Some aspects of international shotcreting practice

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Journal Paper

Synopsis

The International Tunnel and Underground Space Association (ITA) has a number of working groups (WG) that meet at least once a year. One of these is WG12, 'Use of Shotcrete', of which the author is a member. The purpose of this paper is to draw attention to a number of topics that were discussed at the WG12 meetings held in April and September 2008; and also to a number of other matters that arose from the presentation of thirty-four papers at the 5th International Symposium on Sprayed Concrete held in Lillehammer, Norway between 21 and 24 April 2008.

Introduction

ITA Working Group 12 met twice in 2008: firstly at Lillehammer, in Norway—which coincided with the 'Fifth International Symposium on Sprayed Concrete'—and subsequently at Agra in India, at the time of the ITA World Tunnel Congress 2008. In the course of these meetings and at the Lillehammer Sprayed Concrete Symposium, a number of important topics were raised and discussed. The author is a member of this WG and the purpose of this paper is to disseminate the essence of these discussions, while providing some personal comment on a number of these issues.

The topics include:

- Independent testing of fibre-reinforced sprayed concrete using different types of fibres
- Sprayable mortars for fire protection
- Shotcrete operator certification
- Durability of sprayed concrete
- Curing of sprayed concrete
- Energy absorption testing
- Standard specifications

Independent testing of fibre-reinforced sprayed concrete using different types of fibres

There is a wide range of steel and polyethylene fibres that are currently used for reinforcing sprayed concrete. There is, however, a lack of objective and independent comparative test data available on the performance of shotcrete reinforced in this manner.

WG12 has begun a programme of comparative testing of the structural behaviour of fibre-reinforced shotcrete panels at the underground test facility at Hagerbach in Switzerland. Suppliers of fibres are encouraged to submit samples for testing and the initial results from an initial suite of tests will be published shortly. Further discussion on the format of the testing programme took place at both the Lillehammer and Agra WG meetings.

Sprayable mortars for fibre protection

Following the successful one-day symposium, 'Fire Protection Engineering for New and Existing Tunnels', in London in October 2006, the CETU (Centre d'Etudes des Tunnels; General Directorate of Infrastructure, Transport and Sea, France) has begun to collect manufacturers' data of sprayed mortar products that provide enhanced fire protection. These are presented in a standard format and will shortly be available on the ITA website.

Shotcrete operator certification

The quality of in-place sprayed concrete depends on the adoption of appropriate mix designs, the use of suitable equipment and possibly most of all, on the skill of the shotcrete operator. A lot of effort can be put into developing a shotcrete mix with materials, the physical and chemical characteristics of which have been carefully chosen by taking into account the anticipated in-service conditions. All this effort, however, would be completely wasted if poor shotcrete workmanship leads to a lack of homogeneity,

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voids or laminations in the final product. A high level of skill in the 'shooting' of shotcrete is therefore of the utmost importance in ensuring a dense and durable shotcrete.

Adequate training of sprayed concrete operatives has been the subject of attention both overseas and here in South Africa. However, while such training in South Africa has been on a limited, in-house company or project basis (e.g. BASF for mining houses), it has become formalized in a number of countries overseas. The training is usually linked to a formal qualification scheme leading to an operator gaining a competency certificate that is recognised throughout the country or region in which the scheme is run—in much the same way that welders gain certificates of competency for welding work.

A number of such programmes are either in place or are in the process of being set up around the world, as indicated in Table I.

The EFNARC scheme is still being developed and will focus on the accreditation of the trainers of shotcrete operators, with the ultimate aim of establishing a recognized accreditation scheme for shotcrete operators throughout Europe. The ITA supports this initiative.

In North America a certification and qualification scheme for shotcrete nozzlemen was started in 1999 by the American Shotcrete Association (ASA). By 2001 forty-two nozzlemen had been certified under this programme. The responsibility of certification of nozzlemen was then taken over by the American Concrete Institute (ACI), with the ASA continuing to provide the necessary training. Over the past seven years, more than 800 nozzlemen have qualified under this new arrangement. The training and examinations cover both the basic theory of shotcrete mix designs and practical spraying tests. The latter includes the shooting of test panels. Cored samples are then taken from these panels, which are then subjected to materials testing (Morgan and Dufour, 2008).

A similar programme is run in the UK by Morgan Est at its research and development facility in Rugby.

