European Developments in Sprayed Concrete

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Synopsis: There have been considerable developments in sprayed concrete materials, specification, application technology and performance testing in recent years in Europe. Some of these reflect changes elsewhere, such as North America, but others are unique to Europe. This paper gives a brief history of sprayed concrete (shotcrete) development and describes some of the changes in practice that have occurred in recent years, as viewed from the perspectives of the construction process, materials, design, quality and standards. Obstacles to further development of the product and its more widespread use, are described together with some examples of attempts to address such issues in Europe, including the EFNARC specification and development of European (CEN) standards.

Keywords: fibres, repair, rock support, shotcrete, sprayed concrete, specification, standards, test methods, tunnelling.

1 INTRODUCTION

Sprayed concrete technology has made considerable advances over the last 20 years, in response to a variety of pressures and opportunities. This paper describes some of the more recent changes, as seen from a European perspective, but with appropriate reference to development elsewhere. Changes have occurred in various areas of practice, including the production process, materials, design and specification, quality control/assurance and standards. The following sections describe some of these, the agents of change and challenges that remain.

2 PROCESS DEVELOPMENT

The inventor of the process is widely acknowledged to be Carl E Akeley (1864-1926) who experimented with the pneumatic application of plasters and cement mortars at the turn of the century and obtained patents for the equipment and ‘Gunite’ dry process method in 1911. Within a short time larger aggregate was added to make concrete and by the 1950s the term shotcrete became synonymous for both sprayed mortars and concretes. Between 1942-1951 the American Concrete Institute had a standing committee on the subject - Committee 805 on Pneumatically Placed Mortar; this was reactivated in 1957 as Committee 506 on Shotcrete, and became one of the most authoritative sources of technical information and standards (1).

The wet mix process started to be developed around this time in the form of the 'True Gun', although the method had been experimented with (largely unsuccessfully) at the time of the invention of the dry process Cement Gun. Rotating-barrel machines were then developed (based on a Dutch patent of 1929) which were rugged, high output and easy to use. These became very popular for the dry process and have more recently been adapted to spray wet concretes. There was a parallel evolution in wet process equipment with the availability of small, powerful displacement (piston) and peristaltic pumps. This in turn led to the introduction of robot-controlled equipment to cope with the high output (hence high weight) and rapid, falsework-free application required in underground rock support.

These novel methods of placing concrete rapidly established sprayed concrete across a wide range of applications. Each makes use of the uniquely flexible nature of the application technique, which requires minimal formwork, and access space to produce flat or curved surfaces. They include: fire protection of steel framed buildings; new construction and repair of reinforced concrete structures; thin arches, domes and shells; swimming pools, dams and sea defences; rock stabilisation; underground rock support and tunnelling; chimney and tower linings; and refractory concrete for the iron, steel, power and petrochemical industries.

Developments in equipment have been largely by evolution rather than revolution. Some of these have been driven by the need to incorporate new materials into mixes, notably steel fibre reinforcement and additives (admixtures). The majority of rotating barrel/wheel and piston pumps can now handle the former at dosages up to 60kg/m^3, but higher contents can still be problematic. Polypropylene fibres present no difficulties at the base level of 1kg/m^3, but it would be advisable to conduct trials with these types of machine and worm pumps if dosages of the order of 5 kg/m^3 are specified by a designer looking for significant improvements in mechanical properties (such as flexural strength and toughness).

In Europe there has been a drive to reduce losses and pollution, particularly dust. The most effective solution has been to move to the wet process, although some improvements in the dry process have been achieved by the introduction of pre-moisturising augers that feed the dry material into the hopper of the gun. Nevertheless, this application method inevitably results in a dusty environment and rebound is typically 20-25% from vertical surfaces (and greater overhead).

