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AuSS Australian Shotcrete Society

Guideline to Shotcrete Quality Control in Australia

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Preface

Shotcrete is now widely used in Australia across civil construction, tunnelling, mining and related applications, both above and below ground. With that widespread use comes a need for consistent and defensible quality control practices. Australia does not yet have a dedicated national standard for shotcrete quality control. In response, the Australian Shotcrete Society has prepared this guideline to support more consistent practice in the production, sampling, testing and assessment of shotcrete. Its purpose is to consolidate current understanding, articulate shared challenges and support an ongoing industry-wide dialogue aimed at improving the effectiveness, reliability and applicability of shotcrete testing and quality control. The objective is to help practitioners apply quality control in a way that is practical, proportionate and focused on the performance of the material in the works, rather than on testing for its own sake.

Between 2024 and 2025, the Australian Shotcrete Society conducted a national series of interactive workshops with stakeholders from across Australia's construction and mining sectors, including geotechnical and structural engineers, material and admixture suppliers, testing laboratories, equipment manufacturers, contractors, shotcrete applicators and other participants in the shotcrete supply chain. The workshops were designed to encourage open, experience-based discussion and to build a shared understanding of how the requirements, constraints and decisions of each discipline influence the performance of shotcrete as a system.

This transparent exchange highlighted several long-standing obstacles that are not always visible to all parties involved in design, supply, application, equipment manufacture, testing and concrete technology. It also identified opportunities to improve cross-disciplinary coordination, operational efficiency and mutual appreciation of the capabilities and limitations inherent in each part of the shotcrete process. Guided by its mission to promote best practice and continuous improvement, the Society has focused this guideline on the performance, interpretation and practical relevance of existing quality control test methods, while also encouraging broader industry discussion about improved or adapted methods that may offer greater relevance, practicality and value.

In the absence of Australian shotcrete-specific standards, industry practice has drawn on a combination of Australian, European and North American standards, together with selected proprietary or project-specific methods. As a result, multiple approaches to testing and verification are currently used in parallel. This guideline does not seek to displace those standards. Instead, it provides a practical framework for selecting and applying them in the context of Australian projects and within the broader principles of limit state design reflected in standards such as AS 3600, AS 5100.5 and the fib Model Code. It should also be read together with the third edition of the Recommended Practice for Shotcrete in Australia, published by the CIA/AuSS in 2020.

This document is intended for clients, designers, contractors, shotcrete suppliers, spray operators, quality personnel and testing laboratories involved in the delivery and verification of shotcrete works. While it is primarily focussed on wet-mix shotcrete, most of the recommendations are also applicable to dry-mix shotcrete. It is written as a guideline, not as a project specification, and should be applied with engineering judgement having regard to the importance of the structure, the service environment, the construction method, and the relevant statutory and contractual requirements. It does not replace project-specific design, formal specifications, applicable standards or legal obligations. Rather, it is meant to support a more informed, consistent and defensible approach to shotcrete quality control.

The Australian Shotcrete Society has been involved in the evolution of the Australian shotcrete industry for nearly 30 years. It was established in 1998 as a not-for-profit industry group dedicated to improving awareness, understanding and good practice in the use of shotcrete in the Australian mining and construction industries. Its objectives include promoting the appropriate use of shotcrete, encouraging good spraying practice, and supporting specifiers and designers in the effective application of the material. These objectives are advanced through seminars, conferences and the publication of guidance documents such as this one. For further information on the Australian Shotcrete Society, contact Engineers Australia at engineersaustralia.org.au, visit shotcretesociety.org.au, or **call 1300 653 113**.

If you have any comments on specific sections of this guideline, or wish to contribute to future editions, please send your contribution to the Australian Shotcrete Society committee at AustralianShotcreteSocietyAuSS@engineersaustralia.org.au.

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1. Purpose and Philosophy of Quality Control

This guideline is intended to help practitioners apply quality control (QC) to shotcrete in a way that is practical, proportionate and relevant to performance in the works. It is not simply a testing manual. Testing is one tool within QC, but the purpose of QC is broader than simply satisfying a requirement to perform tests. It is to provide confidence that the shotcrete that is supplied, sprayed and incorporated into the works is fit for its intended function and design life. In common usage, quality is often understood simply as how good or bad something is. In reality, quality is an evaluation of how effectively the measurable properties of a material, product or process conform to specified performance requirements or prescribed standards. For practitioners, the key questions are simple: why are we doing quality control, what are we trying to control, how does QC relate to quality assurance (QA), and how much QC is sufficient for a given project?

At its core, QC exists to reduce uncertainty. Shotcrete performance is influenced by materials, batching, transport, accelerator dosage, equipment, nozzle technique, curing, environment and workmanship. The fundamental building blocks of quality are the physical, chemical, mechanical and operational properties that define the behaviour of the material or system. These properties should be measurable, observable or otherwise capable of objective verification if they are to support consistent assessment. Good QC helps ensure safety, supports durability, reduces rework, improves consistency and provides an evidence base for decision-making when non-conformances occur.

1.1 Why are we doing quality control?

Quality Control is undertaken because shotcrete is often relied upon to protect workers, stabilise ground, provide structural capacity, control deformation, achieve durability targets and support long-term serviceability. Failure to control quality can result in unsafe conditions during construction, poor long-term performance, costly remediation and disputes about whether the works satisfy the specification. QC therefore has both a technical and a project delivery function: it helps practitioners identify issues early enough to respond, and it creates the records needed to show that reasonable control was exercised and adequate performance was achieved.

Undertaking QC also protects a contractor's reputation. Producing flawed or dangerous structures leads to costly lawsuits, fines, and long-term damage to a contractor's public image. Consistently meeting expectations, which includes satisfying QC requirements, fosters loyalty and trust with a client leading to repeat business. Lastly, some structures (e.g., public access tunnels) are legally required to adhere to strict construction standards that can only be satisfied by demonstrated compliance with QC requirements.

1.2 What are we trying to control?

Quality is not a property of a material. Likewise, Quality Control does not control a single property or test result. Instead, it controls the reliability of the shotcrete process and the confidence that the placed material is suitable for its intended use. Depending on the project, this may include workability, strength, early-age performance, post-crack performance, durability, bond, thickness, curing conditions, accelerator dosage, fibre content and workmanship. The relevant controls should be selected in response to the design requirements, specification, environmental exposure, construction sequence and consequence of failure. In other words, the object of QC is performance in context, not testing for its own sake.

