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Istanbul lessons

Two EPB TBM drives for the city's new airport

SPRAYING FOR SUCCESS

Dr Alun Thomas of All2plan Consulting outlines some of the rudiments of sprayed concrete and gives a few tips that could prove useful to young engineers – and maybe to those not so young

Right, figure 1: Is that bit rock?

As a professor once noted: "If I could have put the answer on a postcard, I wouldn't have written a book". This article offers a few pointers on sprayed concrete but it cannot pretend to cover all the possible applications and all the important points associated with them. Those selected are those which come immediately to mind. A list of references has been included for those readers interested in learning more. All the ITA Working Group 12 Sprayed Concrete publications are freely available at www.ita-aites.org.

The first piece of advice would be to remember that sprayed concrete is concrete that is sprayed. In other words, one can apply all the normal concrete technology to the material, providing that one makes some simple adjustments to the application and mixes used. This provides a reassuringly solid foundation of well-established concrete technology, from which sprayed concrete has been developed. For example, sprayed concrete mixes have relatively high cement contents to satisfy early strength and spraying requirements. Like all other mixes, a high cement content leads to higher shrinkage and creep capacity.

The primary difference between cast and sprayed concrete is the method of placement – which has a strong influence on the mix design, among other things – and the requirement to carry some load from the moment it is placed – even if that is only its self-weight. This early-age loading heightens the relevance of creep – the continued deformation of the concrete under a sustained load – since the high stress-strength ratio at an early age load increases the amount of creep. This also presents a challenge in applying normal concrete standards, since these are written primarily for concrete which is loaded at 28 days, albeit with some allowances to cover younger ages, down to seven days.

Second, designers should acquaint themselves with construction methods; and vice versa, engineers working with contractors should deepen their understanding of design. This is true for all tunnelling but even more so for sprayed concrete lined (SCL) tunnels as the method of construction has a strong influence on the overall performance. In a similar vein, a structural engineer is recommended to delve into geotechnics and geology. Conversely, those biased towards ground engineering should explore structural design. Tunnelling is fundamentally a matter of ground-structure interaction. Too often, tunnels are designed by people who are excellent in one discipline but blind to another. A balanced understanding is essential to develop the optimum solution.

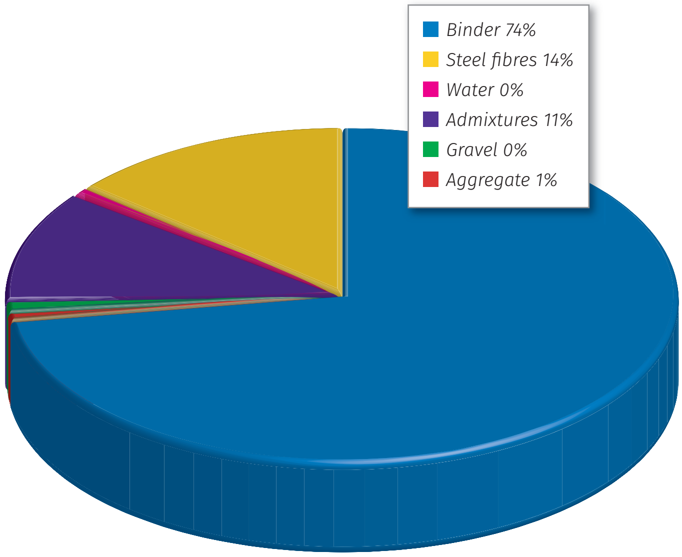
As a first suggestion, start by considering the ground since this is the biggest influence on any tunnel. Focus first on the mechanisms of behaviour in the ground that will help identify the major hazards. Then, the best ways to mitigate those risks can be designed. In this context, it is insightful to draw a distinction between soft ground, blocky rock and hard rock (Thomas 2019a).

There is no sharp boundary between these types of ground and each person will have their own opinion on where to draw the line *(Figure 1)*. However, the mechanisms of ground behaviour are distinctly different and different types of support are needed. The role of sprayed concrete is different in each case (WG12 / ITAtech 2020). Failing to understand this can lead to major problems. Tunnel collapses in fault zones, for example, often occur because a 'blocky rock' or 'hard rock' solution is applied in ground that is behaving like soft ground. This is worth elaborating on since it is a critical step in developing a safe and economic design.

'Soft ground' consists of a weak material which behaves as a continuum, i.e. it deforms like one continuous mass. Due to the moderate to high stress/strength ratio, the ground near the tunnel often deforms plastically too. Support is required quickly to prevent sands from flowing, weak rock from ravelling or deformation in the ground that could lead to a general softening. The early closure of a structural ring of sprayed concrete is often an essential step as this restricts ground movements. Since the ground acts as a continuum, this applies a load all around the ring of concrete. How even this applied load is redistributed will depend on the ground, adjacent features and the geometry of the tunnel.

