Sprayed concrete and carbon: how low can we go?

As the demand for decarbonisation from investors and governments grows, tunnel linings - and their cement content - are coming under scrutiny. What does this mean for sprayed concrete, asks Kristina Smith.

In December last year Shotcrete Services trialled sprayed concrete in which 70% of the cement had been replaced by ground granulated blast furnace slag (GGBS). Tests went on to show that the concrete's performance and durability characteristics were potentially conformant to typical specifications for sprayed concrete linings (SCL) – but with a 60% lower carbon footprint.

A typical SCL mix would contain 480kg per cubic metre of CEM I, or pure Ordinary Portland Cement (OPC). Due to its carbon intensity, the CEM I component of SCL accounts for around 80% of its embodied carbon.

Shotcrete Services' successful trial is significant because using high proportions of supplementary cementitious materials (SCMs) like slag, while commonplace in cast concrete as a means of improving durability, is problematic in sprayed concrete. Such mixes don't work well with contemporary liquid accelerators, which are formulated to work with CEM I cement. This means they can't gain strength quickly enough to be used for SCL.

Shotcrete Services is working on its 'low carbon sprayed concrete' with GGBS supplier Ecocem, Loughborough University, Arup and Peaston Concrete Consultancy. There are still some problems to iron out– of which, more later – but it has the potential to provide a solution for contractors looking to meet carbon reduction targets on major infrastructure projects with sprayed concrete elements.

Looking at the wider picture, reducing the cement content in sprayed concrete is just one piece in a much bigger jigsaw which encompasses issues including new approaches to planning and early design, better design, greater cooperation between designer and contractor, higher standards of execution and – crucially – longevity of the structure.

"If we are thinking about carbon, the idea should be to optimise without overdoing it," cautions Wolfgang Aldrian, principal expert, tunnelling and mining at Master Builders Solutions and an expert on SCL. "A tunnel should last for a long time with minimum refurbishment needs. If you have to close it after 10 years for structural refurbishment, that is not a low carbon solution."

Demanding decarbonisation

The last few years have seen a huge shift in attitudes towards sustainability and environmental issues. National and local governments are still getting up to speed in most regions but, in the meantime, the private sector is stepping in to exert pressure. Shareholders, investors and funders are demanding that companies actively demonstrate their commitment to decarbonisation.

"We have seen that attitude extend to very large underground projects - big mining investments rather than tunnelling at the moment," says Ross Dimmock,

Shotcrete Services successfully sprayed concrete with 70% of its cement replaced by slag, a 60% carbon saving.

"Banks are giving better borrowing rates for mining projects that invest in electric underground fleets."

Ross Dimmock, Normet

Normet's vice president tunnelling. "Owners are looking to invest in a whole fleet of electric underground vehicles, for instance, because they get much better borrowing rates from large central European banks."

Publicly funded infrastructure projects have yet to catch up. Dimmock is frustrated that other Governments don't follow Norway's aggressive decarbonisation lead; it is banning fossil fuel cars from 2025 and already has over 70% electric vehicles, there are government incentives for the construction industry to go green and seven cities have committed to carbon neutrality by 2025.

All the Nordic countries are also advancing fast and other countries are gaining pace. In the UK, HS2's Net Zero Carbon Plan, published in January 2022, says that it will reduce carbon emissions from steel and concrete by 50% by 2030 compared to 2021 levels.

In France, the Grand Paris Express is taking the lead. Société du Grand Paris's chair Jean-François Monteils, appointed in March 2021, has committed to reducing greenhouse gas emissions due to construction by 25%, although timescales and baselines are not yet clear.

"The impact of Grand Paris is very strong in France," comments Benoit de Rivaz, global technical manager at Bekaert Underground Solutions. "There has been a lot of communication, and with the chair actively talking about the subject, it has captured the minds of the people."

