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RECOMMENDED PRACTICE

Shotcreting in Australia

SECOND EDITION

Prepared by:

Australian Shotcrete Society

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The **Australian Shotcrete Society** was formed in 1998 as a not-for-profit industry group committed to improving recognition of the value and uses of shotcrete in the Australian mining and construction industries. Its objectives are to promote the use of shotcrete where appropriate, promote good shotcreting practice, and to educate specifiers and potential designers of shotcrete structures about the best means of using this material. These objectives have been undertaken through seminars and conferences that are held from time to time, and through the publication of this guide.

The Concrete Institute of Australia was selected as a partner in publishing this guide because it is the most appropriate institution for the promotion of good concrete practice and technology within Australia.

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Preface

All Concrete Institute of Australia publications, including this Recommended Practice, are made possible through the continuing support received from our *Platinum and Gold Company Members*. As at 1 September 2010, these include:

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This document has been written as a guide to the use of shotcrete in Australia. It is based on established practice within the Australian context and is targeted toward designers, specifiers, owners, suppliers, contractors and other end users of shotcrete. From limited beginnings in the 1960s, shotcrete has emerged as the first choice for ground support in the general construction and mining industries and is increasingly being used in other applications. Shotcrete is an evolving technology and users of this guide must appreciate that the contents represent the state of knowledge and practice at the date of publication and may be subject to change.

This guide is the second edition of this document, updated and prepared by the Australian Shotcrete Society, a special interest group within the Australasian Tunneling Society (ATS). The ATS is affiliated with AusIMM and Engineers Australia. The Australian Shotcrete Society wishes to acknowledge the valuable input provided by the many practitioners who have contributed to its development from both within the society and the broader shotcreting community, in particular the Concrete Institute of Australia.

This guide was edited by Dr Stefan Bernard. The steering committee for the development of this guide has included the following individuals:

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In addition, numerous individuals also contributed to the development of this edition of the guide. These include Marc Jolin, Pete Tatnall, Rusty Morgan, Atsuma Ishida, Kath Winder and MacMahon Underground P/L. The steering committee thanks these individuals and their employers for their contribution to the guide.

The guide has been arranged into chapters and clauses covering specific areas of information relevant to shotcrete technology. The behavior of structures made with shotcrete more closely resembles that of cast concrete structures than any other type of structure. In the absence of an Australian Standard on shotcrete the chapter within this guide on Design Considerations has been organised in a broadly-similar manner to AS 3600 *Concrete structures*, to facilitate a complementary approach to structural design.

Contents

1 General

1.1 Scope

This guide provides a description of recommended technology and practice for shotcrete processes, materials, specifications, and equipment. It suggests issues that require consideration with respect to structural design and mix design, but does not purport to be a comprehensive standard on design. While this guide provides an overview of processes involved in shotcreting and required performance criteria it does not replace the need for specific expert knowledge in the particular fields discussed.

In writing this guide, the Australian Shotcrete Society has sought to encourage performance-based specifications as opposed to prescriptive specifications for shotcrete.

1.2 Definitions

It is generally accepted that the term "shotcrete" has been adopted in Australia for the description of sprayed concrete in accordance with the American Concrete Institute (ACI) conventions, and the term "shotcrete" will be used throughout this guide. In this document the term "shotcrete" is defined as mortar or concrete conveyed through a hose and pneumatically projected at high velocity onto a surface or substrate.

Adhesion/Bond – the property that causes shotcrete to stick to the substrate after being pneumatically projected on to it through a nozzle.

Admixture – any material deliberately added to concrete before or during mixing, other than cementitious materials, water, aggregates and fibre reinforcement.

Accelerator – a material that is normally added at the shotcrete nozzle having the primary effect of increasing the rate of hydration of the cement, reducing slump and causing rapid stiffening. The term activator is also used to denote a set accelerator.

Bleeding – the movement of the water from within to the surface of the shotcrete resulting from the separation of water from the solid ingredients in the mix.

Build-up – the increase in thickness with successive passes of shotcrete.

Cement – A hydraulic binding material comprising Portland or blended cement complying with Australian Standard AS 3972[1] alone or in combination with one or more supplementary cementitious materials complying with the applicable part(s) of AS 3582[2].

Cohesion – the extent to which the ingredients of mixed concrete, mortar and shotcrete remain fully-mixed and homogeneously bound together when transported, handled, placed, pumped or pneumatically-projected through a nozzle.

Concrete – A mixture of cement, aggregates and water, with or without the addition of chemical admixtures, or other materials, in which the nominal maximum aggregate size is equal to or greater than 5 mm.

Dry-mix Shotcrete – Shotcrete in which all the ingredients are conveyed in a dry state by compressed air to the nozzle, where water is added, and the resultant shotcrete is projected onto the substrate via compressed air at high velocity.

Fall out – A substantial piece or slab of shotcrete that falls away from a sprayed surface some time after spraying. This is not to be confused with rebound that involves particles which bounce off the substrate or in-place shotcrete during the shotcreting process.

Fibres – short slender reinforcing elements typically of high tensile capacity. Commercially-available fibres are normally composed of either steel, polymers, or Alkali Resistant (AR) glass. Fibres are widely incorporated in shotcrete to increase toughness.

Flash coat – a thin shotcrete layer applied for sealing or bonding purposes.

Gunite – the brand name given by the Cement Gun Company in 1907 in the USA to the first mortar that was sprayed. This mortar contained fine aggregate and a high percentage of cement. The term Gunite is not generally used in Australia.

Hydration – the chemical reaction between the cement and water in shotcrete.

Mortar – as for Concrete except "the maximum nominal aggregate size is less than 5 mm".

Macro fibres – relatively large fibres normally used to develop structural levels of performance after cracking of the concrete matrix.

Micro fibres – relatively small diameter fibres used for control of plastic shrinkage cracking, rebound, and spalling in high-temperature applications.

Nozzle/gun finish – the undisturbed final layer of shotcrete as applied from the nozzle without hand finishing.

Nozzleman – the person charged with control of the nozzle and therefore the spraying of the concrete. The term 'sprayer' is used in place of 'nozzleman' in this document.

Overspray – sprayed material, inadvertently deposited on areas surrounding the intended substrate.

Over-thickness – excessive shotcrete material deposited on the intended receiving surface.

Pass – movement of the nozzle over an area of operation during shotcreting (a layer of shotcrete is built up by making several passes).

Pozzolan – a material consisting mainly of silica that together with lime and water forms compounds possessing cementitious properties.

Performance based specification – a specification in which the performance characteristics required of the shotcrete are detailed (eg compressive strength at a particular age of the shotcrete, flexural strength, toughness, density, etc) without prescribing how this performance is to be achieved.

Prescriptive specification – a specification where the nature and/or the quantity of some or all of the shotcrete ingredients and the process by which the shotcrete is produced and applied are specified (eg cement content, etc).

Rebound – that part of the shotcrete which ricochets away from the surface during the spraying process, and deposits on the ground or on nearby surfaces. Rebound consists mainly of larger aggregate particles, and to a lesser extent, fibres, binder and water.

Sand lens/pocket – a zone within the shotcrete containing unmixed fine aggregate with little or no cement, resulting from incomplete mixing.

Sagging or sloughing – downward movement of the shotcrete from its initial and required point of application.

Saturated Surface Dry (SSD) – Aggregates which are internally saturated but externally dry.

Serviceability Limit State (SLS) – To satisfy serviceability limit state criteria, a structure must remain functional for its intended use subject to routine loading. A structure is deemed to satisfy the serviceability limit state when the constituent elements do not deflect by more than certain limits, and when these elements of the structure fall within predetermined vibration limits. In addition, the structure must satisfy other possible requirements such as limits on maximum crack widths in concrete.

Slugging – pulsating or intermittent flow of shotcrete material through the delivery line.

Smoothing layer – a thin layer of shotcrete usually intended to provide a more uniform surface generally applied over an initial layer of shotcrete. This is also often referred to as a finish coat.

Sprayer – the person charged with control of the nozzle and therefore the spraying of the concrete.

Substrate – The surface on to which the shotcrete is projected.

Supplementary cementitious materials – materials conforming to the following: a) Fly ash, complying with AS 3582.1[2]; b)GGBFS, ground granulated blast furnace slag, complying with AS 3582.2[2]; c) Amorphous silica, complying with AS 3582.3[2].

Toughness – Post-crack performance of fibre reinforced shotcrete as measured either by energy absorption under the load-deflection curve, residual strength, or any of a number of parameters derived from the load-deflection curve altered from a sample subject to bending or tension.

Ultimate Limit State (ULS) – To satisfy ultimate limit state criteria, a structure must not collapse when subjected to the peak design load for which it is designed. A structure is deemed to satisfy ultimate limit state criteria if all factored bending, shear, tensile, and compressive stresses are below the factored resistance calculated for all sections under consideration.

Water/binder ratio – the ratio of free water to all binding materials comprising Portland cement, complying with Australian Standard AS 3972[1] and all supplementary cementitious materials complying with the applicable parts of AS 3582[2].

Wet-mix Shotcrete – Shotcrete in which all of the ingredients, including the mixing water, are mixed together before being pumped into the delivery line.

1.3 Types of Shotcrete

There are two types of shotcrete process, as described below.

Wet-mix Shotcrete Process

This is a technique in which cement, aggregate, and water are batched and mixed together prior to being delivered into a pump and conveyed through a hose to a nozzle where it is pneumatically projected onto a surface. Compressed air is introduced to the material flow at the nozzle in order to project the material toward the substrate. Wet shotcrete normally incorporates admixtures and may also include fibres.

Dry-mix Shotcrete Process

This is a technique in which cement and aggregates are batched, mixed and delivered into a purpose-made machine wherein the materials are pneumatically conveyed through hoses or pipes to a nozzle where water is introduced to wet the mixture before it is projected pneumatically into place. The shotcrete may also include admixtures or fibres or a combination of both.

Table 1.1 describes the characteristics of the two processes. It is generally accepted that within Australia the majority of shotcrete is applied by the wet–mix method, however certain applications are more suitable for dry-mix (see **Table 1.1**).

Table 1.1 *Comparison of wet-mix and dry-mix processes for various aspects*

Aspect	Wet-mix	Dry-mix
Equipment	Lower maintenance cost. Higher capital cost.	Higher maintenance cost. Lower capital cost.
Mixing	Accurate mixing at batch plant. Can utilise bulk premix. Wet aggregates acceptable.	Mixing at jobsite, at batch plant, or pre-mixed and delivered either in small bags or in large bulk bags. Performance impaired by wet aggregates. Range limited to max 6% moisture content. More labour intensive.
Output	Moderate to high placement rate. Higher than similar dry mix machines (3 to 10 m^3/hr for hand-held nozzle, up to 25 m^3/hr for remotely-controlled shotcreting equipment).	Low to moderate placement rate (1–5 m^3/hr)
Rebound	Low rebound, typically between 5 to 15% depending on mix design and application.	Generally higher rebound than wet (up to 30%) depending on site conditions and applicator.
Dust	Low dust generated.	Notably higher dust generated.
In-place quality	Consistent quality.	Potentially higher variability in placed quality.
Conveyance through delivery hose	Lower transport distance eg max 200 m with special lines and mixes.	High transport distance eg max 500 m with special equipment.
Applications	Better suited to high application volumes.	Better suited to low application volumes and stop/start operations. Suitable for remote & limited access locations where batching and delivery of concrete are difficult.

1.4 Uses for Shotcrete

1.4.1 General

Shotcrete plays an essential part in today's civil construction and mining industries. It is an extremely versatile material that can be easily and rapidly applied to provide a cost-effective means of construction. Shotcrete is an efficient way of placing concrete and forms an excellent bond to a number of substrates including rock, concrete, masonry and steel. It is suited to a wide range of ground-support applications, linings, and building structures **(Figure 1.1)**.

The main advantages of shotcrete over conventionally-placed concrete are:

- Placement and compaction are carried out as one operation.
- Formwork is generally eliminated.
- The process of placement is quicker.

Following application and an initial period of curing and stiffening shotcrete provides early passive support to the ground. As the shotcrete hardens and gains strength, subsequent deformation generates a significant resistance because the shotcrete also becomes rigid. Properly designed and applied shotcrete remains in place without sagging even in vertical wall and overhead applications. It is especially suited to areas with restricted access by the use of small portable or mobile equipment. Shotcrete is either applied using remotely-controlled or hand-operated equipment. Remotely-controlled equipment is generally used in underground applications to allow safe operation by the nozzleman away from the unsupported area. These advantages have resulted in shotcrete being used for a variety of applications, some of which are listed below, grouped in general areas of application.

Figure 1.1 *Shotcrete has many applications in tunnel construction*

1.4.2 Tunnelling

In tunnelling, shotcrete can be used either for the final lining or as temporary support as the tunnel is advanced. Final linings of fibre-reinforced shotcrete can be in the form of a Single Pass Tunnel Lining (SPTL) using a combination of rock bolts, cable bolts, fibre-reinforced shotcrete, and steel arches (where additional support is required). Shotcrete thicknesses can vary from 50 mm to 500 mm, and can be applied in several layers **(Figure 1.2)**. Shotcrete applied as temporary support should be designed to provide early structural support. This can be followed later by a second layer to provide permanent support. The permanent support lining may take the form of shotcrete, precast concrete segments, or cast insitu concrete.

As shotcrete technology has developed and waterproofing systems improved, SPTL has become a significant method of ground support for civil tunnel construction. Refer to **Clauses 2.3** and **2.4** for more discussion on tunnelling. Thin unreinforced shotcrete linings can also be applied to smooth the rock surface and hence reduce resistance to air-flow.

Figure 1.2 *Structural shotcrete in tunnel applied with remotely-controlled manipulator.*

1.4.3 **Caverns**

Underground caverns for storage of commodities and materials such as oil, gas, effluent and nuclear waste have been built with the use of permanent shotcrete linings **(Figure 1.3)** eg The Elgas gas caverns and North Side Storage Tunnel – both in Sydney.

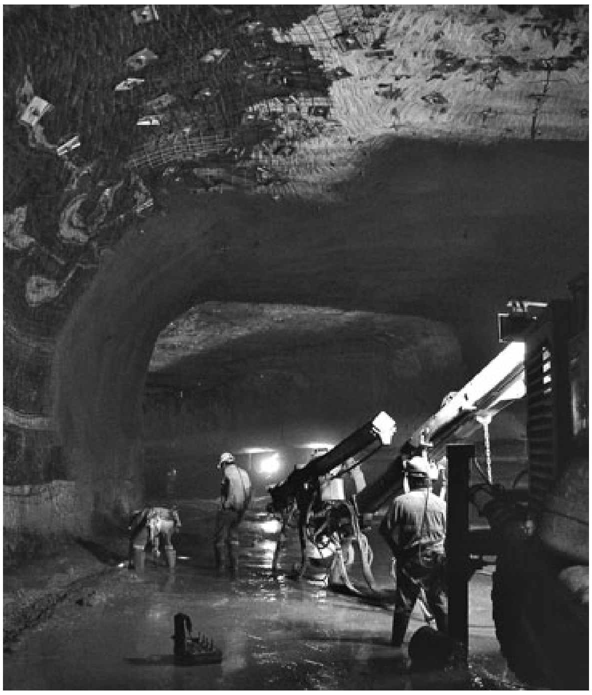


Figure 1.3 *Underground shotcreting in Sydney sandstone*

1.4.4 **Ground Support in Mining**

Mechanised application of shotcrete in Australian mines first occurred in 1994. Initially, shotcrete was applied over installed mesh and bolts in areas of bad ground where mesh alone was inadequate. However, FRS progressively replaced mesh as the preferred method of ground support in underground mines during the 1990's due to the following reasons:

1. The level of ground support achieved with FRS and post-bolting significantly exceeded the level of ground support achieved with bolts and mesh.
2. Increased safety achieved by not exposing personnel to unsupported ground,
3. The speed of mining development improved using shotcrete,
4. The need for rehabilitation of ground support was reduced significantly,
5. The increased availability of mechanised spraying equipment.

One of the key developments that improved the efficiency of using shotcrete for ground support was the move to in-cycle shotcreting. This meant that the shotcrete was applied during the development cycle, after blasting and before the installation of rock bolts. In this way, the use of mesh was not required and the bolts were installed through the shotcrete layer. This method resulted in the bolt plates being installed over the shotcrete layer, providing the optimum connection between the shotcrete layer and the ground.

Installing the shotcrete during the development cycle demanded that the shotcrete achieve early age strength requirements as soon as possible after application to allow the safe re-entry of personnel to continue development. The required early strength has to be determined by the mining engineer on each site but is generally in the order of 1.0 MPa. This can normally be achieved in 3-4 hours after spraying. Test methods are outlined in section 11.4.

Another development that has enhanced the performance of shotcrete in ground support is hydro-scaling. High pressure water washing at pressures between 3000 and 6000 psi has been shown to improve bonding to the substrate by up to 300%. In most cases there is no need for the drilling jumbo to carry out any scaling of the blasted ground. More details on hydro-scaling are contained in section 9.7.2.1.

The performance of the shotcrete layer can be improved by increasing the thickness of the applied layer and/or by increasing the fibre dose. Hence one application system can cope with several different design requirements.

In seismically active areas, some mines are installing mesh over the finished shotcrete layer to provide additional support as un-encased mesh has much greater ductility than encased mesh. Today virtually all underground mines in Australia use shotcrete for ground support. **(Figures 1.4** and **1.5)**

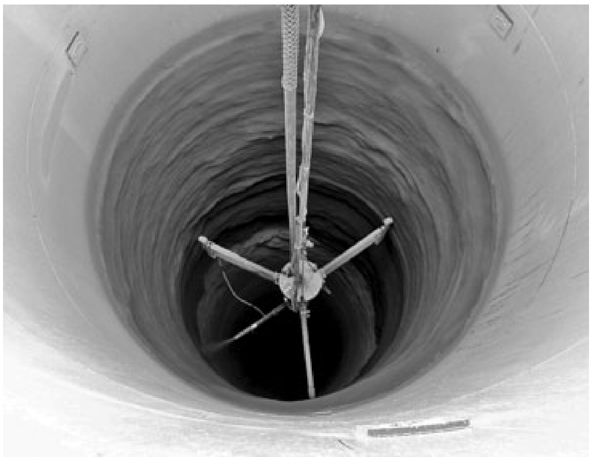


Figure 1.4 *Ventilation shaft sprayed using dry-mix process*

Figure 1.5 *In-cycle shotcreting for rapid excavation of underground tunnels*

1.4.5 **Commercial Buildings**

Shotcrete has a history of application in the construction of buildings. Typical shotcrete applications include underground load bearing elements within multi-storey designs, **Figure 1.6**. Other examples are perimeter and internal load bearing walls to reduce the amount of traditional columns in the structure. Shotcrete has been used as an alternative to cast tilt-up panel construction for portal-framed structures and for aggregate silos, **Figure 1.7**.

Figure 1.6 *Shotcrete applied to loadbearing basement walls*

Figure 1.7 *Aggregate silos constructed from shotcrete*

1.4.6 **Ground Excavation for Basements and Car Parks**

Shotcrete plays an extremely important role in ground support for excavations where ‘boundary to boundary’ or vertical cuts are required. Coupled with soil nails or piles & anchors top down construction is achieved as excavation proceeds delivering the in place permanent basement walls upon conclusion of the excavation to the finished floor level.

1.4.7 **Backfill of subsidence or over excavated surfaces**

Shotcrete can be effectively used to backfill areas of over-excavation or subsidence. Traditional methods such as one sided formwork could require personnel to be exposed to dangerous conditions as well as presenting logistical difficulties for access and construction.

One example is the Shannon Creek Dam spillway walls (completed September 2008) **(Figure 1.8)**. The dam walls were steeply inclined and up to 11m high. The specification for the formed and poured walls was replaced by an alternative shotcrete design. Overbreak was prevalent due to unavoidable ground conditions & challenging excavation angles. Coupled with a double layer of reinforcement this made quality compacted shotcrete application difficult. To solve this, a shotcrete blinding layer was applied to bring the substrate back to line. The reinforcement was then installed and the shotcrete applied and finished with excellent compaction, increased productivity and reduced cost.

Figure 1.8 Shannon Creek Dam spillway walls

1.4.8 **Complex Civil Structures**

Shotcrete is highly suited to structures involving complex geometry, including curved or folded sections. Typical applications include the construction of lightweight roofs, theme parks, zoos, **Figure 1.9**.

Figure 1.9 *Channel surfaces at White Water Facility, Penrith, NSW*

1.4.9 **Channels/Reservoirs & Spillways**

Reservoirs and channels can be constructed by excavating the shape required and shotcreting free-form directly onto the exposed rock or earth. Shotcrete has the ability to be placed, compacted & finished (possibly in one pass) in instances requiring high access, free form or very thick linings. Examples are the Olympic Whitewater Stadium Channel in Sydney and Shannon Creek Dam Spillway in Grafton NSW.

1.4.10 **Embankment Stabilisation**

Shotcrete is widely used for the stabilisation and protection of surface rock and earth. The surface is protected against deterioration by filling in uneven parts and sealing the entire surface. Due to its high shear strength and good bond to rock, shotcrete strengthens loose rock by filling gaps and cracks and thereby prevents loose pieces of rock from falling out. This can prevent progressive surface failure **(Figures 1.10** and **1.11)**. Shotcrete is most effective when used in conjunction with rock or soil anchors.

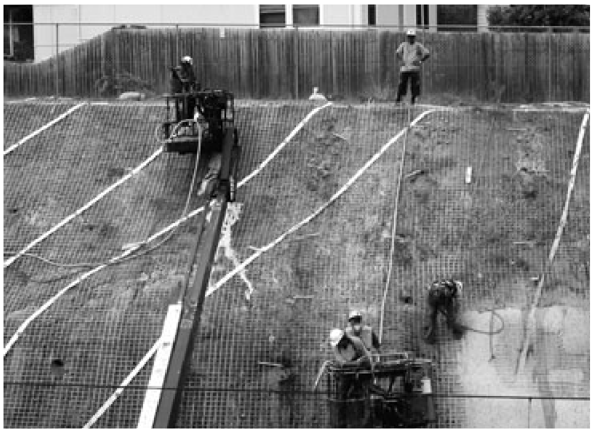


Figure 1.10 *Preparation of embankment for stabilisation by shotcreting*

Figure 1.11 *Application of shotcrete in bank stabilisation*

1.4.11 **Swimming Pools and Skateboard Parks**

These recreational structures are good examples of free-form construction using shotcrete. Both pools and skateboard parks are constructed by excavating a hole in the ground to the required shape, fixing a top board to form the rim, positioning the necessary reinforcement, and shotcreting the structure **(Figure 1.12)**. Constructions of this type are economical, strong, rigid, and durable.

Figure 1.12 *Swimming pool construction with shotcrete*

1.4.12 **Refractories**

Furnaces of all types can be lined or repaired with special blends of shotcrete containing materials such as high-alumina cements and crushed firebricks, which possess enhanced refractory properties. One of the main advantages of refractory shotcrete is that it can be placed quickly and in large volumes in almost inaccessible areas, for example, at height inside chimneys or in remote parts of large furnaces.

1.4.13 **Repair, Restoration, and Strengthening**

Shotcrete can be readily used for the reinstatement of damaged structures. Repair of deteriorated concrete caused by corrosion or spalling, and concrete damaged by fire, are typical applications. Repair and restoration can only take place after the affected areas have been properly identified and prepared. Structures suitable for repair using shotcrete may include bridges, culverts, sewers, dams, towers, ports, buildings, and steel structures **(Figure 1.13)**. Existing concrete structures can be strengthened with shotcrete where construction of the original concrete, for example, may need to be partially cut out and replaced due to honeycombing. Shotcrete can also be used when a structural element needs to be increased in size for the purpose of increasing load capacity. Structural elements that can be strengthened by this means include beams, columns, slabs, masonry walls, tanks, and pipes.

Figure 1.13 *Dry-mix process used for repair of reinforced concrete arch*

1.4.14 **Fire Proofing**

The use of shotcrete as a fireproofing material is common, especially in chemical plants and oil refineries. This process can involve the encasement of steelwork or an increase in thickness of cover concrete using shotcrete. Moreover, shotcrete can be designed to incorporate polypropylene micro fibres to minimise spalling under extreme heat conditions. High temperatures melt the micro fibres allowing water vapour to travel through the voids that were thereby formed and dissipate to the surface, hence minimising internal pressure build up and subsequent spalling.

1.4.15 **Decorative Finishes**

Shotcrete is best suited as a free-form material with an as-placed finish. Smooth surfaces, sharp edges and the like can be provided but they can be costly to produce and rely strongly on site workmanship. Natural-look finishes such as the blocky sandstone of Sydney can also be achieved **(Figure 1.14)**. When finishing coats are applied, they can be sprayed and carved over various existing structures. They can also be coloured to match surrounding areas.

Figure1.14 *Shotcrete finished to resemble native rock*

1.4.16 **Explosion-Proof Structures**

Shotcrete has been used by the military to construct bomb-proof hangars and installations. Many other organisations have used specialised shotcreting materials to construct installations that are designed to withstand explosions, particularly for security-critical buildings or hazardous areas (eg. oil & gas refineries).

1.5 History

The first milestone in the history of shotcrete occurred in **1907** when a machine was invented by Carl Ethan Akeley in the USA (Yoggy[3]). This machine allowed dry materials to be placed pneumatically with the addition of water at the nozzle. In **1910**, a double chambered cement gun, based on the design by Akeley was introduced into the construction industry. “Gunite”, consisting essentially of mortar was used in the USA in the **1920’s** to fireproof mine drifts. The early **1930’s** saw the generic term “shotcrete” introduced by the American Railway Engineering Association to describe the Gunite process. In **1966**, the American Concrete Institute (ACI) adopted the term shotcrete for all pneumatically applied mortar and concrete involving both the dry-mix and the wet-mix processes. The European Union terminology for the same material is *“sprayed concrete”*. In the **1940’s** coarse aggregate (10 mm minus) was introduced into sprayed concrete mixes. The wet shotcrete process was introduced in **1955**. In the late **1960’s** remote-controlled shotcrete equipment was introduced. Steel fibres were first introduced in **1971** in North America, and in **1977** the Norwegians introduced steel fibres in combination with remotely-controlled application on a large scale.

Shotcrete was first reported used in Australia in the mid **1950’s** in such applications as slope stabilisation, refractory linings, etc. Shotcrete was used in several tunnels as part of the Snowy Mountains Hydro Scheme including the Island Bend and Geehi pressure tunnels constructed in the early **1960’s**. Swimming pools were first constructed using shotcrete in the **1960’s**. In **1980**, Sandy Hollow Rail Tunnel in NSW was lined using steel-fibre reinforced wet shotcrete. Prior to **1994**, only a very small amount of dry-spray shotcrete was used in underground mines but still remains prevalent in coal mines. Since then, the increase in the use of wet-mix fibre-reinforced shotcrete has been extremely rapid. In 2008 around 500,000 m^3 was used annually for underground construction in tunnels and mines, and around 300,000 m^3 in civil basements, pools, embankments, etc.

Major infrastructure projects in Australia that have used shotcrete in their construction include Sydney Airport Rail Link, Sydney Eastern Distributor, Melbourne City Link, Vulture St Brisbane, Crafers Tunnel South Australia, Sydney M5 East Motorway, M2 Motorway Sydney, Epping to Chatswood Rail Line, Lane Cove Tunnel, Cross City Tunnel in Sydney, Clem Jones Tunnel, Airport Link Tunnel, Boggo Road Busway Brisbane, Tugun Bypass Queensland, Brunswick to Yelghun Highway NSW, Mount Conjola road Deviation, East Link Project Melbourne, Cronulla Rail line Duplication and Shannon Creek Dam Grafton NSW. Shotcrete has also been widely used to construct swimming pools, facilitate slope stabilisation-retaining structures and for various architectural work **(Figure 1.15)**. Repair and remediation is a relatively small-scale application for shotcrete in Australia.

Figure 1.15 *Shotcrete has been used on many major infrastructure projects throughout Australia*

2

Design Considerations

The overall approach to the design of shotcrete structures resembles the approach used for conventional concrete structures and involves consideration of stability, strength, serviceability, durability, fire resistance and other design requirements.

2.1 Design Considerations for Shotcrete Structures

2.1.1 Design for Stability

Design of shotcrete structures for stability should consider overturning, uplift, buckling, or sliding of the structure as a rigid body. Overturning is primarily relevant to free-standing shotcrete structures (e.g. elevated silos). Uplift (or floatation) is primarily relevant to within-ground structures subject to hydraulic pressure (e.g. empty swimming pools). Sliding is primarily relevant to shotcrete structures subjected to a horizontal load component. Some structures may be subjected to a combination of instabilities such as retaining walls subject to overturning and sliding.

2.1.2 Design for Strength

The intended use of shotcrete will determine the performance requirements that the shotcrete must achieve. This can vary from a full structural support role through to non-loadbearing uses such as a superficial sealing layer or architectural/aesthetic feature. This clause covers design for strength of load bearing shotcrete.

It must be appreciated that interactions between shotcrete and the loads and materials it supports can be very complex and in many cases are presently incapable of being satisfactorily modelled or analysed. For this reason, various simplified analytical methods or empirical approaches to design for strength have been developed. However, the common aim of all design methods is to achieve a load resistance that exceeds the potential imposed load actions by a suitable margin.

The two approaches to strength design are the analytical and the empirical. The analytical approach involves a rationalisation of potential load actions and the corresponding load resistance of the structural system. Either a deterministic or probabilistic approach my be used to the estimation of load and resistance. The empirical approach involves the use of a documented body of past experience relevant to the specific application and prevailing conditions to derive a satisfactory structural system.

In applications involving shotcrete interaction with ground, due to the complexity of structural behaviour and the potentially high level of variability in design parameters, it is good practice to monitor the performance of a shotcrete-based structural system until satisfactory performance has been confirmed. Where adhesion to the substrate is required as part of a structural system, the potential for loss of adhesion is reduced by suitable substrate preparation and by limiting shrinkage and creep. In general it is not recommended that adhesion between shotcrete and a substrate consisting of either hard or soft ground be relied upon in the long term for structural capacity. A long-term connection between lining and substrate can be provided separately through the use of anchoring systems.

It cannot be emphasised too strongly that where shotcrete is to be used for structural purposes the aid of a competent and qualified engineer who is experienced in this type of work should be engaged to carry out the necessary structural design. For the purposes of structural design in civil applications, codes such as AS3600[4] can be relied upon for Ultimate Limit State (ULS) calculations when designing structures comprised of plain shotcrete or shotcrete reinforced with conventional bar reinforcement. When fibres are used as reinforcement then a structural analysis incorporating post-crack residual strengths at appropriate levels of deflection is recommended. Substantial deflections must be assumed at the ULS to account for extreme events hence the toughness of FRS must be considered at large crack widths (>2 mm). Performance data for FRS is obtained from tests as described in Section 11.

