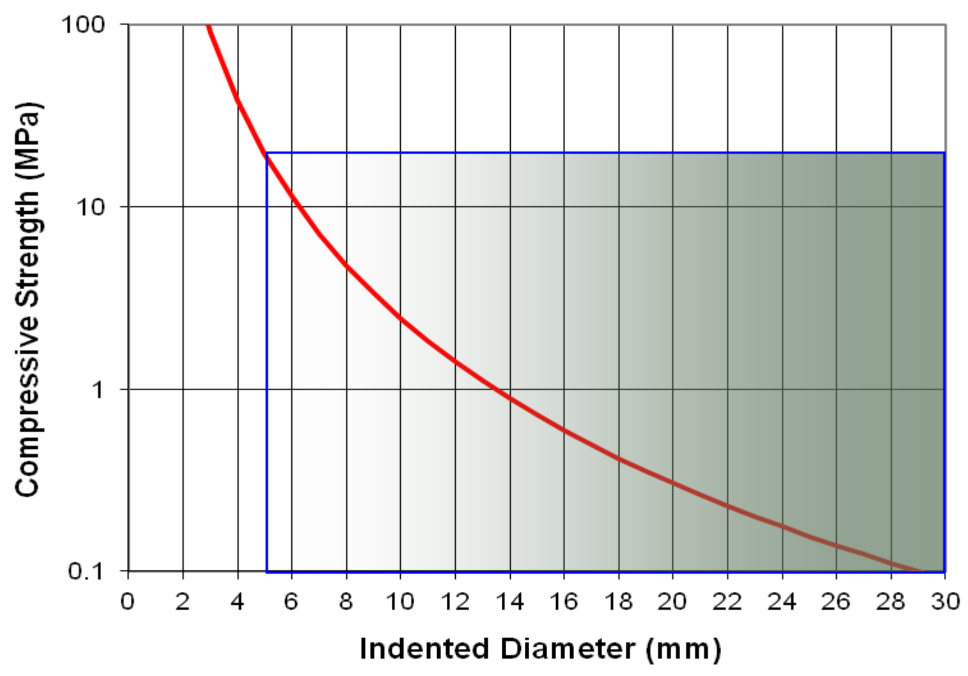


Figure 22: Correlation between diameter of indentation left by modified rebound hammer tip and compressive strength of shotcrete

Note: 1 MPa = 145 psi, 1 mm = 0.394 inch

Rudolf Roeck (Schretter & Cie, Austria, co-authors Juergen Baumgaertner, Robert Galler, Christian Volderauer, Gerhard Pittino) presented a paper on a highly compressible shotcrete. When tunneling through expanding ground, the tunnel liner requires compression elements to harmlessly absorb deformations of the rock. In order to simplify construction, a compressible grout to fill the annular gap between tunnel liner and rock face was developed in the 1990's. By incorporating polystyrene particles into the grout it could be compressed harmlessly by approximately 50%, thus reducing stress peaks in the tunnel liner resulting from ground movements. Advancing the idea of compressible grout, a compressible shotcrete was developed. Roeck at.al. set out to develop a shotcrete with a geometrical compressibility of approximately 5 to 10% while meeting the New Austrian Tunneling Method (NATM) early-age strength requirement for Class J2, and a 28-day compressive strength of minimum 15 MPa (~2200 psi). Their *Comgun* mixture contains polystyrene spheres and steel fibres. Such shotcrete would be useful for single-liner ground support. In tests it was applied as a wet-mix shotcrete conveyed via a piston pump and rubber hoses. The density of the shotcrete was 600 kg/m^3 (~1000 lbs/yd^3). The following Figures 23 and 24 show the early age compressive strength and later-age uniaxial stress-strain curves of the shotcrete.

Figure 23 – Early-age uniaxial compressive strength development and NATM strength classes, log-log-plot. Note: 1 MPa = 145 psi

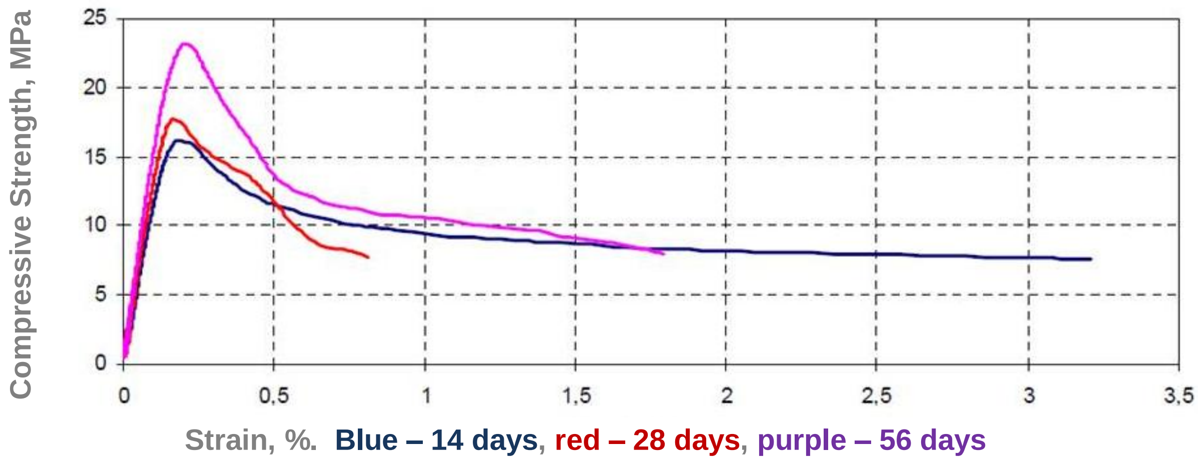


Figure 24 – Uniaxial compressive stress-strain curves
Note: 1 MPa = 145 psi

After conducting initial laboratory tests, a large-scale test was conducted. The inside of a kiln segment [approximately 3 m (10 ft.) diameter] was lined with coiled rubber hose (collapsed by vacuum inside) and a protective sheet, and then shotcreted. The kiln served as a reaction frame, the rubber hose and liner, when pressurised with water, simulated moving ground, and the shotcrete liner was observed for damage while strained by the expanding rubber hoses. The following Figure 25 shows the shotcrete liner being placed inboard of the kiln segment and the protected rubber hose.

Figure 25 – Shotcreting the inside of the mock-up tunnel segment

The shotcrete achieved an average compressive strength of 19 MPa (2800 psi) at 28 days, an average Modulus of Elasticity (compression) of 17 GPa (2500 ksi), and an average Shear Modulus of 16 GPa (2300 ksi). The load test returned a tangential and radial shear failure of the shotcrete liner in one location. Figure 26 shows the movements of 7 survey marks attached to the inside of the shotcrete liner during the test.

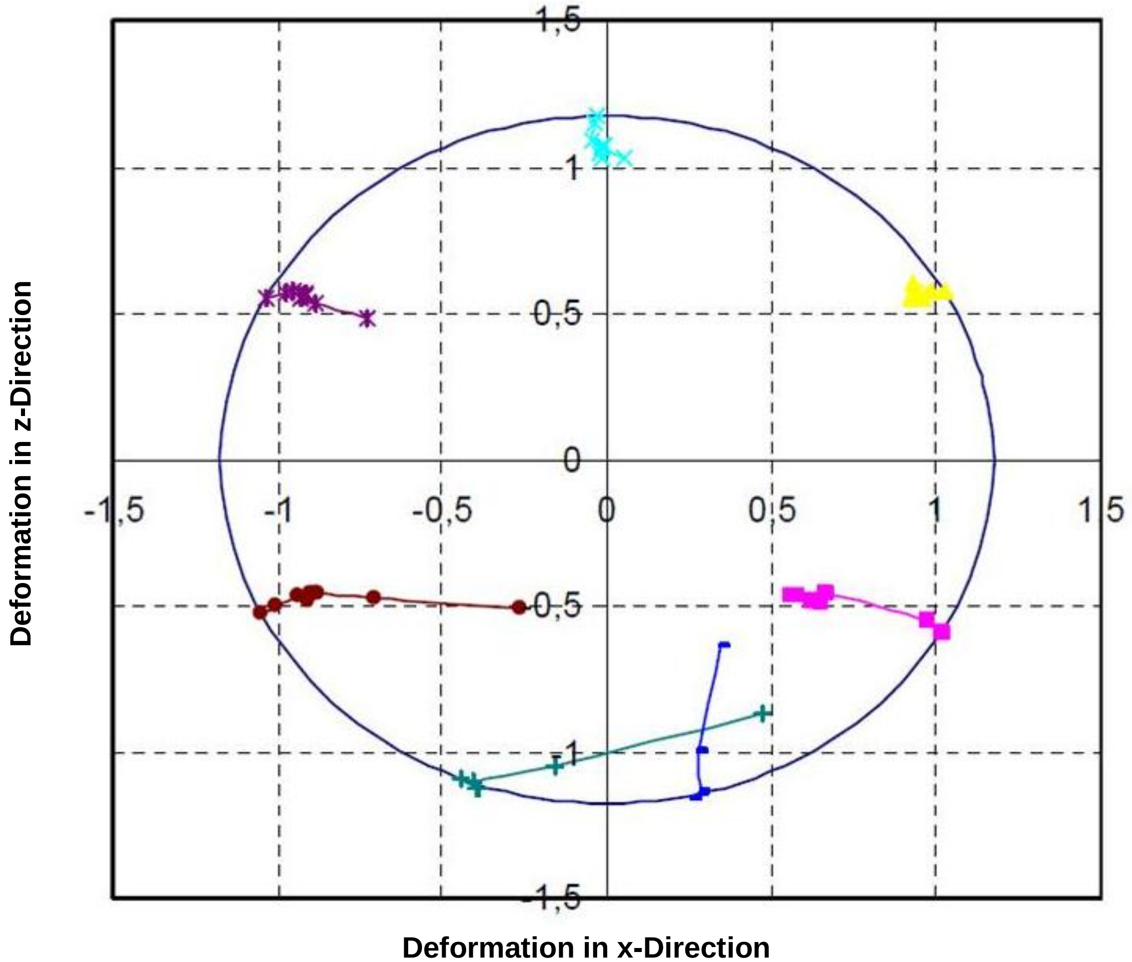


Figure 26: Deformation of the shotcrete liner during the mock-up test in radial and tangential directions. Dimensions in m (1 m = 3.28 ft).

