7th International Symposium on Sprayed Concrete - roundup

In this article, Dr Benoît Jones, Director of the Tunnelling and Underground Space MSc at the University of Warwick, UK, summarises papers and debates at the recent sprayed concrete symposium in Sandefjørd, Norway.

THE INTERNATIONAL SYMPOSIUM ON SPRAYED CONCRETE is usually held every 3 years and is usually organised by the Norwegian Concrete Association. Therefore, it is nearly always held in Norway (except for 2002, when it was held in Davos, Switzerland). It is very well organised, but with a personal touch, and at a scale that means it is possible to talk to nearly everyone at some stage over the 3 days. The Chair of the Organising Committee, Ola Woldmo, was an excellent host and he and Thomas Beck, the Chair of the Scientific Committee, did a great job of managing the presentations and discussions.

In his opening address, Ola Woldmo quoted Tris Thomas's October 2011 Tunnelling Journal editorial, writing about the previous symposium:

> **"[…] a quick congratulations must go to the organisers of the 6th International Symposium on Sprayed Concrete in Tromsø, Norway, in September […] If all you event-organising companies (trying to make pots of cash out of our industry with your tunnelling shows) want to know about quality content, take a lead from this one. One method deliberated over three days by a selection of some of its top practitioners – and some of the Q&A sessions were just like the old days, let's just say not everybody agrees on everything – and long may that continue!"**

I didn't attend the 6th symposium in Tromsø (though I have read the proceedings), but I believe the same compliment could be paid to the 7th in Sandefjørd. The standard of presentations and debate was generally high, and real state-of-the-art knowledge was being shared and discussed by experts in the field.

It was a shame that the symposium was a bit dominated by suppliers – of the 115 participants about half were from chemical, cement, fibre or equipment suppliers, 10% were from universities and the rest were made up of consultants, clients and contractors, mainly from Scandinavian and Baltic countries. Most of the papers were written by academics or suppliers. The contractors, consultants and clients contributed only half a dozen papers, with half of these coming from the Norwegian Public Roads Administration. It would be nice if there were more participants and papers from contractors, consultants and clients, but this is not the organisers' fault, it is your fault, dear readers.

In this article I will try to summarise proceedings. Rather than trying to cover everything, I will try to focus on two specific areas to give a flavour, otherwise this article will either be very long or won't go into any depth. The two areas I'll focus on are 'Flexural strength and energy absorption testing methods' and 'Scale effects, mixing energy, workability and placement'. There were lots of other interesting papers on compressive strength testing using ultrasound and SMUTI, nozzleman training using simulators, spray-applied membranes, temperature effects and various new chemical admixtures, to name but a few of the myriad topics, and I encourage you to get a copy of the proceedings and have a read.

References without years (e.g. "Barton & Grimstad") refer to papers from this symposium, and references with years (e.g. "NB7, 2011") refer to other publications.

Flexural strength and energy absorption testing methods

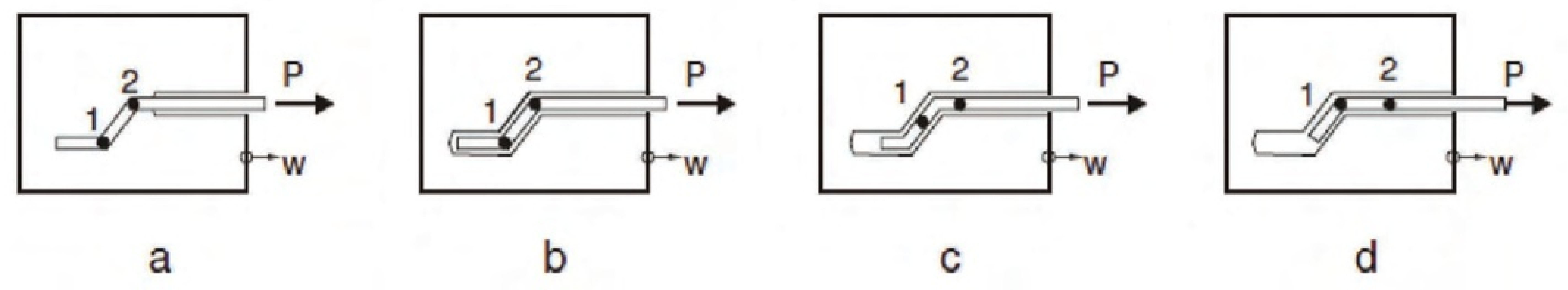
A hot topic at the previous symposium, this was again much discussed.