1.3 How much quality control is enough?

The appropriate level of QC depends on risk. High-consequence permanent works, difficult ground conditions, aggressive environments, tight tolerances and reliance on specialised performance parameters and lack of historical performance data generally justify more intensive controls and more frequent verification. Lower-consequence or temporary works may justify a simpler regime. The aim is not to maximise testing; it is to provide sufficient control to establish confidence that the works meet their required level of safety and performance. This guideline therefore promotes a risk-based approach in which the QC programme is aligned with project importance, exposure conditions, complexity of construction and the consequences of getting it wrong.

Within this framework, appropriate testing should be selected to inform the desired control of the process or verification of performance. Some tests are appropriate for routine production control, some are better suited to pre-construction trials, and some are only justified where the design or exposure conditions require them. The practitioner's task is to choose a balanced QC regime that is practical, timely and meaningful for the project.

2. QC Framework and Risk-Based Approach

A QC framework should define what is to be controlled, how it will be checked, who is responsible, what acceptance criteria apply, and what actions are required when results fall outside those criteria. In practice, this means linking the design and specification requirements to a practical programme of inspections, records, tests, hold points and response actions. A useful framework distinguishes between controls on inputs, controls on production, controls on workmanship and controls on in-place performance.

2.1 Project consequence, risk and feasibility of control

The extent of QC should reflect both the importance of the structure and the practicality of obtaining meaningful information. Some properties can be checked directly and routinely; others can only be inferred indirectly or assessed through trial work, extracted samples or later-age testing. Practitioners should therefore consider both consequence and feasibility when designing a QC programme. High-consequence assets such as major transport tunnels, underground stations, hydro structures and aggressive-environment works usually justify a higher frequency of checks on a broader range of properties than lower-consequence or temporary works. The following table provides indicative guidance on the properties that may need to be assessed and the corresponding level of testing. These properties are in addition to assessments on inputs such as shotcrete ingredients, batching, spraying workmanship, and delivery.

Table 1 Indicative properties and intensity of testing for projects of high, medium, and low importance

Project consequence	Examples	Properties
High	— Motorway and road tunnels — Railway tunnels and stations — Hydro-projects — Sewers — Coastal Defences — Desalination plants	— Slump/flow — Compressive strength — Tensile/flexural strength — Post-crack performance — Durability — Shrinkage — Bond
Medium	— Basements — Underpass — Canals	— Slump/flow — Compressive strength — Tensile/flexural strength — Durability

Project consequence	Examples	Properties
Low	— Swimming pools — Battered slopes — Retaining walls — Drains and retention ponds	— Slump — Compressive strength

2.2 The Relationship Between QA and QC

Quality assurance (QA) and quality control (QC) are related but are not the same. QA is the management system that establishes how quality will be achieved and demonstrated. This will involve procedures, training, document control, inspection and test plans, calibration, traceability, audits and non-conformance management. QC is the operational part that checks whether the product and process actually satisfy the required criteria. In simple terms, QA defines the system; QC applies it to the work.

This publication focuses specifically on QC as one essential component of a broader, integrated quality management system that includes QA. QA is fundamentally proactive: it establishes the plans, procedures, competencies and governance arrangements intended to prevent defects. QC is inherently verification-focused: it uses inspection, testing and records to confirm that the constructed work meets the required criteria and remains safe and fit for purpose. In simple terms, QA helps ensure that the right processes are followed, while QC confirms that the right product has been delivered.

For shotcrete projects, effective QA without effective QC can produce well-documented non-conforming work, while QC without QA can produce isolated test results without traceability or consistent decision-making. Practitioners therefore need both: QA to provide the governance and discipline for the process, and QC to provide the observations, measurements and evidence needed to judge compliance and performance. However, QA is beyond the scope of the present guide.

In Australia, the majority of shotcrete QC testing is performed off site other than fresh property and early-age strength assessment. While controlled laboratory environments and precise instrumentation can improve repeatability, they also introduce a critical vulnerability: the potential for handling-related disturbance or error during sample collection, preparation, extraction, curing and transport. The accuracy of offsite testing therefore depends on careful, consistent and cooperative practice across the full shotcrete supply chain. Improving communication and aligning expectations between designers, material suppliers, contractors, applicators and testing organisations is central to achieving consistent, high-quality outcomes. All these issues should be addressed as part of the QA process that QC resides within, but this is beyond the scope of the present document.

3. Relationship Between Testing and Performance

Testing is essential to QC, but test results should be interpreted carefully. As for all concretes, shotcrete tests do not measure in-situ structural performance directly; they measure the behaviour of samples prepared, cured and loaded under controlled conditions. These tests are valuable because they provide consistency, comparability, and are a basis for verification, but they remain indicators or proxies of performance rather than direct proof of how a lining or structure will behave in service. Understanding this relationship is fundamental to good QC and decision making.

When interpreting QC test results, practitioners should recognise the effect of specimen size. Concrete is a brittle material, and its mechanical performance is influenced by the presence of flaws ranging from microscopic defects to visible voids, air pockets or laminations. Some flaws will be sufficiently large, or sufficiently unfavourably located, to reduce measured performance. As the size of a structure or specimen increases, so does the likelihood of containing critical flaws that influence the result. This statistical size effect should therefore be considered when relating specimen performance to the behaviour of the full-sized structure. It should also be considered when

comparing results between specimens of different sizes. Wherever possible, specimens should be of the same size and geometry when comparing compressive, flexural, or tensile strength. Thus, specimens should be the same size when comparing cast cylinders with cores or cast beams with cut beams. Where this is not practicable, an appropriate size correction factor should be applied to the smaller specimen before comparison is made.

For fibre-reinforced concrete and shotcrete, specimen thickness also has an important influence on flexural performance. Post-crack flexural strength is provided by fibres bridging a crack, and the resistance developed depends in part on the extent of fibre pull-out, which is related to crack width. For a given level of deformation, thicker specimens will generally develop wider cracks than thinner specimens. Specimen thickness should therefore be considered when post-crack performance parameters such as flexural strength are used in design or verification. The selected specimen should ideally be representative of the thickness of the in-situ lining or structural element it is intended to represent. As a guide, beams with a 150 × 150 mm cross-section, such as those used in EN 14651 or ASTM C1609/C1609M, are more appropriate for thicker shotcrete linings of about 100 mm or more, whereas EN 14488-3 (Method A) or ASTM C1550 are more suitable for linings less than 100 mm thick (as these test specimens are only 75 mm thick). Use of a flexural specimen with a markedly different thickness may lead to performance estimates that are not representative of in-situ behaviour.

When comparing the performance of sprayed test specimens with shotcrete in the works, the effect of age should also be considered. The properties of concrete change significantly with age, particularly in the first few weeks after casting or spraying. Because most QC specimens are sampled and tested within this period, the age of the specimen should be taken into account when assessing compliance with design or specification requirements for the in-situ shotcrete. This is especially important at early age, when the properties of shotcrete can change rapidly. Where early-age performance is required, specimens of the same age as the in-situ shotcrete should be tested.