Another objective has been to improve control of the process and hence the final product. A primary concern has been the consistency of the proportions of the mix (in particular most of the in situ product). This has always been variable in the dry process and significant improvements are unlikely, either in the aggregate/cement or water/cement ratios, the latter because of the ‘control’ of the water content by the nozzleman. The wet process has significant advantages in this respect, although site batching may be less reliable than delivery from a batching plant and operatives may still adjust the water content upwards with ad-hoc adjustments at the pump. These sorts of difficulties naturally lead on to the issue of operating procedures and training. In the UK there has been a move to formalise training of sprayed concrete operations and the introduction of an independent certification scheme (2). Initially, the emphasis has been on nozzlemen for the dry process, although the initiative is being widened to cover the wet process. It is now common to see specifications requiring all nozzlemen on a contract to have a certificate awarded by an independent organisation such as the Construction Industry Training Board (CITB), the latter being well established and offering training for a wide range of site operations.

It can be argued, however, that training of individuals does not go far enough and that changes in culture and organisation are necessary to move the industry forward. ‘Construction as a Manufacturing Process' is a topical theme in the UK and proponents would suggest that site-based operations must become better controlled. One approach is to train operatives as a multi-skilled team who can not only work to carefully drawn up procedures, but also understand why it is important to do so. Thus educating the work force becomes an essential part of the changes needed for the construction industry in the future. Better process control can also be achieved by automation, and this is an area in which the sprayed concrete industry has made significant improvements, particularly in equipment for high-volume wet mix applied in tunnels and other underground works.

3 MATERIALS TECHNOLOGY

The second area in which practice has changed is that of materials technology. The material constituents for sprayed concrete are similar to those in ordinary cast structural concrete. Prior to the 1980s most sprayed concrete applications in Europe used an ordinary portland cement/aggregate mix placed by the dry-mix process, typically at a sand/cement ratio of around 3:1 by weight. During the 1980s there have been substantial developments in materials technology including the use of: supplementary cementing materials, such as fly ash and silica fume, as additions or partial replacements for cement; special chemical admixtures; and fibre reinforcement (steel or polypropylene) as an alternative to conventional mesh reinforcement.

The essence of good materials selection is in producing a mix that is compatible with the substrate in terms of strength, stiffness and thermal expansion, whilst meeting the installation requirements which include pump/sprayability, good bond and appropriate strength development. The most crucial aspects of material choice are usually associated with the aggregates and additives.

The grading of aggregates is critical in dry process sprayed concrete due to the lack of external vibration and the changes in mix proportions as a result of rebound. Heavier particles rebound more than the lighter sand grains and cement, resulting in a more finely graded material in situ with higher cement content. Gradings should therefore be kept coarse to ensure a balanced in-situ material. Aggregates should conform to a national standard, e.g. BS 882 (3) for which medium zone is most common, but reference should also be made to EFNARC (4) and ACI Committee 506 (5).

With the wet process aggregate grading is just as critical and dependent on the pumping distance and equipment. There is also the additional crucial requirement to balance the concrete characteristics required to produce a pumpable mix with those characteristics required to project it into place with minimum losses and segregation. The amount of large aggregate particles should be kept low (because of high rebound) and the sand content high (to ensure adequate consistency), with the mix (aggregate plus cementitious components) having a high fines content. Engineers should be guided by equipment manufacturer's recommendations, and there are some independent recommendations on pumping gradings e.g. EFNARC (4), Kempster (6) and Cooke (7). These sources are particularly well suited to high volume piston-pumped concrete mixes but are not necessarily appropriate for the low volume output mortar applications such as for repair and some new construction. A research project at Loughborough University has been investigating the wet process for repair applications in the UK (8). An important part of this has examined the rheological performance of both pre-bagged and designed (site) mixes sprayed through worm and piston pumps. The concept of a rheological audit has been developed (9) with pumpability being characterised by slump, shear vane, rotational viscometer and pressure bleed tests (10). These materials performance parameters are contrasted with the conventional method of specification by the aggregate grading. The latter can be a useful indicator of the suitability of an aggregate, but not the whole picture as the cementitious component(s) contribute to the behaviour of the fluid, including its potential for blockage due to bleeding (de-watering) or excessive friction.