Stefan Bernard presented two papers. The first focused on creep rupture, which is failure under a sustained load after a period of time has elapsed. Steel fibre reinforced round determinate panels were pre-cracked by loading under servo control until average crack widths were between 2.5 and 4mm. They were then gravity loaded with some percentage of the static peak load for up to 9 months. Time to collapse was in excess of 10 days for panels loaded below 70% of static capacity, but steel fibres were found to pull out rapidly and the panels failed under a sustained flexural load of more than 75% of static capacity. Since these all failed in under 5 seconds, I am not sure it can be described as 'creep rupture' and it seems the initial loading needed to achieve the rather large initial crack widths had resulted in a significantly reduced residual capacity of approximately 60-70% of the peak value. It is a strain-softening material, after all. In fact, being able to sustain 60-70% of peak load at 2.5-4mm crack width is actually quite good.

Bernard goes on to compare the performance of these cracked steel fibre reinforced panels to plain concrete beams tested by Zhou (1992). It seemed that at high load ratios, the steel fibre reinforced panels had less resistance to creep rupture, and failed more quickly, than plain concrete. This is a facile comparison because the plain concrete was not pre-cracked, and had it been, it would have lasted zero seconds because it would have been in pieces. Perhaps there is something I am missing. Nevertheless, Bernard is right to remind us that residual flexural strength of steel fibre reinforced concrete with large cracks (2.5 to 4mm) is often less than the peak.

This reduced capacity as crack width increases is due to the hooked ends of the Dramix RC65/35BN fibres. At small deformations, the fibre provides resistance by elongating. As elongation increases, it is enabled by gradual debonding of the fibre

Figure 1: Progressive failure of a hooked-end steel fibre, (a) elongation and partial debonding, (b) fully debonded, (c) deformation of the fibre as it is pulled out of the bend in the concrete (d) pull-out of straightened fibre. Figure from Markovic (2006).



from the concrete, from the crack to the tip. Once the fibre is completely debonded, it is pulled out through the hooked bend in the concrete, resisted by plastic deformation round the bend and friction, as shown in Figure 1.
The fibres, once pulled out, are straight, as shown in Figure 2 from Bernard's paper.

In previous work by Bernard, at smaller crack widths of 0.5-1.0mm, time-dependent widening of the cracks was very slow (Bernard, 2010), and Bernard says, "Steel fibres tend to exhibit a greater degree of load resistance across narrow cracks than macro-synthetic fibres. Moreover, creep deformations (in the form of crack width increase over time) have been shown to be lower for steel FRS than for macro-synthetic, at least for narrow initial crack widths." The implication of the paper presented by Bernard at Sandefjørd on larger crack widths was that macro-synthetic fibres provided better ductility than steel. However, it would have been helpful if some evidence or reference to other work was provided from tests on macro-synthetic reinforced shotcrete panels to back up this claim.