The rate of change in performance generally reduces as concrete matures beyond 28 days, and an exact match between specimen age and the age of the represented structure becomes less critical. In practice, specimens are seldom tested beyond 90 days, and results at this age are commonly taken to represent later-age shotcrete. Within a QC programme, testing at ages greater than 90 days is usually impractical because the opportunity to respond to poor results is limited. Where very long-duration properties are relevant, such as sulphate resistance or chloride penetration, the necessary tests should be undertaken during pre-construction trials rather than during production QC.

Load duration is another factor that affects apparent concrete performance. In general, measured strength decreases as the duration of loading increases, particularly where the applied stress exceeds about 70% of the short-term strength. This occurs because microcracks can form and progressively link under sustained high stress, leading to critical cracking over time. Long-duration strength tests are not generally feasible within a QC programme, as standard tests are based on short-term loading to failure over a period of minutes. Where long-term loading effects are relevant to design or assessment, correction factors may therefore be required (Rüsch, 1960). The effect of load duration on bond strength is less well established, but it is likely to be of a similar order to the effect on tensile strength.

3.1 Sprayed versus Cast Concrete

Shotcrete is both a material and a process. The spraying and compaction process produces a material with a different internal structure from the concrete as supplied, and shotcrete mixtures are typically proportioned differently from cast concrete to support pumping and spraying. In addition, the use of set accelerator during spraying changes the chemistry of the in-situ shotcrete. The extent of this change depends on the type and dosage of accelerator. For this reason, specimens intended to represent in-situ shotcrete should, so far as practicable, be sprayed using the same process, equipment and accelerator regime as the works. This is not always fully achievable, particularly for overhead applications, and the limitations of specimen sampling should then be recognised and recorded.

Spraying affects the in-place material in several ways. Air is expelled during projection and impact, so the final concrete often has a lower air content than the concrete as supplied. Some material rebounds and does not form part of the consolidated lining. Coarse aggregate tends to rebound most strongly from a hard substrate, while fibre rebound can remain significant if nozzle angle, distance or equipment condition are poor. Nozzle wear can also widen the spray pattern, reduce compaction and increase wastage. The spraying process also changes the pore structure of the material and often produces layered deposition. In fibre-reinforced shotcrete, it may also lead to a marked orientation of fibres within the plane of the lining.

The use of a set accelerator changes the chemistry of the in-situ shotcrete. Most modern accelerators are based on aluminium sulphate, which promotes rapid early stiffening and apparent early strength gain through formation of ettringite and related hydrates. This alters the crystal and pore structure of the young concrete and, at high dosage rates, may significantly reduce later-age strength and durability, particularly sulphate resistance. Accelerator dosage should therefore be kept no higher than necessary to achieve the required construction performance and should be monitored through QC.

Uniform distribution of the accelerator is also important. Variations in concrete delivery, including pump pulsation, can cause local over-dosing where accelerator flow remains steady while concrete flow fluctuates. This may create bands of over-accelerated concrete that reduce strength and durability and may adversely affect specimens taken from sprayed panels. High accelerator dosage can also increase rebound and promote a harsh, lumpy surface, particularly where the shotcrete is applied in multiple thin layers rather than being allowed to build as a soft, cohesive layer. Re-incorporation of rebound should be avoided, as it can lead to weak and poorly consolidated shotcrete.

Accelerator dosage should be expressed as a percentage by weight of Portland cement, not total cementitious content. This distinction matters because the accelerator reacts primarily with the clinker phases in Portland cement rather than with inert fillers or supplementary cementitious materials. If dosage is based on total cementitious content rather than actual cement content, the effective dosage relative to the reactive cement fraction may be too high, which can be detrimental to shotcrete performance.

Aluminium sulphate-based set accelerators react primarily with the C_3A phase (tricalcium aluminate) in Portland cement, rapidly forming ettringite and other aluminate hydrates that create the fast set and early stiffening required in sprayed concrete. They also increase the dissolution rate of C_3S (tricalcium silicate) contributing to very early strength. Among all cementitious powders used or available for use in shotcrete, Portland cement is the only one that contains both C_3A and C_3S. For accelerator dosage purposes, the Portland-cement clinker fraction is the principal reactive component. Supplementary cementitious materials should therefore not be treated as equivalent to Portland cement when establishing accelerator dosage. For GP (General Purpose) and GL (General Purpose Limestone) cements, the minimum clinker content specified in the relevant standards is 90% and 85%, respectively. Because these products contain a high and predictable proportion of clinker, they should be treated as cement for the purposes of accelerator dosage calculations.

3.2 Specimen Production

Apart from tests of workability or fibre content, most specimens used in shotcrete quality control are either cast from concrete delivered to site or extracted from sprayed panels or the works after hardening. Because extraction from the works causes damage and requires repair, most sprayed specimens are taken from test panels prepared near the works and sprayed at an inclined angle. These panels should, as far as practicable, include the same set accelerator dosage used in the works. Where very high accelerator dosages make finishing difficult, especially for screeded panel tests such as ASTM C1550, any reduction in dosage should be limited, justified and recorded.

Test panels are intended to represent the shotcrete in the works. Accordingly, the same mix, equipment and nozzle operator should be used wherever practicable, and the spraying technique should match the works as closely as possible. Although inclined panels do not fully represent overhead application, they remain the most practical and safest means of producing routine QC specimens. Specimens should not be moved for at least 24 hours after production. Cast specimens should not be used to represent set-accelerated sprayed shotcrete. Further guidance on specimen production is provided in Section 6 Specimen Production and Testing.

3.3 Accounting for Variability

3.3.1 General

The purpose of Quality Control is to assess the performance of a product against the performance required by design. The specific performance requirements will normally vary from project to project, but the methods by which they are derived are common to most projects. Performance requirements and a corresponding QC testing regime will also depend on the targeted design service life of the shotcrete on a project. For example, water penetration tests are typically not required for temporary shotcrete. In general, Quality Control testing is more rigorous for permanent shotcrete than for temporary shotcrete.

The 'design' value for a shotcrete parameter is the magnitude of the parameter used in the design of the structure (such as water penetration, compressive strength, toughness or residual flexural strength) and is typically based on characteristic values. Characteristic values are defined in relevant standards and are typically the value that at least 95% of results are expected to equal or exceed. For example, if the characteristic UCS design value is 40 MPa, a characteristic value of 40 MPa conventionally represents a lower fractile of the population, such that only 95% of results would be expected to fall below it.

The margin between the characteristic value and a test result for a performance parameter must account for both within-batch and between-batch variability observed in samples of shotcrete tested in a QC programme. The requirement that variability be included to account for the margin between characteristic and test result values reflects the fact that failure to maintain consistent performance from one batch of concrete to the next increases the risk of failures in intermediate batches that are not tested.