De Rivaz points out that tunnel linings – until recently considered the least exciting part of a tunnelling project – are now taking centre stage, thanks to the introduction of carbon reduction goals such as those mentioned above. On Grand Paris, the use of fibre-reinforced concrete for the segments on Line 16 Lot 1 is a first for France, and will deliver steel and hence carbon savings, he says.

Transparent and robust carbon data is vital in measuring and reducing carbon emissions, says De Rivaz. In June last year Bekaert achieved an EPD (Environmental Product Declaration) certificate for its Dramix fibres manufactured at its plant in Petrovice. De Rivaz believes that EPDs, which contain information about a product's carbon footprint, will be coming under closer scrutiny as carbon governance becomes more mature.

The International Tunnelling and Underground Space Association (ITA) announced in April that it was setting up a new activity group focused on low carbon concrete for shafts and linings, which it says are responsible for 60 to 70% of the embodied carbon in a tunnelling project. Benoit Jones, managing director of Inbye Engineering will chair the group. "It will encourage the use of low carbon concretes for sprayed concrete, segmental linings and cast in situ concrete, by providing case studies and recommendations for clients, designers and constructors," says Jones.

Cutting back on cement

Shotcrete Services and Ecocem have been working on their low carbon sprayed concrete for over five years. Now, with other organisations on board, the goal is to get the technology project-ready in time to be used on Skanska Costain Strabag's (SCS's) HS2 Main Works S1 and S2 contracts which involve the southern section of the UK's new high-speed rail line.

Chris Peaston, director at Peaston Concrete Consultancy, came across the technology around three years ago when he was an associate at Arup. Working with Shotcrete Services, Ecocem and Loughborough University, Peaston first obtained internal funding from Arup to develop its understanding of the idea, following which the group won a small research grant from the Institution of Structural Engineers.

Back then, Peaston was working on the specification for the S1 and S2 works, as part of SCS's design team Design House, a consortium of Arup, Typsa and Strabag. "In writing that specification, some of the prescriptive requirements were changed so that it had the potential to use this new material," says Peaston. "They were altered it to make it performance based, and to permit innovation."

A standard sprayed concrete specification – based on the British Tunnelling Society (BTS) specification – mandates liquid accelerators. But the low carbon sprayed concrete employs a powdered accelerator. Manufactured by Japanese company Denka and sold under license by Ecocem, the accelerator principally

"Performance-based specifications enable innovation."

Chris Peaston, Peaston Concrete Consultancy

comprises amorphous calcium aluminate and calcium sulfate.

Powdered accelerators, which were silicate based and highly caustic, were used in the early days of sprayed concrete, combined with wet mix at the nozzle, but were discontinued long ago due to health and safety risks. According to John Reddy, group quality and innovation application manager at Ecocem, the Denka accelerator is a totally different material: it is not caustic and has the same COSHH (Control of Substances Hazardous to Health) considerations as CEM I.

HS2 has provided two tranches of funding to the research through its Innovation Team. The first was awarded to Loughborough University through HS2's Collaboratorium for Research on Infrastructure and Cities (UKCRIC) framework and was used to fund the trials at Shotcrete Services' premises in Kent. The second will be delivered through the SCS contract and will be used to develop the reliability of the present prototype spraying equipment, while safely combining the powdered accelerator.

"Any accelerator must be introduced at the nozzle adjacent to the workface. Powdered accelerators present a unique challenge and we recognise we need to address the related issues," says Peaston.

With SCS's sprayed concrete works on HS2 set to start in around a years' time, Shotcrete Services and partners have work to do to come up with equipment that can create a reliably homogeneous mix. They will also be looking at whether they can increase the proportion of GGBS replacement to 80%, reducing the CEM I content to around 120kg per cubic metre with a commensurate carbon reduction of up to 65%.

"The technology also allows for spraying a CIII/B combination, which has enhanced sulfate resistant and is hitherto unachievable in sprayed concrete," says Peaston.

