Impressions from the Alpbach Shotcrete Conference 2015

By: Roland Heere, Wolfgang Kusterle

The 11th Shotcrete Conference took place in the Alpbach Conference Centre (Alpbach, Austria) from 29 to 30 January 2015. Organiser Professor Wolfgang Kusterle welcomed approximately 260 guests. Visitors value these, now traditional, shotcrete conferences in Alpbach for their interesting presentations, as well as for their relaxed ambience. This article provides a summary of the papers published originally in German. Some of the papers originally published in English are also summarised here, and at times extensively quoted. References provided in [brackets] refer to the references quoted in the original paper. For more details or copies of the conference proceedings (English abstracts, mostly German papers), please contact Shotcrete Magazine (www.shotcrete.org), Wolfgang Kusterle (spritzbeton@kusterle.net) or Roland Heere (rheere@metrotesting.ca).

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Jozef Jasiczak of Poznan University of Technology in Poland (with co-authors Wlodzimierz Majchrzak and Wlodzimierz Czajka, both Torkrete) gave the first presentation. His topic, the *Use of the Dry Mix Shotcrete Process for the Construction of Large Curved Walls at the Museum of the History of Polish Jews in Warsaw*, was covered in Wlodzimierz Czajka: The Museum of the History of Polish Jews, Shotcrete Magazine, Winter 2013. The reader may access the full paper here: http://shotcrete.org/ASA_E_Mag/2013.01_ShotcreteEMag/#/14/

Erich Erhard of Torkrete GmbH, Essen, Germany, followed with a presentation on *Surface Forming Method for Shotcrete Used in Structural Repair and Strengthening Works*. Shotcrete has been successfully used for more than a century and is well established and regulated in codes. The high impact energy facilitates good bond to substrates, and good compaction. However, gun finished surfaces may not be desirable in all cases. In order to obtain architecturally challenging shotcrete surfaces, a fine-grained mortar and pigmented coatings can be applied. Another method includes partial-depth embedment of a pre-fabricated polystyrene template into the still fresh shotcrete surface, followed by the application of a thin layer of pigmented shotcrete into the areas demarcated by the template. This finish coat can then be smoothened or sculptured manually. Before the shotcrete sets, the template is removed, leaving a patterned and colourful surface relief (Fig.1 to 4).

Figure 1-4: Steps to a shotcrete surface relief

The shotcrete materials are frequently supplied to the sites bone dry in bags or silos. It is typically applied using the dry-mix process. Shotcrete appears to tolerate additions of up to 1% iron oxides for pigmentation purposes (red, yellow, brown, black) without problems. Higher addition rates appear to increase stickiness (like silica fume), but also increase the modulus of elasticity. Chromium oxides and cobalt carbonate introduce pastel colours, but may cause instability of the shotcrete. Combinations of white cement and colourful aggregate (e.g. marble sand) result in remarkable colour effects, but often prohibit the use of fly ash or silica fume. The following images show shotcrete jackets created with the method described above. Note that, depending on structural requirements, such jackets can be as thin as 30 mm (1.2”), but may also exceed 200 mm (8”). Reinforcement may vary from minimal to double mats. The shotcrete is usually designed to withstand chloride attack and freeze-thaw exposure. The following images, Figures 5 to 10, illustrate materials samples and actual projects.

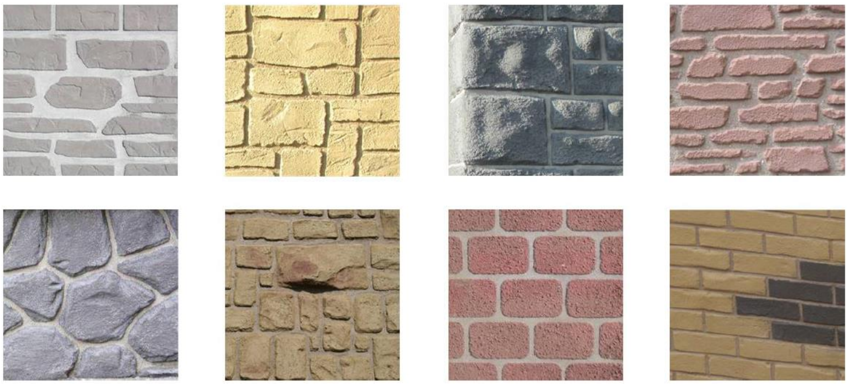


Figure 5: Surface Samples

Figure 6: Bridge Pier…

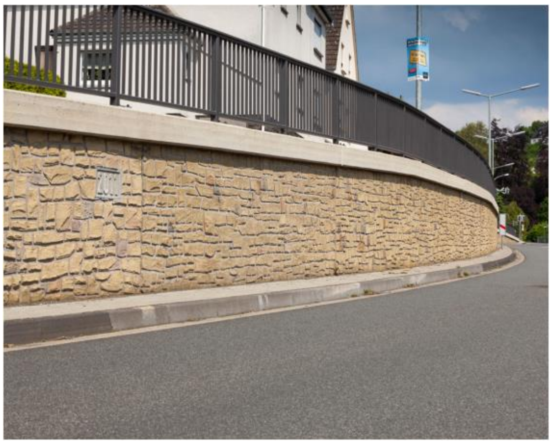


Figure 7: Retaining Wall

Figure 8: Bridge Abutment…

Figure 9: Retaining Wall 2

Figure 10: …Artwork

Dominik Khaur, and co-author Günter Vogl (Junger Baugesellschaft m.b.H., Austria) spoke about *The Application of White Gunite at the Agnesbergtunnel*. The Agnesberg tunnel is a twin tunnel for the Autobahn A7 between Ulm and Würzburg, Germany. Tunnel walls, completed in 1986, have suffered deterioration. Cracks, delamination and spalling started to pose hazards to tunnel users. Due to stricter current codes, extensive rehabilitation was required. This required shutting down one of two tunnels for extensive periods, with the remaining tunnel carrying traffic in both directions.

Originally, the tunnels were constructed as double shells, with the inner shell made of water impermeable concrete serving as the only waterproofing layer. It appears that insufficient mechanical de-coupling of the two shells resulted in excessive stresses, damaging the inner (waterproofing) shell. Leaking ground water contains lime which precipitates in the drainage system. In addition, contamination of the multiple cracks resulted in unappealing esthetics.

The initial plan for the repair included injection of leaking cracks with PU and injection of an acrylic gel into the annular space between inner and outer shell for water proofing. In addition, the tunnel walls were to be cosmetically repaired with a mortar and subsequent coating system. However, due to the large number of cracks, contaminated crack faces, the presence of partially successful previous injection repairs with, at times, undocumented materials, and insufficient gap between the two shells did not allow implementation of the repair work as planned. Instead, owner and contractor decided on the following procedure:

- Omit injection of the waterproofing material into the gap between the two shells
- Inject actively leaking cracks with PU
- Remove a chloride contaminated layer of the inner shell (to <45 mm (1.8") depth, equivalent to 30% of the thickness)
- Reinstate material removed using polymer modified shotcrete (SPCC)
- Apply a 20 mm (0.8") thick layer of white shotcrete to an elevation of 3.6 m (12 m) above ground.

This resulted in the following advantages:

- Better light reflection, possible reduction in illumination cost
- Due to the use of Portland cement based repair materials, moisture ingress did not need to be completely stopped
- Additional concrete cover to protect against chloride ingress from deicer salts
- Expectation of 25 to 30 years of service life before the next rehabilitation
- Favourable behaviour during tunnel fires.

Table 1a below shows the specified and actually achieved properties of the SPCC:

Property	**Specified Value**	**Tolerance**	**Test method**	**Test results**
Chloride Content	≤ 0.05%		EN 1015-17	< 0.05%
Compressive Strength		>80% manufacturer's statement	EN 12190	
1 d				18.5 MPa
3 d				38.1 MPa
7 d				42.9 MPa
28 d	≥ 45 MPa			49.0 MPa
Density			EN 12190	2230 kg/m^3
Modulus of elasticity, 28 d	≥ 20 GPa		EN 3412	22.4 GPa
Tensile bond strength, 28 d	≥ 2.0 MPa		EN 1542	3.2 MPa
Resistance to temperature cycling	Tensile bond strength after 50 cycles		EN 13687-1	2.5 MPa vs. 3.1 MPa reference value
Chloride ingress	Chloride content ≤ 0.6% by mass of cement at 8 to 10 mm depth		EN 13396	0.18% by mass of cement
Sorptivity (capillary water absorption)	≤ 0.5 kg*m^2*h$^{-0.5}$		EN 13057	0.15 kg*m^2*h$^{-0.5}$
Unrestrained shrinkage	≤1.2 mm/m at 90 d		EN 1015-17	1.03 mm/m

Table 1b below provides US conversions of the original table

Property	**Specified Value**	**Tolerance**	**Test method**	**Test results**
Chloride Content	≤ 0.05%		EN 1015-17	< 0.05%
Compressive Strength		>80% manufacturer's statement	EN 12190	
1 d				2680 psi
3 d				5520 psi
7 d				6220 psi
28 d	≥ 6500 psi			7100 psi
Density			EN 12190	3750 lbs/yd^3
Modulus of elasticity, 28 d	≥ 2900 ksi		EN 3412	3250 ksi
Tensile bond strength, 28 d	≥ 290 psi		EN 1542	460 psi
Resistance to temperature cycling	Tensile bond strength after 50 cycles		EN 13687-1	360 psi vs. 450 psi reference value
Chloride ingress	Chloride content ≤ 0.6% by mass of cement at 0.3 to 0.4" depth		EN 13396	0.18% by mass of cement
Sorptivity (capillary water absorption)	≤ 0.5 kg*m^2*h$^{-0.5}$		EN 13057	0.15 kg*m^2*h$^{-0.5}$
Unrestrained shrinkage	≤0.12% at 90 d		EN 1015-17	0.103%

The repair material was placed with piston pumps as well as with augers. Both types of equipment were suitable for the wet-mix process. However, piston pumps proved to be the more reliable. Daily productivity varied between 70 and 130 m^2 (800 and 1400 ft^2) of surface repaired. Final surface finishing included trowel finish and grinding. The following photos show grinding of the tunnel wall, and a tunnel portal

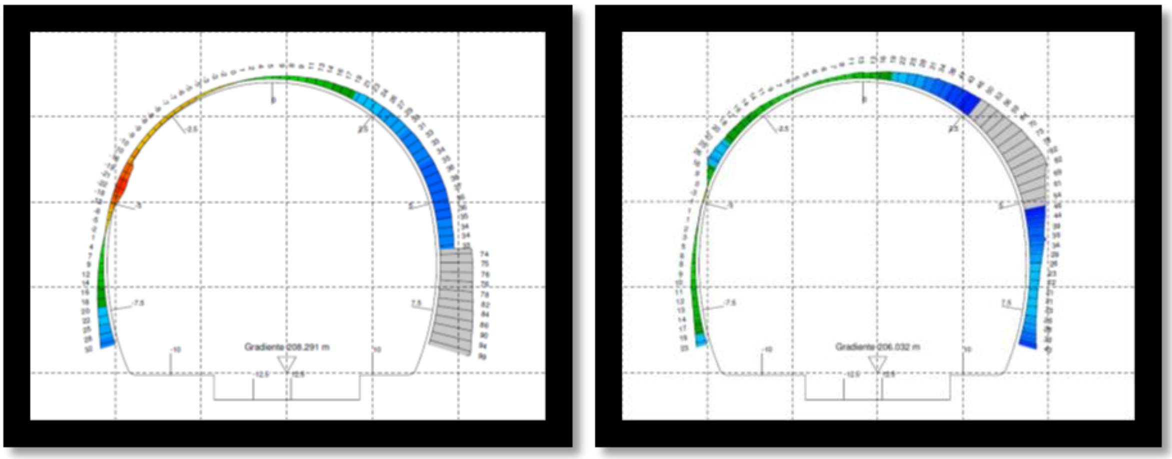
Figure 11: Surface Grinding

Figure 12: Tunnel Portal

Mario Frankenhauser (BeMo Tunnelling GmbH, Innsbruck, Austria) presented on the *Renewal of Old Tunnel Structures of the DB (*German Federal Railway*) by Example of the Bebenrohrtunnel near Witzenhausen*. This rail tunnel is situated in central Germany and was completed in 1875. The original, 935 m long tunnel was designed for double track operation. Due to aging, the tunnel required a thorough rehabilitation. The owner decided to re-dedicate the original tunnel to single-track operation, and build a parallel tunnel (1030 m long) for the second track. Both tunnels would be connected by a rescue tunnel. Both tunnel received concrete rail beds. The tunnel walls were designed as water impermeable concrete to allow the ground water table to recover to its 19th century level.

The work started with the drill-and blast construction of the new tunnel. The concrete tunnel liner received water stop profiles at the centre of its cross section in order to establish water impermeability. This was followed by placing a solid concrete rail bed (System Rheda 2000).

Meanwhile the owner provided a scan profile of the original tunnel, which showed areas which required widening (blue, green, grey) or infill (yellow, orange, red). The total volume of material removal and infill could be optimised by dropping the tunnel invert. Due to an asymmetric existing tunnel profile, a shift of the track axis to one side further reduced the volume of material to be removed or added.



Figures 13 and 14: Profile after surface scanning. Blue, green and grey signify shotcrete application required, yellow, orange and red signify requirement for material removal.

Infill concrete was applied by the wet-mix shotcrete process using a spray manipulator (Meyco Polenza). The shotcrete was batched on site, using local materials. The mix design was approximately:

Cement (CEM I 52.5 R	375 kg/m^3 (631 lbs/yd^3)
Limestone powder	25 kg/m^3 (42 lbs/yd^3)
Water	185 kg/m^3 (37 USGal/yd^3)
w/c-ratio	0.50
Sand 0-2 mm	730 kg/m^3 (1130 lbs/yd^3)
Aggregate 2-8 mm	869 kg/m^3 (1460 lbs/yd^3)
Max. aggregate size	8 mm (0.32”)
Superplasticizer	0.9% by mass of cement
Accelerator	~6% by mass of cement

The early-age compressive strength development followed Curve J2 of the diagram below.

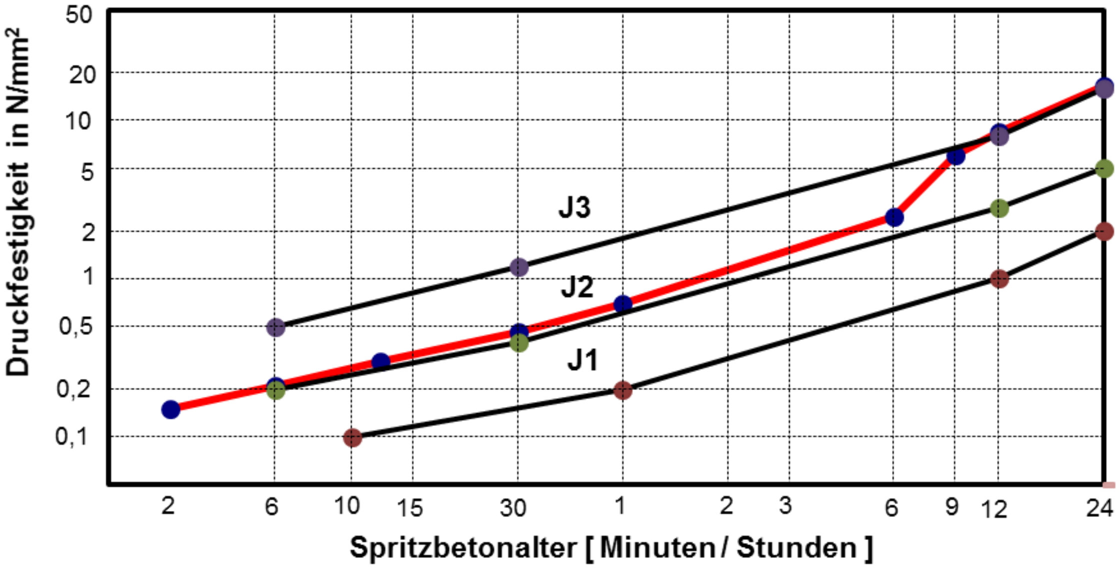


Figure 15: Early-age strength development chart, shotcrete age (minutes, hours on logarithmic scale), vs. compressive strength in N/mm2 = 1 MPa = 145 psi)

The plan stipulated that the substrate was to be cleaned with sandblasting. In addition, rock anchors were installed at a spacing of 2 m (6.5 ft) in both directions. Where shotcrete reached or exceeded 100 mm thickness, the contractor installed a Q188 rebar mat (6 mm (~1/4”) bar diameter at 150 mm (6”) spacing in both directions), attached to the rock anchors. For each additional 300 mm (1 ft) shotcrete thickness, one additional rebar mat was installed. As rock anchors were required in most areas, especially in the tunnel roof, sandblasting was omitted as the anchors provided sufficient bond between substrate and shotcrete liner.

Figure 16: Shotcrete installation using manipulator

A thin, initial layer was sprayed onto the entire substrate surface. Due to the low ambient temperatures during winter, set time issues caused problems with sagging while spraying deep layers. After the initial layer had sufficiently set, the contractor sprayed shotcrete ribs, coinciding with the rock anchors.

Figure 17: Spraying of shotcrete ribs

This was followed by encasing the anchors and spraying the infill to the final line and grade. A site laboratory continuously monitored the shotcrete quality, including the testing and verification of the concrete making materials, testing the fresh properties of the shotcrete, its strength development and conformance with the requirements for the applicable exposure classes. In order to maintain safe working conditions, portions of the tunnel were closed off until the shotcrete achieved sufficient strength for safe self support.