A problem that afflicts fibre-reinforced shotcrete is the very high variability in performance observed for some performance parameters, especially post-crack residual flexural strength. The high variability is caused by the relatively small crack area characteristic of beam specimens and by the critical role of fibre location across the crack face in determining flexural performance. Given that a relatively small number of fibres bridge the crack in a beam test such as EN 14651, the randomness in the location of each fibre across the crack face leads to high variability in apparent performance. This effect is diminished as specimen size increases and the dosage rate of fibres (and thus the number of fibres on the crack face) increases. This is the principal reason why the ASTM C1550 round panel test exhibits relatively low within-batch variability compared to other post-crack performance tests.

A high level of between-batch variability typically reflects an inability to control the consistency of input ingredients or produce a consistent mix design. For shotcrete, high between-batch variability may also reflect differences in the competence of sprayers or the standard of spraying equipment used as well as changes in the consistency of materials supplied to the batching plant. If high between-batch variability is noted, efforts must be made to identify possible inconsistencies in materials, batching, mixing, delivery, operator proficiency, spraying method, accelerator dosage, specimen curing, and specimen handling.

When considering the apparent within-batch standard deviation exhibited by a set of specimens, one must also take into account that the sample standard deviation is typically smaller than the population standard deviation. Moreover, it is the population standard deviation that reflects the true variability in the performance of a material. As the number of replicates in a sample increases (that is, more specimens are used to produce a mean estimate of performance for a batch of concrete), the sample standard deviation will converge toward the population standard deviation. The minimum number of replicates typically required to produce a sample mean and standard deviation that reasonably represents the 'population' is 15. Unfortunately, the use of so many replicates is not feasible in normal QC or even in pre-construction trials because the cost of being 'statistically rigorous' can be significant. It is therefore necessary to adjust the sample mean and standard deviation to reflect that the performance data obtained from the small number of replicate specimens usually used on site (around 3) could be a misrepresentation of the population performance. The standard deviation for a small sample size must be increased to reflect the population standard deviation.

A larger number of specimens should be used during pre-construction trials, especially for highly variable parameters such as post-crack performance of FRS, as these trials will determine the dosage rate of fibres used at the start of construction. It is common to use six beam replicates per sample set when assessing residual flexural strength or energy absorption. Other parameters generally exhibit lower variability, so three replicate specimens are sufficient per sample set. Once the minimum dosage rate of fibres has been determined, three beams are used per sample set during production testing, or three panels are used for panel testing. However, it is recommended that a spare set of test panels be sprayed so that additional beam or panel replicates can be cut and tested should the average for the first three fail. If tested at the same age, typically at 28 days, the performance of the additional tests must be averaged together with the performance of the initial three tests. If tested at a later age (say, 56 or 90 days), they must be considered on their own to determine a sample mean level of performance.

As part of the development of acceptance criteria for test results obtained during production QC testing, one must consider the thresholds at which action must be taken in response to non-conforming results. In general, if the mean of a set of replicate specimens achieves the acceptance value for a parameter, then no action is taken.

If the mean for a set of specimens does not achieve the acceptance criteria, the sample set is non-conforming. For the purpose of this guide, a sample is taken as a set of specimens.

Typically, project requirements and specifications require acceptance criteria to be achieved. However, Australian and international standards for structural design require the use of characteristic values as the basis for design values, which are then linked to the ultimate limit-state reduction factors used in design. It is recommended that acceptance be based on the characteristic level of performance, as this will avoid unnecessary disputes and will be justified under structural codes. A project specification could adopt any value below the characteristic value as a non-conformance to trigger a more detailed assessment of the general performance of the overall mix and shotcrete as placed. For example, the moving average for the last 10 batches could be assessed for conformance thereby providing greater confidence that the mix is generally performing as expected.

Occasionally, a result will be so poor that it qualifies as an outlier. An outlier is a result that differs significantly from other observations; in construction practice such results must be investigated. No more than a single outlier within a sample may be excluded from consideration on the basis that it does not conform to the expected statistical distribution of results, for example, due to an issue with sample preparation or testing. Project specifications should explain how outliers are considered.

3.4 Acceptance Criteria

Commonly adopted QC acceptance criteria for temporary and permanent reinforced shotcrete linings are outlined in the following.

3.4.1 Slump (AS 1012.3)

Slump tests are performed to measure workability, consistency and flowability of fresh concrete delivered to the project site. They serve as a quick site-based test to check or identify improper mixing ratios before the shotcrete is used. Target slumps are to be established in the shotcrete trial mix phase. Slump tests also enable a visual check for fibre and aggregate type. Slump tests are recommended for every shotcrete load delivered to site. Acceptance is based on a simple pass-fail criterion to the specified slump target range.

3.4.2 Density (AS 1012.12)

The density at 28 days of hardened concrete included in the Works, determined in accordance with AS 1012.12 on representative core samples cut from test panels in accordance with AS 1012.14, must not be less than 98% of that of the corresponding density of cast samples taken from the transit mixer in accordance with AS 1012.8.1 and the density of the nominated base mix. Minimum core diameter for density tests should be 75 mm.

3.4.3 Macro Fibre Content (EN 14488-7)

Fibre content should normally be determined from a representative sample of fresh shotcrete in accordance with AS 1012.25.1 and RC 377.01. Fibre must be washed out of the sample and collected, dried, and weighed. The weight of fibre must be related to the volume of the sample in terms of kg/m^3.

The dosage must be assessed against the performance requirements detailed in the project specifications. A non-conforming fibre content test may be acceptable if all of the following apply:

- The average result of three successive fibre content tests exceeds 90% of the approved fibre content,
- All individual results are greater than 80% of the established trial target, and
- Associated production test results for compressive and residual flexural strength, as well as dry density performance of shotcrete, are compliant.

3.4.4 Thickness

Shotcrete thickness should be determined utilising survey profiling before and after the application of individual shotcrete layers, e.g., primary, smoothing layer, and secondary support, as applicable. Unless otherwise specified, alternative methods of measurement using depth indicators may also be acceptable, but do not provide the same level of assurance as a survey scan.

Proof drilling should be undertaken at random locations to undertake spot checks. Spot checks using proof drilling holes at random locations also need to avoid damage to groundwater control systems that are embedded behind or within the shotcrete lining. For acceptance, the minimum shotcrete thickness must comply with the relevant project specification and/or design drawings.

3.4.5 Compressive Strength of Cylinders and Cores (AS 1012.9 and AS 1012.14)

For compression cylinders where the compressive strength differs by more than 3 MPa across three or more specimens in the sample, the assessment criteria set out in AS 1379 Section 6.2.5 allows the exclusion of the lowest strength value.