2.1.3 Design for Serviceability

Serviceability describes the ability of a structure to remain suitable for its intended purpose over its design life. In conjunction with considerations of load resistance, the design of shotcrete structures may have to satisfy serviceability criteria such as limits on deflections and crack widths. Other serviceability criteria commonly applied to shotcrete structures include water-tightness, creep deformation, appearance, surface finish, and abrasion resistance. Deflections and crack widths assumed for Serviceability Limit State (SLS) design are generally much smaller than assumed for the ULS. Acceptable crack widths are generally taken to be no more than 0.3 mm in non-aggressive environments (AS3600).

2.1.4 Design for Fire Resistance

Certain applications for shotcrete may include requirements stipulated in the Building Code of Australia, or by the client, for resistance to fire over a prescribed minimum period of time. This requirement typically takes the form of resistance to critical loss of strength, serviceability, or the transmission of heat and/or smoke.

2.1.5 Design for Durability

Durability describes the ability of a structure to resist the environmental exposure conditions likely to occur during its intended life without the need for undue maintenance. These environmental exposure conditions may include chemical attack of the concrete matrix and corrosion of the reinforcement. Durability requirements for the shotcrete matrix are generally satisfied by controlling the mix design of the concrete matrix through such measures as limiting the maximum w/c ratio or limiting the total content of calcium aluminate depending on the exposure conditions expected (see AS3600). Durability requirements for steel reinforcement are normally satisfied by limiting in-service crack widths to 0.3 mm and ensuring the concrete matrix meets AS3600 requirements for the appropriate exposure class. Maximum acceptable in-service crack widths for shotcrete reinforced with synthetic reinforcement may be much larger than is appropriate for steel reinforcement.

2.1.6 Design for Other Requirements

Certain applications may require consideration of other criteria not included in the above categories, such as operational and environmental requirements. Examples include remoteness of site, restrictions on operational hours, or weather extremes.

2.1.7 Additional Design Considerations for the Shotcrete Matrix

The principal design criteria for the shotcrete matrix are considered above. Less commonly considered design criteria can include density, elastic modulus, abrasion resistance, and fire resistance.

Careful consideration should be given to the fact that all properties of the shotcrete matrix are interdependent and certain performance requirements may be incompatible. Examples include low density with high strength, and high cement content with low drying shrinkage.

2.2 Design Considerations for Reinforcement

2.2.1 General

There are three approaches to reinforcement used in shotcrete structures:

- Unreinforced,
- Conventionally-reinforced with mesh or bars,
- Fibre-reinforced.

2.2.2 Unreinforced Shotcrete

In applications involving exclusively compressive load actions, or no load actions, it may be appropriate to avoid the use of reinforcement. Such structural systems will exhibit very low tensile strength and ductility and thus the potential development of tensile load actions must be avoided.

2.2.3 Conventional Reinforcement

Conventional reinforcement comprises continuous elements such as steel bars, mesh, and welded wire fabric, post-tensioned strands, and materials such as fibre-reinforced plastic composite bars or mesh. Provided effective encapsulation of the reinforcement with shotcrete of suitable quality is achieved, conventionally-reinforced shotcrete elements can be designed in accordance with AS 3600.

To ensure effective encapsulation is achieved, appropriate detailing and fixing of reinforcement, and correct shotcrete placement technique, are crucial.

It is recommended that the minimum bar spacing be 100 mm and staggered laps be considered to make effective encapsulation of bars with shotcrete achievable. In North America ACI 506R suggests that lapped bars be spaced apart a distance of at least three bar diameters of the largest bar. In Australia the convention is that the minimum distance between pairs of lapped bars is three times the maximum aggregate size. The incorporation of more than one layer of reinforcement per application of fresh shotcrete can make it difficult to achieve effective encapsulation without proper preparation, application and shotcrete design, **Figure 2.1**.

Figure 2.1 *Shotcreting through multiple layers of steel reinforcement makes it difficult to achieve effective encapsulation without proper preparation, application and shotcrete design*

Rock bolts often introduce a large point load to a shotcrete lining that needs to be anchored to the lining using reinforcement. These forces can be distributed into the lining more effectively if a suitable rock bolt plate or series of radiating reinforcement bars (sometimes called a 'spider') are used at the end of the bolt. The spider should always be buried within a fibre reinforced shotcrete lining. The plate should be external to the structural layer of shotcrete to be effective and may be covered with non-structural shotcrete.

It is recognised that lattice girders used in underground construction often have reinforcing bars of diameter greater than 16 mm. However, these girders are purpose-designed to permit full encapsulation with shotcrete.

Figure 2.2 *Hooked-end steel fibres may be glued together when packaged to reduce the balling tendency*

Figure 2.3 *Some types of steel fibre, such as these flattened-end fibres are packaged in loose form*

Figure 2.4 *Macro-synthetic fibres*

2.2.4 Fibre Reinforcement

Fibre reinforcement comprises short discrete elements distributed uniformly through the body of the shotcrete (**Figure 2.4**). The individual fibres are typically made of either steel or polymers, although specialist applications have used Alkali Resistant glass or cellulose. Fibres can be introduced to shotcrete for reasons other than structural reinforcement, such as control of rebound and plastic shrinkage, and enhancing fire resistance.

The structural role of fibre reinforcement in shotcrete is to provide toughness (post-crack load capacity). They are not included to increase the tensile or flexural strength of the uncracked concrete matrix. Toughness describes the ability of fibre-reinforced shotcrete to sustain and potentially redistribute load actions after cracking. In deterministic design, the shotcrete structural system is ideally designed not to crack. However, due to the complexity and indeterminate nature of some structural systems, especially when ground-support is involved, there remains the potential for an underestimation of load actions for which post-crack load capacity is crucial to maintaining overall safety and serviceability.

Toughness is quantified in terms of post-crack load-carrying capacity or energy absorption, which is assessed using beam or panel test specimens. Measures of post-crack load capacity derived from beam and panel specimens are used to quantify the ability of a cracked fibre reinforced shotcrete structural system to support load actions.

Guidance on a toughness value to specify for mining applications can be obtained from various geotechnical design tools, as referenced in **Clauses 2.4, 3.5, & 11.6.**

2.3 Design Considerations for Civil Underground Applications

2.3.1 Applied Loads

A precursor to the design of shotcrete is the determination of the acting loads. These are typically determined using the method developed by Terzaghi[5] for wedge analysis or using specialist computer based finite element analyses. In fractured ground, load determination is often modelled using idealised shapes and masses of unstable ground acting as a distributed load on the lining[6].

2.3.2 Design for Stability

Design for structural stability in civil tunnels is typically not a governing factor. However, if members as a whole, or parts thereof, are subject to instability due to overturning, uplift and sliding, they are to be designed in accordance with Australian Standard AS 3600. Stability of an excavated opening is, however, the major concern and is addressed by the following clauses.

2.3.3 Design for Strength

The structure and its components should be designed for strength. Load actions should be determined using AS 3600 for conventionally-reinforced shotcrete and/or other relevant codes of practice and guidelines available for the design of unreinforced and fibre-reinforced shotcrete, for example the DBV German Concrete Society[7] or Barrett & McCreath[6]. Design for shear in shotcrete should be in accordance with AS 3600 although it must be acknowledged that the conventional relation between shear and compressive strength, as outlined in AS 3600, is only relevant for shotcrete with a compressive strength greater than 10 MPa. When the compressive strength of shotcrete is less than 10 MPa the mean shear strength is given by the relationship described by Bernard[8] rather than values obtained by extrapolation of the conventional relation described in AS3600.

Several documents exist that provide guidance on the design of shotcrete linings in a variety of ground conditions. These include guides by AFTES[9] and ICE[10] for thick-shell shotcrete linings in soft ground, and ACI SP57[11] for refractory linings. RILEM TC162[12] provides some assistance on structural properties of FRS but the tests involved are seldom used. Additional information on shotcrete lining design is provided by John & Mattle[13], Hoek et al [14], the BTS [15], and Windsor[16].

Testing for strength should be carried out in accordance with **Clause 11.3** Compressive Strength, **Clause 11.5** Flexural Strength and **Clause 11.6** Toughness, as required.

Adhesion should not be relied upon for structural support in the long term. If the structure relies on adhesion between the shotcrete and the substrate in the short term, the design should specify the minimum requirements for adhesion. Testing for adhesion should be carried out in accordance with **Clause 11.14**.

2.3.4 **Design for Geotechnical Parameters**

A geotechnical consultant or engineer should assess the influence of any measured or predicted stress, structure, joint characteristics, and predicted displacements or deformations over time. Excavation profile and size can affect the shotcrete specifications such as strength and thickness. Examples of design tools that use geotechnical inputs include:

- Q-system (Grimstad & Barton[17])
- RMR system (Bieniawski[18])
- New Austrian Tunnelling Method (NATM)
- Ground Characteristics Curve Method (Brady and Brown[19])
- Numerical modelling

2.3.5 **Design for Serviceability**

The underground structure and its component members should be designed for serviceability by controlling or limiting deflections, cracking, and vibration as appropriate. Design for serviceability should also consider the control of underground and surface settlements within acceptable limits as specified by the project requirements. Other limits may also have to be applied to the shotcrete for surface finish or decorative requirements and waterproofing.

2.3.6 **Design for Durability**

The structure should be designed for durability as defined by the project requirements. Durability may comprise many complex interactions of elements of the structure and the environment it inhabits and these issues may have to be addressed in conjunction with a suitably-qualified expert. Typical issues that influence design for durability include the specified design life (e.g. 20, 50, or 100 years) and exposure to the atmosphere and environment (e.g. involving groundwater chemistry, freeze/thaw conditions, contaminated ground, stray currents, etc.). Specialist texts and consultants familiar with issues of concrete durability and corrosion of reinforcement should be consulted to develop suitable designs when shotcrete structures are expected to encounter aggressive exposure conditions (such as coastal defences).

Figure 2.5 *Shotcrete used in coastal defences must have durability considered in design*

2.3.7 **Design for Fire Resistance**

The structure and its components should, if required, be designed for fire resistance. When appropriate, fire tests may have to be carried out to verify that the nominated fire-resistance level will be achieved. The CSIRO laboratory at North Ryde, Sydney, is presently the only facility in Australia where fire tests can be performed.

2.3.8 **Other Design Requirements**

Special project requirements should be considered as they may affect the characteristics of the shotcrete required. Typical issues that may arise in a civil underground environment include, but are not limited to, restrictions relating to construction hours and provisions for support and embedment for mechanical and electrical fixings.

2.4 Design Considerations for Mining

2.4.1 Design for Strength and Stability

Geotechnical Parameters

The mining industry has traditionally used empirical methods supported by some form of rock-mass classification to design ground support systems. Rock-mass classification systems have been used to group areas of similar geomechanical characteristics, to provide guidelines for stability performance and to select appropriate support. Examples of commonly used systems are:

- Q-system (Grimstad & Barton[17])
- RMR system (Bieniawski[18])
- New Austrian Tunnelling Method (NATM)
- Ground Characteristics Curve Method (Brady and Brown 1985)[19]

Both the Q and RMR classification systems are based on a rating of three principal properties of a rock mass:

- The intact rock strength,
- The frictional properties of discontinuities, and
- The geometry of intact blocks of rock defined by the discontinuities.

The Q system of rock-mass classification was developed for tunnel support in hard rock by Barton et al[20] and is based on a numerical assessment of the rock mass quality using six parameters:

RQD	Rock Quality Designation
Jn	Joint set Number
Jr	Joint Roughness number
Ja	Joint Alteration number
Jw	Joint Water reduction factor
SRF	Stress Reduction Factor

The main advantage of the Q classification system is that it is relatively sensitive to minor variations in rock properties. The descriptions used to assess joint conditions are relatively rigorous and leave less room for subjectivity, compared to other rock-mass classification systems. One disadvantage of the Q system is that it is relatively difficult for inexperienced users to apply (Milne et al[21]).

The use of the Q system for the design of support has also evolved over time. In particular, Grimstad & Barton[17] has introduced a design chart that accounts for the use of fibre-reinforced shotcrete. This is shown in **Figure 2.6.**

Mine design for support with shotcrete tends to differ from tunnel design approaches as the excavation's orientation, depth and stress conditions can vary throughout an underground mine and over the life of the operation. Due to this variance, it is recommended that a geotechnical consultant or engineer should assess the influence of any measured or estimated stress, structure, joint characteristics, and predicted displacements or deformations on the shotcrete over time. Tunnel profile and size can also affect the shotcrete specifications such as strength and thickness. The requirement for shotcrete or other surface control methods must be determined by a geotechnical or otherwise suitably experienced engineer.

Substrate Preparation

Shotcrete performance can be significantly affected by the quality of substrate preparation. Broad considerations are surface cleanliness, water flow, joint infill material, etc. Refer to **Clause 9.5** for Substrate Preparation.

Interaction with other ground support elements

When designing the shotcrete, possible interaction with other support elements such as rock bolts, mesh, bars, straps, arches, and plates must be considered. A geotechnical consultant or engineer should examine and specify these requirements.

2.4.2 Design for Serviceability

Ground water flows

Excessive ground water flows can affect the shotcrete bond to the substrate and the ultimate performance due to excessive water pressure build up behind the shotcrete. Refer to **Clause 5.7.2.2** for suggested techniques to mitigate the risks associated with ground water.

Surface Finish Requirements

A smooth finish may be required for aesthetic reasons, to lower surface roughness and abrasiveness, or to improve ventilation & improve fluid flow. Smooth finishes may also be specified for safety purposes in workshops, car parks, crib rooms or areas where humans or machinery may come into contact. Examples include tunnels requiring water-proof linings incorporating sheet membranes.

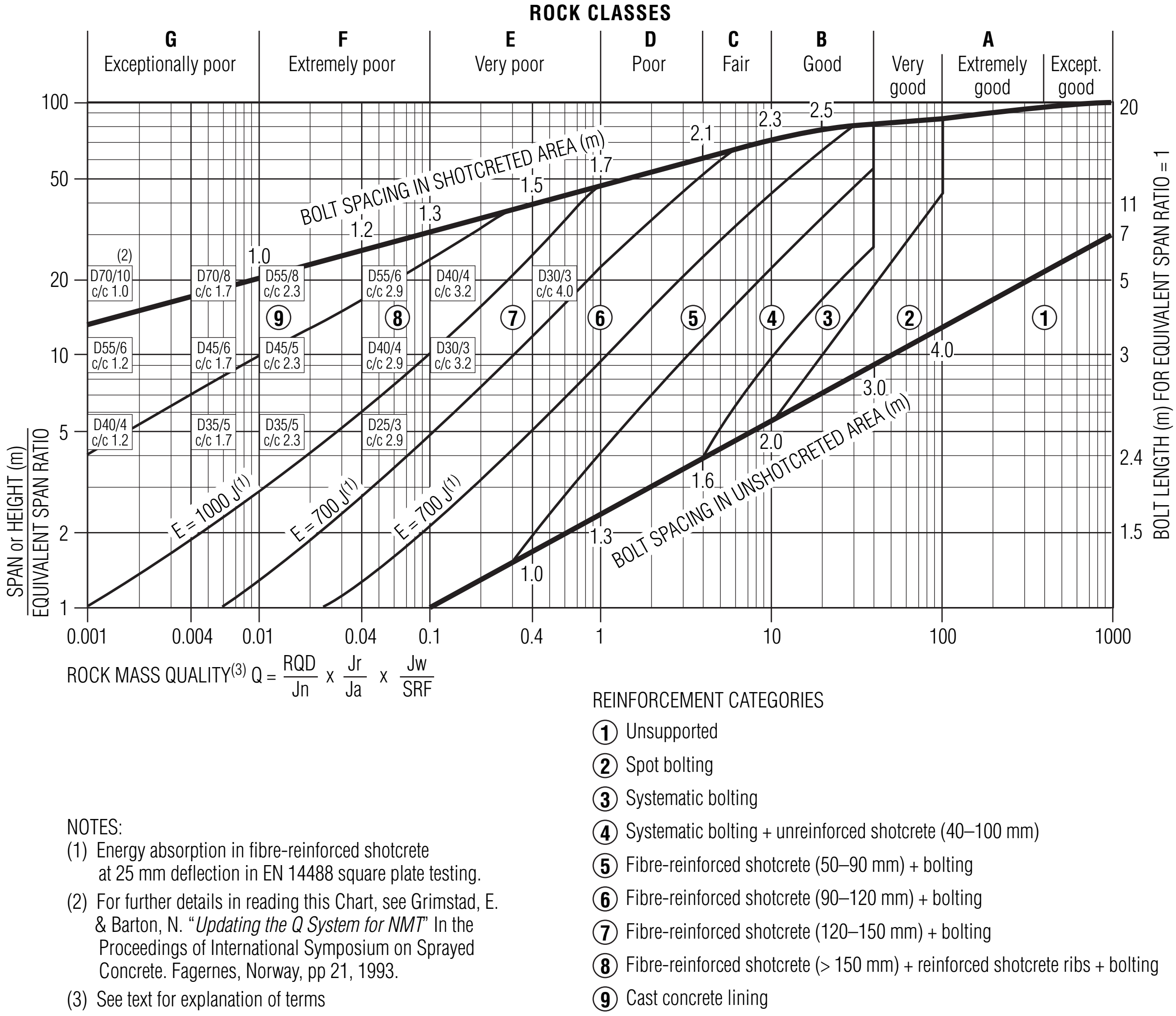


Figure 2.6 *Estimated support categories based on the Tunneling Quality Index, Q (after Grimstad & Barton[17])*

2.4.3 **Design for Durability**

Excavation Life Expectancy

The shotcrete design must consider the required longevity of use in the tunnel, chamber, shaft, ore pass, or other excavation.

Abrasion

In applications where the shotcrete is subjected to wear and tear from rock flows, the abrasion and impact resistant properties may need to be enhanced through the use of higher-toughness shotcrete or through the addition of specialised materials such as corundum.

Temperature and Humidity

Basements, mines and tunnels can have very dry environments with high airflows and temperatures that can cause plastic and/or drying shrinkage cracking. This factor should be evaluated in the design and consideration given to curing. Refer to **Clause 9.5.6** and **Clause 9.6.5**.

Embrittlement

The toughness of FRS changes with age and, under certain circumstances (particularly for a very strong concrete matrix and at large deflections), may fall as the concrete matures (Bernard[22]). For example, toughness sustained at 28 days may not necessarily be retained at later ages. It is therefore necessary to consider the degree of deformation likely to be suffered by a FRS lining at later ages when selecting the type and dosage rate of fibre used as reinforcement. The most severe loading placed on a FRS lining will not necessarily be encountered at early ages.

2.4.4 **Other Design Factors**

Fire Resistance

Fire resistance is generally not considered in shotcrete specifications for mine applications.

Tunnel – Profile and Size

Tunnel profile and size can affect application methods and equipment.

Re-entry time

If the re-entry time is critical to the speed of development, then shotcrete may be applied 'in cycle'. In-cycle shotcrete is defined as the immediate application of shotcrete once a face has been excavated and prior to excavation of the next section, **Figure 2.7.** Refer to **Clause 4.5** and **Chapter 5** for details of admixtures and mix design, which influence early age strength and thus re-entry time.

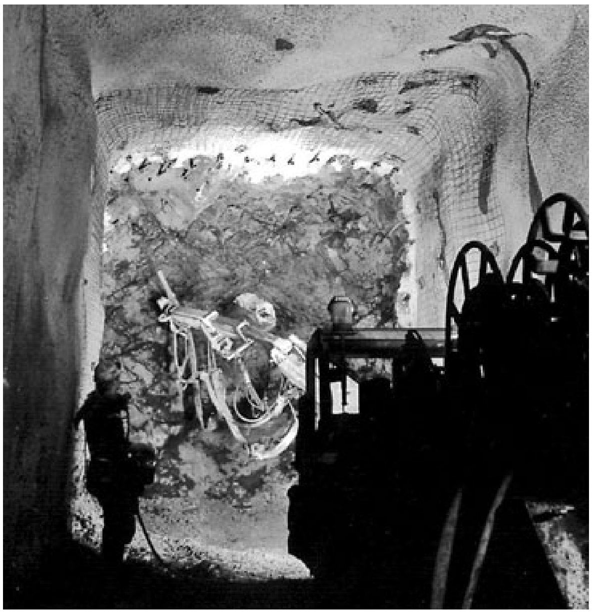


Figure 2.7 *In-cycle shotcrete example*

Raw Material Availability

Consideration should be given to use of available waste materials such as sand, tailings and rock for aggregates provided they can achieve the desired design parameters. Availability and choice of cements, supplementary cementitious materials, admixtures, aggregates, and sands can affect the mix design and performance. Refer to Chapter 4 on constituents and Chapter 5 on mix design. Appropriate storage and availability of raw materials must be considered e.g. aggregate storage bins, moisture contents, weather protection etc.

Delivery

The delivery time from the batch plant and delivery method, e.g. slick line or concrete agitator, could affect the quality and ultimate performance of the shotcrete. It may be possible to mitigate this with appropriate mix design parameters and admixtures (refer to **Chapter 4**). Interaction with other activities must be considered and the use of underground batch plants may provide a suitable alternative to surface plants.

Testing

In specifying certain testing of the shotcrete the user should consider the type and frequency of testing in relation to the importance of the opening and availability of test facilities due to specific limitations as remoteness. This may lead the designer to a more conservative design approach. This will affect the testing specifications (refer to **Clause 10.3**). Consideration of systems for ongoing monitoring may be required for long-term openings or excavations predicted to be subjected to large displacements.

3

Material Properties

The properties of shotcrete may be specified and measured using the following parameters.

3.1 **Slump**

The property of slump is measured using the slump test and is the subsidence that occurs to plastic concrete that has been placed in a standard metal cone after the metal cone has been lifted vertically away from the concrete. Slump is a quantity that in normal concreting practice is used as an approximate indicator of workability. For shotcrete this parameter should not be used as an indicator of pumpability or sprayability. *The slump of a mix is primarily of use in indicating the consistency of mix proportions from batch to batch*. The absolute magnitude of slump required for a given shotcrete mix is not a reliable indicator of the overall quality or suitability of a mix for shotcreting. Slump is measured prior to application using the standard slump test in accordance with Australian Standard AS1012 Part 3.1[23]. **Clause 11.2** describes the method to be used for measuring slump.

The magnitude of slump required for a particular shotcreting application will depend on the characteristics of the project. In general, lower slump mixes (60–80 mm) are more suited to applications in which set accelerators are not used, and higher slump mixes (80–180 mm) are more suited to applications in which set accelerators are used. If set accelerators are used, then the slump should be optimised for operational requirements. For example, the slump may be selected to minimise pump pressure and pulsations in the line, optimize the dispersion of set accelerator into the concrete stream, or ensure that the concrete sticks to the substrate and does not sag or fall off.

The slump of a mix will be reduced through the addition of fibres. Thus, the fall in slump that will normally occur as a result of the addition of fibres will not necessarily indicate a reduction in the overall performance of the mix in relation to placing characteristics. The slump of a mix will be affected by the ambient temperature, age of mix after batching, aggregate gradation (especially the percentage of fines and silt present in the materials) and admixtures included in the mix. Slump can be adjusted to suit operational requirements by adding water reducers or superplasticiser without reducing the 28-day strength of the shotcrete.

3.2 **Compressive Strength**

The primary material property specified for plain shotcrete is compressive strength. Compressive strength is the resistance provided by a material to an axially applied crushing force. The unconfined compressive strength (UCS) of hardened shotcrete is one of many indicators of the quality of the concrete. *The UCS should be used as an indicator of the compressive strength of a mix once hardened, and it can be used as an indirect measure of other mechanical properties of a mix*. The UCS is only indirectly related to other performance measures such as level of compaction, toughness, permeability, and durability, and therefore should not be taken as a singular guide to the quality of a mix.

It is important to distinguish between the compressive strength of shotcrete as supplied compared to its performance in compression in-place. The strength of a mix as supplied can be affected by many variables during the placing process such as temperature, addition of set accelerators, poor spraying and compaction, and inadequate curing. The design strength of shotcrete should be based on the in-place performance of a mix as sprayed, and cores drilled from the insitu concrete are the most appropriate measure of this property. However, cores drilled from a structure require repair and thus cores drilled from a production test panel is a suitable substitute. The compressive strength of shotcrete as sprayed should never be determined by spraying shotcrete into cylinder moulds because of excessive collection of rebound within the moulds. The compressive strength of shotcrete as-supplied is best measured using cast cylinders that incorporate concrete sampled directly as supplied (for example, from the delivery chute of the truck-mounted mobile mixer).

The magnitude of the change in performance of a mix between the as-cast and as-sprayed conditions is an issue that must be considered in design and should ordinarily be determined through pre-construction trials. Excessive changes in the relation between the magnitude of the compressive strength as-sprayed compared to as-supplied (that is, greater than 20% fall) may be a possible indicator of adverse impacts on overall quality caused by, for example, poor spraying technique or curing conditions. An allowance of 20% is usually made for the difference between a standard test cylinder cast from the shotcrete mix and a core taken from a test panel sprayed using the same mix. This takes into account the difference between the standard methods of testing cylinders and testing cores. It also allows for the effect of the shotcrete accelerator on the mix. For instance if a specification of 32 MPa is required for the structure in situ, then it is usual to specify a cylinder strength of 40 MPa for the concrete as delivered. Similarly, a specified insitu strength of 40 MPa would require a cylinder strength of 48 MPa for the concrete as delivered. In non-accelerated shotcrete the difference in compressive strength between the concrete as delivered and as sprayed will be less than for accelerated shotcrete. The compressive strength of shotcrete as sprayed should be determined by spraying a large panel and extracting cores when it has hardened. Refer **Clause 11.3** for test methods.

No assumptions should be made about the relationship between the strength of cast cylinders representing shotcrete as supplied and cores representing shotcrete as sprayed. If such a relationship is required then it should be developed by conducting tests on cast cylinders using shotcrete as supplied and cores representing shotcrete as sprayed. The unconfined compressive strength of cores extracted from in-place shotcrete should be taken to represent the compressive strength of the in-place shotcrete without alteration except for the aspect ratio of the core.

The compressive strength of hardened shotcrete is highly dependent on the water/cementitious content ratio. The water/cementitious content ratio for wet-mix shotcrete normally ranges from 0.4 for civil and underground application to as much as 0.65 for swimming pools. Ratios in the order of 0.35 can be readily achieved through the use of High-Range Water Reducers. The water/cementitious content ratio is within the range 0.3 to 0.5 for dry-mix shotcrete but can vary widely due to uncertain control by the sprayer. For wet-mix shotcrete, compressive strengths (without accelerator) can range between 20 and 70 MPa at 28 days. Infrastructure projects normally specify a minimum strength of 40 MPa at 28 days to be included in the works. Refer to **Table 3.1** for typical strengths encountered in various applications.

Table 3.1 *Typical Insitu UCS ranges for recent australian projects*

Application	Typical strength range
Swimming Pools	25–32 MPa
Basements/Cellars	32–40 MPa
Tunnel linings	40–50 MPa

3.3 Early-Age Strength

Shotcrete for ground support is often required to reach a minimum strength at an early age – often within the first few hours after spraying. Early-age strength is the strength of the shotcrete required at a time earlier than the conventional 28 days specified for normal concrete supply. Cores and cylinders are often inadequate for the task of determining early-age strength. For this reason various indirect methods have been devised for the purpose of testing the early-age strength. An example is a penetrometer which is used by pushing a probe or needle into a freshly-sprayed test surface that is located nearby but away from unsupported ground. Care should be taken to calibrate the penetrometer readings with actual compressive strength values. Four of the available indirect test methods for estimation of early-age compressive strength are described in **Clause 11.4**.

3.4 Flexural Strength

Shotcrete is loaded in flexure in the majority of applications in Australia, for example, in swimming pools, slope stabilisation linings, and tunnel linings. Flexural strength is the strength of a member in bending. If flexural performance is important, it is more appropriate to directly measure the flexural strength of shotcrete and use this for design purposes rather than estimate the flexural performance of the material based on assumed relationships between flexural strength and compressive strength.

The flexural strength of the concrete matrix is also known as the Modulus of Rupture (MOR) and is the theoretical maximum stress reached in the extreme tensile fibre of a test beam at the point of cracking under point loading conditions. This stress is determined on the basis of an elastic distribution of stress through the cross section of the beam.

The magnitude of the flexural strength of shotcrete is usually about 7 to 15% of the compressive strength for both wet and dry mix and can increase with age. The flexural strength is typically measured using a third-point loaded beam and is based on the load at first crack (see **Clause 11.5**). Load capacity beyond first crack is associated with reinforcement and can be measured using toughness tests. If toughness is required because of post-crack load-carrying requirements then a specification for flexural strength may not be necessary.

3.5 Toughness

Toughness is a measure of the post-crack load carrying capacity of fibre reinforced shotcrete. It is an important property where post-crack displacement and deformation are expected. Toughness can be assessed in terms of either the residual load capacity or energy-absorption capacity, typically between the onset of loading and a specified deflection in a beam or panel test and is determined as the area under the load-deflection plot for the test specimen. It is a property that is primarily affected by fibre design and content but can also be strongly influenced by the strength and quality of the shotcrete matrix. The units of measure are Joules (Nm or kNmm).

In Australia and North America the round panel test, as described in ASTM C-1550[24], has become the more common test method for measuring the toughness of fibre-reinforced shotcrete. In other parts of the world, particularly Western Europe, the Euronorm EN 14488-3[25] beam or Euronorm EN 14488-5[25] panel test methods are predominantly used (previously known as the EFNARC beam and panel tests). There is evidence that useful correlations exist between toughness values developed using the various test methods within the range of toughness values normally specified (Bernard[26], Bernard[27]) provided the thickness of the specimens is the same.

The "Q" Rock Quality system commonly used for empirical determination of ground support was updated in 2002 to include EN 14488-5 panel toughness values for fibre-reinforced shotcrete used in ground support linings.(Grimstad and Barton[17]).

Toughness values required for a project depend on the requirements of the application; the values and appropriate test method should be specified by the engineer or geotechnical expert.

In mining applications where significant deflections and crack widths are not only permitted but sometimes seen as a reasonable indication of the economic suitability of the support system, it is common practice to specify performance in terms of toughness determined from panel tests. Conversely, in civil engineering applications, because of the need to keep crack widths to a minimum for long-term durability, the design stress values need to be determined at the relatively low crack widths used in standard beam tests. Typically specified minimum values for toughness in mining applications are listed in **Table 3.2** and civil applications in **Table 3.3**.

