Construction and Repair with Wet-Process Sprayed Concrete and Mortar

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1 Introduction

This document provides practical guidance for designers, specifiers, contractors and [1]clients on all aspects of low-volume wet-process sprayed mortars and concretes. It provides information for both new construction and small-scale repair and covers choice of application method, materials and mixes, specification, pumping and spraying, finishing, curing, testing and performance. The information is a combination of existing good practice and new knowledge acquired during a three-year research project conducted at Loughborough University entitled '*Wet Process Sprayed Concrete for Repair'*. This was funded by both Government[1] and industry, namely Balvac Whitley Moran, Fibre Technology, Fosroc International, Gunform International Ltd and Putzmeister UK Ltd. This document concentrates on wet-process mortars and small aggregate concretes (< 8 mm) applied in thin layers (<100 mm) at low/medium output rates (< 5m^3/hr), in some cases with mesh or fibre reinforcement.

Wet- and dry-process sprayed concrete and mortar has been described by several names in the past, namely shotcrete and gunite. This document uses the terminology standardised by the European Federation of National Associations of Specialist Repair Contractors (EFNARC), namely sprayed concrete, with mixes containing aggregate with a maximum size of 3-4 mm being classed as mortars and anything larger as concretes.

Sprayed concrete can be defined as 'mortar or concrete conveyed through a hose and pneumatically projected at high velocity from a nozzle into place.' In the *wet process*, the constituents (cement, aggregate, admixtures and water) are batched and mixed together before being fed into the delivery equipment or pump. The mix is then conveyed under pressure to the nozzle, where compressed air is injected to project the mix into place. This differs from the *dry process* in which the dry constituents are batched together before being conveyed under pressure through the delivery hose to the nozzle, where pressurised water is introduced and the mix projected into place.

Sprayed concrete and mortar can offer a number of advantages over cast in-situ concrete including:

- reduction or elimination of formwork (with consequent cost savings)
- construction of free-form profiles
- rapid placement of large volumes
- the production of dense, homogenous, high quality concrete
- reduced access problems (by locating the delivery/mixing equipment away from the placing area)
- good bond to substrate and between layers
- reduced thermal stresses (by placing several thinner layers)
- production of unusual finishes.

Disadvantages associated with sprayed concrete and mortar include:

- specialist expertise needed for both good design and construction
- variable concrete quality (though mainly with the dry process)
- high material costs (arising from specialist mixes, high cement contents and wastage due to rebound, overspray and cutback)
- poor encasement behind dense concentrations of reinforcement
- labour-intensive finishing
- effort required in quality control testing to ensure a satisfactory finished product.

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2 Applications of Sprayed Concrete

Many aspects of preparation and construction for sprayed concrete apply equally to new construction and to repair. For both applications it is advisable to seek the views of contractors experienced in sprayed concrete who can provide guidance on the practical aspects of the work and identify any requirements in the draft specification that may cause problems.

2.1 New construction

Conventionally placed concrete is generally cheaper than sprayed concrete but spraying enables the creation of free-formed shapes. Simple domes or hyperbolic parabaloid roofs can be conventionally cast, but they are more rapidly and economically produced by spraying. The as-shot surface can be an architectural feature or thin flash coats can produce various types of finish. Spraying is a popular method of constructing swimming pools, especially modern leisure pools which are frequently complex in shape and other hydraulic structures (Figure 1). Sprayed and cast concrete can be combined e.g. in swimming pools where the base is cast and the walls are sprayed. Sprayed concrete can also provide fire protection for steel frames. The Shanghai Bank in Hong Kong is a high-profile example where $1000m^3$ of concrete was sprayed over an area of $72,000m^2$.

Canal linings, dams, harbours, sea walls and defences, chimney linings, arches, domes and storage tanks can all be constructed with sprayed concrete. One of the largest new constructions in wet-process sprayed concrete was the New Zoological Gardens in Riyadh, Saudi Arabia, where over $12,500m^3$ of concrete was sprayed in structures and finishes (Figure 2). Sprayed refractory concretes are utilised in the cement, iron and steel industries for kiln and furnace linings, chimney flues and casting chambers.

Sprayed concrete has also been used for sculpture. Rachel Whiteread won the Turner prize in 1993 with a sculpture of the inside of a Victorian terraced house which had been sprayed on the inside with sprayed concrete. The existing structure was then carefully demolished to reveal a negative image of the dwelling. This was completed using the dry-process, but in hindsight the wet-process would have been preferable as the better working environment and reduced rebound would have been more suited to the enclosed conditions within the house.

*Figure 1.*Pierepoint canoe slalom

Figure 2. Riyadh zoo, Saudi Arabia

2.2 Underground support

Underground support, rock stabilisation and tunnel linings are a major use of wet-process sprayed concrete but they are outside the scope of this document and a large amount of information is already available on these applications (Daws, 1995; ITA, 1993; Melbye, 1995 and Melbye, 1997). When applied to a rock surface, sprayed concrete is forced into fissures and open joints and helps to bond such features together. It also helps prevent water ingress and protects the rock against deterioration by water and air. Rock bolts and steel fibres are widely utilised in rock stabilisation and underground support. An example in the UK of sprayed concrete providing rock stabilisation is the 100 km North Wales A55 coast road completed in 1994 (Figure 3). The New Austrian Tunnelling Method (NATM) also incorporates sprayed concrete to provide temporary support in soft or weak ground and several guides are available on this technique (Barton, 1995 and ICE, 1996).

Figure 3. Rhualt Hill

2.3 Concrete repair and strengthening

Sprayed concrete repairs have been successfully completed to many structures including: bridge soffits, beams, parapets and abutments; steel and reinforced concrete framed buildings; cathodic protection; cooling towers; industrial chimneys; tunnels; water-retaining structures; jetties, sea walls and other marine structures (Taylor, 1995).

A recent successful example which illustrates the flexibility of wet-process sprayed concrete was the £4.3m contract to strengthen and repair the Lancaster Place Vaults (Figure 4) at the North end of Waterloo bridge in London (Bridge, 1999). For strengthening the brick archways sprayed concrete was cheaper than conventionally cast concrete as the irregular shapes of the arches eliminated the possibility of re-using shutters. 500m^3 of concrete incorporating a plasticiser and a stabiliser was sprayed and an activator was added at the nozzle.

Figure 4. Brick archway strengthening at Lancaster Place Vaults (before application of sprayed concrete)

Causes and types of defects

Repairs can be broadly categorised into structural, serviceability and cosmetic repairs. Structural repairs restore lost sectional or monolithic properties to damaged concrete members, serviceability repairs restore concrete surfaces to a satisfactory operational standard, and cosmetic repairs restore concrete to a satisfactory/acceptable appearance.

A recent survey by Loughborough University of 11 organisations (consultants, contractors and local authorities) involved with concrete repair in the UK found that the main cause of deterioration of concrete leading to repair is the corrosion of steel reinforcement due to the ingress of chlorides and carbonation, with alkali aggregate reaction and the effects of heat following fires being less common causes (Seymour and Turner, 1995). Typical repairs are normally less than 2m^2 in area with a depth of 50 to 100 mm. Most bridge repairs are carried out using flowable concretes, with repairs to high-rise buildings mainly carried out by hand-applied mortars and concretes. A small proportion of each are carried out with dry sprayed concrete, particularly when the area of repair is above 1m^2.

Deterioration of concrete is usually in the form of cracking, caused by the corrosion and subsequent expansion of the steel reinforcement. This expansion causes spalling of the protective concrete layer, thereby further exposing the reinforcement. Reinforcement is usually protected by the alkalinity of the concrete cover but this can fail for two main reasons: carbonation, and chloride-induced corrosion. Carbonation occurs as carbon dioxide from the air produces a weak carbonic acid within the concrete cover zone, which progressively reduces its alkalinity as the carbonation zone moves into the concrete from the surface. The reinforcement is then susceptible to corrosion in the presence of oxygen and water. This deterioration mechanism can also be accelerated by inadequate concrete cover or a permeable concrete cover caused by too high a water/cement ratio, insufficient cement content or inadequate curing. Chloride ions (from de-icing salts, sea-water or from chlorides incorporated in the concrete mix) destroy the passivating oxide film on the embedded steel and, in the pressure of water and oxygen, corrosion occurs.

Concrete can also be damaged by fire and the repair of fire-damaged structures is discussed in the Concrete Society's *Assessment and repair of fire-damaged concrete structures* (1990). Other types of deterioration arise from chemical attack (such as sulfate attack) and physical causes such as the abrasion of sea walls by the action of beach material and the overloading of structures which produces cracks at points of high stress.

Diagnosis

It is essential to carry out an initial survey of the condition of the concrete before any repair work is undertaken in order to identify the problem, quantify the extent of the damage and to prepare appropriate remedial action. It has been estimated that over 90% of concrete deterioration is probably due to design or construction errors, misconceptions in specifications, or bad workmanship (Shaw, 1993). Assessment of damaged structures are outside the scope of this document but various publications are available on the subject (Kay, 1992; King, 1995 and Allen *et al.*, 1993).

Methods of repair

After identifying the source of deterioration, the next step in designing a successful concrete repair is to consider the objective of the repair. This will generally be to restore or enhance one or more of the following: durability, structural strength, function, or appearance (Allen *et al.*, 1993), of which restoration of durability is usually the main requirement. Once this objective is decided appropriate repair materials and removal and repair methods can be chosen, bearing in mind (Mailvaganam, 1991 and Kay, 1992):

- modifications required to remedy the cause of the damage
- overall quantity and size of individual repairs
- time available for repair
- economic viability of each material and method

- access to the structure
- advantages and disadvantages of permanent vs. temporary repairs
- availability of repair materials and methods
- restrictions on noise, dust, vibration, and fumes
- possible requirement for the continued operation of the structure during the repair
- method of disposal of waste.

Possible repair methods include hand-application, wet and dry spraying, flowable materials and new construction. New construction is the most drastic measure but in cases of severe damage or deterioration, demolition and reconstruction may sometimes be more economic than repair, especially when the whole-life costs of the structure are considered.

Hand application of patch repairs is most economical when repairing a small number of isolated repairs. Flowable grouts and concretes are suitable where large volumes of repair material needs to be placed, usually with the aid of shuttering. Repair contracts often incorporate this technique as high densities of reinforcement make hand application and spraying impractical.

Sprayed concrete is often appropriate where concrete or mortar need to be applied: over a large area, such as in the restoration of corrosion or fire-damaged buildings; where access is difficult; and when formwork is impractical. Sprayed concrete or mortar is also chosen when the speed of the repair process is the main consideration, such as tidal work and repairs to industrial processes which have to be shut down for the repairs to take place. Repairs should be completed in accordance with EN1504.

Repair Scenarios

Table 1 summarises the repair scenarios generally encountered in the UK, classified in terms of characteristics common to various repair applications, including; purpose; orientation; geometry; reinforcement; substrate; surface finish; construction method and environment. Four main categories of structure that required repair were identified in the survey by Loughborough University (Seymour and Turner, 1995): reinforced concrete bridges, buildings and tunnels, and masonry structures. The majority of repairs at present are to motorway bridges, with repairs to high rise buildings being the next most common.

The survey found that the orientation was divided equally between overhead and vertical applications and that access to repair sites was often difficult, with the space and time allowed to carry out the repair frequently being limited.

Table 1 Repair Scenarios for investigation using wet process sprayed concrete technology

TYPE OF REPAIR	PURPOSE	GEOMETRY			SUBSTRATE			ENVIRON.	ORIEN.	REINF.	SURFACE FINISH	ACCESS
DESCRIPT.		SIZE	DEPTH	TOL.	PREPARATION	TYPE	SURFACE CHAR.					
bridge soffit	1 cover 2 structural	<2m^3	50-100mm	+/-10mm	hydro-demolition + grit blasting	concrete	AAR Carbonation Chlorides	atmos.	overhead	mesh fibre	trowelled finish, no colour match	limited to night restricted space available.
bridge abutment (marine structures)	1 cover 2 structural	<2m^3	50-100mm	+/-10mm	hydro-demolition + grit blasting	concrete	AAR Carbonation Chlorides	atmos.	vertical	mesh fibre	trowelled finish, no colour match	limited to night restricted space available.
building (water retaining structures + r.c. chimneys)	1 cover 2 structural	<2m^3	50-100mm	+/-10mm	mechanical hydro-demolition + grit blasting	concrete	carbonation (chlorides in car parks)	atmos.	60:40 vertical: overhead	mesh	trowelled, colour match (where no surface coating provided)	external repairs use scaffold, platforms etc.
Fire-damaged structure	structural	<2m^3	50-100mm	+/- 3mm (visible) +/- 10mm (covered)	hydro-demolition + grit blasting	concrete	fire-damage	atmos. (substrate absorbs H_2O at high rate)	50:50 overhead: vertical	mesh (replace damaged steel)	trowelled where visible, otherwise as shot, no colour match	ok
tunnels	structural	<1m^3	100mm	+/-10mm	hydro-demolition + grit blasting	concrete	carbonation chlorides	cool (ventilation fans) can be damp	overhead	mesh, corroded steel replaced	as shot, no colour match	restricted access to road and rail tunnels, pumping long distances
sewer (masonry tunnels + arch bridges)	strengthening	1m^3 +	25-50mm (less than 100mm)	+/-10mm	grit blasting	masonry	deteriorated masonry	warm & damp	curved surface	mesh used (stainless steel)	as shot, no colour match	restricted access through man holes, pumping long distances

Summary

- *Categorise work needed* as either new construction, underground support or as a structural, serviceability or cosmetic repair
- For repair, *conduct a detailed survey* of the concrete condition and the source of damage and/or corrosion. Consider and compare different repair methods. Consult *repair scenarios* to identify type of repair
- *Review documentation* of Concrete Society (1990), European Standard (EN1504 and ENAAA (Appendix A.3)), EFNARC (1996) and SCA (1999)
- *Make decision* on suitability of sprayed concrete for the appropriate parts of the works

3. The Wet Process

3.1 Background

Sprayed concrete is attractive because of the flexibility of the application process and the elimination of formwork, but to date nearly all low-volume sprayed concrete projects in the UK have been carried out using the dry process. The wet process has become dominant for large-scale tunnel construction, sometimes involving robot-controlled spraying but is not a common solution for low-volume work. Low-to-medium-volume wet-spray applications are increasing, especially for repair, because of the better consistency of the sprayed material and reduced dependence on operator skill, as well as the improvements in materials and production technology, particularly its stop/start flexibility. Low-volume wet-spraying has traditionally been used in continental Europe for the application of sand/cement renders and plasters, which are typically 10-20 mm thick. It has become the standard method for the applying plaster in many European countries, although little is done in the UK.

In some countries there has been a big swing towards the wet process, partly because of better control over mix proportions (particularly the water/cement ratio). These include Norway and Sweden, where the majority of work is wet process, and the USA where the two techniques have a roughly equal share and are both used for repair. Although the proportion of wet-sprayed concrete is increasing in the UK, other countries (in particular Germany) are predominately orientated towards the dry process. These differences partly reflect the functional emphasis of the two processes i.e. wet mix for high output applications such as tunnelling, and dry mix for low-to-medium output applications such as repair, or situations requiring greater transport distances and flexibility like mining.

There is relatively little quantitative data available on wet-process sprayed concrete for repair. However, increasing interest in the process is demonstrated by a number of recent articles and papers which have an industrial perspective, including Beaupré *et al.* (1999), Collins *et al*. (1997), Garshol (1999), Heere *et al.* (1996), Jomha and Suhr (1997), Norris (1999), Lane and Chaplin (1998), Osborne (1998) and Oliver (1998). Previous publications by the authors have discussed the materials, installation and physical properties of sprayed concrete (Austin and Robins, 1995), the associated application methods and quality considerations (Austin, 1996), and both the rheology (Austin *et al.*, 1999a and Austin *et al.*, 1999b) and hardened performance (Austin *et al.,*1999c) of wet-process sprayed mortars. Other published research includes work conducted on the long-term performance (Mangat and O'Flaherty, 1996) and the structural effectiveness (Mays and Barnes, 1996) of sprayed concrete repairs.

3.2 Comparison with dry-process sprayed concrete

The dry process is capable of producing high quality concrete but has several drawbacks, including the difficulty of achieving quality and consistency, high material losses, and a dusty and dirty working environment. The wet process has the potential to produce more consistent concrete, with lower wastage, and in a healthier working environment.

Both methods have their advantages, and before a decision on process type can be taken detailed consideration of design and application must be made. For example, dry spraying is well suited to contracts that require an intermittent supply whilst the wet process is more suited to contracts that require continuous spraying, little rebound and dust and more control over the mix quality. The choice of spraying method influences both the drawing up of the specification and the choice of associated quality control procedures. With the wet process the minimum cement content and maximum water/cement ratio can both be specified and checked for compliance. This is difficult with the dry process as compliance must be checked in-situ and so compressive strength is usually specified. An alternative is to specify a prescribed mix which would give the desired performance when placed (section 4). However, the specifier is unlikely to know the local materials available (e.g. aggregates) and so a poor mix may be prescribed. Batching control and in-situ testing are therefore still important with prescribed mixes. Pre-blended proprietary mixes are commonly specified in both the wet and the dry processes to overcome problems of mix design and batch inconsistency.

Factors to consider when choosing a spraying system include:

- output required, distance of the pump to the nozzle and the availability and size of associated equipment (compressor, hoses, nozzle etc.) (section 3.3)
- mixing and batching facilities available (section 4.10)
- effects of rebound (both economical and environmental) (sections 3.6 and 8.5)
- required consistency and quality (sections 4, 5 and 10)
- additions and admixtures required (sections 4.4 and 4.5)
- permissible dust, noise and vibration levels (sections 3, 6.4 and 8.5)
- skill of the nozzleman (section 3.4 and 8)
- spraying frequency required (sections 6 and 8)

- type of finish (section 9)
- availability of materials (section 4)
- economic considerations such as equipment, energy and material costs (sections 3, 4 and 6)

Only when all these factors are considered can an informed and accurate choice be made as to the type and size of the spraying equipment.

3.3 Equipment

Various types of pump are suitable for the wet-mix spraying of mortars and concretes. The main requirement is that the pumps should be capable of delivering a continuous, even flow of material to the nozzle. The choice of equipment should be left to the contractor.

The two main types of pump are:

1. the piston pump (Figure 5), for medium to high outputs (5-20m^3/hr);
2. the worm or screw pump (Figure 6) for low outputs ($<$5m^3/hr).

Figure 5. Typical medium output piston pump (Gunform's Reed B10)

Figure 6. Typical worm pump (Putzmeister P11)

Due to the relatively small size of the opening in the rotor-stator in worm pumps, they can only pump aggregate up to approximately 4 mm in size, and are unable to pump steel fibres. Their main disadvantage is high wear, especially with coarser aggregates (Muller, 1984). The speed and capacity of the pump, and its ability to handle different size aggregates and consistencies of mortar, are all affected by the size and type of worm, the type of rubber of the sleeve and the size and the clearances of the worm in the sleeve (Gordon, 1993). Worm pumps are usually powered by 2- or 3-phase electric motors or diesel or petrol engines. They produce a continuous and pulsation-free mortar supply and as they require no valves (unlike piston pumps), they are generally reliable.

Piston pumps, both single and double action, can deliver both mortar and concrete mixes at larger outputs than worm pumps, although the flow sometimes pulsates more due to the pumping action of the pistons. They are powered by either diesel or petrol engines.