The ASTM C1550 round determinate panel test is the most popular type of test for fibre reinforced shotcrete in Australian mines, where relatively thin shotcrete linings are used in hard rock, and "safety against the unexpected", i.e. large ground deformations and hence large crack widths, is important (both the Bjøntegaard, Myren & Skjølsvold and Bjøntegaard, Myren, Klemetsrud & Kompen papers also discuss this in the context of Norway's geology). In these cases, it is perhaps reasonable to want to know how the shotcrete will behave at crack widths well in excess of the 0.1-0.3mm usually prescribed for the serviceability limit state, and this is why the round panel test is preferred. Bernard states that it is normal practice to expect cracks of 5-10mm in width in Australian mines, and that in these cases macro-synthetic fibres have more ductility than steel fibres and also do not suffer corrosion or embrittlement. In his second paper (Bernard, Clements, Duffield & Morgan) he states that all Australian mines now use macro-synthetic fibres exclusively, although this was disputed in the discussion by Francis Kennedy, a fellow Australian.

Øyvind Bjøntegaard of the Norwegian Public Roads Administration was a frequent presence on the podium, because he was involved in three papers and his co-workers were on maternity leave. He presented round robin test results on nominally identical round panels tested at four laboratories, which demonstrated a within-lab coefficient of variation of 5.5-12.2% on energy absorption at 25mm central deflection (Bjøntegaard, Myren & Skjølsvold), which was in line with previous round robin trials.

Bjøntegaard, Myren, Klemetsrud & Kompen described a study of the effect of age on energy absorption capacity, from 2 days to 1 year. Bernard (2008), in a very important piece of work, had previously shown that time could have an adverse effect on energy absorption capacity. The increase in concrete strength with age and hence better bond to the fibres led to fibre failure in the cracks rather than bond failure, resulting in a much more brittle behaviour. Fibres provide more ductile behaviour when they are gradually pulled out. Bernard called this process 'embrittlement', though some may find this term confusing because this term is usually used for materials experiencing chemical changes due to aging and it sounds as though the fibre itself is becoming more brittle, which is not the case, it is the fibre reinforced concrete as a composite material that is becoming more brittle due to high concrete strength.

In Bjøntegaard, Myren, Klemetsrud & Kompen's study, round panels were sprayed and tested according to NB7 (2011), with three steel fibre reinforced shotcrete and three macro-synthetic reinforced shotcrete panels tested at each

Figure 2: Straightened fibres after total pull-out (Bernard, 2014)

age. The dosage was 35kg/m³ for the steel fibres and 6kg/m³ for the macro-synthetic fibres, meaning that the number of fibres in the mix was much higher for the macro-synthetic fibres, but the 28 day energy absorption was predicted to be similar based on experience. Results were presented at 5mm and 25mm central deflection. The crack widths were not measured but would increase with increasing central deflection and would be probably around half the central deflection value. At the smaller crack widths at a deflection of 5mm, the steel fibre reinforced shotcrete showed little change in energy absorption with time and the energy values were slightly higher than for the macro synthetic polypropylene fibres. At 25mm deflection they found that at ages greater than 7 days, corresponding to concrete cube strengths greater than 50MPa, the steel fibre reinforced concrete panels absorbed less energy than they did at younger ages, and this continued to get worse as the concrete got older and stronger. The cube strength was from cast specimens, so the true compressive strength could be estimated at around 35MPa, based on the correlation in the accompanying paper by Myren & Bjøntegaard.

The macro synthetic polypropylene fibres did not show the same embrittlement and in fact showed improved performance with age at both 5mm and 25mm deflection.