Sergej Rempel and coauthors Josef Hegger and Norbert Will (all RWTH Aachen, Germany), presented on *Textile-reinforced Protection Layers for Maintenance of Hydraulic Structures*. Numerous water reservoirs in Germany require significant maintenance. Concrete, often decades old, has suffered from mechanical attack, freeze-thaw cycling and leaching. A standard repair procedure includes the installation of a self-supporting reinforced concrete jacket. The disadvantage of such a jacket is its corrosion-susceptible steel reinforcement requiring deep concrete covers. As an alternative, the authors developed a textile-reinforced mortar jacket with greatly reduced thickness. The jacket is mainly exposed to forces resulting from its self-weight, temperature fluctuations and pore water pressures. Due to the low jacket thickness of only 40 to 45 mm (1.6 to 1.8”) traditional concrete anchors are unsuitable. The design, at this time, ignores freeze-thaw effects on the substrate concrete (which may result to cohesion failure inside water saturated substrate concrete). However, temperature differentials across the jacket of 10°C (50°F), self-weight, and pore water pressures of 50 kPa (7.25 psi) were considered.

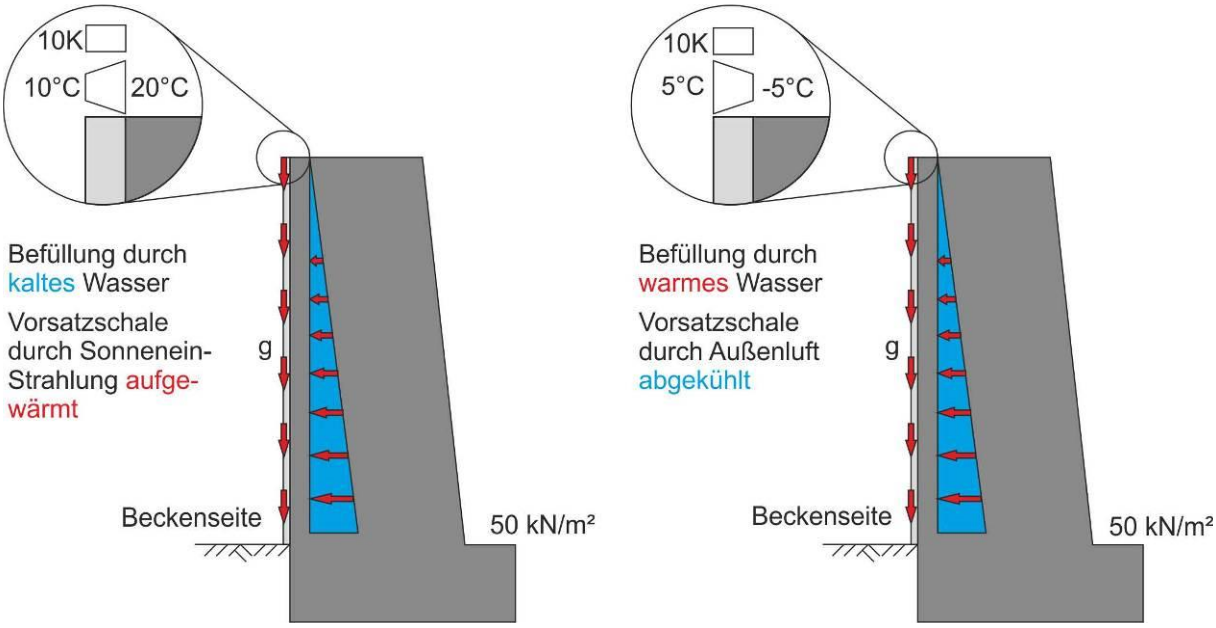


Figure 18: Hydrostatic pressure and thermal gradients (temperature differentials of 10K = 10°C = 18°F)

The forces may create tension in the anchors, and flexural stresses in the jacket. As the bending moments can be positive as well as negative, the reinforcement of the jacket must be able to counteract both.

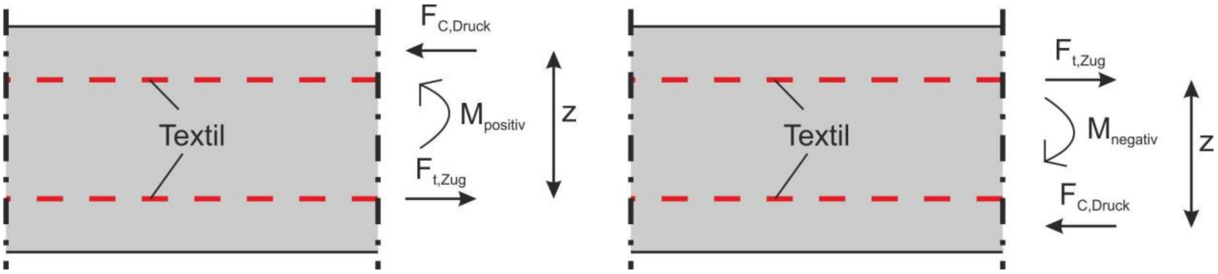


Figure 19: Possible loads and bending moments

Spray mortar is used as the bulk material of the jacket. It is reinforced with carbon fibre reinforced polymer (CFRP) mats which can be assembled in the shape of 3-D cages. Table 2 below presents typical properties of the CFRP:

Table 2a – FRP performance

	Example 1	**Example 2**
Fibre	Carbon	Carbon
Manufacturer	V. Fraas / Groz-Beckert	Solidian
Resin (Matrix)	Epoxy	Epoxy
Roving spacing, x/y-direction [mm]	21 / 23	21 / 21
Cross-section, mat, x/y-direction [mm^2/m]	44 / 40	90 / 90
Cross-section, individual roving, x/y–direction [mm^2]	0.92 / 0.92	1.89 / 1.89
Ultimate tensile stress, x/y–direction [MPa]	2400 / 3050	~ 3100 / 2900
Ultimate tensile elongation, x/y-direction [%]	2.37 / 1.15	1.91 / 0.94

Table 2b – FRP performance, US conversion

	Example 1	**Example 2**
Fibre	Carbon	Carbon
Manufacturer	V. Fraas / Groz-Beckert	Solidian
Resin (Matrix)	Epoxy	Epoxy
Roving spacing, x/y-direction [inches]	0.83 / 0.91	0.83 / 0.83
Cross-section, mat, x/y-direction [inch^2/yd]	0.057 / 0.063	0.13 / 0.13
Cross-section, individual roving, x/y–direction [mm^2]	0.0014 / 0.0014	0.0029
Ultimate tensile stress, x/y–direction [ksi]	350 / 440	~ 450 / 420
Ultimate tensile elongation, x/y-direction [%]	2.37 / 1.15	1.91 / 0.94

As an alternative to 3-D-mats, two layers of textiles, separated with spacers, can be used. The shotcrete was applied using the dry-mix method. Due to the small roving spacing, the aggregate size was restricted. Table 3 below presents important shotcrete properties.

Table 3a – Shotcrete properties

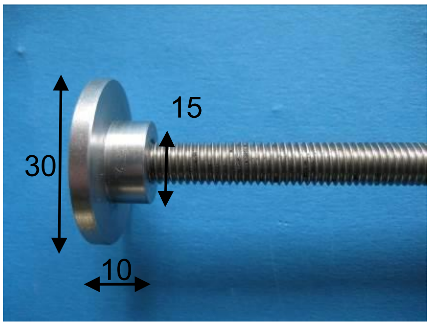
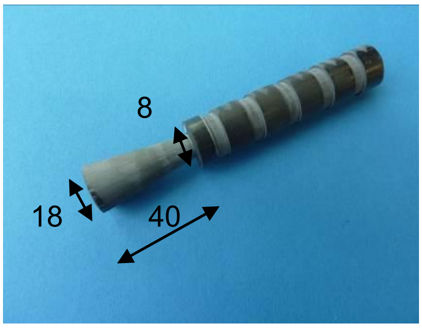
Property	**Mortar 1**
Mortar type	S-A2, polymer-modified
Maximum aggregate size	6 mm
Modulus of elasticity	21.5 GPa
Compressive strength	25 MPa
Flexural strength	5.1 MPa
Shrinkage	-410 * 10^{-6}
Tensile bond strength	1.2 MPa

Table 3b – Shotcrete properties, US conversion

Property	**Mortar 1**
Mortar type	S-A2, polymer-modified
Maximum aggregate size	~1/4”
Modulus of elasticity	3120 ksi
Compressive strength	3600 psi
Flexural strength	740 psi
Shrinkage	-410 * 10^{-6}
Tensile bond strength	170 psi

Adequate anchorage of the relatively thin CFRP reinforced shotcrete jacket could not be accomplished with traditional steel anchors. Two new systems were tested: stainless steel and carbon fibre, see Table 4 below

Table.4: Anchor systems

Property	Anchor 1	Anchor 2
		
Material	Stainless steel	CFRP
System	Bushing and threaded bar (M8)	Wedge
Diameter	30 / 15 mm (1.18 / 0.59“)	18 / 8 mm (0.71 / 0.31“)
Length	10 mm (~3/8“)	40 mm (1.57“)

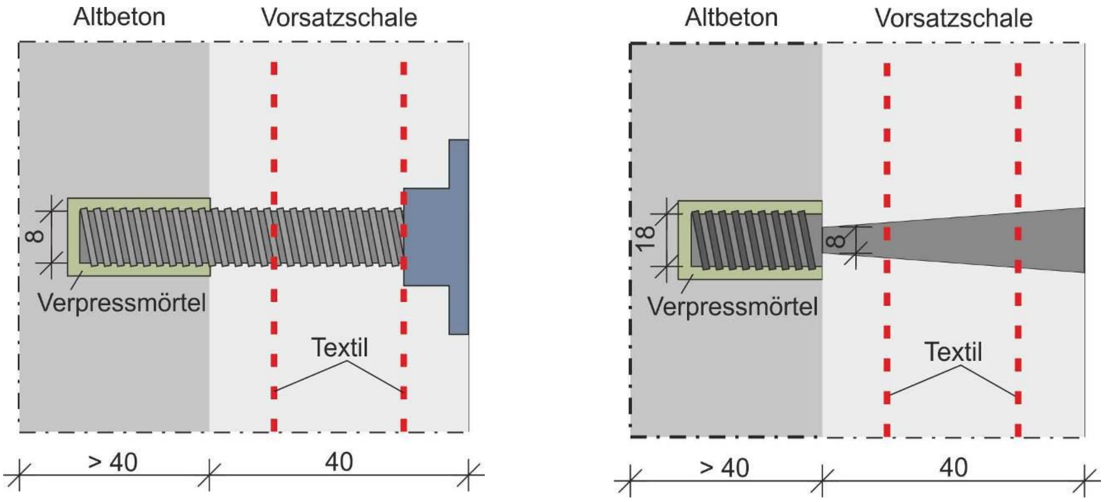


Figure 20: Sketch of both systems after installation (Dimensions in mm, 1 mm ~ 0.04")

Of particular note is the conical anchor base of the carbon system, which is milled to its final shape, and embedded in mortar.

Production of test specimens reinforced with separate textile mats required five steps:

1. Install 15 mm (0.6") layer of shotcrete
2. Install first layer of reinforcing mat
3. Apply 20 mm (0.8") of shotcrete
4. Install 2nd layer of reinforcing mat
5. Install 10 mm (0.4") of cover shotcrete.

This procedure allows for a good embedment of the reinforcement into the shotcrete. However, the reinforcing mats tend to suffer from misalignment. The following image shows a cross-section of a specimen.

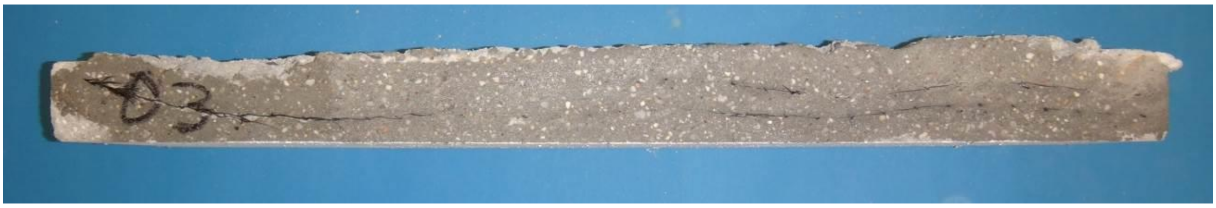


Figure 21: Cross-section of system with separate mats

If textile mats mounted on spacers, or 3-D mats are used, only a two-stage-construction procedure is required:

1. Mount reinforcing cage
2. Apply shotcrete to the full thickness of the element.

Following this procedure, the final position of the reinforcement can be controlled tightly. In addition, anchors can be installed after the reinforcing mat has been mounted on the substrate, avoiding position mismatches. However, the risk of introducing spray shadows increase with this method. However, such defects can be minimized by proper installation of the two mats.

Figure 22: Cross section of system with 3-D mat

Four-point bending tests on slab specimens demonstrated significant ductility of all specimens, for all methods of reinforcement.

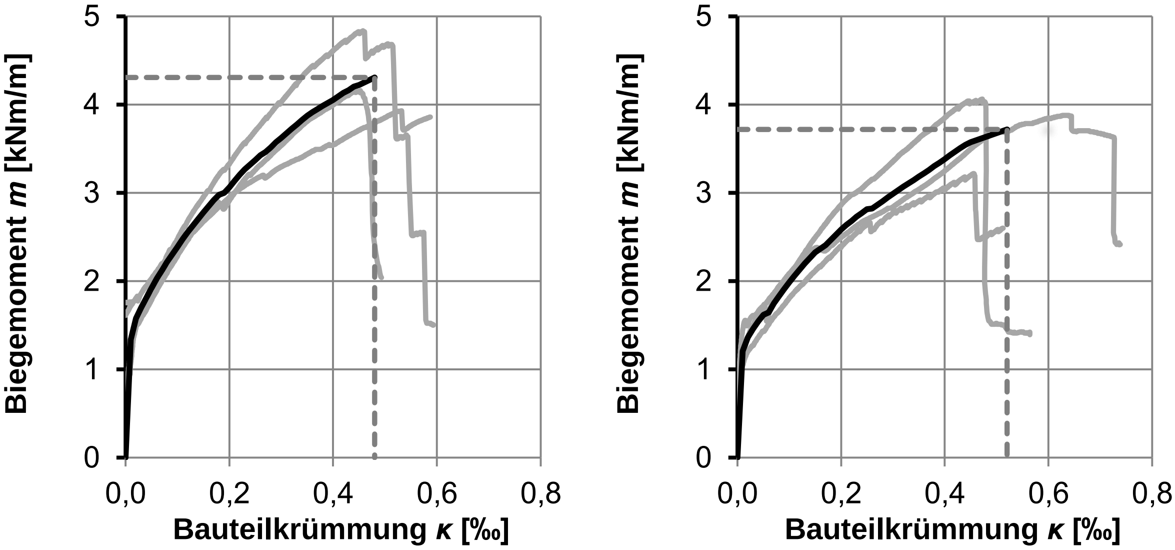


Figure 23: Moment-deflection diagram for 4-point bending tests; left: with spacers; right: without spacers (curvature in units of 0.1% vs. bending moment (kNm/m), note 1 kNm/m = 225 ftlbs/ft

The following image shows the failure mode of a specimen with a 3-D reinforcement mat.

Figure 24: 3-D reinforced specimen after bending test

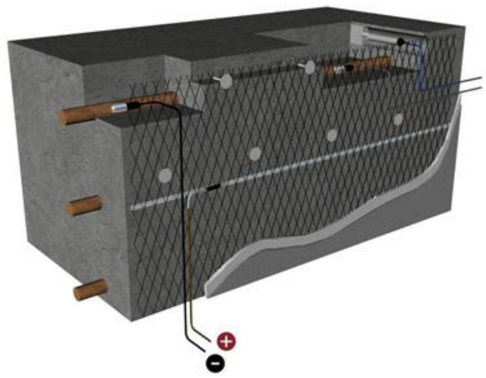
The steel anchors achieved on average 18.1 kN (4070 lbs) pull-out resistance, while the carbon anchors achieved on average 16.2 kN (3640 lbs). Failure in the un-restrained tests generally occurred by conical concrete shear fracture following the development of radial bending cracks. The results indicate that 5 anchors per m^2 would suffice to forces resulting from resist temperature gradients of 10°C (18°F) and a pore water pressure of 50 kPa. (7.25 psi)

Hernani Esteves, with co-authors Sebastian Mayer, Ronny Stöcklein and Rajko Adamovic, all Ed. Züblin AG, Stuttgart, Germany, presented on *Cathodic Protection and Fire Protection at the Rendsburg Road Tunnel*. Cathodic protection of reinforced concrete structures has been used for more than 3 decades. It has found increasing acceptance in Germany since approximately 15 years ago. The Rendsburg road tunnel, completed in 1961, required extensive rehabilitation due to chloride induced corrosion. The tunnel crosses the canal connecting the Baltic to the North Sea. It is a 640 m (2100 ft) long twin tunnel with two lanes per cross-section, Chlorides from seepage and road salts resulted in high corrosion potentials especially in lower sections of the tunnel walls. Chloride loads were as high as 0.2% by mass of concrete, indicating elevated corrosion risk. Exploratory excavations showed corroding rebar.

To protect the tunnel walls from rapid deterioration, concrete repair including a cathodic protection system (KKS-System) was required. The KKS-System was designed to induce approximately 20 mA/m^2 current. Due to variable exposure to chlorides with height, the walls were divided into two separate protection zones. The bottom zone reached from slab level (zero) to 1.3 m (~4 ft), while the top zone reached from 1.3 to 2.6 m (~4 to 8.5 ft) above roadway. The KKS-System was designed so that the operator can adjust the protective currents separately for the top and bottom zones. In total 24 protection areas were formed. Each of these areas covered 150 to 350 m^2 (1600 to 3200 ft^2), with a total of 6200 m^2 (67,000 ft^2).