For compression cores, a result may be taken to be acceptable if the mean for a test set of cores is equal to or greater than 0.87 times the specified characteristic design strength (AS 5100.5, Clause A6.4.2). For example, if the characteristic design value and specified characteristic strength is 40MPa, then mean strength results as low as 34.8 MPa would be considered acceptable.

3.4.6 Flexural strength for beams

For flexural strength assessed using beams (e.g. EN 14651 and ASTM C1609/C1609M), a result for fLOP or the Modulus of Rupture of the concrete matrix is taken to be acceptable if the mean for a test set of cut beams is equal to or greater than 0.87 times the specified characteristic design strength (AS 5100.5, Clause A6.4.2). For example, if the characteristic design value of Modulus of Rupture and QC acceptance value is 3 MPa, then strength results as low as 2.6 MPa would be considered acceptable. This acceptance criterion does not apply to any measure of post-crack performance in any test.

3.4.7 Water Penetration (EN 12390-8)

Limits on water penetration are typically specified for shotcrete with a design life of 100 years or more. Each sample for permeability testing should comprise three 150 mm diameter cores to be tested in accordance with EN 12390-8 at age of 56 days. The water permeability at 56 days is then taken as the mean of all three test specimens. The acceptance criterion is that the mean value does not exceed the specified limits for the nominated exposure class.

3.4.8 Shrinkage Strain (AS 1012.13)

Shrinkage strain tests should be performed on a shotcrete base mix dosed with the nominated fibre content. The average result of three test specimens is recommended to demonstrate compliance with the specified shrinkage strain limit. Production testing may also be specified by clients where shrinkage is an important factor to ensure a durable structure. It is noted that meeting an acceptable shrinkage criterion does not necessarily ensure that shrinkage cracks will not form. Where project requirements include specified crack width limits and the need for repair when exceeded, additional shrinkage tests are recommended during the production stage to support responses to potential non-conformance reports related to crack width remediation.

3.4.9 Chloride diffusion (Nordtest Build 492)

Tests are recommended for shotcrete with conventional reinforcement for the base/trial mix phase as a minimum and should also be undertaken as part of production testing where durability requirements are stringent. For the average test result, the chloride diffusion should not exceed the specified limit derived from a project-specific durability assessment that defines shotcrete cover over steel reinforcing bars.

3.5 Non-Conformance Reports

A 'non-conformance' (NC) is a test result that fails to satisfy project specifications. The contractor is normally the entity that has the responsibility to respond to the occurrence of a non conformance but a request to the Contractor to raise a non-conformance can also be made by relevant project stakeholders, e.g. designer, independent verifier or certifier, project principal, client or other stakeholders. If a non-conformance occurs, a non-conformance Report (NCR) must be raised and forwarded by the contractor to the designer who recommends an appropriate action to take or approves contractor's corrective actions. The NCR is also typically forwarded to the independent verifier or certifier and project principal or client for consideration.

The designer must assess the seriousness of the NCR and assess whether it actually affects the safety and serviceability of the structure or whether other mitigating circumstances allow the NC to be accepted. For example, if the residual flexural strength of FRS used in the lining falls below the required acceptance criteria, but the thickness of the lining is greater than the design requirement, the total moment resistance of the lining may still satisfy the design requirements.

If non-conformances occur in the performance of materials that form part of products supplied to the project, they need only be considered at the project level if they could affect the performance of the final products used on site. For example, if a non-conformance in aggregate used to produce concrete occurs, but there is no non-conformance in the affected batches of concrete, the concrete supplier must act to correct the non-conformance but no further action is needed at the project level.

It is generally recommended that NCRs be raised and acted upon promptly so that, if the non-conformance is caused by a systemic problem, an appropriate correction is made to prevent further non-conformances.

A common non-conformance concerns a failure to conduct tests in accordance with project requirements or specifications. If the test was restricted to the compressive strength of either the concrete supplied or the test panels, an appropriate response would be to take cores from the works and test them instead. Similarly, if slump or wash-out tests for fibre content were missed but strength and post-crack performance were satisfactory, then the non-conformance will not generate serious consequences for the project. Water permeability and density can also be assessed using in situ cores. However, if the omitted test was for post-crack performance, there is no way to assess whether the in-situ shotcrete still satisfies project requirements. A possible response is to confirm that the sprayed thickness is acceptable, then monitor whether cracks form in the affected shotcrete area and assess the results for the previous and following batches. If no cracks occur, then the post-crack performance may be considered acceptable.

A failure to conduct drying shrinkage tests can possibly be addressed with reference to maximum allowable crack widths. The occurrence of drying shrinkage cracks in the affected shotcrete area should be monitored. If maximum crack widths by project completion are satisfactory, no further action is required. However, if crack widths exceed the allowable maximums, some action, such as epoxy/grout injection, is usually required.

Non-Conformances that are more difficult to address include relative density and excessive compressive strength (due to concerns about embrittlement). Designers should work with the client during the detailed design stage to agree on procedures to be followed in case these common non-conformances occur.

4. Responsibilities and Governance

Effective QC depends on clear roles, competent people and disciplined governance. The client, designer, principal contractor, specialist subcontractors, spray operators, testing personnel and laboratories each influence the quality of the finished shotcrete, and responsibilities should be explicit in the project quality documentation. Governance arrangements should define decision rights, hold points, reporting lines, records, management of non-conformances and how lessons from QC results are fed back into production. These responsibilities sit alongside statutory duties and contractual obligations, but from the perspective of a practitioner the immediate requirement is simple: everyone involved in QC should know what they are expected to check, record, review and act upon.

4.1 Legal and Contractual Considerations

Shotcrete works are subject to applicable work health and safety legislation, regulations, and project-specific contractual requirements. For mining projects, additional mine safety legislation and site requirements may also apply. This section provides general guidance on the relationship between QC, governance and legal obligations. It is not legal advice and should be read together with the relevant legislation, codes of practice, contract documents and project requirements.

Codes of practice and similar guidance documents provide practical direction on how legislative duties may be met in the workplace. Those involved in shotcrete works should be familiar with the requirements relevant to their role, including any jurisdiction-specific guidance that applies to design, construction, excavation, silica risk management and temporary works.

Useful codes of practice relevant to the shotcrete workflow include:

- **Code of Practice:** Construction Work
- **Code of Practice:** Excavation Work
- **Code of Practice:** Safe Design of Structures
- **Code of Practice:** Managing risks of respirable crystalline silica in the workplace

SafeWork NSW is currently revising a long-overdue Code of Practice for Tunnels under Construction that addresses shotcrete-related WHS hazards and risks. These requirements may be adapted by other Australian states. Shotcrete practitioners should therefore become familiar with the SafeWork NSW requirements if and when they are adopted more broadly.