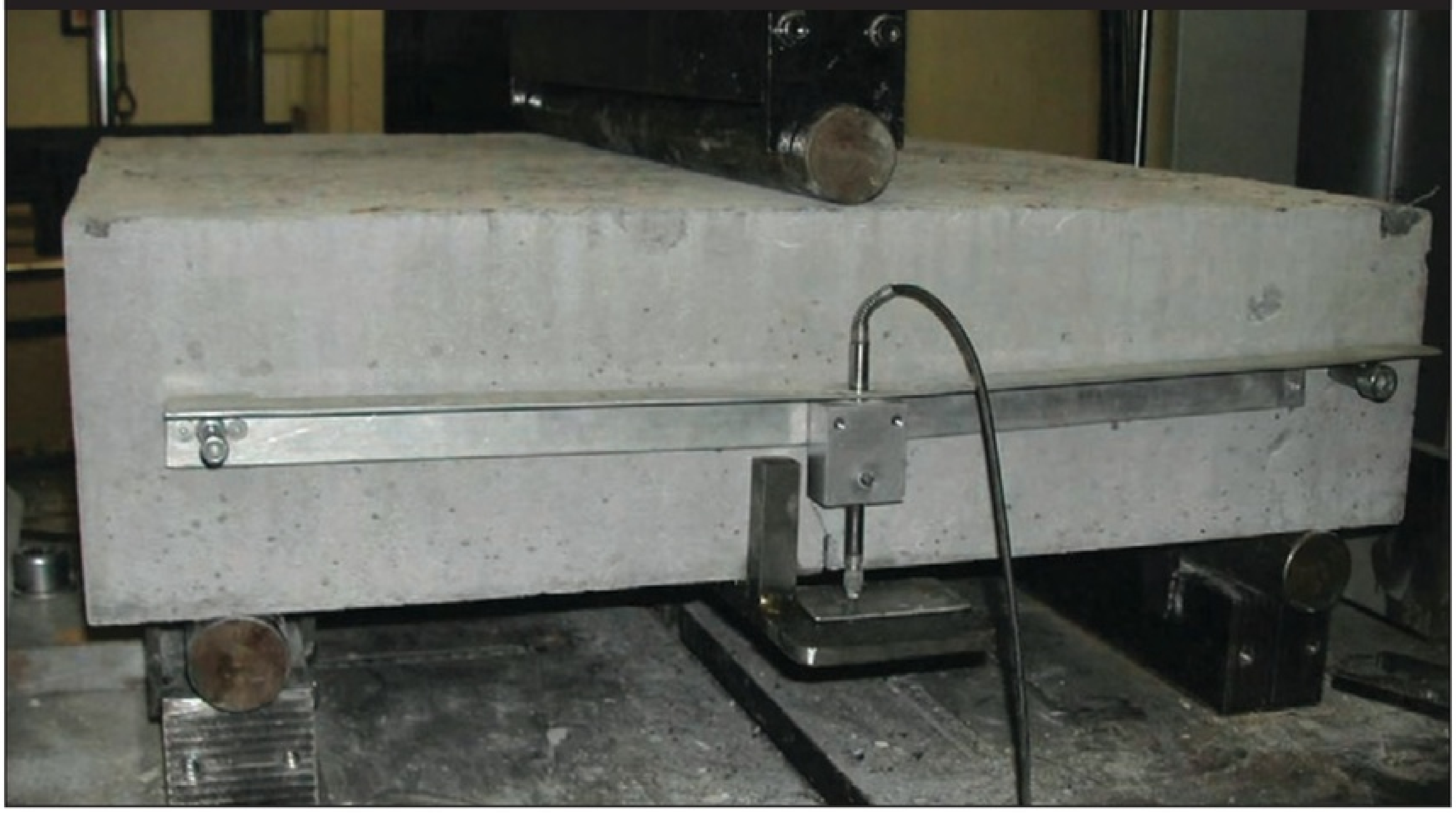
This is not the full story, and it is not so simple as to say that based on these tests macro-synthetic fibres are better than steel. The load-displacement graphs for the three steel fibre reinforced panels and the 3 macro-synthetic fibre reinforced panels at 91 days shown in Bjøntegaard, Myren, Klemetsrud & Kompen's paper show that at low values of displacement the energy absorption of the steel fibres (the area under the load-displacement curve) is far superior, and they are perhaps beginning to even out at somewhere just after 5mm deflection. It is probably fair to deduce from this that steel fibres will be much more effective at minimising crack widths and meeting serviceability requirements. Beam tests according to EN14651, upon which a structural design to the FIB Model Code 2010 (FIB, 2013) would be based, go up to a crack width of 3.5mm, in which case the steel fibres would in most cases outperform the macro-synthetic fibres.