A variety of additives and admixtures are added to sprayed concrete, particularly with the wet process, to improve strength, adhesiveness, cohesiveness, freezing/thawing and abrasion resistance characteristics, and to reduce rebound. Increased material costs can be offset by savings in the amount of sprayed concrete and labour. Accelerators are common in the dry process to increase early strength and reduce dust; the most common are sodium silicates, carbonates and aluminates. In the wet process an accelerator (often sodium silicate) is sometimes added at the nozzle to ensure rapid set. In any case it is crucial to keep the accelerator dosage at the absolute minimum to achieve the desired results as strength (and durability) reduces with age and dosage level. Prediction of the setting and strength gain (and subsequent long-term strength loss) is notoriously difficult, as the response of a mix is sensitive to the types and sources of both the cement and accelerator. This problem is neatly illustrated by Prudêncio et al (11) who compared carbonate and aluminate admixtures and also showed that laboratory tests on mortar pastes, whilst giving useful indications, cannot be relied upon to predict the behaviour of a sprayed concrete. It is best to conduct an evaluation either during pre-construction testing or by laboratory sprayed investigations, such as those recommended by the EFNARC (4) appendix. There is also a draft European Standard out for public comment on Admixtures for Concrete, Mortar and Grout – Part 5: Admixtures for Sprayed Concrete (12).

Water-reducers (commonly lignosulphonic acids or hydroxylated carboxylic acids) and super-plasticizers are also employed in the wet process to improve workability and cohesiveness. This may be particularly important in the hot climates where evaporation and stiffening rates are high. Polymer latex additives (such as styrene-butadiene/acrylate) have been incorporated to try and improve adhesion, resistance to chlorides and freeze-thaw attack, and to reduce permeability. In a recent paper Ghio and Monteiro (13) have shown that polysaccharide gums may be beneficial in obtaining a balance between pumpability and sprayability by reducing apparent viscosity at high shear rates (e.g.

in the mixer), but having less affect at low shear (i.e. after spraying) and hence allowing good build. They also observed improvements in bond strength to reinforcing bars.

Silica fume is now a common addition in both the dry and wet processes, usually at between 5 and 10% by weight replacement of cement. Higher silica fume levels can result in surface cracking, particularly in hot climates. There are many advantages claimed for this pozzolanic material including a reduction in rebound, easier application of thicker layers, lower dust in the dry process, better adhesion to both dry and wet surfaces, improved resistance to wash-out by water, and improved strength and durability. Whilst it undoubtedly helps in the production process, the benefits in terms of hardened properties cannot be guaranteed. It clearly produces substantial reductions in rebound losses, up to 50% in the dry process, which is a very significant advantage with this production process. This alone may be an adequate justification for its inclusion. The cause of the reduction in rebound appears to be largely associated with the increased water demand resulting from the inclusion of silica fume, as opposed to the cohesive effects of the silica fume particles (14). However this work has also shown that the benefits normally associated with silica fume in terms of strength and durability, based on research work into conventionally cast concrete, should not be expected automatically with dry process sprayed concrete. This is because of the adhesion and cohesion requirements and the increased water demand brought about by the silica fume which together result in higher water/cementitious ratios in cement replacement mixes countering the benefits of silica fume on hardened properties.

Recent work by Armelin and Banthia (15) to develop a theoretical model of aggregate rebound for dry process sprayed concrete has thrown further light onto the mechanics by which increases in cement, water and silica fume content can reduce rebound. Related studies (16, 17) into steel fibre rebound have suggested that the critical parameters in reducing losses of these expensive additions are not the fibre mass but the fibre diameter and length, thicker or shorter fibres leading to less rebound.

Material rebound with the wet process is low, typically 5-10% being reported for vertical surfaces. Little detailed information is available due to the lack of concern over such relatively small losses. The dosage of accelerator admixture may however be adjusted to take account of the orientation and hardness of the surface to be sprayed.

4 APPLICATIONS

As stated earlier, sprayed concrete continues to be applied in a variety of applications. These markets are well established and relatively mature. In Europe commercial development is associated with growing these markets, rather than opening up new ones. Changes in materials technology and the construction process, including those described in previous sections, have facilitated many of developments in applications. For example, steel fibre reinforcement and wet process improvements were instrumental in revolutionising sprayed concrete for rock support in tunnels in Scandinavia (particularly Norway) in the late 1980s and some of this technology was transferred into the UK in the last five years for tunnelling projects in London clay.