Table 3.2 *Typical toughness values specified in recent Australian mining projects*

Type of support	Specified toughness[1]
Non-structural or low deformation	280 Joules
Moderate ground support	360 Joules
High-level ground support	450 Joules

NOTES: [1] 40 mm deflection in ASTM C-1550

Table 3.3 *Typical toughness values specified in recent Australian civil projects*

Deformation	Specified toughness
Small	3 MPa residual flexural strength[1]
Large	400 Joules[2]

NOTES: [1] 3 mm deflection in EN 14488-3 beam, but actual values must depend on engineering analysis.
[2] 40 mm deflection in ASTM C-1550 to support localised ground instability.

3.6 Density (Mass/unit Volume)

The density (mass/unit volume) of good-quality normal-weight shotcrete is typically between 2200 and 2400 kg/m3. However, density is not a good indicator of compaction unless a history for the particular mix design is available. Variations will occur as a result of changes in mix design, selection of source rocks such as basalt, dolerite, or similar high-density rocks to produce aggregates, and changes in compaction. The relative density of in-place shotcrete compared to the cast shotcrete as supplied provides an indication of application quality and should be greater than 98%.

The effect of inadequate compaction of shotcrete can be a significant reduction in compressive and flexural strength (approximately 4% for each 1% void content). Inadequate compaction can be measured as a reduction in in-place density compared to density as supplied when measured in accordance with AS 1012[23].

3.7 Modulus of Elasticity

The Modulus of Elasticity (E_C), often referred to as Young's Modulus, is a measure of the mechanical rigidity of shotcrete. The Modulus of Elasticity generally falls between 25-30 GPa at an age of 1 year.

Accelerated shotcrete is generally less stiff than non-accelerated shotcrete. The Modulus of Elasticity is affected by the type of coarse aggregate used in a mix, but is difficult to control and therefore is rarely specified in shotcrete applications.

3.8 Drying Shrinkage

The unrestrained drying shrinkage of a material is the extent to which the material decreases in length over a linear dimension when the moisture content of the material is reduced. The restrained drying shrinkage of a material will be less than the unrestrained drying shrinkage but the relation between the two parameters is complex. The drying shrinkage of shotcrete varies with water content, aggregate type and size, and mix proportions, but generally falls within the range 800–1200 microstrain at 56 days when tested in accordance with AS 1012.13. This is higher than most low-slump conventional-cast concrete because of the higher cement content and comparatively low coarse aggregate fractions required for pumpability and sprayability. The relatively high drying shrinkage experienced by shotcrete may require a closer control-joint spacing.

3.9 Creep

Creep is the time-dependent deformation of a material under load. The creep strain suffered by a material is commonly expressed as a multiple of the short-term strain suffered as a result of elastic deformation. This multiplier is termed the 'creep coefficient'. For concrete, creep in compression can be measured using AS 1012.16. The creep of shotcrete in flexure is not necessarily related to the creep of the same material in compression, especially after cracking has occurred. A limited amount of information is available on the rate of creep of fibre-reinforced shotcrete in flexure after cracking (Bernard[28]; McKay & Trottier[29])

For a well designed shotcrete mix with a low water-cementitious ratio, a magnitude of creep strain similar to those exhibited by high–quality cast concrete can be expected. When the water content is high the creep strain suffered under a given level of stress will be higher. The creep coefficient of cast concrete in compression can be estimated using AS 3600. The creep coefficient of shotcrete will be higher than that of cast concrete due to the higher paste content.

3.10 Coefficient of Thermal Expansion

The coefficient of thermal expansion is the rate at which shotcrete expands or contracts as temperature increases or decreases. A value of the coefficient of thermal expansion is generally required for crack control calculations, in particular for high-temperature applications (ie. refractory linings).

An estimate of 11 µstrain/C is usually adopted, although for both shotcrete and conventional concrete the coefficient of thermal expansion appears to vary directly with the coefficient of thermal expansion of the coarse aggregate which depends on the silica content (the greater the silica content the greater the coefficient of thermal expansion of the aggregate, Neville[30]).

3.11 Durability

3.11.1 General

The term durability describes the ability of shotcrete to resist aggressive influences within the service environment that it is exposed to. The aggressive influences may include climate, extremes of temperature, seawater, chemical contact, or impact and abrasion. Shotcrete can exhibit durability comparable to conventional cast concrete, thus most durability considerations and tests that apply to conventional concrete also apply to shotcrete.

The use of high doses of set accelerator in shotcrete can be detrimental to durability if not accounted for in mix design, but may reduce the effects of freeze thaw. The resistance of dry-process shotcrete to freeze/thaw can be greater than that of wet-process shotcrete provided water/cementitious content levels are maintained at low levels. Incorporating an air-entraining agent into wet-process shotcrete can reduce this performance difference, but a significant amount of entrained air present during mixing will be lost in the process of spraying (eg. 18% initial air content reduced to 6% in-place air content following spraying, Beaupre et al.[31]).

3.11.2 **Chloride and Sulfate Content**

Chlorides may be present in the shotcrete as supplied if they have been incorporated into the mix through the use of contaminated aggregate, seawater, brackish water, or by admixtures containing chlorides. The main concerns due to the presence of chloride ions in shotcrete are the adverse effects on corrosion of steel reinforcement and increased drying shrinkage.

An excessive level of sulfates may be present in shotcrete as supplied due to the composition of the ingredients (ie. the cement, aggregate, admixtures and water). The most frequent adverse effects on shotcrete due to the presence of excessive sulfates are on its soundness, setting times, and later-age strengths.

3.11.3 **Water Penetration Through Bulk Shotcrete**

The permeability of concrete is a measure of its resistance to the passage of gases or liquids. Unfortunately, permeability is difficult to measure directly, hence parameters like the depth of penetration of water through a sample of concrete after a given period of exposure are used to indicate relative permeability. The penetration depth of water through shotcrete included in the works can be determined in accordance with DIN 1048 Part 5[32]. The maximum allowable penetration depth for various exposure conditions can vary between 25 and 30 mm, but it must be considered that the normal variability in this parameter for well-prepared samples is about 15–20 mm depth of penetration.

3.11.4 **Water Absorptivity and Compaction Testing**

Absorptivity of concrete is the measure of the amount of water (or other liquid) which the concrete will ‘soak up’ when immersed in the liquid through voids and pores present in the concrete (CCAA[33]). The absorptivity of shotcrete is therefore an indirect measure of the volume of voids in the material. Various tests can be carried out in relation to voids content in shotcrete, and maximum values can be specified (eg. maximum volume of apparent permeable voids of 17%, or maximum boiled absorption ratio of 8%, according to ASTM C642[34]). These tests are often specified for shotcrete to check the degree of insitu compaction. They are usually performed on cores taken from sprayed test panels.

The level of compaction achieved can also be measured as the relative density of in-place shotcrete compared to the density of cast shotcrete (see **Clause 3.6**).

3.11.5 **Alkali-Silica Reactivity (ASR)**

This reaction normally occurs between reactive silica constituents within aggregate and the alkalis in cement and is also known as Alkali Aggregate Reactivity (AAR). The reaction starts with an attack on the siliceous minerals in the aggregate by alkaline hydroxides in pore water derived from alkalis which may have originated from within the concrete, via Na_2O and K_2O in the cement etc, or externally by some other source. This results in an alkali-silica gel being formed, either in planes of weakness or pores in the aggregate (where reactive silica is present), or on the surface of the aggregate particles. This can affect bond between the aggregate and the surrounding hydrated cement paste. The ‘gel’ imbibes water and may swell causing expansion of the aggregate and possible cracking of the concrete. This reaction only takes place in the presence of moisture. Suitable blended cement can be an effective means of reducing the expansion due to ASR. Aggregates should be tested for potential reactivity and a scheme for management of potential ASR be established. Aggregates should comply with the requirements of Australian Standard AS 2758.1[35].

3.12 **Bond to Substrate**

Bond strength between a layer of shotcrete and an underlying substrate is dependent on many variables including the type and condition of the substrate. Different materials exhibit widely varying bonding capability. To maximise the development of bond the surface to be sprayed should be clean and sound. It has been noted that hydro-scaling preparation promotes higher bonding capacity (Clements et al[36]), and in some applications a bonding agent may also promote improved capacity. Bond strength development at early ages is poorly understood but some information on this topic is provided by Bernard[8].

Due to the unknown character of most substrates, specifying minimum bond strength development between shotcrete and an underlying substrate should be avoided. It is more rational to specify a surface preparation method that will maximise opportunities for bond development to the substrate. There is no available Australia Standard for testing bond strength between shotcrete and substrate but several methods are currently employed internationally, including the EFNARC bond test and Swedish Standard 137243[37] test. A simple test to examine the existence of any bond is hammer sounding. Refer to **Clause 11.14** for test procedures.

Specifiers should be aware that bond between a shotcrete lining and deforming ground will most likely reduce to zero over time. Bolted connections between a lining and ground are normally used in these situations. Because of the above reasons, bond is rarely specified.

4

Constituent Materials

Shotcrete consists of cement, sand and coarser aggregates, water and admixtures and often fibres. The water/binder (w/b) ratio is the mass of water divided by the total mass of binder comprising all cementitious materials in the shotcrete mix. The water/binder ratio is important as it has a major effect on the strength, shrinkage, and durability of shotcrete.

4.1 Cement

Cement should be Portland or blended cement used alone or in combination with one or more supplementary cementitious materials, that in turn must comply with Australian standards. In Australia, the principal Portland and blended cement classifications used are Type GP (General Purpose Portland), Type GB (General Purpose Blended), Type HE (High Early Strength), Type LH (Low Heat), Type SL (Shrinkage Limited), Type SR (Sulfate Resisting).

Some shotcrete applications may require High Alumina Cement (HAC). HAC is imported into Australia and does not comply with AS 3972[1]. It differs markedly from Portland cement in its chemical composition and in its hydration characteristics. HAC is characterised by a very rapid rate of early strength gain accompanied by high heat evolution. Refer **Clause 5.5** Special Mixes. Also refer to CCAA T41[33] for further information on *"Hydraulic Cements"*.

4.2 Supplementary Cementitious Materials

4.2.1 Normal Grade Fly Ash

Fly ash is a finely-divided inorganic pozzolanic material which can be added to concrete and mortar to improve or achieve certain properties in the fresh and/or hardened states. Fly ash in shotcrete can also provide lubrication between larger particles within the mix due to its spherical shape and thereby reduce water demand, increase workability, and can help reduce alkali-aggregate reactivity at particular content levels. Addition of fly ash reduces the overall reactivity of the mix and this should be considered when using shotcrete accelerators.

A typical fly ash content in shotcrete generally ranges between 10% to 25% by weight of total cementitious materials depending on cement type and application. When using fly ash as a substitute for part of the cement content, consideration must be given to the effect on early strength development and fly ash quality. Normal grade fly ash for use in shotcrete should comply with the requirements of AS 3582.1[2].

4.2.2 Special Grade Fly Ash

Special grade flyash is a more reactive flyash with average particle size that is finer than that of normal grade fly ash and around one quarter that of Portland cement. This inorganic pozzolanic material can be added to concrete and mortar to improve or achieve certain properties in the fresh and/or hardened states. It can perform similarly to silica fume at particular dose rates. If used in shotcrete it should comply with the requirements of AS 3582.1[2].

4.2.3 Silica Fume

Silica fume is a form of amorphous silica (AS 3582.3[2]) and is a finely-divided, densified highly-reactive inorganic pozzolanic material which can be added to shotcrete to improve or achieve certain properties in the fresh and/or hardened states. The benefits of silica fume use in shotcrete include: higher strengths (28 days and beyond) including compressive and flexural performance; improved durability including reduced permeability due to pore blocking as its average particle size is significantly smaller than a General Purpose cement particle; reduced rebound; improved bond to substrates; improved pumpability; reduced wear in the pump and nozzle; improved mix cohesiveness; and thicker single-pass applications. It should be noted that silica fume does not improve strength development prior to 7 days age.

A typical dosage rate of silica fume in shotcrete generally ranges between 5% to 10% by weight of cementitious materials. It is recommended that expert opinion be consulted to determine appropriate silica fume levels.

4.2.4 Amorphous Silica other than Silica Fume

AS 3582.3[2] was revised in 2002 to include sources of silica in addition to silica fume. The standard was re-titled “Amorphous silica” which was defined as “a very-fine pozzolanic material composed of mostly non-crystalline silica.” Typical sources of such amorphous silica include volcanic vents and precipitated silica from industrial processes.

4.2.5 Slag – Ground Granulated Blast Furnace Slag (GGBFS)

Ground granulated iron blast-furnace slag (AS 3582.2[2]) is a fine granular latent hydraulic binding material which can be added to concrete and mortar to improve or achieve certain properties in the fresh and/or hardened states. These properties include; lower heat of hydration, slower set times, increased sulfate resistance, and higher chloride-ion resistance. GGBFS can exhibit interaction problems with shotcrete set accelerators.

4.3 Aggregates

All aggregates should comply with Australian Standard AS 2758.1[35]. Each individual aggregate in the mix should have a consistent grading in accordance with the allowable variation of AS 2758.1 from the original aggregate proposed for use. Gradings of individual aggregates outside the requirements of AS 2758.1 may be used if it can be shown that such use in shotcrete of a similar mix design can provide the particular performance required. The use of finer sands generally results in higher drying shrinkage while the use of coarser sands generally results in more rebound. For acceptable combined aggregate gradings of the shotcrete mix refer to **Chapter 5**.

The chloride-ion and the sulfate-ion content of each aggregate should be determined in accordance with the relevant Australian standards prior to proposal for use in the shotcrete.

4.4 Mixing Water

Water quality can have a significant effect on shotcrete performance. Mixing water should be drawn from a source of acceptable quality complying with Australian Standard AS 1379[38] and comprise potable water if possible. If potable water is not available then further testing is required to determine suitability. Dissolved solids greater than 3000 ppm may affect shotcrete performance and durability. When required, use chilled or heated water to adjust or control the mix temperature during batching

4.5 Chemical Admixtures

4.5.1 General

Chemical admixtures and their use should comply with Australian Standard AS 1478.1[39] where applicable. Where two or more admixtures are proposed for incorporation into a shotcrete mix, their compatibility should be tested prior to use to ensure no ill-effects or the manufacturers of the admixtures should certify the suitability of the proposed sequence of addition and their compatibility. Shotcrete set accelerators and other admixtures, which are added to the shotcrete at the nozzle or at the delivery hose, should be dispensed by calibrated mechanical means at dose rates not exceeding the maximum recommended by the manufacturer. Re-addition of most admixtures becomes increasingly less effective as the age of a mix increases.

There are four main categories of chemical admixture as listed below. They are used to improve certain aspects of shotcrete performance such as pumpability, hydration control, and strength.

4.5.2 Low-Range Water Reducers

Water reducers are used to improve workability and/or reduce the water/cementitious ratio. Other effects such as retardation may occur and expert opinion may need to be sought where such slow setting is experienced. Refer to manufacturer’s recommendations and AS 1478.1 for specific details. Water reducers may be formulated to have neutral setting, set retarding or set accelerating characteristics. The performance of each type is to comply with the requirements of AS 1478.1 for that particular type.

4.5.3 High-Range Water Reducers (Superplasticisers)

High-range water reducers and their use should comply with Australian Standard AS 1478.1. High-range water reducers are used to either increase the strength or increase the workability of a mix, considerably, without loss of strength. The development of superplasticiser technology has allowed lower water/binder ratios to be used, with higher strengths, greater workability, and improved pumpability. Superplasticisers are normally only added to wet-mix shotcrete. Dose rates (depending on type of superplasticiser) generally range from 0.5% to 2% by weight of cementitious materials.

4.5.4 **Hydration Control Admixtures**

Concrete that is required to be transported for considerable distances or maintained in a workable state for a number of hours or days, requires the addition of special admixtures to maintain suitable workability. The process of cement hydration leading to setting causes a rapid reduction in workability through the interlocking of Calcium Silicate Hydrate (CSH) crystals. To overcome this process, a hydration control admixture (commonly known as a 'stabilizer') may be added that effectively coats the cement grains and temporarily stops the normal hydration process. The extension of time before the onset of setting that is achieved through this process is determined by the dose level of the admixture.

Where the hydration of the shotcrete has been temporarily halted it can be re-activated by the addition of a set accelerator or left to set slowly by waiting for the CSH crystal structure to penetrate the coating and interlock with the surrounding cement grains (AS 1478.1). Slump loss may still occur with hydration control admixtures in place. The concrete should be re-mixed for a sufficient period of time prior to use to overcome possible segregation that can occur while waiting.

4.5.5 **Accelerators**

Accelerators are primarily used to aid the placement of shotcrete by promoting the early setting of the mix. They may also accelerate early strength development. Overdosing of a set accelerator can retard the rate of strength development and compromise durability therefore manufacturer's recommendations should be followed. Set accelerators are added to the concrete at the nozzle or at the delivery hose in wet shotcrete and added at the bowl or nozzle for dry shotcrete. Advantages of the use of shotcrete accelerators include large reductions in fall-out, increased layer thicknesses (particularly in overhead applications), and increased speed of construction. Shotcrete accelerators should be alkali-free and non-caustic. This type of accelerator has a pH of approximately 3 which provides a safer working environment for shotcreting operators compared to the older type of caustic accelerators (pH > 12).

Shotcrete accelerators may reduce concrete strength in the long term compared to a control without accelerator. Strength reduction occurs as the dosage increases, and it is therefore important that accelerator test data is available and maximum dose rates are controlled. Dose rates generally range from 3% to 8% by weight of cementitious materials. Accelerators are normally supplied in a liquid form but are also available as a powder.

Set accelerators for shotcrete should not be confused with hydration accelerators commonly used for cast concrete. The two classes of accelerator comprise distinctly different groups of chemicals with different reaction pathways and different effects on rate of setting, rate of hydration, durability of the concrete matrix, and (sometimes) corrosion of steel reinforcement.

Accelerators for cast concrete promote an increase in the rate of hydration of normal calcium-silicate-hydrates. Accelerators for shotcrete promote rapid setting by generating ettringite crystals or promote stiffening through generation of gel products between the cement particles in suspension in the paste. The formation of ettringite crystals or gels can be very fast making the shotcrete stiffen rapidly. **Table 4.1** includes a list of chemicals available for promotion of accelerated hardening in cast concrete and for accelerated setting for shotcrete.

Table 4.1 *Accelerators for cast concrete and shotcrete*

Class/Category	Active component	Characteristics
Chemicals for accelerated hardening (for cast concrete)		
Calcium Chloride	$CaCl_2$	Relatively fast, increases bleed and shrinkage, promotes steel corrosion
Calcium Nitrate	$CaNO_3$	Safe but relatively slow, increases shrinkage
Triethanolamine	$C_6H_{15}NO_3$	Safe but relatively slow Increases shrinkage
Chemicals for accelerated setting (for shotcrete)		
Hydroxides	NaOH, KOH	Highly caustic, harmful to eyes
Carbonates	Na_2CO_3, K_2CO_3	Highly caustic, harmful to eyes
Sodium Aluminates	$NaAlO_2$	Caustic, promotes stiffening through gel formation
Sodium Silicate (Waterglass)	$NaO{\cdot}nSiO_2$	Highly caustic, harmful, promotes stiffening through gel formation
Calcium Aluminate	$CaO\text{-}Al_2O_3$	Non caustic, mildly alkaline, safe alkali-free powder-based accelerator
Aluminium Sulfate	$Al_2(SO_4)_3$	Non caustic, mildly acidic, safe alkali-free powder or liquid accelerator

Modern alkali-free set accelerators for shotcrete are drawn exclusively from the last two categories shown in **Table 4.1**. They are termed ‘alkali-free’ because they lack the alkali ions (either sodium Na^+ or potassium K^+), associated with the earlier classes of shotcrete accelerator. All of the earlier alkali-rich shotcrete accelerators were dangerous because of the caustic burns they could inflict on skin, lungs, and especially eyes. All the alkali-rich set accelerators are effectively banded from use in Australia.

All of the accelerators commonly used in cast concrete are insufficiently fast to promote useful stiffening of shotcrete for overhead applications. They are typically added into the agitator bowl and mixed into the concrete, and take approximately 1 hour before enhancing the rate of hydration. However, their effect on hydration appears to be supplemental to that of normal alkali-free set accelerators and thus may be used in addition to normal set accelerators for shotcrete, but not as a replacement.

Note that both calcium aluminate-based and aluminium sulfate-based set accelerators promote the rapid formation of ettringite crystals as the stiffening mechanism in young shotcrete. This hydration product compromises the durability of the concrete matrix against sulfate attack and thus the minimum amount of shotcrete set accelerator necessary to satisfy operational requirements should be used.

4.6 Fibre Reinforcement

Fibres are short (up to 65 mm long) slender elements (less than 1 mm diameter) typically of high tensile capacity. They may be added for the purpose of improving impact resistance, or shrinkage control, but their main role is to provide post crack load capacity (toughness) to the shotcrete. Fibres generally do not increase the tensile or flexural strength of the concrete matrix when used at normal dosage rates.

The benefits of fibres compared to the use of steel mesh reinforcement include more even distribution of reinforcement throughout the shotcrete, improved overall economy, reduction in rebound, and improved compaction. Fibre reinforced shotcrete can also follow an uneven profile more efficiently than mesh reinforcement. Vibration of mesh leading to de-bonding from the substrate is also avoided. Logistics can also be simplified compared to mesh reinforcement, with improvements in application, safety, and productivity.

Characteristics of the fibres affecting shotcrete performance include: aspect ratio (overall length to diameter), tensile strength, shape, and the dose rate (kg/m^3 of shotcrete). However, if post-crack performance of the shotcrete is important then the principal criterion that needs to be specified is toughness.

Typical fibre reinforcement materials include: drawn steel wire, slit steel sheet, or polypropylene (monofilament or fibrillated). Less common materials used for fibres include nylon, glass, aramide and carbon. Fibres generally can be categorized as structural (steel and macro-synthetic fibres) and non-structural (micro-synthetic fibres). Structural fibre post-crack performance should be specified in terms of toughness (refer to **Clause 3.5**). Micro-synthetic fibres are generally only used to control plastic shrinkage cracking but are also useful for reducing rebound in addition to spalling of shotcrete when subjected to fire loading. The dosage rate of micro-synthetic fibres is generally specified at approximately 1 to 2 kg/m^3 of shotcrete for this purpose.

Although it is recommended that fibre counting is not specified, verification of actual addition of fibre can be based on a fibre-count test. However, this is an unreliable test due to the poor distribution of fibres through small samples. Fibre counting can be done using a washout test for wet-fibre reinforced shotcrete or by counting fibres in crushed cores or cracked toughness specimens. These test methods are described in **Chapter 11**.

4.7 Steel Mesh or Bar Reinforcement

As in conventionally-reinforced concrete, steel is used in situations where shotcrete is required to withstand tensile stresses. The amount of reinforcement required for structural purposes should be calculated in accordance with AS 3600. Recommended mesh sizes are any wire on a minimum of 50 x 50mm or 100 x100mm grid spacing or greater, eg F51, SL82 or more. It is emphasised that the soundest structure will be obtained when the reinforcing steel is designed and placed to cause the least interference with placement. Smaller bar diameters should be used to assist encapsulation, with a 16 mm bar being the normal maximum size. Where larger diameter bars are required, exceptional care should be taken in encasing them with shotcrete. Reinforcement should be supported and held clear of the surface to be shotcreted at a minimum distance of 25 mm but always in accordance with cover requirement specified on the design drawings. Swimming pools should have a minimum cover of 50 mm. All reinforcement should comply with AS/NZS 4671[40]. To prevent vibration of the steel bars during shotcreting they should be tied rigidly in place.

4.8 Other Additives

These may include coloured pigments, additives for permeability and shrinkage-control, or internal curing, together with others listed in AS 1478.1. All additives should be used in accordance with manufacturer's recommendations and compatibility requirements.

5

Mix Design

5.1 General

Many of the principles of normal concrete technology can be applied to the mix design of shotcrete, particularly that produced by the wet-mix process. The major differences between conventional concrete and shotcrete are in aggregate gradation, cementitious content, method of conveyance and placement, and selection of chemical admixtures. The mix design process in particular needs to consider, but is not limited to, issues including:

Sprayability – the mix must be capable of being conveyed and placed for the particular application with minimum rebound. Applications may have horizontal, vertical, or overhead surfaces.

Strength – it must satisfy early-strength and long-term strength requirements, depending on the application. The effect of set accelerators on long-term strength needs to be considered.

Compaction – the mix must be able to be compacted to form a dense, homogeneous material.

The design and trialling of a shotcrete mix should be based on the anticipated conditions which will prevail on site so that, under these conditions and with the nominated application method and nozzle operators, shotcrete of the quality specified will be produced. There are two general approaches to specifications, the performance-based approach and the prescriptive approach.

- Prescriptive specifications focus on particulars of how shotcrete is to be proportioned, produced and placed but seldom include assessment of the in-place properties of the final product. This approach discourages innovation by constraining a contractor's ability to use new technologies and methods of application to achieve the required result more effectively. It can also promote poor practice by omitting the requirement to prove that the performance of the in-place shotcrete is satisfactory.
- Performance-based specifications focus on producing in-place shotcrete exhibiting a minimum level of performance that conforms to requirements determined through design. The particulars of how this is achieved are left to the contractor, thus he or she is encouraged to find the most effective means of satisfying the minimum levels of performance economically. This will often include a critical evaluation of every facet of production and placement which can assist in rooting out poor practices. Specifications are normally tailored to the particular site application and type of structure (eg. swimming pools or tunnels). Specifiers should take care not to specify inappropriately high levels of performance when this is not required as the result will be unnecessarily expensive shotcrete.

5.2 Wet-Mix Shotcrete

For major infrastructure work, the design and trialling of a shotcrete mix is normally carried out in two stages. The first stage involves the design of the base mix. The second is the trialling of the shotcrete mix sprayed into test panels. The trial base mix includes the proposed materials and mix proportions, all admixtures including nozzle-added admixtures, and proposed fibres at the proposed dosage (if fibre reinforcement is nominated).

The choice of mix proportions for shotcreting of major infrastructure work is usually based on a specified compressive strength, slump limits, density, flexural strength/toughness, drying shrinkage, permeability, durability (including exposure classifications where nominated), and site application. Pumped mixes normally contain a higher percentage of sand/fines than normal, for lubrication and to eliminate segregation.

Proportioning the aggregates in the mix to fit previously proven combined grading limits can shorten the design process and increase the likelihood of arriving at a satisfactory mix design. Gradings outside the ranges shown in **Table 5.1** may be used if preconstruction testing proves that they give satisfactory results, or if acceptable results are available from previous use of the proposed combined aggregate grading. At remote mine sites local materials may vary and these need more detailed analysis.

Table 5.1 gives examples of recommended combined aggregate grading ranges from a variety of Remote Spraying in Mining and Civil Tunnel Projects sources for mixes of various maximum aggregate sizes.

Table 5.1 *Combined aggregate gradings for various specifications*

Sieve size (mm)	Percent passing for specification: ACI 506[41] Fine grading	ACI 506[41] Coarse grading	RTA B82[42]	AFTES[9]
19.0	-	-	-	-
13.2	-	100	100	100
9.5	100	90-100	90-100	85-95
4.75	95-100	70-100	70-85	60-75
2.36	80-100	50-70	50-70	45-60
1.18	50-65	35-55	35-55	30-45
0.600	25-60	20-35	20-40	20-35
0.300	10-30	8-20	8-20	10-20
0.150	2-10	2-10	2-10	7-12

It is suggested that *ACI 506 fine grading* may be used for fine aggregate shotcrete such as mortar. Sand for "finish" or "flash" coats may be finer than for this grading. However, the use of finer sands generally results in higher drying shrinkage. The use of coarser sands generally results in more rebound. The combined grading curve should be continuous and not gap graded.

Examples of mix designs for wet-mix shotcrete using remote spraying, in both mining and civil tunnel infrastructure projects are shown in **Table 5.2.** Typical toughness requirements for wet-mix shotcrete used in mining and civil tunnel projects in Australia are listed in **Tables 3.2** and **3.3.** Equipment used for manual spraying performs differently to remote-controlled or robotic spraying rigs and, as such, the mix design should be altered accordingly. A typical wet-mix design when using manual shotcrete application is shown in **Table 5.3**.

Table 5.2 *Typical wet-mix shotcrete mix designs for remote spraying in mining and civil tunnel projects*

Constituent materials	Mix design/m^3 for: Mining	Civil tunnel
Strength grade (MPa)	40	40
Cement (kg)	440	420
Cement Type	GP	SL
Fly ash (kg)	Optional	60
Silica fume (kg)	20	40
10 mm aggregate (kg)	500	450
Coarse sand (kg)	680	780
Fine sand (kg)	500	380
Total water (litres)	200	208
Steel fibre (kg) OR Macro-synthetic fibre (kg)	30–40 5–8	40–60 9–10
Water reducer admix. (litres)	1	1
Superplasticiser admix. (litres)	3	3
Hydration control admix. (litres)	2	1
Nominal slump (mm)	120–150	120–150
Water/cementitious material ratio	0.40–0.48	0.38–0.45

Table 5.3 *Typical wet-mix shotcrete mix design for manual spraying*

Constituent materials	Mix design/m^3
Cement (kg)	335
Fly ash (kg)	85
10 mm coarse aggregate (kg)	610
Coarse sand (kg)	585
Fine sand (kg)	530
Water reducer (litres)	1.6
Superplasticer (litres)	1.0
Air Entraining Agent (litres)	0.1
Water (litres)	200
Slump (mm)	60

Maximum steel-fibre dosage for dry-mix shotcrete is normally 30 kg/m^3, but can be up to 50 kg/m^3 with special equipment.

5.3 Dry-Mix Shotcrete

Aggregates should be proportioned to fit similar combined aggregate grading as for wet-mix shotcrete. A typical dry-mix shotcrete mix is shown in **Table 5.4.** Typical toughness requirements for dry-mix shotcrete used in Australia are given in **Table 3.2**. For overhead application, the mixes can be proportioned to the finer side of the gradation envelope, to the middle for vertical applications, and to the coarser side of the gradation for downward application.

Table 5.4 *Typical dry-mix shotcrete mix design*

Constituent materials	Mix design/m^3
Strength grade (MPa)	40
Cement (kg)	420
Silica fume (kg)	50
7-mm aggregate (kg)	350
Coarse sand (kg)	755
Fine sand (kg)	625
Steel fibres (kg) OR	30–40 OR
Macro-synthetic fibres (kg)	5–8
Accelerator admix. (litres)	20 (as required)
Superplasticiser admix. (litres)	Nil
Water reducer admix. (litres)	Nil
Air Entraining Agent (litres)	Nil
Water (litres)	150–200 (controlled at nozzle)

5.4 Swimming Pool Mix Design

For swimming pool work the design of a shotcrete mix has traditionally been based on particular strength grades and trial results from past work. Indicative base mixes can vary between 16–24% cementitious content, 18–25% coarse aggregate and a sand content between 60 and 70% of total aggregate content.