Alberto Belloli (Rowa Tunnelling Logistics AG, Switzerland; first author **Heinz Jenni**) talked on the state-of-the-art shotcrete manipulators, mounted on tunnel boring machines (TBMs), or integrated into drill-and-blast tunneling equipment. Remote controlled shotcrete manipulator arms are being used to stabilise rock faces immediately after cutting (zone L1) and for lining of stabilised or self-supporting ground behind the tunneling machine (zone L2). In particular, shotcrete manipulators are now custom-mounted on tunnelling machines, providing 360° access to the tunnel wall, as well as longitudinal movements independently of the TBM's advance. Baffles and curtains minimise rebound and dust exposure to crew and equipment. Some manipulator arms are even designed to move through openings in the stopped cutter head of Tunnel Reaming Machines, stabilising the tunnel face with shotcrete where required. Belloli showed current examples of tunnelling equipment with integrated shotcrete actuators. They included:

- Uetliberg-tunnel (Switzerland): A Tunnel Reaming Machine was widening the pilot tunnel from 5 m (16.4 ft) diameter to its intended profile of 14.4 m (47 ft) rough diameter.

A manipulator applied shotcrete to stabilise fallouts ahead of the cutter head, from between the spokes of the cutter head.

- Gotthard base tunnel (Switzerland): The structure comprises two 9.58 m (31.4 ft) wide, approximately parallel tunnels. The two TBMs worked from Amsteg towards Sedrun. They were equipped with shotcrete manipulators able to spray the entire circumference of the tunnel walls. The manipulators were also able to longitudinally move by 8 m (26 ft) relatively to the TBM, thus removing the task of shotcreting from the critical path. Figure 27 shows a photograph and a sketch of the system.

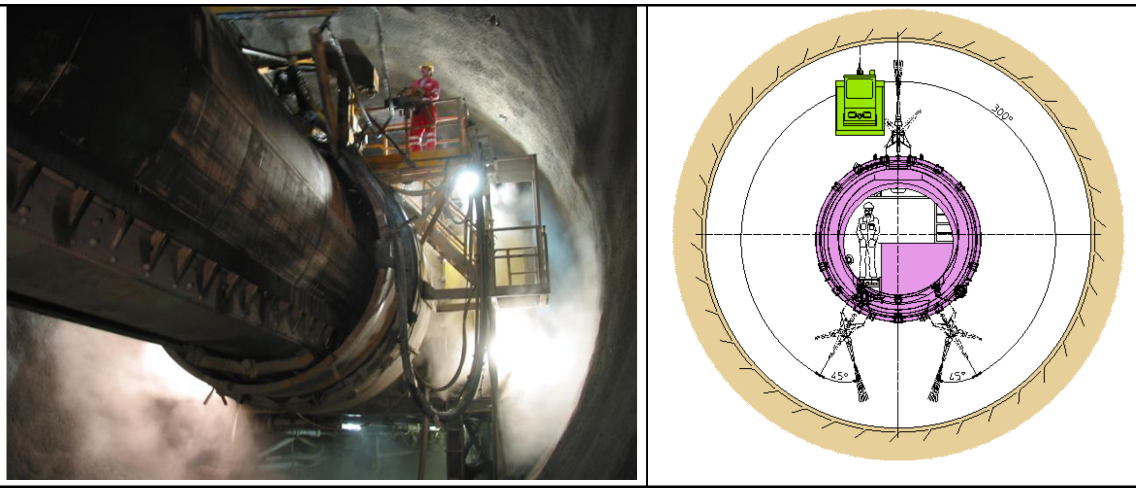


Figure 27: Shotcrete Manipulator in the Gotthard Base Tunnel (Amsteg)

- Niagara Tunnel Facility Project (Canada): Here a TBM tunnelled through geologically challenging formations, initially on a downward slope of 7.8%, then levelling out, and finally 7.3% rising. The tunnel diameter was 14.4 m (47 ft). Two shotcrete manipulators in the L2-Zone were able to cover the entire tunnel circumference under all orientations of the TBM. Figure 28 shows a schematic of the shotcrete manipulators.

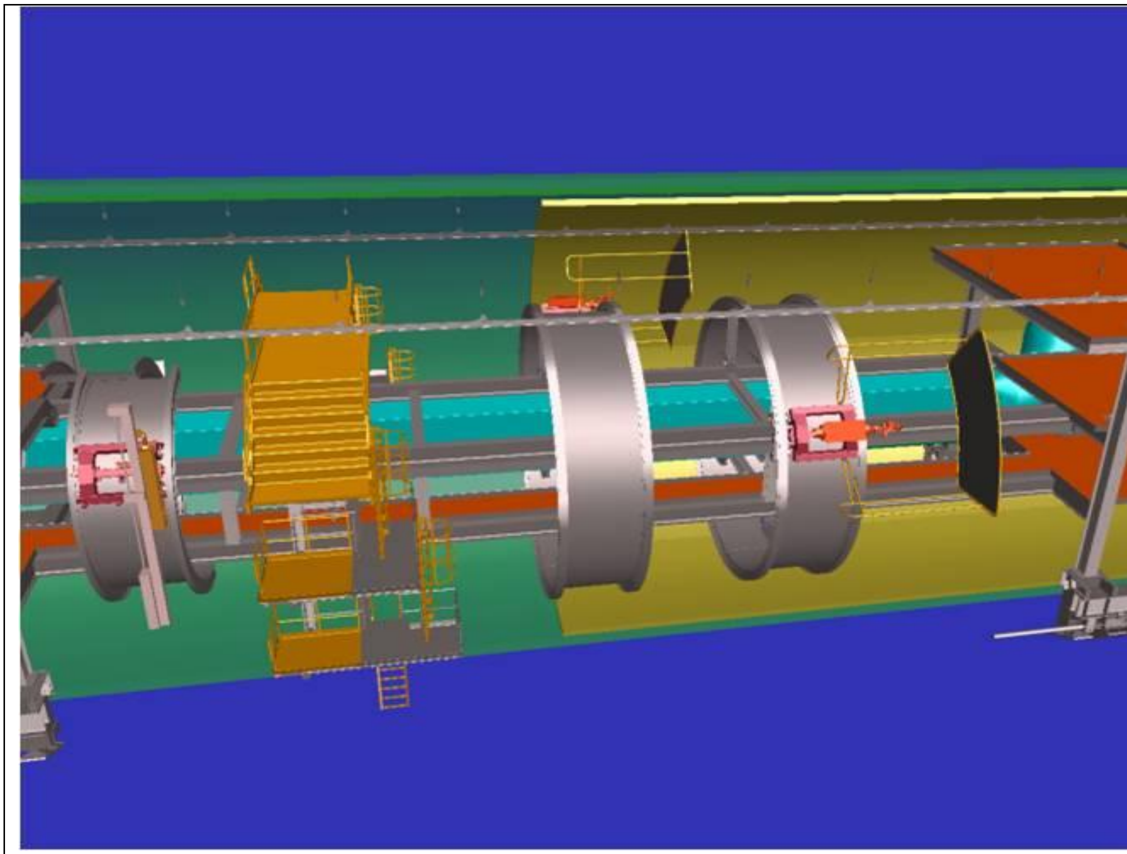


Figure 28: Shotcrete Manipulators on TBM at Niagara Falls

- The hydropower project at Linthal (Switzerland) required an 8 m (26 ft) diameter access tunnel, sloping at 24%. The TBM was designed to excavate the tunnel working upwards. Two shotcrete manipulators integrated into the TBM tail constructed the tunnel liner. Baffles, shrouding and rebound collector tubs were mounted so that contamination of the TBM as well as the tunnel floor could be dramatically reduced, as shown in Figure 29.

Figure 29: Dust and rebound collection in shotcrete work zone, Amsteg

- The La Muela II hydropower expansion project in Spain required a tunnel built downwards by the drill-and-blast method. One of the particular challenges was the 45° down-slope of the tunnel. Figure 30 provides an impression of the rail-mounted equipment, which also included a shotcrete manipulator. The manipulator is designed so that it can be quickly installed to, and removed from, the head of the excavator arm.

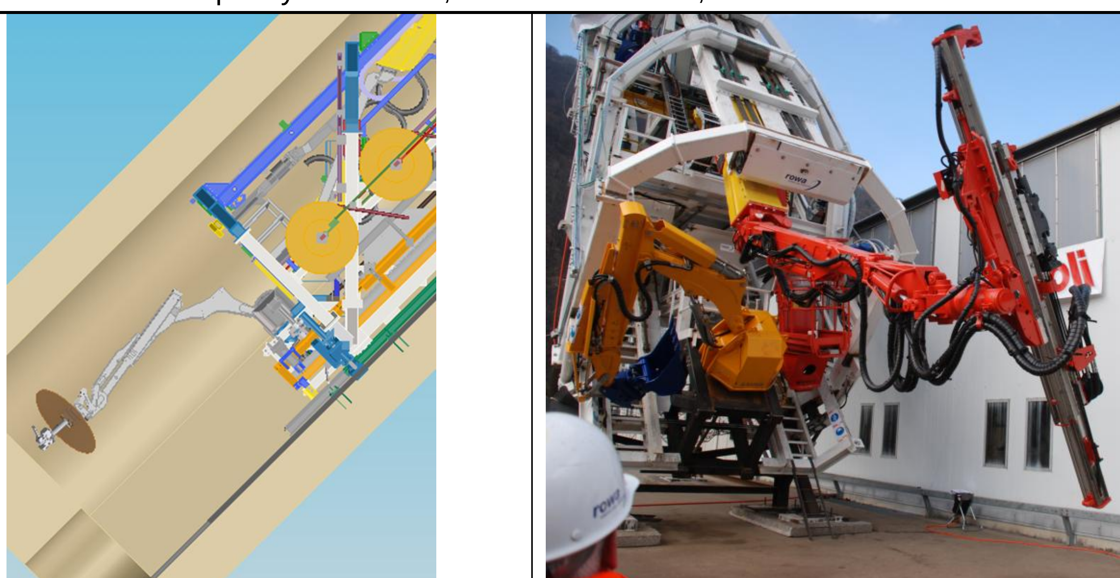


Figure 30: Tunneling equipment. Note: shotcrete nozzle mounted to excavator arm in schematics shown left, excavator bucket mounted in photograph shown right.