Aldrian's theory of a more modest cement replacement regime comes from his observation of Austrian practice, where engineers created a mix design for low leaching because drainage pipes were too often blocked. The mix has 280kg per cubic metre of CEM I and 140kg per cubic metre of SCM which can be a mix of fly ash, slag and limestone, with a minimum reactivity as defined by Austrian standards.

"They use the same accelerator at the same dosage [as for a standard mix]," says Aldrian. "The acceleration is comparable. In Austria it has more or less taken over."

"The idea should be to optimise without overdoing it."

Wolfgang Aldrian, Master Builders Solutions

Dr Sauer & Partners deployed sophisticated design tools to ensure that the linings of the vast underground station caverns for Toronto's Eglinton line were as slim as possible.

The Austrian mix requires a decent quality of cement, says Aldrian, going on to explain that all sprayed concrete operations need stability of cement. Variation in the make-up of the cement means that the concrete mix can behave wildly differently with the same dose of accelerator.

Aldrian believes that calcinated clay offers hope as a good SCM for the future, as both slag and fly ash will become less available as coal-fired power stations shut down and steel manufacturing operations use more and more recycled materials and move to different locations around the world. "For us the question is can it be accelerated?" says Aldrian. "This is something we need to look into."

Better design

According to Dr Sauer & Partner's technical director, Thomas Schwind, the most important step towards lowering the carbon footprint of infrastructure projects is better design.

"As engineers, our duty on carbon savings is to use the materials we have more efficiently," he says. "Replacing some of the cement with pozzolanic materials can be helpful, but there are big opportunities in not using so much of the material."

The inter-dependence of efficient design, cost savings and carbon savings was recently demonstrated on the Eglinton Crosstown light rail project in Toronto, Canada, a 30-year, CAD $9.1bn Public Private Partnership (PPP). The form of construction contract – design-build, under the PPP umbrella – meant that the contractor was pushing the design team for cost and schedule efficiencies from day one, says Schwind.

Concessionaire Crosslinx Transit Solutions chose to replace three of the planned cut-and-cover stations with large SEM (sequential excavated method) mined caverns. There were various reasons for this, says Schwind, including avoiding the constraints and risks of utilities relocation, reducing disruption at the surface, program flexibility and resource flexibility.