Australian Standard AS 2783[43] sets out requirements for the structural design and construction of swimming pools constructed wholly or partly of either in situ or pneumatically-applied reinforced concrete. AS 2783 applies to pools with a surface area not greater than 100 square metres and with an overall length not greater than 15 metres. The Standard advises that the requirements set out in the Standard may be applied to larger structures but may not be sufficient for such structures.

AS 2783 also states that the structure shall be designed and constructed in accordance with the requirements of that Standard and the requirements of AS 3600 and AS 3735[44] as applicable.

The following recommendations are made in relation to shotcrete mix designs for swimming pools in general. It is recommended that the mix design should generally be in accordance with AS 2783 with the following to be emphasised (where they are currently called up) and the additional requirements adopted.

- Materials used to be in accordance with AS 1379[38].
- Minimum cementitious content of the shotcrete to be 350 kg/m3.
- Maximum water to cementitious material ratio to be 0.55.
- Maximum size of of aggregate to be 10 mm.
- Combined aggregate grading to comply with one of the combined grading envelopes shown in Table 5.1. Combined gradings outside these ranges may be used if pre-construction testing proves they give satisfactory results or if acceptable results are available from previous use of the proposed combined aggregate grading.
- Minimum 28-day characteristic compressive strength to be 25 MPa.
- 28-day compressive strength capability of the proposed shotcrete mix to be verified prior to supply by compressive strength testing. This should be carried out at the age of 28 days of standard cylinder specimens made from the mix as supplied or from cylinder specimens taken from test panels of the pneumatically-applied shotcrete and cured under standard conditions. It is recommended that the minimum acceptable 28-day compressive strength test result should be 32 MPa for standard cylinder specimens cast from the shotcrete as supplied and 25 MPa for specimens taken from test panels.

5.5 **Special Mixes**

Shotcrete is occasionally required to exhibit special properties (eg. low unit weight, insulating qualities, resistance to heat, resistance to acids, requirements of a special aggregate finish).

Lightweight aggregate mixes are being sprayed in increasing quantities for wall and floor construction. Lightweight shotcrete is best adapted to thin, lightly-reinforced sections. Particular care should be taken in planning and executing the job where structural members are involved. Perlite and vermiculite manufactured aggregates provide low-density concrete in the range of 400–1000 kg/m^3 (Neville[30]). It should be noted that these aggregates should be moist surface saturated prior to mixing, and mix trials should be carried out for strength, density, and shrinkage values. Mixes may need to be refined for pumpability.

Shotcrete is frequently employed for fireproofing structural-steel members, and lightweight aggregates are sometimes used in these mixes. The shotcrete also strengthens the members and can be included in calculations of gross structural section.

High-alumina cement is preferred over Portland cement for certain applications where rapid hardening or where heat resistance or acid resistance is desired. For refractory linings, calcium-aluminate cement is commonly used in combination with a heat-resistant aggregate. These lightweight aggregates include natural volcanic aggregates such as scoria and pumice, and manufactured aggregates such as expanded clay, shale and blast-furnace slag. These products make good moderate-to-structural-strength concrete.

It should be noted that calcium-aluminate cement should be fully investigated for any particular application because of its fast-setting properties, its high early heat of hydration, and possible reduction of long-term strength by the process known as conversion. Concrete made with calcium aluminate cement is also highly susceptible to sulfate attack associated with, for example, sea water. Additional information on the performance of this type of cement is dealt with by Neville[30].

Successful spraying of special mixes may require different placement techniques, methods of installation, and equipment. Only applicators with the requisite expertise and experience should be used. Additional information on refractory applications may be found in ACI 547R[45] and Special Publication No. 57[11]. Recommendations of the cement and aggregate manufacturers should generally be followed in this matter.

Abrasion-resistant shotcrete mixes are based on corundum or other such hardwearing aggregates. The matrix of the mix is different to normal shotcrete and should be specified by an engineer with expertise in this area.

5.6 **Combined Aggregate Grading Curves**

The combination of the gradings of the individual aggregate fractions within a shotcrete mix should be such as to provide minimum segregation while the shotcrete is being conveyed, good pumping and spraying characteristics, low rebound, and maximum density when it is placed. It is therefore necessary to check the combined grading of the aggregate particles of all of the aggregate fractions in the proportion in which they are to be used when the proposed design of the shotcrete is being considered.

The following example demonstrates how the combined aggregate grading can be determined from the proportion of each individual aggregate fraction in the mix design. In the example it is assumed that all of the aggregates have the same specific gravity. The physical composition of shotcrete and concrete is, however, based on volumetric proportions. If the specific gravities of the individual aggregate fractions differ appreciably from one another, the proportions should be adjusted accordingly (eg. normal dense weight aggregate and lighter weight aggregate). The aggregate quantities and proportions for the particular mix design used this example are as shown in **Table 5.5** (aggregate quantities on a saturated surface dry basis).

Table 5.5 *Example aggregate fractures in a typical shotcrete mix*

Aggregate description	Mass of aggregate (kg/m^3 of shotcrete) (saturated surface dry)	Proportion of total aggregate (by mass)
10 mm aggregate	235	14%
5 mm aggregate	265	16%
Coarse sand	680	40%
Fine sand	500	30%

The accompanying **Table 5.6** shows how the combined aggregate grading is calculated. The heading immediately above each column identifies the information contained in the columns immediately below eg sieve sizes, aggregate nominal size and its individual grading, the proportion(%) of that sized aggregate in the total aggregate, and the calculated combined aggregate grading (being the sum of columns 3, 5, 7 and 9 for each separate sieve size). For a maximum nominal size of 10 mm aggregate, these sizes are arranged in reducing size from 13.2 mm to 0.150 mm (150 microns). 0.075 mm is also normally included as the minimum sized fraction.

The contribution of each aggregate to the particle size distribution of the combined aggregates is calculated by multiplying the proportion of the total aggregate content of each individual aggregate by the percentage of that aggregate that passes the particular sieve size being considered. For example, the contribution of the 10 mm agg to the 13.2 mm size is 100% multiplied by the 14% being the proportion of the total aggregate that the 10 mm agg contributes (ie 14%). Similarly, the contribution of the 10 mm agg to the 4.75 mm size of the total aggregate content is 14% of 6% which is rounded off to 1% (Column 3).

The Combined Grading of the total aggregate for this particular mix design is shown in Column 10 (being the sum of the respective values in Column 3, 5, 7 and 9 for that sieve size) Once the Combined Aggregate Grading has been determined it can be judged for its suitability by comparison with the various recommended combined grading ranges or others that have been shown to be suitable in practice. Computer-based spreadsheets can easily be developed to implement the method of combining grading curves to produce plots of the type shown in **Figure 5.1**.

Table 5.6 *Example calculation of combined grading for a shotcrete mix using materials listed in Table 5.5*

Sieve Size (mm)	10 mm aggregate (14%)		5 mm aggregate (16%)		Coarse sand (40%)		Fine sand (30%)		Combined aggregate grading
	Individual grading (%)	Contribution to combined grading (%)	Individual grading (%)	Contribution to combined grading (%)	Individual grading (%)	Contribution to combined grading (%)	Individual grading (%)	Contribution to combined grading (%)	Sum of columns 3, 5,7 & 9
13.2	100	14	100	16	100	40	100	30	100
9.5	92	13	100	16	100	40	100	30	99
4.75	6	1	86	14	100	40	100	30	85
2.36	0	0	8	1	93	37	100	30	68
1.18			0	0	84	34	100	30	64
0.6					60	24	79	24	48
0.3					25	10	43	13	23
0.15					2	0.8	4	1.2	2
0.075					1	0.4	3	0.9	1.3

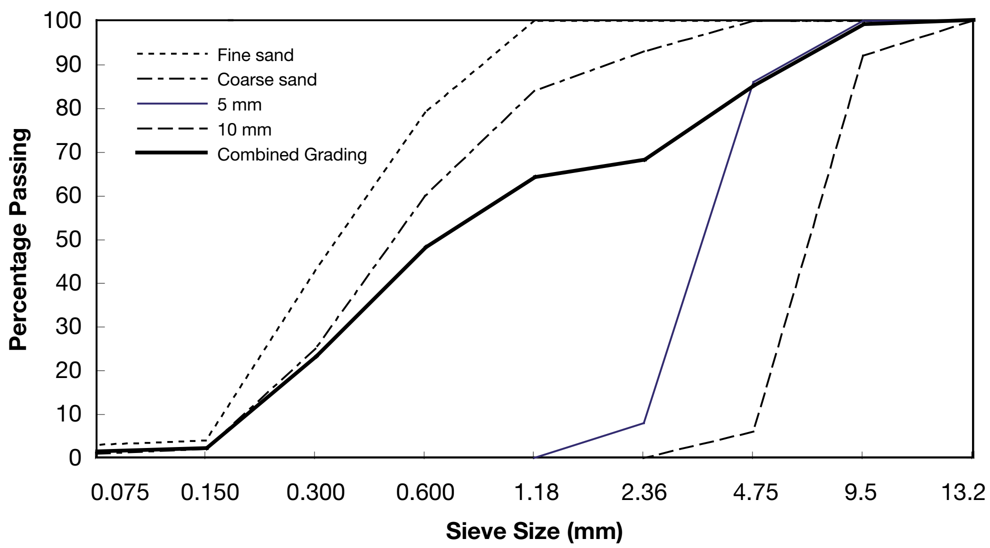


Figure 5.1 *Individual and combined grading curves for aggregates in example*

5.7 Mix Design Trouble-shooting

5.7.1 Pumping and Blockage Problems

Concrete pumpability is defined as the capacity of a concrete under pressure to be mobilized while maintaining its initial properties (Gray[46], Beaupré [47]). The research efforts reported in recent times on the pumpability of concrete usually focus on either the *stability* of concrete under pressure, or on its *mobility* under pressure.

In relation to stability the main concern about fresh concrete under pressure is the possibility of segregation, i.e. the separation of the paste from the aggregate phase, which usually leads to line blockage. This phenomenon occurs when the pressure applied to the concrete pushes the paste through the aggregate skeleton leading to the accumulation of coarser particles in the form of a plug that blocks the line (Browne & Bamforth[48]). This segregation is often associated with mixtures having poor grading and/or shape of aggregate particles or excessive wetness in the mix.

Shotcrete normally lacks a sufficient coarse aggregate fraction above 4.75 mm to exhibit much interference between these particles. Despite this, blockages are commonly composed of the larger coarse aggregate particles that have become separated from the finer fractions and accumulate at a constriction or point of high friction in the line. Efforts to prevent blockages through mix design improvements should focus on refining the combined grading curve to produce a smooth and continuous curve from 4.75 mm down. In addition, the coarse aggregate fraction (4.75 mm and above) should not exceed 500 kg/m^3. As a rule of thumb, about 20% of the combined aggregate content of a mix must pass the 300 micrometre sieve, and at least 450 kg/m^3 of cementitious materials and aggregate must pass 150 micrometres in order to pump adequately.

5.7.1.1. Common Causes of Blockages

A mix containing a well-graded aggregate will exhibit constructive mechanical interference between particles of differing size to prevent segregation under the action of a pressure gradient. This helps the concrete stream to move uniformly through the line in response to a pressure gradient. In a *poorly graded mix* this interference is diminished or absent so fine particles flow between the coarser particles causing the coarser aggregate particles to become separated from finer particles and accumulate into a plug. The causes of poor aggregate grading may include: inconsistent moisture contents in the aggregate fractions as they are batched that are not compensated for by adjustment to weights, or washing out of fine fractions from stockpiles due to heavy rain, or poor monitoring during crushing or extraction.

Segregation of particles and subsequent blockages are made worse by *high pumping pressures*. Any factor that increases resistance to flow, and thus necessitates increased pumping pressure, will lead to a greater tendency for blockage formation. The phenomenon is made worse by high friction associated with insufficient lubrication caused either by a rough line wall or inadequate paste in the mixture. Blockages are commonly associated with constrictions such as reducers in the concrete line and very long pumping distances. The use of excessively long rubber hoses, tight radii in either steel or rubber hoses, or excessively short reducers are all commonly associated with blockages. The rubber hose that is suspended from a remotely-controlled manipulator arm is particularly susceptible to blockages. When a blockage occurs in this hose it is therefore useful to lay the line flat and straight to unblock it. Stubborn blockage problems may possibly be overcome by changes to the line geometry to reduce the resistance to flow.

Excessive wetness in the mix will encourage segregation of particles. An alternative to a change in grading to alleviate blockages is therefore a reduction in slump. Mobility of fine particles relative to coarser particles is increased (that is, made worse) by raising the fluidity of the fine particle (paste) fraction. Reducing the slump, and thus the fluidity, may help to reduce blockages, but will not overcome pumping problems associated with very poorly graded aggregates.

Excessive *porosity* and especially *vesicularity* in coarse aggregates can also lead to pumping problems. Such aggregates should be batched in the Saturated Surface Dry (SSD) condition to try to minimize problems. Flaky and misshapen aggregate particles are also problematic with regard to pumping. The proportion of misshapen aggregate particles that is permissible in a shotcrete mix should be no more than 10% which is lower than is acceptable for cast concrete. Any attempt to rectify deficient aggregate gradings or shape characteristics by adding more cement is usually counter-productive because additional ultra-fines will increase the tendency to segregation.

Solutions to pumping and blockage problems should, in most cases, be possible through attention to the development of a smooth and continuous combined grading curve with particular attention paid to the finer fractions. The fine fractions may vary widely in the original aggregate source or they may be washed out by rain in a stockpile. If the fine fractions cannot be controlled adequately in the original source, then it may be necessary to wash the coarse aggregate and sand fractions to remove the fines, establish the grading of the washed fines, and re-introduce fines in controlled amounts through the use of, for example, crusher fines, graded silt, calcined clay, or a 'fatty' builder's sand. The shape of the grading curve at the fine end is thereby constrained more tightly than would otherwise be possible. If this is deemed too expensive (because washing aggregate is costly) entrained air may possibly be used as a substitute because entrained air bubbles act like fine aggregate particles in suspension. However, this will only work for low pressure pumping over relatively short distances. Alternately, the cohesion of the mix may be increased through the use of micro-synthetic or fibrillated synthetic fibres or some form of supplementary cementitious material. These small fibres help to hold the coarse and fine particles together in a flowing material and produce an effect similar to increased cohesion.

5.7.1.2 **Changes in Air Void System**

A common problem associated with pumping is modification of the air void system. Indeed, the use of pumps to transport concrete generally results in a loss of air ranging anywhere from one to three percent (Du & Folliard,[49]). It has also been shown that the resulting air-void system possesses no or very few bubbles with diameters below 50 μm (Pigeon et al[50]). The mechanisms believed to be responsible for this phenomenon are suction and dissolution during the pumping or placing process.

The *suction* mechanism occurs when the concrete is subjected to negative pressures. In a piston-actuated pump, the piston-chamber fills up with concrete not only by gravity action but also by a suction effect caused by the retracting piston. This movement causes a decrease in pressure, which can cause the air to expand to larger bubbles and (later) escape from the concrete. This phenomenon can also be observed in a vertical section of hose where the concrete is in free fall.

The *dissolution* mechanism is explained by Dyer [51]. While the concrete is pressurized upon pumping it is believed that the smaller air bubbles dissolve in the surrounding water (**Figure 5.2**). When the concrete depressurizes upon exiting the line, the air returns but within the larger bubbles that did not previously completely dissolve instead of forming new small air bubbles.

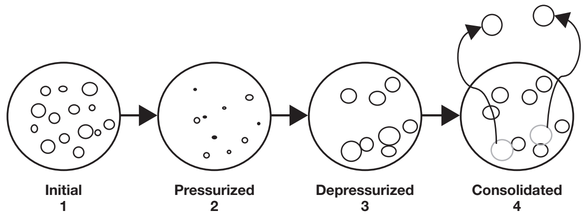


Figure 5.2 *Air loss during and after pumping, according to Dyer* [51]

In addition to the dissolution mechanism, the pressurization time and maximum pressure reached are also important parameters in the air loss effect. It is important to emphasize that this mechanism does not alter the air content significantly. The final air volume remains practically the same but alters the spacing factor. However, the stability of the larger air bubbles formed is such that these bubbles will escape more easily upon handling and consolidation of the concrete, hence the reported air losses. Given that at least a part of the workability of wet shotcrete is attributable to entrained air content it follows that pumping can reduce the workability of shotcrete.

5.7.1.3 **Minimum Paste Content**

The thickness of the paste boundary on the inside of the pumping line during flow varies with the type of line used to pump the concrete (typically, steel tube or rubber hose). The proportion of paste available within a mix that is required to lubricate the line surface also varies with the diameter of the line. Small diameter lines require a higher proportion of the total available paste than large diameter lines. This partly explains why it is easier to pump concrete through a large diameter line than through a small diameter line. Work by Jolin & Beaupre[52] and Jolin et al[53] has shown that the paste content of the mix has a major influence on the pumpability of concrete and that the air content of the paste must be considered when estimating the useful amount of paste available. The *Active Paste Concept* is defined as the *amount of paste (%) present in the concrete while under pressure in the line*, which represents the amount of paste required to create the lubricating layer against the line wall and to fill the inter-granular voids. This is a *volumetric interpretation* of the paste content as the material is under pressure. The actual paste volume diminishes as pressure is applied to the concrete since the air volume diminishes to negligible values.

To estimate the minimum active paste content required to obtain pumpable shotcrete it is necessary to know the porosity of the aggregate fraction (that is, the volume proportion of space between aggregate particles), the density of the paste fraction, the percentage air content, and the diameter of the line through which the concrete is to be pumped. Based on estimates derived by Jolin et al [53] , the minimum active paste content for a 50 mm line is about 33% (by volume) and for a 75 mm line is about 30%. Note that these estimates are subject to slight variation based on the grading characteristics of the aggregate. To obtain the total paste content required for the production of a suitable mix one must add the entrained air content which is about 3-4% (of the total concrete volume) for normal shotcrete (with no AEA) or about 8-15% (of the total concrete volume) when an AEA is used. The air content of highly air entrained shotcrete is best estimated by measuring the density of the wet shotcrete before and after the AEA is added and noting the difference since normal air content meters do not work for air contents in excess of 10%. These estimates of minimum paste content are for pumping requirements only and do not necessarily indicate good spraying or adhesion characteristics.

5.7.2 Shotcrete Not Sticking to Substrate

When spraying onto a vertical or overhead substrate it is necessary that the shotcrete stick to the surface for a sufficient period of time while in the wet state so that it can harden and remain in place permanently. Failure to stick to the surface can lead to the concrete sagging or falling off entirely, all of which require annoying and/or expensive repair. In many cases fallouts will also compromise the ability of the shotcrete to stabilize ground. A sticky mix that remains firmly in place after spraying is completed presents many advantages to the contractor and owner.

Failure of shotcrete to stick to the surface may be caused either by insufficient adhesion *between* the concrete and substrate or insufficient cohesion *within* the concrete itself. Inadequate adhesion is usually manifested as fallouts of wet shotcrete with debonding clearly taking place at the substrate boundary. Inadequate cohesion can be manifested in many ways but is commonly revealed by separation of the majority of the lining from a boundary layer of (often wet looking) concrete that remains attached to the substrate.

5.7.2.1 Adhesion Problems

Inadequate adhesion can be caused by:

1. Inherently low adhesive paste characteristics. Most cement paste exhibits a degree of stickiness, but exceptions occur and when low stickiness is apparent the cement may require supplementation with amorphous silica powder or similar materials. Finely ground inert fillers such as calcium carbonate powder also assist adhesion.
2. Poor spraying technique such as spraying from an excessive distance, low or excessively high air pressure, or building up too thick a layer in one pass.
3. A dry substrate surface leading to moisture depletion in the contact zone, desiccation of concrete, and bond loss. The solution to this situation is to pre-wet the substrate.
4. Dirt on the substrate which is often caused by caked-on material from construction activity or dust and rebound from earlier shotcreting operations. The solution to this problem is high pressure water-jetting or cleaning prior to shotcreting.
5. Oil on the substrate. This can be caused by hydraulic oil mist from faulty construction or mining equipment. Oil on the substrate must be removed if bond is to be achieved. Hydraulic fluid should *never* be used to lubricate the concrete line prior to pumping because of the health risk posed by hydraulic fluid aerosols and the risk to bond development on nearby rock surfaces and possible detrimental effects on the mix.
6. Excessive water on substrate, often associated with ground water inflow. This can be a difficult problem to solve. Fall-outs can sometimes be overcome by spraying very rapidly and using a high dosage rate of set accelerator, but this will compromise the long-term performance of

the concrete. An alternative that can work in circumstances involving point inflows of water is to install an intermediate substrate such as a strip drain to create a diversion path for water pressure to be relieved. One can also spray the lining around the points of wetness or water ingress, let this set, install a drain to relieve water pressure at the point of ingress, and then attack the difficult area by spraying a mix containing 2 kg/m^3 of micro-synthetic fibre in a bridging fashion between adjacent areas of hardened shotcrete. A second alternative is to first bolt a layer of mesh over the difficult area and use this as an anchoring scaffold for a subsequent layer of fibre reinforced shotcrete. Most options for tackling areas of high water inflow are slow and expensive but few alternatives exist.

It must be noted that wet shotcrete falling off with a rock attached probably indicates inadequate scaling prior to spraying and does not necessarily indicate poor adhesion. Flaky ground comprising, for example, shale, schist, or phyllite, may be particularly prone to fall-outs if the layering has an unfavorable orientation. Mechanical or hydro-scaling may possibly remove the loose pieces of ground, or mesh may be used as a bridge for the FRS over particularly flaky areas.

5.7.2.2 Cohesion Problems

Poor cohesion of shotcrete is typically manifested in two ways. The first is related to cohesion as a property of wet concrete prior to spraying. This type of cohesion is a property of shotcrete in the plastic state that is related to its propensity to segregate during mixing and placing if it not well proportioned or mixed effectively. Maintaining the cohesion of a shotcrete mix through careful design and the minimization of water of convenience reduces the likelihood of heavier aggregate settling out of the mix and also reduces the potential for the paste component formed by the water and cementitous fractions to separate from the aggregates during transportation and when subjected to a pressure gradient.

The second manifestion of poor cohesion in shotcrete occurs in the shotcrete as sprayed onto the substrate. This type of poor cohesion can lead to fall-outs from overhead sprayed surfaces and sagging of wet shotcrete on walls.

Inadequate cohesion leading to fall-outs can be caused by:

1. Poor mix design. Use of well-graded aggregates with good shape characteristics and careful attention paid to the fine fractions will aid cohesion but may not be sufficient to overcome cohesion problems if the shotcrete is excessively wet.
2. Poor cementitious fraction. General purpose cement on its own may not create a sufficiently cohesive mix, so consider including amorphous silica powder or similar materials. Users should be aware that General Purpose cement will normally contain 5% mineral additives hence care should be taken when adding further mineral additives. The fineness of the cement will also affect cohesion and water demand and therefore should be monitored.
3. Low set accelerator dosage rate. Set accelerators are essential when spraying overhead but optional when spraying vertical surfaces. Not only must an adequate dosage rate of set accelerator be used to keep shotcrete in place overhead, but an accelerator that is chemically compatible with the cement is required. If the accelerator is either too old, chemically incompatible, or the concrete temperature is too low, then adequate stiffening may not occur resulting in poor cohesion.
4. Irregular dosing of set accelerator which can lead to the creation of non-accelerated lenses of concrete within a lining that lack the cohesion of set accelerated shotcrete. This problem is exacerbated by the use of hydration stabilizers as this can allow the non-accelerated lenses to remain fluid and cohesionless for a long period after spraying. Methods of dispersing set accelerator uniformly into a stream of concrete at the nozzle are described in Section 6.4.
5. Excessive fluidity can exacerbate cohesion problems. Cohesion generally falls as slump increases, so excessively wet shotcrete may be prone to internal ruptures leading to fall-outs. High moisture content within a mix can lead to internal bleeding which will cause ruptures and therefore must be avoided. Use of an Air Entraining Agent (AEA) to create workability in the mix prior to spraying rather than relying exclusively on water or a water-reducing admixture is one means of improving cohesion within well compacted in-place shotcrete.

However, excess entrained air must be eliminated by proper compaction during spraying and steps should be taken to ensure this has been achieved. Care is required when using this approach to cohesion enhancement and expert advice should be sought.

6. The cohesion of wet shotcrete may be aided by the inclusion of 1-2 kg/m^3 of micro-synthetic fibres. The fibres should have a diameter in the range 18-35 µm and a length of about 12 mm. Adding these to the mix prior to agitation will lead to some loss of slump that should not be compensated for by addition of water. Adding a suitable superplasticiser or about 8-15% entrained air through the use of an AEA to recover the lost slump will generally result in spraying characteristics that will be similar to or better than the original shotcrete without micro-synthetic fibres.

Cohesion is best assessed in the field by spraying an inverted cone of concrete onto an overhead surface without the use of set accelerator. Spraying should be continued until the cone of concrete falls off, whereupon the maximum build-up capacity prior to failure can be estimated. A low cohesion concrete will typically sustain a maximum build-up capacity of only 50 mm, normally cohesive concrete can manage 100-120 mm, and highly cohesive concrete can sustain at least 150 mm of build-up capacity before collapse. If build-up capacity is limited by a cohesive failure, then the build-up capacities listed above will typically increase as the slump of the concrete is reduced and will substantially increase when a set accelerator is added. Experience has shown that adhesive failure will typically limit maximum build-up capacity to 250-300 mm even for the best shotcrete mixes regardless of slump and set accelerator usage.

5.7.3 **Slick Lines**

Slick lines are used in some deep underground mines to provide efficient transfer of shotcrete from the surface to the lower working levels in the mine. For instance, at Mt Isa Mine, Australia, the shotcrete can be dropped up to 1,700m. Typically the shotcrete is delivered into the slick line at the surface from a conventional transit mixer and collected underground in an underground agitator truck.

Key aspects to slick line design are:

- Diameter varies from 150 to 225 mm with 200 mm considered optimal
- The vertical pipe must be plumbed without bends or deviations to prevent uneven wear
- The design of the remixing kettle at the base of the drop line.

There are two types of slick line delivery: plug flow, and free fall. In plug flow, the mix maintains its cohesion and does not segregate. This is essential when delivering material directly to a structure (ie shaft lining). Smaller diameter lines are required (150mm or less) and slump control is critical. Risk of line blockage is relatively high with this method. In the free fall delivery method, the material segregates as it travels down the pipe but remixes in the mixing kettle at the base of the drop. The kettle is essentially a pipe with a blank end. It is made from very thick steel sections as it is subject to very high wear and tear.

Slick lines in Australian mines all use the free fall method to minimise the risk of blockages as these are time consuming and expensive to repair. Generally a minimum slump of 180mm is recommended and the mix is stabilised to provide at least 6 – 8 hours of workable life. Fibres can be added prior to transfer but some mines, fearing blockages, elect to add the fibres to the mix underground. In this regard, polypropylene fibres provide less abrasion on the drop pipe.

It is essential to prime (slick) the line prior to use. The large surface area of the pipe wall can retain a surface film of water sufficient to radically alter the water/cement ratio of the mix. This can be overcome by priming the line with up to 0.2m^3 of shotcrete which goes to waste. The underground receiving facility must be designed to cope with such waste. If the line is used continuously (say a load every 2-3 hours) and sufficient levels of set stabiliser are used, then it does not need to be washed out between loads. However it is essential to wash the line thoroughly at each break in transfer and at end of shift. The pipe must be maintained free of build-up, leakages, and wear to function effectively.

6

Shotcrete Equipment

6.1 Introduction

The selection of shotcrete equipment depends on numerous factors. They include:

- Specification of the project,
- Type of application,
- The proposed placement rate of the shotcrete,
- Times available for shotcreting,
- Type of shotcrete process (wet or dry),
- Access to the site or sites and physical size of the work face to determine feasibility of various shotcrete equipment configurations,
- Availability and quality of local materials, and
- The proposed shotcrete delivery system including conveying distance.

A basic complement of equipment for wet shotcreting usually consists of a concrete pump, compressor, nozzle and delivery hose. For dry shotcreting the basic complement of equipment includes a pressurized chamber, compressor, nozzle, and delivery hose. Over recent years the technology in shotcrete equipment has advanced to a level that now includes remote-controlled spraying, integrated accelerator dosing pumps, on-board compressors, hydro-scaling facilities, etc.

The selected configuration of equipment should be capable of discharging the mixture into the delivery hose under close quality control, and deliver to the nozzle a continuous, smooth stream of uniformly-mixed material at the proper velocity.

As a guide, hand-held shotcrete-placing rate is between 3 and 10 m^3/hr. The range of shotcrete outputs from various dry-mix machines is between 1 and 5 m^3/hr. The range of shotcrete outputs for various wet-mix machines is between 3 and 25 m^3/hr. Because of the large variety of machines available shotcrete applicators should always refer to the manufacturer's operating specifications.

6.2 Dry-Mix Equipment

6.2.1 General

Dry-mix shotcrete equipment can be divided into two distinct types, either single- or double-chamber machines, or continuous-feed machines, usually called rotary machines.

6.2.2 Single- and Double-Chamber Machines

Single-chamber machines provide intermittent operation by placing material into the chamber and closing, then air-pressurising the chamber, causing the material to feed into a delivery hose or pipe. When the chamber is empty, it is depressurised and refilled, and the operation repeated (**Figures 6.1** and **6.2**).

Double-chamber machines allow for a more continuous operation by using the upper chamber as an airlock during the material feeding cycle.