A sprayed concrete lining should be designed to act mainly in compression – hence the geometry is usually relatively round – but some additional reinforcement may be needed to cope with bending moments. Examples of soft ground include sands and clays but can also include highly-fractured rock masses under high stress, since they exhibit this type of behaviour.

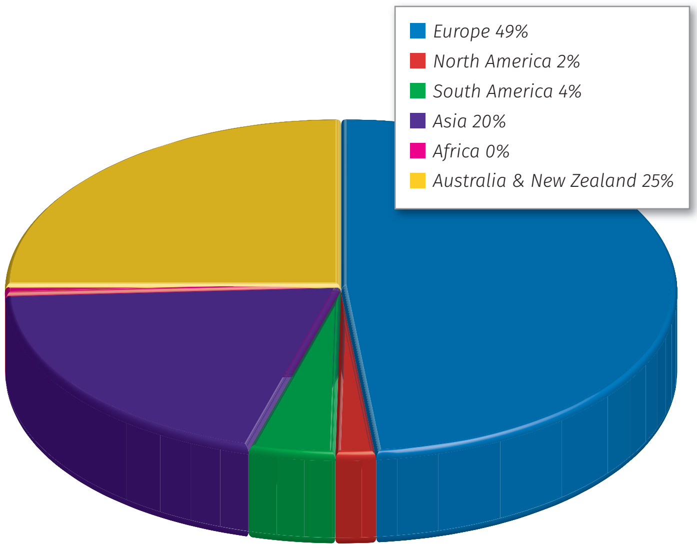
'Blocky rock' is exactly that – a rock mass formed of blocks. In most cases, the combination of the low to moderate stress/strength ratio and the spacing of the joints and fractures leads to a situation where controlling block failures is the most important task.



Above, figure 2: Components of the carbon footprint of a sprayed concrete mix

The obvious failure mechanisms here are the loosening of these blocks, block fall-out, followed by a progressive unravelling of the rock mass. Rock support has to be applied quickly to hold these blocks in place. Pre-support with spiling or pipe arches might even be needed. Depending on the stress/strength ratio, this may be combined with some plasticity but often the ground is stable enough for an arch of sprayed concrete with rock bolts to suffice, rather than a closed ring. The goal is to preserve the intact strength of the rock mass as far as possible. Admittedly this is the goal in all tunnelling but it is arguably more pertinent in this case.

'Hard rock' consists of rock with a high strength and widely-spaced jointing. In low-stress environments, hard rock behaves like a continuum and the response to tunnelling of the rock mass is often elastic. Here sprayed concrete serves supplementary functions: securing



Below, figure 3: Geographical distribution of PSCL projects worldwide

Above, figure 4:
SMART DRIVE electrically-powered spraying robot
PHOTO: NORMET

the small wedges in between rock bolts; sealing joints – which prevents fall-out or the loss of key blocks; and protecting the rock from weathering – which prevents the opening of joints, the loss of joint strength or deterioration of the rock itself, in certain cases. Hence relatively thin layers of sprayed concrete are all that is needed in addition to the rock bolts, for example, as specified in the better rock classes of the Q-system.

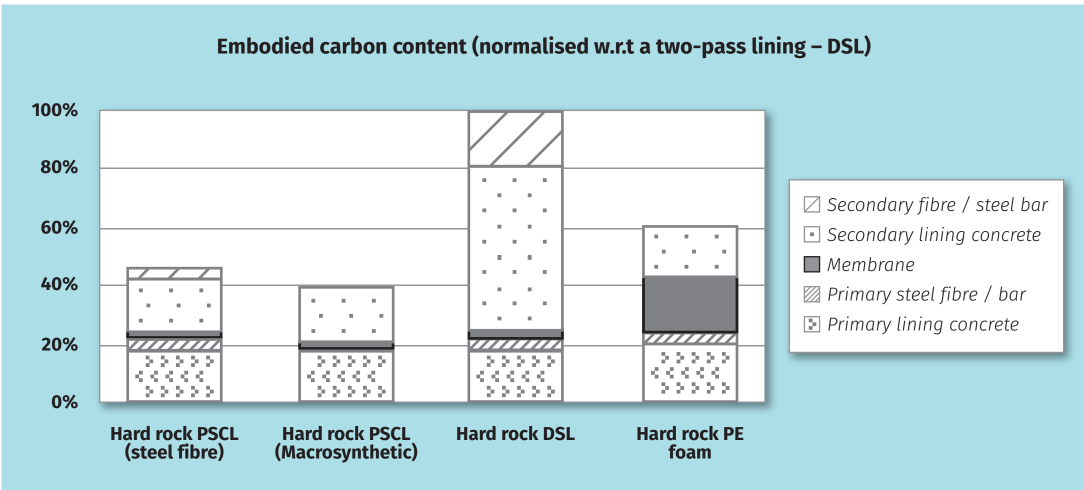
There are of course exceptions to these general cases. Highly stressed hard rock is a different case since it may exhibit phenomena such as rock burst and squeezing. Those are quite special cases, whereas the preceding discussion covers most of the cases encountered in tunnelling and illustrates how a consideration of the mechanisms of ground behaviour lead to the design of the support.