Installation of the KKS system requires the following steps:

- Surface preparation with high-pressure water blasting
- Installation of oxide-coated titanium mesh anode attached to polymer inserts (see images below):



- Encasement of the mesh in 50 mm (2”) shotcrete. Temporary metal rails were installed to provide visual clues on the shotcrete thickness and to guide the cutting rods during finishing operation (see image below):

- Impression of a test current during shotcrete work to verify that no unintended grounding of the mesh takes place

The shotcrete needed to meet, amongst others, the following requirements:

- Electrical resistance 50 to 200% of substrate concrete at different ambient relative humidities (see image below):

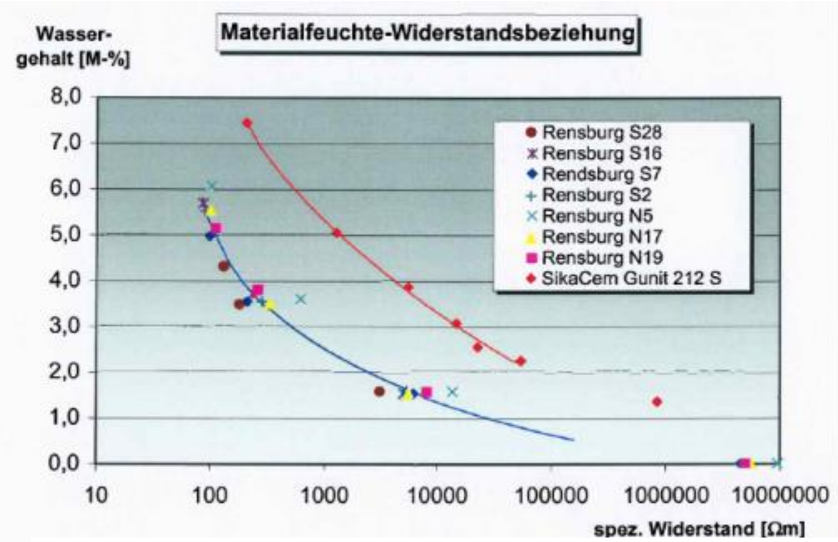


Figure 25: Resistivity vs. water content

- Fire resistance (ZTV-ING Table 5.1.4), see image below:

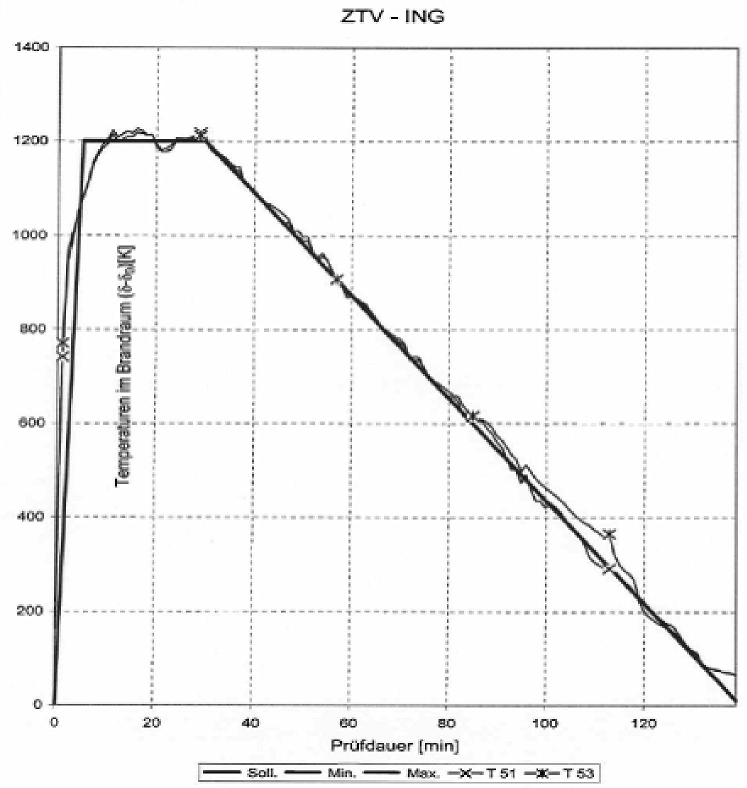


Figure 26: Test duration vs. Temperature in test chamber [°C]

- Dynamic modulus of elasticity: minimum 35 GPa (5100 ksi) at 28 days.

Test results demonstrated the following shotcrete properties (Sikacem Gunit 212):

- Tensile bond strength: Minimum 2.5 MPa (360 psi), Average 3.2 MPa (460 psi), Standard deviation 0.4 MPa (60 psi)

- Average density: 2122 kg/m^3 (3570 lbs/yd3)
- Average dynamic modulus of elasticity: 36 GPa (5200 ksi)
- Average flexural strength: 11.0 MPa (1600 psi)
- Average compressive strength 41.9 MPa (6080 psi).

Martin Fischer and co-author Matthias Hoffman, both BeMo Tunnelling GmbH, Innsbruck, Austria, presented on *Reinforced Shotcrete with Bar Diameters up to 32 mm (1.25”)*. The paper was submitted in English and can be obtained by contacting spritzbeton@kusterle.net. However, for reader interest, below are (at times paraphrased) excerpts from the paper.

The Crossrail project in London is currently the largest infrastructure project in Europe. It includes the construction of a 118 km (73 miles) long regional commuter railway line, which will link the surroundings to the west and east of the capital with Central London. Furthermore, it will improve the connections to Heathrow and Canary Wharf. The core piece of the project is the 2 x 21 km (2 x 13 miles) long tunnel route crossing Central London with 8 underground stations, 5 of which are built using the Sprayed Concrete Lining (SCL) Method.

Based on the safety requirement that no one should be below unsupported ground at any time, the construction stages for bar reinforced areas as e.g. at tunnel junctions at the station tunnels on Crossrail were the following:

- Construction of the primary lining of the parent tunnel with steel fibre reinforced concrete
- Construction of a primary lining thickening in required areas inside the already existing primary lining (e.g. around openings of child tunnel) to accommodate required bar reinforcement in a safe environment
- Breakout of child tunnel or other structures once the thickening gained its full strength

Due to the absolute priority of safety during all construction stages and related structural requirements (e.g. 120 years lifetime) it became necessary to install reinforced shotcrete with bar diameters up to 32 mm (1.25”). Planned quality control through coring of the structure in the very early construction stages identified shadowing in some areas which initiated a study to find the maximum possible bar sizes to be sprayed in for permanent works. Therefore, large scale trials with bar diameters bigger than 14 mm (0.55”) have been carried out prior installation and analysed systematically according to ACI 506.2-95 “Specification for Shotcrete” [1].

In order to investigate all possible influences and impacts of different bar diameters and bar arrangements large test fields have been set up around the tunnel circumference in one of the approximately 6 m (20 ft) diameter temporary pilot tunnels of the station platform tunnels (see also Figure 27).

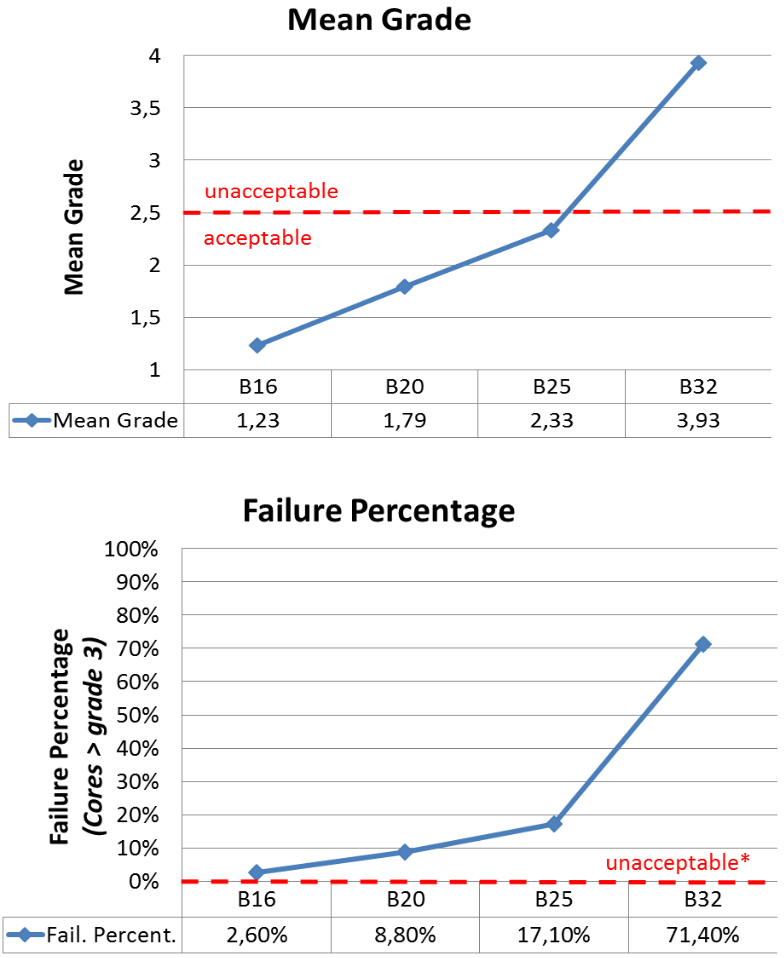
Figure 27: Overview on Trial Arrangements for one of the Test Fields

In order to best encapsulate large diameter rebar, a shotcrete mix with a very moderate strength gain development (around J1 curve according to Austrian Sprayed Concrete Guideline [2]) and a high remaining workability in the first seconds after application had to be developed.

For the trials a mix with 420 kg/m³ (710 lbs/yd^3) CEM I 52.5 N Castle / Ketton, 6% Microsilica and BASF SA160 accelerator (dosage between approx. 3 and 6%) has been applied through a Meyco Potenza robot. The accelerator product used was originally developed as one of the first alkali-free suspensions of accelerators which basically consists of aluminium sulphate and organic components for gluing effect. The general behaviour is a very slow reaction in the early phase (up to about 1h) and good strength gain thereafter. Based on the findings of the trials, BBMV's accelerator supplier BK Giulini developed the F2000CR accelerator, a product for shotcrete encasing reinforcement, with a behaviour similar to SA160 while setting. This new product contains an inorganic retarder, which is active in the first 10 -15 minutes with no effect on the further strength development.

About 400 cores have been taken from all test fields and each core has been reviewed and classified by a joint expert team according to the ACI 506.02-95 core grade definitions. The following trends on the impact of different reinforcement diameters and different reinforcement arrangements can be identified:

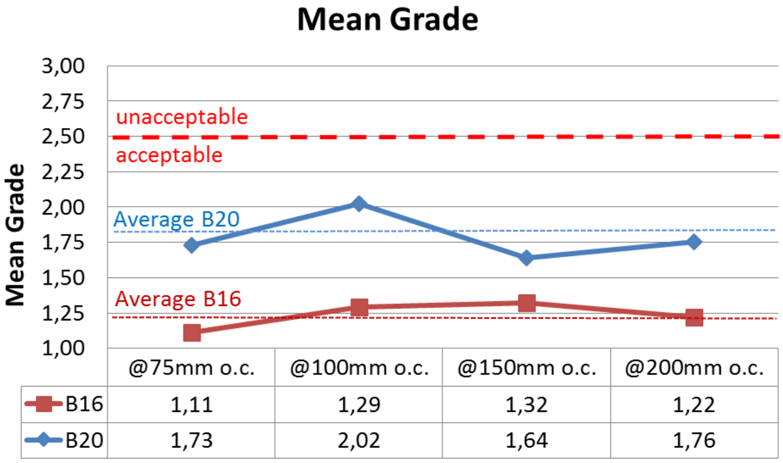
The results in Fig. 28 clearly show, that the rebar diameter provides a big impact on the quality of rebar encapsulation. When looking at the two indicators of mean value of core grading according to ACI 506.2-95 as well as the percentage of cores above core grade 3 (unacceptable according to ACI 506.2-95), a clear trend can be identified. These results include an average on all cores taken including lap splices, overhead spraying and varying rebar distances.

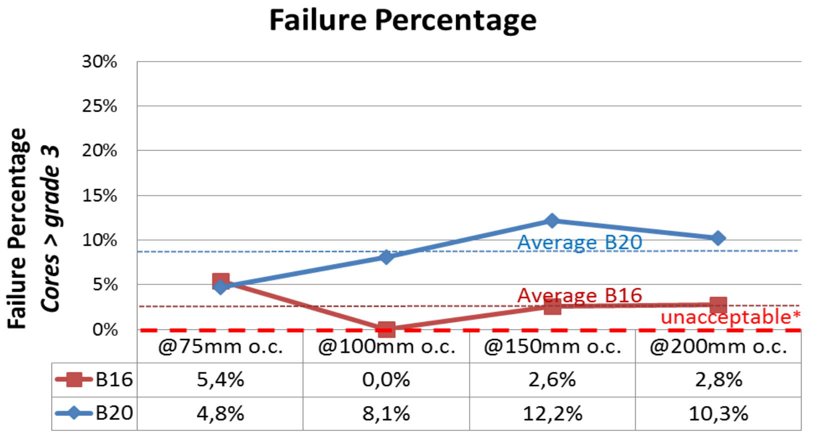


*according to ACI 506.2-95 cores with a grade >3 are unacceptable

Figure 28: Comparative Results on Key Core Quality Indicators for Differenct Bar Diameters

In addition, the effect of rebar spacing was evaluated. Figure 29 shows the results:

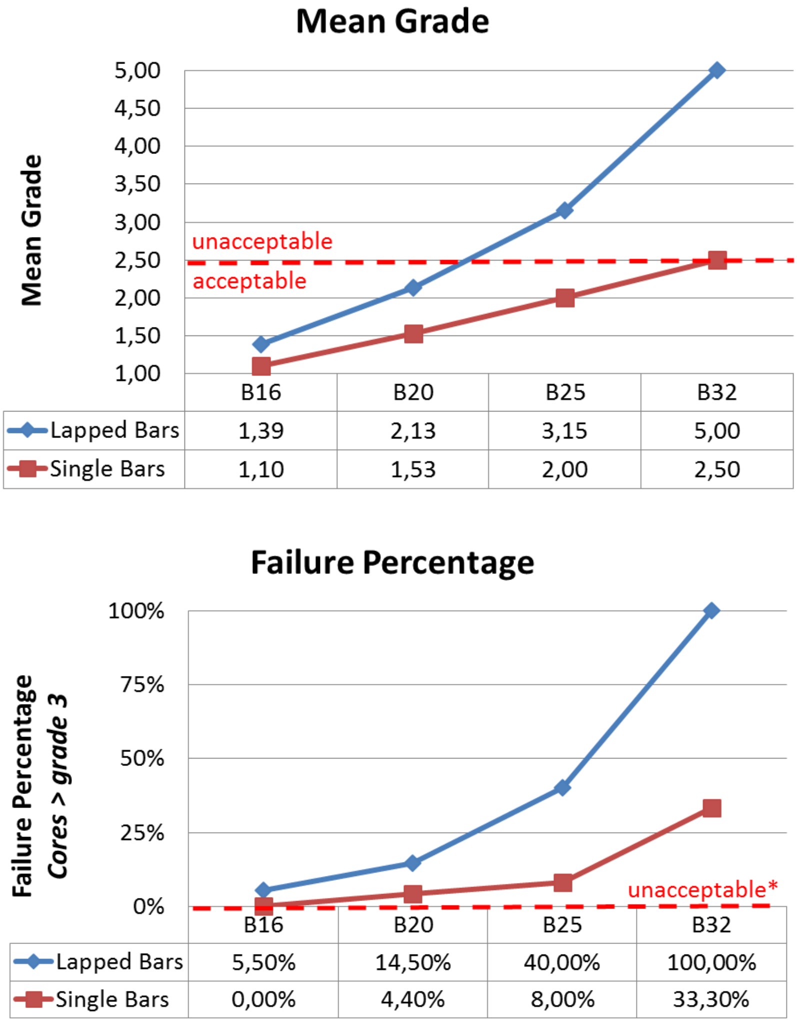




*according to ACI 506.2-95 cores with a grade >3 are unacceptable

Figure 29: Mean Core Grading/Failure Percentage for different rebar spacing

Finally, when evaluating the effects of lapping, the authors found the following trends shown in Figure 30:



*according to ACI 506.2-95 cores with a grade >3 are unacceptable

Figure 30: Mean Core Grading/Failure Percentage on lapped bars for different bar diameters

In addition, the paper detailed the effects of overhead spraying and the relation between spray shadows and load capacity of the tunnel walls were evaluated.

The authors then analysed the bond behaviour of rebar encased in shotcrete containing spray shadows. They argue that bond strength initially results from chemical adhesion between steel and hardened cement, but this resistance can be overcome at very low stress levels. Once slip occurs, friction contributes to bond. In plain round bars, this is the major component of strength. With ribbed bars, under increasing slip bond depends principally on the bearing, or mechanical interlock, between ribs and the surrounding concrete (see **Error! Reference source not found.**31). The forces on the bar surface are balanced by compressive and shear stresses on the concrete contact surfaces, which are induced into tensile stresses that can result in cracks.