Bjøntegaard, Myren, Klemetsrud & Kompen don't say what exact fibres were used, only that the steel ones were hooked-end, 35mm long, diameter 0.55mm and tensile strength 1250MPa and the macro-synthetic fibres have a continuously embossed surface, with length 54mm and tensile strength 640MPa. They suggest that improvements in performance may be achieved by reducing the concrete strength, using a higher fibre dosage or using higher strength fibres and they are currently in the process of investigating these issues. Early results presented in the paper indicate that using a lower (30kg/m³) dosage of higher strength steel fibres results in similar performance before 7 days, but energy absorption actually improves with higher concrete strengths beyond 50MPa up to the most recent test result at 90 days and 88MPa. These steel fibres consistently performed better than the macro-synthetic fibres at low and high displacements and at early and mature ages, with no sign of embrittlement.

Another aspect affecting perceived performance of fibre reinforced shotcrete is the testing method itself. ASTM C1550 specifies an 800mm diameter, 75mm thick round determinate panel (RDP) supported at three radial points. In Norway round panels are also used (NB7, 2011), but they are 600mm diameter, 100mm thick and have a continuous support around the circumference. The EN14488-5 square panel (also referred to as the EFNARC plate test) is 600x600mm and 100mm thick and also continuously supported. Benoît de Rivaz, of Bekaert, discussed all these tests and made the point that although there is a correlation between energy absorption in the EN and Norwegian tests, there cannot be a correlation with the RDP tests because it is determinate and the other tests are indeterminate.

Many people have had difficulties with EN14651 beam tests, because they seem to have larger scatter than panel tests, probably due to the variability in the number of fibres at the critical part of the section, which is a relatively small cross-sectional area. However, they are necessary because the panel tests do not directly give values of the parameters needed for structural design. De Rivaz talked about a proposed new EFNARC test; a 3-point bending test on a 600x600x100mm square panel, with a notch (Figure 3). The advantage is that by analogy with the beam test, it provides values of residual flexural strength (fR1 and fR3 values) for use with the FIB Model Code 2010 (FIB, 2013), but should have less scatter in the results.

Figure 3: Three point bending test on square panel with notch (from de Rivaz)



The new EFNARC test was examined in a paper by Uotinen, Suikkanen & Siren using the original yield-line theory, a modified yield-line theory, a fracture mechanics approach and finite element analysis. One problem they highlight is that surface roughness may cause unequal loading on the top of the slab.

The consensus in the ensuing discussions seemed to be that if you wish to design your shotcrete for large deformations while spanning between rockbolts, then perhaps specifying energy absorption values at large deformations in round or square panel tests is the way forward, as the most recent version of the Q-system does (Barton & Grimstad). In this case, thin linings with macro-synthetic fibres may be an option, although it seems that similar or even better performance may be achievable with steel fibres at the right dosage and tensile strength, ensuring they are compatible with the concrete strength to avoid embrittlement. Any of the panel tests can be used. In this case design parameters are less important, because the shotcrete is not acting as a structural arch.

In soft ground, where linings tend to be thicker and are acting as an arch rather than spanning between rockbolts, and if you wish to design a lining for serviceability limit state as well as the ultimate limit state, then at present it seems the situation is a bit inadequate. The new EFNARC test described by de Rivaz may be a possible solution, as could similar larger or wider beams or simple methods of running a test and interpreting it without needing a notch. This is an area that needs a whole lot more research and I personally would like to hear from anyone that has views on this matter.