Gerhard Pittino (Montanuniversitaet Leoben, Austria, co-author Robert Galler) gave a presentation on testing fibre reinforced shotcrete for toughness. The Austrian and European code ÖNORM EN 14488-5 specifies testing square panels with 600 mm (2 ft) edge length and 100 mm (4 in) thickness. For the test, the panel is fully supported near all four edges over a width of 20 mm (0.8 in) with a clearance of 500 mm (20 in) between parallel supports, and loaded centrically with a square loading tip of 100 mm (4 in) side length. The loading rate is 1 ± 0.1 mm/min (0.04±0.004 in/min). End deflection of the centre is 30 mm (1.2 in); however, the deformation energy is calculated to 25 mm (1 in) centre point deflection only. As test specimens generally have some geometrical imperfections (particular with respect to thickness and warp), there are concerns about the effect of such imperfections on the test results.

In a first round of tests, 3 specimens reinforced with 8 kg/m^3 (13 lbs/yd^3) Enduro HPP polymer fibres were tested. While panels P1 and P3 were tested under standard loading conditions, panel P2 was loaded at 10 times the deflection rate. The increased loading rate appeared to have increased the pre-crack load resistance and decreased total energy absorption, though the statistical significance of this is still under discussion. Figure 31 shows the test results.

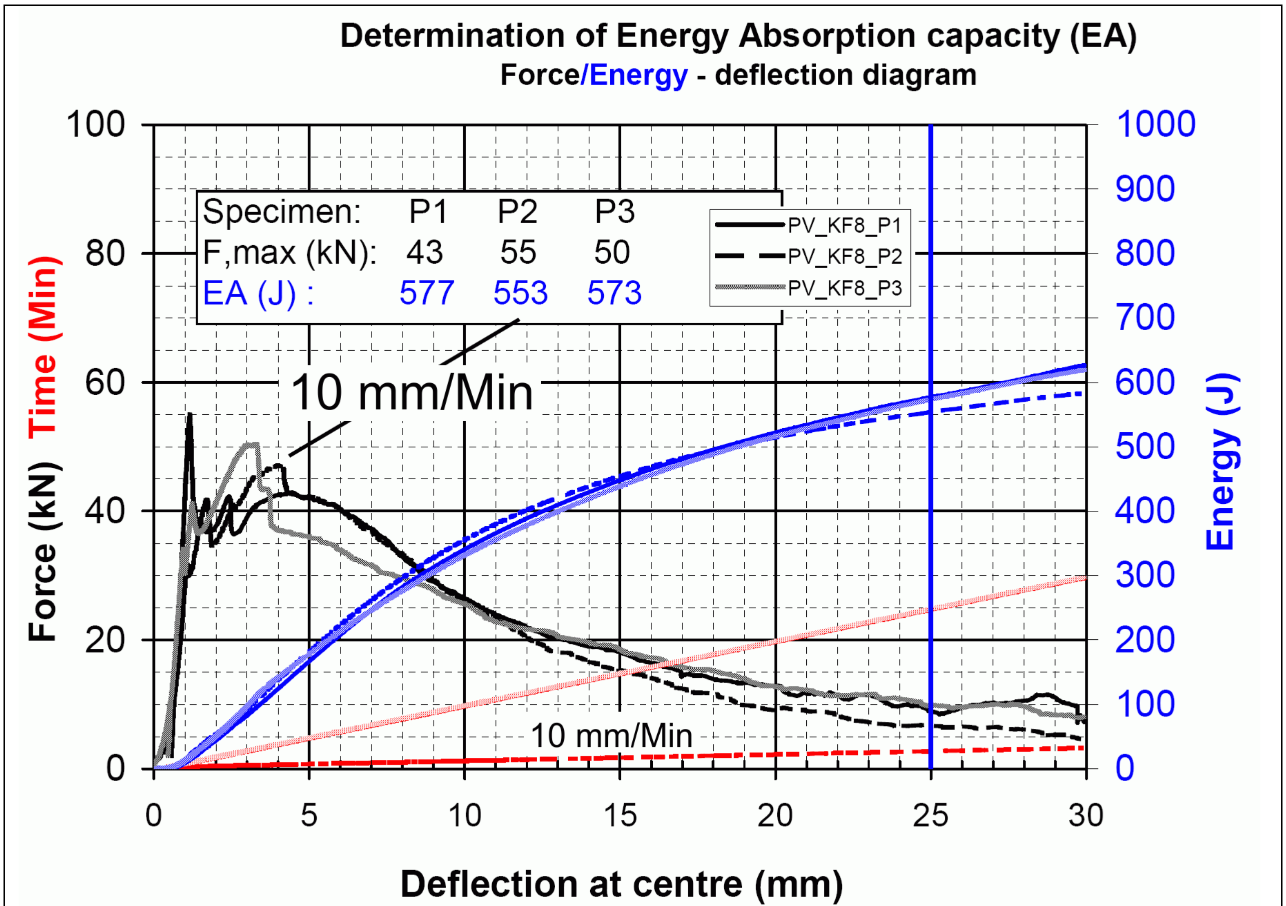


Figure 31 – OENORM EN 14488-5 Plate Test. Panel P2 tested at 10 times the standard loading rate (dotted lines). *Note: 1 kN = 225 lbsf, 1 mm = 0.039 in, 1 J = 1 Nm = 0.74 ftlbs*

Consequently, a computer simulation with Flac was run. The test plate was modelled using 36,000 cubes each with 10 mm (0.39 in) edge length. The material properties were determined in triaxial tests. A strain-softening tensile strength was selected as 2 MPa (290 psi) at zero strain to 0.1 MPa (14 psi) at 200 microstrain. The modulus of elasticity was set to 20 GPa (2900 ksi). The computer simulation showed that deviations in thickness have the most significant effect on simulated test results. Other non-uniformities were less relevant. However, warp-induced non-uniform seating does affected the peak load, and may result in several peaks as the cracks develop successively. This can be understood by realising that under deformation all four corners of a perfect slab would lift off the load frame, and the slab would be seated only near the centres of their edge supports. Real panels with a warped bottom face may not be fully seated. During loading, premature cracking will result in re-seating of the panel, and edge supports similar to that of a perfect slab will ensue at fairly low deflections. The table in Figure 32 shows the effect of imperfections on load resistance. These results will be verified by further plate tests.

Run	Description of Imperfection (Standard: 600 x 600 x 100 mm)	Peak Load, kN	Peak Load Compared to Standard Test Result, %
27	110 mm deep	23.93	118
34	700 mm x 700 mm	20.86	103
28	640 mm x 640 mm	20.56	101
31	One sloped edge (+50 mm)	20.36	100
26	**Fully compliant with standard**	**20.30**	**100**
30	One sloped edge (-50 mm)	20.22	100
32	540 mm x 600 mm	20.02	99
33	540 mm x 540 mm	19.80	98
29	90 mm deep	17.14	84

Figure 32 – Effect of Imperfections on Peak Load, Numerical Analysis. *Note: 1 mm = 0.039 in., 1 kN = 225 lbsf.*

The authors also found that the stiffness of the load frame significantly affected the load resistance of the panels, which requires more attention. Finally, the current model assumes uniform fibre distribution, while computer tomography shows that fibres are not uniformly distributed. Therefore, future models will include variations in the seating stiffness, warp of the test panels, and non-uniform fibre distributions.

Robert Bader (Brugg Contec AG, Romanshorn, Switzerland; first author Josef Kaufmann, EMPA; Mario Manser, Brugg) gave a presentation on creep of polyolefin fibre reinforced shotcrete. While steel fibre reinforced shotcrete is well-established for underground construction, synthetic fibre reinforced shotcrete is not yet universally accepted. Advantages of polyolefin fibres like good workability, low potential for injury and damage to waterproofing membranes, acid resistance, or durability, are tempered by their lower modulus of elasticity and creep under stress.