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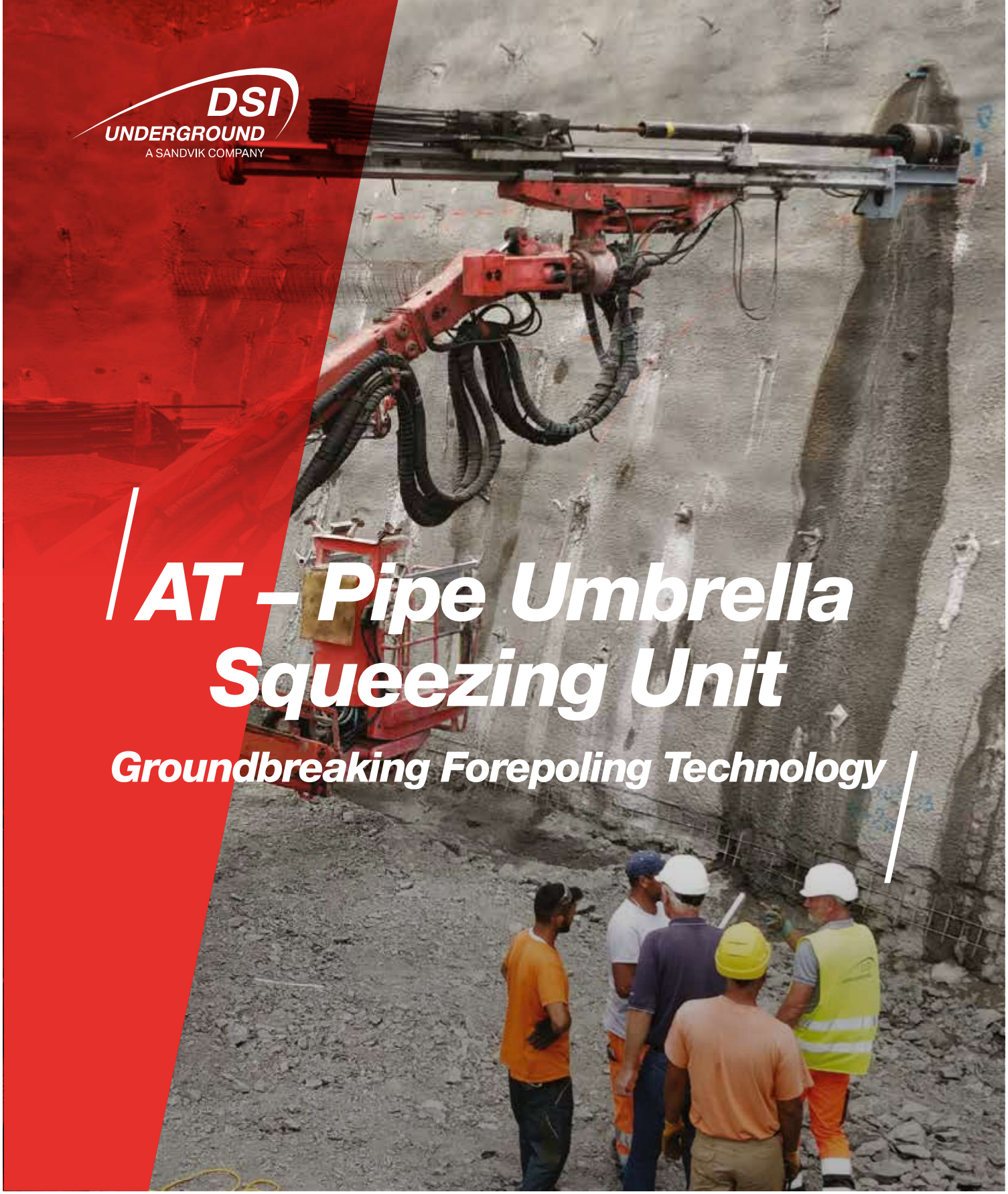

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"During the design process we were talking about how to make the linings thinner, how to make slabs thinner, how to be leaner and more efficient," says Schwind. "The main goals were cost savings or schedule savings, but in doing this we also saved significantly on carbon too."

The new 19km-long line runs underground for 10km, with 15 of its 25 stations underground. The three SEM caverns, which are around 17m wide, 14m high and up to 500m long are relatively shallow and had to be excavated through over-consolidated and highly variable glacial soils.

The structure of the cavern linings is double shell: a primary lining, PVC sheet membrane and a secondary lining. Both primary and secondary linings are of a similar thickness, between 400 and 450mm with both linings considered permanent; that is, taking loads in the permanent state.

"We minimised the thickness of the lining using very sophisticated analysis," says Schwind. "We used 3D FEM analysis, very complex elastic plastic concrete models that allowed for redistribution of stresses in the shells and allowed us to utilise the materials to the best effect."

Dr Sauer & Partners specified fibre reinforced concrete, with the contractor electing to use macrosynthetic fibres from Master Builders Solutions rather than steel ones. "They came out on top in the economic assessment," says Schwind. "We prescribed the performance, flexural strength, residual strength. If the mix can provide the properties we require, we are okay with that."

At points where a concourse slab connects with the walls of a cavern, steel car reinforcement was used. Dr Sauer & Partner's design deployed hollow core elements for the slab, saving on cost and weight but also on carbon.

Getting the shape right in design and in construction is vital in minimising material use, says Schwind. "For us, shape control is very important," he says. "It is important to create tunnel shapes that experience the expected loading conditions, under compression and therefore not needing a high percentage of reinforcement."

Because inner linings often are not in compression, they can be prone to cracking. "Many of our inner linings have very little load. Often, they are simply a safety feature," says Aldrian. "If this is true, it is only lightly loaded and you get shrinkage cracks, unless you pay close attention to the curing, because it's not loaded."