Scale effects, mixing energy, workability and placement

Myrdal & Griffith presented results of a preliminary study comparing the effectiveness of consistence control admixtures (e.g. superplasticisers) and retarding admixtures in improving workability. In the laboratory, using a desktop Hobart mixer, they unexpectedly found that sodium gluconate retarder did a better of job of retaining workability than commercial consistence control admixtures, and when alkali-free accelerator was added, the early strength was better. However, when these same trials were repeated with full-scale spraying, they found the early strength was better with the consistence control admixtures. They attributed this disparity in the results to the method of mixing the accelerator into the concrete; in the laboratory mixing is relatively gentle compared to the nozzle of typical spraying equipment.

The most common method of trialling new admixtures is to mix small quantities of mortar either by hand or using a desktop mixer, but Myrdal & Griffith's study demonstrated that the results are not always reliable due to the reduced mixing energy available. In addition, strength results using these methods are always lower than for sprayed concrete due to the difficulty of mixing accelerator homogeneously and then having to manually compact accelerated mortar into prism moulds, which results in inferior compaction.

Lindlar, Oblak, Lootens & Stenger described attempts to overcome these shortcomings using small scale spraying equipment in a laboratory. The 'pilot scale' equipment allows 50 litres of ordinary shotcrete with aggregates up to 8mm to be sprayed using a single long piston pump. Panels of sufficient size to enable needle tests and Hilti gun tests can be sprayed. The 'mini-shot' equipment is much smaller scale, spraying only the paste without sand or aggregate (described in more detail in Oblak, Lindlar & Lootens). Estimates of strength can be made by using a 'Pulsment' ultrasound spectrometer (for more information on this, see paper by Lootens, Hansson, Oblak & Lindlar). Compared to full-scale field trials, the estimated strengths appear to be reasonably similar, so this may be a very efficient way of comparing the effects of different admixtures. However, it is unclear in both papers how the ultrasound correlation with strength was obtained (if it was done using the data presented then it is of course not surprising that there is a good correlation) and how repeatable it may be with different water/cement ratios, cement types, supplementary cementitious materials and admixtures.

Reinhold & Wetzig performed full-scale spraying trials at the Hagerbach Test Gallery varying air flow and nozzle distance and measuring the effect on sprayed concrete properties. Increasing nozzle distance will result in lower impact

REFERENCES

Proceedings of the 7th International Symposium on Sprayed Concrete – Modern Use of Wet Mix Sprayed Concrete for Underground Support, Sandefjørd, Norway, 16th – 19th June 2014, edited by Thomas Beck, Ola Woldmo and Siri Engen, and published may be obtained from the Norwegian Concrete Association by contacting Siri Engen siri.engen@tekna.no .

Papers from the Sandefjørd symposium cited in this article are:

Barton, N. & Grimstad, E. (pp.33-49). Q-system application in NMT and NATM and the consequences of overbreak.
Bernard, S. (pp.56-66). Creep rupture of steel fibre reinforced shotcrete loaded in flexure.
Bernard, S., Clements, M. J. K., Duffield, S. & Morgan, R. (pp.67-75). Development of macro-synthetic fibre reinforced shotcrete in Australia.
Bjøntegaard, Ø., Myren, S. & Skjølsvold, O. (pp.76-87). Energy absorption capacity of fibre reinforced sprayed concrete (FRSC) panels: round robin test results.
Bjøntegaard, Ø., Myren, S., Klemetsrud, K. & Kompen, R. (pp.88-97). Fibre reinforced sprayed concrete (FRSC): Energy absorption capacity from 2 days age to one year.
De Rivaz, B. (pp.124-135). Test method of sprayed concrete – energy absorption of EN14488-5 and residual strength of EFNARC.
Ginouse, N. & Jolin, M. (pp.173-183). Characterization of placement phenomenon in wet sprayed concrete.
Jolin, M., Melo, F. & Bissonnette, B. (pp.233-244). Concrete durability applied to sprayed concrete mixture design.
Lindlar, B., Oblak, L., Lootens, D. & Stenger, C. (pp.282-286). From tunnel to laboratory: scaling of shotcrete testing.
Lootens, D., Hansson, M., Oblak, L. & Lindlar, B. (pp.287-293). Ultrasonic wave propagation for strength measurements: application in shotcrete.
Myren, S. A. & Bjøntegaard, Ø. (pp.305-313). Fibre reinforced sprayed concrete (FRSC): Mechanical properties and pre structure characteristics.
Oblak, L., Lindlar, B. & Lootens (pp.314-319). Mini spray unit for shotcrete laboratory tests.
Reinhold, M. & Wetzig, V. (pp.320-329). Influences of air-flow at nozzle-distance on sprayed concrete properties.
Uotinen, L., Suikannen, J. & Siren, T. (pp.387-400). Modified yield-line theory approach to determine sprayed concrete flexural capacity.