For more practical advice on sprayed concrete, there are a range of excellent publications – some of which are available for free. Noteworthy as good sources of advice on sprayed concrete in terms of properties, application and specifications are the guidelines from industry organisations, such as ACI and EFNARC. Particularly noteworthy are the reports from ACI 506 – such as the *Guide to Shotcrete* – and the EFNARC *'Guidance on execution'*. ITA Working Group 12 has also published a wide range of reports. The most recent ones have focussed on *Permanent Sprayed Concrete Linings* (WG12 / ITAtech 2020) and fibre reinforcement (the latter was published separately by Bernard & Thomas (2020) but it is also freely available). As well as covering design aspects, safety and case studies, the PSCL report also explores the issues of skills, certification and virtual-reality training.

Despite the technological advances, sprayed concrete linings are formed inside tunnels in a challenging environment and the operatives involved still have a large influence on the quality. This echoes the earlier remarks about the benefits of engineers understanding the construction processes in reality.

In addition to providing a wealth of information for engineers, these documents can form the basis for project specifications. In this context the European suite of specification and test documents (starting with EN 14487 and EN 14488) and the American equivalents from ACI and ASTM are probably the best examples.

When writing specifications, they should be comprehensive, consistent, easy to use and enforceable. The level of testing should be appropriate to the scale of the project. EN 14487 offers a good framework in this sense with a system of different testing regimes for different types of projects. The subject of testing can be a bit bewildering and it is best to avoid mixing test methods from different families of specifications.



Right, figure 5:
Normalised embodied carbon content for different lining options with respect to the double-shell lining

The PSCL report (WG12 / ITAtech 2020) reviews the most commonly used specifications and test methods. The report also includes some suggestions on how best to use them.

While it has already been mentioned that some of these documents are freely available, young engineers are strongly recommended to blend the information they find with advice from more experienced engineers. Do not be afraid to ask questions. This is how we all learn. The corollary of this is that senior engineers should support their younger team members. Too often, it seems that young engineers are abandoned to solve problems on their own. This is a false economy. A little help from an experienced professional can guide a less experienced team to a better solution – and faster than they alone can achieve.

The environmental impact of construction is attracting more and more attention, and rightly so, since we have much to do if we are to reduce this impact to a sustainable level while at the same time meeting society's demands for better infrastructure. Engineers are ideally placed to achieve this because they understand the technical demands in a tunnel and the options for change. Reducing the impact of an SCL tunnel is a tough challenge because cement content plays a major role in the work *(Figure 2)* and – at present – it is difficult to reduce it.

New technologies are emerging – such as accelerators for cement replacements and geopolymer concrete – along with other low-carbon alternatives for significant components, such as recycled glass as a sand replacement, and macro-synthetic or basalt fibres instead of steel mesh. However, it will take time for some of these to become widely available. The leading equipment manufacturers already offer low emission or electrically-powered equipment so emissions can be minimised in this area *(Figure 4)*.

The reality is that the biggest – and, in technical terms, easiest – savings in embodied carbon come from improving the overall design concepts since this will lead to a reduction in the quantities of materials that are used (Thomas 2019b) – Figure 5 shows an example of the potential reductions.

Much of what has been described above will be familiar to many readers as 'primary' support. However, there is an increasing trend towards using sprayed concrete for permanent linings. And this extends beyond the sprayed concrete itself to other components, such as rock bolts.

In some regions, permanent sprayed concrete and rock bolts are commonly used (e.g. Scandinavia) and, more recently, permanent SCL tunnels have been built in soft ground too (WG12 / ITAtech 2020) – Figure 3. From a technical standpoint, this is perfectly possible and, from environmental and economic perspectives, is highly desirable since it will reduce both the carbon footprint and the financial cost. Often the only obstacles are a lack of know-how and restrictive engineering practices. This leads to the last point.

A final piece of advice to young engineers would be to remain curious. Look at new innovations with an open mind and consider what they might offer you. Do not be trapped in a straitjacket of existing codes because inevitably they lag behind innovation. If we are to overcome challenges such as the urgent need to make tunnelling more sustainable, then we need to innovate.

FURTHER INFORMATION

For readers interested in learning more, Dr Alun Thomas will be giving an online course on soft ground tunnelling in September 2021 (https://ingeoexpert.com/en/courses-online/soft-ground-tunnelling-course/). Readers can also read his book on SCL tunnelling (also available in Turkish and Chinese).

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Agree or disagree..

Let us know what your experience has taught you. Or let us know what topic should be included in future Rules of Thumb columns: editor@tunnelsandtunnelling.com