Schwind explains the impact of a close relationship between designer and contractor: "There was very good cooperation with the contractor which meant we could explain and communicate directly to the contractor where the quality was really needed, what the critical sections were and what they needed to focus on," he says. "When you know the people in the field very well, you can communicate with them."

High quality, long life

One of the reasons that some sprayed concrete linings are overdesigned, is that the quality of application can be unreliable. Aldrian believes that to assure quality there should be more rigour in assuring the competency of the nozzle operatives.

"As engineers, our duty is to use materials more efficiently."

Thomas Schwind, Dr Sauer & Partners

"You don't need a licence to spray a concrete lining that is supposed to last for 100 years. This for me does not make sense." While competency can be high in regions where sprayed concrete is an established technology, this is not the case for developing markets. In these regions, providing training to nozzle operatives is important from a long-term carbon reduction perspective, says Aldrian, because it means structures will last longer.

Alongside an experienced nozzle operative comes the need for high-performing machinery, to ensure that all the components of the shotcrete are sufficiently mixed to create a homogenous end product. "You need an uninterrupted stream at the nozzle or at least significantly reduced pulsation," says Aldrian. However, he observes that such technology and its impact has not been valued in the past.

Assuming that the spraying equipment is good enough, the next step could be to introduce technology that helps to limit overspraying – and hence carbon. Normet is developing its SmartScan system so that it can provide real-time information on the profile, rather than the nozzleman having to wait for information to be processed. The latest georeferenced system is called SmartScan Align.

In the great scheme of things, whilst switching to electric drive spraying robots has some impact on the carbon footprint of a project, says Ross: "The real savings are not so much in the sprayers but in the materials transport in and out of the tunnels." The carbon due to the cement in the linings still dominates the equation. However, there are benefits to electric vehicles beyond lowering embodied carbon: the trucks do not produce particulate matter, they are cooler, quieter, require less ventilation and less maintenance, says Dimmock.

Though the take-up of electric tunnelling equipment is low outside of Norway, there is interest from other countries. And other manufacturers are rising to the challenge.

Having launched a hybrid truck-mounted concrete pump in November 2021, Putzmeister is now preparing to launch the all-electric iONTRON truck mixer later this year. With a battery capacity of 350kW/h, the truck will have an eight-hour working window, says the manufacturer.

Another way?

Even with designs and materials optimised, nozzle operatives trained and competent, and lining thicknesses laser controlled, sprayed concrete linings creates a lot of waste. Over-excavation, over-spraying, rebound and rejected batches of concrete mean that up to twice the design quantity of sprayed concrete can be used.

Over-excavation is the biggest problem, says Dimmock. Even with the most diligent control, it is impossible to avoid, since it is the condition of the ground itself which often means that more of the rock than intended comes away. Rebound too can be significant: 10% loss for rebound is pretty standard according to Dimmock, but in some regions it can be as high as 30%, depending on the process employed.

Benoit Jones thinks that sprayed concrete may be overused now and that the industry should look at more radical alternatives.

"We're probably doing shotcrete as well as it can be done," he says. "We are incrementally reducing the carbon footprint by using replacement cements, working with different accelerators that work with low carbon concrete and I feel like we need to do something a bit more revolutionary."

Jones looks back to an era in London when the tricky junctions and shapes of metro tunnels were accommodated by specially made cast iron segments and thinks that a more cost-effective and carbon-effective modern-day mechanised and automated version would be a good solution. Offsite manufacture also removes quality issues and reduces waste, he points out.

Dimmock thinks that owners should be going

Crosslinx Transit Solutions chose to construct three stations on Toronto's Eglinton line using SEM rather than cut-and-cover. Oakwood Station, pictured here, was one of them.

for a much more holistic approach, as set out in PAS 2080 – carbon management in infrastructure, rather than simply setting carbon reduction targets for contractors once contracts have been won. PAS 2080, published in 2016 and being updated this year, asks owners and designers to look at alternatives very early in the planning and design process.