Other references:

Bernard, E. S. (2008). Embrittlement of fibre reinforced shotcrete. Shotcrete, summer 2008.
Bernard, E. S. (2010). Influence of Fiber Type on Creep Deformation of Cracked Fiber Reinforced Shotcrete Panels, ACI Journal of Materials 107, No. 5, 474-480.
FIB (2013). FIB Model Code for Concrete Structures 2010. Berlin: Ernst & Sohn.
Markovic, I. (2006). High Performance Hybrid-fibre Concrete: Development and Utilisation. Doctoral Thesis, Technical University of Delft.
NB7 (2011). Norwegian Concrete Association Publication no.7: Sprayed concrete for rock support. Oslo: Tekna.
Zhou, F. P. (1992). Time-dependent crack growth and fracture in concrete. Doctoral thesis TVBM-1011, Lund Institute of Technology.

velocities and increasing air flow will increase impact velocities. They also used a high-speed camera to film the stream of shotcrete from the nozzle and estimate particle velocities. Particles with optimal impact velocity will penetrate into the freshly sprayed concrete surface. Too high a velocity results in craters and disaggregation, while too low a velocity results in poor compaction and increased rebound. At a nozzle distance of 1.5m, it was found that varying air flow from 5 to 16.5m^3/min had a negligible effect on concrete density or strength. At an air flow of 10m^3/min, varying the nozzle distance from 0.8 to 2.5m had little effect also. The optimum was 1.5m nozzle distance coupled with an air flow of 10m^3/min, which is broadly in line with best practice. Rebound was found to increase with nozzle distance and was lowest at 0.8m, where fibre contents in the sprayed concrete were also found to be highest. The highest air flow coupled with the largest nozzle distance resulted in disaggregation, and the panels sprayed at the lowest nozzle distance of 0.8m had a very uneven surface, reflecting the difficulty in spraying evenly when the nozzle is so close.

> **“The consensus in the ensuing discussions seemed to be that if you wish to design your shotcrete for large deformations while spanning between rockbolts, then perhaps specifying energy absorption values at large deformations in round or square panel tests is the way forward,”**

Ginouse & Jolin of the Université Laval in Canada described a carefully designed study of the placement phenomenon of wet sprayed concrete. They used arrays of tubes to capture the stream of shotcrete through the air, and then compared this with shotcrete as-placed onto a flat wall in order to quantify the effects of impact and rebound on the mass distribution. They found that at the periphery of the spray stream, and on the wall, there were more paste and fines – this was attributed to the lubricating layer of paste and fines around the inside of the hose as the wet mix shotcrete is pumped. This experimental method could be very helpful for the optimisation of spraying equipment.

In a further paper, Jolin, Melo & Bissonnette accentuated the importance of particle size distribution in achieving a flowing mix that pumps well, does not segregate and compacts well. In North America it is becoming common practice to add air-entraining admixtures to shotcrete to achieve 10-15% air content. This improves workability, and on impact the air is driven out producing an immediate slump-killing effect. This means lower water-cement ratios can be used with lower accelerator dosages.