The quality and properties of the in-situ material are influenced more by the projection of the mortar (i.e. nozzle design, spray velocity) than by the pumping technique (Austin *et al.*, 1999c). The pump type (worm or piston) has little effect on the in-situ compressive and flexural strength although it can affect the bond strength, mainly due to the stream velocity and water/cement ratio. The type of pump and size of air compressor (which influences the velocity of the concrete or mortar stream) affects the encasement of the reinforcement; high-velocity piston and large-diameter worm pumps generally produce better encasement than small-diameter worm pumps.

All-in-one mobile units are available, with all the necessary equipment (spraying machine, water pump, hoses etc.) and energy sources (compressed air, electrical power) on board. The latest technology in dual-mixing worm pumps (Figure 7) offers significant advantages over current equipment in providing superior two-stage mixing, automation of water addition and nozzle-operated pump controls.

Stop/start flexibility can be enhanced by including hydration suspension/activation admixtures (common in high volume tunnelling). However, the complication (and cost) of the materials and dosing equipment is likely to make this inappropriate for small-scale applications. Better, in these circumstances, to plan the daily work schedule to include concentrated periods of pumping and spraying activity (section 6.1).

The size of hose required depends upon the output of the pump and the size of the fibres (if present), 50-100 mm diameter hoses being typical. Regular cleaning and checking are essential to ensure safety and longevity.

Compressed air free of contaminants and continuous in supply is needed and an adequately sized compressor is essential. For a small-diameter worm pump a compressor of at least 10 cfm (0.00472 m^3/s) is needed, with 40 cfm (0.019 m^3/s) providing a superior and more controllable stream. Double-acting piston pumps require 250-365 cfm (0.12-0.17 m^3/s) compressors, which are commonly found on construction sites for powering breaking tools.

Information on nozzles and spraying is given in section 8.

Figure 8. Dual-mixing worm pump (Possibly M-Tecs Duo-mix)

3.4 Personnel and training

It is the consultant's responsibility to train the staff involved with the design of sprayed concrete and they should be aware of the advantages and disadvantages (section 1), operational limitations (sections 2 and 3) and health and safety aspects of sprayed concrete (section 6.4). The contractor is responsible for training the staff that manage the contracting work. These staff should also possess additional experience on similar projects. Courses are available that cover materials, safety, plant and the environment. It is essential to train the key operatives of the mixer, pump and nozzle in their various duties as the quality of sprayed concrete or mortar is operator-dependent and bad quality work is very often the result of poor spraying. They should be adequately trained in basic concrete technology, correct plant maintenance and operation and how to work safely. The Sprayed Concrete Association support an independent certification scheme whereby site operatives can be trained and then assessed practically and by written and oral tests. Courses can be run in-house or provided by national bodies (Construction Industry Training Board, 1994; Sprayed Concrete Association, 1994; American Concrete Institute, 1982). Periodic testing and refresher courses may be necessary if certain sprayed concrete applications have not been carried out by the operative for some time. Some specifications now require all nozzlemen on a contract to possess an independently assessed certificate in sprayed concrete.

3.5 Common mistakes

Consequences of poor spraying include voidage around reinforcing bars, entrapment of rebound and excessive loss of material due to overspray, cutback and rebound (section 8). Voids around bars can be formed (Figure 8) by excessive lapping of bars, by fixing bars too close to the substrate or where overspray has built up on the face of the reinforcement.

- *Rebound* (section 8.5) is material that has been sprayed but has not adhered to the in-situ material and rebound that has not fallen to the ground or been removed with a blow pipe can become trapped within the sprayed material. Since rebound is approximately 90% aggregate and fibres this can form a weak layer within the material. The amount of rebound is typically 5-10% for vertical surfaces for the wet process and can be minimised by good spraying. Bad placement of formwork without gaps in the shutters can also lead to rebound entrapment
- *Overspray* is material that misses the surface; which if it is not removed it can leave an un-consolidated thickness of low quality material, which when sprayed onto can form a weak bond. Adequate protection of adjacent structures may be needed to avoid overspray causing damage
- *Cutback* is material which is shot but subsequently removed before setting. The amount of overspray and cutback material should be small if the spraying is done by a skilled nozzleman with guiding wires/boards.

Figure 8. Example of voidage behind reinforcement

Operatives can be tempted to add too much water to a mix, especially if problems are encountered with pumping the material. This can cause the material to sag or slough after it has been sprayed and will also reduce the strength and durability of the hardened material.

Adequate preparation of the substrate is essential and a repair may be only as good as its bond to the substrate (section 6.3). Substrate preparation is often not given the time and attention needed to produce a long-lasting and durable repair. Problems can be encountered due to inadequate cleaning and both over- and under-wetting of the substrate. Care is not always taken with the floating and finishing of the material (section 9). This can lead to sections of the material being pulled away from the substrate or forms which reduces the bond strength and spoils the appearance.

Inadequate or non-existent curing is possibly one of the most common causes of sub-standard sprayed concrete (section 9.4). This is usually the final stage of the construction sequence, and one that is frequently hurried. Inadequate curing allows moisture to escape from the concrete and prevents complete hydration of the cement from taking place. This can be exacerbated by sunlight and wind, especially in exposed locations (Figure 9). Inadequate curing can also cause excessive shrinkage and hence cracking of the surface, which may allow the ingress of water and chlorides into the structure, where present.

Figure 9. Cracking due to inadequate curing at Budbrooke

3.6 Costs

It is usually necessary, for each new contract, to compare the cost of using sprayed concrete or mortar and conventionally cast material. Points to bear in mind when considering sprayed concrete or mortar are:

- higher material costs due to the higher cement content and possible inclusion of chemical admixtures
- wastage of material from rebound
- need for specialist plant (pump, gun/nozzle, water supply and compressed air) and skilled labour

Greater effort (and therefore cost) is also usually needed for quality control testing. These additional costs will be offset by the reduction in formwork and falsework and the possible increase in output. The total costs of both the application and the long-term effectiveness of the repair/construction should also be considered. Factors that influence cost include:

- access available
- transportation needed
- available construction time
- required long-term durability
- quantity of new reinforcement needed
- finish required

The points listed in section 2.3 will also influence the overall cost of the application.

A decision also needs to be made whether to spray pre-blended proprietary mortars (section 4.8) or site-batched materials (section 4.9). Pre-blended materials are more expensive but the higher costs can be offset by reductions in quality control testing, by having a more consistent product with a more even flow of material and fewer blockages than is possible with a site-batched material. Site-batched materials are usually cheaper, depending on available material sources, but additional batching equipment is usually required.

Summary

- The wet and dry processes should be *compared* by considering all the factors listed in section 3.2
- *Advice* on the type of pump should be sought from both manufacturers and contractors
- All associated equipment (hoses, nozzles and air supply) should be *clean* and *free from wear and of a size compatible with the pump.* It should be remembered that worm pumps can only pump mortars with a maximum aggregate size of 3-4 mm (depending on type of pump –consult the manufacturer)
- All design and construction work should comply with the *Health and Safety at Work Act and CDM Regulations.* The contractor is responsible for supplying protective overalls, gloves, eye protection and masks/respirators
- All materials should be covered by relevant *COSHH regulations* and handled and disposed of safely
- The designer, contractor and operatives should all be *adequately trained* in sprayed concrete technology, application and safety. Operatives should preferably posses a *certificate of competence* from the CITB or similar

4 Materials and Mixes

4.1 Mix Design

The material constituents of sprayed concrete are similar to those in ordinary cast structural concrete. Until the 1980s, most of the sprayed concrete in Europe typically incorporated a Portland cement and sand mix in proportions of approximately 1:3. Since then supplementary cementing materials (such as silica fume and fly ash), special admixtures (such as retarders and superplasticisers) and fibre reinforcement have all been increasingly used.

The survey conducted by Loughborough University (Seymour and Turner, 1995) found that most sprayed and hand-applied repairs are carried out with pre-blended proprietary materials and products. This is because they are perceived to be of higher quality than site-batched materials (in terms of the consistency of the ingredients) or ready-mixed concrete. Ready-mix is reserved for large-volume repairs and new construction. Contractors and local authorities carry out few, if any, quality control tests on these pre-blended materials, considering such tests to be unnecessary and too costly.

Sprayed concrete can be specified using either the designed mix or prescribed mix approach. BS 5328 (1991) defines a designed mix as a “mix for which the purchaser is responsible for specifying the required performance and the producer is responsible for selecting the mix proportions to produce the required performance”. The mix is designed by the contractor to achieve the specified compressive strength and/or other specified properties, such as minimum cement content, minimum fibre content (in-situ), maximum water/cement ratio, flexural strength, toughness, early-age strength, permeability and bond (King, 1995). This method is preferable for sprayed concrete as the contractor is free to select constituents to produce the best pumping performance for a mix.

The prescribed mix is defined by BS 5328 (1991) as a “mix for which the purchaser specifies the proportions of the constituents and is responsible for ensuring that these proportions will produce a concrete with the performance required”. Reliable previous experience with the available materials is usually needed , either from a previous project or from a pre-construction trial. The specification includes such data as cement type and content, water/cement ratio, fibre content, type and quantity of aggregate, admixtures and additives. It must be clear whether the proportions apply to the original mix or to the in-situ material.

The mix designer must bear in mind the mechanics of concrete pumping, as the concrete must not only meet specification for strength, but must also pumpability and sprayability requirements. An effective sprayed concrete mix should be the stiffest mix that will:

- pump through the nozzle
- remain at a workable consistency when left in the hose during breaks in pumping
- not stiffen under the increased temperatures which may occur in pumped material (the pump can cause considerable increases in temperature in a long spraying operation)
- will atomise easily with the available air supply

Mix design is affected by materials, pumping distance and required output rate, and with the wide range of materials, applications and equipment available, no single mix proportion can be applied to all cases. Where the mix is to be sprayed onto a substrate, it must be compatible with this substrate in terms of strength, stiffness and thermal expansion. Further information on sprayed concrete and mortar mix design can be found in AFNOR (1992), Austin (1995), Cooke (1990), ITA (1993), King (1995), Melbye (1997) and SCA (1990).

4.2 Cements

Portland cement (PC) was incorporated in most sprayed concrete produced before 1980 (Robins, 1995). Recently, rapid setting and high-early strength cements have been introduced in sprayed concrete, although PC is still the most common binder. It is, however, increasingly combined with supplementary cementing materials (additions) such as silica fume and fly ash. All cements should conform to EN 197.

In the design of normal concrete mixes, the cement content is minimised for reasons of economy. This is also the case for pumped or sprayed concrete, although a higher cement content is necessary to facilitate adhesion and build-up thickness and to form a lubricating layer around the inside of the pipe. The greater the proportion of voids within the aggregate, the greater the amount of cement or filler needed to fill them to reduce bleeding during pumping and to increase density. Increased cement content is also known to reduce rebound. Various recommended cement contents for pumped or wet-process sprayed concrete are given in Table 2.

Table 2. Recommended cement contents for wet-process sprayed concrete

Source	**Cement content (kg/m^3)**
BCPA, 1979	300
EFNARC, 1996	300 minimum
AFNOR, 1992 (Surface repair)	350
Warner, 1995a	390
Morgan, 1995	400-500
Beaupre, 1994	400-450
Morgan and Wolseifer, 1992	400
AFNOR, 1992: Repair of reinforced concrete structures	450
AFNOR, 1992: Repair of masonry	500

Neville (1995) reports work published by the DoE (1972) stating that the volumetric cement content must be at least equal to the void content of the aggregate (with very fine material other than cement included with the aggregate). The relationship between the cement content, void content and the pumpability is shown in Figure 10. However, this does not take into account the influence of the aggregate particle shape on the void content, which is discussed in the following section.

Figure 10. Effect of cement content and void content on pumpability (Johansson, 1976).

4.3 Aggregate

Natural gravels and sands are usually better for pumping than crushed rock because of their rounded particle shape, and more continuous grading which minimises the void content. Coarse aggregate of marine or river origin is also preferable, as flaky, irregular particles of crushed rock are more abrasive and cause heavy wear on pumps and hoses. However, some crushed aggregates (e.g. Portland stone) can produce very effective and pumpable mortars (Austin *et al*., 1999a).

Aggregate grading is critical to the rheological properties of a fresh mix, and to the structure of the hardened product. For piston pumping, the maximum aggregate size should be 8-10 mm for repair (depending on the type of pump - consult the manufacturer) although up to 16mm is found in tunnelling work. Heavier aggregate particles rebound more than the lighter sand grains and cement, so limiting the maximum aggregate size also minimises loss through rebound. An increase in the proportion of coarse aggregate has also been shown to increase the pumping pressure needed and reduce the mix workability (Norris, 1999). The maximum aggregate size which can be pumped using a worm pump is 3-4 mm, with the larger aggregate causing the most wear on the rubber lining of the rotor-stator. All aggregate should also conform to a standard such as BS 882, for which the medium zone grading is most common.

The total voids between the compacted aggregates in a mix should be kept to a minimum. This minimises the potential for the mix to bleed as the aggregate particles 'lock' together, resisting the flow of liquid out of the mix. The ideal grading is that in which the voids between the largest particle size are filled with particles of the next size fraction down, and so on. This is achieved by using a combined grading (aggregate, cement and powdered additions) which is as continuous as practicably possible. The total air voids of the aggregate and the combined dry mix can be checked and compared with similar mixes with the air voids test developed by Browne and Bamforth (1977).

Engineers and specifiers should be guided by equipment manufacturer's recommendations and for piston pumping of larger aggregate mixes independent advice on gradings is available (Cooke, 1990 and Kempster, 1969). EFNARC (1996), Malmberg (1993) and Melbye *et al.* (1995) also provide advice on aggregate gradings. They suggest that for wet mix-process spraying the aggregate grading (<8 mm) should fall within the limits shown in Figure 11. The grading limits for wet mix-process spraying recommended by AFNOR (1992) are also shown. For worm pumping the grading is especially important, yet little information exists compared with the larger aggregate piston pumped mixes. Figure 12 shows the aggregate grading zone derived from the Loughborough University research for mortar mixes (up to 2 mm maximum aggregate). For all types of mix, the overall grading of both the aggregate and the cementitious component must be considered as well as the aggregate grading (section 4.9).

The fine part of the grading for all types of mix is particularly critical. Too little fine material leads to segregation and bleeding of the mix. This can be compensated for by adding extra cement or silica fume. Too much fine material makes a mix stiff and difficult to handle. This can be rectified by increasing the workability of the mix (which may reduce the compressive strength and the build value), or by adding water-reducing admixtures (which will increase the cost).

If the aggregate: cement ratio is 1:1 or 2:1, the mix is very unlikely to segregate unless it is also extremely wet (Kempster, 1967). However, such cement-rich mixes are rarely sprayed, and more common proportions of 3:1 and upwards are more likely to have segregation problems. The fines content (<80µm) including cement should be greater than 17% of the dry mix by weight (AFNOR, 1992).

Figure 11. Recommended aggregate gradings for wet-process sprayed concrete (8 mm max.)

Figure 12. Recommended aggregate gradings for wet-process mortars (2 mm max.) (Austin *et al.*, 2000)

4.4 Additions

Silica fume
Silica fume is the most common addition in sprayed concrete. It can reduce bleeding and segregation within a mix and thus improve pumpability. It produces better cohesion and adhesion so that thicker layers can be sprayed with minimal rebound. Silica fume is approximately 100 times finer than cement and has a significantly higher reactive silica (SiO_2) content, which ensures that it combines with and distributes the products of hydration more effectively, thus improving the density and homogeneity of the concrete (Neville, 1995) and reducing porosity and permeability. It is generally added as a cement replacement in wet-process sprayed concrete, usually between 2 and 8% by weight of cement; levels above 10% can result in surface cracking, especially in hot climates as well as reducing the alkalinity. In the wet process it is often added in conjunction with a water reducer or superplasticiser to maintain workability.

Silica fume can be added in condensed or un-densified powdered form or as a slurry. The slurry, a 50/50 aqueous suspension of silica fume powder, was developed to overcome the problems of handling and transporting silica fume in its powdered form and common in the wet process.

Ground granulated blast-furnace slag (GGBS) and Fly ash
GGBS and fly ash (pulverised fuel ash, PFA) are less common additives than silica fume, although their inclusion is on the increase. GGBS and PFA are generally added up to a maximum replacement level of 70% and 35% respectively. They are included to reduce the heat of hydration within thick sprayed concrete applications as they slow down the hydration process. PFA can improve the workability and pumpability of a mix made with harsh aggregates or a large proportions of fibres and also provide additional fines to enhance adhesion and cohesion in situations where excessively high cement contents need to be avoided. Fly ash should comply with EN 450 and GGBS with BS 6699.

4.5 Additives

Admixtures can add significant flexibility to wet-process sprayed concrete and overcome some of the potential shortcomings of the method (e.g. poor stop/start flexibility). A plasticiser will reduce the water/cement ratio (thereby increasing the strength and durability) whilst maintaining the required workability (and hence pumpability). Stabilisers prolong the workable life of the concrete whilst accelerators are added at the nozzle to initiate setting once the concrete has been sprayed. However, admixtures are an additional expense, can be caustic in nature and can be detrimental to some properties of the sprayed concrete (e.g. accelerators can reduce long-term strength). All admixtures are sophisticated chemicals and advice should always be sought from the manufacturer about dosage and application rates. Admixtures can alter their behaviour when added in combination, so care should be taken to ensure compatability. Admixtures for sprayed concrete should comply with the requirements of EN 934-2 and EN 934-6 or BS 5075, Parts 1, 2 and 3 or EFNARC (1996).

Superplasticisers and water reducers
Superplasticisers are high performance water-reducers which disperse the fines more effectively within a mix and therefore improve workability and cohesion. The two commonest types are sulphonated melamine formaldehyde condensates (which form a lubricating film on the particle surfaces) and sulphonated napthalene formaldehyde condensates (which electrically charge the cement particles so that they repel each other although many hybrids now

exist. Water reducers are commonly lignosulphonic acids or hydroxylated carboxylic acids and are utilised in a similar way to superplasticisers. The dosage of superplasticisers and water reducers depends on the mix specification, water/cement ratio, required workability, and cement and aggregate types.

Superplasticisers can reduce the water/cement ratio for a given workability (thereby improving the compressive strength and other properties) or to increase the workability for a given water/cement ratio (thereby increasing the pumpability of a mix). The workability will usually return to normal approximately 20 minutes after the addition of the superplasticiser (depending on the type) and so should be added immediately before placing. They do not adversely affect the final hardened properties of the concrete, although the setting time may be increased slightly.

Air entrainment
Air-entraining agents are added to wet-sprayed concretes to create a hardened concrete with small, well-distributed air pores which act can contain frozen water which has expanded, consequently improving freeze-thaw durability and de-icing chemical scaling resistance. ACI Standard 506.2 (1994) specifies that wet-mix shotcrete exposed to severe freeze-thaw conditions must be air-entrained, but up to half the air content can be lost on impact during the spraying process (Nordstrom, 1996). It can therefore be difficult to achieve an in-situ air content above 4% although there is some evidence to suggest that sprayed concretes require a lower air content (2-3%) for freeze-thaw resistance than conventionally placed concrete (Robins, 1995). Air-entrainment can also reduce the flow resistance in a pump line, to some extent acting as a lubricant between the particles. The entrained air is then forced out as the mix impacts on the substrate, thus stiffening the mix. However, air entrainment can sometimes cause difficulties when pumping under high pressure as the bubbles can be compressed or destroyed. The flow properties of the mix then revert to those of the same mix in its un-air-entrained state, which can lead to segregation and blocking of the pump. A pre-construction pumping trial should highlight any problems with the air entrainment.