Tunnelling project clients should ask for broad-brush carbon assessments at the time of tender, says Aldrian, something that will be included in ITA guidance on BIM for tunnelling when it is published.

"I urge the owners to take responsibility, stay open minded, and ask their designers to put carbon assessments in the tender documents," says Aldrian. "Ask bidders to do a simplified carbon assessment on day one for every bid, perhaps just looking at concrete and steel."

Low carbon enablers

Leadership on carbon will come from owners, particularly where infrastructure programmes require funding from financial institutions or the private sector, which in turn will impact on procurement and processes. Contractors who come to the table with a carbon counting game in hand may start to see competitive advantage soon.

As the examples of Eglinton and HS2's S1 and S2 contracts demonstrate, performance-based specifications, rather than prescriptive ones, aid innovation such as higher proportions of SCMs or alternative fibre materials. Clearly, this demands expertise and specialist knowledge from those writing the specifications.

Efficient structural design is low-carbon design because it reduces the use of materials and resources. This requires the designers to trust in the competency of the contractor, which can be fostered through procurement routes that involve contractors early.

"The basis of overly conservative design is concern over what happens if something goes wrong," says Schwind. "If we know who is building it and we are convinced that they can build it to the quality we need, then we can be less conservative."

In summary, the focus on carbon emissions can be a catalyst to drive greater levels of professionalism and competence – in sprayed concrete and beyond.

SUPERCON: ditching the waterproofing layer

Norway's SUPERCON project aims to develop a sprayed concrete lining which is waterproof – but requires no waterproofing layer. So, rather than having a PVC waterproofing membrane or a sprayed waterproofing membrane between the primary and secondary layer, the secondary layer itself is watertight.

The traditional tunnel lining system in Norway consists of sprayed concrete initial support on the rock mass and a free-standing precast inner lining with insulation behind it. However, the inner linings have a short life – around 50 years – so cast in-situ linings and segmental linings with TBM-excavated tunnels have recently been used.

The aim of SUPERCON is to produce an alternative to all of these which would be long-lasting, with a lower carbon footprint than any of the above methods. "It would reduce the total concrete consumption dramatically and could also reduce the excavation cross section because you would be applying a thinner inner lining," says Karl Gunnar Holter, a senior specialist at the Norwegian Geotechnical Institute (NGI), one of the leaders of the research who has been researching the water and vapour permeability of sprayed concrete and membranes for several years. NGI is working with research foundation SINTEF and The Norwegian University of Science and Technology (NTNU) on the SUPERCON programme, with industry support too.

To make the secondary layer sufficiently watertight means limiting cracking. To do this, the researchers are looking into binder technology to reduce shrinkage, polymer technology to improve ductility and watertightness and fibres to better distribute cracks.

The end of April saw a series of field tests, carried out on one of rail authority Bane Nor's and the main contractor Veidekke's tunnelling projects in Drammen, in the south-east of Norway. "We carried out the in-situ tests to investigate a number of mix design adjustments, innovative measures to make the sprayed concrete waterproof and to be able to spray it onto moist and dripping surfaces," says Holter.

Technologies under test include a hydration accelerator from Master Builders Solutions, Xseed, which is normally used in cast concrete and polymer modification of the concrete, as well as different set accelerators and shrinkage reduction agents. Up to 25% of the cement was replaced with fly ash and limestone. Bekaert proposed a new version of its 3D steel fibres for the SUPERCON project, which are very short with a very high tensile strength and small diameter.

"With the performance of these fibres we want the cracks to distribute nicely into microfissures." The goal is for the cracks to be less than 0.1 to 0.15mm wide.

The results of the April trial are currently being processed and analysed. Holter, who is animateur on the International Tunnelling Association's working group 12 on sprayed concrete, hopes to be able to provide more information at the working goup meeting during World Tunnelling Congress in Copenhagen in September this year.