4.1.1 Safe Design

Safe design means the integration of control measures early in the design process to eliminate, or, if this is not reasonably practicable, minimise risks to health and safety throughout the life of the structure being designed. The safe design of a structure will always be part of a wider set of design objectives, including practicability, aesthetics, cost and functionality. While occasionally competing, these objectives need to be balanced in a manner that does not compromise the health and safety of those who work on or use the structure over its life.

4.1.2 Client Responsibilities

Clients should provide relevant project information, including known hazards, design intent and project requirements, and should support appropriate consultation between designers and constructors. The level of QA and QC required for a project is ordinarily established through the specification and project quality documentation and should reflect the risk, importance and service environment of the works.

4.1.3 Principal Contractor Responsibilities

The principal contractor may be the client, or they may be engaged by the client to manage and control the workplace. The principal contractor has a duty to ensure the construction work is planned and managed in a manner that eliminates or minimises health and safety risks so far as is reasonably practicable. This includes consultation with designers who develop designs, and workers who undertake excavation and construction activities.

Principal contractors should ensure that appropriate risk controls, competence requirements and project controls are implemented. For shotcrete works this typically includes competent spray operators, suitable inspection and QC test plans, management of non-conformances, and feedback mechanisms that allow production quality to be improved during the works.

4.1.4 Designer Responsibilities

Designers should consider the information provided by the client and constructor, apply relevant standards and engineering judgement, and communicate the assumptions, requirements and limitations of the design to the contractor. For shotcrete works this may include the required material properties, workmanship assumptions, construction sequence constraints and minimum QC requirements. Designers should also engage with interfacing disciplines and construction teams where this is necessary to align the design with practical delivery.

Designers should also ensure that specified shotcrete properties and QC requirements are appropriate for the project and reasonably achievable in practice. Where non-conformances arise, assessment should be based on the design intent, the available evidence, and the significance of the departure.

4.1.5 Worker Responsibilities

Workers, including spray operators, testing personnel and supervisors, should follow project requirements, use the specified materials and methods, and take reasonable care in the execution of their tasks. In the context of shotcrete QC, this includes applying the specified process, recording the required information, and reporting non-conformances or unsafe conditions.

4.1.6 Summary

In practice, many of the project and WHS responsibilities described above are also relevant to how accountability is assessed when defects, safety incidents or disputes arise. Clear roles, competent execution, and reliable records are therefore central to effective shotcrete QC.

4.2 Negligence in Shotcrete Operations

Shotcrete work involves shared responsibilities across design, construction, supervision and testing. Where defects or failures occur, the responsibilities of different parties may be examined in light of their role in producing the shotcrete works, the control they exercised, the requirements that applied to them, and the records available. For practitioners, the key implication is straightforward: QC activities should be competently undertaken, appropriately documented and acted upon when results indicate a problem.

In a negligence-related dispute, there are four elements every claimant must prove, as described in the table below:

Table 2 Elements of negligence relevant to shotcrete operations

Duty of Care	Do all roles in the shotcreting process owe a legal obligation to take care? In shotcrete works, the duty of care is commonly established through proximity and foreseeability: shotcrete directly protects workers, equipment, and the public from structural failure, and reliance on appropriate design and proper workmanship is both real and foreseeable. The scope of duty will be shaped by the contractual matrix and the specific control exercised. In NSW the Design and Building Practitioners Act 2020 (NSW) imposes a statutory duty of care on anyone who 'carries out construction work', which includes buildings and major infrastructure projects. This statutory duty does not currently apply nationally, but in jurisdictions outside of NSW, common law negligence principles govern.
Breach	Did the person fall below the standard of a reasonable professional in that role? Codes and standards are the primary evidence of that standard, but they are not the standard itself. Departure from an applicable code, without documented engineering justification, is prima facie evidence of breach. Typical codes and standards that define appropriate practice include, AuSS-CIA, 2020, agency standards such as TfNSW R68 and B82, ACI 506.2-13, and the EFNARC European Specification. All these documents carry differing legal weight and should not be treated as equivalent. The weight depends on whether the instrument was contractually incorporated (project specification, ITP, drawings) or is merely general industry practice, the edition applied at the time of the work, and whether its requirements were mandatory or advisory. Compliance to a code or standard is also not a complete defence. For example, a common or codified practice may itself be negligent where better knowledge was available. It should also be noted that specialists claiming particular shotcrete expertise are held to the standard of that expertise and not the general labourer. This is particularly relevant for specialist roles such as the shotcrete operator and testers. Further, where a widely accepted professional practice defence is raised, courts will assess whether adherence to that practice was itself reasonable in the specific circumstances.
Causation	Did the breach cause a loss? Causation is assessed having regard to what was known or should have been reasonably known at the time of the relevant act or omission — not with the benefit of hindsight. Evidence of what the defendant actually considered at the time is relevant to that assessment. Examples of causally relevant breaches in shotcrete work include defective application leading to delamination, failed or absent testing enabling substandard work to remain in place, or ignored monitoring data permitting progressive deterioration.
Damage	Was there recoverable loss? In defect claims the principal head (category) of damage is the cost of rectification, but only where the remedial work is both necessary to produce conformity and a reasonable course to adopt. Where it is not, the measure is diminution in value. Courts award the cost of restoring the plaintiff to the position they would have been in if there was no breach. These costs could include repair and replacement costs, consequential loss, and economic loss. Consequential losses in tunnelling include prolongation, standing time, plant downtime, disruption to subsequent trades, and liquidated damages passed down the contractual chain. These costs frequently exceed the rectification cost and may be excluded by contract. Pure economic loss for defective building work is separately constrained at common law, but some jurisdictions may have specific legislation that addresses economic loss caused by defects. Where the failure causes injury or death, damages in Australia are assessed under relevant state civil liability legislation, as well as relevant WHS legislation. Regardless of the damage claimed, all heads of damage are subject to mitigation, contributory negligence, and apportionment.

4.2.1 Allocation of responsibilities

Responsibility for shotcrete quality may involve more than one party. Designers, contractors, specialist subcontractors, supervisors, testing personnel and project managers may each have responsibilities according to their role, the control they exercise and the project requirements that apply. The practical importance of this for QC is that records, decisions and response actions should be clear, traceable and proportionate to the significance of the work.