Polymers
Latex solutions (such as styrene-butadiene rubber (SBR)) are added to improve bleeding resistance, pumpability and adhesion. It is also claimed that they can improve the tensile and flexural strength, permeability, abrasion and chemical resistance of the hardened concrete (Warner, 1995a). The latex should be proportioned at about 10-15% of latex solids by weight of cement.

Research has recently been completed on the addition of polysaccharide gums in sprayed concrete, which appear to produce a balance between pumpability and sprayability by reducing apparent viscosity at high shear rates (e.g. in the mixer), but have less affect at low shear (i.e. after spraying) and hence allow good build (Ghio and Monteiro, 1998).

Accelerators
Accelerators are rarely required in low-volume applications but can be essential when rapid strength development is necessary. They are available in powdered form (mainly for dry spraying) or liquid form (generally added at the nozzle). It is important to keep the accelerator dosage as low as possible to achieve the desired results as strength and durability reduce with age and dosage level. Accelerators can reduce the 28 day strengths of control mixes without accelerators by 25-40% (ASCE, 1995). Prediction of the setting and strength gain is difficult as they are dependent on the types and sources of both the cement and the accelerator. Therefore, trials should be conducted each time an accelerator is added, either at a different dosage level or with a new mix design. There are a variety of types, the more recent being low-caustic to minimise adverse health effects.

Retarders and stabilisers
Traditional retarders are not common in sprayed concrete work. However, stabilisers are often incorporated (in conjunction with an activator added at the nozzle) to control hydration where long periods of standing-time are expected in the spraying process, seen as in underground work where the concrete is batched above ground and then conveyed large distances to spraying pump.

4.6 Fibres

Steel fibres are added to provide ductility, to control shrinkage effects, to improve impact resistance, whilst giving a load-bearing capacity comparable to steel mesh. Fibre contents are typically in the range 40-80 kg/m^3, depending on the required toughness and type of fibre. Steel fibres in sprayed concrete have lengths of 20-40 mm and aspect ratios (i.e. length/diameter) between 50-100. The higher the fibre aspect ratio and volume concentration, the better the performance of the hardened sprayed concrete but the bigger the impact on production as it becomes more difficult to mix, pump and spray due to the fibres becoming tangled together. Steel fibres should comply with the requirements given in ASTM A820 and their length should not exceed 0.7 of the internal diameter of the pipe or hose (EFNARC, 1996). Compared with the dry process, a much greater proportion of steel fibres are retained in-situ with the wet process. This has been one of the main drivers behind the change to the wet process in underground projects.

It is important to ensure that they are uniformly distributed at the specified fibre content. Fibres can be added to the mix by manual site-batching, automated site-batching or pre-bagging. Manual addition is the cheapest method, but it is difficult to control fibre content and fibre dispersion. Automated site batching can be done at the batching plant (not recommended), at the conveyor to the pump or in the transporter immediately before unloading into the pump.

Monofilament and collated fibrillated polypropylene fibres can also be added to wet-process sprayed concrete. At low addition rates (0.9 kg/m^3 being a typical dosage rate) the benefits are mainly to the fresh properties such as improved cohesiveness and reduced plastic shrinkage cracking, but recently, higher dosages (4-7 kg/m^3) have been added to provide toughness behaviour similar to steel fibre reinforced sprayed concrete (Morgan, 1992). At low addition rates, no problems should be encountered when pumping, but at higher addition rates it is advisable to conduct trials with the mixes and the pump that will be on site, the mix more difficult to pump and spray. Polypropylene fibres also provide a degree of fire protection to sprayed concrete or mortar. As the heat increases the fibres melt, thus creating voids through which the expansive vapours can escape, thereby delaying explosive spalling of the material.

4.7 Reinforcement

Wire mesh is included to limit the development of cracks resulting from shrinkage, thermal movement and flexure. AFNOR (1992) recommends that sprayed concrete be reinforced with steel mesh when the total thickness exceeds 50 mm and that the reinforcement has the smallest possible diameter, with a minimum diameter of 3 mm. Reinforcement should comply with EN 10080 or BS 4466:1989. The arrangement of reinforcing bars should enable the sprayed concrete to fill behind and fully encase the steel. Layers of bars and mesh should be staggered for the same reasons and should not be spliced or laid together. The Sprayed Concrete Association (1999) recommend that bars should have a maximum diameter of 25 mm and be spaced at least 50 mm apart (or four times the bar diameter, whichever is the greater) and at least three times the maximum bar diameter (or 40 mm, whichever is the greater) away from the substrate. With two layers of reinforcement a better repair or structure is produced if the second reinforcing layer is not placed until the first has been sprayed. This reduces the likelihood of voids behind the reinforcement. Further guidance on spraying is given in section 8.

Reference should be made to reinforced concrete standards (e.g. Eurocodes or BS 8110, 1997) for guidance on depth of cover to reinforcement, which should be appropriate to the exposure condition and EN206 class of the sprayed concrete.

4.8 Pre-blended mixes

Most pre-blended proprietary cement-based products designed for hand application are suitable for pumping and spraying through both worm and piston pumps, but mixes designed specifically for spraying should have better pumping characteristics. It is strongly recommended that pre-construction pumping and spraying are conducted to ensure that both the material and pumping equipment are suitable (unless there is documented evidence of the successful application of the proposed combination of mix and plant). There are an increasing number of pre-blended fine mortars available specifically for wet-process spraying, although the number of pre-blended coarse mortars is still limited.

Commercial mix designs are a balance between increased sophistication (and, it is hoped, performance) and cost. A sprayed material must be both pumpable and sprayable, and produce a finished product with adequate in-situ properties. Some pre-blended materials may have up to seven aggregates and fillers blended together to give handling and performance properties superior to site batched materials (Gordon, 1995). Manufacturers of concrete repair materials (both for hand and sprayed applications) provide a range of data on the performance of their products but it is often unclear how they were tested and whether the test samples were cast, taken from a test panel or from in-situ concrete. Caution should be taken with inadequate performance data published by manufacturers and reference made to independent test data when possible.

There are several hundred commercially available concrete repair materials, the two most common types being SBR-modified cementitious mixes and Portland cement/sand mortar mixes. Investigations at Loughborough University (Austin *et al.*, 1999a) found that these typically contain all or most of the following constituents: fine aggregates (75 μm to 2 mm); lightweight fillers (75 μm to 300 μm); Portland cement in an aggregate/cement ratio of 1.3:1 to 3.4:1; silica fume (typically 5% of the Portland cement); admixtures such as SBR; polypropylene fibres; and chemical shrinkage compensators. The research also showed that lightweight mortars have considerably lower compressive, flexural and bond strengths and higher drying shrinkage than normal-weight mortars.

Factory-batched products can incorporate fillers, cement replacements such as silica fume, polymers, rheology modifiers and pigments, at controlled and consistent rates of addition. The major disadvantage of pre-blended materials is their higher cost compared to site-batched materials, when is particularly disadvantageous with high-volume construction where the material costs are a significant proportion of the total costs. The key question, therefore, is whether each component's inclusion can be justified in terms of benefit and cost. It has been found (see below) that uncomplicated mixes can produce acceptable performance.

4.9 Site mixes

Recent research has shown that relatively simple laboratory-designed mortars can have compressive and flexural strengths comparable with the best commercially available pre-blended mortars (Austin *et al.*, 1999c). They can be considerably cheaper than proprietary mixes, provided materials of sufficient quality are available locally and the batching and mixing facilities can adequately mix and disperse the constituents.

For worm pumping of fine aggregate mixes (with a maximum aggregate size of 3-4 mm), the combined grading of a mortar is very important. In order to pump successfully, the voids content of the combined dry constituents (aggregate, cement, fillers, silica fume) must be kept to a minimum in order to minimise bleeding of the wet mix. Pressure bleed tests, air void measurements and wet and dry gradings can be conducted to optimise the mix design (section 10.4).

Loughborough University has conducted research into the combined grading needed to pump effectively through a small diameter worm pump and have established a recommended grading zone as shown in Figure 13. Particle distributions below this zone are likely to be prone to bleeding (causing pump blockages) and those above may result in unacceptably higher pumping pressures (due to high friction) or adverse effects from an excessive cement content. In addition it is recommended that air voids content of the combined material is in the range 38 to 50 %.

Figure 13. Combined grading zone (aggregate and cementitious components) for mortars through small-diameter worm pumps

AFNOR (1992) also emphasise the importance of the combined grading of the dry constituents and their recommended grading envelope for both dry- and wet-process sprayed concrete is given in Figure 14. Aggregate above 8 mm should be kept to a minimum as larger particles constitute the majority of the rebound.

Figure 14. Combined grading envelope for concretes (through piston pumps) (AFNOR, 1992)

4.10 Batching and mixing

For low output applications (up to 3-5 m^3/hr) materials are normally batched on site either in a conventional drum mixer or one integral with the pump. For medium to large output applications (above 5 m^3/hr) a ready-mix batching plant is appropriate with the mix transported to the pump. For very large pumping operations a site batching plant may be justified. Thorough mixing is essential to ensure that the constituents are evenly distributed throughout the mix, with a minimum mixing time of 3 minutes. The aggregate/cement ratio and water/cement ratios are critical to both the rheological and hardened properties of a mix and therefore proper supervision and control of all water-additions must be maintained. The workability of ready-mix batching plant concrete can be variable, so all precautions should be taken to ensure consistency of supply. Strict control of site-batched concrete must also be maintained to ensure that operatives do not increase the water content at the pump.

Water added for mixing should comply with EN 1008 or BS 3148:1980. The water content is critical for pumping as well as strength and durability. If too low, coarse aggregate particles will not move in a coherent mass in suspension, but exert pressure on the walls of the pipe. Excess water will lead to segregation. The ACI (1990) recommends a water/cement ratio of 0.40-0.55 for wet-process sprayed concrete, with EFNARC stating a maximum of 0.55. Further details on the water content required to ensure sufficient pumpability are given in section 7.

Summary

- Most low-volume wet-spraying is currently done with *pre-blended proprietary mixes* although mixes of equal quality can be obtained from *site-batched materials* if suitable materials are available and care is taken in the mix design, weighing, batching and mixing process.

- A thorough *evaluation and comparison* of alternative pre-blended and site-batched mixes should always be conducted by the designer. Choose the *simplest combination* of cement, aggregate, additives and additions that can be installed satisfactorily and produce the appropriate levels of performance.
- A mix must be *pumpable* and *sprayable* as well as producing the necessary *in-situ hardened properties.*
- A *relatively high cement content* is needed to facilitate adhesion and build-up thickness, reduce rebound and form a lubricating layer around the inside of the pipe.
- The *total voids of the aggregate* should be kept to a *minimum.* The voids content of the *combined* grading (aggregate and cementitious material) should also be kept to a *minimum* to minimise bleeding and segregation.
- *Silica fume* reduces bleeding and segregation and improves cohesion and adhesion.
- *Admixtures* are relatively expensive and often hazardous and these aspects should be taken into consideration. Always consult manufacturer's recommendations. A *pre-construction pumping and spraying trial* should be conducted for each different combination of admixtures.
- *Steel fibres* can provide ductility and toughness, control shrinkage and improve impact resistance. Fibres must be *adequately and evenly dispersed* throughout the mix.
- *Polypropylene fibres* improve cohesiveness and may reduce plastic shrinkage cracking. They can also improve the toughness characteristics and fire-resistance properties of the hardened concrete at higher doses. However, *pumping can become difficult* at high dosage levels.
- *Steel reinforcement* is needed when the thickness of the spray concrete exceeds 50 mm and should be arranged so that the sprayed material can *fully encase all the bars.*
- Most pre-blended proprietary mortars are suitable for pumping through worm or piston pumps. A *pre-construction pumping and spraying trial* should be conducted with each new type of mix. Concrete mixes (>4mm aggregate) must be piston-pumped.
- Each batch should be mixed for at least *3 minutes*. All constituents should be equally distributed throughout the mix.

5 Specification

5.1 Design

Specifications for sprayed concrete are sometimes inadequate due to the designer's lack of understanding of the production process and the properties of sprayed concrete. The structural design of sprayed concrete is essentially the same as for conventionally cast concrete, the only difference being its method of placement. It is also reinforced in the same manner, with steel bars or mesh. The same codes of practice and standards can therefore be followed for the design of sprayed concrete structures e.g. BS 5400 for bridges and BS 8110 for structures or the equivalent Eurocodes. However, certain practical considerations should be kept in mind that are particular to sprayed concrete:

- *mix design* - the concrete or mortar needs to satisfy pumpability and sprayability requirements as well as providing adequate in-situ hardened properties (section 4.1)
- *reinforcement* - steel bars and mesh are an obstacle to the sprayed material and certain rules need to be observed regarding their size, placement and spacing (section 4.7)
- *tolerances* - fine tolerances are more difficult to obtain with sprayed concrete (see below)
- *finish* - smooth, flat surfaces are more difficult to obtain with sprayed concrete (section 9)
- *health and safety* - relevant regulations must be followed (section 6.4) and extra care is needed on contracts involving confined working or working from scaffolding
- *quality control* - this is more difficult with sprayed concrete and requires closer supervision compared with conventionally cast concrete as the action of pumping and spraying the material alters the properties of the mix (section 10.2).

The selection of a concrete material should be based upon knowledge of its physical and chemical properties in conjunction with the exposure environment, as well as the task that it will be required to perform. When selecting materials, especially pre-blended proprietary products, relevant and independent data should be sought to supplement the advice of material suppliers.

Measurement
The method of measurement and Bill of Quantities must be carefully considered, as standard methods for general civil engineering may be inappropriate. A standard method was proposed by the Construction and Formwork Committee of The Concrete Society (1981) but this is now outdated and virtually no other guidance exists.

Tolerances
Careful consideration should be given to allowable tolerances on sprayed concrete. Specifying inappropriate tolerances can result in the unnecessary rejection of sound work, which can lead in turn to disputes about whether the specification is unreasonable. It may be necessary to cut back and possibly overwork (i.e. excessive floating) the sprayed surface in order to achieve a tight tolerance, which can reduce the concrete's quality and its bond to the substrate, particularly on thin overlays (<50 mm). Designers should therefore be realistic when setting tolerances. The client should be advised about the likely appearance of the finished surface. If appearance and aesthetics are important then it may be advisable to conduct full-scale trials to determine an appropriate tolerance and finishing/curing regime that is to the client's satisfaction and within the contractor's ability. The designer, contractor and client can then agree before the construction begins on the acceptable tolerances and finish. Recommended tolerances for sprayed concrete (both wet and dry) are given in Kolf and Gebler (1993) and Gebler (1995).

5.2 Standards

The most recent European specification is the EFNARC *Specification for Sprayed Concrete* published in 1996. It covers concretes and mortars and both the wet and dry processes. It includes details on:

- constituents (cements, aggregates, reinforcement and fibres etc)
- composition (aggregate gradings, addition levels, working temperatures etc)
- durability requirements (chloride and alkali content)
- spraying (preparation, execution and curing)
- requirements for the final hardened product (compressive and flexural strength classes, bond strength, fibre content and toughness classes etc)
- hardened test methods (spraying panels, compressive and flexural strength, modulus of elasticity, permeability, fibre content etc)
- quality control (preconstruction testing, testing frequency, alignment control)
- admixtures (definitions, specifications, requirements, reference mixes and test methods and associated test methods).

The EFNARC document was put before the CEN (Comitè Européan de Normalisation) committee TC104/WG10 which is producing EN standards for sprayed concrete and associated test methods, with the latest drafts being prepared in September 1999. The British Standards Institution has not produced any national standards relating to sprayed concrete, but has supported moves towards developing a European Standard. These European standards are detailed in Appendix A.3 along with relevant general concrete standards in A.2. Appendix A.4 gives details of test methods for repair prepared by TC104/SC8.

The main specification in the United States is the ACI's *Standard Specification for Materials, Proportioning and Application of Shotcrete (ACI 506, 1990),* which was revised in 1994 as AC1 506.2. These specifications are also complemented by several ASTM national standards relating to sprayed concrete:

- *C1141-89 - Standard specification for admixtures for shotcrete*
- *C1140-89 - Standard practice for preparing and testing specimens from shotcrete concrete panels*
- *C1117-89 - Standard test method for time of setting of shotcrete mixtures by penetration resistance*

The French standard AFNOR NF P95-102 introduced in 1992 (with an English translation in 1997) relates only to repair and strengthening, but gives detailed, pragmatic advice for sprayed concrete applications in general. Germany introduced DIN 18 551 in 1979, which concentrates mainly on production and quality control. AFTES, the French Association for Underground Works, has published a report: *Recommendations on sprayed concrete: Technology and practice (1992).*

A helpful document has been produced by the International Tunnelling Association, *Shotcrete for rock support: Guidelines and recommendations - a compilation (1993).* This summarises the specification and guidance documents in the 15 ITA member countries and includes substantial references to the documents published by ACI, AFTES, ASTM, DIN, EFNARC and others.

5.3 Codes of Practice

Many guides and Codes of Practice have been published on the spraying of concretes and mortars, including:

- *Guide to Shotcrete* (ACI Committee 506R, 1990)
- *Standard Practice for Shotcrete* (ASCE, 1995)
- *Code of Practice for Sprayed Concrete* (Concrete Society Construction and Formwork Committee, 1980)
- *Code of Good Practice* (Sprayed concrete Association, 1990)
- *Introduction to Sprayed Concrete* (Sprayed Concrete Association, 1999)

Other relevant publications on pumping, spraying and concrete repair are listed in section 13.

Summary

- Sprayed concrete can be *designed* in a similar way to conventionally cast concrete as long as practical considerations particular to sprayed concrete are kept in mind
- Designers should be *realistic* when setting *tolerances* and the designer, contractor and client should agree before construction begins on the acceptable tolerances and finish
- The *EFNARC specification* should be consulted together with the relevant *CEN standards* as they become available
- It is often appropriate to *seek the advice* of a specialist sprayed concrete contractor, particularly with regard to method statements

6 Planning and Preparation

6.1 Planning

Many aspects of sprayed concrete preparation and production, including substrate preparation, formwork construction, construction joints, finishing and curing are similar to cast concrete construction. For an effective and durable sprayed construction or repair to be completed, established good practice needs to be followed by skilled and trained operatives with planning and supervision from a knowledgeable and experienced engineer. Appropriate cycles of preparation, spraying and finishing should be adopted to suit the application. For the wet process, it is often advisable to prepare large sections at a time for spraying so that once spraying commences a large volume can be placed in one continuous process. This minimises pauses in the work which could create blockages and also reduces the number of times that the pump and line need to be cleaned out, which is both time consuming and uneconomic. When planning a spraying operation the points listed in sections 2.3 and 3.2 should all be considered. Health and safety aspects to consider are listed in section 6.4, which includes advice on plant and equipment, materials, personnel and site operations.

6.2 Equipment preparation

A key requirement when setting up the pumping equipment is ensuring that it is close to the point of spraying. This will minimise the hose lengths required which in turn will require a smaller air and pump pressure than would be needed for longer hoses. Working procedures should be adopted to suit the equipment and application in terms of batching and appropriate spraying cycles. Guidance should always be sought from the equipment manufacturers and experienced contractors to ensure safe and reliable operation of the equipment. Some safety check points are included in section 6.4.