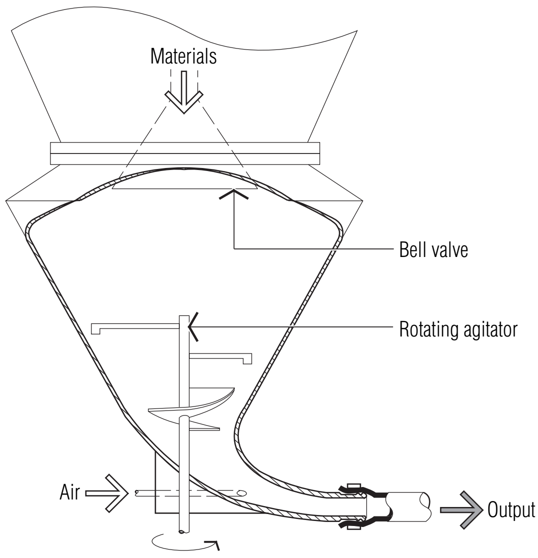


Figure 6.1 *Detail of single-chamber machine*

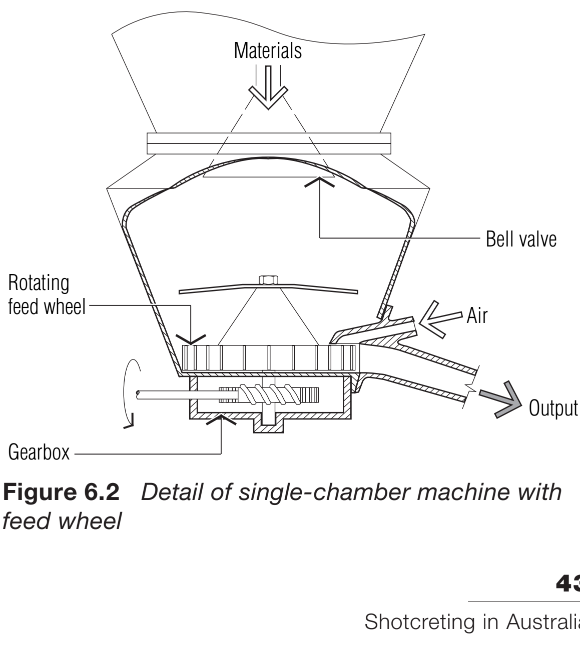


Figure 6.2 *Detail of single-chamber machine with feed wheel*

6.2.3 **Rotary Machines**

There are generally two types of rotary machine available.

Rotary-barrel machine (**Figures 6.3** and **6.4**) utilises sealing pads on the top and bottom of the rotating element. Material is gravity fed from the hopper into the cavities of the rotor in one area of its rotational plane and discharged downward from these cavities with air pressure at the opposite point in its rotation. Additional air is introduced into the outlet neck to provide proper volume and pressure for material delivery down the hose.

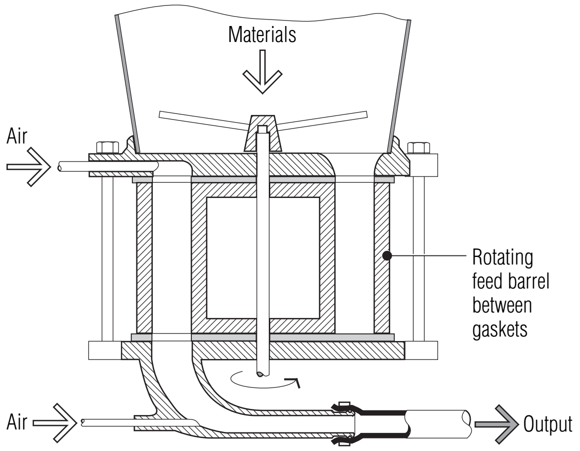


Figure 6.3 *Detail of rotary-barrel machine*

Figure 6.4 *Typical rotary-barrel machine*

Rotary-feed-bowl machine (**Figures 6.5** and **6.6**) utilises one sealing segment on the top surface of the rotating element. Material is gravity fed from the top hopper into U-cavities in the rotor and discharged into the outlet neck when that particular cavity is aligned under the sealing segment, air being injected down one leg of the U and carrying the material into the material hose.

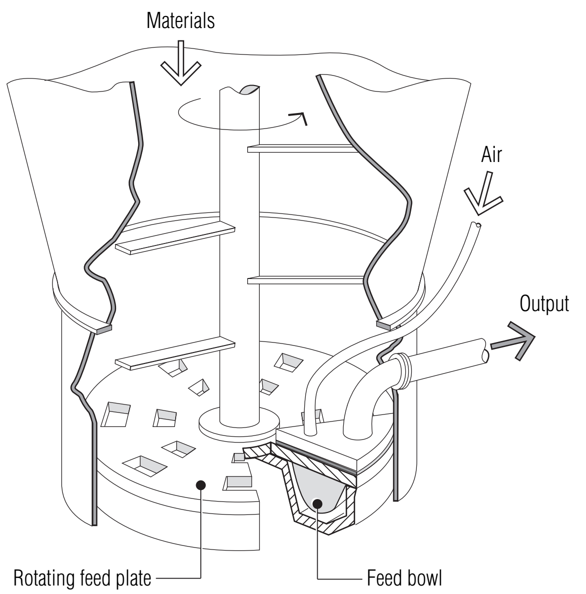


Figure 6.5 *Detail of rotary-feed-bowl machine*

Figure 6.6 *Typical rotary-feed-bowl machine*

Some rotary machines have been modified to handle both wet-mix and dry-mix spraying. No conversion is needed nor are additional accessories necessary.

6.3 Wet-Mix Equipment

Wet-mix shotcrete equipment can be defined as either positive-displacement equipment or pneumatic-feed machines.

Positive-displacement machines make up the majority of the market and are either equipped with mechanical or hydraulic-powered pistons with a variety of cycling valves and surge-reducing devices (**Figure 6.7**), or peristaltic-type squeeze pumps using mechanical rollers to squeeze the shotcrete through a tube into a delivery hose, (**Figure 6.8**). Also, worm pumps (rotor/stator pumps) are used where off-set blades force the mix through a tube. This type of pump is primarily used for application of render or plaster mixes incorporating fine aggregates generally 4 mm minus, but can handle up to 8 mm with the appropriate pump configuration (**Figure 6.9**). All the above positive-displacement machines have compressed air introduced at the nozzle to pneumatically apply the shotcrete mix.

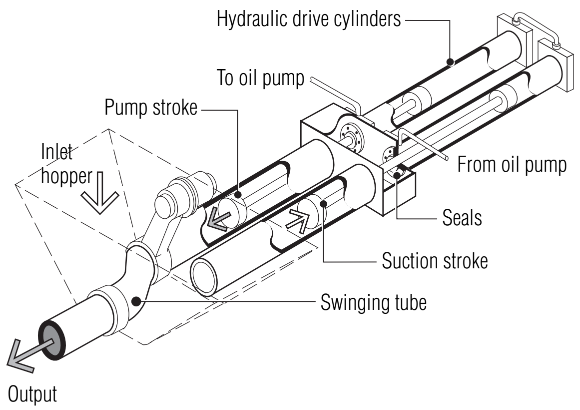


Figure 6.7 *Detail of positive-displacement piston-type wet-mix equipment*

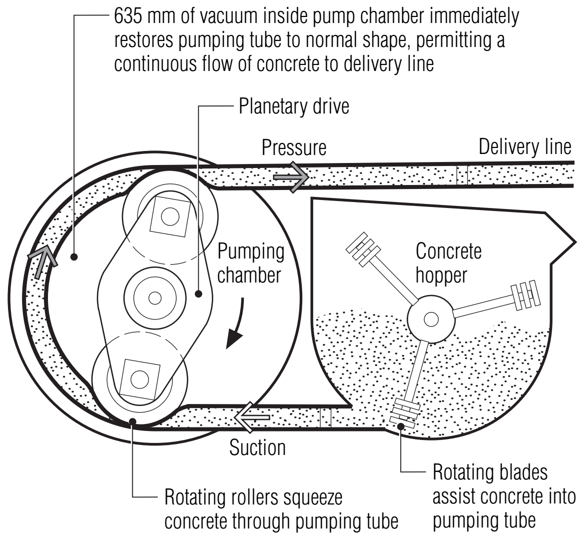


Figure 6.8 *Detail of peristaltic-type (squeeze pump) wet-mix equipment*

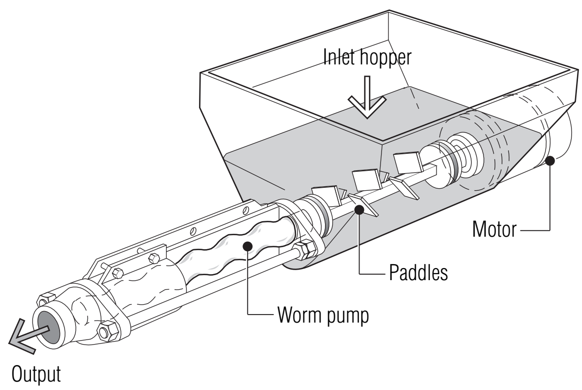


Figure 6.9 *Detail of worm (mono) pump wet-mix equipment*

Pneumatic-feed machines utilise dry-mix technology, as described in **Clause 6.2**, to convey wet-mix shotcrete.

6.4 Ancillary Equipment

6.4.1 Remote-Controlled Equipment

Remote-controlled shotcreting equipment is used to improve the safety and productivity of the operators by:

- Keeping the operator away from unsupported ground,
- Minimising exposure to rebound and dust,
- Allowing access to difficult areas,
- Being less physically demanding than hand-held spraying,
- Increasing productivity through higher volumetric output. The equipment typically consists of a rotating telescopic boom, lance-mounted nozzle, and shotcrete pump mounted onto a vehicle for mobility, while the sprayer controls nozzle movements and pump with remote hand controls. (Figures 6.10 and 6.11).

Figure 6.10 *Remote-controlled shotcreting rig for mining applications*

6.4.2 Dosing Pumps and Systems for Set

Various pumps can be used when dosing accelerators. The type of pump is important because of a need for consistent and accurate dose rates. Typically the two types of pumps used to achieve this are mono or peristaltic (hose) pumps. The capacity of the dosing pump is also important, as a rate of up to 10% of the cementitious content per cubic metre of shotcrete may be required.

Accurate dosing is important and some shotcrete rigs have integrated computerised systems that control and monitor the accelerator dose rates. These units are incorporated into the shotcrete rigs control systems.

Figure 6.11 *Remote-controlled shotcreting rig for tunnel and infrastructure applications*

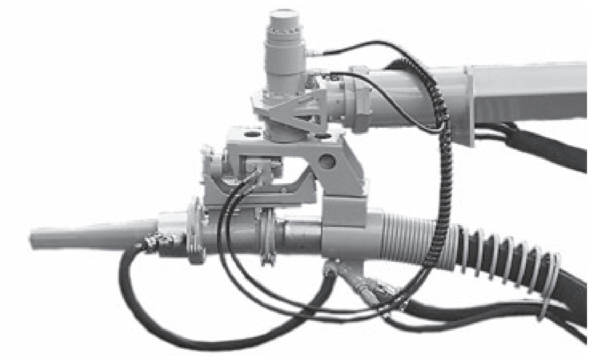


Figure 6.12 *Typical remote-controlled wet-mix nozzle assembly*

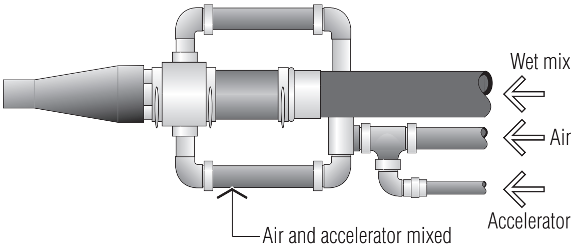
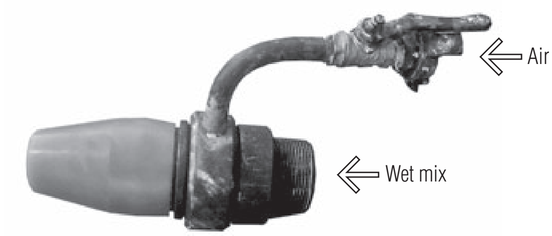
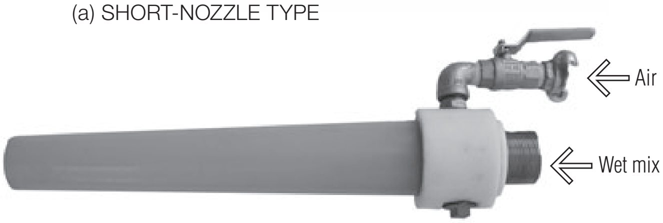


Figure 6.13 *Details of typical wet-mix nozzle for remote-controlled applications*



(a) SHORT-NOZZLE TYPE



(b) LONG-NOZZLE TYPE

Figure 6.14 *Typical hand-held wet-mix nozzles*

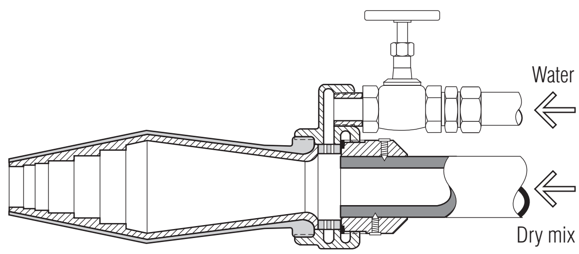
6.4.3 **Nozzles**

The nozzle design is important as it affects the compaction of the sprayed concrete, the rebound during spraying, and the consistency of the mix when dry spraying. In the majority of cases mixing of accelerator takes place in the shotcrete nozzle (**Figures 6.12**, **6.13** and **6.14(b)**). In the dry process, the water ring and assembly within the nozzle is critical to ensure thorough wetting of the mix (**Figure 6.15**).

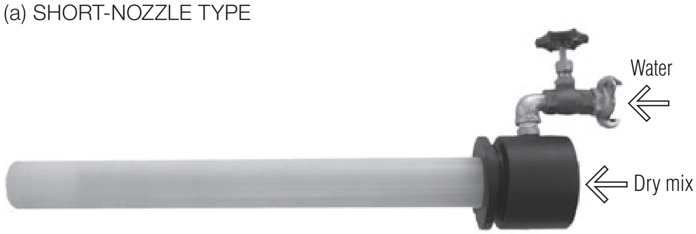
6.4.4 **Material-Delivery Hoses**

Material-delivery hoses are available in several different materials and diameters and should be matched to the shotcrete process. Consideration should be given to the constituent material properties, length of delivery line, working pressures and spraying rates required. The internal hose diameter should be a minimum 4 times the size of the largest aggregate particle size in the mix. When shotcreting with steel fibres in the mix, the fibre length should preferably be no more than 70% of the diameter of the hose. For synthetic fibres this requirement can be relaxed however trials should be undertaken to ensure balling or blockages do not occur.

The last section of the hose before the nozzle should be flexible, have an abrasion-resistant tube, be non-collapsible and also be resistant to kinking. The pressure rating of the hose should always be checked and always be in accordance with the pump manufactures recommendations. All connections and couplings or clamps are to be fitted correctly and have proper safety restraints for blow-out protection.



(a) SHORT-NOZZLE TYPE



(b) LONG-NOZZLE TYPE

Figure 6.15 *Typical hand-held dry-mix nozzles*

7

Batching and Mixing

7.1 Batching of Wet-Mix Shotcrete

Batching is the process of weighing or measuring out by volume the ingredients as specified. *Mixing* is the process of combining the ingredients so that they are uniformly distributed. *Agitating* is maintaining the mix in a usable condition until required.

Shotcrete and mortar should be batched and mixed in accordance with the requirements of AS 1379. The ability of the mixer to mix uniformly should have been established by testing for uniformity of mixing as specified in AS 1379. The production of shotcrete or concrete in Australia is generally done by what is commonly called the dry-batching or the mobile-mixing method. Alternative methods such as central- and staged-mixing are used, although not as widely as the mobile-mixing method. The Australian Standard for mixing guidelines shall be adhered to for each mixing method.

Although no one method in batching concrete is generally better than the other if the concrete is mixed in accordance with the Australian Standards and equipment manufacturers instructions, each method may provide the user a more efficient method of concrete production depending on their specific circumstances and requirements.

Central Mixing

Central mixing is carried out from a permanently-mounted mixer located adjacent, or is part of the suppliers batching equipment. The ingredients are completely mixed before discharge into the appropriate handling equipment.

Staged Mixing

Staged mixing is where the producer partially mixes all the batch ingredients in a central mixer before transferring the partially-mixed ingredients to a mobile mixer for final mixing before discharge.

Mobile Mixing

Mobile mixing is a truck-mounted mixer that is charged with all the ingredients, at a centralised batch plant. This method is the most widely adopted system for concrete or shotcrete production in Australia.

7.2 Batching of Dry-Mix Shotcrete

Most dry ingredients are usually premixed at a factory, packed in bags, or batched at a concrete plant. The moisture content of the mix (prior to the majority of water being added at the nozzle) should be between 2 and 5% to minimise dust production at the shotcrete pump. More than 5% moisture content can cause blockages in the line.

7.3 Mix Consistency

7.3.1 General

The concrete or mortar required for shotcreting depends on the type of conveyance equipment, distance of delivery and the application procedure. For a given cement content and W/C ratio the consistency or flow can be adjusted by chemical admixtures added at the mixing plant or on site.

7.3.2 Fibres and Admixtures

The manufacturer or distributor should be consulted for the recommended methods of addition, which can vary between types of fibres. At large sites it is becoming more common to use automated dosing for fibres.

Admixtures should be dosed in accordance with AS 1379 and specific manufacturers recommendations Typically admixtures are dosed within ± 5%/ml, with automatic dosing equipment.

7.3.3 Temperature at Batching

Shotcrete or mortar should not generally be batched if the temperature of the materials are below 5˚C or more than 35˚C, unless adequate precautions are undertaken. In conditions outside this range a concrete technologist should be consulted.

8 Delivery

8.1 General

Delivery involves getting the shotcrete to the equipment in adequate quantities when required and is a major consideration, particularly in underground construction. There are many ways to get the shotcrete to site including truck-mounted shotcrete agitator, slick-line, bore-holes and dry-bulk bags. The choice of delivery method for the shotcrete material depends mainly on the shotcrete process (wet or dry), access, material handling system, location of working places, and demand of shotcrete per shift.

Transportation of the mixed shotcrete from the mixing plant to the point of placement must be carried out in a vehicle that will prevent segregation, loss of material and premature stiffening.

8.2 Truck-Mounted Agitator

When delivering shotcrete in a truck-mounted agitator it is necessary that the vehicle provides adequate agitation. Equipment or plant that is identified as shotcrete agitating plant should not be used for mixing concrete until it has been shown by the mixing uniformity test procedure laid down in AS 1379 that the equipment or plant can mix shotcrete uniformly.

8.3 Slick Line

When transporting shotcrete down an inclined or vertical slick line certain aspects need to be considered. Generally the slick-line diameter should be between 150–300 mm depending on the vertical drop and mix consistency. Since shotcrete is an abrasive material, consideration of wear rates due to free fall velocities and associated friction should be made.

Before a slick line is used, it should be lubricated with a cement and or suitable slurry mix. Also some form of energy dissipator is required at the end of the line to control the exit of the concrete from the line. This is generally achieved using a 'kettle' of some suitable design. The kettle may also, if designed in such a way, perform the function of a re-mixer in case any minor segregation has occurred.

More information about slick lines is described in **Clause 5.7.3**.

8.4 Pumping

Shotcrete pumps are used to convey shotcrete through a pipeline, or hose, to the nozzle. The pump should be in good operating condition and well maintained. Particular care should be taken when washing out the pump and lines at the end of each shift.

Information on pumps and related matters can be accessed from the following sources:

- American Concrete Institute web site at: *www.aci-int.org*
- American Shotcrete Association web site at: *www.shotcrete.org*
- International Centre for Geotechnics and Underground Construction web site at: *www.icguc.com*

9

Application

9.1 General

The application of shotcrete can be divided into two primary methods, hand spraying and mechanised spraying. Hand spraying is generally used for applications in civil construction and concrete repair. Mechanised spraying is used in underground mining and tunnelling applications and is ideally suited to overhead application. Mechanised spraying can, in instances where access and height are within their capacity, be used also for the stabilisation of slopes in open pit mines. Road & rail cuttings are generally more suited to hand spraying where boom lifts and cherry pickers allow the sprayer to reach higher and distant areas. There are other more specialised methods of mechanised application available such as remote shaft lining and the use of shotcrete spray equipment mounted onto tunnel boring machines.

The use of experienced and competent operators who have been adequately trained in the application of shotcrete is essential to ensure the quality of any shotcrete application. It is essential to carefully consider the equipment type, condition, and performance requirements before the commencement of spraying. Well-trained, competent & experienced site supervision is paramount.

9.2 Services

9.2.1 Power

A reliable and earthed electrical power supply at the correct voltage should be provided to electrically-powered machines in accordance with the relevant Australian and site standards.

9.2.2 Water

Water quality and temperature will affect the shotcrete performance. The water should be of potable quality and of suitable temperature, typically 18–25˚C for shotcreting applications. Water quality should comply with AS 1379[38]. It is also important to have an adequate supply of water with sufficient pressure and availability for the particular application, curing (when carried out), and cleaning.

9.2.3 Lighting

Lighting is important to improve safety and helps the crew to spray a quality product with the correct thickness and minimum rebound.

9.2.4 Ventilation

All enclosed areas need to be well ventilated due to the dust, fumes and other airborne contaminants created during the process of shotcrete application from the equipment and shotcrete. In underground mining applications, quality ventilation is essential to dilute and remove machinery fumes, dust and chemicals from the area being sprayed.

9.2.5 Compressed Air

A well maintained supply of compressed, clean, dry air is needed with adequate pressure and volume. The supply depends on the particular equipment specification, the condition of the equipment, on-site operating conditions, hose length and diameter.

As a guide, typical air requirements are:

- For wet shotcreting, the air consumption is about 12 m3/minute (425 cfm) at a pressure of about 600–700 kPa (88–102 psi).
- For dry shotcreting, the air consumption is about 15 m3/minute (530 cfm) at a pressure between 300–600 kPa (44–88 psi).

9.3 Training

The training of shotcrete personnel is essential. The sprayer is the key to successfully placed shotcrete, whether it is by wet or dry process or manual or remote controlled placement. They should be considered a skilled operator who physically directs and controls the placement of the shotcrete. They must also have a thorough understanding of the equipment's operation, maintenance requirements, safety procedures and quality requirements of the project. There is no published training material for sprayers in Australia. North American practice differs from that in Australia, but published material is available for North American sprayers. No widely recognized programme of sprayer certification is available in Australia. One could examine the ACI Craftsman Workbook CP-60[54] and the ACI Concrete Craftsman Series 4 (CCS4)[55] *Shotcrete* *for the Craftsman* as a starting point for certification of hand sprayers but this is of limited relevance in Australia. Some shotcreting contractors in Australia have already developed their own training programmes and initiatives by which personnel are certified under these in-house programmes after being trained by proven & highly experienced operatives.

9.4 Safety

9.4.1 General

In the first instance it is necessary that statutory and site specific Occupational Health and Safety regulations are adhered to without exception. In particular the following should be undertaken and reviewed as a minimum:

Competency & training of operators and personnel

Statutory & industry inductions

Site inductions

Full safety plan must be in place to include at least

- Risk assessments
- Job safety & environmental analysis
- Safe work method statements
- House keeping
- Equipment prestart checks & maintenance
- Toolbox talks
- Unsupported ground work procedures
- Product MSDS requirements
- Moving equipment
- Explosives
- Work place inspections

9.4.2 Minimum Recommended Protective Equipment

All personnel must wear a safety helmet for head protection, approved footwear and high visibility vest. The sprayer and others near the shotcreting operation also require protection from rebound, cement dust and slurry, such as approved dust masks, respirators, eye and ear protection (see AS1067, AS1270, AS1337, AS 1715, and AS1800). Due to the irritating nature of wet cement and various chemicals used in shotcrete, skin protection such as a barrier cream is essential. Appropriate protective clothing for the sprayer (long sleeves and pants) should always be worn. The minimum additional PPE requirements for an underground sprayer is goggles and respirator or the use of an "airstream" type positive displacement helmet which filters air using a small motor that runs from a standard underground cap-lamp battery pack (see **Figure 9.2**). The stream of filtered air is directed at the visor preventing it from fogging.

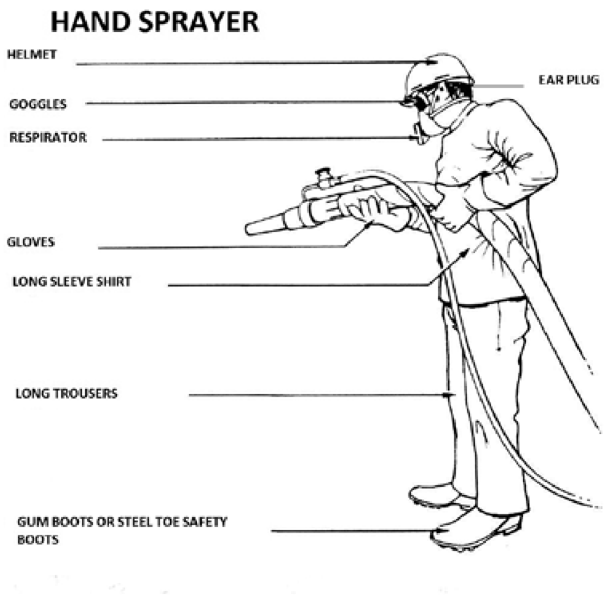


Figure 9.1 *Personal protective clothing and equipment appropriate for a hand-spray nozzleman*

Figure 9.2 *Operator wearing an "air stream" helmet*

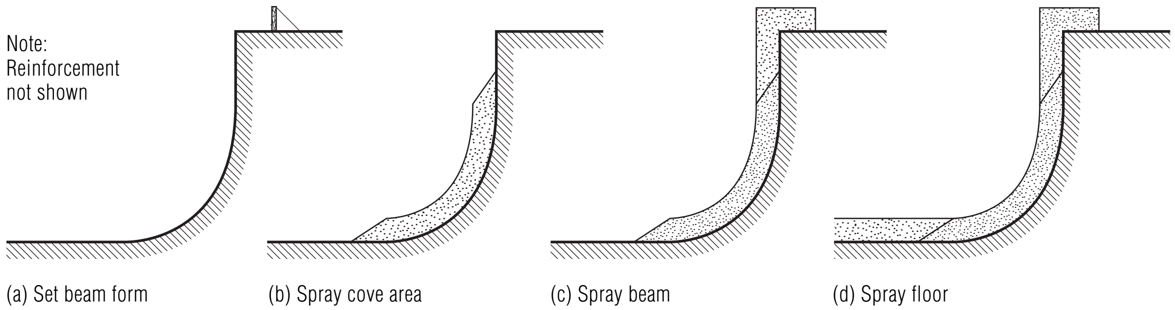


Figure 9.3 *Careful sequencing when spraying free-form shotcrete on earth surfaces, such as inground swimming pools, can prevent slippage*

9.5 Hand Spraying

9.5.1 Substrate and Surface Preparation

9.5.1.1 General

The surface preparation required depends on the condition and nature of the substrate against which shotcrete is to be placed. In all cases, where flows of water could interfere with the application of shotcrete or cause leaching of cement, the water should be sealed off or diverted by pipes, gutters, strip drains or sheets to points where they may be plugged off after spraying. In underground construction, pre-injection of various strata using cementitious or chemical grouts is often used to prevent water ingress.

Most importantly, all substrates or surfaces should be clean, free of dust, oil, excessive water and other contaminants which might interfere with bond. Pre-damping of most surfaces other than steel and impervious formwork is essential to minimise loss of moisture in shotcrete.

The following provides particular recommendations for different surfaces.

9.5.1.2 Formwork

Non-rigid formwork is used where the appearance of the back of the shotcrete is of no importance. Examples include Hessian, or fine-gauge expanded metal attached to light framework. It should be firmly fixed and held taut to minimise vibration or flapping so that sagging is avoided and good compaction of the shotcrete can occur.

Rigid formwork. Timber or steel formwork where used should be coated with a purpose-designed release agent to prevent absorption of moisture and adhesion of the shotcrete. Additionally, it should be adequately supported and strengthened to prevent excessive vibration and deflection.

A polythene membrane stretched over the form can also provide a separating surface. Plywood is generally sufficient for rigid formwork. Smooth-faced materials need only be employed when the face is to be accurately positioned and a 'fair-faced' surface provided.

9.5.1.3 Other Surfaces

Earth Surfaces

The range of shotcrete applications covering earth surfaces are broad and include swimming pools, slope stabilisation and protection, canal linings, open channels, reservoirs etc. Proper preparation and compaction of the earth is essential to prevent erosion during application. The earth surface is then trimmed to line and grade to provide adequate support and to ensure the design thickness of the shotcrete. A moisture barrier may be installed which will prevent movement of moisture from the newly-placed shotcrete into the earth. Extra care in the sequence of application (**Figure 9.3**) or a flashcoat is recommended to prevent shotcrete slippage.

Rock Surfaces

The substrate should be free from loose materials, dust and films (such as oils). This can generally be achieved by using a combination of water and compressed-air jet. Wet sandblasting can also be considered. In underground tunnels and mines, 'scaling' is often carried out by mechanical hydraulic-pick hammer, or high-pressure hydro scaling to remove loose rocks and scats. Cleaning should start from the top working downwards.

Timber Forms

If forms are to be removed after use, a form-release agent should be applied to the form to prevent absorption of moisture and to inhibit the bond between shotcrete and the form.

Steel Surfaces

Before shotcrete is applied over steel surfaces, grit blasting or other appropriate methods should remove all traces of loose mill scale, rust, oil, paint, or other contaminants.

Shotcrete/Concrete Surfaces

All loose, cracked or deteriorated surfaces should be removed and taken back to sound concrete. Water blasting, chipping, scabbling, light hydro demolition or other mechanical means should be used to remove any contaminated concrete, from chemicals, oils or corrosion products. Where reinforcement is exposed, it should be free from loose rust, scale or other deleterious matter likely to effect durability and bonding. If required a chemical bonding agent or slurry coat can be applied to the surface. Where shotcrete is to be placed against a smooth concrete surface, it should be abraded using either of the aforementioned mechanical methods.

Masonry Surfaces

Require preparation similar to that of concrete surfaces. Moisture absorption of the masonry is normally high and pre-wetting usually considered essential.

Frozen surfaces

Should generally not be shotcreted, particularly where bond and rapid setting characteristics are required.

9.5.2 Spraying Procedure

9.5.2.1 Temperature at Point of Application

Shotcrete or mortar should not be applied if the temperature at the time of application is less than 5˚C or more than 35˚C, unless adequate precautions are undertaken. When necessary to do so it is essential to seek advice from a qualified concrete technologist to achieve the desired results.

9.5.2.2 Windy and Draughty Conditions

It can be difficult to spray shotcrete in windy conditions. If there is a likelihood of extreme conditions, provision should be made to screen the nozzle, the jet and the surface to be treated to prevent the mix from being blown out of the jet. In the open, a light metal cone fitted over the nozzle tip at its apex can sometimes suffice. Particular consideration should be given to stray paste or mist particles that can easily travel with wind settling on surrounding surfaces, or in high wind situations, some distance away.

Winds and draughts also promote cracking by rapidly drying the fresh concrete. Screening of the applied surface should be provided where possible and evaporation retardant considered. Curing procedures should be applied as soon as possible.

9.5.2.3 Rainy Conditions

Unless adequate protection is provided, shotcrete should not be placed during rain or when rain appears imminent. On exposed sites fresh shotcrete must be protected against rain. Heavy rain falling on freshly-placed shotcrete may cause it to slip or run compromising finish and appearance and will, at least, reduce its final surface strength and durability.