A new bi-component polymer fibre (Type 1, 50 mm / 2 in long; Type 2, 30 mm / 1.2 in long) was developed to reduce creep under load. The fibre comprises a stiff, high-modulus core and a mantle with enhanced bonding characteristics to concrete. The authors studied long-term creep in a series of plate bending tests to EN 14488-5 on shotcrete [8 mm (0.3 in.) maximum aggregate size] and concrete [32 mm (1.3 in) maximum aggregate size], as well as on EN 14651 beam specimens. Note that all samples were pre-cracked before creep testing. The authors used the mix designs and fibre dosages shown in Figures 33 and 34, respectively:

	Sand 0-4 mm, kg/m^3	Gravel 4-8 mm, kg/m^3	Gravel 8-16 mm, kg/m^3	Gravel 16-32 mm, kg/m^3	Cement CEM I 42,5N kg/m^3	Water, kg/m^3	w/c-ratio	High Range Water Reducer, kg/m^3
Mix 1	1156	544	0	0	450	202.5	0.45	4.5
Mix 2	640	320	340	700	300	150	0.5	1.5

Figure 33: Proportions of base mixes. *Note that 1 kg/m^3 = 1.65 lbs/yd^3, 1 mm = 0.039 in.*

	Mix (see Figure 33)	Fibre Type	Fibre Length, mm	Fibre Content, % by vol.
Batch 1	1	Type 1	50	1.0
Batch 2	1	Type 1	50	0.5
Batch 3	2	Type 1	50	0.5
Batch 4	1	Type 2	30	0.5

Figure 34: Proportions of individual batches. *Note that 1 mm = 0.039 in.*

The following Figures 35 and 36 show the test arrangements:

Figure 35: Creep testing of beam specimens

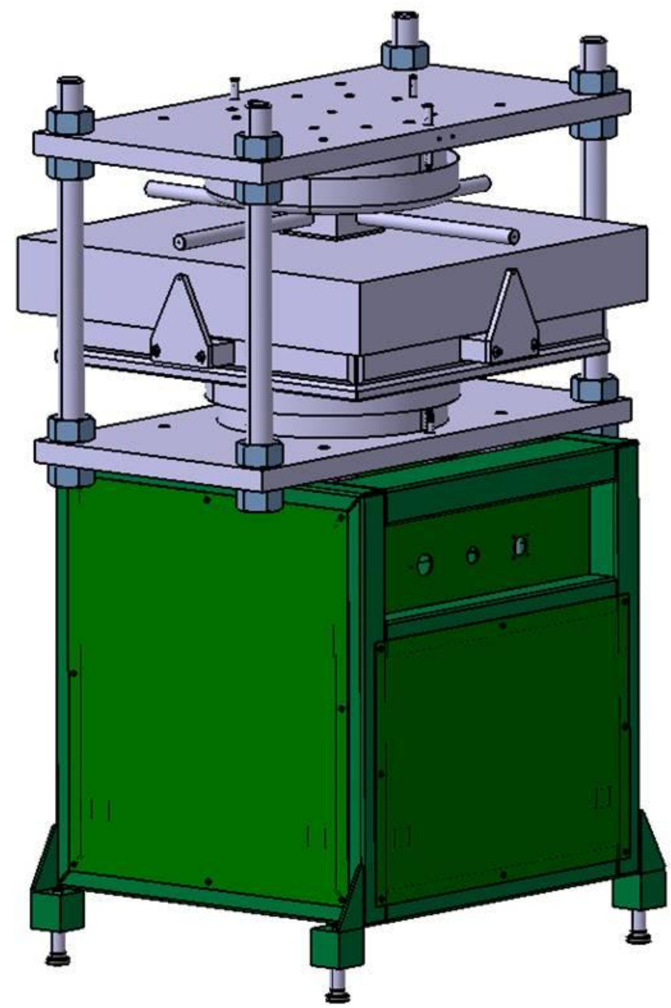


Figure 36: Creep testing of plates

Creep test results after approximately 400 days test duration are now available. The authors are of the opinion that creep of their fibre at the fibre-concrete interface has been significantly reduced compared to traditional polyolefin fibres. Figures 37 to 39 below show the average creep of beam and plate specimens, respectively.

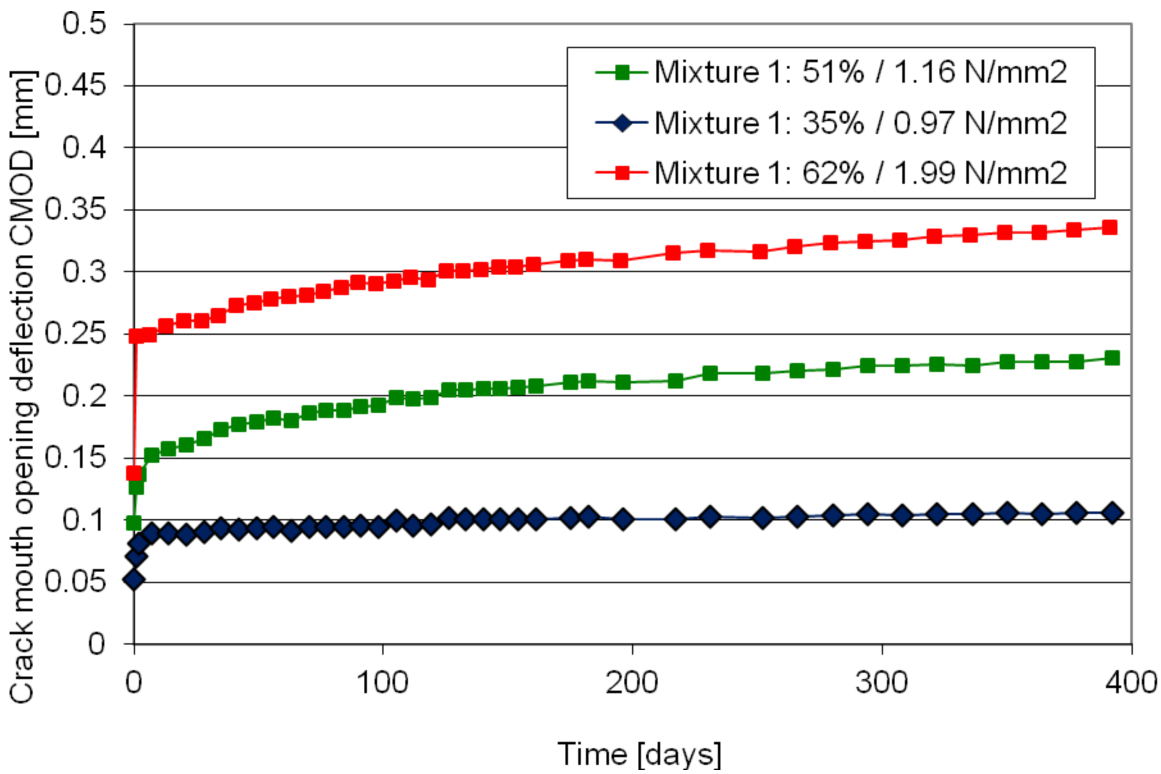


Figure 37: Crack mouth opening vs. time, beam test, 1 % by volume fibre content. Load level expressed as % of load at 0.5 mm deflection. Note that 1 mm = 0.039 in, 1 N/mm^2 = 1 MPa = 145 psi.

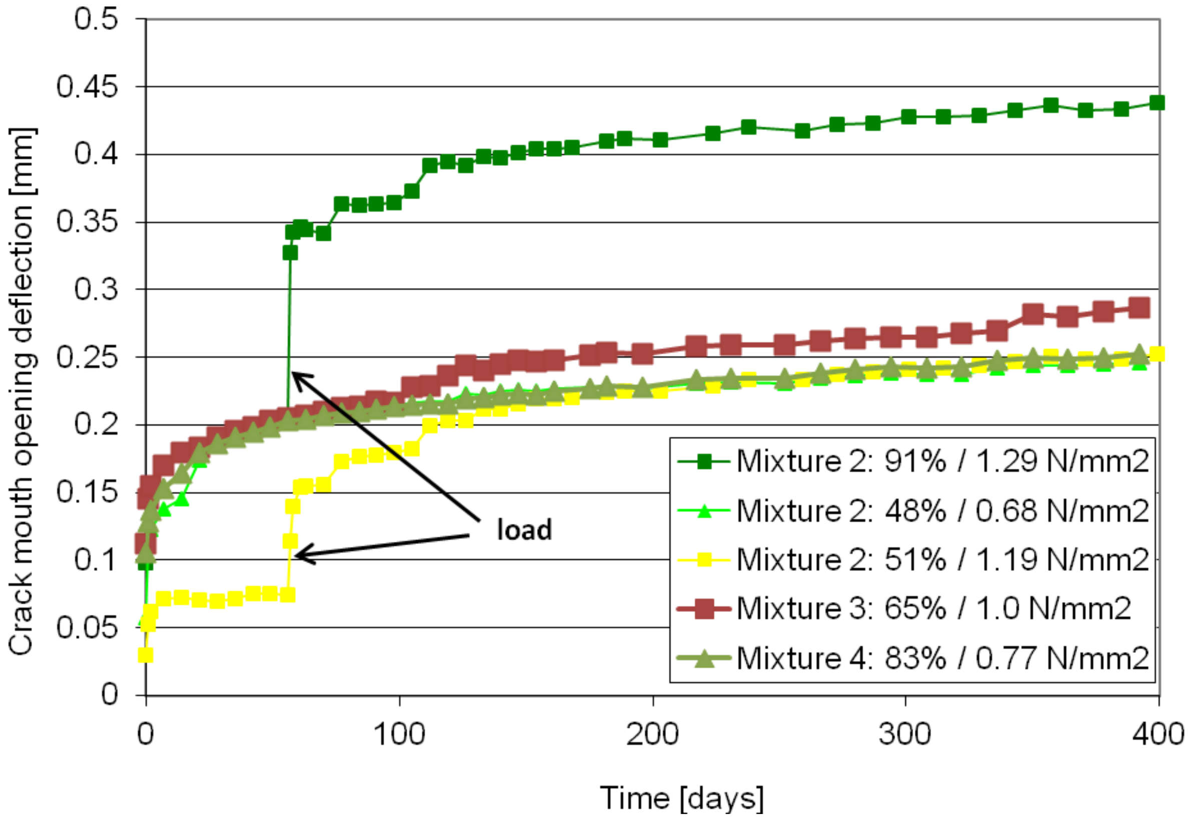


Figure 38: Crack mouth opening vs. time, beam tests, 0.5 % by vol. fibre content. Note that 1 mm = 0.039 in, 1 N/mm^2 = 1 MPa = 145 psi.