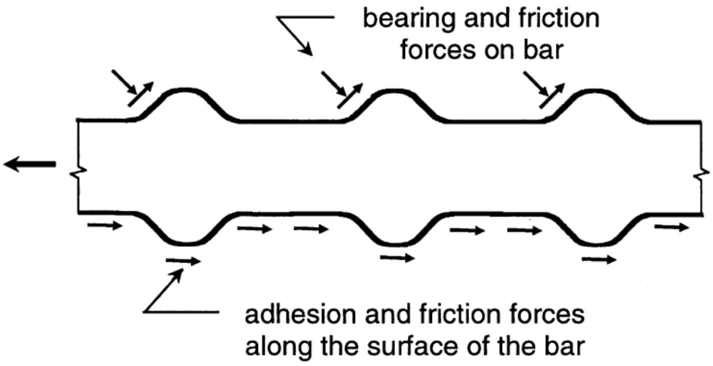


Figure 31: Bond force transfer mechanisms according to [3]

Simplified bond stress may be regarded as a shear stress over the surface of a bar, although bond, anchorage, development, and splice strength are structural properties, dependent not only on the materials but also on the geometry of the reinforcing bar and the structural member itself.

As a consequence bond stress-slip laws are based on experimental results. A typical bond stress-slip curve is given in Figure 32.

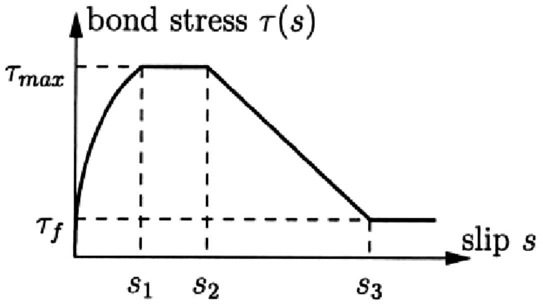


Figure 32: Bond stress – slip relationship according to CEB-FIP Model Code 1990 ([4])

Bond stress typically increases with slip up to a peak value τ_{max}. If slip is increased further bond stress decreases to a residual value τ_f.

The distribution of bond stresses along the bar is nonlinear. Since the distance between the cracks and the amount of tensile load carried by concrete varies, the real distribution of bond stresses along the length of a bar cannot be predicted. Thus in the following bond stresses were considered uniform over the developed or spliced length of the reinforcement.

Because of the unpredictable nonlinear distribution of bond stress along a rebar most international codes of specifications (ACI, Eurocode) use the concept of development length rather than bond stress. The main requirement for safety against bond failure is to provide a sufficient extension of the length of the bar beyond the point where the steel is required to develop its yield stress and this length must be at least equal to its development length.

According to [6] the bond strength f_{bd} is

$$f_{bd} = 2.25 \times \eta_1 \times \eta_2 \times f_{ctd} \quad (1)$$

Note that η_1 and η_2 are factors for consideration of bond quality and bar diameter respectively. Further, f_{ctd} is the design value of concrete tensile strength. The required development length $l_{b,req}$ follows from equating the bond force F_b with the rebar force F_s (assuming yielding of the bar, design value of yield strength f_{yd}):

$$F_b = F_s \quad (2)$$

$$f_{bd} \times d_s \times \pi \times l_{b,req} = f_{yd} \times d_s^2 \times \pi / 4 \quad (3)$$

$$l_{b,req} = d_s/4 \times f_{yd}/f_{bd} \quad (4)$$

Shadowing behind rebars reduces the bond capacity. As a remedy to ensure composite interaction of rebars and concrete the development length can be increased. Formally this may be done along the lines of Eurocode 2 [6] by reducing the factor for bond quality η_1 of equation (1). E.g. if the percentage of grade > 2.5 according to ACI 506 [1] is 30 %, then the development length should be increased by approximately 30%.

For the sprayed junction with 32 mm bars which showed shadowing in some areas and initiated these trials, the design was reviewed and considered acceptable for the temporary condition because the short term value of f_{ctd} is considerably larger than its long term value. For the permanent (long term) condition modifications were made to strengthen the secondary lining to compensate for the reduced bond and strength of the primary lining in the long term.

Note that this is a first attempt to describe the influence of shadowing. Experiments and further scientific work shall be undertaken to check if this simplistic approach is appropriate or not.

Roland Heere of Metro Testing Laboratories Ltd., Burnaby, Canada, presented on *Structural Shotcrete in Vancouver*. Due to a high seismic risk in the Greater Vancouver area, concrete structures are heavily reinforced. Since approximately 1998, structural shotcrete has been used increasingly, first for repair and rehabilitation, then for new construction. There is little guidance in local standards and codes for structural shotcrete, although project documents often refer to ACI 506.

The Vancouver construction industry often uses structural shotcrete for underground perimeter walls of large residential and commercial structures. Typically the construction crews first install a drainage system, over which the rebar mat is placed. This is followed by crack risers to control the locations of shrinkage cracks, and guide wires to mark the plane of the intended finished shotcrete surface. Rebar congestion can be quite extensive do to high seismic loads, as shown in Figure 33.

Figure 33: Reinforcing bar congestion

Approximately 7 to 10 workers form a shotcrete crew, comprising:

- One or two experienced nozzlemen
- A helper positioning the tail end of the concrete hose and communicating with the pump operator
- The pump operator, who also is responsible for the shotcrete consistency as discharged into the pump and the proper operation of the compressor

- Two to three qualified concrete finishers
- Two to three helpers to remove rebound and set scaffolding.

Typical equipment includes:

- Mobile compressor (~150 – 200 L/s, 375 to 450 cfm)
- Mobile shotcrete pump (~40 m^3/h, 50 yd^3/h)
- Concrete hoses
- Nozzle with short rubber tip
- A-frame type working platforms
- Assorted hand and finishing tools.

Figure 34 shows a typical truck loaded with equipment for a structural shotcrete projects.

Figure 34: Typical Wet-mix shotcrete equipment set up

Structural wet-mix shotcrete contractors almost exclusively use ready-mix concrete for their projects. Initially, such mixes contained silica fume to allow adequate cohesion while maintaining a workable slump. Nowadays silica fume is limited to higher-end structural shotcretes (50 to 60 MPa *(7200 to 8700 psi)* compressive strength at 28 or 56 days), while the "bread-and-butter" mixes (with nominal 35 and 40 MPa *(5000 to 6000 psi)* compressive strength at 28 days) are produced with Type GU cement and a small portion of fly ash. Water/cementing materials ratios are approximately 0.45 for the regular mixes, while as-delivered fresh air contents in the 6 to 9% are common. During the hot season, set retarders may be required to maintain 1.5 hours work life, while the addition of a mild accelerator may be beneficial in winter in order to maintain the desired production rate without sagging and sloughing. Aggregate conforms largely to ASTM C1436, although sometimes the maximum aggregate size is increased to 14 mm (0.55"). Large aggregate sizes appear to benefit consolidation, but pose a hazard when ricocheting off a rebar or other hard surface. Synthetic microfibers are sometimes added to shotcrete mixes with low w/cm-ratios or silica fume mixes, in order to mitigate explosive spalling to which such mixes are prone during fires.

Shotcrete construction requires the following general steps:

1. Where required, erection of a one-sided form
2. Where required, installation of the drain mats
3. Installation of the rebar mat. Typical are 15M to 25M (~5/8 to 1") bars for the main reinforcement, 10M to 15M ~3/8 to 5/8") for stirrups, and two mats per wall, with additional rebar in seismic reinforcement zones
4. Installation of crack initiators and waterstop profiles
5. Installation of guide wires
6. Cleaning substrate surfaces if required
7. Where required, manual application of water-stop mortars or slurries (although depending on the produce this may have to be timed so that the shotcrete will not disturb it
8. Bulking of the shotcrete to approximately 30 mm (1.2") short of the final surface, covering all rebar. Use of pencil vibrators where reinforcement is congested
9. Spraying of the finish coat.

Shotcrete quality control is provided by independent laboratories. It may start with monitoring production of a mock-up of the most congested rebar lay-out, flowed by coring and core evaluation. The quality control of production shotcrete includes placement monitoring, testing slump, air content and temperature, and determining the compressive strength obtained from test panels shot daily.

Martin Herbrand and co-author Josef Hegger, both RWTH Aachen, Department for Concrete Construction, Germany presented on *Shear Strengthening of Prestressed Concrete Beams with Textile Reinforced Sprayed Concrete under Cyclic Loading*. Due to old German design codes, pre-stressed concrete bridge girders designed before 1969 may not have adequate, if any, shear reinforcement. In addition, increased traffic loads have increased live loads beyond original design assumptions. Thus, installation of additional shear reinforcement is vital to properly maintain numerous aging bridge structures. Traditional shear strengthening include methods like external pre-stressing, insertion of shear bars, or application of externally bonded carbon fibre reinforced polymers (CFRP). The authors researched the suitability of combining carbon fibre reinforcement (CFR) embedded in shotcrete. Experience with CFR embedded in cast concrete has been available and appears to be promising.

In a first step, the authors determined the tensile behavior of fibre reinforcement embedded in shotcrete. The materials investigated had the following characteristics:

- Shotcrete test strips 880 mm (36") long, 100 mm (4") wide and 25 to 30 (1 to 1.2") mm thick
- Shotcrete with 4 mm (0.16") maximum aggregate size, and polymer modified shotcrete with 2 mm (0.08") maximum aggregate size
- Reinforcement with glass and carbon fibre mats, with and without polymer matrix.

From the initially investigated 13 material combinations, the following was selected for further studies:

- Polymer-modified shotcrete (Stocrete TS 100)
- Carbon fibre mat (55 mm^2/m *(0.08 in^2/yd)* specific cross-section) with a nominal tensile strength of 1136 MPa (16.5 ksi)

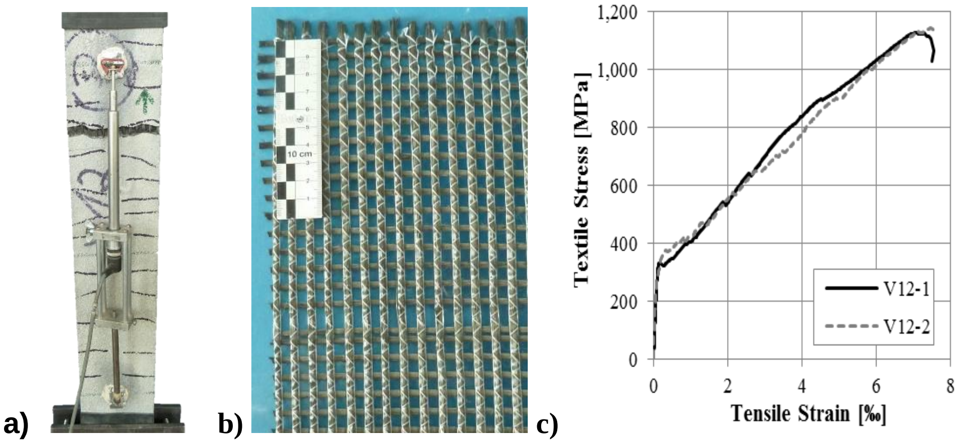


Figure 35: a) Sample strip; b) carbon fibre mat; c) sample stress-strain curve (200 MPa = 29 ksi)

The large-scale tests were conducted on the following beam geometries:

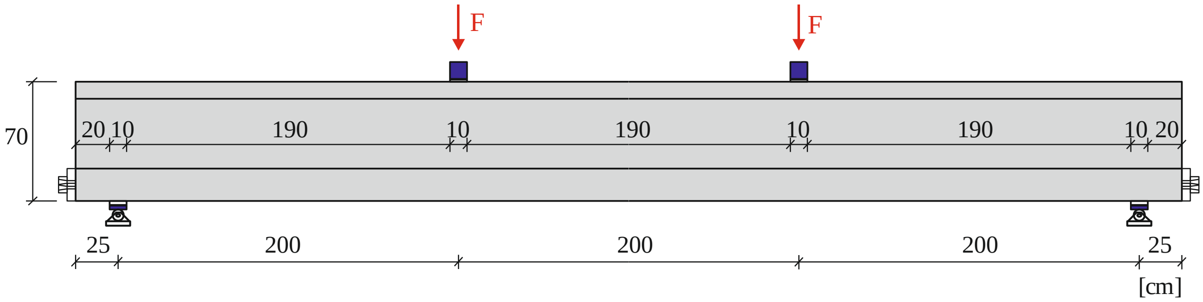


Figure 36: Load testing arrangement. Dimensions in cm, 1 cm ~ 0.39")

Two different beam cross-sections, with and without internal steel shear reinforcement, were tested. Figure 37 below presents the cross-sections:

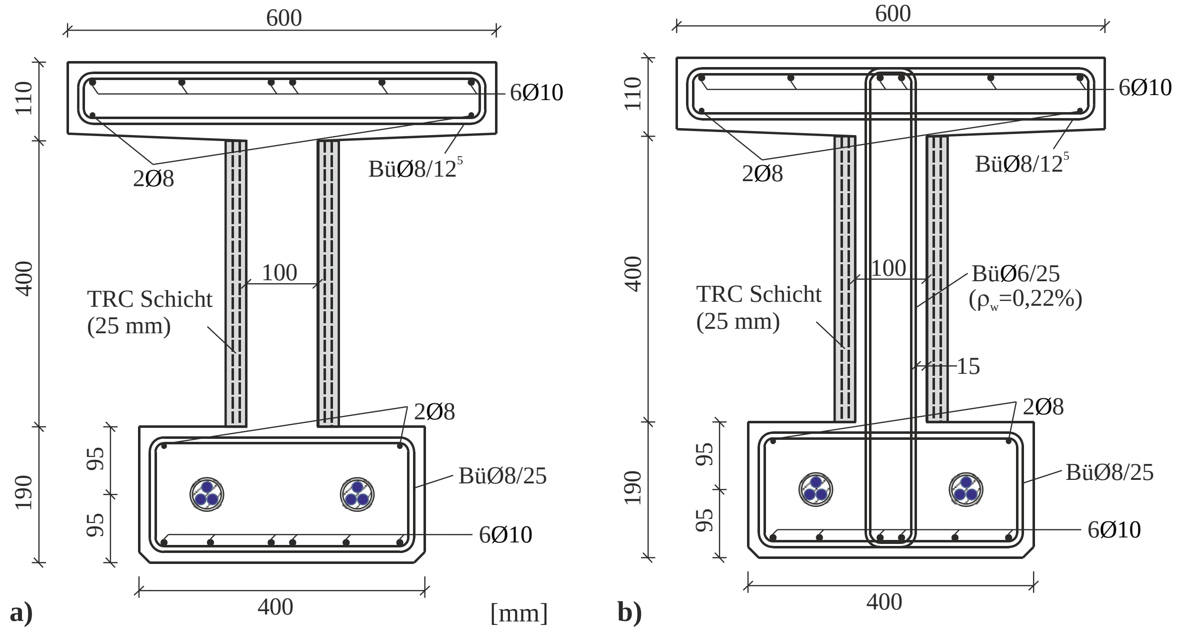


Figure 37 a and b: Beam cross-sections, dimensions in mm, 1 mm ~ 0.039"

The shotcrete was applied with a Sika Rotor gun AL-257 in thin-stream mode.

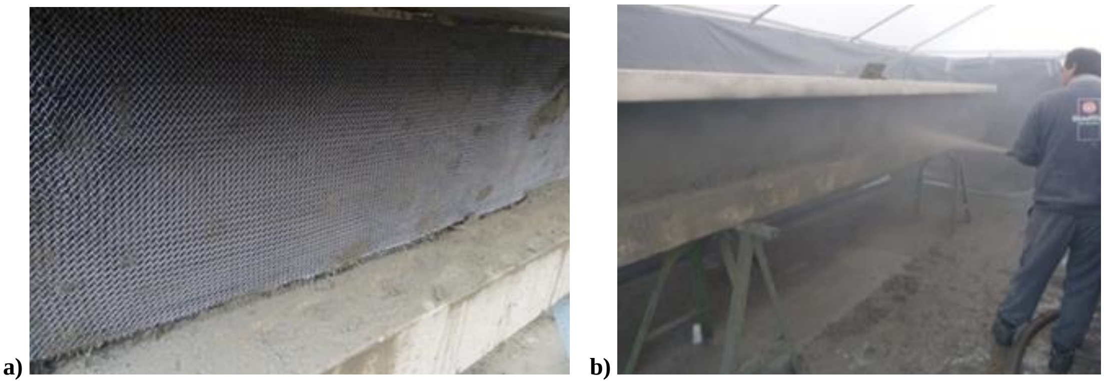


Figure 38: a) Textile reinforcement installed; b) Shotcrete application

After installation and curing of the fibre mats and the shotcrete, the beams were tested for 5000 load cycles. Depending on the test specimen, the swelling loads varied between lows of 20% and 80% of first crack load, and highs of 58% to 110% of first crack load.

The results showed that the reinforcement significantly increased fatigue resistance as well as ultimate load resistance of the strengthened beams. Typically, cyclic loads could be increased by 30 to 40% over the original specimens, while maintaining 1 to 3 million load cycles. Moreover, the residual strengths of the carbon fibre reinforced shotcrete strengthened beams after the fatigue testing were 30 to 50% higher than those of the original beams. In summary, carbon fibre reinforced shotcrete appears to be a very effective material to increase shear capacity of pre-stressed bridge girders.

Rolf Breitenbücher of the Ruhruniversität Bochum, Germany, presented on the *Relations between various technical guidelines for sprayed concrete / sprayed mortar in Germany*. His presentation was highly specific for the users of German codes, and thus may be of great interest to a limited number of readers. They are encouraged to contact the author for more information. In general, Breitenbücher stated that the fundamental European code for shotcrete is EN 14487 Parts 1 and 2. This is supplemented in Germany by DIN 18551, which also covers sprayed mortar. The rules for materials certification and acceptance are complex. It is noteworthy that the codes stipulate different quality control measures for wet- and dry-mix shotcrete, respectively. As wet-mix shotcrete may be delivered as ready-mix under the responsibility of the ready-mix supplier, the dry-mix shotcrete is essentially batched on site, shifting some of the responsibility for the base mixture to the applicator.