9.5.2.4 Set Up

Once the crew and equipment have established their work area the material delivery hoses/pipes are checked by connecting them directly to an air supply fitted with a pressure gauge to ensure that they are clear. Most shotcrete machines are fitted with a take-off point near the gauge for this purpose. Dirty pipes and hoses must be cleaned by kinking, twisting or lightly hammering and blowing out. The material-delivery hoses are connected with as few bends as possible and without any kinks. The reducer should be located as close as possible to the pump discharge point. After the equipment is checked, the hose is securely connected to the shotcrete pump. All delivery lines from the pump to the nozzle should be securely fixed and fully lubricated with cement slurry or approved line lubricant. Under no circumstances shall any petroleum products be used to lubricate the lines.

The delivered mix to the pump should be checked for batch time and appropriate slump before being discharged into the shotcrete pump. With accelerated shotcrete mixes, it is essential not to apply shotcrete into the works until it exhibits the correct setting performance for the project and the accelerator dose rate is correctly calibrated at the nozzle. This operation is normally carried out in a nominated trial area. Furthermore, the correct air pressure and volume for the specific spraying operation should be evaluated by the sprayer and adjusted accordingly.

9.5.2.5 Hand Spraying Technique

Distance from nozzle to the receiving face should be between 0.6 to 1.0 m for hand spraying to achieve the highest degree of compaction and lowest rebound. The optimum distance is influenced by aggregate size, grading curve, required surface finish, air pressure and speed of conveyed material. The nozzle should be directed perpendicular to the face at all times. Manipulation of the nozzle to place shotcrete during either machine or hand spraying should be a circular to oval motion (**Figure 9.4**).

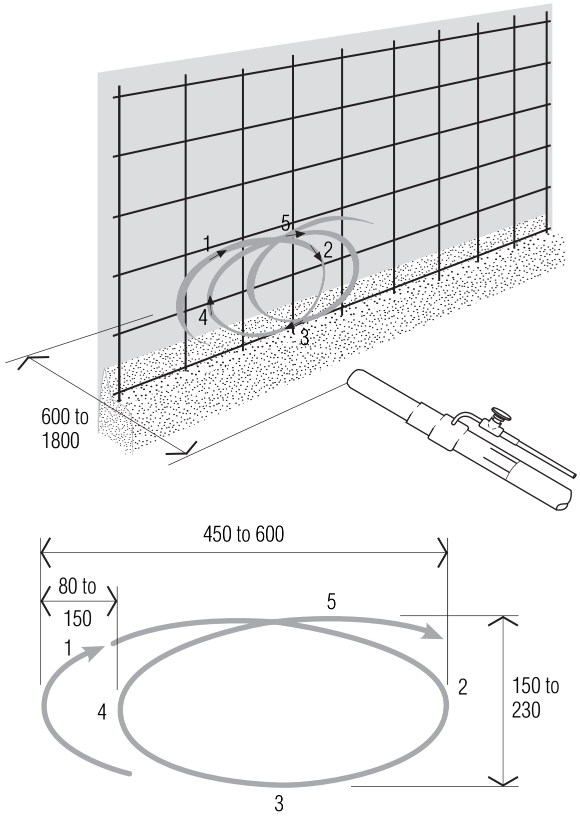


Figure 9.4 *Circular shotcreting motion, and progress of shotcreting from ground up to minimise incorporation of rebound into works*

The sprayer should firstly fill all over-breaks and zones of weakness such as fissures, faults, gravel zones and soft spots if applicable (this process is normally limited to rock/soil surfaces). Spraying should then commence from the lower sections moving methodically upwards (**Figure 9.5**). If accelerator is used, dose rates may be marginally increased as the shotcrete application moves from the base up the wall and overhead. In some cases it may be prudent to apply a series of thinner layers rather than attempting to spray the entire thickness in one pass of the nozzle. Where thick layers are applied, it is important that the top surface be maintained at an approximately 45° slope (**Figure 9.6**). It is important that no subsidence or sagging of the shotcrete occurs. Caution must be taken not to incorporate into the wall any rebound lying at the base of the wall.

The shotcrete should emerge in a steady uninterrupted flow. Should the flow become intermittent the operator should direct the nozzle away from the work until the spray becomes uniform. Adjoining surfaces that are not required to be sprayed should be protected from overspray. Overspray on these adjoining surfaces should be removed.

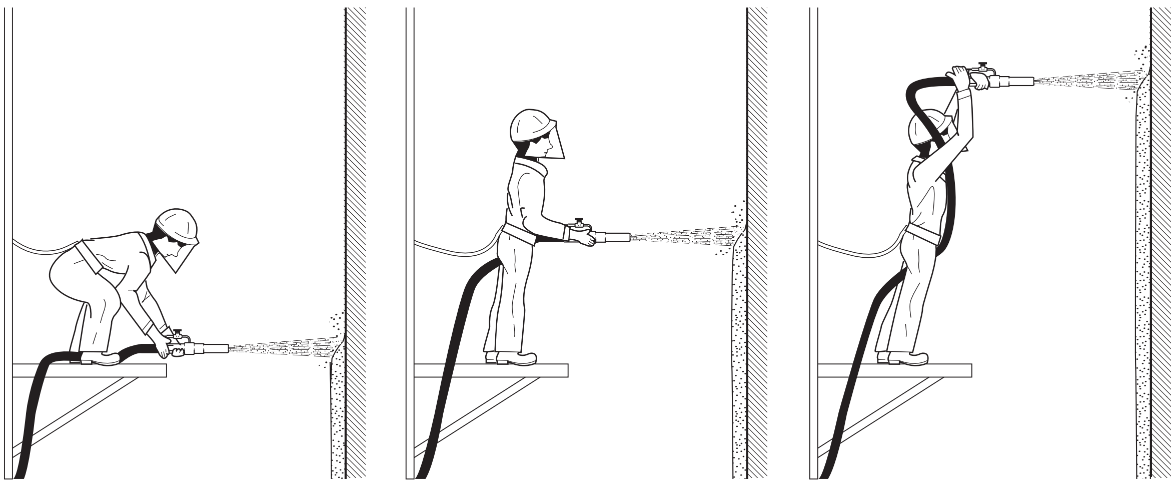


Figure 9.5 *Spraying should commence from the ground and move methodically upwards*

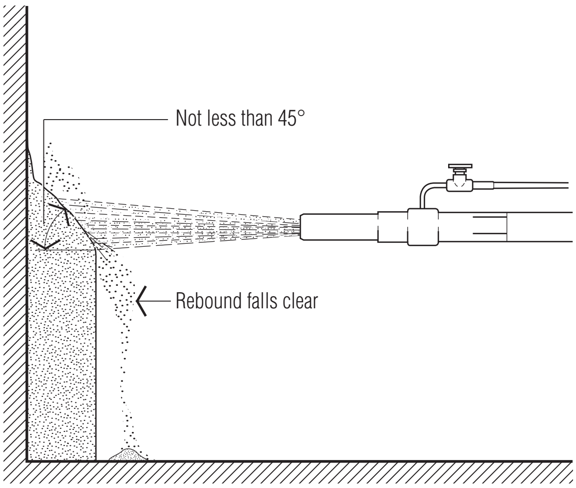


Figure 9.6 *The top edge should be maintained at not less than 45° to avoid rebound material contaminating the shotcrete*

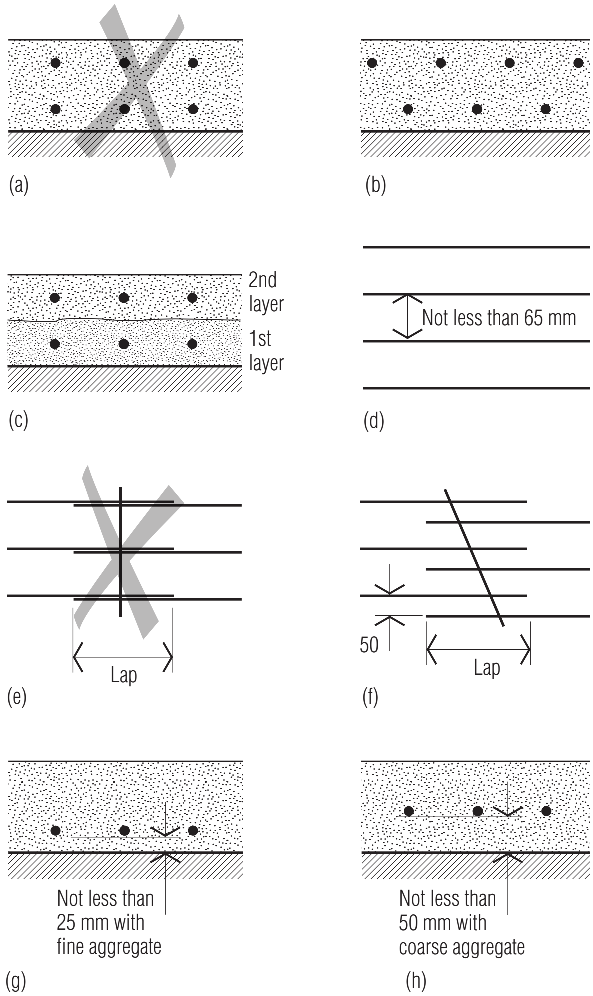


Figure 9.7 *Recommended placement of reinforcing bars relative to substrate and other bars*

9.5.2.6 **Encapsulation of Reinforcement**

Any materials or fixtures to be encapsulated by the shotcrete need to be adequately secured and positioned prior to spraying. Steel mesh reinforcement or rebar should be designed and arranged to facilitate encapsulation and minimise rebound (**Figure 9.7**). When spraying through and encasing reinforcing bars the nozzle should be held closer to the work and at varying angles to permit better encapsulation and to facilitate the removal of rebound. This procedure forces the shotcrete behind the bar while minimising build-up on its front face (**Figure 9.8**). Where bars are closely spaced and it is impractical to spray one layer at a time, more than one layer of bars may be sprayed concurrently, provided the nozzle changes position to ensure encapsulation. If more than 50 mm cover of plain shotcrete is applied, the likelihood of fall-outs is increased, especially when screeding and floating.

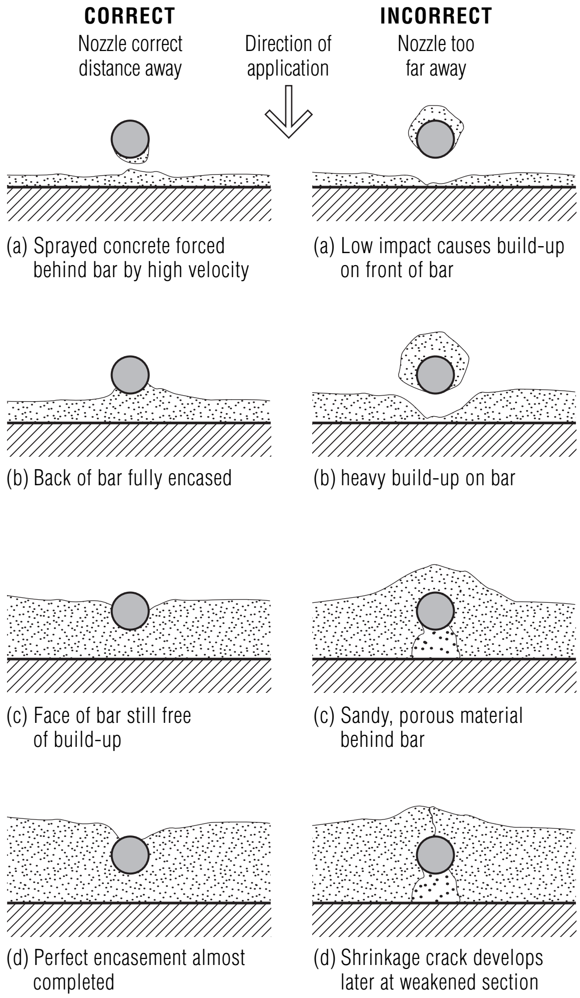


Figure 9.8 *Consequences of poor spraying practice for encapsulation of reinforcing bars*

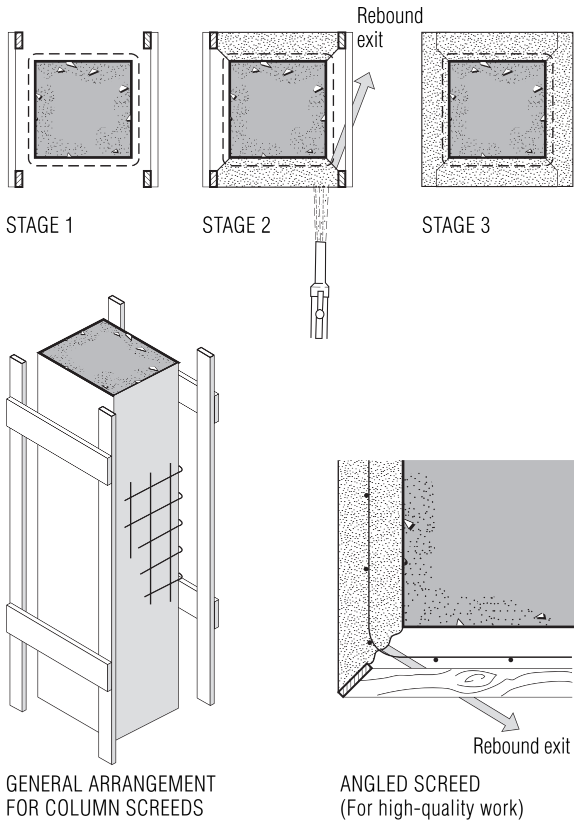


Figure 9.9 *Conventional forms used as alignment control for encasement of an existing column with shotcrete*

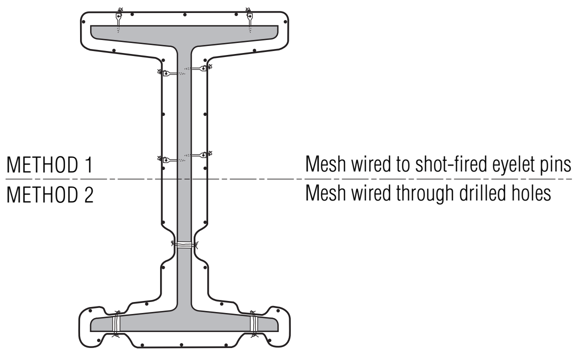


Figure 9.10 *Two methods of anchoring reinforcement to a steel beam for encasement with shotcrete*

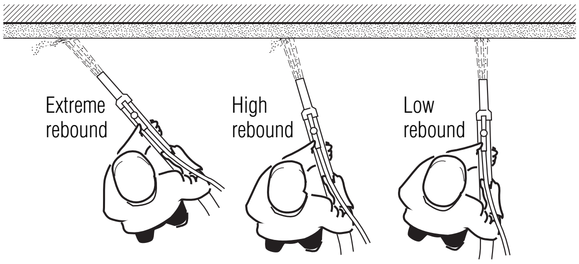


Figure 9.11 *Rebound can be limited by the skill of the nozzleman*

9.5.2.7 Alignment Control

An effective and proven form of alignment control is necessary to establish the required thickness and profiles of the finished shotcrete. Alignment control can be accomplished by the use of guide wires, guide strips, depth gauges, depth probes, conventional forms, or laser guides (**Figures 9.9** and **9.10**).

9.5.2.8 Rebound

Rebound is shotcrete that does not adhere to the surface being sprayed and which ricochets out of the area of placed shotcrete. It must not be re-used in the shotcrete machine nor incorporated in the works. When the jet is directed against a rigid surface the proportion of rebound may be higher then normal. Once a cushion coat of mortar forms on the intended surface the amount of rebound generally reduces. Thus, thicker sections of shotcrete have lower overall rebound than thin sections.

The percentage of rebound depends on a number of factors including:

- Skill and experience of the sprayer and his operation of the nozzle or manipulator (**Figure 9.11**). The distance between the nozzle and substrate has a large influence on rebound as well as the angle of application. The angle of application should be as close as possible to perpendicular.
- Efficiency of the shotcreting equipment, including the air pressure supplied,
- Mix design including aggregate size and grading. (Rebound increases significantly when maximum aggregate size is greater than 14 mm),
- Workability of the concrete,
- Selection of supplementary cementitious materials such as amorphous silica powder or similar materials also helps stick the shotcrete to the wall,
- Type and roughness of surface,
- Depth of shotcrete already on the substrate

9.5.3 Joints

9.5.3.1 Construction or Expansion Joints

End-of-day joints and construction joints are very important in the satisfactory use of shotcrete for construction and protection. An unformed end-of-day or construction joint (**Figure 9.12a**) should come to a tapered edge, over a width of 200 to 300 mm for thicknesses up to 75 mm, and with a proportionately greater width for greater thicknesses. The surface on the taper is brushed to remove laitance and rebound, and allowed to set, but is not to be cut or trowelled in any way. Before shotcreting recommences, the taper is cleaned with an air-water blast and wetted. The whole taper is covered with fresh concrete as soon as possible and the thickness built up from there. Where the joint is expected to transfer compressive load the joint should be formed as a butt joint. For example this would typically occur in a longitudinal joint in an arch or wall.

Screed joints and stop-end joints (**Figure 9.12b** and **9.12c**) are treated similarly; they allow for more even joint work. Joint (b) is often used where the spraying ends at a construction joint. The use of a chemical-bonding agent can be used. Joints (a), (b) and (c) can be further improved by coating the taper with a bonding agent prior to spraying. A cut-back joint (**Figure 9.12d**) is used with marine work; the top surface of the taper has been removed by gentle hacking to prevent possible joint failure due to salt contamination of the taper surface.

For water-tight joints, the use of internal water stops is not recommended as they provide traps for rebound. **Figure 9.13** shows recommended approaches for water-tight joints. Where no specific joints are required in design dummy or V joints are often cut into the face of shotcrete at intervals to break up long spans of walls and attempt to induce controlled cracking.

9.5.3.2 Contraction or Control Joints

Contraction joints may be provided by the pre-positioning of full-thickness strips, usually wood or steel, which are left in place, or by saw cutting the shotcrete shortly after it has achieved final set. The spacing of contraction joints depends on the application and should be designated on the plans. In practice, the spacing usually varies between 5 to 10 m on expected movements.

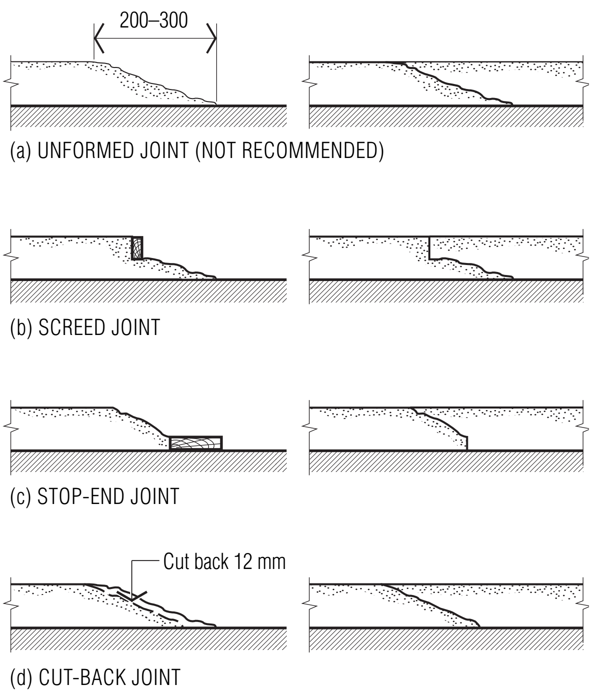


Figure 9.12 *Recommended Practice for Joints in Shotcreted Walls*

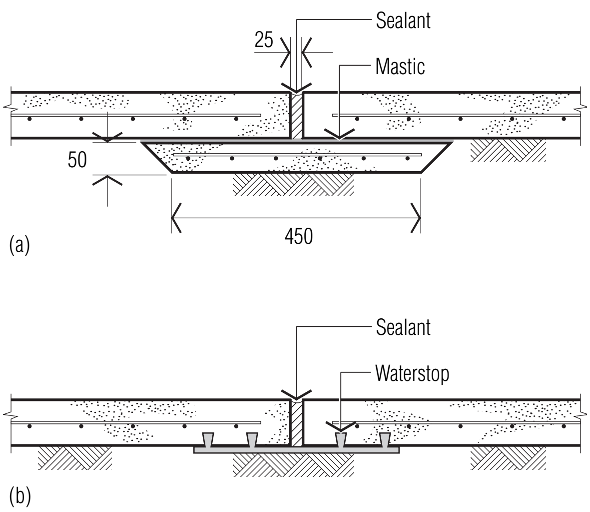


Figure 9.13 *Two methods of producing water-tight joints in shotcreted walls*

9.5.4 **Finishing**

9.5.4.1 **Natural Finishes**

The nozzle/gun finish is the natural finish left by the nozzle after the shotcrete is brought to approximate line and level. It leaves a textured, uneven surface, which is suitable for many applications (**Figure 9.14**).

Figure 9.14 *The "off-nozzle" finish can be suitable for many applications*

9.5.4.2 **Architectural Finishes**

In applications where better alignment, appearance, or smoothness is required, the shotcrete is placed slightly beyond the guide strips, screed/guide wires, or forms. It is allowed to stiffen to the point where the surface will not pull or crack when screeded. Excess material is then trimmed, sliced or screeded to a true line and grade. This is called a *screed finish* which is straight vertically and horizontally but the face remains open exhibiting the drag marks of aggregate and some holes. It is then possible, if required, to steel trowel which offers a smooth glassy finish or Woodfloat and then sponge the screeded surface offering a render like final finish.

In general, an assistant following behind the sprayer does the cutting and trowelling. It is bad practice to trowel too-heavily as this disturbs the shotcrete and destroys its essential compaction.

With a skilled operator it is possible to achieve high-quality decorative and unique architectural forms such as rocks, sandstone blocks and rock faces (**Figure 9.15**).

Figure 9.15 *Decorative rock-like finish to shotcrete wall*

9.5.6 **Curing**

The same curing considerations for concrete apply to shotcrete. Shotcrete, like concrete, must be properly cured so that its potential strength and durability are fully developed. This is particularly true for thin sections, textured surfaces and lower water/cement ratios that can be associated with shotcrete.

All shotcrete surfaces should be cured by one or more of the following methods:

- Wet curing,
- Liquid membrane-forming curing compounds,
- Internal curing agents,
- Natural curing.

Wet curing may be carried out using hessian, canvas or plastic sheets or other suitable materials provided they are kept continually wet. Water used for curing should comply with AS 1379[38]. Wet curing should be applied to surfaces immediately after the completion of the application and finishing operations. Where wet curing is to be used , a minimum of three continuous days water curing or equivalent should be specified, and in particular applications, seven continuous days water curing or equivalent may be specified.

Liquid membrane-forming curing compounds should comply with the requirements of AS 3799[56]. Curing agents that impair bond should not be used where a further layer of shotcrete is to be applied. If necessary, the curing agent should be removed by water jetting, grit blasting or a similar process, before application of the next layer (eg. EFNARC specification[57]).

Internal curing agents are available and have been used on many projects. They conform to the requirements for curing compounds in AS 1379[38] *Specification and supply of concrete*.

Natural curing may be considered if atmospheric conditions surrounding the shotcrete are suitable, such as when the relative humidity is at or above 85%. Care should be taken to ensure that the concrete does not dry out due to reduced relative humidity, higher air temperature or increased wind/air speed particularly in tunnels.

Rapid drying of shotcrete at the end of the specified curing period should be avoided. For all curing regimes, the shotcrete surface should be maintained at a temperature not less than 5°C throughout the curing period.

9.6 **Shotcreting Sequences**

9.6.1 Retaining wall

The sequence of photos shown in Figures 9.16(a) to (f) shows the method by which a reinforced retaining wall can be constructed as a series of shotcreted shoring panels between piles. The process begins by installing the piles followed by installation of ground anchors and placement of reinforcing steel to the required dimensions and profile. Spraying commences at the base of each panel (a) and proceeds by working up toward the top (b). Once the top has been completed the shotcrete surface is marked using a level (c) and screeding proceeds (d). The walls are then floated (e) before a final finish is applied using a sponge (f).

Figure 9.16 *Summarising the general process in a typical project. (a) begin spraying from the ground up, single-layer reinforcement preferred (b) topping-off, keep top surface at not less than 45° (c) establishing lines using spirit level (d) begin screeding to reference surface (e) complete screeding and floating (f) finish surface with a sponge*

9.6.2. **Swimming Pool**

To construct a swimming pool using shotcrete, the pool is at first formed up, reinforcement and plumbing installed ready to be sprayed (See **Figure 9.17**a). (b) Spraying starts from the radius at the bottom of each wall and proceeds until the walls and radii are completed. As the walls are sprayed, cutting and screeding commences, (c) the tops and/or coping are then cut to level. (d) The floor is then sprayed, and finally (e) the steps, spa, and other details are cut and hand-sculpted.

9.17 (a) *Formwork, steelwork, and fittings ready for shotcreting.*

9.17 (b) *Spraying the walls from the bottom up.*

9.17 (c) *Cutting and screeding of walls following spraying*

9.17 (d) *Cutting the walls and coping*

9.17 (e) *Spraying the floor of the pool*

9.17 (f) *Cutting and hand-sculpting the steps*

9.6.3 In-ground Holding Tank

Shotcrete is an effect method to place concrete onto ground surfaces to produce free-form structures such as holding tanks. The sequence of photos in 9.18 (a) to (f) shows the construction of a storm water holding tank. After excavation of the hole and installation of reinforcement and services (if required) (a), spraying commences at the base of each inclined wall (b) and proceeds upward to the crest (c). The sprayed surface is progressively cut, screeded, and floated (d) until all the walls are completed. The floor is cast using the same shotcrete mix as used for the walls (e). The floor and walls are finished using steel trowels or a bull float (f).

9.18 (a) *Reinforcement in place prior to start of spraying.*

9.18 (b) *Spraying commences at base of each wall.*

9.18 (c) *Proceed to the top of each wall and cut to finish.*

9.18 (d) *Cut, screed, and float each wall, finish using steel trowel.*

9.18 (e) *Cast the base of the tank using the same shotcrete mix.*

9.18 (f) *The tank floor is completed using bull floats only.*

9.7 **Mechanised Spraying**

Mechanised spraying is used extensively in underground and open pit mining and in civil tunnelling and slope stabilisation activities. Mechanised spraying (most commonly using the wet mix system) allows the application of higher volumes of shotcrete and has the advantage of remote application where the machine operator can guide a boom mounted nozzle to reach areas that would otherwise be inaccessible. This section relates primarily to the use of mobile, wet mix shotcrete machines as described in section 6.4.1, though other mechanised methods are also discussed briefly. Typical machines are shown in **Figure 9.19**.

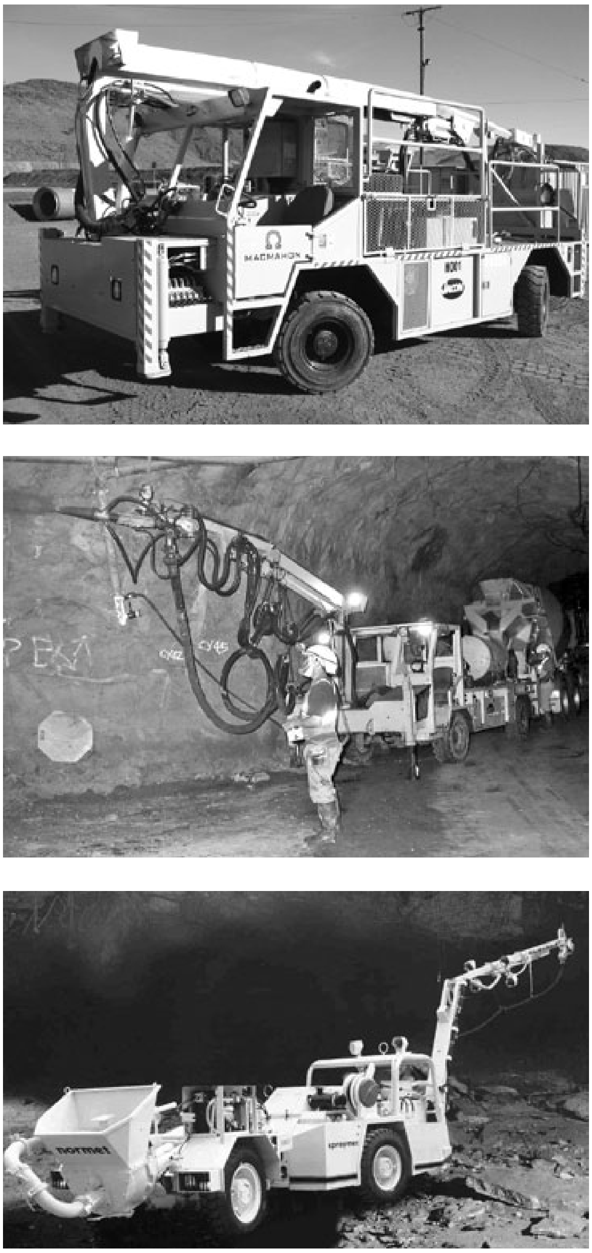


Figure 9.19 *Examples of wet mix spraying machines*

The advantages of mechanised spraying include higher output which can reduce cycle times, cost savings due to reduced labour and rebound, improved quality and improved working conditions for the sprayer.

9.7.1 **Set Up**

9.7.1.1 **Inspecting for Hazards Prior to Spraying**

Before approaching any area where shotcrete is to be applied, the machine should be parked in a safe position and an inspection of the work area should be carried out on foot. As shotcrete is often applied in areas where there is no or insufficient ground support existing, the risk of rockfall should be assessed and a safe position within supported ground should be ascertained for the rig to be set up. In an underground environment, the ventilation to the work site should be assessed for its adequacy to remove the dust and fumes that will be generated during spraying from the work area. Access to the work area by other personnel and equipment not related to the shotcrete process should be restricted through use of signage and barricades.

The surface to be shotcreted should be examined for any remaining misfired explosives (if it has been exposed through recent blasting), loose ground, water seepage and any signs of ground movement. The operator should also take this opportunity to identify any areas that will be difficult to spray (such as shadows). In an underground environment, adequate lighting is critical to ensure that these hazards can be identified by the operator and a high-powered hand-held torch is recommended for inspections. After a thorough inspection and risk assessment, the shotcrete machine can be moved into position.

9.7.1.2 **Set up of Machines**

Spray machines are usually supplied with concrete through the use of a mobile agitator truck. These trucks may be used to both mix and transport the concrete or simply to transport it (see figure x). Commonly, the truck will discharge the concrete mix into a hopper located at the rear of the spray machine. The concrete agitator truck will reverse up to the spray machine hopper and is guided into position by a spotter. The spotter needs to remain in view of the agitator truck operator at all times. All personnel involved in this process must be aware of the risk of being crushed between the spray machine hopper and the rear of the agitator truck and communication is of paramount importance, especially in an underground environment where it will be dark and may be noisy.