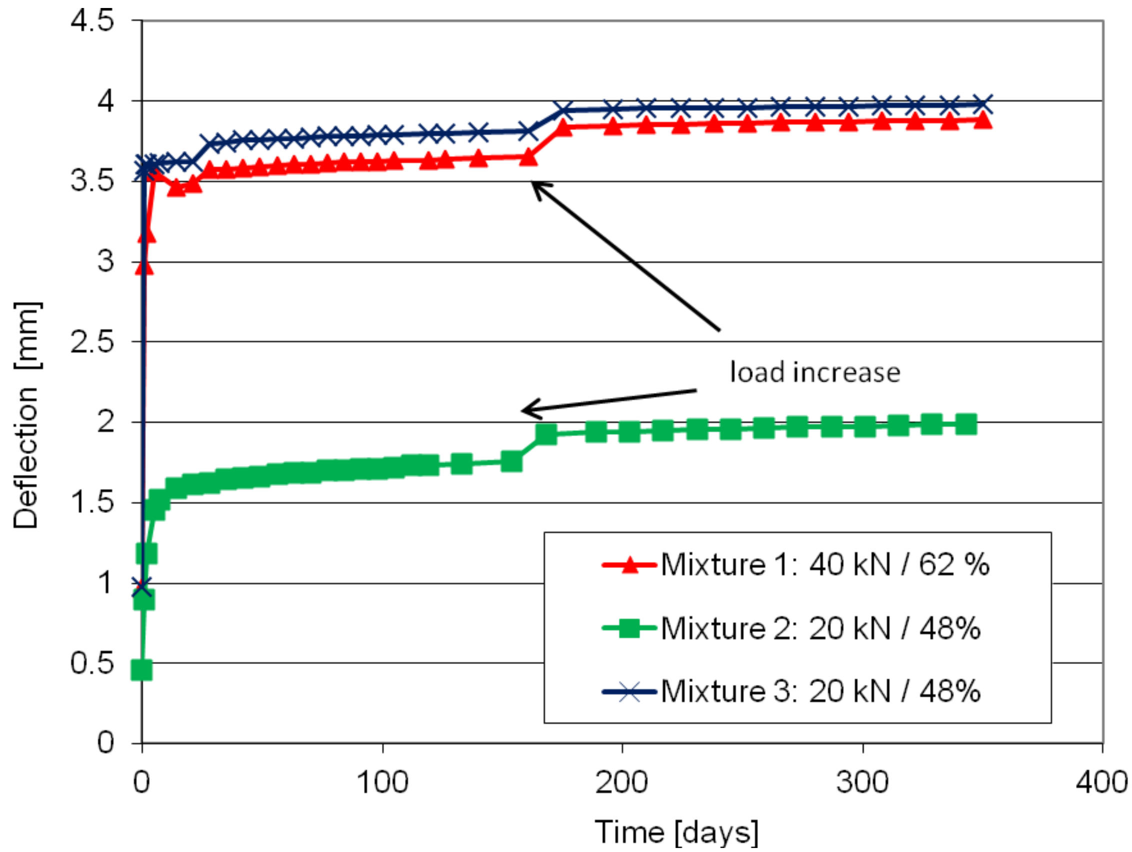


Figure 39: Cracked plate centre point deflection vs. time. Note that 1 mm = 0.039 in, 1 kN = 225 lbsf.

The authors conclude that, depending on mix and fibre addition rate, bi-component fibre reinforced concrete and shotcrete may be able to permanently sustain as much as 60% of the load after first-crack. In a later discussion with the audience the argument was raised that creep may be desirable in overloaded locations of a tunnel liner. As creep runs its course, stresses will reduce in the cracked location, and be distributed to other un-cracked locations of the liner. However, this in turn may result in unacceptable deformations.

Benoit De Rivaz (Baekert, Zwevegem, Belgium) reported on testing of fibre shotcrete to determine design properties. His presentation was in English. It can be found in the conference proceedings. Therefore only a brief summary is provided here. Ductility test methods for fibre reinforced shotcrete are given in European Standard EN 14487-1. This standard refers to 14488-5 for plate tests (also known as EFNARC-test) and 14488-3 for beam tests. The author discusses specimen preparation, curing and the testing regime, before proposing a modified plate test which exposes a notched plate to three-point bending. Figure 40 shows the test set-up:

Figure 40: Proposed three-point bending test on notched plate

The advantages of the proposed test method lie in their simplicity and good repeatability, as substantially more fibres span the cracked cross-section compared to traditional beam tests. However, sample preparation requires great accuracy. A deflection-control test machine, either running at constant centre point displacement or constant crack mouth opening displacement, with a total compliance of a minimum 200 kN/mm (including load cell and specimen support) is recommended. (Note that 200 kN/mm ~$1.1*10^6$ lbsf/in.)

Norbert Reichard (ÖSTU-STETTIN GmbH, Leoben, Austria) reported on a non-magnetic shotcrete tunnel liner for the "Conrad-Observatorium", a geophysical research station in Austria. Researchers studying geomagnetism needed to place equipment underground in a network of tunnels. The total length of tunnels and shafts was 1050 m (3400 ft). The tunnels and shafts were constructed using the New Austrian Tunnelling Method (drill-and-blast, shotcrete liner). In order to avoid interference with geomagnetic experiments, only no metallic materials were allowed for the construction. This required:

- Use of white cement (reduced ferrous content) for shotcrete and anchor grout
- Use of polymer fibres in shotcrete
- Use of glass-fibre reinforced composite (GFRP) reinforced reinforcing mats
- Use of GFRP rock anchors.

The shotcrete contained 380 kg/m^3 (630 lbs/yd^3) white cement, 7.5 to 8% powdered accelerator by mass of cement, and 7 kg/m^3 (12 lbs/yd^3) polyolefin fibres. The material was applied using the dry-mix process. Due to the resulting high fibre loss, the initially required toughness of 700 J (518 ftlbs) (EN 14488-5) could not be achieved.

In water leaking fault zones, the structural shotcrete liner received a polyurea waterproofing membrane. A final, 50 mm (2 in) thick, layer of dry-mix shotcrete with 1 kg/m^3 (1.6 lbs/yd^3) polypropylene microfibers provided fire protection for the waterproofing membrane. The white cement content of this finish coat shotcrete was only 350 kg/m^3 (580 lbs/yd^3). The following Figure 41 shows the dry-mix application of the mixture containing white cement. Note the high reflectance of the shotcrete surface.

Figure 41: Underground application of dry-mix shotcrete containing white cement

Stefan Krispel (Research Institute of the Austrian Cement Industry, Vienna, Austria) gave a presentation on construction and grinding of shotcrete with white cement. Austrian roadway tunnel surfaces with cast inner liners require an extensive treatment with epoxy levelling layers [up to 2 mm (0.08 in) thick], followed by an epoxy coating [200 μm (0.008 in) thick], in order to provide adequately reflective surfaces. Contamination from exhaust and dust demands frequent cleaning. Installing surface-ground white cement mortar tunnel liners may reduce construction and maintenance costs. Krispel researched a mortar mix with 2 mm (0.08 in) maximum aggregate diameter, and white cement as binder.

The initial phase of the research included an extensive testing of aggregates and mortar mixes for workability and light reflectance. He then tested the best performing mortars for various properties, like chloride diffusion resistance, freeze-thaw resistance, pressurised water ingress and compressive strength. Test panels were deliberately contaminated with soot-oil-water mixtures, and then aggressively cleaned with a water pressure washer [10 MPa (1500 psi) water pressure] and manual scrubbing with a brush. The change in light reflectance was determined after each of 3 contamination-cleaning cycles.

A subsequent larger-scale test included the installation of different mortar samples onto the surface of a test tunnel. After applying and curing the mortar, its surface was ground to remove paste and expose aggregates so that its appearance even after repeat maintenance episodes (pressure washing, and grinding if necessary) will not substantially change. Compared to epoxy coatings, the white cement mortar liners promise greatly increased durability and better resistance to aggressive maintenance measures. The following Figures 42 and 43 show the test tunnel and the grinding equipment, respectively.