- **Designer:** the designer is responsible for the design assumptions, specified performance requirements and any QC provisions included in the design and specification. This may include defining required shotcrete properties, acceptance criteria and the approach to assessing non-conformances.
- **Shotcrete operator:** the operator is responsible for applying the shotcrete in accordance with the specification, approved procedures and accepted good practice, including thickness control, workmanship, layer sequencing and management of rebound.
- **Supervisor or foreman:** the supervisor is responsible for overseeing the work, checking compliance with project requirements, and ensuring that non-conformances are reported and addressed appropriately.
- **QC tester or laboratory technician:** testing personnel are responsible for carrying out the required tests in accordance with the nominated methods, maintaining traceable records, and reporting results accurately and in a timely manner.
- **Project manager or superintendent:** project management personnel are responsible for coordinating the QC framework, ensuring that responsibilities are implemented, and confirming that issues requiring review are escalated appropriately.
- **Head contractor or developer:** the head contractor or developer is typically responsible for ensuring that the required project controls, subcontract interfaces, and acceptance processes are in place across the delivery chain.

4.2.2 Evidence of negligence

The following examples illustrate how poor QC practice can weaken confidence in the quality of the work and complicate later review or dispute resolution.

Table 3 Examples of QC practice that may weaken evidence of competent shotcrete delivery

Failure to Test	Failure to conduct required tests may possibly constitute a systemic breach of statutory and contractual obligations. Where testing records are absent, adverse inferences against the defendant may be drawn. Each untested panel, core, or adhesion pull-off represents a gap in the evidentiary defence.
Ignoring results	When non-conforming results are identified, failure to investigate, assess significance and implement appropriate corrective action may materially weaken evidence of competent delivery. NCRs closed without genuine corrective action may be characterised as a serious departure from reasonable practice.
Data manipulation	Moving alarm thresholds, disabling convergence alerts, or adjusting monitoring parameters without proper justification may be treated as evidence of deliberate avoidance rather than professional judgement. Where this is established on the facts, it will significantly undermine the defendant's credibility and may be relevant to the assessment of damages.

Record keeping: Project records should be complete, timely and reliable. QC records, communications, equipment logs and related documentation may all become important if performance is later questioned. Good practice is therefore to maintain clear contemporaneous project records in accordance with the project quality system.

4.2.3 The standard applied to the shotcrete operator specifically

Shotcrete operators are generally assessed against the standard reasonably expected of a competent person performing that role at the time the work was carried out. Where an operator is engaged as a specialist, the expected standard may reflect that specialist skill and experience. For QC purposes, the implication is that work should be carried out in accordance with the specification, applicable procedures and accepted good practice, and departures should be justified and recorded.

The practice implication of this standard is that clear QC requirements, reliable testing, appropriate management of non-conformances, and good record keeping are fundamental to demonstrating that shotcrete work has been planned, executed and reviewed in a competent and defensible manner.

5. Commercial and Contractual Principles

Contractual requirements are also central to shotcrete QC. Contracts and specifications should clearly allocate responsibilities for design, supply, spraying, inspection, testing, non-conformance management and acceptance of the works. QC requirements should be expressed in a way that is practical, traceable and aligned with the design intent, so that all parties understand what is required and how compliance will be assessed.

These principles should flow through the project contract and any relevant subcontracts. In practice, this means that the design requirements, workmanship obligations, testing regime, acceptance criteria and response processes for non-conformances should be consistent across the project delivery chain, with responsibilities allocated clearly enough to avoid gaps or overlap.

A common contractual arrangement is for the designer to specify the required shotcrete performance, workmanship and QC obligations, and for the contractor to implement the work in accordance with those requirements. In this context, QC requirements should be clear enough that compliance can be assessed consistently across design, supply, spraying, testing and acceptance of the works.

6. Specimen Production and Testing

Once the QC approach and required verification methods have been defined, specimen production and testing become critical to obtaining reliable information. Even a well-conceived QC programme can be undermined by poor sampling, damaged specimens, inconsistent curing, inadequate traceability, or test methods that are not well matched to the property being assessed. The following guidance therefore focuses on practical measures that improve the reliability and representativeness of specimens from production through to testing.

6.1 Testing Environment

Tests can either be conducted at the work face, on site, or in a laboratory environment. Early-age tests are normally conducted at the immediate work face as this type of testing often involves testing the shotcrete in place or sprayed into test panels adjacent to the works. On-site tests of wet shotcrete as delivered, such as slump/spread, or wash-out tests, should be conducted on concrete delivered to site. In both these environments, the temperature and atmospheric conditions prevailing during testing should be representative of the conditions experienced by the shotcrete during and immediately after spraying as these conditions can strongly affect the performance of the concrete.

The laboratory is a more controlled environment that ensures more repeatable conditions during the testing of hardened shotcrete. This is achieved by controlling or managing variables such as humidity, temperature and drying/curing conditions that have a significant effect on the material's strength, shrinkage, and other characteristics. A controlled environment allows for reliable comparisons between different shotcrete mixes and additives whilst also providing more reliable test data for quality assurance and design and an understanding of the behaviours that cured shotcrete exhibits under different conditions.

6.2 Application Environment

Unlike the controlled environment of a laboratory, mining, tunnelling and civil areas of application (i.e. the working drives or headings) are essentially "uncontrolled" as variables including humidity, temperature, air flow, drying/curing conditions, degree of compaction and accelerator dosage are subject to change on any given day. Testing samples that are sprayed within the working environment will help to accurately assess the properties of the final product under actual application conditions, thereby accounting for factors such as nozzle manipulation, curing location, and curing methods (Figure 1). On-site factors that should be controlled and recorded include:

- Accelerator dosage used for spraying the samples as well as the dosage used for in-situ spraying.
- Nozzle distance from the sample at the time of spraying as well as the air pressure (if available).

Knowledge of these factors will go a long way to ensuring that test results reflect the performance of the in-place shotcrete as accurately as possible.

Damage caused by premature handling of samples seriously impacts the results or even negates the usefulness of the samples. For this reason, it is recommended that the samples be sprayed in an area that matches the work site environmental conditions as closely as possible, and in which they can be left undisturbed for a minimum of 24 hours after spraying, after which they can be carefully moved to a suitable curing facility.



Figure 1 Spraying panels for cores and post-crack performance assessment

6.2.1 Moulds and Equipment

Moulds used in shotcrete testing, whether for cast or sprayed specimens, should comply with the relevant standards for each specific test and should always be kept in good condition (for example, ASTM C1140/C1140M, ASTM C1550, or EN 14488-1). Any damage that is detected should be repaired or the mould should be replaced to ensure the accuracy of collected data. For cast specimens, established standards should be followed, while sprayed specimens often require custom-made moulds prepared in advance near the spraying location.

Moulds that are used to produce beams of 150 × 150 mm cross-section should have a minimum recommended size at the base of 800 × 800 mm and be 200 mm thick with peripheral flanges inclined at 45°. Moulds that are to be used to produce cores should be about 400 × 400 mm at the base and 250 mm thick with flanges inclined at 45° (Figure 1). The moulds should be oiled using form release oil prior to spraying; do not use diesel or hydraulic oil. Moulds should ideally be made of welded steel sheet or plate and include handles and lifting points/fork tine loops for mechanical handling. The shotcrete process and harsh on-site environments often cause damage to moulds, so regular inspection and maintenance are essential.