SANCOT feels that there is considerable merit in establishing such a scheme here in South Africa. This will be a major focus of an ITA sponsored two-day symposium on the use of shotcrete to be held near Johannesburg on 2 and 3 of March next year.

Table I

Different types of certification (Larive and Gremillon, 2007)

Country/ Organisation	Type		Process	
	Robot	Manual	Dry	Wet
Brazil		✓	✓	
France	✓	✓	✓	
Norway	✓	✓		✓
Sweden	✓	✓	✓	✓
ACI		✓	✓	✓
EFNARC	✓		✓	
	Experience		**Position**	
	Theoretical	**Practical**	**Vertical**	**Overhead**
Brazil			✓	
France	✓	✓	✓	✓
Norway	✓			
Sweden	✓			
ACI	✓	✓	✓	✓
EFNARC	✓	✓	✓	✓

Durability of sprayed concrete

The durability of sprayed concrete depends on two aspects:

➤ The design of the concrete mix (taking into account the physical and chemical characteristics of each constituent), to match the needs of the chemical and physical exposure conditions to which the sprayed concrete will be subjected

➤ The actual physical (and chemical) properties of the *in situ* shotcrete

The difficulties associated with the former have been the subject of much work in different parts of the world. A classic example was given at the Lillehammer conference (Haglia, 2008), where the effects of highly aggressive groundwaters on a range of subsea and other tunnels were examined in great detail. Another example is the extensive study programme that was carried out a few years ago on the long-term chemical stability of the 'accelerated sprayed concrete' used for the underground works at Terminal 5, Heathrow (Hilar *et al.*, 2005).

In the case of the physical *in situ* properties of the in-place product there is general agreement that a durable shotcrete needs to be uniformly dense and relatively impermeable. Some specifications require the permeability to be less than 10^{-12} m/s.

But how does one monitor the quality of the finished product? Density testing (alone) has proved unreliable, and classic forms of permeability testing are generally unsuitable for regular day-to-day site testing of finished work. Some specifications refer to the use of the simplified permeability test described in DIN 1048-5, which has been incorporated into BS EN 12390-8:2000. The author is not familiar with the use of this test but wonders about its suitability for testing sprayed concrete as specimens 'shall be cubic, cylindrical or prismatic of length of edge or diameter, not less than 150 mm'.

One needs a proven test method that is simple, quick, and relatively inexpensive.

For nearly twenty years the sprayed concrete specifications for most major underground civil engineering projects carried out in Southern Africa have required the routine *in situ* testing of in-place shotcrete to provide assurance of its potential durability. The properties of boiled absorption (BA) and volume of permeable voids (VPV) are measured for this purpose, making use of the standard American test procedures described in ASTM C 642-06.

The first published reference to the use of these material properties for assessing the quality of shotcrete was made in a paper by P. Seabrook of Vancouver, BC, Canada in the 1970s. Following a large amount of research and development work then carried out by HBT AGRA Ltd (in Canada), the company adopted this approach and suggested BA and VPV indicator values, as shown in Table II.

This approach continues to be widely used for the routine monitoring of the potential durability of in-place sprayed concrete in North America and Southern Africa. However, with two exceptions known to the author, specifications drawn up in Europe are strangely silent on this topic (e.g. EFNARC, EN 14487/8/9, and Norwegian NB7 and NPRA

Table II

Suggested indicators of shotcrete quality (Morgan, 1994)

Volume of permeable voids, % (VPV)	Boiled absorption, % (BA)	Suggested quality indicator
Less than 14	Less than 6	Excellent
14–17	6–8	Good
17–19	8–9	Fair
Greater than 19	Greater than 9	Marginal

standard shotcrete specifications). Some of these do make mention of the testing of permeability but, as noted above, such tests do not lend themselves to routine work as they tend to be protracted and expensive to carry out.

The two European specifications that do mention VPV and BA testing are the British Tunnelling Society's Standard Tunnelling Specification and a similar one, published as an Appendix to a BASF publication (Melby, 2006). While both mention these tests, they leave it to the designer to stipulate the acceptable limits.

The 1993 and 2001 WG12 state-of-the-art reports on shotcrete (Malmberg, 1993; and Franzen *et al.*, 2001 respectively), quite rightly pointed out that the question of shotcrete durability is a complex one. It is clear that there are still wide-ranging views on this issue. At the Agra WG12 meeting the group undertook to look into the matter further with a view to publishing recommendations on the issue.