Before starting work, especially before batching, all equipment (both hired and in-house) must be checked to ensure that it is in a fit state to carry out the proposed programme of work. Pumps should be checked for mixing performance, rotor stators for wear and adjustment and motors for starting and long term running ability, including fuel quantity. The air and water supplies should also be checked for consistency and running ability. Hoses and nozzles should be checked for both internal and external wear. Hoses with any imperfections should be discarded as they can fail at high pressure with potentially serious consequences.

6.3 Surface preparation

Before the start of any concrete repair or modification work the damaged or deteriorated concrete must be removed. Care must be taken to ensure that all the damaged or deteriorated concrete has been removed and that no damage is done to the substrate concrete, particularly with high impact tools, during this operation. Concrete removal techniques include cutting (e.g. diamond sawing, thermal lances and high-pressure water jetting), impacting (e.g. hand-held or machine-operated jackhammers) and pre-splitting (e.g. hydraulic splitters or expansive chemical agents). High-pressure water jetting is the most effective surface preparation technique due to the minimisation of noise and dust, the absence of potentially damaging mechanical vibration and abrasion and the fact that the water removes inferior concrete whilst leaving sound concrete intact.

The preparation of the substrate directly influences the bond strength of the sprayed concrete and so the placed sprayed material can be considered only as good as the effectiveness of the substrate surface preparation. The surface should be structurally sound and free from dirt, dust, oil, grease and running water.

It is general practice to wet the substrate before the application of the sprayed concrete or mortar, with saturated surface dry (SSD) being the ideal condition. However, the surface must not be over-wetted, as this can increase the water/cement ratio of the cement paste at the bond surface, resulting in higher shrinkage and lower strength. If the substrate is too dry water is drawn out of the sprayed mortar or concrete in contact with the substrate, inhibiting the hydration of the cement and thus reducing the bond strength.

Concrete or mortar should not be sprayed onto a frozen substrate or when the air temperature is below $3^{o}C$ (SCA, 1990).

Bonding agents

Bonding agents or slurries are sometimes applied to improve the bond between the substrate and the sprayed concrete. However, the bond may be impaired if the bonding agent dries before the concrete is sprayed or if it is applied too thickly. A thick layer of bonding agent can sometimes act as a lubricant and cause the new material to slough or slide. It is also argued that a bonding agent can lose its effectiveness since it can be driven off the substrate during the initial pass of sprayed concrete. Generally speaking, a good quality sprayed concrete or mortar applied onto a properly prepared, SSD, structurally sound substrate will provide an adequate bond onto vertical surfaces; however a bonding agent or slurry may be helpful for overhead work or thick layers.

Formwork

One of the main advantages of sprayed concrete is the reduction or elimination of formwork. If some formwork is required then it is generally similar to that for conventionally cast concrete, although the hydraulic pressures will be less due to the ability of the sprayed concrete to support itself. Plywood facing material is suitable and need not be more than 12 mm thick for vertical forms. Like conventional vertical formwork, backing members need to resist the applied forces. It is important to fix the formwork rigidly, as the force of the sprayed concrete can vibrate the form and disturb the build-up of material. The formwork should also be self-supporting and must be braced to prevent it falling inwards. However, the tendency for conventional double forms to lift during concrete placement does not apply to sprayed concrete. The formwork for sprayed roof structures is similar to that for conventional cast roofs and must be designed to carry the thickness of concrete, reinforcement, operatives and equipment. When spraying overhead there is very little force applied to the formwork and it should be designed to resist any forces placed on it by the spraying process.

Temporary screed boards are often erected to form corners, edges and construction and expansion joints. These need to be secured a small distance away from the substrate to allow the rebound and compressed air to escape. They are then removed prior to spraying the adjacent face.

Guide strips and ground (piano) wires can guide cutting back the material to produce surface profiles. Plastic or metal depth gauges can also help form profiles, although care has to be taken that they do not affect the integrity of the material. Isolated repairs are often small in area and the finished line and level can be taken from the surrounding concrete.

It is recommended that a chemical release agent is applied to all formwork, as conventional emulsion or oil release agents can be pushed along the form by the concrete stream.

Further details on formwork can be found in the EFNARC specification and in Austin (1995) and Taylor (1995).

6.4 Health and safety

The main health and safety considerations relevant to sprayed concrete are summarised in this section. The contractor should ensure that all personnel on site are fully aware of the dangers of sprayed concrete and conversant with the safety procedures and precautions that are needed. Miller (1995) provides advice and guidance on all aspects of site safety for sprayed concrete operations.

The spraying process is inherently dangerous as it involves spraying dense particles at high velocity onto a hard surface only a few feet away from the operator. Legislation regulations that apply to construction operations are equally applicable to sprayed concrete work. Under the Health and Safety at Work Act (1974) everybody concerned with the design and construction process is required to do what is '*reasonably practicable*' for safety. From October 1994, consultants and clients were given greater responsibility under EC directives in the form of the Construction (Design and Management) Regulations (HSE, 1994). These regulations require the nomination of people to safety roles, at both the design and construction stages, and also requires a safety plan to be formulated, which must be initiated during the design stage.

Safety on site can be divided into four main sections, plant and equipment, materials, personnel and site operations:

Plant and equipment

- All plant should be well maintained, kept clean and set on level ground with good working access around it
- Rotating parts within the spraying equipment (including the mixer and any associated equipment) should be protected with metal guards
- The usual safety precautions should be taken when dealing with electric cables, plugs and connections
- Hoses (particularly hose connections) and any other pneumatic or hydraulic systems should regularly be checked for signs of wear and fatigue. It is advisable to keep spare hoses and connectors in order to minimise delays due to hose failures.

Materials

- Care must be always be taken when handling hazardous substances such as accelerators and other additives and operatives should be trained in their use
- Materials must be covered by the relevant COSHH regulations (HSE, 1999) where applicable and all waste materials should be disposed of safely and within local tipping and waste disposal regulations.
- Bagged materials should be supplied in 25 kg bags if possible rather than 50 kg to minimize the possibility of back injuries
- Dry materials should be stored in watertight containers or under cover to avoid bags from becoming wet and splitting, causing fine powder to be released into the atmosphere

Personnel

- Due to the serious hazard to exposed skin and eyes, personal protective equipment and clothing must be worn by all those in the vicinity of the spraying work
- Long sleeved overalls, strong gloves, head protector (to BS 5470), safety shoes (to BS 1870 (EN 345) and BS 4972 (EN 346)) and eye protection (goggles or visor (to BS 2092)) should always be worn
- Dust masks or respirators should be worn and special care should be taken in enclosed areas
- If the nozzleman and pump operator can not visibly communicate with one another, then an alternative means of communication, such as short wave or VHF radios are required
- If any of the crew are on scaffolding or an elevated work station, then harnesses must be worn

Site operations

- Scaffolding should be at least 1.8m wide, preferably more, to allow adequate working space
- Care should be taken when working in confined spaces such as sewers, tunnels or shafts. Gas detection equipment should be employed and forced or natural ventilation should be introduced where needed
- It may be necessary to protect the nozzleman from inclement weather and the sprayed material from rain (which may wash away the material), wind and sun (which may dry it out too quickly)
- All protection should be designed to make the working environment safer and more comfortable for the operative, which in turn will increase production and improve the quality of the work
- Any accidents on site should be reported and investigated. Only by investigation and implementation of safeguards can further incidents be avoided
- Adequate welfare facilities must be provided for the operatives, including hot and cold water, WCs and changing facilities
- Every site must have a first aid kit and all operatives should know where it is located and who is qualified to apply first aid

Summary

- *Plan the construction process* carefully to ensure safety, efficiency and effectiveness
- *Check all equipment* to confirm that it will operate safely
- *Prepare the substrate*. Sprayed concrete or mortar is only as effective as the substrate onto which it is sprayed. *High pressure water jetting* is the most effective at removing deficient concrete and *saturated surface dry* is the ideal surface condition
- Ensure *formwork* is secure enough to withstand the pressure of spraying and has sufficient gaps for the escape of rebound and compressed air

7 Pumping

Detailed information on pumping of concretes and mortars can be found in a Good Practice Guide published by the Concrete Society (1999). Further helpful information has also been published by Cooke (1990) and the British Concrete Pumping Association (1990).

7.1 Basic rheology

Rheology is the science of deformation and flow of matter and is concerned with the relationships between stress, strain and time. In fresh concrete, the field of rheology is related to the flow properties and mobility of concrete before it sets. Critical fresh properties of sprayed concrete include workability, stability, adhesion and plastic shrinkage. Adhesion is commonly quantified by build thickness. The terms ‘pumpability’ and ‘sprayability’ are frequently applied but are difficult to define and measure in quantitative terms. However, measurement of such properties as viscosity, shear strength, slump and flow, measured before pumping, can act as a guide to pumpability.

A rheological audit enables the mixing, pumping and spraying processes to be broken down into stages (Figure 15) to characterise pumpability and sprayability (Austin *et al.*,1999a and 1999b). Rotational viscometers, slump, shear vane, build and pressure bleed tests can be used at different stages of the audit, together providing a guide to the pumpability and sprayability of a mix (section 7.2 and 8 respectively).

Figure 15. Rheological audit.

7.2 Pumpability and stability

Pumpability can be defined as the mobility and stability of concrete in an enclosed pipe under pressure, where mobility is the ability of fresh concrete to flow, and stability the capacity of concrete to maintain its initial homogeneity during transport, handling and placing.

To pump any mix the force exerted by the pump must first overcome the friction between the pipeline and the concrete, the inertia of the concrete in the pipe, the resistance of the internal components of the concrete to readjustments at tapers and bends, the energy needed to change direction and the pressure due to the head of concrete when placing higher than the level of the pump. The pressure must be transmitted by the water in the concrete. The water content is therefore critical, not just for the water/cement ratio as in conventionally cast concrete, but for the pumpability (and sprayability) of a mix. The mix must be workable enough to be pumped, yet must be stiff enough not to slough or sag once it has been sprayed. These contradictory requirements make proper mix design essential if an appropriate balance is to be obtained. At the correct or critical water content, friction develops only at the surface of the pipe, and in a thin 1-2.5 mm thick of lubricating layer which allows plug flow to occur. This plug consists of aggregate, sand and cement particles, all separated by a continuous water layer which is hydraulically linked to the water in the lubricating layer (Figure 16). The velocity across the width of the plug is constant, and drops across the lubricating layer to zero at the pipe wall.

As a rough guide a slump of 50-80 mm is a good compromise between pumpability and ‘shootability’ (Beaupré, 1994). The shear vane test has also been shown to be a quick and convenient method of determining workability at any stage of the process, that does not require a sample to be taken. Shear strengths of 0.8 to 1.5 kPa for mortars and 0.8 to 2.2 kPa for concretes (8 mm max.) are indicative of an appropriate workability.

Practical experience and/or a pre-construction pumping/spraying trial are needed to determine the exact workability and water content required. As well as the water content, the grading of the constituents and the presence of polymers both have a significant effect on the flow resistance and torque viscosity, and hence on the pumpability of the mix. Tests to predict the pumpability of a mix are discussed in sections 7.4 and 10.4.

As stated earlier, the lubricating layer on the inside of the line allows the mortar or concrete to flow through the line. It is essential therefore that the line is lubricated before pumping with a rich grout of cement and water to prevent any initial blockages.

Piston pumps typically operate at pressures of about 6 MPa (900 psi) and worm pumps operate at about 0.5-1.0 MPa (75-150 psi). Air is injected at the nozzle at typical pressures of 0.5-0.7 MPa (75-100 psi) (Austin, 1995).

Figure 16. Plug flow (Concrete Society, 1998)

7.3 Blockages

There are two main reasons why blockages (excluding any mechanical problems) occur in pipelines:

1. water is forced out of the mix and the dry material jams in the pipe (i.e. bleeding under pressure occurs);
2. the frictional resistance of the mix constituents on the pipe wall becomes too great, usually due to a high proportion of fine material (cement and filler) in the mix.

Both of these blockages can occur due to poor grading and proportioning of the constituent materials (see sections 4.3 and 4.9). The first type of blockage (bleeding) may occur when the cement content is too low, or if the mix includes a poor or badly graded aggregate. This may be remedied by either increasing the proportion of fines within the aggregate grading, increasing the cement content, or both. A pressure bleed test can be conducted to measure the rate and amount of bleeding of a mortar or concrete (sections 7.4 and 10.4).

The second type of blockage is caused by excessive friction due to long pipes or hoses, high cement contents or low workability. The solution may be to increase the aggregate content (therefore decreasing the proportion of fines) and the slump, and possibly to introduce a plasticiser.

Blockages can also be caused by oversized particles within the mix, either aggregate or foreign particles. Clearing blockages can be extremely dangerous if the pressure in the pipeline is not released prior to the dismantling of the hose and equipment. The pressure within the line must always be reduced by turning off the pump before breaking any of the connections in the pipeline. Further details are given by the BCPA (1982).

7.4 Test methods

Tests for measuring the pumpability and rheology of fresh concretes and mortars include slump, flow table, shear vane, rotational viscometers and pressure bleed tests. These are described in detail in section 10.4. No single test is available that will provide a simple yes or no answer to a material's pumpability, but they can give a guide. There is usually no substitute for trial pumping of the material through the equipment that will be on site. This allows full examination of the proposed mix and of any adjustments made.

Summary

- A *rheological audit* can break down the pumping/spraying process into a series of discrete stages to characterize pumpability and sprayability
- A mix must be *workable enough* to be pumped yet *stiff enough* not to slough or sag once it has been sprayed, with a slump of 50-80 mm being a typical value (depending on the mix design)
- Blockages occur due to *bleeding* of the mix or *excessive friction* within the hose or pipe. These are both influenced by the grading (both of the aggregate and overall) and the mix design
- A rich *grout* of cement and water must always be pumped down the line *prior to the pumping* of the mortar or concrete in order to lubricate the line
- Great care should be taken to ensure that *all the pressure* is released within the pump and the line before any blockages are cleared

8 Spraying

8.1 Spraying process

Planning
The nature of the wet process demands that spraying is done continuously, in discrete sessions that avoid unnecessary stopping and starting. Planning of work in each shift is therefore essential (see section 6.1)

Distance
Spraying should generally be done at a distance of 0.5 - 2.0 metres from the receiving surface, with a distance of approximately 1 metre being common in order to obtain adequate compaction and minimum overspray. Overhead spraying needs to be done closer to the surface as gravity reduces the impact velocity and increases rebound. Lower volume spraying often has a lower particle velocity and so the nozzle can be held closer to the surface.

Layer thickness
The thickness of each layer will be determined by the amount that can be applied without it sloughing off, which in turn is influenced by the position of reinforcement, plane of application (vertical or overhead), mix design and the constituents (the latter governing the concrete's cohesion and adhesion to the substrate). Overhead work is generally applied in 25 - 50 mm layers as thicker layers may sag or cause dropouts (Gebler, 1995), but thickness up to 100 mm or even 150 mm can be achieved on vertical surfaces.

Spraying angle
The nozzle must in general be at 90^{o} to the receiving surface as at oblique angles the rebound is greater and the compaction is less. Accepted good practice is to gyrate the nozzle and to rotate the stream in a series of small oval or circular patterns across the surface. This method of application has been proven to reduce rebound and dust generation and increase material uniformity (Maidl, 1991).

Spraying technique
In general, the material is built up from the bottom with care being taken to fully encase the reinforcement and to avoid the inclusion of rebound and air pockets. When applying thick single layers the top edge needs to be sloped (or 'benched') to enable the rebound to fall clear (Figure 17). A blow pipe controlled by an operative can remove the accumulated rebound ahead of the nozzleman and the concrete stream. Internal corners should be sprayed first to prevent the build up of rebound and overspray.

When spraying a second layer, the preceding layer should be allowed to stiffen and then all loose or excess material should be scraped or brushed away before the second layer is added. The nozzle should be held closer than normal and at a slight angle when spraying through and encasing reinforcement to minimise both voidage and the accumulation of rebound. Wherever possible, sections should be sprayed to their complete design thickness in one layer, thereby reducing the possibility of cold joints and laminations within the concrete.

Figure 17. Bench gunning of sprayed concrete

8.2 Nozzle

Several nozzle designs are available (Figure 18), the main difference being the manner in which the compressed air is injected to project the concrete: either transversely into the concrete stream or around the circumference of the nozzle through a ring of jets. Nozzles for low output worm pumps and medium output piston pumps also differ. Worm pumps are often operated with small, simple, steel or brass nozzles designed for applying plasters and renders. Piston pumps have nozzles up to 300 mm in length, usually tapered with a steel hose/air supply connection and a stiff rubber neck.

Waste may be minimised (and the stream made more uniform) by changing the design of the nozzle orifice. With small diameter worm pumps the small amount of waste produced (< 5%) is due mainly to repeated accumulation and dislodging of material at the nozzle, rather than an excessive amount of rebound. The design of the nozzle can also affect the dispersion angle of the stream and the size of the 'flocs' of material (Figure 19). These can sometimes be adjusted on site by altering the distance between the nozzle orifice and the point of air addition.

Some recently designed nozzles for low volume pumping incorporate on/off switches for the pump and/or the compressed air supply. This enables the pump operative to concentrate on supplying the pump with material rather than watching the nozzleman. More advanced nozzles also incorporate means of administrating accelerators into the stream although these can be inconsistent and are often an unnecessary complication and expense on small machines.

Nozzles and hoses are available where the compressed air and the accelerator are added to the concrete or mortar up to 6 m behind the nozzle. This ensures better mixing of the accelerator and concrete and also makes the nozzle lighter to hold for the nozzleman. With some nozzles additional air can be added at the nozzle like a standard nozzle.

Figure 18. nozzle types for wet-spraying

Figure 19. Spray stream captured by high-speed video

8.3 Adhesion/build

Modern pre-blended proprietary mortars have low water/cement ratios and are thixotropic. This means that they can be sprayed in much thicker layers than when applied by hand. An increase of 2 or 3 times in thickness may be possible, dependent on orientation.

A simple build test can be conducted by spraying the mortar or concrete onto a well-prepared vertical substrate (e.g. grit-blasted and saturated surface dry) to obtain as high a build as possible (Figure 20). The material will fail under its own weight either cohesively (by internal shear of the mortar), adhesively (by failure of the bond between the substrate and the mortar) or by a combination of both. The sprayed material (including the part that came away from the substrate and the part still adhered) can then be weighed and the total weight, the failure mode and the maximum depth of build can be recorded. The maximum tensile and shear (flow) strengths of the material can then be calculated from these values (Austin *et al*., 1999a).

At low workability, an increase in slump produces a slightly wetter, and therefore more cohesive mix, thereby increasing the build (Figure 21). As the slump increases from zero there is initially no increase in build as the material is too dry to adhere to the substrate. As the slump increases further (approximately 10 - 20 mm, depending on the mix) the mix becomes more cohesive and the build increases until it reaches a maximum at which the mix possesses both its maximum tensile and shear (flow) strength. Past this point the mix begins to fail in shear as the slump, and hence the fluidity, increases (approximately 50 – 80 mm). A maximum slump is then reached (typically around 140 mm) at which point the mix is too fluid to adhere to the substrate and the build is therefore zero.

Tensile bond strengths of all non-lightweight pre-blended proprietary mortars sprayed onto a well prepared substrate should comfortably exceed the minimum of 0.8 MPa as recommended by the Concrete Society (1990). It should be remembered that the bond strength depends not only on the strength of the applied mortar or concrete but also on the nature and standard of preparation of the receiving substrate.

Figure 20. A build test

Figure 21. Simplified relationship of maximum failure (shear and bending stress).