Figure 42: Test tunnel

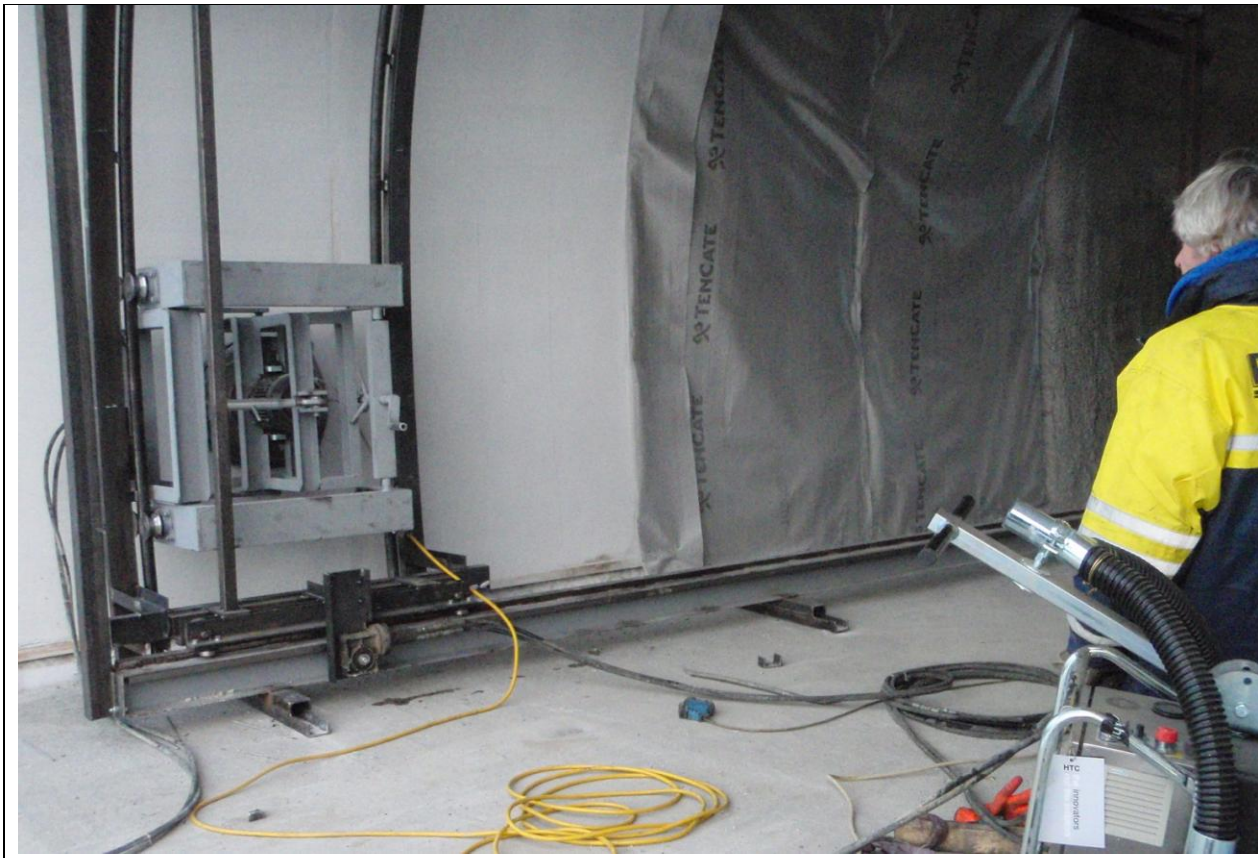


Figure 43: Equipment for surface grinding of tunnel wall

Philipp Holzer (Consulting engineer, Vienna, Austria; co-authors Helmut Schada, Turgay Öztürk) gave a presentation on the durability, protection, and shotcrete repair of steel reinforced concrete infrastructure. As steel reinforced concrete structures are exposed to aggressive environments, particularly to chlorides, they deteriorate at a significant rate. Holzer emphasised that concrete near surfaces (approximately the top 30 mm) tends to have a higher permeability than at greater depth. Near-surface reinforcement is therefore particularly susceptible to deterioration, even if the concrete on average is of low permeability. Many infrastructure objects may not achieve an expected service life of 100 years due to rapid deterioration, and strong measures of intervention may be required in such cases.

The Austrian Guideline *OEVBB-Richtlinie Erhaltung und Instandsetzung von Bauten aus Beton und Stahlbeton 2010* (Maintenance and repair of reinforced concrete structures) provides the following guidelines for monitoring and repairing chloride-affected structures:

Chloride-contaminated reinforced concrete				
Chloride content, % by Mass of Cement	**Corrosion**	**Urgent repair required**	**Mandatory inspection**	**Recommendations**
>0.6	No	No	-	Prevent ingress of chloride laden solutions
>0.6	Yes	Yes	-	Repair immediately
0.6 – 1.0	No	No	Every 1 to 3 years	Frequent inspections, schedule repairs as required
0.6 – 1.0	Yes	Yes	-	Repair immediately
>1.0	No	No	Annually	Frequent inspections, schedule repairs as required
>1.0	Yes	Yes	-	Repair immediately if corrosion is detected

Figure 44: Example of Austrian inspection and repair guidelines for chloride contaminated concrete

Where repairs are required, the use of polymer modified mortars may be advantageous. Typically, polymer contents of minimum 5% impart substantial benefits on repair mortars. The following characteristics of polymer mortars should be considered when selecting suitable repair materials for concrete infrastructure:

- Relatively high tensile bond strength on substrate concrete
- Relatively low compressive strength if modified with thermoplastic polymers
- Relatively high tensile and flexural strengths, and toughness
- Relatively low modulus of elasticity
- Reduced capillary water flow
- Reduced or retarded shrinkage
- Increased creep
- Thermal expansion coefficient may differ from substrate concrete.

The German ZTV-W (2008), Specifications for Protection and Repair of Concrete for Hydraulic Structures, recommends the following tensile bond strengths for repair materials on mature substrate concrete:

Substrate Concrete Class	Substrate Concrete Compressive Strength, MPa	Minimum Average Tensile Bond Strength of Repair Material, MPa	Minimum Individual Tensile Bond Strength of Repair Material, MPa
A1	<10	Not specified	Not specified
A2	>10	0.8	0.5
A3	>20	1.2	0.8
A4	>30	1.5	1.0

Figure 46: Example of German specification (ZTV-W) for bond strengths of repair materials

Where a protection of substrate concrete or shotcrete is essential, Holzer recommends a treatment with a hydrophobing agent for additional durability. Depending on the protection level required (Level 1 – least, Level 3 – highest), the following materials should be considered:

- Level 1: silicon – micro emulsion concentrate, solvent-based systems, <20% solids
- Level 2: single application of high viscosity watery emulsion, or multiple applications of low-viscosity silanes, 100% solids
- Level 3: high viscosity (gel) silanes.

In particular Level 3 treatments can penetrate approximately 10 mm into the concrete, effectively protecting the substrate concrete from chloride ingress for one to two decades. Thus two treatments, spaced at 15 years, may provide an additional 3 decades of service life to an at-risk structure. Holzer argues that preventative treatment of un-damaged as well as freshly repaired structures with a hydrophobic agent will be highly cost-effective and will reduce the environmental footprint, due to the significantly increased life expectancy of the treated structure. Figure 45 below shows the effect of silane treatments on chloride ingress into concrete (Gerdes, 2002).

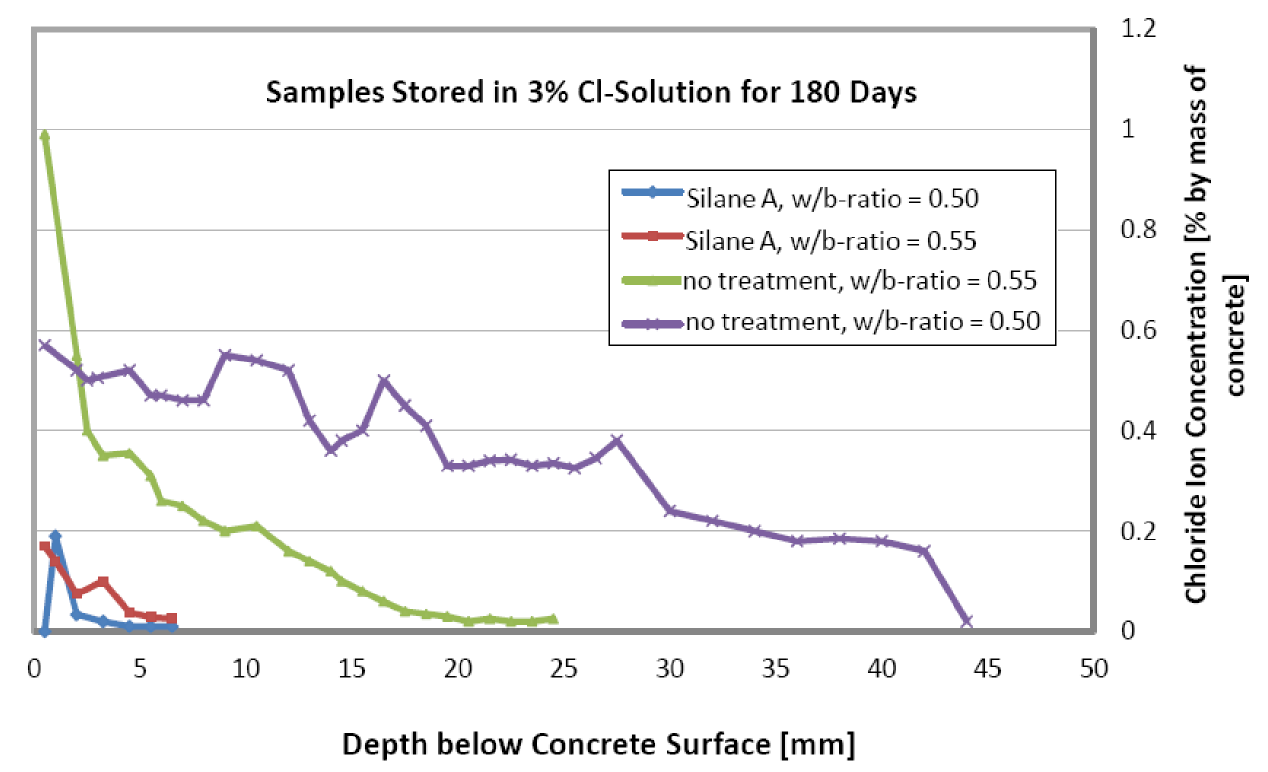


Figure 45: Chloride ingress into treated and non-treated concrete (Results from Gerdes, 2002)

Josef Tritthart (Graz University, Austria, co-authors Dietmar Klammer, Florian Mittermeyr, Andrea Brunnsteiner) talked about thaumasite degradation of concrete. The authors observed sulphate attack on concrete tunnel liners in locations where the ground water contained no more than approximately 500 mg/L SO_4^{2-}. Typically, this concentration is considered to be fairly non-aggressive. However, the following aggravating factors were discovered:

- Ground water, after penetrating into the concrete, evaporated and deposited sulphates well beyond the saturation threshold in the concrete's pore water
- Calcium ions from the $Ca(OH)_2$ dissolved in the pore water were consumed by chemical reactions (ettringite and thaumasite formation, or formation of $CaCO_3$ with carbonic acid). Other easily soluble alkali ions then were able to occupy positions in the pore water which the calcium ions had vacated
- The concrete supplied new alkalis (Na^+, K^+) to the pore water.

Expansive ettringite ($3CaO{*}Al_2O_3{*}3CaSO_4{*}32H_2O$) formation in concrete is quite common in the presence of excessive sulphate (SO_4^{2-}) concentrations. However, less frequently occurring and therefore not as widely known is thaumasite formation. Necessary conditions for thaumasite formation are the presence of sulphates as well as carbonates (in carbonatious aggregates like dolomite and calcite, CO_2-loaded ground water etc.), and temperatures below 15°C (59°F). Thaumasite formation weakens the concrete, ultimately to the point of disintegration, and is thus of concern.