In tunnel construction, quality control requirements also cover early-age strength development and leaching, specified by ZTV-ING, Part 5, Clause 1. Early-age strength tests by various penetration methods are specified in EN14488-2. Concerns about leaching also dictate limitations on Na_2O contents in accelerators, set out in ZTV-ING.

General shotcrete codes do not cover all aspects related to the use of polymer modified shotcretes. Some gaps remain in the shotcrete codes DIN EN 14487 with respect to sprayed mortar with 4 mm maximum aggregate size. Such material is however covered under DIN 18551. Ironically, although sprayed mortar with maximum 4 mm aggregate size is permitted for use in new construction, applicable codes for concrete repair do not formally allow its use. However, some regulations apply, like a maximum allowable thickness of 30 mm (1.2”).

Shotcrete repairs of concrete structures require minimum 30 mm (1.2”) thickness for structures with predominantly static (permanent) loads, while this minimum increases to 50 mm (2.0”) for structures with predominantly dynamic loads. Where the thickness of the shotcrete or sprayed mortar is insufficient for adequate embedment and cover of anchors, the tensile bond strength of the repair material to the substrate must be ensured by means of a suitable surface preparation.

Where shotcrete is used for water retaining and marine structures, *BAW-Merkblatt; Spritzbetonmörtel/Spritzbeton nach ZTV-W LB219* requires that the effect of the conveyance system on the performance of the material must also be considered. If pump, hose length of pumping rate exceeds the boundaries set by the pre-construction tests, a new certification is required. Further, the same document requires minimum 90 mm (3.5”) thickness for steel reinforced shotcrete, while un-reinforced shotcrete needs to maintain 20 to 60 mm (0.8 to 2.4”) thickness.

Wolfgang Kusterle, OTH Regensburg, Germany, presented on the *Determination of compressive strength of young sprayed concrete – specifications, testing procedure, interpretation*. To ensure a safe and expedient construction of tunnels, the early-age strength development of structural shotcrete must be known. While sluggish strength development slows down construction or exposes the miners to the dangers of insufficiently supported ground, excessively rapid strength development may interfere with the quality of the shotcrete placement (i.e. increases the risk of voids around rebar), and increase rebound.

In order to test the in-situ strength of shotcrete, laboratory tests are insufficient. In-situ tests require good repeatability, rugged equipment, suitability for gun-finished shotcrete with a compressive strength of 0 to 15 MPa. The currently most common test method is the penetration test initially described by Sällström in 1968 and adapted and improved by Kusterle in 1983. The procedure is now prescribed in EN 14488-2.

The needle penetrometer test requires a tester to push a needle with 3.0±0.1 mm (0.118±0.004”) diameter and a 60±5° pointed tip to a depth of 15 mm (0.59”) while measuring the force required to do so. A calibration chart relates penetration force to compressive strength. This test is suitable to determine compressive strengths of maximum 1.0 MPa (145 psi). Minimum 10 individual tests are required for one general location and time. Note that for very low compressive strengths, a needle diameter with 9 mm (0.35”) and flatter tip is used.

For shotcrete strengths of 2 MPa (290 MPa) or higher, the powder activated stud driving test is suitable. It requires a powder actuated tool and steel studs with 3.7 mm (0.146”) diameter and of various lengths. For the higher range of compressive strengths, a bolt pull-out device is also required. To conduct the test, the powder-actuated tool drives the stud with an energy of 96±8 J minimum 20 mm (3/4”) into the shotcrete. The standoffs of the bolts can be correlated to a compressive strength using a calibration chart. For shotcretes with compressive strengths >2 MPa (300 psi), measuring the pull-out resistance of the studs is also required. Note that the type and hardness of shotcrete aggregate affects the measurements. Calibrations are necessary. They can be conducted on cast shotcrete samples, if the mixture is enriched with cementitious materials in order to correct for the lack of rebound. Correlation coefficients should be >0.85. The author provides a detailed tabulation of shotcrete mixtures, aggregate gradations and aggregate mineralogy used as a base for the standard calibration curves applicable to the Hilti DX-450-SCT stud driving equipment.

Table 5 below shows the test procedures and equipment suitable for various strength ranges of shotcrete.

Table 5a: Currently codified test ranges and applicable specifications

Strength range	Method	Cartridge	Power setting DX 450-SCT	Max. aggregate, mm	Mix	Specification**
“Setting”	Penetration needle method Ø 9 mm	-	-	0-8 0-16	Not relevant	OVBB 1991 OVBB 1998
0.2 to 1.2 MPa	Penetration needle method Ø 3 mm	-	-	0-8 0-11 0-16	mixed dolomitic limestone (not relevant for this method)	EN 14488-2 OVBB 2004 OVBB 2009 OVBB 1991 EN14488-2
1 to 8 Mpa	Stud driving method Hilti DX 450	White***, Special Method	1*	0-8/11	mixed dolomitic limestone	OVBB 1998
2 to 16 Mpa	Stud driving method Hilti DX 450-SCT	**Green Standard Method**	1*	0-8/11 0-16	mixed dolomitic limestone	EN 14488-2 OVBB 2009 OVBB 2004 OVBB 1991
				0-16	hard aggregate (diabase)	EN 14488-2
17 to 56 Mpa	Stud driving method Hilti DX 450-SCT	Yellow Special Method	2*	0-8/11	mixed dolomitic limestone	OVBB 1998 OVBB 2004

** calibrated for piston guide L140 (corresponds with used equipment of the Hilti DX 450-SCT, item number 233871), in the exceptional case of the use of the piston guide L125, different power settings need to be applied.*
*** OVBB = concurrent OVBB guideline „Sprayed Concrete“*
**** Outdated method, generally not in use any longer*

Table 5b: Currently codified test ranges and applicable specifications, converted to US units

Strength range	**Method**	**Cartridge**	**Power setting DX 450-SCT**	**Max. aggregate, inches**	**Mix**	**Specification****
“Setting”	Penetration needle method Ø 0.354”	-	-	0-0.3 0-0.6	Not relevant	OVBB 1991 OVBB 1998
30 to 170 psi	Penetration needle method Ø 0.118”	-	-	0-0.3 0-0.4 0-0.6	mixed dolomitic limestone (not relevant for this method)	EN 14488-2 OVBB 2004 OVBB 2009 OVBB 1991 EN14488-2
140 to 1200 psi	Stud driving method Hilti DX 450	White***, Special Method	1*	0-0.3/0.4	mixed dolomitic limestone	OVBB 1998
290 to 2300 psi	Stud driving method Hilti DX 450-SCT	**Green Standard Method**	1*	0-0.3/0.4 0-0.6	mixed dolomitic limestone	EN 14488-2 OVBB 2009 OVBB 2004 OVBB 1991
				0-0.6	hard aggregate (diabase)	EN 14488-2
2500 to 8100 psi	Stud driving method Hilti DX 450-SCT	Yellow Special Method	2*	0-0.3/0.4	mixed dolomitic limestone	OVBB 1998 OVBB 2004

** calibrated for piston guide L140 (corresponds with used equipment of the Hilti DX 450-SCT, item number 233871), in the exceptional case of the use of the piston guide L125, different power settings need to be applied.*
*** OVBB = concurrent OVBB guideline „Sprayed Concrete“*
**** outdated method, generally not in use any longer*

Helmut Huber and the author developed the well-established early-age strength classification to EN14487-1, standardised in 1989. In order to minimise risk to miners during overhead shotcrete application, while also minimising dust and rebound exposure, the optimum early-age compressive strength range for shotcrete overhead applications is 0.1 to 0.2 MPa (14 to 29 psi). Class J1 is recommended for applications of multiple thin layers onto dry substrate without specific structural requirements. Class J2 is suitable for the application of thick layers and overhead shooting where quick ground support is necessary. Class J3 is limited to applications in areas with water ingress, very poor rock conditions or where rapid advancement of the work is essential.

In order to ensure test results representative for the shotcrete, the author recommended the following:

- Use the penetration tests only if minimum individual layer thickness is 100 mm (4”)
- Avoid porous shotcrete areas
- Fibres embedded in the shotcrete can be ignored as they do not usually affect the test results significantly
- Tests on the test panel instead of in situ are now quite common. However, it should be remembered that test panels should be cured adequately and should not be moved before they reach 2.0 MPa compressive strength or an age of 18 hours, depending on the applicable code
- During needle penetration tests, the needle must be advanced slowly, steadily and not beyond 15 mm penetration depth
- Bolt penetration tests must be conducted in un-disturbed areas, sufficiently distal from areas previously tested with the needle or bolt penetrometer
- Proper instrument maintenance and setting are essential for obtaining valid test results
- A sufficient number of tests is required to properly identify outliers.

Benedict Lindlar, and co-authors Christian Stenger and Didier Lootens, all Sika Technology AG, Zürich, Switzerland, presented a paper on *Miniaturised laboratory spray method for shotcrete – new possibilities for the product development, mix design optimisation and quality control*. In order to design a shotcrete mixture for a particular application, with particular concrete making materials, extensive trials may be required. However, the process of spraying concrete affects the performance of the mortar or concrete placed. Therefor the preparation and testing of mortar samples in the laboratory may not provide sufficient information to predict the in-situ performance of a shotcrete. On the other hand, full-scale trials of a shotcrete mixtures require a substantial effort on time, materials and equipment.

Traditionally, a laboratory test would not address all peculiarities of the shotcrete process. For instance, addition of a liquid accelerator to the shotcrete at the nozzle cannot be adequately duplicated in a standard laboratory mixer. The shear forces acting on a mortar in a shotcrete nozzle exceed the shear forces in a mixer by approximately 5 to 6 orders of magnitude, but act for a much shorter time. This may result in notable differences of the product. Tests have shown that such forces initiate significant differences in the chemical reactions during early-age strength development of shotcrete compared to mortar prepared in a traditional mixer. The authors conclude that the chemical system which is tested in a traditional laboratory batch may differ significantly from an actual field-applied shotcrete. As a consequence, they propose a miniaturised laboratory shotcrete test system. Assuming that chemically inert materials like sand and gravel do not greatly affect the hydration processes, such a miniaturised system can be reduced to test the chemically active materials of the shotcrete mixture only. However, the effect of heat of hydration must be considered, as pure pastes will release more energy per unit mass than a shotcrete mixture. The specimen size must be selected so that this effect can be minimised. The *MiniShot* system developed by the authors maintains sample temperature rises of no more than 5°C (9°F).

Figure 39: MiniShot-Laboratory System. Left: MiniShot spray applicator, centre: test specimen; right: detector of ultrasound spectrometer.

This system is comprised of a miniaturised spraying device and a *Pulsment* ultrasound spectrometer for non-destructive compressive strength determination. Characteristic for the system are:

- Material shear rates during spraying: 10^5 to 10^6 s^{-1}
- Synchronization of paste and accelerator feed by means of frequency controlled linear induction motors
- Spraying the specimen onto the detector of an 800 kHz ultrasound spectrometer
- Continuous determination of shear modulus by means of ultrasound spectrometry; shear modulus is related to the compressive strength.

The following images show test results obtained with the MiniShot system and the results of actual field trials with shotcrete mixtures based on the laboratory trials.

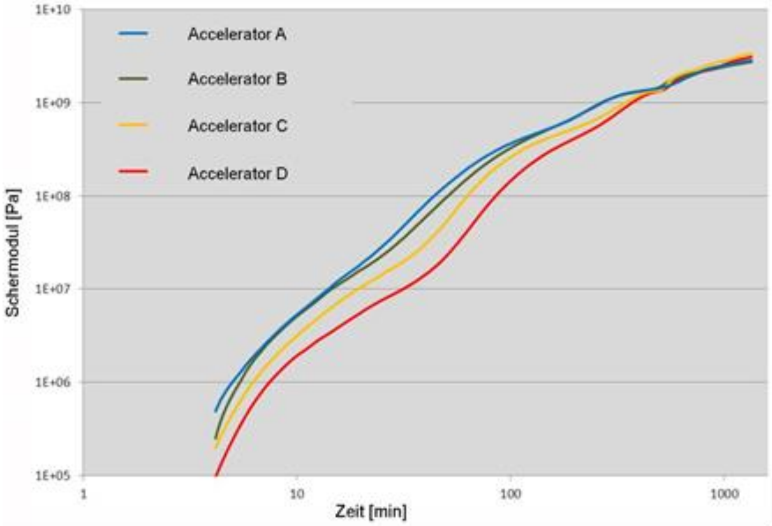


Figure 40a: Comparative tests. Mortar sample in MiniShot Laboratory. Logarithmic time scale (minutes) vs. shear modulus (1E+06 Pa = 145 psi)

Impressions from the Alpbach Shotcrete Conference 2015

By: Roland Heere, Wolfgang Kusterle

The 11th Shotcrete Conference took place in the Alpbach Conference Centre (Alpbach, Austria) from 29 to 30 January 2015. Organiser Professor Wolfgang Kusterle welcomed approximately 260 guests. Visitors value these, now traditional, shotcrete conferences in Alpbach for their interesting presentations, as well as for their relaxed ambience. This article provides a summary of the papers published originally in German. Some of the papers originally published in English are also summarised here, and at times extensively quoted. References provided in [brackets] refer to the references quoted in the original paper. For more details or copies of the conference proceedings (English abstracts, mostly German papers), please contact Shotcrete Magazine (www.shotcrete.org), Wolfgang Kusterle (spritzbeton@kusterle.net) or Roland Heere (rheere@metrotesting.ca).

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Original Conference I.D. number	First Author	Title
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3	Erich Erhard	Surface Forming Method for Shotcrete Used in Structural Repair and Strengthening Works
4	Dominik Khaur	The Application of White Gunite at the Agnesbergtunnel
5	Mario Frankenhauser	Renewal of Old Tunnel Structures of the DB (German Federal Railway) by Example of the Bebenrohrtunnel near Witzenhausen
6	Sergej Rempel	Textile-reinforced Protection Layers for Maintenance of Hydraulic Structures
7	Hernani Esteves	Cathodic Protection and Fire Protection at the Rendsburg Road Tunnel
8	Martin Fischer	Reinforced Shotcrete with Bar Diameters up to 32 mm
9	Roland Heere	Structural Shotcrete in Vancouver
10	Martin Herbrand	Shear Strengthening of Prestressed Concrete Beams with Textile Reinforced Sprayed Concrete under Cyclic Loading
11	Rolf Breitenbücher	Relations between various technical guidelines for sprayed concrete / sprayed mortar in Germany
12	Wolfgang Kusterle	Determination of compressive strength of young sprayed concrete – specifications, testing procedure, interpretation
13	Benedict Lindlar	Miniaturised laboratory spray method for shotcrete – new possibilities for the product development, mix design optimisation and quality control
14	Volker Wetzig	Influence of air consumption and nozzle distance on properties of applied sprayed shotcrete
15	Maria Thurman	Potential for precipitations – lab tests and sprayed mortar tests for the reduction of calcium leaching
16	Walter Pichler	Sprayed concrete with reduced precipitation potential – practical experiences from major construction sites in Austria
17	Stefan Lemke	A controversial discussion: spray-applied membranes for tunnelling
18	Sebastian Schmidt	Verification of the bond strength of sprayed concrete – general conclusions and outlook for single tunnel linings
19	Anders Ansell	In-situ observations and laboratory testing of shrinkage cracking in shotcrete soft drains
20	*Götz Vollmann*	Development of a sprayed concrete with high fibre content as a countermeasure for buildings under fire and explosive loads
21	Luke Pinkerton	Twisted steel micro reinforcement (TSMR) for shotcrete
22	Benoit De Rivaz	EFNARC creep test procedure description for sprayed concrete and test results with steel and synthetic fibres

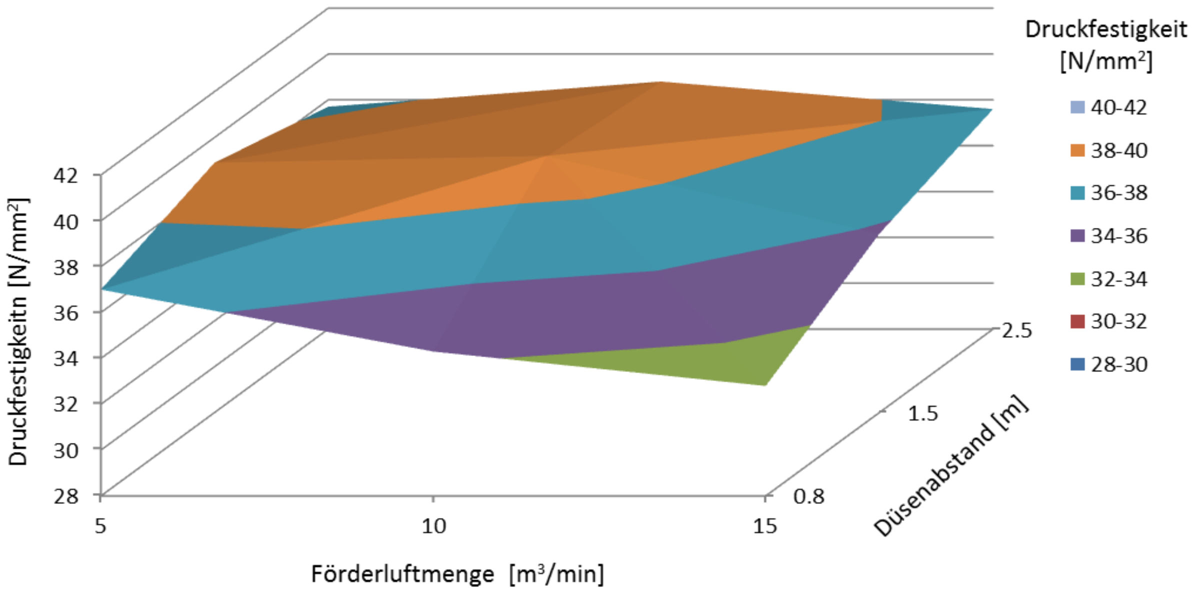


Figure 41: Comparative tests. Field trial. (Logarithmic time scale, minutes and hours; vs. compressive strength, logarithmic scale, 1 MPa = 145 psi)