Curing of shotcrete

The benefits of properly curing newly placed concrete are well understood in the civil engineering industry. Moist conditions have to be provided to ensure that the hydration process takes place to the fullest extent, thereby allowing the concrete to attain its maximum potential strength while minimizing the detrimental effects of phenomena such as shrinkage.

In short, proper curing:

- Limits cracking due to plastic shrinkage
- Limits early thermal contraction and long-term drying shrinkage
- Ensures an effective bond between successive layers of shotcrete by preventing premature surface dehydration
- Ensures consistent strength development.

When it comes to the use of sprayed concrete, it often seems that the above is not fully appreciated. This probably stems from the fact that when shotcrete was first employed in tunnelling work its use was considered a temporary expedient. It provided 'temporary' support—which was then augmented ('replaced') by a 'permanent' *in situ* concrete lining.

In a similar vein, the service-life requirements in the mining industry (where perhaps more than 80% of all shotcrete is placed in Southern Africa), are generally much less demanding than those in the civil engineering industry. This simply reinforces an attitude that shotcrete is a temporary expedient and that quality control of sprayed concrete is of no benefit and unnecessary.

Furthermore, it is commonly assumed that because underground shotcreting work is not done in the open air and away from sunlight, that the ambient humidity is high enough for full hydration to take place. This is generally not the case, especially where the ventilation is what it should be for health and safety reasons.

As a consequence of the above, a culture has developed that insists that it is unnecessary to cure shotcrete. The fact remains that only by ensuring proper curing will the design strength and other properties be obtained. It is surely short-sighted and costly to adopt the attitude that this does not matter as the design of the shotcrete mixes can be adjusted (enriched) to ensure that the residual uncured strength provides the design strength. This overlooks a wide range of unsatisfactory consequences which, although possibly acceptable in a 'temporary' support situation, are quite unacceptable where the shotcrete is used as a permanent lining with an expected service life of 60 years or more*.

The principle methods that can be employed for curing shotcrete are:

- Water-spraying at frequent intervals—but inevitably there are difficulties in ensuring that this is actually done
- Ensuring that the ambient relative humidity is 80% or higher—not always a satisfactory solution as the working environment may become unacceptable
- Curing membranes—generally not suitable for use where multiple layers of shotcrete are required
- Internal curing by using special additives, e.g. Meyco TCC 735
- Internal curing by using sintered, lightweight aggregates—available in the US, but maybe not elsewhere.

The first three methods listed (water-spraying, humidity control, and membranes) have their limitations and internal curing methods certainly have the appeal of simplicity and a sense of 'foolproofness'.

Internal curing with additives

Some hold that the use of special additives to effect internal curing is expensive and of doubtful value. Nonetheless, these materials have been used in the South African mining industry at South Deep and Impala (Erasmus *et al.*, 2001; and Bothma, 2001) where the design life of the permanent shotcrete linings was an important consideration.

In Chapter 4 of the book *Sprayed Concrete for Rock*

* *In the UK it is now not uncommon for specifications to require a 120 year design life for sprayed concrete; eg the underground works for Terminal 5 at Heathrow (Hilar et al, 2005).*

Support produced by BASF (Melby *et al.*, 2006), the authors go to some lengths to demonstrate that the product Meyco TCC 735 is effective and economical to use. With its use the curing process begins immediately, whereas with externally applied methods there is an inevitable and undesirable delay. The writers also stress that its use has a number of other benefits and hence refer to it as a 'concrete-improving system'. They refer to a number of case histories that demonstrated that the use of this product has the following benefits:

- ➤ Increased bonding compared to no curing; from 0.6 to more than 2.0 Mpa
- ➤ Increased density compared with shotcrete treated with external curing agents (greater by more than 15%)
- ➤ Increased strength compared with air cured shotcrete or shotcrete treated with external curing agent (greater by more than 10% at 28 days)
- ➤ Substantial reduction in water absorption (see Table III)
- ➤ Substantial cost savings (see Table IV).

Internal curing with special aggregates

The use of sintered lightweight aggregates as a means of internal curing has been the subject of a recent draft ACI report (Roberts *et al.*, 2008). Entitled 'Internal Curing of Concrete', this (as yet) unpublished report begins by pointing out that the inclusion of certain materials in a concrete mix can provide a source of water that can be desorbed into the surrounding mass of concrete. Examples of such materials are:

- ➤ Pre-wetted lightweight aggregates (e.g. expanded shale, clay and slate)
- ➤ Super absorbent polymers
- ➤ Wood fibres
- ➤ Absorbent limestone aggregates.