The OEVBB (Austrian Concrete Association) is currently conducting a long-term study on various mortar samples stored in sulphate solutions at temperatures between 5° and 20°C (41 – 68°F). Interim results (after 1.5 years) show that mortar probes containing limestone aggregates and exposed to solutions with 3000 mg/L SO_4^{2-} have been visibly damaged by thaumasite, while samples stored in solutions with no more than 600 mg/L SO_4^{2-} content have not yet been damaged. Of note was that storing samples in solutions with 6000 mg/L SO_4^{2-} at 20°C (68°F) also induced surface damage due to thaumasite formation (in addition to ettringite formation). Apparently some thaumasite formation can take place at temperatures above 15°C (59°F).

An investigation of Austrian tunnels discovered several instances of severe thaumasite damage to shotcrete liners. Figure 47 shows a shotcrete which, although intact on the surface, was nonetheless destroyed by thaumasite forming from the direction of the underlying rock.

Figure 47: Thaumasite destroying shotcrete tunnel liner

Core samples from damaged and undamaged shotcrete from affected sites were evaluated. They were sliced into 10 mm (0.39 in) thick increments in order to detect the profile of chemical changes in the shotcrete. The slices were analysed for alkali, silica and sulphate content, as well as for numerous other marker ions. In addition, pore water was pressed from the specimens in order to determine the balance between lighter and heavier isotopes of hydrogen and oxygen. As water made of the lighter isotopes evaporates more readily than water with heavy isotopes, such pore water will concentrate up in concrete affected by evaporation. The analysis proved that ground water did indeed migrate through the shotcrete, depositing sulphates in the pores and leaching sodium to the surface. Mirabilite ($Na_2SO_4{*}10H_2O$) deposits (see Figure 48) on the shotcrete surfaces were additional markers of evaporation driving a transport mechanism for sodium and sulphates through the shotcrete.

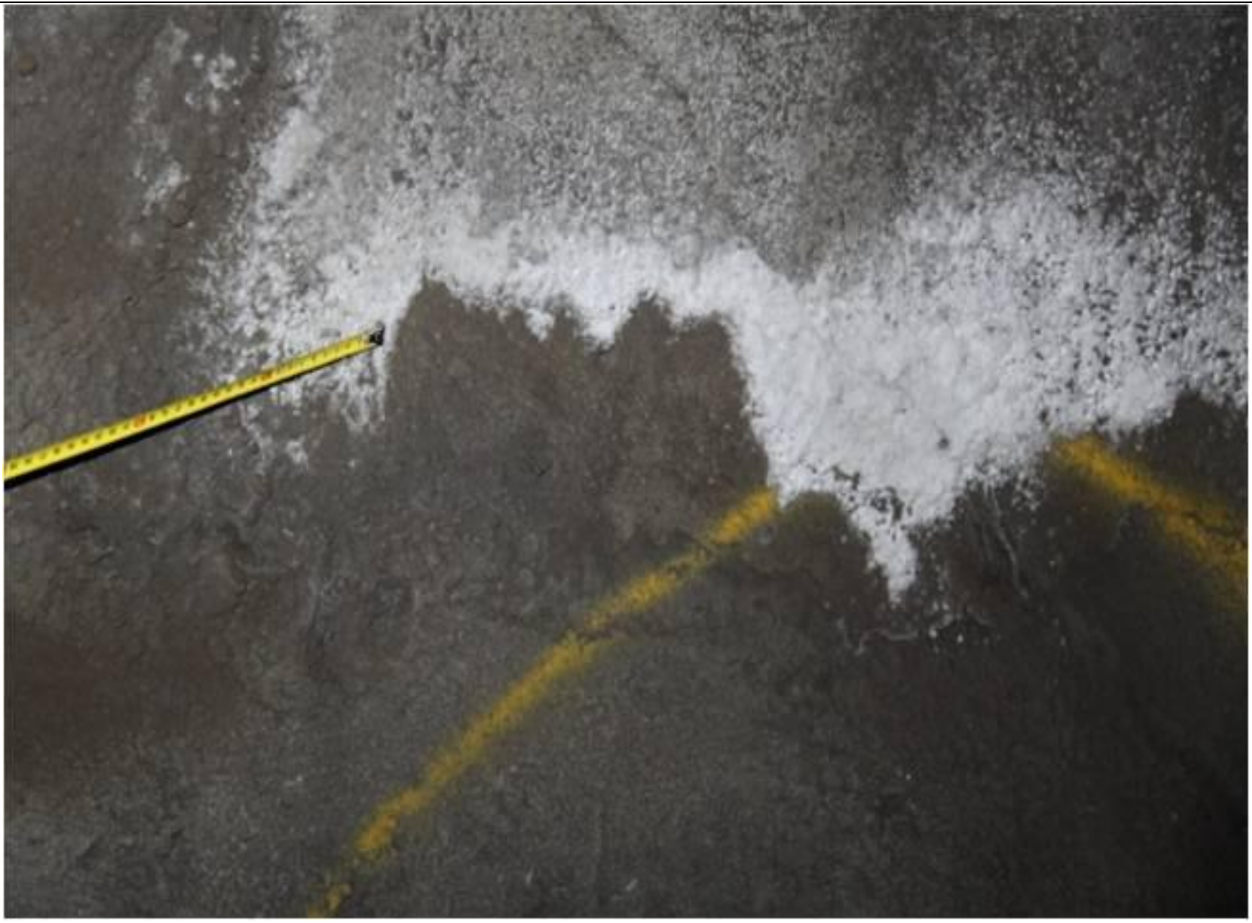


Figure 48: Mirabilite deposit on a shotcrete surface; typical marker of evaporation

Because the deposition of sulphate ions was highest towards the rock side of the shotcrete, thaumasite attack progressed faster at that depth, while the shotcrete surface remained in visibly good condition. This occurred mainly outside of the main tunnel in a location where a thin and porous shotcrete layer had been applied to stabilise the rock surface. There water was able to migrate through the porous shotcrete and evaporate. Conversely, where substantial evaporation was not possible due to a much thicker and denser shotcrete liner installed in the main tunnel, no severe thaumasite deterioration was detected. However, at specific locations of the main tunnel liner, where water could penetrate and evaporate more freely, e. g. at joints, thaumasite-damage did occur and severely attacked the shotcrete, starting at the interface with the rock and progressing towards the shotcrete surface.

Walter Pichler (Materialconsult, Hart im Zillertal, Austria, co-authors Andreas Saxer, Wolfgang Kusterle) gave a presentation on calcium carbonate precipitation in tunnel drainage systems, which can result in very costly maintenance efforts to re-open partially or fully blocked drainage systems. Several mechanisms can be involved, for instance:

- Ground water with a high carbonic acid content (H_2CO_3) dissolves calcium carbonate present in the ground and transforms it into bicarbonate ($Ca(HCO_3)_2$). As such water enters the drainage system, its temperature and pressure as well as the partial pressure of the CO_2 may change, which can result in a precipitation of calcium carbonate ($CaCO_3$).

- Ground water which is in equilibrium or of high hardness may change its pH value when contacting hardened shotcrete or concrete. This may result in a precipitation of calcium carbonate.
- Ground water may dissolve $Ca(OH)_2$ from the shotcrete and concrete. The uptake of CO_2 from the air may then lead to calcium carbonate precipitation.

The following Figure 49 summarises important precipitation issues:

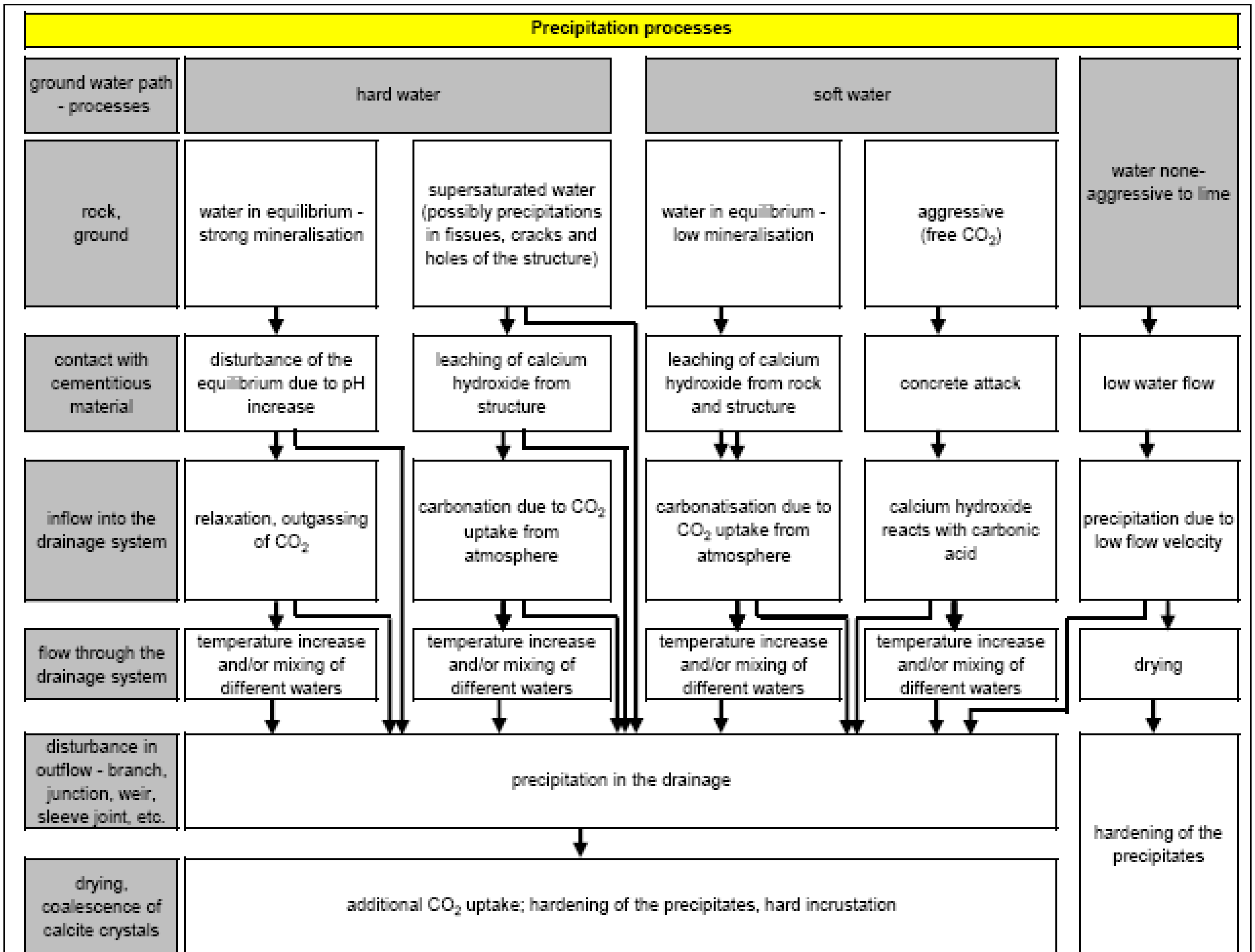


Figure 49: Schematics of calcite precipitation processes resulting in blockages of tunnel drainage systems [Austrian guideline *Tunnelentwaesserung* (tunnel drainage systems)]