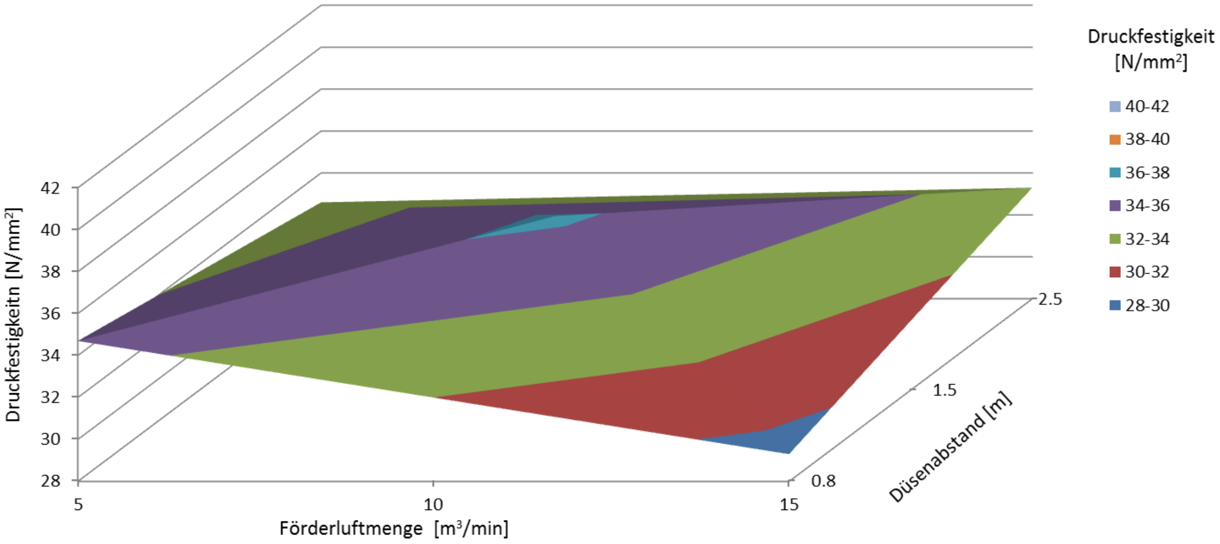


Figure 42: Compressive strength vs. air volume flow (Förderluftmenge) and nozzle distance (Düsenabstand), Accelerator addition rate was 9%. Testing of in situ core samples. Note: 1 N/mm^2 = 145 psi; 1 m^3/min = 35 cfm; 1 m = 3.3 ft.)

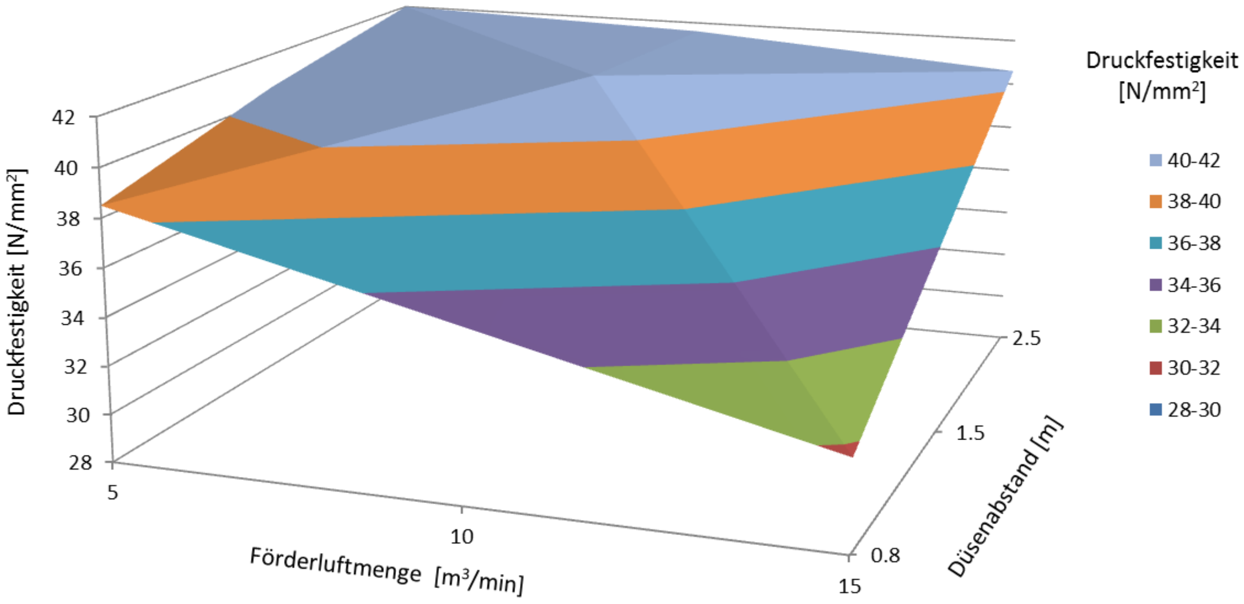


Figure 43: Compressive strength vs. air volume flow (Förderluftmenge) and nozzle distance (Düsenabstand), Accelerator addition rate was 9%. Testing of cores from test panels. Note: 1 N/mm^2 = 145 psi; 1 m^3/min = 35 cfm: 1 m = 3.3 ft.

Maria Thumann (OTH Regensburg, Germany) and co-authors Michael Hartmeier (Rohrdorfer Zement, Germany), Andreas Saxer (University Innsbruck, Austria), and Wolfgang Kusterle (OTH Regensburg, Germany) presented on the *Potential for precipitations – lab tests and sprayed mortar tests for the reduction of calcium leaching*. Calcium hydroxide leaching from shotcrete can result in the formation of precipitates in the drainage systems of tunnels. As this can compromise the serviceability of tunnels, the Bavarian Research Council funded project REDUV to study means to reduce leaching and precipitation of calcium hydroxide. Figure 44 shows an example of a drainage conduit partly obstructed by precipitate.

Figure 44: Precipitate in a drainage conduit

Figure 45 below provides a schematics of a tunnel cross section, potential paths for the water, and general mechanisms for leaching and depositing:

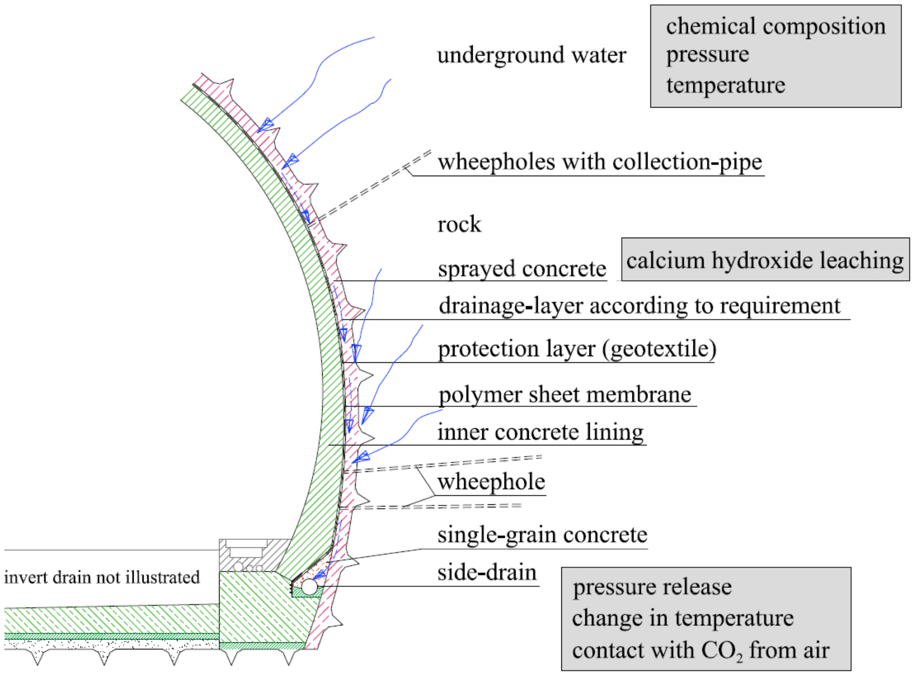


Figure 45: The way of the water into the tunnel

Although complex processes cause the formation of precipitates, the basics involve availability of calcium hydroxide from the hydration of the cement, porous matrix allowing water to percolate, and high addition rates of older generation set accelerators. In more detail the balance between carbonic acid, carbon dioxide and calcium carbonate in the ground water, if disturbed, can result in precipitation:

$$Ca(HCO_3)_2 \rightleftarrows CaCO_3 + CO_2 + H_2O \qquad (1)$$

When pressurized ground water enters the drainage tunnel, its pressure drops and it may become oversaturated with dissolved gases and minerals, which then fall out:

$$Ca(HCO_3)_2 \rightarrow CaCO_3 + CO_2\uparrow + H_2O \qquad (2)$$

In the presence of older generation alkali accelerators, the following mechanism may also be present, resulting in precipitation:

$$Ca(HCO_3)_2 + Na(OH) \rightarrow CaCO_3 + NaHCO_3 + H_2O \qquad (3)$$

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2\,CaCO_3 + 2\,H_2C \qquad (4)$$

Acidic water, containing carbonic acid, is able to dissolve calcium hydroxide from the cement matrix and from carbonatious aggregates. This can also result in calcite precipitation:

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2C \qquad (5)$$

If the ground water contains dissolved calcium hydroxide, contact with carbon dioxide in the air and evaporation may also result in precipitation, particularly if the velocity of the water flow in the drainage tunnel is slow:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (6)$$

To reduce precipitation, the Austrian shotcrete and tunnel drainage codes specify the use of Class RV shotcrete. In order to develop a shotcrete mixture with low precipitation potential while maintaining sufficient early-age strength development, the authors experimented with different binders, admixtures, water contents and aggregates in the laboratory in a first phase. In a second phase, experiments with accelerated spray mortars identified suitable set accelerators. Shotcrete field trials were conducted in a third phase.

In Phase One, the authors compared a reference mix (450 kg/m^3 *(760 lbs/yd^3*) cement, 150 kg/m^3 *(250 lbs/yd^3*) silica flour, silica sand and a water/binder ratio of 0.52 to experimental mixtures. They evaluated the leaching potential of the mixtures according to "*Österreichische Bautechnik Vereinigung: Festlegung des Reduzierten Versinterungspotentials. Merkblatt. Wien, 07.2012*." This involves extracting 50 mm (2") diameter and 100 mm (4") long core samples, storage of the samples in de-ionised water (water mass is 4 times the shotcrete mass). The water is then removed and analysed for Calcium, electric conductivity and pH. This procedure is repeated three times. Thereafter, the core specimens are dried and their porosity is determined, similar to ASTM C642, except that the samples were not boiled. For the tests, the leaching coefficient RV (in g/kg, or 10^{-3}) was determined. The following figures present the results:

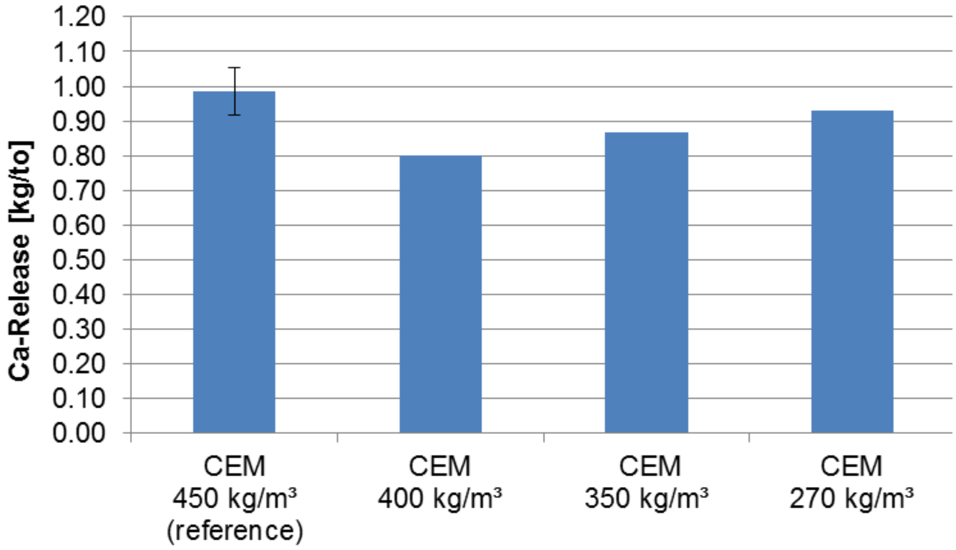


Figure 46: Leaching vs. cement content, constant w/cm-ratio. Note: 1 kg/to = 0.1%, 100 kg/m3 ~ 170 lbs/yd3.

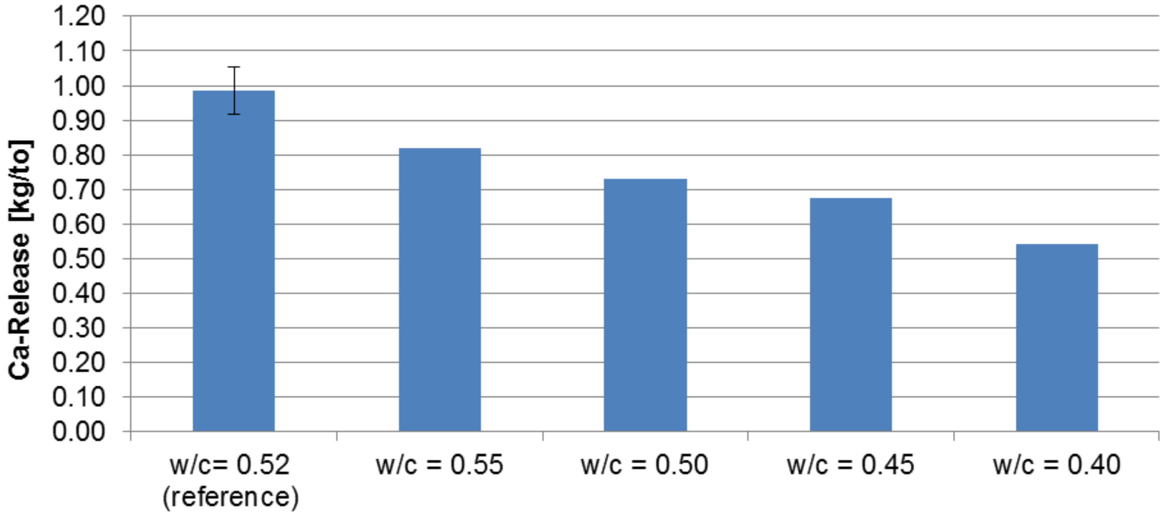


Figure 47: Leaching vs. w/cm-ratio. Note: highest W/B = w/cm ratio sample shown out of sequence!. 1 kg/to = 0.1%.

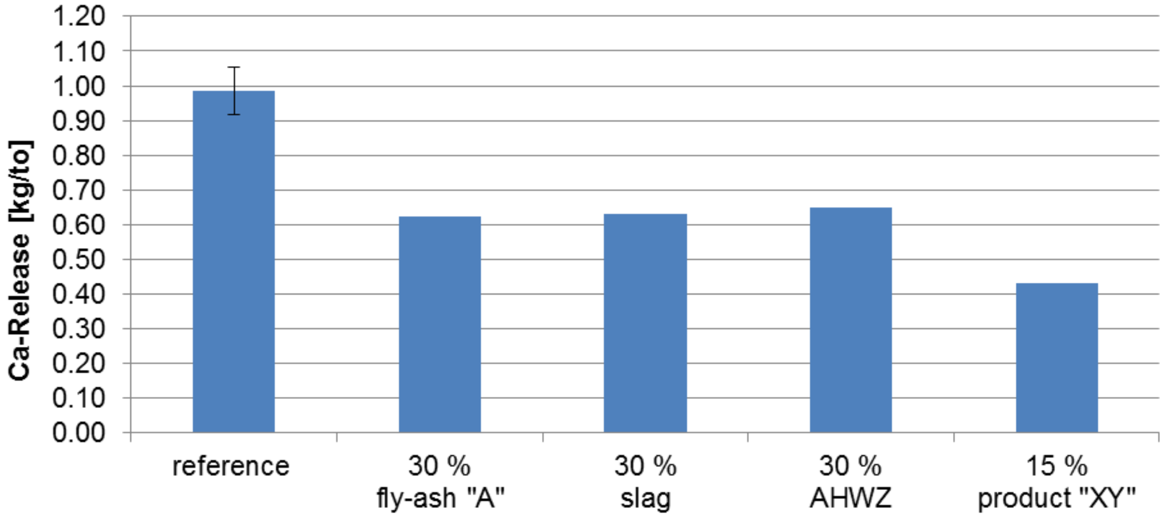


Figure 48: Leaching vs. cement replacement by supplementary cementitious material and content. Sequence from left to right: plain control; 30% fly ash "A"; 30% blast furnace slag; 30% ternary blend of fly ash, slag and limestone: 15% unidentified product XY. Note: 1 kg/to = 0.1%.