8.4 Particle stream

Stream velocities of around 10 m/s are common with small worm pumps and 20 - 30 m/s for piston pumps, depending on the air pressure (typically 0.5 - 0.7 MPa (75 - 100 psi) for a piston pump). The spraying arc (typically 20 - 45 degrees) is determined by both the nozzle design and by the distance of the air outlet(s) from the nozzle aperture, which can usually be manually adjusted (see section 8.2). If this distance is small then the spraying arc will be wide and vice versa. The arc should be wide enough for the stream to travel around and behind any reinforcing bars, but narrow enough that a controllable stream can be produced. The nozzle will need to be adjusted for different air pressures, mix designs and pumps, and several spraying arcs can be tried during a pre-construction trial. The arc also affects how close the nozzle needs to be to the substrate (section 8.1).

8.5 Rebound

Rebound is the material which strikes the surface but does not adhere. This is usually 5 - 10% of the material sprayed at vertical surfaces by the wet process compared with 20 - 30% by the dry process. High rebound occurs either with large aggregates (8 - 12 mm), poor mix design, high steel fibre contents or when thin layers (30 - 50 mm) are applied.

The consequences of rebound are more than the cost per cubic metre of sprayed concrete. With high-volume, high-velocity work the rebound is largely composed of aggregates so the in-situ material tends to have a higher cement content than the designed mix. This cement-rich mix is then more prone to both thermal contraction and drying shrinkage cracking. Also, removal and disposal of waster material can incur significant costs.

Rebound can be reduced by the inclusion of silica fume, well-graded aggregates that contain a small proportion, if any, of larger (>8 mm) particles and by increasing the proportion of cement and water within a mix.

8.6 Compaction

Compaction is simply the removal of entrapped air from fresh concrete. For cast concrete, this is generally achieved by applying energy through vibration. For sprayed concrete, compaction is achieved by the momentum of the particles, which depends on the amount and pressure of compressed air added at the nozzle, their impact on the receiving surface, and also by the pumping process (pumping compaction). The total compaction is the removal of air due to both pumping and spraying.

Wet spraying produces compaction levels similar to cast concrete that has been well vibrated and greater compaction than hand application. The latter results in both higher densities (fresh and hardened) and higher strengths (compressive, tensile and flexural). Increases in compressive strength of up to 30% are sometimes possible for a sprayed material compared with hand application, depending on the material and the spraying process (Gordon, 1993).

Summary

- *Plan* the day’s work activity to minimise unnecessary delays and waiting time during spraying sessions
- Spraying should be done in a series of small *oval or circular patterns* at 90º to the receiving surface at a distance of approximately one metre. Material should be built up from the *bottom* with internal corners being sprayed first. Care should be taken to *fully encase* any reinforcement and to avoid the inclusion of rebound
- A *build test* can be conducted and the water content adjusted to achieve maximum build
- The spraying arc can be adjusted at the nozzle to produce a *controllable stream* and the stream velocity can be adjusted by altering the air pressure
- *Rebound can be minimised* by reducing the proportion of large aggregate within a mix, spraying in thick layers and increasing the proportion of cement, silica fume or water within the mix

9 Finishing and Curing

9.1 Surface finish and appearance

The preferred finish of sprayed concrete is a natural or gunned finish as the material will not have been disturbed by finishing and will possess its best possible characteristics in terms of bond, strength and durability. Due to the stiffness of the placed material, there is a risk that working or trowelling the surface will disturb the material and reduce the bond to the substrate, or disturb the homogeneity of the material. However, it is recommended that the as-shot surface is brushed with a soft brush approximately one hour after spraying to reduce the occurrence of shrinkage cracks. A textured finish can be obtained by a trowel, float or brush. A flash coat can also be applied (section 9.2). Wetting of the surface prior to trowelling should be avoided as this can produce surface crazing.

9.2 Coatings

Flash and finish coatings are thin layers of mortar or fine concrete sprayed onto the finished sprayed concrete to: cover exposed reinforcing fibres; produce a smoother, more workable finish; or to create a different colour finish. Flash coats are usually applied as a surface coating (up to about 6 mm) at a higher water content and with finer aggregate than the main layer. A finish coat, typically 6 to 25 mm thick, is often applied to walls to provide greater uniformity of the sprayed concrete in appearance and texture.

If the appearance of the in-situ material is important then a surface coating is advisable. Filling cracks on the surface rarely hides them, and frequently makes them more conspicuous. Coatings are available that can bridge fine cracks of up to 0.1 mm. Advice from manufacturers should be sought about the products available and their application.

9.3 Climate

The temperature of sprayed concrete should ideally be between 10º and 38ºC (50º and 100ºF) and should not vary by more than ±5ºC (±10ºF) during the spraying process in order to maintain uniform concrete quality.

Slump loss, strength loss, increased setting rate and air content control are all problems associated with hot weather spraying. Mix constituents should be tested at elevated temperatures and materials should be chosen to minimise slump loss and problems due to increased water demand. Keeping the concrete cool and the hose lines protected from direct sunlight and hot ground will be beneficial. Retarders should be added only when essential. Additions such as GGBS and PFA (section 4.4) can also be effective at reducing high temperature effects.

Sprayed concrete should be protected against freezing and should not be applied below 5ºC (40ºF). EFNARC (1996) states that protection against frost is needed until the sprayed concrete has developed a compressive strength of 5 MPa.

Spraying operations should be stopped if high winds hinder adequate spraying, if heavy rain disturbs placed material or if very hot sunlight causes too rapid drying out of the material. High wind speeds can also cause the concrete to dry out too rapidly.

9.4 Curing

Curing of sprayed concrete is vital as early moisture loss can result in high permeability, low strength, surface cracking and a short life span. Sprayed concrete and mortar is usually applied in thin sections compared with conventionally cast concrete and hence it is more prone to drying out from the surface. Effective curing maintains a high relative humidity inside the material so that hydration of the cement can take place. If the relative humidity falls below around 90% hydration stops. Damp hessian and spray- or brush-applied chemical curing membranes can provide adequate curing if applied properly. For a natural gun finish the curing membrane should be applied at a heavier rate than for smoother finishes, approximately double being normal. Curing compounds should have been tested to BS 7542:1992. Ideally the concrete should be kept moist for 7 days at a temperature above 5ºC (ACI, 1990). ACI (1994) recommends five methods for curing sprayed concrete:

- ponding or continuous sprinkling with water
- covering with an absorptive mat or sand that is kept continuously wet
- covering with impervious sheet material
- curing compounds
- natural curing (only if the ambient relative humidity is maintained above 5%).

The most effective of these is ponding or continuous sprinkling. However, these methods are usually impractical for sprayed concrete so sprayable curing compounds and impervious sheets (e.g. polythene) are most common due to their ease of application.

Extra care should be taken when curing in hot or cold weather. In high temperatures the concrete should be protected from direct sunlight and the surface prevented from drying out. In cold weather, the temperature should be kept above 5ºC and if freezing is a possibility then water curing should not be used. Application of a low atmospheric pressure saturated steam at 50ºC (120ºF) or less is effective, although for small repairs this is usually uneconomic.

Most of the standards and codes of practice mentioned in sections 5.2 and 5.3 provide requirements and advice on the curing of sprayed concrete, as do standards for cast concrete (e.g. EN 206, ACI 308) which are also applicable.

9.5 Renders

The low-volume wet-process lends itself ideally to the application of renders of all types. Detailed guidance is given in Concrete Society Good Concrete Guide 3 (Concrete Society, 2000). Many renders can be classed as fine cementitious mortars and can be pumped and sprayed in the same way. Extra care needs to be taken (e.g. with curing and finishing) as they are applied in thin layers.

Summary

- The preferred finish for sprayed concrete in terms of bond, strength and durability is *a natural, gunned or ‘as-shot’ finish*
- *Care should be taken* not to disturb the material when working or trowelling the surface and wetting of the surface should be avoided
- *Flash or finish coatings* of mortar or fine concrete can be applied to improve the finish or to cover exposed steel fibres
- Spraying should ideally be done at a *constant temperature* between 10ºC and 38ºC (50ºF and 100ºF) and precautions should be taken with the mix design, equipment and curing during *excessively hot or cold conditions*.
- *Early and effective curing* of sprayed concrete is essential and extra care should be taken in adverse weather conditions

10 Testing and Performance

10.1 Pre-construction testing

Pre-construction testing should form an integral part of the specification (section 5). Even with an experienced designer and contractor, it is sensible to conduct a trial with the materials and equipment that will be used for the construction. This may identify flaws in the specification and any unsatisfactory procedures or operatives.

ACI 506 (1990) details investigations that can be undertaken before starting work on site to verify that the quality of sprayed concrete required in the specification can be obtained in the actual structure. It recommends that test panels (section 10.3) be sprayed in each of the positions that work is likely to be done (e.g. horizontal, vertical or overhead) for each of the proposed mix designs. These panels should be visually examined (for soundness, encasement and uniformity of material) and tested for strength, bond, water absorption, shrinkage and resistance to freeze/thaw action (section 10.4.2). The flexural strength, toughness and fibre content of the in-situ material can also be measured. During pre-construction testing, the fresh properties of the concrete can also be tested, including water demand, workability, pumpability/sprayability, rebound, air content and fresh density (section 10.4.1).

10.2 Quality control

Quality control of sprayed concrete can be more demanding than for conventionally cast concrete as the in-situ mix proportions may differ from the batched proportions and the concrete quality is more operator-dependent. These problems are, however, less significant with the wet process than with the dry process. The most reliable method for determining the quality of the in-situ sprayed material is by drilling cores from a typical sprayed section, although this is costly and sometimes impracticable. The next best method is to drill cores from sprayed test panels (section 10.3).

Quality control procedures should be included in the specification (section 5) and regarded as a critical part of all contracts: this is not always the case at present. The test methods required (including the relevant standard) and the required levels of performance should be included. The number of samples required, minimum average value and minimum individual value should all be included. The frequency of the tests should be decided by the designer, bearing in mind the function of the sprayed concrete, its design life, the difficulty of installation, the environmental classification and the consequences of a failure (EFNARC, 1996).

The stage in the mixing, pumping and spraying process at which the sample is taken is also important. Fresh samples taken after the material is mixed but before it is pumped can be tested to monitor the batching consistency. Samples taken after spraying are also important if admixtures are introduced at the nozzle.

Bond tests should be an integral part of the quality control procedure, including both sounding (tapping the hardened concrete with a rod to locate voids) and core testing (section 10.4.2). In-situ coring is obviously more representative than coring a test panel and is the only effective method that can examine specific areas of the construction for bond, compaction and other properties.

Whilst measuring in-situ properties is clearly the best approach for quality control purposes, with low volume worm pumps, acceptable results can be obtained by spraying directly into moulds (a quicker, cheaper and more convenient option). These could be supplemented when required by testing samples cut from in-situ or test panels. Recent research has shown (Austin *et al.*, 1999c) that for low-volume worm pumps, a good correlation exists between in-situ cube strengths and cubes sprayed in moulds (Figure 22), despite the difficulty in obtaining a sample with no voids and low rebound (samples with excessive voidage being discarded). Densities and flexural strengths from specimens sprayed directly into moulds were also found to be comparable with the in-situ values, provided that voids and rebound were minimised. However, the output of the pump and the size and design of the nozzle did influence the compressive strengths and densities of the cube specimens sprayed directly into the moulds: the small worm pump (with the lowest output) achieving better compaction (and therefore better strength and density) with this technique than the higher output piston pumps (see Figure 23). A more detailed discussion on quality control can be found elsewhere (Austin, 1995).

Figure 22. Compressive strengths of mortars (Austin *et al.*, 1999c)

Figure 23. Compressive strengths of fine concretes (Goodier *et al.*, 2000)

10.3 Test panels and sampling

Test panels sprayed under field conditions can be used both for pre-construction testing (section 10.1) and for obtaining test specimens for quality control during construction (section 10.2). Most specifications for sprayed concrete projects call for test panels to be made during construction, from which test specimens can be cored or sawn. Typical sizes are 500 to 750 mm square and 100 to 150 mm thick. EFNARC (1996) recommends minimum plan dimensions of 600x600 mm for hand spraying with a minimum thickness of 100 mm. The panel should not be moved within 18 hours of being sprayed and curing should continue for 7 days or until the specimens have been extracted. One disadvantage of sprayed test panels is that the operator knows that it is for producing test specimens and consequently the sample may not be representative of the actual structure. The effect of the backing material and the panel edges may also affect the concrete properties.

As with all concrete, appropriate procedures are necessary for sampling from test panels or in-situ. CEN TC104/WG10 has proposed a test method (EN104-185:Part1:Sampling) that has gone for public comment (see Appendix A).

10.4 Test methods

Many countries have national standards for the testing of fresh and hardened concrete and some of these can be applied to sprayed concrete. This document gives the relevant EN method where available and corresponding British Standard. Several countries have standards specifically for sprayed concrete (section 5.2). The EFNARC specification (1996) and Guidelines (1999) provide the most recent and relevant European information on test methods for sprayed concrete, together with the draft EN test methods proposed by CEN TC104/WG10. A list of relevant standards is given in an Appendix.

10.4.1 Fresh concrete

As mentioned in section 7.4, no single test gives a complete indication of the pumpability and sprayability of concrete or mortar, but tests can be conducted in combination to give a guide. There is no substitute for actually pumping the material through the equipment that will be used for the application, as the mix performance can vary with the type of pump. Put simply, a material needs to be workable enough to be pumped at an effective rate without segregation or bleeding, yet stiff enough not to slough or sag once projected onto the receiving surface.

Care should be taken when testing thixotropic materials, as a result from a test where the material is static (such as the slump or shear vane) can produce a different indication of a material's workability to one where the material is in motion (such as a rotational viscometer or vebe).

Slump
Slump tests can be conducted to EN12350-2 (or BS 1881: Part102) for quality assurance purposes and to provide an indication of the workability of the mix, but the result should not be taken as the sole guide to pumpability as two mixes can have the same slump, but one will pump and the other will not. However, as a guide a mix with a slump of 50 - 80 mm will generally have a good balance between pumpability and sprayability assuming no accelerators are added at the nozzle.

Flow/spread table
This test to EN12350-5 (or BS 1881: Part105) is particularly useful for high workability and superplasticised mixes where collapsed slumps are recorded. It also provides a visual check on segregation and cohesion. It is a simple and portable test but wide variations in results can be obtained if care is not taken.

Rotational viscometers
Rotational viscometers such as the 2-point apparatus (Tattersall, 1991) and the Viskomat (Banfill, 1994) can provide information on the yield value and plastic viscosity of a mix, and these properties can characterise the workability and pumpability of a mix (Figure 24). However, care needs to be taken with mortars and concretes of low workability (below 75 mm slump) as the rotating impeller on the 2-point apparatus, which measures the material's resistance, can sometimes create a void in the material, making the results meaningless. Low workability materials can be tested by modifying the 2-point test so that the impeller moves in a planetary motion. The Viskomat also has problems with low workability materials, and it cannot test mixes which contain particles larger than 2 mm

in size. Although providing detailed information on the workability of a concrete or mortar, the sensitivity, size and cost of these apparatus make them unsuitable for site work.

Figure 24. Two-point test

Shear vane

A shear vane test is carried out with simple, portable apparatus (designed for measuring the shear strength of soils) and gives an indication of the workability of a mortar at various points in the pumping and spraying process (Figure 25). It consists of a torque measuring device at the head of the instrument and a set of vanes to provide sufficient shear resistance to register on the torque scale. The shear strength of the mortar can be determined from the maximum torque. As would be expected, there is a decrease in shear strength as slump increases, but the shear strength for mortars is more sensitive to change over the typical slump range of 50 to 75mm (Figure 26). The shear strength of fine concretes is generally higher than for mortars at a particular slump due to the shear resistance provided by the larger aggregates. This test method has potential because: (i) it is a simple and quick, hand-held site test; (ii) the vane can be inserted into the mix within a mixer, open pump hopper or fresh pumped or sprayed sample (tracing the rheological audit trail- section 7.1); and (iii) it measures an engineering property.

Figure 25. A shear vane test

Figure 26. Relationship between shear vane strength and slump

Pressure bleed test

A pressure bleed apparatus (Figure 27) can measure the rate and amount of bleeding of a mortar or concrete. It consists of a 125 mm diameter steel cylinder which is filled with approximately 1.7 litres of mortar or concrete and then subjected to a load (e.g.12.2 kN equivalent to a pressure of 10 bar which is typical of a small worm pump) via a piston. This compresses the sample and forces the liquid component through a 75μm mesh. The rate and amount of bleeding can be measured using an electronic balance and a data logger. Tests can be conducted at various pressures to emulate pressures found in different types of pump. A high rate of bleeding indicates that the material would bleed when placed under similar pressures in a pump.

Research has shown (Austin *et al*., 1999a) that highly polymer-modified mixes bleed less and at a slower rate than un-modified mixes (Figure 28). Also, mixes with a lower proportion of fine material bleed more. However, the rate and amount of bleeding is also a function of the water content, and a mix with a large proportion of fine material (cement, fine aggregate and fillers) needs a higher water content to obtain the same workability as a mix with a smaller proportion of fine material.

Figure 27. Pressure bleed apparatus

Figure 28. Typical pressure bleed results (Austin *et al.*, 1999a)

Air content

Tests to measure air content do not differentiate between trapped and entrained air, the latter influencing the resistance to freeze/thaw action.

The pressure test to EN12350-7 (or BS 1881: Part106) is portable and simple to operate by trained personnel. The test is conducted on approximately 300 ml of material and a result can be obtained in a few minutes. The process of pumping and spraying collapses some of the air bubbles within the mix and so the concrete before pumping will have a higher air content to the material in the line, which will in turn be greater than that of the material in-situ. Initial air contents of around 10-15 % are needed to obtain around 5% in-situ with a piston pump. It has also been shown (Beaupre *et al.*, 1999) that entrained air can help the spraying process by increasing pumpability whilst also obtaining a good build in-situ as air is removed. However, excessive initial air contents (more than 18%) are problematic as the concrete may be too compressible in the hose and prevent pumping.

Fresh density
Fresh wet density of concrete can be measured to EN12350-6 (or BS 1881: Part107) by weighing a sample of fresh concrete and dividing this value by its volume. However, this requires an accurate weighing device better than 20g, which is not always available on site. It is also possible to cut out an in-situ sample and determine its density by weighting it in air and water.

Fibre content
Simple wash-out tests can be conducted to measure the in-situ fibre content, although compared with dry spraying, the rebound for wet-sprayed materials is very low and so this test may not always be necessary. The fibre content can also be measured using hardened specimens taken in-situ, although this is a more difficult process. A core or cube is weighed, crushed and the steel fibres removed, usually with a magnet. These are then weighed and can be recorded as a percentage weight of the concrete or mortar. Appropriate tests methods for fresh and hardened concrete are given by EFNARC (1996) and CEN TC104/WG10's draft method EN104-192.

10.4.2 Hardened concrete

Compressive strength is usually the principle measure of quality of sprayed concrete. Cores taken from the in-situ concrete also allow visual inspection and grading of the sprayed concrete for voids and imperfections. A method for grading cores taken from sprayed concrete or mortar is described by Gebler (1995).