In order to reduce calcite precipitation created by the ground water leaching calcium hydroxide from the concrete or shotcrete matrix, the construction material can be optimised. The use of low cement contents [minimum 280 kg/m^3 (460 lbs/yd^3)] to maintain early-age strength requirements in combination with supplementary cementitious material may be beneficial. The materials designer should aim to reduce the free $Ca(OH)_2$ content in the hardened matrix.

The Austrian Guideline for tunnel drainage and for shotcrete now both contain clauses specifying precipitation limits. The limits are defined as the RV value. The authors developed a test method to estimate the precipitation potential of concrete and shotcrete mixtures. The test includes preparation of specimens, storage under defined conditions, and measuring the rate of leaching calcium (Ca^{2+}). Interim results from a long-term test program by the authors demonstrated that the use of pozzolans, in particular of metakaolin, may have substantial benefits in reducing leaching and precipitation potentials. Note that at this time, no results for silica fume modified shotcretes are available yet. Figure 50 below shows the reduction in precipitation potential as a function of replacement level of cement with various pozzolans.

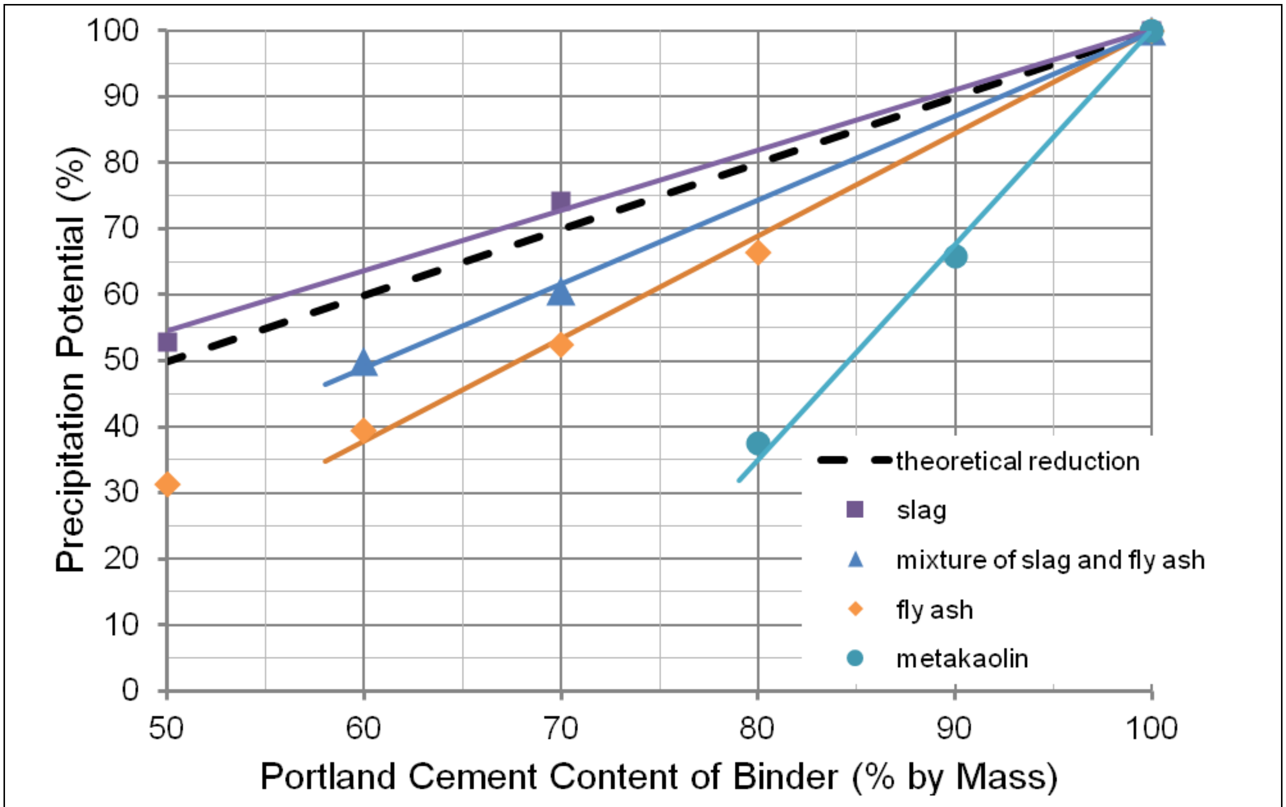


Figure 50: Precipitation Potential vs. Portland Cement Content of Binder

Based on their test results, the authors give guidelines for the estimation of the precipitation potential and the possible scatter in test results. The actual precipitation at any given location is subject to many boundary conditions (quality, temperature, pressure of the ground water; rock types; geometry of the drainage system; ambient air temperature and quality), so that site specific condition evaluations are necessary to predict precipitation risks with reasonable accuracy.

Tom Melbye (Normet, Huenenberg, Switzerland; main author Janne Lehto, co-author Roland Harbron) presented the EFNARC Nozzleman Certification Program. The EFNARC program is specifically designed to certify experienced nozzlemen for underground application of wet sprayed concrete with robotic equipment or spray manipulators. The course is endorsed by ITA-CET with the objective to expand the certification process throughout the industry. Nozzleman examiners are trained and certified by EFNARC. They have to be experienced in tunnelling and shotcrete technology, and are required to take an EFNARC education program as well as an examination. The training program for the examiners requires approximately 2.5 days and includes:

- Explanation of the nozzleman certification program
- Seminar on the topics to be presented in the nozzleman training program (see further below)
- Practical testing of concrete and shotcrete
- Practical application of shotcrete using a robot in an actual tunnel (Hagerbach Test Gallery)
- Theoretical examination
- Observation and evaluation of nozzlemen who will deliberately incorporate deficiencies into their work
- Oral examination
- Acceptance of professional obligations as nozzleman certifier.

Their certification is valid for 3 years. They will travel to construction sites to certify nozzlemen on site.

Adequate education and skills are essential for a nozzleman to perform under challenging tunnelling conditions while producing a high-quality product. Melby showed in Figure 51 below two shotcrete core specimens. Both samples were produced on the same site with the same shotcrete mix and the same equipment, but by two different nozzlemen. The difference between the two final products is self-evident.

Figure 51: Effect of a Nozzleman's Skill on Shotcrete Quality. The samples were shot by different nozzlemen, but with the same shotcrete mix, the same robot and in similar locations of the same site.

The EFNARC certification program includes a nozzleman training school. The core topics of the training program are:

- Concrete technology
- Constituents of concrete
- Admixtures and supplementary cementitious materials
- Fibre concrete technology
- Shotcrete equipment
- Expectations of owners and specifiers
- Selection of equipment
- Starting and stopping shotcrete application
- Shotcrete curing.

The nozzleman examination includes the following:

- Theoretical examination on the contents of the training program
- Practical examination on:
  - Preparation for shooting
  - Shotcrete application
  - Trouble shooting
  - Safety, environmental aspects and health hazards.

Similar to the Examiner's certification, nozzleman certifications are valid for 3 years and require re-examination before renewal.

Marc Jolin (Laval University, Canada), Matthieu Thomassin and John Nehasil submitted a paper on the ACI / ASA nozzleman certification. As that document is published in the conference proceedings in English, and Shotcrete Magazine is generally keeping readers informed in detail on this subject, a summary is not provided here.

Ernst Fleischhacker and **Dietmar Thomaseth** (Wasser-Tirol, Austria) dissected shotcrete construction projects. They observed the components from research to development to planning and final application and found that a flawless project remains elusive. They observed that on one side enormous knowledge has been amassed by research and development, and that almost all designs, processes and materials are defined and constrained by extensive codes, but that on the other side such overload of sometimes conflicting requirements, codes and specifications will make fully compliant construction impossible. Furthermore, the flurry of rules, regulations and codes may tempt designers and applicators to abdicate from their personal responsibility to think through what they ought to create, and to provide a functional and economical product of good quality and durability. Problems are aggravated by the tendency that partners in the project do not generally communicate before problems arise, and afterwards focus their efforts on assigning blame rather than solving the problems. Fleischhacker and Thomaseth illustrate their philosophical considerations with hilarious examples from actual construction projects. This first author will refrain from spoiling Fleischhacker and Thomaseth's satires by an inadequate attempt of translation. He would rather like to challenge the memories of the readers to recall episodes of applied absurdity from their own professional lives. Maybe *Shotcrete Magazine* can be persuaded to allocate half a page each month to the most entertaining reader submission on the topic of "*How things went wrong*"?