The report goes on to say that especially with low w/c mixes 'the beneficial effect of external water curing is limited to the surface of the concrete. As a result, external water cannot penetrate into the concrete to maintain a saturated capillary pore system and thus avoid its self-desiccation. The solution is to supply water reservoirs on the inside through incorporation of sufficient absorbent agents (usually saturated lightweight aggregates) in place of a part of the normal weight aggregates. These desorb water to the hydrating cement when and where needed. This process is called internal curing (IC).'

The draft report then focuses on the use of saturated lightweight aggregate as it 'is the only technique that is currently commercially available in North America (other than absorbent normal weight coarse aggregate).'

It points out that concrete with a w/c ratio of more than 0.45 has mixing water to hydrate the cement, with the help of external water. However, it goes on to say, that this is not the case where the w/c ratio is 0.40 or less.

Most South African shotcrete specifications require a w/c of between 0.35 and 0.45 (e.g. Ingula)—a range, which is perhaps marginal in terms of this consideration. Nonetheless, subject to availability, it is felt that this method could benefit the internal curing of shotcrete, particularly as external methods are generally unreliable.

The 1993 WG12 state-of-the-art report referred to above (Malmberg, 1993) reflected a wide range of attitudes towards the curing of shotcrete. At the Agra WG12 meeting the group undertook to revisit the issue with the aim of publishing recommendations on the matter.

Energy absorption capacity testing (EAC)

Considerable dissatisfaction was expressed at the Lillehammer conference on the method of testing for EAC as specified in the newly published EN 14487/8/9 suite of standard specifications for sprayed concrete. This requires test that panels be sprayed into a 1 000 × 1 000 mm mould to a thickness of 100 mm. The panels are subsequently trimmed to 600 × 600 mm in size before testing. The Norwegians have long followed the practice of spraying circular panels of 600 mm in diameter and point out that panels of this size are much easier to handle (Kompen, 2008a).

The method of supporting the sample during the test also drew much comment, with considerable interest being shown

Table III

Water absorption of drilled core samples (gm/cm²) after Testor, 1997

	Meyco TCC 735	External curing	Uncured
10 min	0.06	0.08	0.07
1 hour	0.12	0.16	0.14
24 hours	0.24	0.43	0.43
7 days	0.37	0.69	0.70

Table IV

Cost comparison between curing shotcrete by means of water, external and internal methods (SFr per cubic metre) after Melby, 2006

	Water curing	External curing	Concrete improver (internal curing)
Material	-	14.00	15.00
Application			
Labour	25.20	1.00	-
Plant	280.00	18.00	-
Removal			
Labour	-	10.80	-
Plant	-	80.00	-
Total costs per m³	305.20	123.80	15.00

in the use of the ASTM C 1550 round panel test. This involves the application of a central point load to a circular panel 800 mm in diameter and 75 mm thick. The repeatability of the post-crack performance is said to be superior to that obtained using conventional beams (Bernard, 2008). This type of panel is referred to by some authors as a 'round determinate panel'. Bjontegaard (2008) reports that in comparative testing the coefficient of variation of the residual strength at 3.0 mm deflection has been found to be in the region of:

- 20% in third point beam tests
- 9% in EFNARC tests, and
- 6.3% in round determinate panel tests.

Standard specifications

Between 2005 and 2007 CEN, the European Standardisation Organisation issued a suite of 11 specifications for sprayed concrete under the generic numbers of EN 14487 to EN 14489. They cover both wet and dry shotcreting methods. These standards are now mandatory for all EU or EEA countries.

The decision to produce these standards was in line with the idea of removing obstacles for trade across Europe. It was not the result of pioneering work but rather an attempt to summarize the best of existing specifications throughout the region. Some feel that they suffer from compromise and that they are not as precise or comprehensive as they may have been and leave too many items for interpretation (Kompen, 2008b).

Conclusion

The technology relating to the use of sprayed concrete continues to develop at a pace that makes many publications out of date before the ink is dry. In such circumstances it is imperative to make a conscious effort to keep abreast of the latest developments in the field. To this end, SANCOT is organizing a two-day ITA-sponsored conference entitled 'Shotcrete for Africa' to be held near Johannesburg on the 2 and 3 March 2009. Many of the topics mentioned in this paper will be covered and there will be a particular emphasis on the proposed establishment of a shotcrete nozzleman's accreditation programme in South Africa.

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