Which application fields are ripe for development? Three possibilities are repair, ground support and new construction, all of which requirement improvements in control, reliability and environmental impact. In Europe the repair of concrete and masonry structures is still predominately carried out by the dry process, including for example the fire damaged Channel Tunnel (18) with a 4.5:1 mix with 30kg/m³ of steel fibre reinforcement. A description of other examples can be found elsewhere (19, 20). It is often argued that the dry process can: produce higher performance concrete; be applied with stop/start flexibility; and be easier for overhead work. Whilst high quality concrete can be produced by this process it has fundamental weaknesses associated with the lack of control of the water/cementitious ratio, high losses and a dirty environment. The author believes that, as with tunnelling work, it is inevitable that repair will move towards the wet process to overcome these problems. Considerable work needs to be done to develop the technology for repair, particularly with worm pump applications, which are well suited to low-volume installations. A current research project (8) is helping to improve our understanding of the process and resulting performance, and has demonstrated its potential to install high quality mortars (with maximum aggregates sizes from 2 to 6mm) suited to a range of repair situations. Morgan (21) describes one of a series of repair applications carried out in Canada using wet mix sprayed concrete containing steel or polyolefin fibres and air entrainment. Pumping mixes with air contents around 10% produced 4-5% insitu, sufficient for frost resistance, whilst also improving the production process because the high air content reduces flow resistance in the line and the loss of air during spraying stiffens the mix as it is placed. The principle here is similar to that of polysaccharide gums (13).

In the field of underground support, tunnelling continues apace in Europe. In the UK there have been major works on the Jubilee and Heathrow Express underground lines in London and the Regents Cavern on Jersey. On the continent recent examples include the 8-km long Somport tunnel between Spain and France and the Gotthard rail tunnel in Switzerland (22). All of these projects involved wet process sprayed concrete, often with a steel fibre reinforcement layer, acting as secondary or primary support. Osborne (23) describes the London tube projects and reports the view that control has improved considerably in the last five years, due to: changes in mix design and accelerators; better dosing and pumping equipment; mechanisation of robotic spraying; and improved training, operative skills and management systems. These must be the themes of future developments in this field together with the establishment of more accurate structural analysis techniques and widely accepted design methods and codes of practice. The reader is referred elsewhere for detailed discussion of design methods relating to NATM and the Norwegian method (24) and rock stabilisation and support (25).

5 SPECIFICATION AND STANDARDS

5. 1 GOOD PRACTICE IN SPECIFICATION

In the past, specifications for sprayed fibre concrete have often been weak, partly because of a lack of understanding on the part of the designer of the production process and the properties of sprayed concretes. Given a basic knowledge of the material and a clear idea of why it is being used, it should not be too difficult to draw up an adequate specification (26).

The most recent European specification is the EFNARC *Specification for Sprayed Concrete* (4) published in 1996. The contents include: materials, concrete and durability requirements; mix composition; execution of spraying; requirements for final product (compressive strength, flexural strength and toughness, bond strength, fibre content, permeability and frost resistance); test methods; quality control; and an appendix on admixtures. Both the EFNARC specification and DIN 18 551 (27) have recently been put before the CEN committee TC/104/SC8/WG10 which is producing an EN standard for sprayed concrete (see below).

The most substantive documentation in the United States includes the American Concrete Institute's *Standard Specification for Materials, Proportioning and Application of Shotcrete* (5). A revision of this specification has been proposed, titled *Standard Specifications for Structural Concrete*. The main difference is the addition of a checklist containing over 30 notes to the architect/engineer to assist in document preparation using the standard specification; this is an excellent document and highly recommended reading for all engineers involved in sprayed concrete work.

What might be good advice to the engineer responsible for specification, based on European experience? In order to avoid some of the more common problems associated with sprayed concrete, a number of recommendations can be made:

(i) Materials

Do not to place too much reliance on the advice of materials suppliers and avoid reference to proprietary products. Refer to published data when selecting materials and identifying likely levels of performance.