Sample manufacture
With the dry process it is only possible to test samples cut from panels or from the in-situ concrete. However, wet-process sprayed concrete offers the possibilities of either casting the wet mix into a mould or spraying directly into the mould. As shown in Figure 29, a cube or beam obtained from spraying into a mould from a worm pump has a strength similar to that of a sample sawn from a sprayed panel (Austin *et al.*, 1999c). However, care has to be taken that voids are not created when spraying into a cube mould as this can result in a lower, non-representative compressive strength and so this method is only recommended for low-volume worm pumps. In-situ cube and flexural strengths are generally higher than those of corresponding cast cubes, due mainly to the greater compaction obtained with the spraying process (section 8.6). The hardened density also follows this trend.

Figure 29. Effect of sample manufacture on cube strength of mortars (Austin *et al.*, 1999c)

When sawing specimens from a sprayed panel, material within 125 mm of the panel edge should be discarded to avoid the effects of rebound entrapment (unless it is the end of a beam used for flexural or toughness testing). Specimens should not be tested if evidence of laminations or defects is found, although these defects should be recorded and reported. Care must also be taken when compacting cast cubes to ensure that all the trapped air is removed, especially with some polymer-modified proprietary mixes as their viscous nature makes it difficult for air to escape.

Compressive strength
Compressive strength is normally measured from cores in accordance with EN 12504 Part1 (or BS 1881 Part 120:1983). It is recommended that a core diameter and length is selected to obtain either a 1:1 ratio for comparison with cube strength or 1:2 when comparing with cylinder strengths.

Compressive strength tests can also be carried out on cast cubes, in-situ cubes and on specimens sprayed into moulds in accordance with EN 12390 Part3 (or BS 1881: Part116.) Sawn cubes can also be tested in accordance with these standards except that they must be capped on their loading faces.

Figure 22 shows that 28 day compressive strengths of 30-50MPa are typical of worm-pumped pre-blended repair mortar, whilst 40-60MPa can easily be achieved with piston-pumped fine concretes (Figure 23). As with all concrete the strengths is largely controlled by the water/cement ratio (Figure 30).

Figure 30. Typical relationship between strength and water/cement ratio

Density

Density can be determined by weighting a sample in air and water in accordance with EN12390 Part7 (or BS 1881 Part114:1983). Pre-blended mortars an have values from 1800-2000 kg/m^3, whereas concretes can attain 2100-2300 kg/m^3.

Flexural strength

Beams can be sawn from panels or cast into moulds (even sprayed into moulds with a worm pump) in accordance with EN12390-5 (or BS1881: Part 118). EFNARC (1996) recommends using beams with dimensions of 75x125x600 mm on a 450 mm span cut from sprayed panels, although this is primarily for testing steel fibre reinforced concrete. If the sides in contact with the loading points are not flat they need to be ground or capped before testing. Observations should be made of the quantity and size of air voids within the specimens, especially those obtained from spraying directly into a mould. Typical strengths are 5-7 MPa with pre-blended mortars and 5-8 MPa with fine concretes. Good correlation has been found between in-situ and sprayed mould compressive cube strengths and flexural strengths, providing that no large voids or excessive rebound is present (Austin *et al.*, 1999c).

Elastic modulus

The modulus of elasticity should be measured in accordance with EN ISO 6784 or BS 1881: Part121 for concretes or prEN13412 for repair materials. Typical values are 22-26 GPa and 25-35 GPa for pre-blended mortars and site-batched concretes respectively. The relationship with compressive strength is similar to that of conventionally cast concrete.

Bond strength

Without an adequate bond the sprayed concrete layer will be ineffective, no matter how high the quality of the concrete itself. The pull-off test is the most common method in which a partially cored specimen is pulled from its substrate in-situ. Laboratory tensile tests on cores can also be undertaken and both of these methods are being proposed as European standard tests (EN1542 and EN104-188 of TC 104/WG10 respectively). Cores should be 50-60 mm in diameter and loaded at a rate of 1.0-3.0 MPa per minute. CIRIA have published a technical note on pull-off tests for concrete (McLeish, 1993) which describes the relevant codes, standards and equipment available as well as making recommendations for good practice.

Bond strengths are often greater than the tensile strength of the substrate. Recent research has shown that most pre-blended proprietary mortars will achieve a bond strength of at least 1.7 MPa at 28 days (with the exception of lightweight mortars) which comfortably exceeds the Concrete Society recommended minimum bond strength of 0.8 MPa (Austin *et al.*, 1999c). The mortars tested for this research had a relatively narrow range of bond strengths (1.7-2.25 MPa), despite having a broad range of in-situ compressive strengths (25-57 MPa).

Shrinkage

Shrinkage is an important property of a concrete or mortar, yet published values can be confusing or misleading because the shrinkage value obtained is dependent upon the test method, the timing of the test, and the environment in which the specimen is placed. Shrinkage figures quoted in specifications without definition and reference to defined test conditions are meaningless. It is also important to distinguish between plastic shrinkage (that occurs within a short time after placing) and drying shrinkage (which can take place for several months or even years). Shrinkage is a complex phenomena and is affected by w/c ratio, cement content, aggregate content, curing regime and length of cure, size and shape of test specimen, surface area/volume ratio of test specimen, relative humidity and size of aggregate. It is proportional to the water/cement ratio and inversely proportional to the aggregate/cement ratio. The shrinkage at the surface of the sprayed concrete may be expected to be greater than that deeper within the concrete which is more protected from drying out. This can cause differential shrinkage which can in turn induce tensile stresses and therefore cracking. Wet mix sprayed concrete displays higher shrinkage than dry-mix sprayed concrete due to the higher water/cement ratio needed for the wet mix to pump effectively.

Prism sizes to monitor shrinkage vary according to standards, although even the largest are too small to spray directly into a mould. The test method for repair materials is prEN12617. BS 1881:Part5 specifies specimens to be cast 75x75x229 mm in size, although this size can also be sawn from sprayed panels. Pairs of demec pips (measuring studs) can be glued to three of the longitudinal faces at a 200 mm gauge length the day after spraying. Research has shown that cast and sawn prisms taken from wet-sprayed panels prepared in this way and stored at 20^{0}C and 50% RH exhibit very similar rates of shrinkage. However, quoting shrinkage results conducted under laboratory conditions should be done with caution when discussing in-situ repairs and their performance. Although pre-blended proprietary mortars and site-batched concretes exhibit a wide range of drying shrinkage rates (typically 600-1400 and 600-900 microstrain respectively, at 28 days) data from restrained shrinkage specimens has suggested that the shrinkage of a repair is influenced more by the ambient conditions into which it is placed (mainly temperature and humidity, but also rain, wind and sunlight) than by the properties of the mortar itself (Austin *et al.*, 1999c).

Permeability and absorption
The permeability of all mortar and concrete is important as it has a direct bearing on the material's durability. High permeability can lead to corrosion of the steel bar or mesh reinforcement with consequent loss in performance. In-situ cores may be taken for water absorption, sorptivity or intrinsic permeability determinations. CIRIA have produced a technical note classifying the different types of permeability test available for concrete repair materials and coatings (Leeming, 1993).

EFNARC (1996) recommends the ISO 7031 water penetration method. The initial surface absorption test (BS 1881: Part 5) measures the rate of absorption of water by the surface zone of the concrete or mortar under a head of 200 mm. The water sorptivity test is another useful test (RILEM, 1974) that is also now proposed for repair materials, prEN13057. Dry samples of the concrete or mortar are placed in water to a depth of 2 mm and the weight gain over time is recorded for a period of approximately four hours. This measures the rate of capillary-rise absorption of water without a head of water (unlike the ISAT), which is a more common scenario for a typical concrete or mortar. It is also a simple test requiring minimal equipment. Typical values of sorptivity of wet-process mortars and concretes are 0.01-0.05 mm/min^{½} and 0.05 – 0.15 mm/min^{½} respectively.

Gas permeability can be measured by forcing air or oxygen (a pressure of 3.45×10^5 N/m^2 (50 psi) being typical) through a dried sample of mortar or concrete, frequently 20 mm by 55 mm diameter or similar. More details of these are given by the Concrete Society (1987). Air permeability decreases as compressive strength increases, and most pre-blended proprietary mortars have a permeability significantly lower than normal strength concrete (around 1-810^{-17} m^2.

Residual strength (toughness)
A beam flexure test is commonly used on steel fibre reinforced sprayed concrete to provide information on the first peak, ultimate and residual flexural strengths (i.e. toughness), which are affected by the in-situ fibre content. The test is, however, considerably more complicated than a simple compressive or flexural test. The EFNARC (1996) beam test (consisting of a 125x75 mm beam on a 450 mm span) is commonly specified on large European sprayed concrete projects for both pre-construction testing and routine quality control to check compliance with specified minimum peak and residual flexural strengths. However, on smaller contracts it may be sufficient to monitor compressive strength and in-situ fibre content during construction.

Freeze-thaw resistance
EFNARC (1996) recommend conducting freeze/thaw tests to ASTM C666. Sprayed concrete samples without significant air contents will be seen to deteriorate progressively during the test. Tests have shown that good air-entrainment can be achieved in wet-process silica fume sprayed concrete containing steel fibres, and therefore good freeze/thaw resistance, without the addition of air-entraining agents (Opsahl and Buhre, 1985). However, it is generally accepted that air-entraining admixtures are necessary for wet-process sprayed concrete and mortars that will be exposed to freeze/thaw action. If air-entraining agents are added, then up to half of the air content can be lost during the pumping and spraying process, depending on the mix and equipment.

Other points to consider when endeavouring to produce freeze/thaw durable sprayed concrete and mortars include (Robins, 1995): using aggregates which themselves are resistant to frost attack; ensuring that the workmanship and spraying are of the highest quality, as any defects or voids will aid frost attack; and using a high cement content (at least 350 kg/m^3) and a low water/cement ratio (below 0.5, possibly with a water-reducer).

Other tests
Other tests for conventionally cast concrete are equally applicable to sprayed concrete including: hammer tests, gamma radiography, rebound hammer, cover meter devices, and the measurement of ultrasonic pulse velocity. Hammers are a crude but cheap and effective way of sounding the concrete to locate hollow areas, poor compaction, and lack of bond. The fibre steel content can also be measured using cores taken from in-situ or from test panels. This method is described in the EFNARC specification and the draft EN104-192 standard produced by CEN TC104/WG10.

Summary

- *Pre-construction testing* should be an integral part of any specification and should be done with the materials, equipment and personnel that will be used for the actual construction

- *Quality control procedures* should also be part of the specification and should include the regular spraying and testing of *test panels* throughout the construction together with the taking and testing of cores in-situ
- With low output worm pumps representative cube and beam specimens can also be obtained from *spraying into the moulds*, although care should be taken not to trap rebound or create voids
- No single test is available that will provide a yes or no answer to a materials pumpability and there is usually no substitution for an actual *pumping and spraying trial*
- A *slump* of 50-80 mm is a good balance between pumpability and sprayability for a basic mix although this should not be taken as a definitive guide. *Rotational viscometers* and the *pressure bleed test* are sophisticated apparatus which are unsuitable for site work but are important laboratory instruments
- The *shear vane, flow table* and *air content apparatus* are all useful Quality Control tests for use on site although none can provide a definitive guide to a materials pumpability
- For the wet process, *compressive strength tests* can be conducted on cast cubes, cubes sawn from a test panel and in-situ cores. Sprayed compressive strengths are generally higher than corresponding cast strengths, and those obtained from spraying directly into a cube or beam mould with a low-output worm pump are similar to the strengths obtained from sawn specimens
- *Bond strength* is important and in-situ core pull-off and laboratory tensile tests can provide a good indication of a material's bond strength
- *C*are should be taken when quoting and specifying *shrinkage values* and reference should always be made to the *test method and conditions*. For the wet process, cast prisms and prisms sawn from sprayed test panels exhibit very similar rates of shrinkage. However, care should be taken as the shrinkage of an in-situ repair is influenced more by the *ambient conditions* in which it is placed than by the properties of the repair itself
- *Sorptivity, air permeability and water penetration tests* can all provide a good indication of the *durability* of a concrete or mortar
- The *beam flexure test*, although complicated compared with other strength tests, is considered the best Quality Control test for sprayed fibre concrete or mortar
- *Freeze-thaw testing* is essential for any concrete or mortar that is to be subjected to frost action in service. *Air-entrainment* is necessary with the wet-process to obtain the air void structure needed for *freeze-thaw resistance*. It should be remembered that spraying can reduce a material's air content by approximately half

11 References

ACI COMMITTEE 308R (1991), *Standard practice for curing concrete*, American Concrete Institute, Detroit, USA.

ACI COMMITTEE 506R (1990*), Guide to Shotcrete (ACI 506R-90),* American Concrete Institute, Detroit, USA, pp.41.

ACI COMMITTEE 506 (1994*), Proposed Revision of: Specification for Materials, Proportioning, and Application of Shotcrete (ACI 506.2),* ACI Materials Journal, Jan-Feb., pp.108-115.

ACI COMMITTEE 506.3R (1982*), Guide to certification of shotcrete nozzleman (ACI 506.3R-82),* American Concrete Institute, Detroit, USA.

AFNOR NF P95-102 06 (1997), *Repair and strengthening of concrete and masonry structures-sprayed concrete specifications for techniques and materials*, AFNOR (English translation).

AMERICAN SOCIETY OF CIVIL ENGINEERS (1995), *Standard Practice for Shotcrete,* ASCE Press, New York, USA, pp.66.

ASSOCIATION FRANCAISE DES TRAVAUX EN SOUTERRAIN (AFTES) (1992), *Recommendations on sprayed concrete: Technology and practice.* Report of AFTES Working group No.6, Paris.

ALLEN, R.T.L., EDWARDS, S.C. AND SHAW, J.D.N. (1993*), The Repair of Concrete Structures*, Glasgow Blackie Academic and Professional, Glasgow, UK.

AUSTIN, S.A.(1995), Materials selection, specification and quality control, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.87-112.

AUSTIN, S.A. (1996), Concrete repair with sprayed concrete; methods and quality issues, *Procs. of Int. Conf. on Deterioration of Reinforced Concrete in the Gulf and Methods of Repair*, Muscat, Oman, December, pp. 165-185.

AUSTIN, S.A. (1999), European developments in sprayed concrete, *Procs Concrete Institute of Australia Biennial Conference CIA 99*, Sydney, pp. 38-46.

AUSTIN, S.A., GOODIER, C.I., AND ROBINS, P.J. (2000), *Low-volume wet-process sprayed concrete: pumping and spraying*, in writing.

AUSTIN, S.A., ROBINS, P.J.R. (Eds.) (1995), *Sprayed Concrete: Properties, design and installation*, Whittles Publishing, Latheronwheel, UK (ISBN 1-870325-01-X) and McGraw Hill, USA (ISBN 0-07-057148-1).

AUSTIN, S.A., ROBINS, P.J. AND GOODIER, C.I. (1999a), The rheological performance of fine mortars in wet process sprayed concrete, *Magazine of Concrete Research*,Vol.51, No.5, October 1999.

AUSTIN, S.A., ROBINS, P.J. AND GOODIER, C.I. (1999b), Workability, shear strength and build of wet-process sprayed mortars, *Proc. Int. Congress on Creating with Concrete*, Dundee, September 1999.

AUSTIN, S.A., ROBINS, P.J. AND GOODIER, C.I. (1999c), The hardened performance of wet process sprayed mortars, accepted for publication in *Magazine of Concrete Research*, December 1999.

AUSTIN, S.A., ROBINS, P.J. AND GOODIER, C.I. (2000), *Wet-process sprayed mortars and concretes for repair*, in writing.

BCPA (1982), *Advisory code for safety in concrete pumping*, British Concrete Pumping Association, 2nd edition, Fleet, London.

BCPA (1990), *The manual of pumped concrete practice*, British Concrete Pumping Association, Fleet, London.

BANFILL, P.F.G. (1994), Rheological methods for assessing the flow properties of mortar and related materials, *Construction and Building Materials*, Vol.8, No.1, pp.43-50.

BARTON, N. (1995), Design for tunnel support, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.150-170.

BEAUPRÉ, D. (1994), Rheology of high performance shotcrete. *PhD Thesis*, University of British Colombia, February 1994.

BEAUPRÉ, D., DUMAIS, N., MERCIER, S., LACOMBE, P. AND JOLIN, M. (1999), Innovations in the field of shotcrete repairs, *Specialist Techniques and Materials for Concrete Construction* (Eds. Dhir, R.K. and Henderson, N.A.), Proc. of the Int. Conf. at the University of Dundee, Scotland, UK, 8-10 Sept. 1999, Thomas Telford, pp.137-162.

BRIDGE, R. (1999), Sprayed concrete repair to London vaults, *Concrete*, June, pp.48-49.

BROWNE, R.D. AND BAMFORTH, P.B. (1977), Tests to establish concrete pumpability, *ACI Journal*, May, pp.193-203.

COLLINS, M.P., ADEBAR, P., SEABROOK, P.T., KUCHMA, D., SACRE, P. (1997), External repair of cracked grain silos, *Concrete International*, November, pp.22-28.

CONCRETE INDUSTRY TRAINING BOARD (1994), *Certification scheme for nozzlemen*, CITB, King's Lynn, UK.

CONCRETE SOCIETY CONSTRUCTION AND FORMWORK COMMITTEE (1981), *Guidance on the measurement of sprayed concrete*, Concrete Society, London.