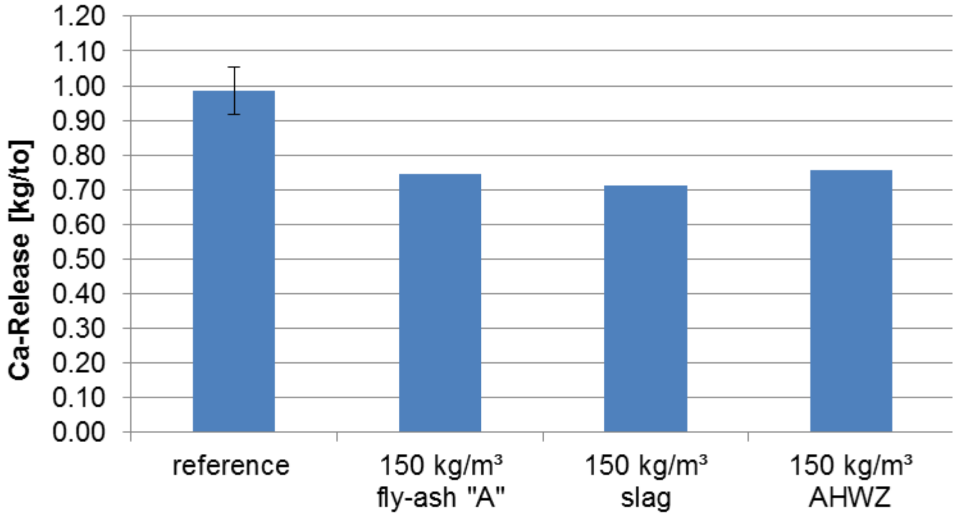


Figure 49: Leaching vs. addition rate of supplementary cementitious material. Sequence from left to right: plain control; 150 kg/m3 fly ash "A"; 150 kg/m3 blast furnace slag; 150 kg/m3 ternary blend of fly ash, slag and limestone. Note: 1 kg/to = 0.1%. 100 kg/m3 ~ 170 lbs/yd3.

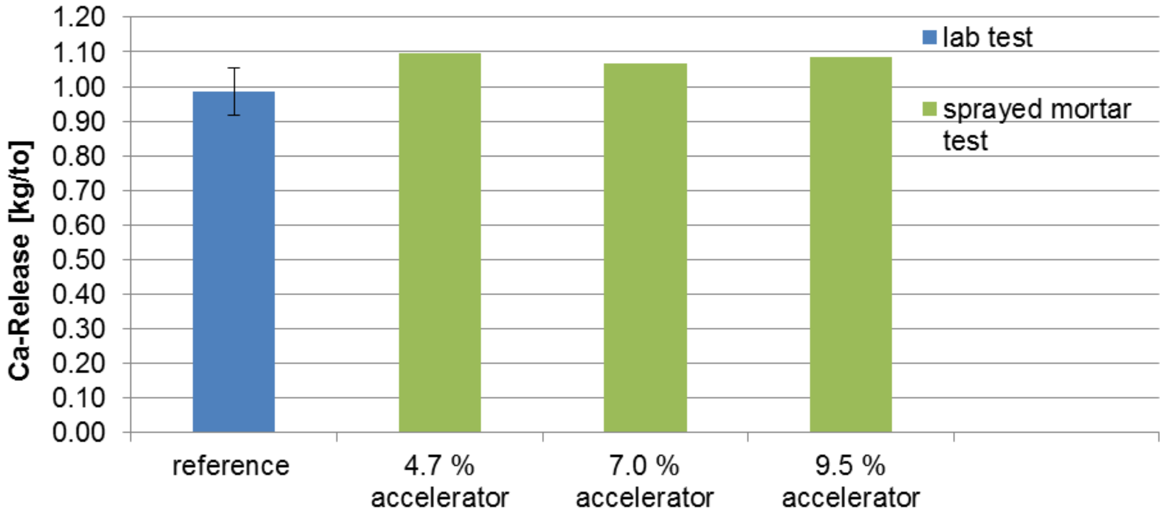


Figure 50: Leaching vs. Accelerator addition rate (blue: Laboratory test; green: sprayed mortars with 4.7, 7.0 and 9.5% accelerator by mass of cement. Note: 1 kg/to = 0.1%;

Walter Pichler (Pichler ZT GmbH, Hart) and co-authors Hanns Wagner (ÖBB-Infrastruktur AG, Graz) and Romed Insam (Brenner Basistunnel BBT SE, Innsbruck) presented on *Sprayed concrete with reduced precipitation potential – practical experiences from major construction sites in Austria*. The mitigation of precipitated leachate in tunnel drains is expensive, as it may require approximately 15% of tunnel maintenance costs. Development of a suitable leaching test to select shotcretes with low maintenance requirements is thus desirable. Leaching tests on shotcrete have been conducted for decades, in order to evaluate the durability of shotcrete, to assess the effect of the hardened shotcrete on the environment and to predict precipitates in drainage systems. However, such tests were not part of mandatory codes. Table 6 below summarises the currently used leaching tests:

Table 6: German and Austrian Leaching Tests

Method	**Description**	**Eluent**			**Duration**	**Origin**
		Replacement	Distilled water	CO_2-content		
DEV-S4	Crush and shake sample. Filter eluate and separate in centrifuge.	no	yes	no	24 h	DIN 38414-S4
Submersion bath	Complete submersion in flowing water	no	yes	no	24 h	ÖENORM S 2072
Leaching cell	Test panel 500 x700 mm, continuous supply of elunent	yes	yes	no	3.5 h	Philipp Holzmann AG
Permeation cell	Meandering flow permeates 10 mm thick sample slices	yes	yes	no	3.5 h	TU Munich
Flow cell	6 samples placed in flow of elunet. Water temperature 4°C	no	no	yes	28 d	Ruhr-Universität Bochum, Umwelt- und Tunnel-Technologie

Note: 1 mm = 0.0394“

For the first time, the 2008 pilot project specification for the Koralm – tunnel in Austria required a limit on the shotcrete’s precipitation potential, with 0.30 g/kg (0.030%). After evaluating different test methods, the Submersion Bath method was selected. Due to the use of distilled water as a leachant, this method can only detect the dissolution of calcium hydroxide. The dissolution potential of calcite cannot be determined by this method.

Subsequently, precipitation limits were specified for Sections KAT1, KAT2 and KAT3 of the Koralm – tunnel, the Pummersdorf tunnel, Sections SBT1.1 SBT 2.1 and SBT3.1 of the Semmering base tunnel and the Granitztal tunnels. In most of these projects the ground water has a low mineral content, increasing its leaching potential.

In order to minimise leaching and precipitation potential, shotcrete should be produced with a minimised cement clinker content. A cement replacement of 30% is desirable, although it requires high early strength cements in order to maintain adequate early-age shotcrete strength. The following table compares two shotcrete cements (A and B) to a standard cement:

Table 7: Cement description

Property	Cement A: CEM I 52,5 R	Cement B: CEM I 52,5 R	Reference Cement: CEM II/A-S 52,5 N
Blaine fineness (cm^2/g)	5520	4900	4600
1 d compressive strength (MPa / psi)	32 / 4600	29 / 4200	20 / 2900
28 d compressive strength (MPa / psi)	64 / 9300	62 / 9000	62 / 9000

The following table shows the mix proportions of two shotcrete mixes. Mix SpC25/30(56)/II/J2/XC4/RV0,70 is designed to meet the precipitation limits specified, while Mix SpC25/30(56)/II/J2/XC4 is a reference mix.

Table 8: Mix Designs

	SpC25/30(56)/II/J2/XC4/RV0,70	SpC25/30(56)/II/J2/XC4
Limitation of Precipitation?	Yes	No
Cement CEM I 52,5 R	280-320 kg/m^3 (470 to 540 lbs/yd^3)	-
Cement CEM II/A-S 42,5 R	-	420 kg/m^3 (710 lbs/yd^3)
AHWZ (ternary blend of fly ash, slag and limestone)	140-100 kg/m^3 (240 to 170 lbs/yd^3)	-
Water content	200 l/m^3 (40 USGal/yd^3)	200 l/m^3 (40 USGal/yd^3)
Admixtures	As required	As required
Aggregate content	ca. 1800 kg/m^3 (~3000 lbs/yd^3)	ca. 1800 kg/m^3 (~3000 lbs/yd^3)
Portion of 0-4 mm (0-0.16") size sand	70-75 %	70-75 %
Portion of 4-8 mm (0.16 to 0.31") size aggregates	30-25 %	30-25 %

Note that where pressurised ground water is present, increasing the cement content from 280 to 320 kg/m^3 (470 to 540 lbs/yd^3) has been highly beneficial. Aggregate gradations and type of set accelerators however have not shown significant effects on leaching. In summary, optimising the concrete mixtures can help reduce leaching by approximately 25% for wet-mix shotcrete, and approximately 30% for dry-mix shotcrete. Note however that the leaching potential of a standard dry mix shotcrete exceeds the standard wet-mix by more than $^1/_3$. Finally, the use of sulphate resistant cement may increase the leaching potential compared to regular Portland cement. This is attributed to the lack of the C_3A phase in sulphate resistant cements.

Stefan Lemke (Sika Services AG, Zürich, Switzerland) presented on *A controversial discussion: spray-applied membranes for tunnelling*. Sprayed, poured, painted or squeegeed membranes based on epoxies, acrylates, polyureas or polyurethanes have a long history in the sealing or waterproofing of industrial floors, roofs, bridge decks and for splash guards in tunnels. Their application requires smooth dry and clean surfaces and ambient conditions. Therefore use of such membranes as waterproofing in entire tunnels –with their more complex geometry and challenging surface and ambient conditions- is however not yet wide spread. However, the ease of spray or brush applying a membrane to a tunnel liner, instead of installing sheets of cured materials, is a strong incentive for such materials.

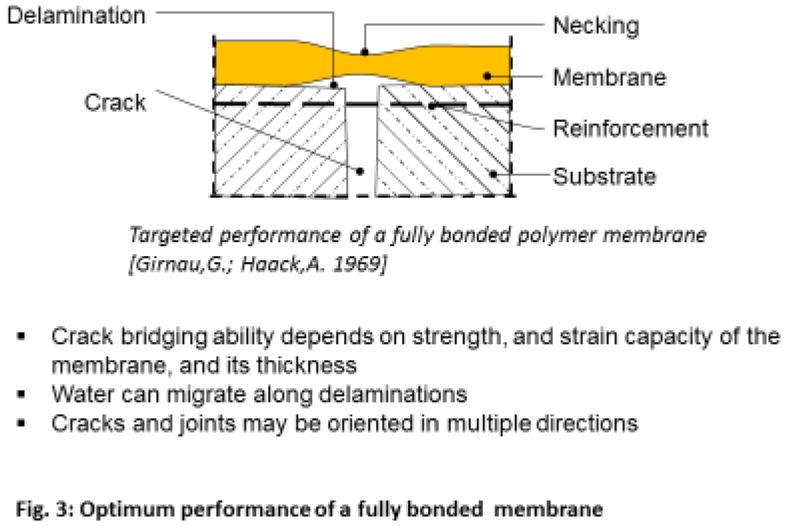
Currently the most common materials for spray- and brush applied membranes are latex-like materials, often with cementitious filler, based on ethylene vinyl acetate, acrylates, methyl methacrylate or polyurea. There are significant difference between these materials, for instance with respect to set time, swelling, durability or sensitivity to substrate conditions. For instance, immature membranes may blister or crack if the substrate is leaking water and the inner, structural, layer has not yet been constructed. Figure 51 a and b below show examples of such early-age deficiencies.

Figure 51 a & b: a) Blistering and delamination of spray-applied membrane, b) Tension cracks in spray-applied membrane

In order to protect spray-applied membranes from water-induced damage at early ages, the substrate surface may have to be sealed, for instance with water-stop gunite. However, if that is required, the question arises whether an additional membrane is even required, particularly when considering that the cost for a spray-applied mortar is similar to that of a membrane. Further, as the initial layer of shotcrete will likely be exposed to pressurized ground water, it must resist all chemical and leaching action of such water in order to form a permanent and reliable substrate for the waterproofing membrane. In general, a spray-applied membrane has to meet the following conditions:

- The membrane will be exposed to ground water and its chemical effects, and must resist it
- A spray-applied membrane embedded into a tunnel liner is part of the structural system. It must maintain all structurally relevant properties over the entire service life of the tunnel liner
- The bond between membrane and adjacent layers must be stable over the service life of the tunnel liner
- Where the membrane cannot meet all durability requirements, the liner cannot be considered part of the structural system.

It appears to be intuitively correct to assume that the bond strength between a membrane and the substrate should always meet or exceed a fixed minimum value. However, the substrate shotcrete will likely crack, which would strain a fully bonded membrane more than a membrane which is able to delaminate at the edges of the crack. On the other hand, excessive delaminating of a membrane would allow water to migrate between membrane and substrate, partially defeating the membrane’s purpose (See Fig. 52).



Targeted performance of a fully bonded polymer membrane [Girnau,G.; Haack,A. 1969]

- Crack bridging ability depends on strength, and strain capacity of the membrane, and its thickness
- Water can migrate along delaminations
- Cracks and joints may be oriented in multiple directions

Fig. 3: Optimum performance of a fully bonded membrane

Figure 52: Optimum performance of a fully bonded membrane

The following needs to be addressed:

- Partial delamination may create paths for water leakage on either side of the membrane, which must be limited
- The spray-applied membrane must be continuous and homogeneous in order to protect the inner structural layer
- A minimum thickness is required for crack bridging and to compensate for substrate surface roughness; multiple layers of membrane application may be required
- Both minimum and maximum bond strength limits must be specified and maintained
- The maximum crack widths of the substrate must be controlled.

Overall, a multi-layer monolithic tunnel liner with a bonded spray-applied membrane raises the following questions and concerns:

- A polymer membrane may creep under load
- A membrane's viscosity and cohesion is dependent on layer thickness, polymer content, swelling potential and water absorption
- Is the bond between layers facilitated by mechanical or chemical means?
- Crack bridging ability is a function of strain-to-rupture, actual strain and layer thickness.
- Cracks and joints require a membrane to strain in several directions
- In order to transfer shear loads across the membrane, it must be relatively stiff, which conflicts with some of the above described properties
- If the outer layer of the liner is fully water saturated, then the design must assume full hydrostatic pressure of the ground water acting on the membrane and the inner layer.

Sebastian Schmidt, Technische Universität München, Germany, Gereon Behnen, Büchting+Streit AG, München, Germany, and Oliver Fischer, Technische Universität München, Germany, presented on the *Verification of the bond strength of sprayed concrete – general conclusions and outlook for single tunnel linings*. Where single tunnel liners are used, the bond between the structural shotcrete liners sandwiching a water proofing membrane becomes very important for the structural behavior of the lining. As there may be normal compression stresses (from ground pressures and water) across the interfaces between the layers, tensile bond and shear resistance may be higher than expected from specimens tested in uniaxial mode. Current design codes and specifications may not take the effect of such multiaxial stress situations into account, nor do they fully address the effects of surface preparation techniques, spraying technology or differential shrinkage between shotcrete layers, on tensile and shear bond. Due to the curvature of tunnel linings, the roughness of shotcrete surfaces and normal stresses it may be possible to reduce the bond strength requirements conventionally applied to concrete construction joints.

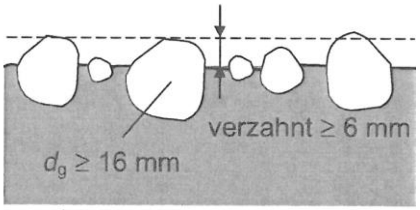
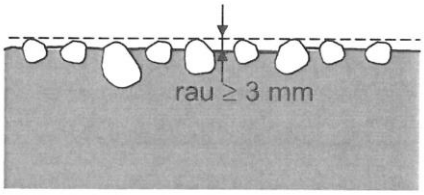
The current German design code for concrete construction joints, DIN EN 1992-1-1, considers the effects of adhesion, friction and shear reinforcement on the shear resistance of a joint:

$$v_{Rdi} = c_i \cdot f_{ctd} + \mu \cdot \sigma_N + \rho \cdot f_{yd} \, (1.2\mu \cdot \sin\alpha + \cos\alpha) < 0.50 \cdot v \cdot f_{cd} \qquad (1)$$

Where:
c_i: surface roughness coefficient
f_{ctd}: tensile strength of concrete;
μ: friction coefficient;
σ_N: stress due to minimum force normal to joint;
ρ: reinforcement ratio of shear joint;
f_{yd}: nominal yield strength of reinforcing steel;
α: orientation angle of reinforcement;
v: strength reduction coefficient for surface roughness in joint surface;
f_{cd}: nominal concrete compressive strength.