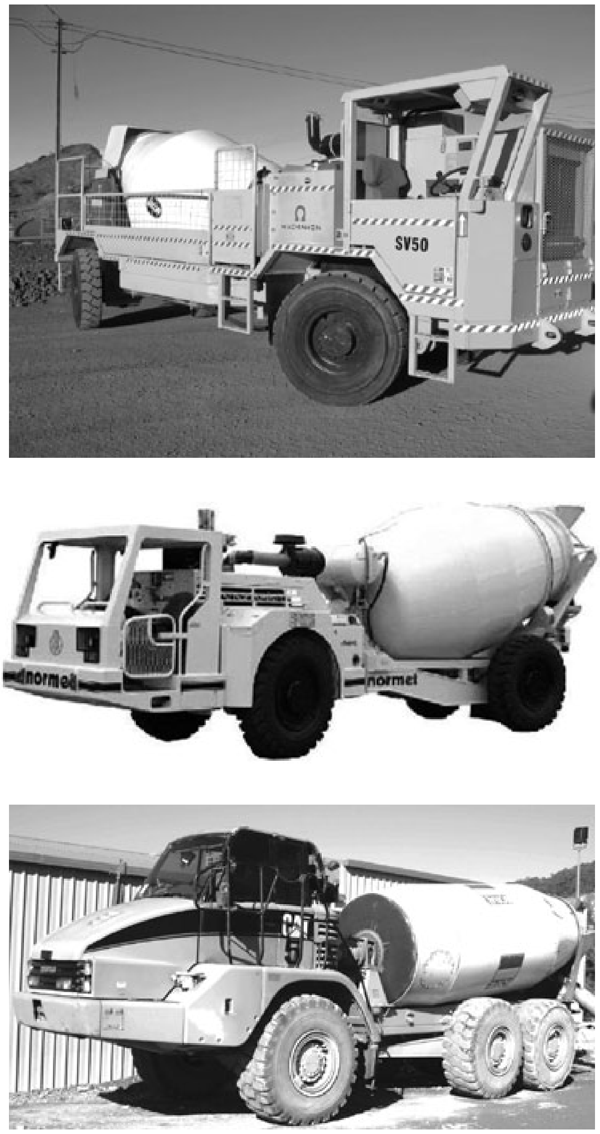


Figure 9.20 *Examples of underground agitator trucks used in mines*

When working on inclines or declines, agitator truck wheels are chocked so that uncontrolled movement of machinery does not occur. The shotcrete machine is stabilised through the use of hydraulic jack legs. Conventional road-going agitators are not recommended for use in mines because they do not have brakes of sufficient capacity.

9.7.1.3 Dealing with Delays

In a mining environment it is not unusual for delays to shotcreting to occur. In the event of delays, care must be taken to prevent hydration of the concrete. Stabiliser must be applied to the load at the recommended dosage rates and continuous mixing should be avoided. Any chemical or water addition after batch should be noted on the concrete delivery docket records. Water addition should be avoided due to detrimental effects on strength. When the load is able to be sprayed again, the bowl should be spun for a sufficient period of time before discharge to ensure that the load is remixed adequately.

9.7.2 Preparation of Substrate

Preparation of the substrate is critical to the performance of shotcrete. In mining and most civil applications, the substrate is commonly rock or soil. Shotcrete is also often used in mining when developing tunnels through backfilled stopes. Backfill can essentially be considered a consolidated soil like material.

To ensure adequate bond of the shotcrete to the substrate, all material such as dust and loose rock should be removed prior to the application of shotcrete. Removal of loose rock is achieved through a process known as scaling. The surface should also be damp (but without free water) to prevent the bond area drying out due to the absorption effect of the shotcrete setting. The surface should be cleaned immediately before spraying to prevent dust resettling on the surface.

9.7.2.1 Scaling

There are several types of scaling used in mining and civil applications, though the most common are mechanical scaling using either a purpose built scaling machine or a development drill or "hydro-scaling" using a water jet (Clements et al[36]). Hydroscaling improves bond strength in addition to removing lose ground. Scaling may not be appropriate at all in some situations where very weak rock or soils exist or where backfill masses are being mined through. In these instances, the substrate is usually prepared by lightly washing the surface only.

Where shotcrete is to be applied to ground, mechanical scaling using a hammer or drill bit is not necessarily required. This is because the small fissures and cracks in the ground will be filled with shotcrete, thus stabilising the loose ground with the added advantage of maintaining a better drive profile.

Hydroscaling uses a high pressure water jet to remove loose rocks and dust from a surface. The water pressure will typically be kept between about 3000psi and 6000psi to be effective. Hydroscaling pumps are usually fitted to shotcrete spray machines to enable the same piece of equipment to both hydroscale and spray. The hydroscale nozzle is located at the head of the boom, close to the spray nozzle.

When hydroscaling an area, the shotcrete adjacent to where the current application will occur should also be hydroscaled at least one metre back from the fresh rock to ensure adequate bond of the overlapping shotcrete to the previously applied shotcrete. The operator should then progressively scale the rock to be sprayed from closest to farthest and from top to bottom such that the boom is never exposed to unscaled ground. If large, unstable blocks are visible that may pose a hazard to the boom during spraying and cannot be removed using hydroscaling, mechanical scaling may be required before shotcrete application commences. If an area is mechanically scaled, it is still advantageous to hydroscale to ensure complete removal of any remaining dust and films.

9.7.2.3 Back forming

Shotcrete can also be applied to formwork of some kind in order to form a structure such as a barricade or protection for mine services (such as cables and pipe work). Often in underground mining steel mesh and hessian cloth are used for this purpose. When preparing a surface such as this to be sprayed it is important to minimise movement of the material used as formwork so that excessive rebound does not result.

9.7.2.4 Other Considerations

Rock surfaces that are to be shotcreted may be required to be geotechnically mapped or photographed as they will be obscured by the lining. Ideally this is performed after scaling and before spraying.

Excessive water ingress is a problem for mechanical spraying as with hand spraying and measures may need to be taken to reduce or divert the water flow prior to spraying. Alternatively, drains may be pre-installed to allow the water to flow out of the shotcrete instead of building up pressure behind it.

9.7.3 Spraying Procedure

9.7.3.1 Preparing to Spray

Before any shotcrete is sprayed, the shotcrete machine should be carefully coated with a layer of form oil to assist with cleaning of the machine after spraying. The shotcrete nozzle should be checked for cleanliness and wear. Both of these factors can affect the shotcrete velocity through the nozzle and hence the compaction that is achieved. Most nozzles have some form of wear marker inherent in their design which will indicate when they are required to be changed.

Accelerator lines must also be checked before spraying is commenced. This is done by turning the air valve to the nozzle off, pointing the nozzle to the ground (to stop accelerator flowing down the concrete lines) and slowly turning on the air supply to check for leaks and pressure and then turning on the accelerator. The flow of the accelerator can be checked from a gauge on the pump, or assessed through timing the discharge into a calibration jug. It should be ensured that the dosage rate matches the manufacturer's recommendations for the cement content of the mix.

The shotcrete machine's pump and delivery lines must initially be primed using a small amount of slurry. This material should be discharged onto the floor of the excavation and not applied to the surface to be supported. Priming may not be required if the lines are still wet following cleaning from a previous load.

The slump and condition of the shotcrete mix should be assessed by the sprayer as it is initially discharged into the hopper. The slump of the shotcrete can usually be visually assessed adequately by an experienced operator or alternatively a slump test may be performed. The sprayer should also take this opportunity to check the mix for any evidence of fibre balling or other large lumps which may cause blockages. The protective grid over the shotcrete hopper must be put into place to stop any large material entering the hopper.

Before spraying commences, the sprayer must also consider where he or she should be standing. The necessary position is under supported ground in a location where the area for shotcrete to be applied to is clearly visible. When operating in a tunnel end, the sprayer will usually need to start on one side of the machine to spray the first half and then will be required to walk around the machine and agitator truck to a second position where the area to be sprayed on the other side of the tunnel is visible from.

9.7.3.2 Spray Technique

To minimise rebound and maximise compaction, the nozzle must always be kept a distance of one to two metres from the surface being sprayed. The correct nozzle angle is also important and should be as close as perpendicular to the surface as possible.

The sprayer must first spray all fissures and faults to ensure that they are filled with shotcrete. All back angles (shadows) and possible areas of rebound accumulation should then be sprayed (see **Figure 9.21**). Following this, the first layer of shotcrete may be sprayed onto the surface. The operator should start at the lowest point and work forward in a horizontal oscillating pattern to spray an even layer of shotcrete onto the surface.

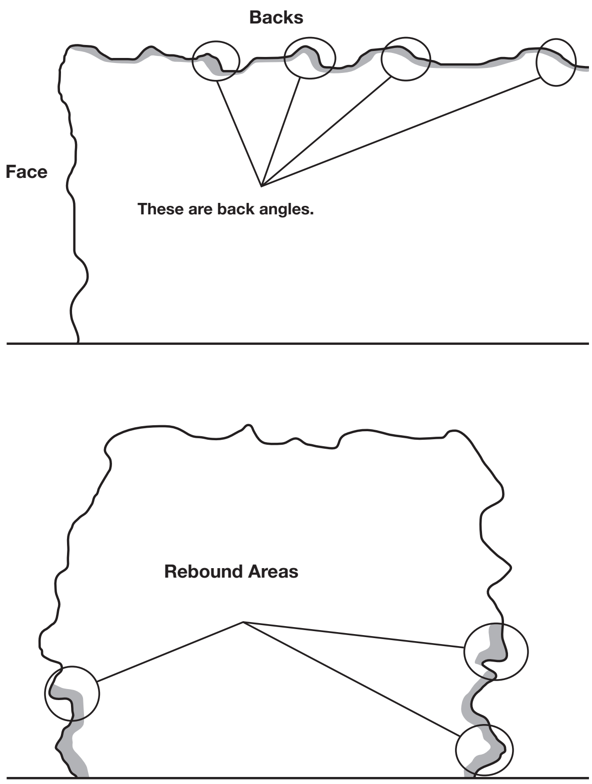


Figure 9.21 *Illustration of back angles and rebound areas common in tunnels*

Shotcrete is generally applied in layers of approximately 25mm (especially when being applied overhead) to prevent fallout. Ideally, the operator should wait ten minutes between layers to ensure adequate set of the first layer before applying the second. Most mining applications require shotcrete thickness of between 50mm and 100mm and civil applications commonly require a thickness in excess of 100mm.

Thickness control is important to ensure not only that adequate thickness is being achieved, but also that the application is of even thickness and that shotcrete is not being wasted due to excessive thickness. Methods of thickness control during spraying include using metal probes of a set length mounted on the end of the shotcrete boom to check the depth of the wet shotcrete and the use of stick on depth indicators which may be applied before spraying commences. Both methods have some disadvantages: boom mounted probes can cause damage to delicate boom hydraulics if they are not used carefully, do not provide an indication of excessive thickness and do not provide a permanent record of thickness. Stick on depth indicators are time consuming to apply, are often dislodged by the force of spraying and may be obscured by the spraying. Both methods only provide point data, and when shotcrete is applied to rough surfaces this can be far from representative.

Shotcrete thickness can also be measured by several methods post spraying. The most common method in use is the drilling and measuring of probe holes, though the small number usually drilled combined with the fact that they only provide point data suggest this method is of questionable value. There is also ample evidence that drilled probe holes provide initiation points for cracking of shotcrete. More representative areal data can be obtained through the generation of before and after three dimensional surveys of the areas being sprayed. This has been achieved through the use of laser scanners and more recently has been achieved through photogrammetry. A survey must be taken after hydroscaling and then one after spraying. The two surveys can then be compared and a “thickness map” generated.

If spraying an area where access is required to the area to continue tunnel advance, it is common to spray a “re-entry panel” of shotcrete on an area of wall under supported ground. This panel can be marked with the date and time of spraying and a penetrometer may then be used to check the strength development of the shotcrete without entry into the area sprayed being necessary. All sprayed areas should be barricaded or a sign used to indicate the hazard of wet shotcrete.

9.7.4 **Cleaning the Machine**

Cleaning should take place directly after spraying is completed to avoid any build up of concrete within the hopper and lines and on the body of the machine. Cleaning should be completed by ensuring that the concrete pump is in the correct position (may differ depending on the type of machine), removing the nozzle and fitting a “blow out” cap in its place. The hopper door should be dropped and any remaining shotcrete should be hosed out of the hopper. All concrete lines should be back blown, first with air until the concrete is cleared and then water should be used to flush the lines until clean water runs through them and out of the bottom of the hopper. Pump cylinders should be inspected to ensure that they are free of all concrete. The entire machine should then be cleaned using a high pressure cleaner and form oil sprayed over it again.

9.6.5 **Curing**

Shotcrete applied underground in mining environments is generally not cured. There is great difficulty in curing shotcrete in the underground mining environment due to the hot rock surface, evaporation through high velocity ventilation flow, and the lack of access in tunnels being actively developed. Shrinkage cracking of the shotcrete is exacerbated due to this lack of curing. Water spray curing is sometimes used in civil applications though for mining where shotcrete is often applied “in-cycle” it would obstruct production and extend cycle times.

Internal curing agents are also available and have been estimated to increase the performance of mechanical properties of shotcrete by at least 20% for a 2-5% increase in cost (Windsor[16]). They are not currently used widely in mining but represent a potential area of improvement.

9.6.6 **Application by Specialised Methods**

Several other mechanised methods of shotcrete application have been developed for more specialised applications. The lining of shafts and other vertical openings with shotcrete applied remotely and the use of shotcrete machines with tunnel boring machines both have increased in popularity due to increasingly demanding safety standards removing personnel from areas where there are hazards due to the presence of unsupported ground.

9.6.6.1 **Remote Shaft Lining**

Two types of mechanised shotcrete application are used in vertical developments. If a man-riding platform is being used in the shaft to facilitate the installation of bolts, services and other support, shotcrete may be applied to the shaft walls in advance of the platform by the use of a shotcrete spray head mounted below the platform.

Fully remote control rigs (**Figures 9.22** and **9.23**) have also been developed for use in shafts where there is to be no personnel access at all. The machines are operated from a control cabin on the surface and lowered down the shaft by way of a winching system. Cameras can then be used to monitor the spraying. Shaft depths of up to 400m are able to be sprayed with this system.

Typically, dry shotcrete is used in vertical applications greater than 50m in depth. This is due to the weight of the material that must be conveyed down the delivery lines.

Figure 9.22 *Remote shaft lining rig in construction yard.*

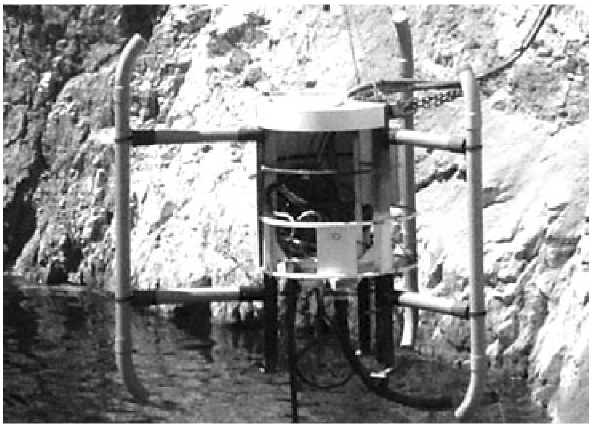


Figure 9.23 *remote shaft lining rig being used to spray inaccessible area.*

9.6.6.2 **Tunnel Boring Machines (TBMs)**

Shotcrete application can be incorporated into a TBM by mounting either a shotcrete spray boom that is to be manually operated by a sprayer or a spray robot directly onto the TBM. This can be achieved for both small and large diameter TBMs (**Figure 9.24**).

Figure 9.24 *Shotcrete spray robot mounted on a large diameter TBM (top) and a spray boom mounted on a small diameter TBM (above).*

10

Performance Requirements

10.1 **Quality Control**

A program of Quality Control and Quality Assurance is essential to the achievement of quality shotcrete. The objective of Quality Control is to ensure that the performance of the shotcrete in-place meets minimum design requirements. Quality Control covers many different facets of shotcrete production and placement. This will usually start with mix design, testing and approval of constituent materials and placing equipment, and selection of suitably qualified personnel, and proceed to on-going performance testing of the in-place shotcrete. Pre-construction trials can be used as part of benchmarking for Quality Control on major projects.

Pre-construction trialling should be carried out using plant, materials, and personnel identical to that proposed for the works and be undertaken in sufficient time before the commencement of the works to allow completion of testing, resolution of problems, and approval. However, pre-construction trials on their own do not guarantee that performance requirements will be met and thus ongoing Quality Control testing is an essential part of overall Quality Assurance.

10.2 **Preconstruction Trials**

At least a month prior to commencing construction, test panels and in some instances a section of sample work should be sprayed using each proposed base mix. The sprayer should be experienced and the shotcrete equipment should be in good working order. The test panels should be at least 600 x 600 mm constructed to a thickness that is at least twice the diameter of cores extracted from the panel. Where reinforcement in the form of steel fabric, bars, or fibres is used, the same reinforcement shall be provided in at least half of the panel. Separate test specimens shall be made for toughness testing and the dimensions of these will depend on the requirements of the toughness test selected for the project. Test panels should be inclined at an angle of about 45° against a vertical surface during spraying. It is recommended that at least three cores and at least five toughness panels be produced and tested for each mix for determination of performance benchmarks during pre-construction trials.

Sampling and testing will usually be carried out for compressive strength, density, permeability and toughness. Test panels should be covered in plastic and/or curing agents as soon as practical after production to prevent moisture loss. Where it has been shown that the same materials, mix designs, equipment, procedures, and personnel have given satisfactory results in similar works, the Superintendent may exercise discretion in accepting the construction of test panels concurrently with the first shotcrete placed in the works. If required, sections of sample work may also be assessed for specified finish.

The following results should be assessed as part of pre-qualification of a mix for infrastructure projects:

- The average result, for each concrete parameter specified for the cast state, of specimens sampled from the trial mix (transit mixer).
- The average result, for each concrete parameter specified for the sprayed state, of specimens extracted from the test panels.
- The average result for concrete density and relative concrete density taken from the transit mixer and extracted from the works.
- The result of toughness testing.

The panels should be inspected to ensure the minimum thickness is achieved, and internal cut surfaces are free of defects such as voids, lenses, and poorly consolidated regions. An assessment should be undertaken of the measures required to achieve dense and homogeneous shotcrete without segregation, sloughing, collapsing, excessive rebound, or other visible imperfections.

10.3 **Frequency of Testing**

The frequency of testing of shotcrete will depend on the type of project under consideration, the importance of the structure, and the total volume of shotcrete involved. The frequency of testing can be specified on the basis of volume of shotcrete consumed, area of shotcrete sprayed, or time.

Recommended frequencies for civil tunnel and underground projects are given in **Table 10.1**, while those for mining applications are given in **Table 10.2**.

Table 10.1 *Recommended frequency of testing for civil tunnel and underground projects*

Characteristic analysed	Test method	Minimum frequency
Supply and delivery of concrete		
Grading of coarse aggregate – Deviation from nominated grading	AS 1141.11	One per week
Grading of fine aggregate – Deviation from nominated grading	AS 1141.11	One per week
Slump	AS 1012.3 Method 1	One per batch of concrete
Production of test panels		
Spraying of production test panels (with the works)	–	One panel per 50 m^3 or per day of spraying
Thickness and visual inspection		
From the Works – Frequency of drilling holes	–	One random hole for each 50 m^2 or part there of
Determination of 28-day compressive strength, density and relative density		
From concrete supply – Frequency of moulding specimens and testing	AS 1012.8 and AS 1012.9	One set of 3 cylinders per 50 m^3 or part there of
From test panels – Frequency of drilling test specimens	AS 1012.14	One set of 3 cores per Test panel
Determination of water penetration depth		
From test panels – Frequency of drilling test specimens	AS 1012.14 DIN 1048 Part 5	One set per week's production
Determination of toughness		
From production of shotcrete - Frequency of making test specimen sets	ASTM C1550	One set per one day's production

Table 10.2 *Recommended frequency of testing for mining applications*

Characteristic analysed	Test method	Minimum frequency
Supply and delivery of concrete		
Grading of coarse aggregate – Deviation from nominated grading	AS 1141.11	One per month
Grading of fine aggregate – Deviation from nominated grading	AS 1141.11	One per month
Slump	AS 1012.3 Method 1	One per concrete test load
Production of test panels		
Spraying of production test panels (with the works)	–	Once or twice per week
Thickness and visual inspection		
From the Works – Frequency of probing	–	One random probe or hole for each 50 m^2 or part there of
Determination of 28-day compressive strength, density and relative density		
From concrete supply – Frequency of moulding specimens and testing	AS 1012.8 and AS 1012.9	One set of 3 cylinders per 50 m^3 or part there of
From test panels – Frequency of drilling test specimens	AS 1012.14	One set of 3 of cores per Test panel
Determination of toughness		
From production of shotcrete – Frequency of making test specimen sets	ASTM C1550	One set per week or per 250 m^3 or part there of, whichever is more frequent

10.4 Quality Systems

10.4.1 General

Each project may have a particular level of quality assurance requirements or quality system in place. A shotcrete quality assurance plan should be prepared for every project and can be used as a stand alone plan or can be integrated into the project quality system.

10.4.2 Quality Assurance Planning

Successful shotcreting requires a detailed and comprehensive quality-management plan that provides traceability on all aspects of the process and allows the contractor to take effective and appropriate action should any problem be identified (AS/NZS-ISO9001). Quality Assurance encourages contractors to self-diagnose problems and continuously improve processes to maintain the consistency of the QC testing regime. Quality Assurance should not be seen as a burden but an opportunity to learn about shotcreting skills and methods of optimizing performance. Quality Assurance is particularly useful for the training of staff but only if operators are included in feedback on performance and records that are properly maintained and audited. An example of a simple management plan is shown in **Table 10.3**.

10.4.3 Records

Accurate records should be kept of the concrete supply and shotcrete placement for each project. The records should include, but not limited to, the following:

- All materials delivered to the concrete pump and spraying machine. The provision of Manufacturer's Identification Certificate in accordance with AS 1379 should be provided.
- The shotcreted area each day should be recorded by referencing to established grid lines or similar notations. Each batch (truck load) of materials delivered to the machine should be recorded and noted as to the shotcreted areas it has been applied to on the site.
- Any malfunctions of equipment which may result in unsatisfactory in-place shotcrete.
- Locations of unscheduled joints and their treatment.

Table 10.3 *Typical basic management plan*

Parameter	Test parameter	Comments
Pre-shotcreting	Mix composition	Pre-determined based on approved mix
	Grading	Sieve analysis
	Concrete production	Consistency and uniformity are essential
	Stock levels	Buffer stock essential
	Storage conditions	Stored according to suppliers' recommendations
	Equipment condition	Preventive maintenance and daily inspections
	Services (power, water, lighting)	Must be checked each shift
	Safety	Suitable risk assessment and safe work procedures should always be used
During and after shotcreting	Substrate condition	Must be checked and prepared to a suitable standard
	Accelerator level	Set based on conditions and specified limits
	Early strength	Minimum strength requirements should be checked before re-entry
	Thickness	Use gauges, probes, or drilling
	Rebound	Frequently monitored by nozzleman
	Surface finish	Visual inspection
	Curing	Monitor changes in ambient conditions
	Test samples	Use accredited facilities
	Safety	Suitable risk assessment and safe work procedures should always be used
Days after shotcreting	Adhesion	Conduct soundings for bond
	Effectiveness of ground support	Monitor ground stability

11

Test Methods

11.1 Introduction

Numerous tests have been devised for the purpose of determining the properties of shotcrete in the wet and hardened states. The following is a list of available test methods for the determination of these properties. Experience in regular use of each of these test methods increases the reliability of results. Australian Standard test methods must always be used where available. However, as appropriate Australian Standards do not exist for many of the properties commonly required for shotcrete, foreign standards can be used in these cases. Where more than one foreign standard is available for tests related to a particular property, this Guide will provide a recommendation as to the most appropriate method to use. See **Chapter 13**, *Bibliography*, for a complete list of appropriate Australian and International Standards.

When any of the following tests are required to be undertaken a NATA-accredited laboratory that is accredited to undertake the test in question should be used.

11.2 Slump

The slump of shotcrete is normally measured in the same way as for conventionally-cast concrete in accordance with AS 1012.3. The test apparatus must be placed on level ground and wetted before use. The shotcrete is placed in the test apparatus, consisting of a frustum of a cone, in three layers of equal height and each layer rodded with a designated steel rod 25 times before the succeeding layer is placed. After the final layer is rodded the top surface of the shotcrete is struck off and the cone is lifted vertically from the shotcrete. The extent to which the shotcrete subsides below the height of the cone after the cone is completely removed is measured as the “slump” of the shotcrete.

11.3 Compressive Strength

The compressive strength of cast cylinders should be tested in accordance with AS 1012.9 using cylinder test specimens prepared in accordance with AS 1012.8. Cylinder test specimens are cast in two layers with each layer consolidated using a designated steel rod before the succeeding layer is cast. The upper free surface of the test cylinder should be screeded flat prior to covering with a lid to limit evaporation. Specimens should not be disturbed during initial hardening. The compressive strength of cores should be tested in accordance with AS 1012.14 using cores secured in accordance with AS 1012.14.

By convention, the strength of concrete at 28 days is normally taken to represent the long-term strength of this material. However, the 28-day strength may not be appropriate for all shotcreting applications. For example, if a certain minimum strength is required at a given early age, then strength should be measured at the same early age using an appropriate test method.

11.4 Methods of Measuring Early-Age Compressive Strength

11.4.1 General

Cast cylinders and cores are generally inappropriate to the measurement of compressive strength at ages earlier than 48 hours. Other methods of measuring the compressive strength of shotcrete by indirect means exist and should be used. A summary of the available early-age test methods is included below.

Measurement of early-age strength development is appropriate for assessment of the ability of shotcrete to support unstable ground and provides an indication of safe re-entry times adjacent to freshly-sprayed shotcrete. The most appropriate type of test to measure the early indirect-compressive strength up to 1 MPa is the *Needle Penetrometer.* The only effective means of assessing direct-compressive strength up to 8 MPa at early ages is the *Beam-End Tester.* The *Soil Penetrometer* provides an over-estimate of compressive strength, unless the results are corrected using the method by Bernard and Geltinger[58] while the *Hilti Gun* requires a power-actuated tool operators’ certificate to operate. Measurement of compressive strength at 28 days or later using *Cores* is appropriate for permanent applications.

11.4.2 **Soil Penetrometer**

A soil penetrometer is a proprietary device consisting of a sprung flat-ended steel plunger calibrated to indicate the approximate compressive strength of the soil/concrete when forced into the surface a distance of about 6 mm (**Figure 11.1**). The device is used at approximately 6–10 locations across the surface of freshly-sprayed shotcrete at each age of testing, and readings are taken at 10–20 minute intervals until the required strength is achieved.

Figure 11.1 *Soil penetrometer in use*

Although this test has the advantages that it is easy and inexpensive to perform, virtually non-destructive, and the test equipment can be readily carried around by operatives, an important disadvantage is that the device over-estimates compressive strength by a significant margin, and the results are strongly affected by the presence of aggregate and fibres. Estimating the correct depth of penetrometer can also be difficult on a rough surface.

11.4.3 **Needle Penetrometers**

The needle penetrometer consists of a 3-mm diameter steel needle at the end of a spring that is forced into the surface of setting concrete. The force required to drive the needle to a depth of 15 mm is used to determine the approximate compressive strength with the aid of a calibration chart (**Figure 11.2**). This method is suitable for determining compressive strengths up to 1.0 MPa. This type of needle penetrometer should not be confused with Vicat needle penetrometers and other types of needle penetrometers that are widely used to assess setting times for conventionally-cast concrete.

Advantages of the needle penetrometer are that it is a readily-portable device that is quick and easy to use. The disadvantage is that results are influenced by the presence of fibre and aggregate particles getting in the way of the needle, and the requirement to drive the needle steadily into the surface of the concrete is often difficult to achieve. Driving the needle into a drying shotcrete surface can also lead to over-estimates of strength, and use of the calibration chart is time-consuming.

Figure 11.2 *Needle penetrometer*

11.4.4 **Beam-End Tester**

The ASTM C116-based beam-end tester (Bernard & Geltinger[58]) is the only early-age strength testing device that involves direct compressive failure of concrete samples. Beams measuring 75 x 75 x 400 mm are produced by spraying shotcrete into an open-ended mould (other sizes can be used if desired). The absence of ends helps to prevent rebound getting caught inside the beam mould. After spraying and cutting back to size, the beams are left to harden and can be extracted from the mould and tested when the strength exceeds about 0.5 MPa (as measured using the needle penetrometer). Portions of the beams are subjected to direct compression between the platens of the test device and the compressive strength is worked out on the basis of the area of the platens (**Figure 11.3**). About 3–4 tests can be obtained using each beam.

Figure 11.3 *Beam-end tester in use*

Extracting the beams from the mould can be difficult at early ages, so use of pressed metal inserts are recommended. The metal inserts sit in the mould during spraying and are then removed with the beam inside. The fresh concrete beam remains in the pressed metal insert (made using approximately 0.5-mm thick steel sheet) until it is time to test, whereupon the mould is 'peeled off' the beam like a wrapping. In most cases, the beam survives this process without breaking, even if it is only 20–30 minutes old.

The beam-end tester has the advantage that a direct compressive strength estimate is obtained. No calibration against other methods of measurement is therefore necessary, indeed, the indirect methods are calibrated against data obtained using this test. The disadvantage of this method is that the beams are produced and stored separately from the lining, so that if a significant difference in temperature exists between concrete within the lining and ambient air then the rate of strength gain will be affected. Measures can be taken to ensure the results are relevant, for example, by storing the beams under cover immediately adjacent to the lining so that the heat of hydration from the lining keeps the beams warm. Another disadvantage of the beams is that rebound can be trapped in the mould and incorporated into the beam if spraying is not performed carefully.

11.4.5 **Hilti Gun-Test Method**

This method is suitable for shotcrete strengths between 2 and 18 MPa. A proprietary nail is shot into shotcrete using a Hilti DX450 nail gun and the embedded length is recorded. A nut is screwed onto the protruding end of the nail and a pull tester is placed under the nut. As the nail is progressively extracted the maximum pull-load is recorded on the dial and converted into compressive strength as a function of the embedded nail length. To obtain a reliable result it is recommended that at least 8 nails be used for each test age.