CONCRETE SOCIETY, (1987), *Permeability testing of site concrete,* Technical report No.31, Concrete Society, Slough, UK.
CONCRETE SOCIETY, (1990), *Assessment and repair of fire-damaged concrete structures*, Technical report No.33, Concrete Society, Slough, UK.
CONCRETE SOCIETY (1999), *Pumping concrete,* Good Concrete Guide 2.
CONCRETE SOCIETY (1999), *Rendering -a practical handbook,* Good Concrete Guide 3
COOKE, T.H. (1990), Concrete Pumping and Spraying: a practical guide, Thomas Telford Ltd, London.
DAWS, G. (1995), Rock stabilization and underground support, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.297-316.
DEPARTMENT OF THE ENVIRONMENT (1972), Guide to Concrete Pumping, HMSO, London.
DIN 18 551 (1991), Sprayed concrete; production and quality control, Deutsches Institut für Normung, Berlin.
EFNARC (1996), European specification for sprayed concrete, European Federation of National Association of Specialist Repair Contractors and Material Suppliers for the Construction Industry, Aldershot, UK.
GARSHOL, K.F. (1999), Shotcrete: international practices and trends, *Specialist Techniques and Materials for Concrete Construction* (Eds. Dhir, R.K. and Henderson, N.A.), Proc. of the Int. Conf. at the Uni. of Dundee, Scotland, UK, 8-10 Sept. 1999, Thomas Telford, pp.163-172.
GEBLER, S.H. (1995), Construction Practice and Quality Control, Sprayed Concrete: Properties, Design and Application (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.204-228.
GHIO, V.A. AND MONTEIRO, P.J.M. (1998), The effects of polysaccharide gum additives on the shotcrete process, ACI Materials Journal, 95 (2), March/April, pp.152-157.
GOODIER, C.I., AUSTIN, S.A., AND ROBINS, P.J. (2000), *Low-volume wet-process sprayed concrete: hardened properties,* in writing.
GORDON, K, (1995), Specialist Pre-Blended materials, in AUSTIN, S.A. AND ROBINS, P.J.R., *Sprayed Concrete: Properties, Design and Application,* , Whittles Publishing, Latheronwheel, UK pp.16-30.
GORDON, K. (1993), Wet spray application of polymer modified pre-packaged repair mortars, *Proc. of IBRACON/ICPIC Brazilian workshop on polymers in concrete,* Hotel Tropical da Bahia, Salvador City, Bahia, Brazil, 17-20 October.
HEALTH AND SAFETY EXECUTIVE (1999), *Control of Substances Hazardous to Health (COSHH) Regulations*.
HEALTH AND SAFETY EXECUTIVE (1994), Construction (Design and Management) Regulations.
HEERE, R., MORGAN, D., BANTHIA, N., YOGENDRAN, Y., (1996), Evaluation of shotcrete repaired dams in British Columbia, *Concrete International,* March, pp 24-29.
HUDD, R.W. (1989), *Measurement of Concrete Permeability,* PhD Thesis, Loughborough University.
HMSO (1974), Health and Safety at Work etc. Act, London.
INSTITUTION OF CIVIL ENGINEERS (1996), *Sprayed concrete linings (NATM) for tunnels in soft ground*, ICE design and practice guide, Thomas Telford, London, pp.88.
INTERNATIONAL TUNNELLING ASSOCIATION (1993), *Shotcrete for rock support, guidelines and recommendations -a compilation*, BeFo, Swedish Rock Engineering Research Foundation, Stockholm.
JOMHA, A.I.J. AND SUHR, J. (1997), New repair technique short down time and strong protection, *Deterioration and repair of reinforced concrete in the Arabian gulf*, edition 1, Vol.1, ACI/Concrete Society, Bahrain, pp.367-375.
KAY, T. (1992), *Assessment & Renovation of Concrete Structures*, Longman Scientific & Technical, Harlow, England, pp.25-48.
KEMPSTER, E. (1969), Pumpable Concrete, *Contract Journal,* 229, June, pp.605-607 and 740-741.
KING, E.S. (1995), Design for Structural Application, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.113-149.
KOLF, P. AND GEBLER, S. (1993), Shotcrete Application Tolerances, *Concrete Construction,* 38, (4), pp.287-289
LANE, I.R. AND CHAPLIN, K.J.(1998), Testing the spray option, *Concrete Engineering International,* July/August, pp.40-42.
LEEMING, M.B. (1993), *Standard tests for repair materials and coatings for concrete, part 2: Permeability tests,* CIRIA Technical note 140, CIRIA, London.
LOVELOCK, P.E.R. (1970), *Laboratory Measurement of Soil and Rock Permeability*, Institute of Geological Science, London.
MAIDL, B.R., (1991), Shotcrete Robot for Improving Working Conditions, Quality and Economy in Civil Engineering and Tunnelling, *Automation and Robotics in Construction,* 8th Int. Symposium, Vol.1, June, Stuttgart, Germany, pp.85-94.
MAILVAGANAM, N.P. (1991), *Repair and Protection of Concrete Structures,* CRC Press, London, p.473.
MANGAT, P.S. AND O'FLAHERTY, F.J. (1996), Long Term Performance of Sprayed Concrete Repair in Highway Structures, *Sprayed Concrete Technology (Ed. Austin, S.A.),* E&FN Spon (ISBN 0-419-22270-7), London.

MAYS, G.C. AND BARNES, R.A. (1996), Sprayed Concrete Repairs - Their Structural Effectiveness, *Sprayed Concrete Technology (Ed. Austin, S.A.),* E&FN Spon (ISBN 0-419-22270-7), London.
MCLEISH, A. (1993), *Standard tests for repair materials and coatings for concrete,* CIRIA Technical note 139, CIRIA, London.
MELBYE, T. (1997), *Sprayed concrete for rock support,* MBT International Underground Construction Group, MBT Ltd., Zurich, pp.198.
MELBYE, T. (1995), Shotcrete for rock support, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.317-356.
MILLER, D. (1995), Site safety, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.266-275.
MORGAN, D.R, MCASKILL, RICHARDSON, B.W. AND ZELLERS, R.C. (1989), A comparative evaluation of plain, polypropylene fibre, steel fibre and wire mesh reinforced shotcretes, *Transportation Research Record 1226,* Washington, D.C., pp.78-87.
MULLER, D. (1984), *Concrete Spraying - Wet or Dry?*, Putzmeister internal paper, April.
NEVILLE, A.M.(1995), *Properties of Concrete*, 4th edition, Longman, London.
NORRIS, P. (1999), 'Wet mix sprayed concrete helps to set the ground rules', *Concrete*, Vol.33, No 5., May.
OLIVER, A. (1998), Down to Design, *New Civil Engineer*, 1 October, pp.16-20.
OSBORNE, J. (1998), 'Set to spray', *Concrete Engineering International*, September, pp.11-15
RILEM Technical Committee 14-CPC (1974), Tentative Recommendations No 11.2, *'Absorption of Water by Capillary'*, Mater. Struct., Vol.7, No 40, pp.295-297.
ROBINS, P.J.R (1995), Materials, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.7-15.
SCHLEIBINGER GERÄTE, Haager Strasse 2, 8255 Schwindegg, Germany.
SEYMOUR, J. AND TURNER, N.J. (1995), *Wet process sprayed concrete technology for repair - repair scenarios*, Internal Report, Department of Civil and Building Engineering, Loughborough University, U.K., November.
SHAW, J.D.N. (1993), Concrete Decay: Causes and Remedies, *Construction Repair*, Jan./Feb., Vol.7, No.1, pp.24-33.
SPRAYED CONCRETE ASSOCIATION (1990), *Code of Good Practice*, SCA, Aldershot, UK.
SPRAYED CONCRETE ASSOCIATION (1994), *Guide to certification of sprayed concrete nozzlemen,* SCA, Aldershot, UK.
SPRAYED CONCRETE ASSOCIATION (1999), *Introduction to Sprayed Concrete*, SCA, Aldershot, UK.
TATTERSALL, G.H. (1991), *Workability and Quality Control of Concrete*. E&FN Spon, London.
TAYLOR, G. (1995), Repair, *Sprayed Concrete: Properties, Design and Application* (Eds. Austin, S.A. and Robins, P.J.), Whittles Publishing, Latheronwheel, UK, pp.287-296.
WARNER, J. (1995a), Understanding Shotcrete -The Fundamentals, *Concrete International*, May, pp.59-64.
WARNER, J. (1995b), Understanding Shotcrete- Finishing, Curing, and Quality Control, *Concrete International*, August 1995, p.72-74.
WYKEHAM FARRANCE ENGINEERING LTD, Weston Road, Slough, Berks., SL1 4HW.

12 Further Reading

AUSTIN, S.A. (ed.) (1996), *Sprayed concrete technology*, E&FN Spon (ISBN 0-419-22270-7), London.

AUSTIN, S.A., ROBINS, P.J. AND GOODIER, C.I. (1998), Sprayed repair, *Concrete Engineering International*, Vol.2, No.4, May-June, pp. 47-51 (Invited).

AUSTIN, S.A. (1997), Repair with sprayed concrete, *Concrete*, Vol.31, No.1, January, pp. 18-26. (Invited).

AUSTIN, S.A., ROBINS, P.J.R. (eds.), *Sprayed Concrete: properties, design and installation*, Whittles Publishing, Latheronwheel, UK (ISBN 1-870325-01-X) and McGraw Hill, USA (ISBN 0-07-057148-1), 1995, 382 pp.

BEAUPRE, D. (1994), *Rheology of high performance shotcrete*, PhD Thesis, University of British Colombia, February.

CONCRETE SOCIETY (1990), *Assessment and repair of fire-damaged concrete structures*, Technical report No.33.

EMBERSON, M.K. AND MAYS, G.C. (1990), Significance of property mismatch in the patch repair of structural concrete, Part 1, Properties of repair system, *Magazine of Concrete Research*, 42(152), pp. 147-160.

Appendix A – Relevant Standards

A.1 Scope

This appendix gives details of standards relevant to wet process sprayed concrete and repair. It includes European (CEN), UK (BSI) and certain US (ASTM) standard specifications and test methods. Table A.1 compares the documents for the main requirements and properties of sprayed concrete. The following sections give further details. Note that concrete tests called up by EN206 have recently been renumbered into two series: EN12350 for fresh concrete and EN12390 for hardened properties.

Table A.1 Common Standards

Purpose	CEN	BS
Sprayed concrete	ENAAA:	–
Repair	EN1504	–
Portland cement	EN197	BS12
Concrete	EN206	–
Aggregate		BS882
Slump	EN12350 – 2	BS1881: Part 102
Air content	EN12350 – 7	BS1881: Part 106
Making and curing specimens	EN12390 – 2	BS1881: Part 108-111
Density	EN12390 – 7	BS1881: Part 114
Compressive strength	EN12390 – 3	BS1881: Part 116
Flexural strength	EN12390 – 5	BS1881: Part 118
Cored samples	EN12504 – 1	BS1881: Part 120
Sampling	ENBBB: Part 1	BS1881: Part 101
Bond strength	ENBBB: Part 4 or EN1542	–
Thickness	ENBBB: Part 6	–
Capillary absorption	EN13057	–

A.2 Test methods for concrete

The following test methods have been called up by EN206 and may be applicable to sprayed concrete:

EN 197 Cement - composition, specifications and conformity criteria.
EN 206 Concrete - performance, production, placing and compliance criteria.
EN 450 Fly ash for concrete - Definitions, requirements and quality control.
EN 934 Admixtures for concrete, mortars and grouts
Part 2: Concrete admixtures-definition, specification and conformity criteria.
Part 5: Sprayed concrete admixtures - definition, specification and conformity criteria.
Part 6: Sampling, quality control, evaluation of conformity and marking and labelling.
EN 1008 Mixing water for concrete.
EN 1542 Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off.
EN 10080 Steels for reinforcement of concrete. Weldable, ribbed reinforcing steel B500. Technically delivery conditions for bars, coils and welded fabric.

EN 12350 Testing fresh concrete

Part 1 : Sampling
Part 2 : Determination of consistency – Slump test
Part 3 : Determination of consistency of fresh concrete – VEBE test
Part 4 : Determination of consistency of fresh concrete – Degree of compatibility
Part 5 : Determination of consistency of fresh concrete – Flow table test
Part 6 : Determination of density of fresh concrete
Part 7 : Determination of air content of fresh concrete – pressure methods

EN 12390 Testing hardened concrete

Part 1 : Shape, dimensions and other requirements for specimens and moulds for strength tests
Part 2 : Making and curing specimens for strength tests
Part 3 : Determination of compressive strength of test specimens
Part 4 : Determination of compressive strength – specification for compressive testing machines
Part 5 : Determination of flexural strength of test specimens
Part 6 : Determination of tensile splitting strength of test specimens
Part 7 : Determination of density of hardened concrete

EN 12504 Testing concrete in structures

Part 1 : Cored samples – Taking, examining and testing in compression
Part 2 : Non-destructive testing – Determination of rebound number
Part 3 : Determination of pullout force

A.3 Methods of CEN/TC104/WG10 sprayed concrete

The following two standards, one covering definitions, specification, conformity and execution, the other test methods, have been drafted by working Group 10 and sent for public enquiry in 2000.

EN AAA[1] Sprayed concrete

104 – 182 Part 1 : Definitions, specification and conformity
104 – 183/4 Part 2 : Execution

EN BBB[1] Sprayed concrete – test members

104 – 185 Part 1 : Sampling
104 – 186 Part 2 : Determination of compressive strength of young sprayed concrete
104 – 187 Part 3 : Determination of flexural and residual strength
104 – 188 Part 4 : Determination of bond strength
104 – 190 Part 5 : Determination of energy absorption
104 – 191 Part 6 : Determination of thickness of sprayed layers
104 – 192 Part 7 : Determination of fibre content
104 – 189 Part 8 : Determination of frost resistance

A.4 Methods of CEN/TC104/SC8 concrete repair

The following standards govern the protection and repair of concrete structures, which were mainly drafted by sub-committee 8.

EN 1504 Products and systems for the protection and repair of concrete structures – definitions, requirements, quality control, evaluation of conformity.

Part 1 : General scope and definitions
Part 2 : Surface protection systems
Part 3 : Structural and non structural repair
Part 4 : Structural bonding
Part 5 : Concrete injection
Part 6 : Grouting to anchor reinforcement or to fill external voids
Part 7 : Reinforcement corrosion prevention
Part 8 : Quality control and evaluation of conformity
Part 9 : General principles for the use of products and systems

Part 10: Site application of products and systems and quality control of the works

EN 1542	Bond strength by pull-off
prEN 121921	Granulometry
prEN 12617	Shrinkage (Dimensional stability)
prEN 13057	Capillary water absorption
prEN 13294	Determination of stiffening time
prEN 13295	Carbonation resistance
prEN 13395	Workability/consistency
prEN 13396	Chloride ingress
prEN 13687	Thermal compatibility
prEN 13412	Modulus of elasticity in compression

A.5 British Standards

Many of the standards listed below have or will be superseded by EN standard, but are listed for completeness.

BS 12: 1996	Specification for Portland cements
BS 882: 1983	Specification for aggregates from natural sources for concrete
BS 1881: Part5: 1970	Determination of changes in length on drying and wetting (initial drying shrinkage, drying shrinkage and wetting expansion)
BS 1881: Part105: 1984	Method for determination of flow
BS 1881: Part 106: 1983	Method for determination of air content of fresh concrete
BS 1881: Part 107: 1983	Method for determination of density of compacted fresh concrete
BS 1881: Part 116: 1983	Method for determination of compressive strength of concrete cubes
BS 1881: Part 118: 1983	Method for determination of flexural strength
BS 1881: Part121: 1983	Method for determination of static modulus of elasticity in compression
BS 3148: 1980	Tests for water for making concrete (including notes on the suitability of the water
BS 4466: 1989	Specification for scheduling, dimensioning, bending and cutting of steel reinforcement for concrete
BS 4550: Part 3(3.5): 1978	Methods of testing cement: determination of standard consistence
BS 5075: Part 1: 1982	Specification for accelerating admixtures, retarding admixtures and water reducing admixtures
BS 5075: Part 2: 1982	Specification for air-entraining admixtures
BS 5075: Part 3: 1985	Specification for super plasticizing admixtures
BS 5328: 1991	Concrete
BS 5400: 1990	Steel, concrete and composite bridges
BS 6699: 1992	Specification for ground granulated blast furnace slag for use with Portland cement
BS 7542: 1992	Test for curing compounds for concrete
BS 8110	Structural use of concrete *Part 1: Code of practice for design and construction*

A.5 American Standards

The European standards should always be used, but the ASTM standards are listed for completeness.

ASTM 360-82	Ball penetration in fresh Portland cement concrete
ASTM C666-90	Standard test procedures for rapid freezing and thawing of concrete
ASTM A 820-90	Specification for steel fibres -Reinforced concrete
ASTM 260-92	Test for ball penetration in freshly mixed hydraulic cement concrete
ASTM C672-92	Test for scaling resistance of concrete surfaces exposed to de-icing chemicals
ASTM C1117-89	Standard test method for time of setting of shotcrete mixtures by penetration resistance
ASTM C1018-92	Standard test method for flexural toughness and first-crack strength of fibre-reinforced concrete
ASTM C1140-98	Standard practice for preparing and testing specimens from shotcrete test panels
ASTM C1141-95	Standard specification for admixtures for shotcrete

Figure 1. Pierepoint canoe slalom (Slide from Austin & Robins (eds.), *Sprayed Concrete: properties, design and installation*, Whittles Publishing, Latheronwheel, UK (ISBN 1-870325-01-X) and McGraw Hill, USA (ISBN 0-07-057148-1), 1995, 382 pp.)

Figure 2. Riyadh zoo, Saudi Arabia (Slide from Austin & Robins (eds.), *Sprayed Concrete: properties, design and installation*, Whittles Publishing, Latheronwheel, UK (ISBN 1-870325-01-X) and McGraw Hill, USA (ISBN 0-07-057148-1), 1995, 382 pp.)

Figure 3. Rhualt Hill (Slide courtesy of Ove Arup & Partners)

Figure 4. Brick archway strengthening at Lancaster Place Vaults (before application of sprayed concrete) (photograph)

Figure 5. Typical medium output piston pump (photograph)

Figure 6. Typical worm pump (Putzmeister P11) (Putzmeister trade brochure)

Figure 7. Dual-mixing worm pump (photograph)

Figure 8. Example of voidage behind reinforcement (photograph)

Figure 9. Cracking due to inadequate curing (photograph)

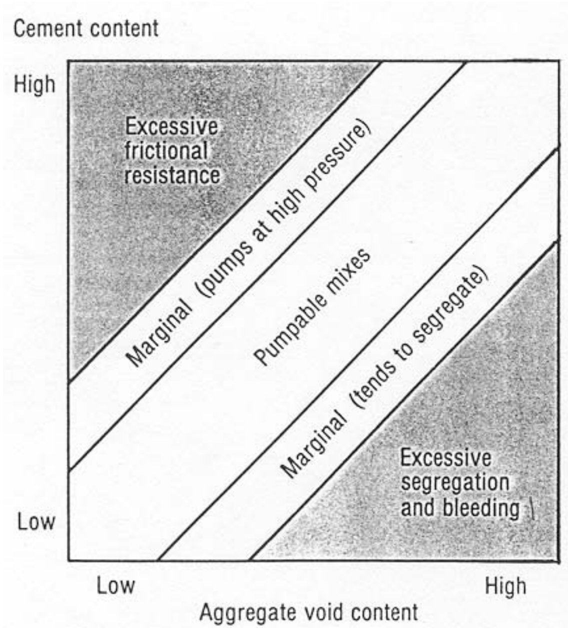

Figure 10. Effect of cement content and void content on pump ability (Concrete Society, 1998)

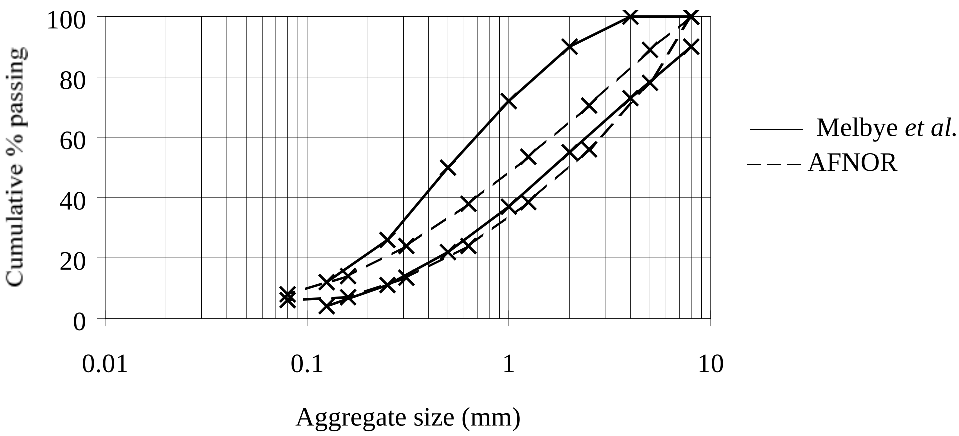

Figure 11. Recommended aggregate gradings for wet-process sprayed concrete (8 mm max.)