(ii) Preparation

Preparation and bond to the substrate are of vital importance. Make sure appropriate cleaning and roughening techniques are specified to achieve a rough and sound bond. Avoid mechanical action where possible and specify high pressure water jetting or grit blasting. Ensure bond checks form part of the quality control requirements, including both sounding (tapping with a rod) and core pull-off techniques.

(iii) Construction method

Seek the views of contractors experienced in sprayed concrete, who will be able to give valuable guidance on the practical aspects of applying a draft specification and identify requirements that are unrealistic. They can also advise on the choice of process (dry or wet). The wet process is predominant in tunnelling and is now taking a significant part of the new construction and repair markets. If it can provide the levels of flexibility and performance necessary it should be given serious consideration, either as an option or a requirement, because it potentially offers the more consistent and controlled (by water/cement ratio) product.

(iv) Pre-construction testing

Ensure this forms part of the specification. Preconstruction trials and tests are an invaluable part of the design and construction process. Even with a combination of experienced designer and contractor it is usually sensible to have a trial of the particular materials and equipment that are proposed. If there are flaws in the specification, it is better to find them now than during construction. Trials will also identify inadequate contractors or operatives. Whenever possible makes it a requirement that all nozzlemen are trained and has passed a recognised independent certification scheme.

(v) Performance

Provide a clear set of requirements, identifying the test methods (standard whenever possible) and the required levels of performance. State the numbers of samples, minimum average value and minimum individual value for each test.

(vi) Bills of Quantities

Think carefully about the method of measurement and Bill presentation, as national methods for general civil engineering may be inadequate. Unfortunately the method proposed by the Construction Committee of the Concrete Society (28) has become outdated and virtually no other guidance exists. There is a need for new documentation.

(vii) Tolerances

Problems with tolerances are common. Specifying a tight set of tolerances can result in the unnecessary rejection of sound work and disputes with the contractor who believes the contract is unreasonable. In addition it may be necessary to cut back and possibly overwork the sprayed surface in order to achieve a fine tolerance, which can reduce the concrete's quality and its bond to the substrate, particularly on thin overlays (less than 50mm). Designers should therefore be realistic in setting tolerance bands and advise the client of the likely appearance. Kolf and Gebler (29) have recommended some reasonable tolerance limits. Where aesthetics are important it may be advisable to hold full-scale trials to determine an appropriate tolerance/finishing regime that is to the client's and contractor's satisfaction.

5.2 CEN STANDARDS DEVELOPMENT

Following behind developments in construction practice has been the introduction of standards for practice, testing and specification. The USA was most prolific in this respect, starting with the American Concrete Institute Committee 805 Standard of 1951, which was subsequently revised and augmented by a range of documentation under Committee 506 and complemented by the production of five ASTM national standards since 1988. Europe was slower to respond, with codes of practice and standard specifications being produced in the UK between 1976 and 1981, by the Association of Gunite Contractors and the Concrete Society. The first national standard came from Germany in 1979 with DIN 18551 (27). French and Norwegian standards have followed in the last few years.

CEN (Comitè Européen de Normalisation) Technical Committee 104 for concrete established a Working Group for sprayed concrete (TC104/WG10) in 1995 to produce a European standard and necessary test methods. The Group set up four Task Groups to develop:

TG1 - Repair, Upgrading and New Structures
TG2 - Strengthening of Ground
TG3 - Test methods
TG4 - Definitions and General Requirements

The aim was to propose a standard building on the EFNARC Specification (4) together with the German DIN18551 (27) and to a lesser extent the French AFNOR (30) standard (which only relates to repair and strengthening, but gives detailed, pragmatic advice for these types of applications). The EFNARC document has been particularly influential because of the wide European consultation involved in its production and its emphasis on specification. This is in contrast to the DIN standard's concentration on production and quality control. It was also the intention to produce a standard in three parts, covering general definitions, new construction/repair and ground support, with reference to new, separate standards for test methods where required. However, in the evolution of the documentation it has become clear that there is considerable scope for common sections relating to the two categories of application and it is now hoped that a single document will be possible. The latest drafts (as of August 1998) propose common sections for all applications (put in Part 1) with the exception of Execution:

(i) Part 1: Definitions, Specifications, Requirements and Conformity

Scope
Normative References
Definitions - Mix Component, Product, Process, Properties, Execution, Operative, Test/Verification
Classification - Consistence of wet mix, Exposure classes related to environmental conditions, Hardened sprayed concrete, Young sprayed concrete, Fibre reinforced sprayed concrete
Requirements for constituent materials - Cement, Aggregates, Mixing water, Admixtures, Additions, Polymers modified sprayed concrete, Fibres, Steel reinforcement
Requirements for sprayed concrete composition - Type cement, use of aggregates, use of admixtures, use of additions, use of fibre, Curing compound, Consistence of wet mix sprayed concrete, Temperature of basic mix, Chloride content, Resistance to alkali-silica reaction, Requirements related to exposure classes, Water/cement ratio, Density of fresh concrete, Sampling
Requirements related to performance and durability - Density, Modulus of elasticity, Flexural strength, Resistance to water penetration, Frost resistance, Bond strength, Thickness
Requirement related to fibre reinforced sprayed concrete - Fibre content, First peak flexural strength, Residual strength class, Energy absorption capacity
Specification of sprayed concrete - Specifying designed mixes, Specifying prescribed mixes
Assessment of conformity - Inspection classification, Pre-construction testing, Production control, Conformity criteria (covering: early strength development, compressive strength, flexural strength of FRC, energy absorption capacity of FRC, fibre content, water penetration, frost resistance, bond strength and thickness)

(ii) Part 2 Repair and Upgrading Of Structural Members and For New Structures

Execution - Documentation of actions, Scaffolding, Preparation of substrate, Placing reinforcement, Formwork, Pre-wetting, Spraying, Surface of finished concrete, Curing, Protection against frost

(iii) Part 3 Strengthening of Ground

Execution of Sprayed Concrete - Reinforcement, Procedure before commencing work, Procedure in connection with each delivery of concrete, Equipment and installation, Batching and mixing, Executing of spraying, Curing and protection, Protection against frost, Spraying on reinforcement

6 QUALITY CONTROL AND TEST METHODS

6.1 QUALITY CONTROL

Quality control of sprayed concrete is more difficult than that for conventional cast concrete because the mix proportions in situ may differ substantially from the batched proportions and the concrete quality is more operative dependent. The most reliable determination of the quality of sprayed concrete in place is obtained by testing samples extracted from a typical sprayed section. However, this is a costly procedure and it may sometimes be impracticable to obtain specimens this way for regular control tests. The next best solution, though this has its shortcomings, is to extract cores from test panels gunned under field conditions. Test panels are also of use before the start of construction to check that the gunning crew can produce the required quality of sprayed concrete using the equipment, materials and mix proportions proposed for the works.

Preconstruction testing is a vital part of the design/construction process. A number of authorities describe good practice including ACI Committee 506 (5) who give details of the investigations that may be carried out prior to the start of the field work to verify that the specified quality of sprayed concrete can actually be expected in the structure. They recommend that test panels (minimum 750mm square) be sprayed from each position required by the work (downhand, vertical or overhead) and for each mix design being considered. In addition to visual examination (for soundness and uniformity of material) and strength measurements, tests for bond, water absorption, shrinkage, resistance to freezing/thawing and other properties are also suggested. Further guidance is given by EFNARC (4) who recommend checking: water demand, workability and pumpability/sprayability, rebound, air content, density (for the fresh concrete); and compressive and flexural strength, toughness, fibre content and bond (for the hardened concrete).

Most specifications for sprayed concrete projects call for the making of test panels during construction (typical between 500 and 750mm square and 100-150mm thick), from which test specimens are cut or sawn. Whilst test panels are more convenient that in-situ sampling, an obvious disadvantage is that the operator is aware that a test specimen is being produced and consequently the sample may not necessarily be a representative one. The edge effect of the panel and the backing material may also affect the concrete properties. European guidance on the preparation and testing of test panels for sprayed concrete is given by EFNARC (4).