The advantages of this method are that strengths in the range 2–18 MPa can be determined, and the strength measured is the actual insitu strength between 20 and 50 mm through the thickness of a shotcrete lining. The disadvantages are the high cost of the equipment and fasteners, the fact that explosive cartridges are used, and the relatively long length of time required to conduct the measurements. Moreover, the guns do not always fire the fastener into the concrete correctly.

11.5 **Flexural Strength**

The flexural strength of plain shotcrete should be determined using beams sawn from panels. If sprayed panels are not available then beams can be sawn from the in-place works but this is expensive, difficult, and normally not common practice. The preferred size of beam should be 100 x 100 x 350 mm or 150 x 150 x 500 mm extracted in accordance with ASTM C-1140 and tested in accordance with AS 1012.11 or ASTM C-78.

If the flexural strength of fibre-reinforced shotcrete is required, beams measuring 100 x 100 x 350 mm or 150 x 150 x 500 mm should be extracted in accordance with ASTM C-1140 and tested in accordance with ASTM C-1609. If the EN 14488-3 beam size is used, then the specimen shall be cut to 125 x 75 x 600 mm.

If the thickness of the in-place shotcrete is insufficient to allow 100-mm thick beams to be extracted, sawn beams measuring 75 x 125 x 600 mm should be cut from the works and tested in accordance with EN 14488-3. Cast samples of shotcrete can also be used with these beam sizes but the performance of such samples must not be taken to represent the performance of shotcrete as sprayed.

11.6 **Toughness Testing**

11.6.1 General

The term “Toughness Testing” is now used generically to refer to a whole suite of potential test methods, with there being many different types of beam and panel tests from different countries to choose from. Some well-accepted tests, established over many years, have been superseded in recent years.

In Australia the most common toughness test for quality control of fibre-reinforced shotcrete has become the ASTM C-1550 test using a 75 mm thick x 800 mm diameter round panel. However, an alternative is the 100 x 600 x 600 mm square panel produced and tested in accordance with EN 14488-5 (formerly EFNARC European Specification for Sprayed Concrete).

If beam tests are specified, the preferred test is specified in EN 14488-3 utilising a 75 x 125 x 600 mm third-point-loaded beam; alternatives are the 100 x 100 x 350 mm or 150 x 150 x 600 mm ASTM C-1609 third-point-loaded beams.

Panels should be used whenever a relative measure of toughness is sufficient for design or quality-control purposes. The principal advantage of panels is the superior repeatability of toughness values derived from these tests compared to beams. The typical level of within-batch variability for toughness values derived using ASTM C-1550 round panels is about 7% and from EN 14488-5 square panels is about 10% (Bernard[26]).

Evidence of a correlation between the post-crack performance of EN 14488-3 beams and ASTM C-1550 panels was demonstrated by Bernard[27] and this can be used to develop post-crack design data for the flexural performance of fibre-reinforced shotcrete based on the output of a set of ASTM C-1550 panel tests.

Beams should normally only be used when a direct estimate of the Modulus of Rupture and the residual flexural strength of fibre-reinforced shotcrete are required. EN 14488-3 beams are the only practical option for toughness testing when a sample is required to be extracted from works less than 100-mm thick. The EN 14488-3 beam also has the advantage that it is more representative of thin shotcrete linings that are often close to 75-mm thick. The typical level of within-batch variability for beam-derived toughness values is about 12% at small crack widths (0.5 mm central deflection) ranging up to 20% for larger crack widths (3.0 mm central deflection).

In choosing the test method to use for a project, the thickness of the specimen in comparison to the design thickness of the insitu lining may be considered. The appropriate test method should be selected by the engineer or geotechnical expert.

11.6.2 Round-Panel Test Method – ASTM C1550

In this test method a 75 mm thick x 800 mm diameter round panel test specimen which is simply supported on three pivots symmetrically arranged around its circumference, is loaded at its centre (**Figure 11.4**). The energy absorbed up to a specified central deflection, or load resistance exhibited at a specified deflection, is taken to represent the ability of a fibre-reinforced shotcrete to redistribute stress following cracking and therefore continue to offer structural support.

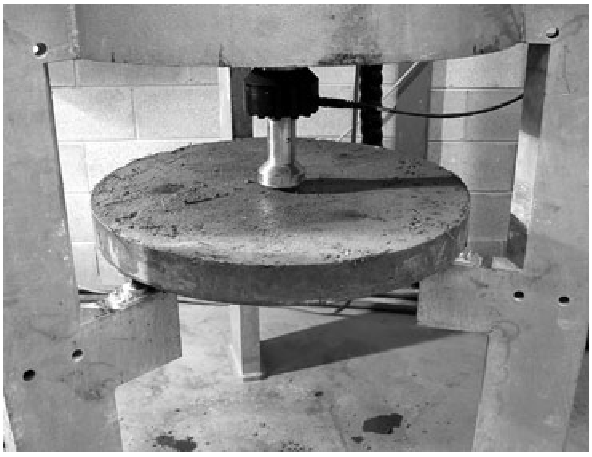


Figure 11.4 *ASTM C-1550 round panel test in servo-controlled test rig*

Selection of the most appropriate central deflection at which performance is specified depends on the intended application for the material. Performance at low levels of deformation are appropriate to serviceability requirements, while performance at large levels of deformation are appropriate to ultimate strength requirements such as unstable ground in mines. The energy absorbed up to 1–5 mm post-crack central deflection is applicable to situations in which the material is required to hold cracks tightly closed at low levels of deformation. Examples include, final linings in underground civil structures such as railway tunnels that may be required to remain water-tight. The energy absorbed up to 40 mm deflection is more applicable to situations in which the material is expected to suffer severe deformation insitu, for example, shotcrete linings in mine drives and temporary linings in swelling ground.

The minimum number of ASTM C-1550 round panels comprising a set of specimens is two. It is recommended that a minimum of three be produced in case one of the specimens is damaged prior to testing. Round panels must be tested in a suitable servo-controlled test machine, such as the type shown in **Figure 11.4**, in order to comply with ASTM C-1550. Performance is calculated as the energy (measured in Joules) under the load-deflection curve.

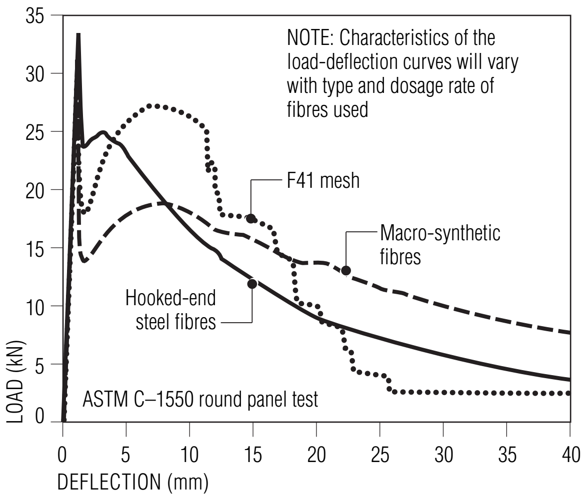


Figure 11.6 *Typical differences in load-deflection characteristics for shotcrete reinforced with steel mesh, steel fibres, and macro-synthetic fibres in ASTM C-1550 round panel test*

Typical load-deflection curves produced for ASTM C-1550 rounds panels are shown in **Figures 11.5** and **11.6**

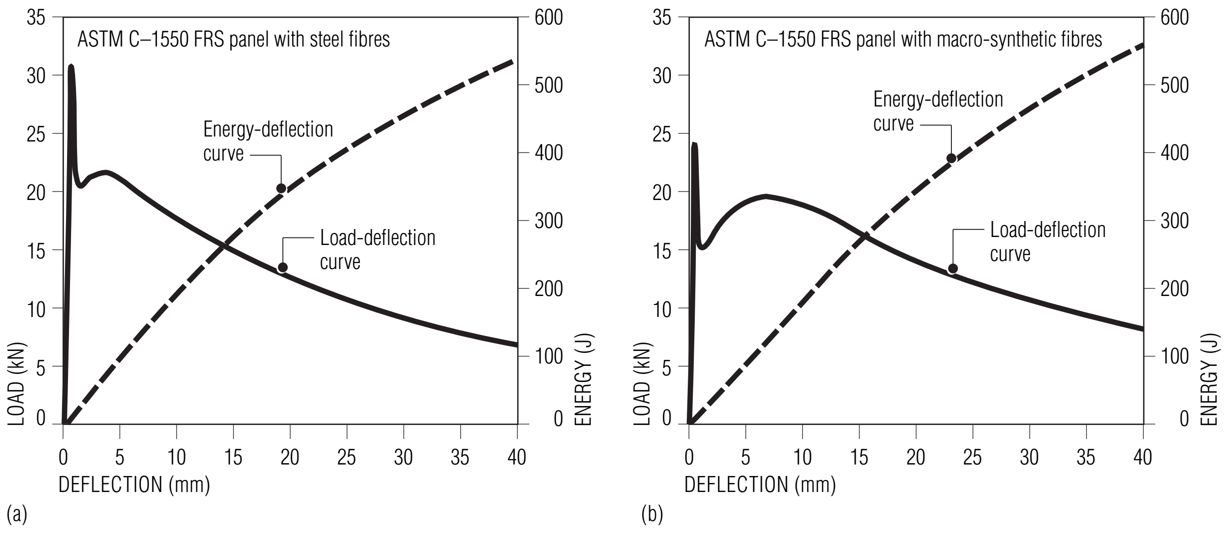


Figure 11.5 *Examples of load-deflection curves obtained from ASTM C-1550 round panels reinforced with (a) steel fibres and (b) macro-synthetic fibres*

11.6.3 **Square-Panel Test Method – EN 14488-5**

This test involves a concrete panel measuring 600 X 600 X 100 mm thick simply supported along all four edges while subjected a centre-point load (**Figure 11.7**). A load-deflection curve is obtained up to a central deflection of 25 mm (**Figure 11.8**). Performance is calculated as the energy (measured in Joules) under the load-deflection curve.

The minimum number of EN 14488-5 panels comprising a set of specimens is two. It is recommended that a minimum of three be produced in case one of the specimens is damaged prior to testing. EN 14488-5 panels are now less-commonly used in Australia as the specimens are larger and therefore more expensive to produce, transport and handle on site and in the test laboratory.

Research has shown that, for typical fibre reinforced shotcrete mixes with toughnesses in the range 300 – 500 Joules (ASTM C-1550), the energy absorbed by a given mix in a square EN 14488-5 panel test at 25 mm central deflection is approximately 2.5 times the magnitude of energy absorbed by the same mix in the ASTM C-1550 at 40 mm central deflection (Bernard[59]).

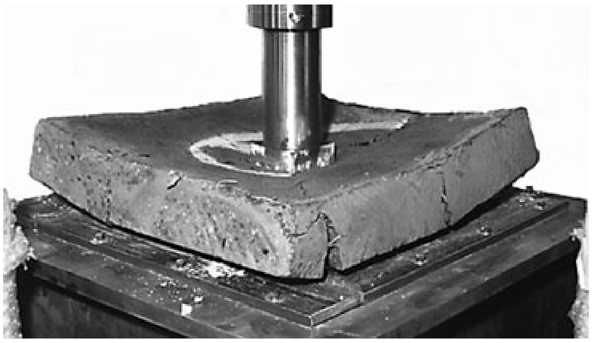


Figure 11.7 *EN 14488 panel test using square test panel*

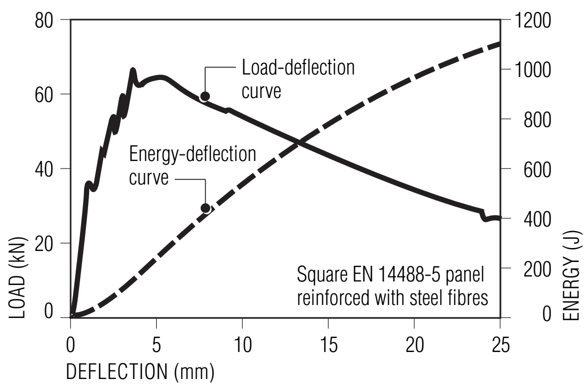


Figure 11.8 *Example of load-deflection curves obtained from square EN 14488-5 panels reinforced with steel fibres*

11.6.4 **Beam-Test Method – ASTM C-1609**

In this method a third-point loaded beam with dimensions of 100 X 100 X 350 mm (on a span of 300 mm) or 150 X 150 X 600 (on a span of 450 mm) is subjected to uni-axial bending (**Figure 11.9**). The load-deflection curve derived from this test can be used to determine the Modulus of Rupture representing the flexural strength of the concrete matrix and residual strengths or energy absorption representing the toughness of the fibre-reinforced shotcrete. Beams are now seldom used for quality control because the variability in results is too high to produce useful indicators of performance change.

Beams are normally produced in sets of three or more; one set of specimens must comprise at least three beams. Typical load-deflection curves for ASTM C-1609 beams reinforced with a high-dosage rate of fibres are shown in **Figure 11.10**. The means by which the performance parameters referred to in C-1609 are defined, are illustrated in this Figure.

Reported results are the first peak load and flexural strength, ultimate load and flexural strength and residual load and flexural strength values. Loads are reported in units of force (kN) and strengths are reported in units of stress (MPa).

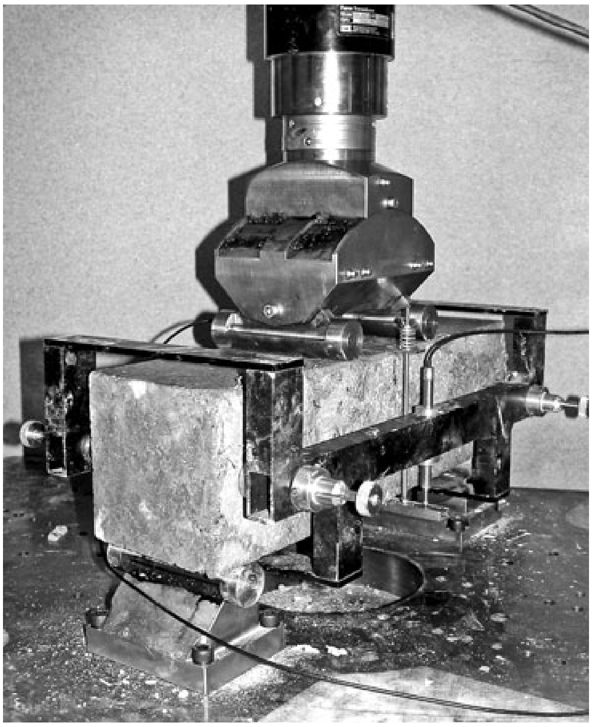
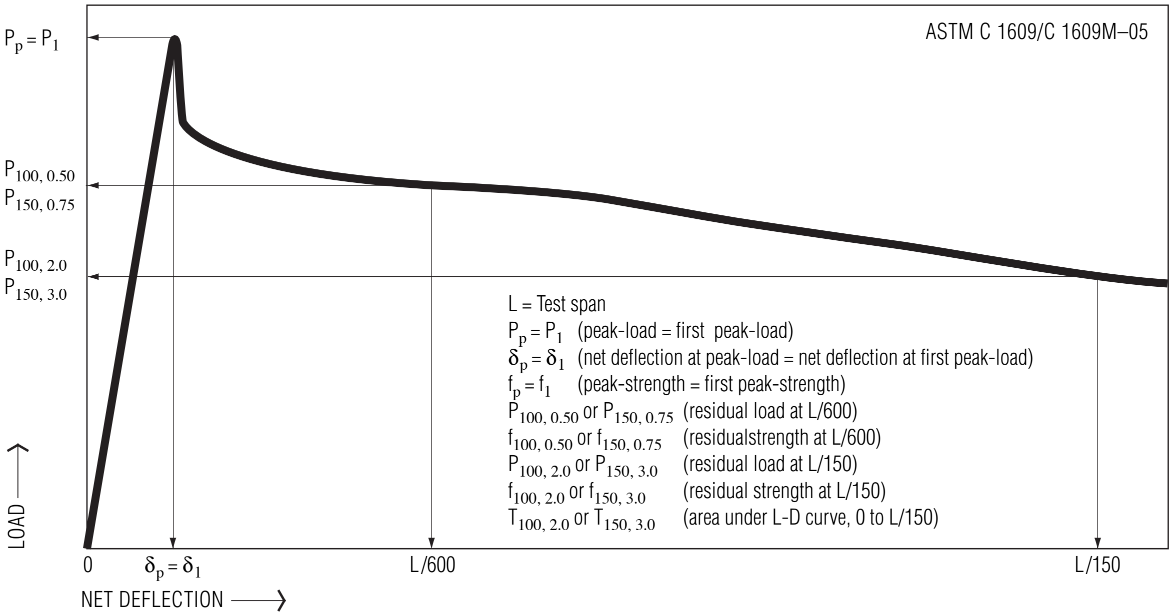
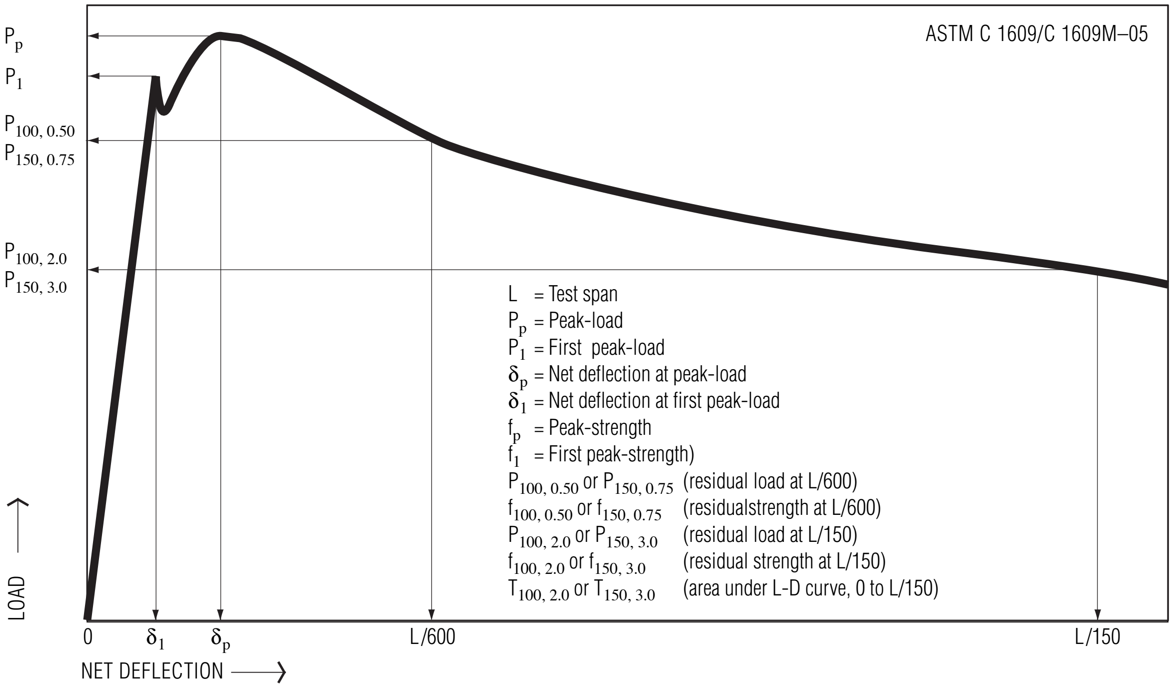


Figure 11.9 *ASTM C-1609 beam test in progress*



(a) PEAK-LOAD EQUALS FIRST PEAK-LOAD



(b) PEAK-LOAD GREATER THAN FIRST PEAK-LOAD

Figure 11.10 *Typical load-deflection results for beams with high-dosage rates of fibres from ASTM C-1609 beam test*

11.6.5 Beam-Test Method – EN 14488-3 beam

The EN 14488-3 beam test involves third-point loading of a sawn shotcrete beam with dimensions of 75 x 125 x 600 mm on a span of 450 mm (**Figure 11.11**). The advantage of a reduced depth of specimen compared to other beam-test methods is that it results in a more flexible beam which is less demanding on the test machine. Beams are now seldom used for quality control because the variability in results is too high to produce useful indicators of performance change.

EN 14488-3 beams are normally produced in sets of three or more; one set of specimens must comprise at least three beams. Reported results are the first peak load and flexural strength, ultimate load and flexural strength and residual load and flexural strength values. Loads are reported in units of force (kN) and strengths are reported in units of stress (MPa).

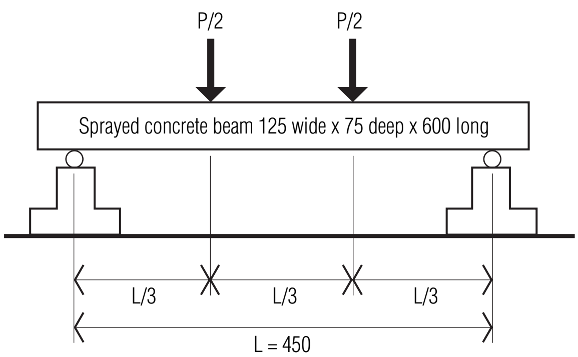


Figure 11.11 *EN 14488-3 beam test subject to third-point loading*

11.7 Density (Mass/Unit Volume)

The density of hardened shotcrete should be determined in accordance with AS 1012.12. The density of wet shotcrete should be determined in accordance with AS 1012.5. Shotcrete should never be sprayed into the sample vessel for this test, instead a sample of cast shotcrete or cores extracted from a sprayed test panel should be used.

11.8 Drying Shrinkage

The unrestrained drying shrinkage of cast shotcrete specimens should be measured in accordance with AS 1012.13

The unrestrained drying shrinkage of cast shotcrete beams is related to the drying shrinkage suffered by in-place shotcrete on a rigid substrate but the relation between these two forms of shrinkage is complex and difficult to predict. Shotcrete should not be sprayed into the moulds used for AS1012.13 as the inclusion of rebound will corrupt the results.

11.9 Creep

The creep of cast shotcrete in compression should be determined by conducting tests on cylinders in accordance with AS 1012.16.

The AS 1012.16 test involves a cylinder subjected to continuous compression that suffers drying shrinkage strains in addition to creep strains. The contribution of drying shrinkage to the total measured strain in a creep specimen can be determined by conducting shrinkage tests on the same cast shotcrete in accordance with AS 1012.13. The creep of cast shotcrete in compression is only weakly related to the creep behaviour of in-place shotcrete loaded in flexure. Moreover, the post-crack creep behaviour of fibre-reinforced shotcrete in bending is not related to the creep behaviour of cast fibre-reinforced shotcrete in compression.

11.10 Coefficient of Thermal Expansion

A method of determining the linear coefficient of thermal expansion of oven-dry 'chemical resistant' mortar is given in ASTM C 531 and of saturated concrete in US Corps of Engineers Standard CRD-C 39. AASHTO Test Method TP 60 can also be used for cores extracted from in-place shotcrete.

11.11 Alkali-Silica Reactivity (ASR)

Standards Australia HB79 should be consulted for information regarding ASR and suitable tests to use with proposed combinations of aggregates and cements.

11.12 **Soluble Salts**

Sulfate and chloride-ion contents should be determined by testing of hardened concrete and concrete aggregates in accordance with AS 1012.20 and AS 1141. Recommended limits and testing requirements for acid-soluble sulfate-ion content of hardened concrete may be obtained from AS 1379 and RTA B82 Clause 2.7[42].

11.13 **Water Penetration through Bulk Shotcrete**

Water penetration depth can be determined in accordance with DIN 1048 Part 5.

This test involves the extraction of a 150-mm diameter core of shotcrete which is sawn to reveal a flat face perpendicular to the direction of drilling. Water under a pressure of 1 MPa is applied to the flat-sawn surface for a period of 3 days after which the depth of water penetration is determined by breaking the core diametrically and applying "methyl blue" that reveals the penetration depth. The results of this test can be seriously compromised by the presence of cracks in the sample which may be caused by shrinkage, sloughing after spraying, or coring.

11.14 **Bond Strength (Adhesion)**

Adhesion is a very difficult property to measure. All the existing test methods involve proprietary equipment for the extraction of a core from in-place shotcrete. The strength of adhesion between the shotcrete and the underlying substrate can be determined in accordance with Section 10.6 of the EFNARC European Specification for Sprayed Concrete. An alternative test, for the determination of adhesive strength, is Swedish Standard SS 137243.

The EFNARC method involves extraction of a core in direct tension from a single core hole (**Figure 11.12**) while the Swedish Standard 137243 method involves the generation of concentric core holes and use of an extraction device that ensures concentric loading (**Figure 11.13**). Debonding of shotcrete from the substrate can also be revealed by drumminess of the shotcrete lining in response to simple hammer soundings.

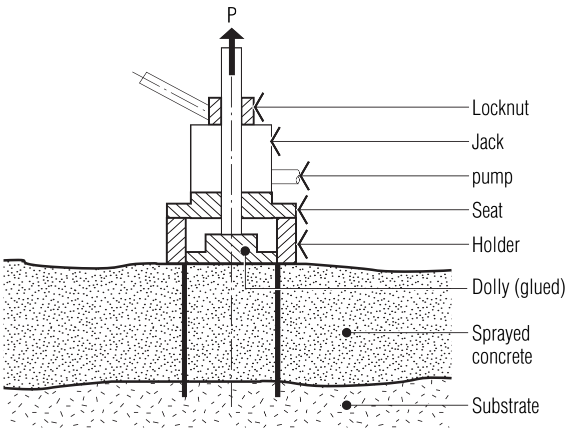


Figure 11.12 *Pertinent features of EFNARC Bond test apparatus*

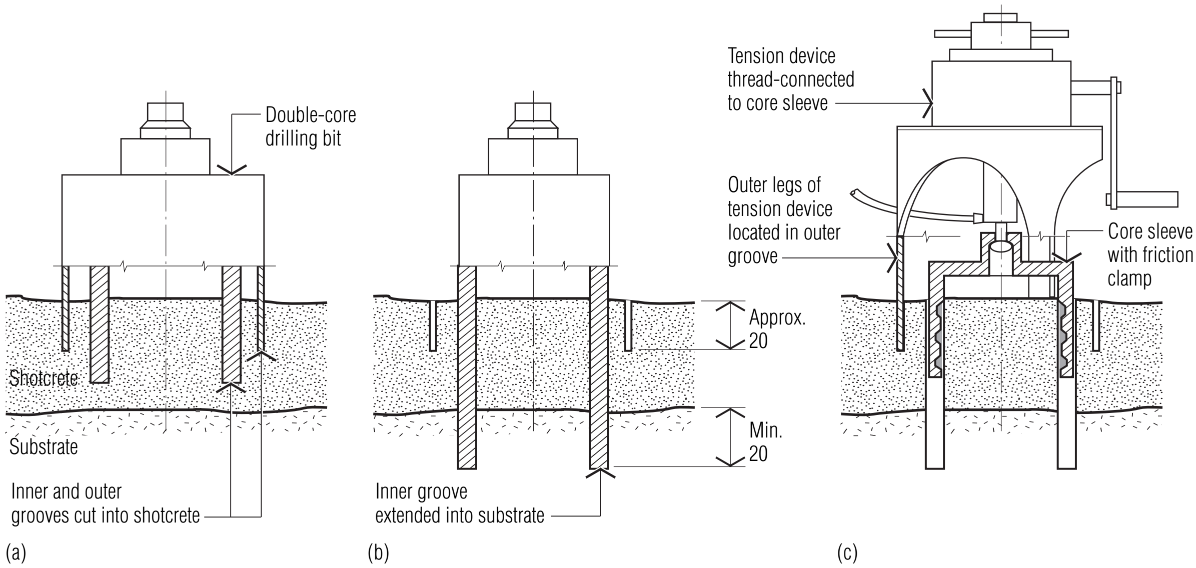


Figure 11.13 *Process of conducting bond test using Swedish Standard 137243*

The Swedish standard 137243 uses a similar method of producing the core, but a double-coring drill bit cuts two grooves with the inner core extending past the shotcrete into the substrate. A specially-designed tension device is then located over the inner core, with outer legs located in outer groove. The central core is then extracted and the peak-tensile load used to determine the bond strength. This method has the advantage that minimal moments are applied to the core during extraction, hence the result is more representative of the true bond strength of the shotcrete.

11.15 **Freeze/Thaw Resistance**

The freeze-thaw resistance of hardened shotcrete should be determined in accordance with ASTM C-666. If the shotcrete surface is expected to suffer salt exposure in addition to freeze-thaw action, then the resistance of the material should be assessed using ASTM C-672. If air entrainment is included with the shotcrete both wet- and dry-mix will typically satisfy freeze-thaw testing without difficulty. However, if the aggregates or any other mix component is suspected of being non-resistant to freezing, then ASTM C-666 should be used. Note that freeze-thaw resistance is only an issue if the shotcrete is expected to be saturated in place and then frozen.

Shotcrete surfaces tend to suffer more deterioration due to salt damage than cast concrete when using ASTM C-672 because of the quality of the finish (vertical surfaces as opposed to flat work). This test is most suitable for road-side shotcrete and industrial applications when shotcrete is the final exposed surface. If set accelerator is used the ASTM C-666 freeze-thaw test is essential for freezing conditions. This test is very effective in distinguishing freeze-thaw resistant from inferior shotcrete subject to set accelerator over-dose.

11.16 **Determination of Fibre Content**

There are two alternative methods of determining the fibre content of shotcrete: RTA B82 Method, and the EFNARC Method. These methods are only applicable to the determination of fibre content for steel fibres and macro-synthetics; they are not appropriate for micro-synthetic fibres. Due to the small sample sizes used, both tests are highly unreliable as the fibre counts obtained have been found to be weakly related to both the dosage rate of fibres added to the concrete and the performance achieved.

RTA B82 Method[42]

Determination of fibre content of wet shotcrete should be based on a wet sample taken from the mixer of a known volume not less than 6 litres. The sample should be washed and the fibre content separated, dried, and weighed with results reported to the nearest 2 grams. The result is reported as the weight of fibres per cubic metre of shotcrete. The results of this method are highly variable and it is recommended that a volume of concrete much greater than 6 Litres be used.

EFNARC Method[57]

Determination of fibre content of hardened shotcrete should be undertaken in accordance with Section 10.9 of the EFNARC European Specification for Sprayed Concrete. This test involves extraction of cores from the shotcrete under investigation, determination of the volume of the cores, followed by crushing and separation of the fibres. The weight of fibres separated from the shotcrete is divided by the volume of the cores to determine the dosage rate of fibres in kg/m^3. This method is subject to very high variability and is therefore not recommended. Fibre counting can also be undertaken for cracked toughness specimens but the variability in counts is very high and the relation to performance is weak.

12

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ASA:	www.shotcrete.org
JCI:	www.jsce.org.jp
Standards Australia:	www.standard.org.au
EFNARC:	www.efnarc.org

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