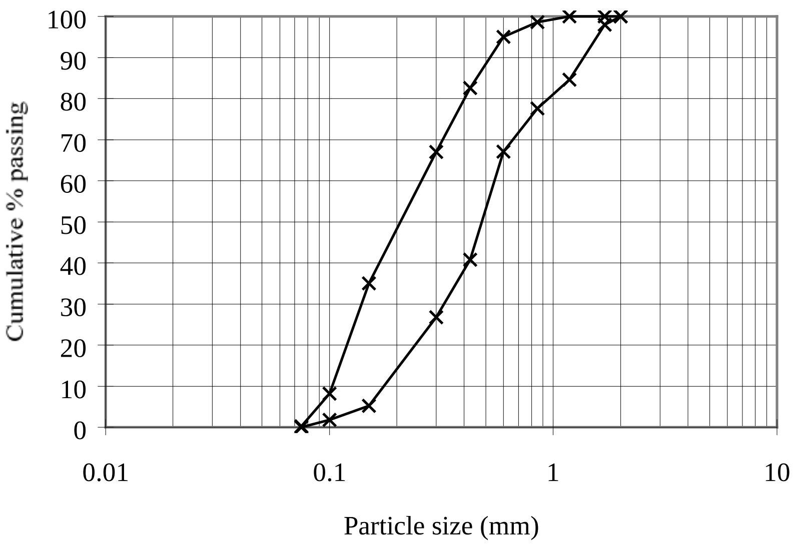

Figure 12. Recommended aggregate gradings for wet-process mortars (2 mm max.) (Austin *et al.*, 2000)

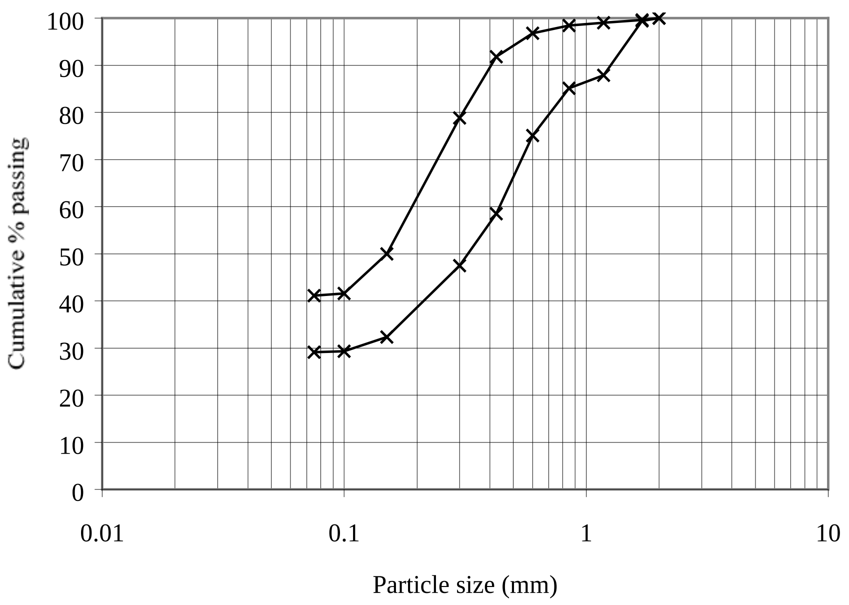

Figure 13. Combined grading zone (aggregate and cementitious components) for mortars through small-diameter worm pumps (Austin *et al.*, 2000)

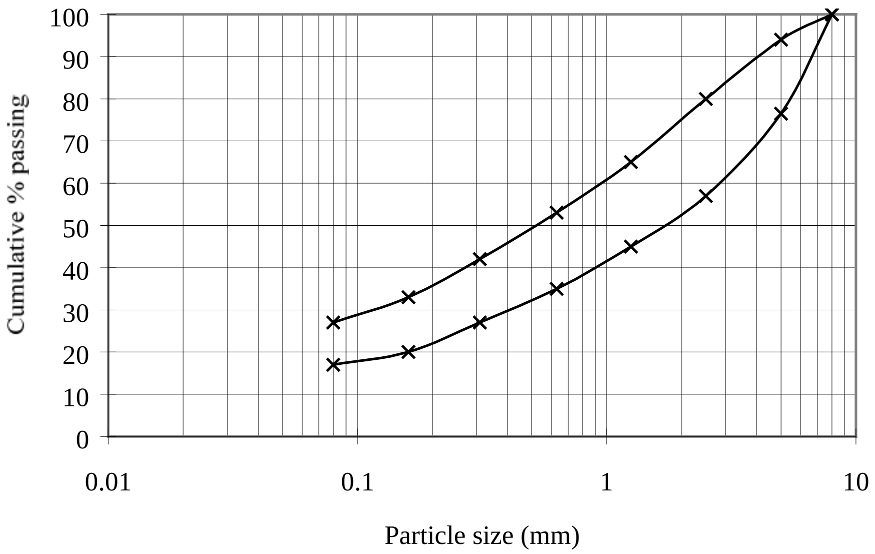

Figure 14. Combined grading envelope for concretes (through piston pumps) (AFNOR, 1992)

	Stage in pumping/spraying process				
	Mixer	**Pump**	**Hose**	**Stream**	**In-situ**
Shear rate	High	Low-medium	Zero (Plug flow)	Zero	Zero
Pressure	Atmospheric	Atmospheric	High - Reducing to atmospheric	Atmospheric	Atmospheric
Rheological tests	Tattersall two-point Rotational viscometer Slump, flow table Shear vane		Pressure Bleed		Build Grading of Cores Reinforcement Encasement

Figure 15. Rheological audit (Austin *et al.*, 1999a)

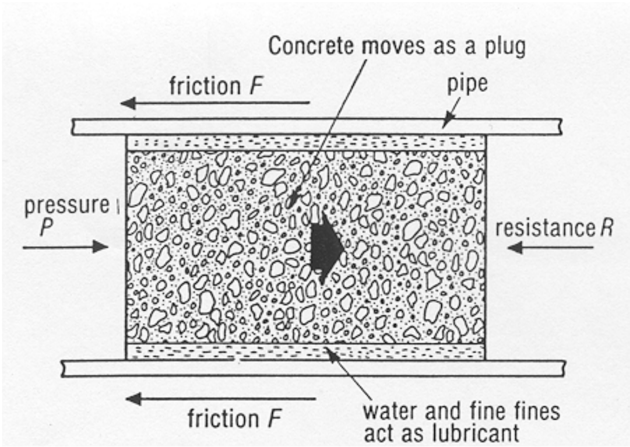

Figure 16. Plug flow (Concrete Society, 1998)

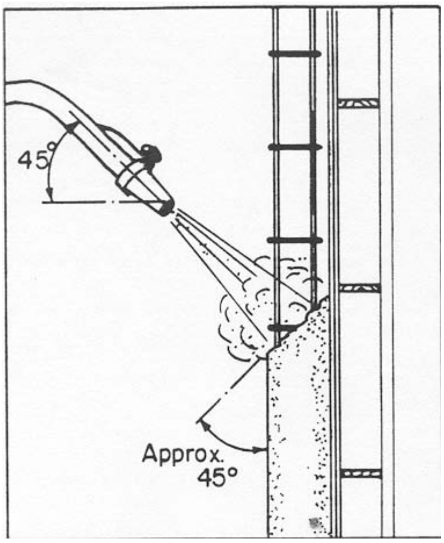

Figure 17. Bench gunning of sprayed concrete (ASCE, 1995)

(a) Worm pump

(b) Piston pump

Figure 18. Nozzle types for wet spraying (personal photographs)

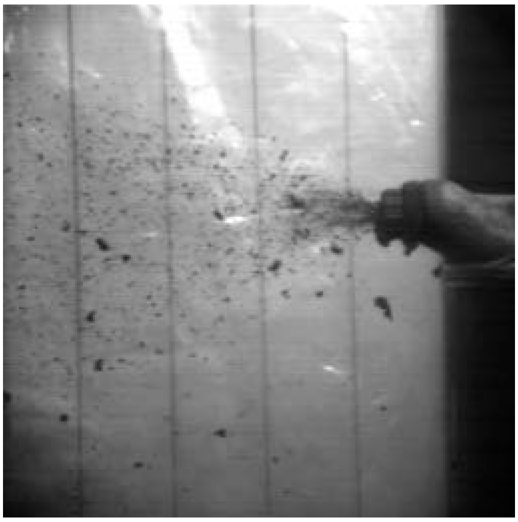

Figure 19. Spray stream captured by high-speed video (photograph)

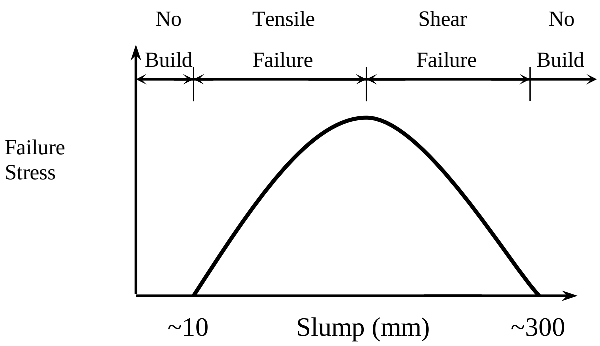

Figure 20. A build test (photograph)

Figure 21. Simplified relationship of maximum failure (shear and bending stress) (Austin *et al.*, 1999a)

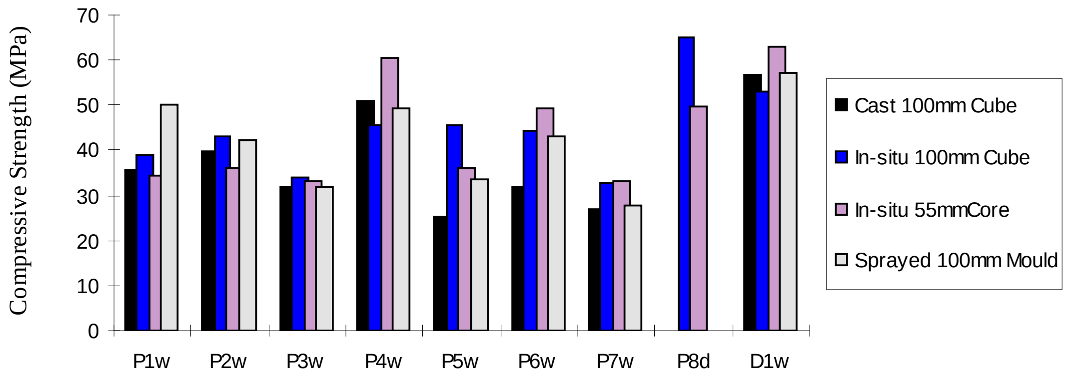

Figure 22. Compressive strengths of mortars (Austin *et al.*, 1999c)

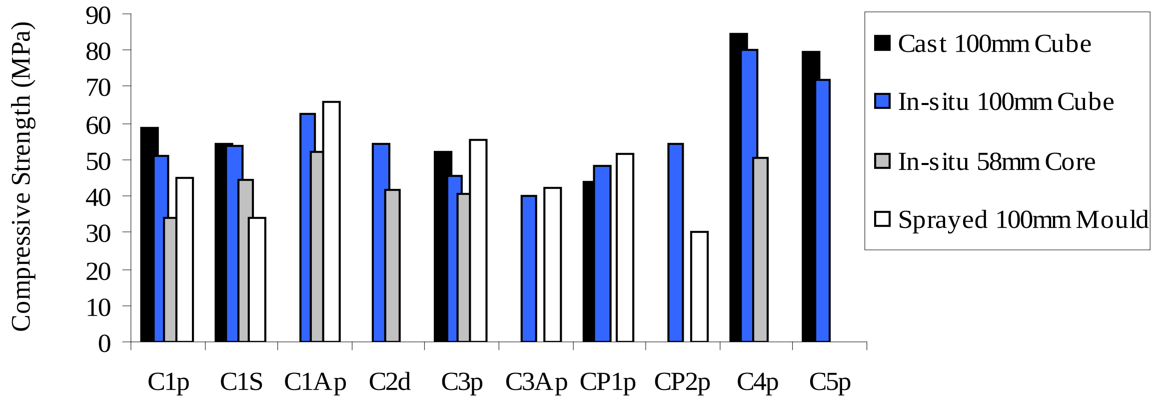

Figure 23. Compressive strengths of fine concretes (Goodier *et al.*, 2000)

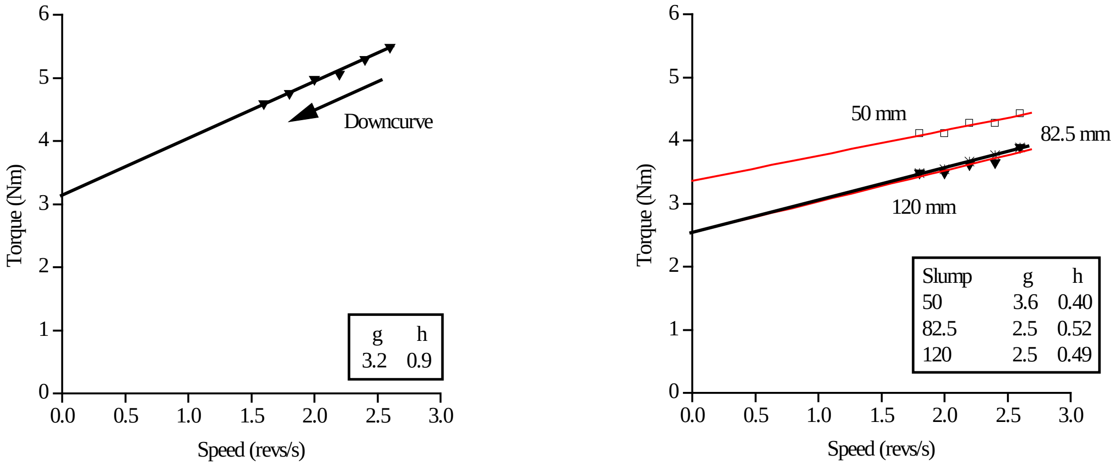

Figure 24. Two-point test (Austin *et al.*, 1999a)

Figure 25. A shear vane test (photograph)

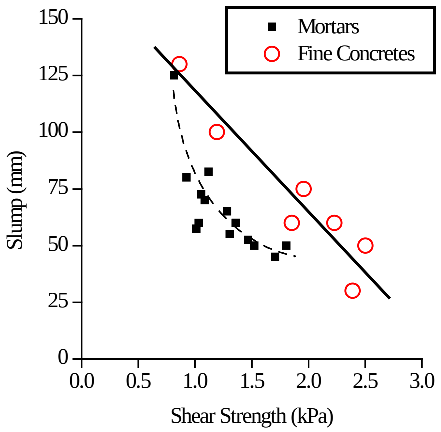

Figure 26. Relationship between shear vane strength and slump (Austin *et al.*, 2000)

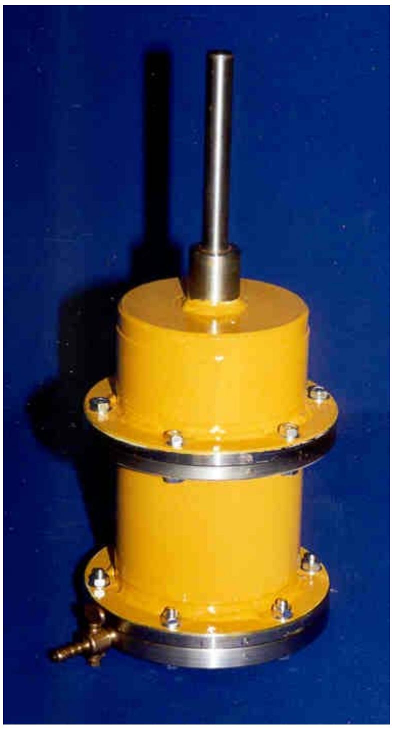

Figure 27. Pressure bleed apparatus (photograph)

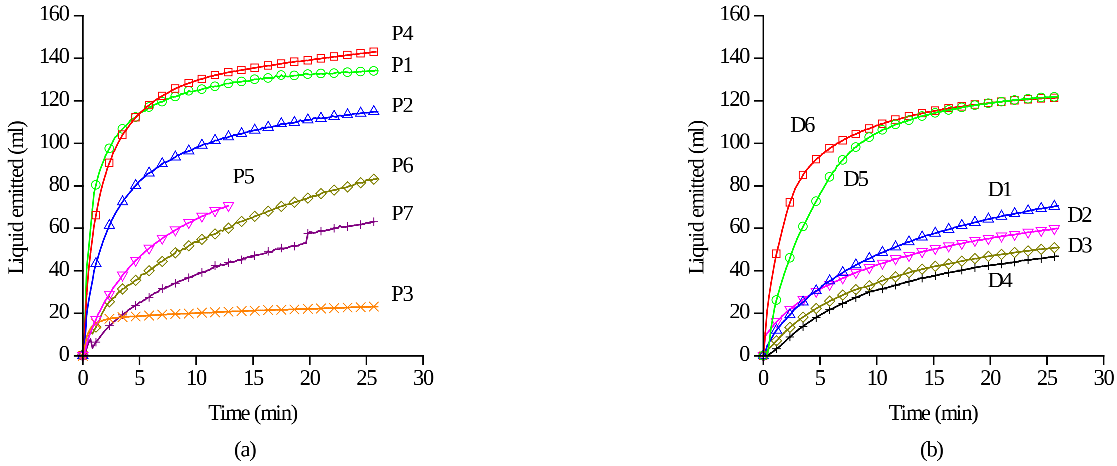

Figure 28. Typical pressure bleed results (a) Pre-blended mortars (b) site-batched mortars (Austin *et al.*, 1999a)

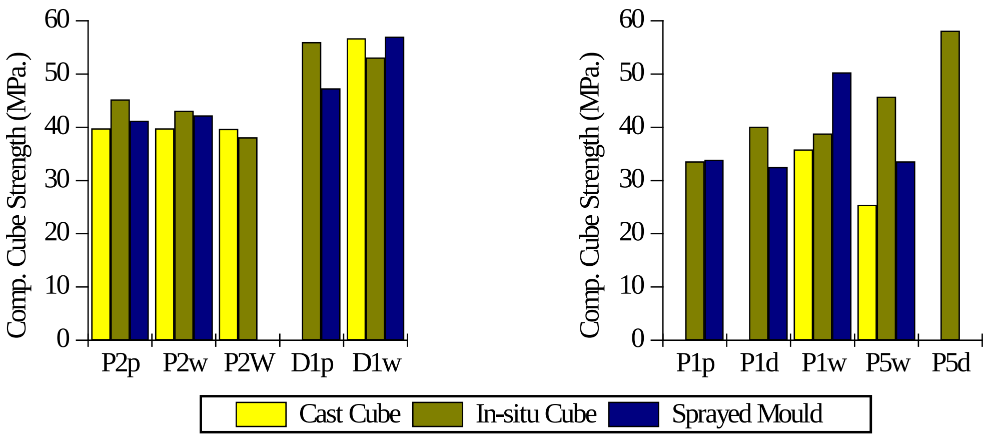

Figure 29. Effect of sample manufacture on cube strength of mortars (Austin *et al.*, 1999c)

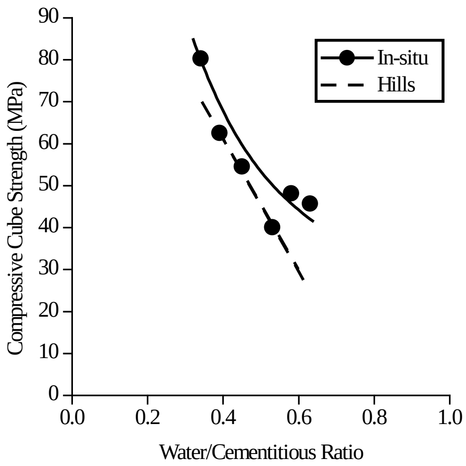

Figure 30. Typical relationship between strength and water/cement ratio (Goodier *et al.*, 2000)