6.2 TESTING APPROPRIATE PROPERTIES

Compressive strength is the principal measure of quality control of sprayed concrete in Europe and gives a reliable indication of matrix quality of sprayed fibre concrete. Cores also allow visual inspection and grading of sprayed concrete quality. Most countries have appropriate national standards. In-situ coring is clearly superior to coring a test panel from the point of view of obtaining representative test specimens and it is also the only effective method that can be used to investigate specific areas for bond, compaction and other properties. Compressive testing of cores extracted from test panels is sometimes permitted for routine quality control, but it is prudent to take test cores periodically from the completed work to ensure that the control tests reflect the quality of material in the structure.

A beam flexure test is clearly a potential candidate as a quality control test for sprayed fibre concrete since it yields information on limit of proportionality, ultimate and residual flexural strengths (i.e. toughness); these are important properties of fibre concrete and are all affected by in-situ fibre content. However, beam and slab samples can only be obtained from test panels and the test method is considerably more complicated than a core test. On major contracts in Europe the EFNARC (4) beam test (125 x 75mm on a 450mm span) is commonly specified for both pre-construction testing and routine quality control to check compliance with specified minimum peak and residual flexural strengths. On smaller contracts it may be sufficient to monitor compressive strength and in-situ fibre content during production. The slab (plate) test described in the EFNARC document is much less common, although it has been used regularly in France on railway contracts. It simulates a rock bolt loading, but has the disadvantage that the measurement (area under the load-deflection curve) does not relate to any fundamental engineering parameter that can be incorporated into design calculations. Recent work by Bernard (31) and Marti et al (32) has tried to address some of the problems of the method, including modifications that improve consistency and provide a means of analysis based on scientific principles. Such an approach is being considered currently by CEN.

An important property of all sprayed concretes is the bond strength between the sprayed concrete and its substrate. Without an adequate bond, a sprayed concrete layer is ineffective no matter what the quality of the concrete itself. In the past this was rarely measured because of the lack of a suitable test; reliance was placed on soundness tests (like tapping). Suitable quality control test methods are now available, including the core pull-off test in which a partially cored specimen is pulled from its substrate in situ, and laboratory tensile tests on cores. Both of these methods are being proposed as European standard tests. CIRIA (33) has published three technical notes on standard tests for repair materials, including one on pull-off tests. This useful document describes relevant codes and standards, as well as the range of equipment available, and makes recommendations on good practice. The author has also reported on tensile (34) and shear bond (35) testing of concrete, in particular on the influence of material properties, surface conditions, testing method and material mismatch. The latter paper also builds on a bond failure-envelope concept (36) that can be used by design engineers to determine the likelihood of bond failure in any combination of normal and shear stresses. Bond testing should form part of any significant sprayed concrete quality control programme and is being increasingly specified.

The permeation characteristics of sprayed concrete are often important as they have a direct bearing on the concrete's durability. A sprayed concrete layer usually contains steel, in the form of bar or mesh reinforcement and is therefore prone to corrosion as a result of carbonation or chloride ingress. Cores may be used for water absorption, sorptivity or intrinsic permeability determinations, these being of particular relevance with water retaining linings. EFNARC [5] recommend the use of an ISO water penetration method.

6.3 EUROPEAN TEST METHODS

Task Group 3 of TC104/WG10 has now reviewed all the potential tests required for sprayed concrete or called up by the drafts of the main standard. The Group’s approach has been to recommend existing CEN standards for concrete or, if necessary, modifications to the same, the latter being usually associated with specimen manufacture. However, it has been necessary to propose seven new test methods covering: test panels and sampling; thickness; fibre content; flexural and residual strength of fibre reinforced concrete (FRC); frost resistance; early age strength; and energy absorption of FRC (slab test). The drafts of the first five are well advanced and have been proposed for formal enquiry.

7 CONCLUSION

This paper has reviewed a wide range of issues relating to sprayed concrete practice in Europe. It has been shown that considerable advances have been made in recent years, particularly with the wet process, materials technology, robotic equipment and publication of documentation for specification and testing. Challenges still remain including: codes of practice for structural design methods for ground support; improving the reliability of repair applications together with prediction of service life; and better training and education for both site personnel and design staff who remain uninformed of latest good practice.

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