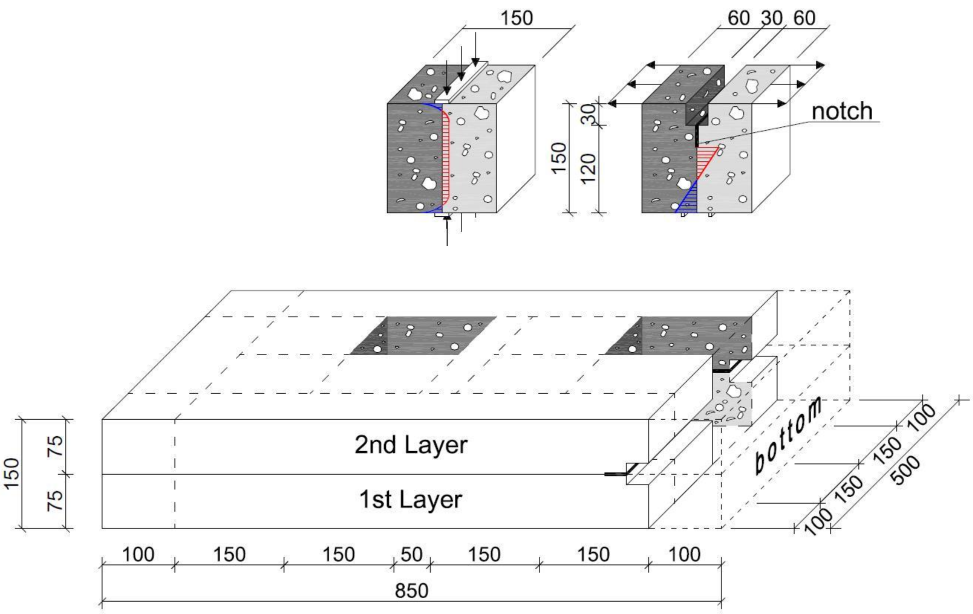
Table 9 below shows the surface roughness coefficients relevant for shotcrete:

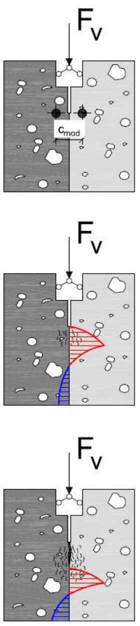
Table 9: Surface condition of the substrate

Type	Surface condition		c_i
interlock	Min. 6 mm exposure of aggregate if maximum aggregate size $d_g \geq 16$ mm; $R_t \geq 3{,}0$ mm;. $R_p \geq 2{,}2$ mm		0,50
rough	Min. 3 mm exposure of aggregate; $R_t \geq 1{,}5$ mm; $R_p \geq 1{,}1$ mm		0,40[1]

[1] $c_i = 0$ where joint is in tension.
R_t: average depth of troughs; R_p: height of peaks
1 mm = 0.0394“

Other methods are also described in the paper. In order to verify theoretical models, large-scale splitting tests were conducted as follows (all dimensions in mm, 1 mm = 0.0394”):





Note that the concrete bottom layer with nominally 37 MPa (5400 psi) cylinder strength was conditioned to meet the surface conditions shown in Table 10 below, before a 2nd layer, of dry-mix shotcrete, with the same nominal strength was sprayed and cured.

Table 10: Test parameters

Property	Surface roughness conditioning	1) hydro demolition 2) grit blasting
	Surface roughness	1) rough 2) interlocked 3) gun finish
	Surface moisture conditioning	1) air dried 2) wetted
	Substrate angle, from horizontal	1) 0° 2) 90°
	Concrete application	1) sprayed 2) cast
	Age of base plate	1) 28 days 2) 105 days

The following figures summarize the test results:

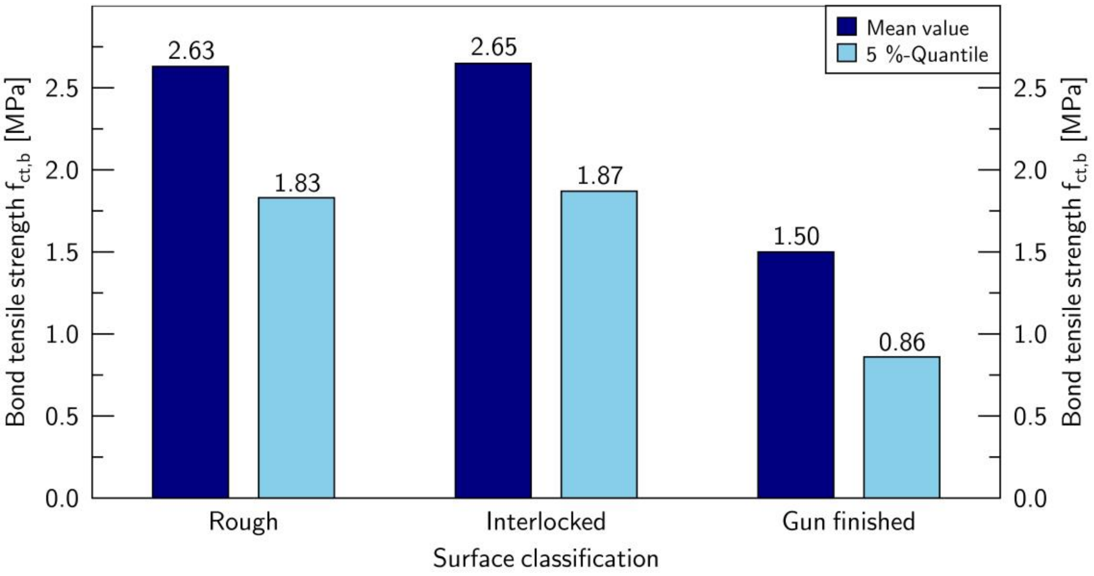


Figure 53: Average and lower 5-% fraction tensile bond strengths, 1 MPa = 145 psi

In addition, shrinkage tests showed that a significant difference between cast and sprayed concretes:

- Dry-mix shotcrete shrinkage: 0.12%
- Wet-mix shotcrete shrinkage:0.11%
- Base concrete shrinkage: 0.05%.

Of note was also the observation that shear force transmission in un-reinforced flat joints correlates well with the tensile strength of the joint. However, the curved joints of tunnels and the confinement of the joint by the inner layer and the rock, resist slippage of a joint even if it is completely delaminated. This is shown in principle in Figure 54 below. A numerical analysis of this effect is attempted by means of a finite element analysis.

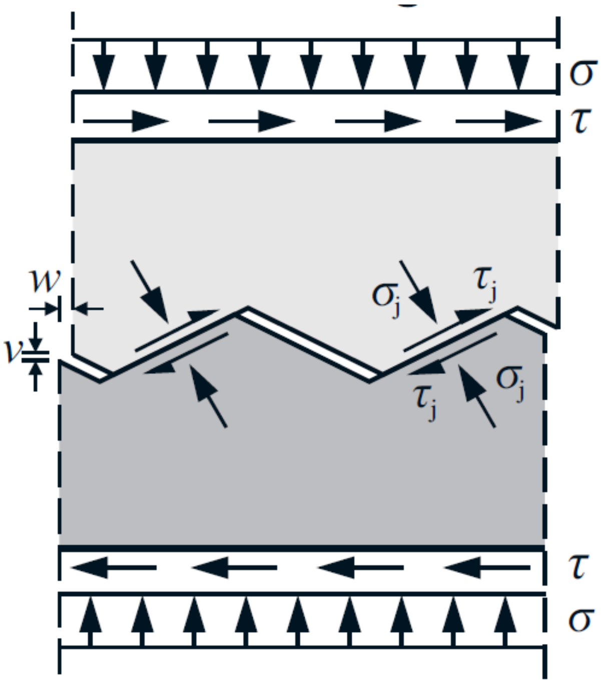


Figure 54: Activation of friction resistance through interlock

Anders Ansell (KTH Royal Institute of Technology, Stockolm, Sweden), and Lars Bryne (Vattenfa; Research and Development AB, Älvkarleby, Sweden, presented on *In-situ observations and laboratory testing of shrinkage cracking in shotcrete soft drains.* Their paper is available in English in the proceedings, and can be ordered from spritzbeton@kusterle.net. The following is the synopsis of their paper:

In Scandinavian traffic tunnels soft drains covered with shotcrete are often installed to lead away un-wanted water, giving little resistance to shotcrete shrinkage, which may cause severe cracking. Mapping of shrinkage cracks was done in situ, followed by analyses focused on stresses due to drying shrinkage and various time of waiting between turns of spraying, with or without water curing. The effect of dilatation joints has also been investigated. A recently developed laboratory test set-up with shotcrete on instrumented granite slabs represent shrinkage of shotcrete on soft drains. The test results indicate that addition of glass fibres could reduce the cracking problem.

Of particular interest to the reader may be the experiments with glass fibre reinforced shotcrete and shrinkage testing of restrained and un-restrained shotcrete slabs, as well as the effect of partial restrains on crack spacing, for which the following two images provide some information

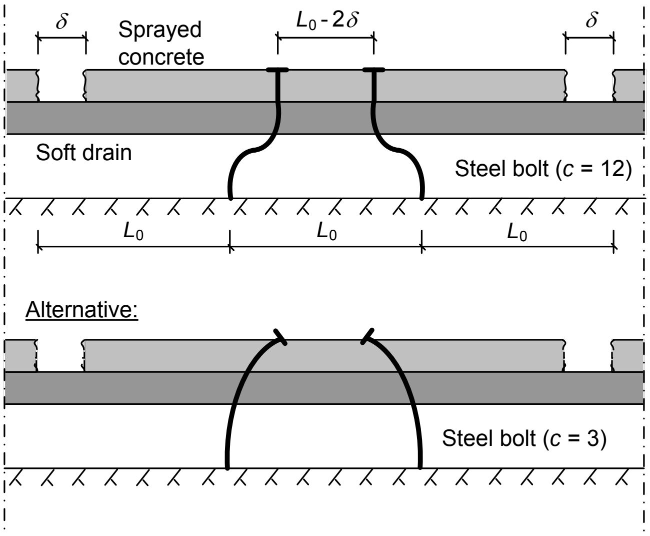


Figure 55: Shrinkage cracking of bolt anchored shotcrete on soft drains. Here c is a stiffness coefficient, depending on the connection between bolt and shotcrete. From [9].

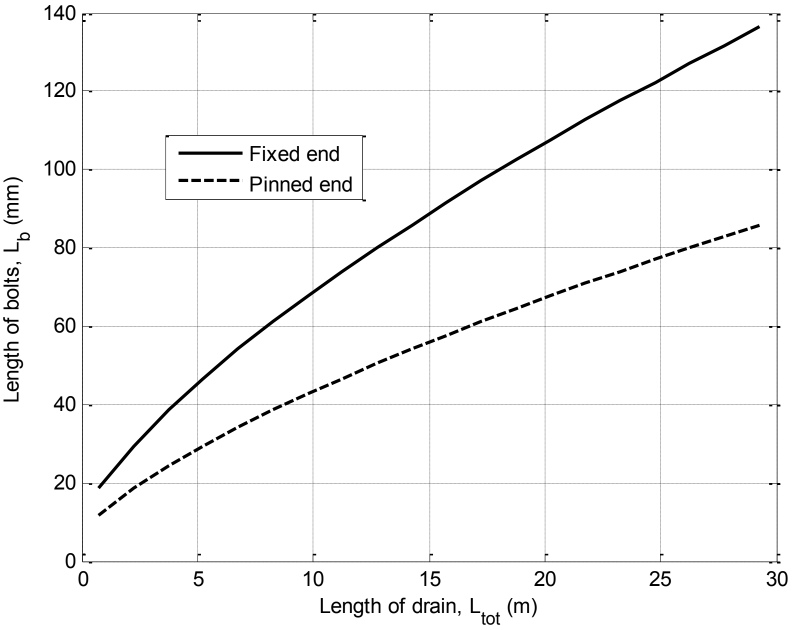


Figure 56: Relation between un-cracked length of shotcreted drain and length of anchoring steel bolts. From [9]. 1 m = 3.28 ft, 1 mm = 0.0394".

Götz Vollmann, Markus Thewes (both Ruhr-Universität Bochum, Germany) and Eugen Kleen (MC Bauchemie, Bottrop, Germany) presented on the *Development of a sprayed concrete with high fiber content as a countermeasure for buildings under fire and explosive loads.*

Infrastructure like bridges and tunnels are subject to low-probability but high-consequence events like fires caused by accidents of dangerous goods transports or by deliberate action. In order to mitigate the effects of such potentially disastrous events, protective measures like installation of shielding with tough and heat resistant materials may be selected. Applications are however limited to simple geometries. For more elaborate geometries, a protective shotcrete layer appears to be desirable. However, in order to achieve significantly improved performance under explosive and fire loads, ultra-high-strength shotcretes with > 2% by volume fibre content would be required. Such materials are is not currently in commercial use. The authors provided a systematic description of required specifications and the state-of-the-art in shotcrete technology with respect to resisting fire and explosion loads.

With respect to fire, the following standard fires should be considered:

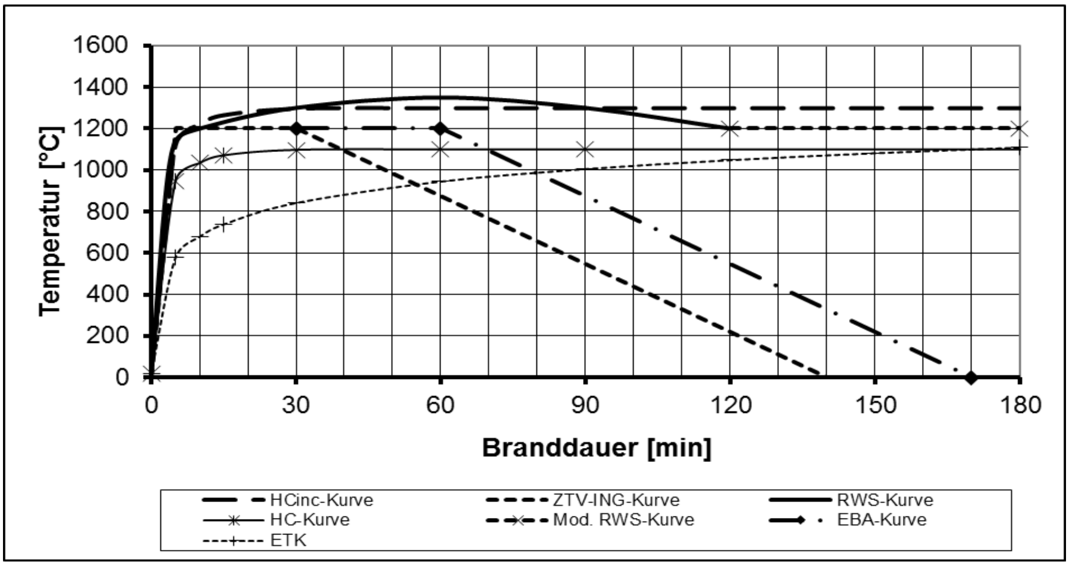


Figure 57: Relevant temperature vs. time curves for the design of fire resistance
Note: Duration of fire (Branddauer) plotted in minutes, vs. test temperature in °C. 1400°C ~ 2550°F.

Typically, concrete covers of >60 mm (>2.4”) are required to maintain rebar temperatures below 300°C (570°F) during those standard fires. In order to prevent spalling, polypropylene fibre contents of 1.5 kg/m^3 (0.15% by vol.) are required. For high strength concretes, this dosage is increased to 3 kg/m^3 (0.3% by vol.) in order to address increased propensity of explosive spalling at high temperatures.

Explosions are capable of building compressive stresses on the order of several GPa (hundreds of ksi) at the exposed face which may result in crater formation or full destruction. The reverse face can suffer crater formation due to reflected waves. The following image shows examples:

Figure 58: Reinforced concrete slab with punching failure due to explosion

In order to resist such failure modes, shotcretes with compressive strengths >110 MPa (>16 ksi) and fibre contents >140 kg/m^3 (235 lbs/yd^3), preferably a combination of macro and micro steel fibres have shown promise. However, such high fibre loads cannot be incorporated while maintaining pumpability of a traditional shotcrete. To obtain pumpable and shootable shotcrete, entraining air contents well beyond commonly acceptable proportions was necessary. In order to not reduce compressive strength of the shotcrete due to excessive air contents, the authors added defoaming and accelerating admixtures at the nozzle. The resulting shotcrete achieved densities in the 2400 kg/m^3 (4000 lbs/yd^3) range and compressive strengths well above 110 MPa (16 ksi). Concrete structures which receive a protective coating with such shotcrete (~100 to 120 mm, or 4 to 5", thick) appear to fare significantly better than un-protected structures when exposed to fire or explosions. Research is continuing.

Luke Pinkerton and Hans Hausfeld, both Helix Steel, Ann Arbor, USA, presented on *Twisted steel micro reinforcement (TSMR) for shotcrete*. Their paper is available in English in the proceedings, and can be ordered from spritzbeton@kusterle.net. The following is the synopsis of their paper:

Steel fibers have been used to reinforce shotcrete, replacing traditional steel wire mesh, for over twenty years. They are added to shotcrete to improve energy absorption, crack resistance and provide ductility. All three properties are very important for support systems designed for tunnel and mine conditions. TSMR (Twisted Steel Micro Reinforcement), takes shotcrete reinforcement one step further.

The twisted anchorage and yielding properties of these new fibers provide all these benefits and more at much lower dosages than had previously thought possible – 50% lower than hooked type fibers. Significant improvements in compressive, splitting tensile and flexural strengths have been documented.

Benoit De Rivaz of Bekaert Maccaferri Underground Solutions BVBA, Aals, Belgium, presented on *EFNARC creep test procedure description for sprayed concrete and test results with steel and synthetic fibres*. His paper is available in English in the proceedings, and can be ordered from spritzbeton@kusterle.net. The following is the synopsis of the paper:

Creep is a term used to define the tendency of a material to develop increasing strains through time when under a sustained load, thus resulting in increasing deflection or elongation values (depending on the type of loading) with time in relation to the initial, instantaneous strain that the material experiences directly after the load is applied.

A new test procedure concerning long term behaviour of fibre reinforced concrete under constant load has recently been proposed by EFNARC [1]. The test procedure is based on the square panel test and extended for a pre-cracked panel exposed to constant load.

This paper describes the results of an experimental campaign aimed at investigating the long term behaviour of steel and macro synthetic-fibre reinforced concrete plates on continuous support. The tests show the differences in the long term behaviour for shotcrete with different types of fibres.