Summary

I hope this short review of a selection of papers from the symposium gives a flavour of the proceedings. These types of conferences are crucial to sharing knowledge and reaching consensus on better methods of spraying concrete and better testing methods. They are also great for putting new ideas out there and seeing what the experts think.

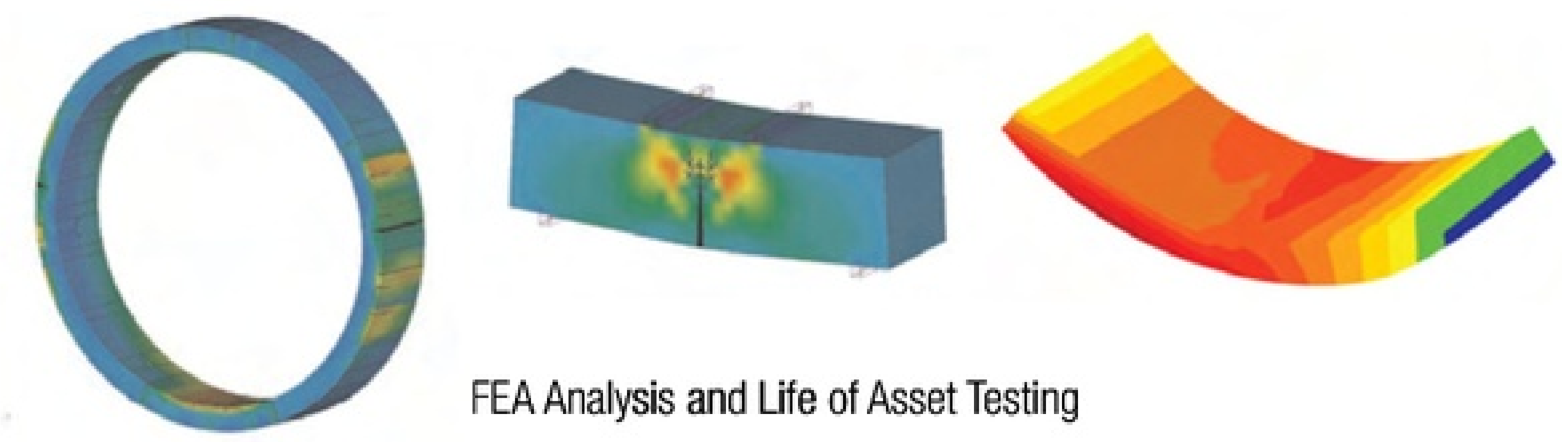
Elasto Plastic Concrete
THE SYNTHETIC FIBRE EXPERTS

Scan to find out more

WWW.ELASTOPLASTIC.COM

Get total synthetic fibre reinforcement solutions with Elasto Plastic Concrete.

- Expert Shotcrete and Concrete Advice
- Expert Synthetic Fibre Reinforcement Advice
- Engineered and Finite Element Analysis Designs


FEA Analysis and Life of Asset Testing


USED IN SPRAYED CONCRETE LININGS


USED IN CAST IN-SITU LININGS


USED IN SEGMENTAL LININGS

EPC'S BARCHIP FIBRE BENEFITS

- LONG TERM DURABILITY - Barchip reinforcement does not rust or corrode
- OPTIMISED DOSE RATE - Using finite element analysis
- UP TO 80 % REDUCTION - In transport, handling and storage costs
- TRIED AND TESTED - By major corporations and engineering experts worldwide
- SYNTHETIC FRC - Can be used to replace steel FRC with no adverse affects due to creep
- ELIMINATES - Bending, cutting and placing of steel mesh
- REDUCES HANDLING, Transport and storage or steel materials
- REDUCES MAINTENANCE - Of shotcrete equipment, particularly hoses and nozzles

WHEN PERFORMANCE MATTERS, CHOOSE ELASTO PLASTIC CONCRETE