In addition to moulds, any measuring equipment such as beam end testers or needle penetrometers should be calibrated in accordance with manufacturer recommendations, typically yearly but more frequently if required because of site quality assurance policies, frequency of use, or exposure to harsh conditions. Concrete finishing tools such as straight edges, builder's levels, flat trowels, screeds, and mag floats should also be kept clean and free of damage to ensure efficient finishing of samples and the production of reliable test results.

6.2.2 Area Preparation

The area where the test panels are sprayed and cured should maintain ambient conditions that are as close to the spraying area conditions as possible to ensure that the test results are relevant to the actual working environment. Ensure the area is safe with adequate ventilation, ground support is installed and services such as air and water are close to the test area.

Ideally, the specimen production area should have flat ground and be free of loose, dry, fine material that can be stirred up and contaminate the moulds whilst spraying. If this is unavoidable, the ground should be wetted down prior to spraying to suppress dust.

Panels should be supported in a sturdy manner to prevent movement when spraying and placed on a 50° to 60° angle to the horizontal, ideally raised off the ground slightly (approximately 100 mm) on pieces of timber to help reduce the amount of foreign material blown into the mould from the ground during application (Figure 2). Placing moulds in a vertical orientation is also recommended but this can cause problems of shotcrete retention when moulds are oiled. Raising the moulds also helps when finishing the panels. There should also be a water supply available together with hessian or burlap and plastic to cover the samples for curing once finished.

6.2.3 Mould Preparation

All moulds should be coated with a suitable concrete release agent or form release oil to aid de-moulding, thereby making removal easier and reducing the risk of damage. Care should be taken to avoid pooling of excess oil which can be achieved by wiping down with a clean rag. Under no circumstances should diesel or hydraulic oil be used, as both interfere with cement chemistry and compromise specimen quality. When spraying into panels and moulds, the shotcrete should contain set accelerator dosed at the same rate as used in situ, and panels should be of uniform thickness, and not excessively thick as this makes them too heavy to transport and difficult to cut.

Overspray and concrete hanging over the sides should be removed while fresh to facilitate later demoulding and transport. Panels should be spaced sufficiently apart to allow workers access for cleaning and manoeuvring. Adjacent moulds should be covered with form ply or equivalent to prevent debris accumulating during spraying. Other than for open-ended ASTM C116 beamlet moulds, spraying shotcrete directly into individual beam or cylinder moulds is not recommended, as rebound material becomes trapped and leads to poorly consolidated specimens. Instead, beams should be cut from larger panels with splayed sides to avoid rebound contamination. If rebound or overspray accumulates in a mould, it should be removed before spraying resumes. Once hardened, panels should be demoulded carefully, avoiding excessive force such as hammering, which can damage the young concrete and leave imprints on the mould.



Figure 2 Keep the panels adequately spaced and the spraying area free of obstacles to allow access during panel spraying

6.2.4 Application and Production

Operator skill, knowledge, and application technique are critical to achieving a successful shotcrete campaign, and the spraying of test specimens should be treated with the same care as ground support since test results directly reflect the in-cycle product. Spray machine settings play an important role, with pump speed adjusted to ensure smooth, controlled application and minimal pulsation, while accelerator dosage should be carefully set as a percentage by weight of cement (commonly abbreviated as bwc, excluding supplementary cementitious materials). The accelerator dosing equipment should be calibrated at regular intervals (specified within a project QA programme) to confirm the rate of chemical delivery.

Panels should be sprayed and finished one at a time. The dosage should be the same as the dosage used for in-situ spraying. If it is found that panels cannot be sprayed, screeded, and finished one at a time at the dosage rate used for the in-situ shotcrete then it is advisable to re-visit the dose rate specified for in-situ spraying and determine if this can safely be reduced and still meet the operational requirements. Whilst a higher dose rate might improve the early strength and re-entry times, over-dosing can lead to excess rebound, poor compaction, lower ultimate long-term strength, and potential laminations or long-term deterioration of bond to the substrate.

If satisfied that the specified in-situ accelerator dose rate does not adversely affect the long-term durability of the shotcrete but is so high that a panel cannot be finished satisfactorily, then it is recommended that the dosage be reduced by no more than 20% relative to that used for in-situ spraying and the dosage applied to spray the panels should be recorded as well as the dosage of the in-situ shotcrete. However, end beam specimens used for early strength and re-entry testing should always be sprayed with the same dosage as the in-situ shotcrete and cured under the same conditions as the working heading. A reduced dosage rate of set accelerator is not needed when spraying panels for cores and cut beams as these specimens do not require a smooth finished surface.

Spraying should begin at the bottom of a panel, building thickness before moving upward to prevent rebound or dry material from being incorporated, with the nozzle kept perpendicular at a distance of 1.0–2.0 m from the mould (ideally 1.5 m). The process should be completed in one continuous cycle without interruption. Any stoppage requires the panel to be emptied, cleaned, and restarted to avoid lamination defects. Panels should be sprayed to as close to uniform thickness as possible, and as close to the required final thickness as possible, so that the requirement for screeding is minimised. Panels for beams and cores can be sprayed to a greater thickness but avoid overly thick panels with a bumpy surface as production of beams and cores from such panels is difficult. Casting panels instead of spraying or spraying without accelerator is unacceptable.

Concrete hanging over the sides of the mould should be removed while the concrete is fresh to facilitate later removal of the mould. Deep overspray around the mould should also be removed while the shotcrete is fresh to allow the mould and test panel to be extracted from its location when de-moulding and transport is required. If screeding is required using set accelerated shotcrete, the panels should be sprayed one at a time and immediately screeded before spraying the next panel. This is to allow workers access to each panel to screed and finish the surface while the shotcrete is still relatively soft.

When beams are cut from panels, their orientation relative to the spraying direction and position relative to the edges should be marked so that stresses imposed during testing replicate in-situ bending stresses. Beams should measure 150 × 150 mm in cross-section with a minimum length of 550 mm (Figure 3), maintaining squareness within ±2 mm. The beam should be cut from a section of the sprayed panel that is no less than 50 mm from the lateral edges, and all six faces of each beam should be saw-cut. The flatness of beams and panels should be controlled so that no point is more than 2 mm higher than another when placed on a flat surface to ensure reliable and representative test results. The location of each cut beam from within the test panel should be noted, and these locations should be consistent for all sprayed panels. Cores can be drilled from the same panel if space allows (Figure 3).

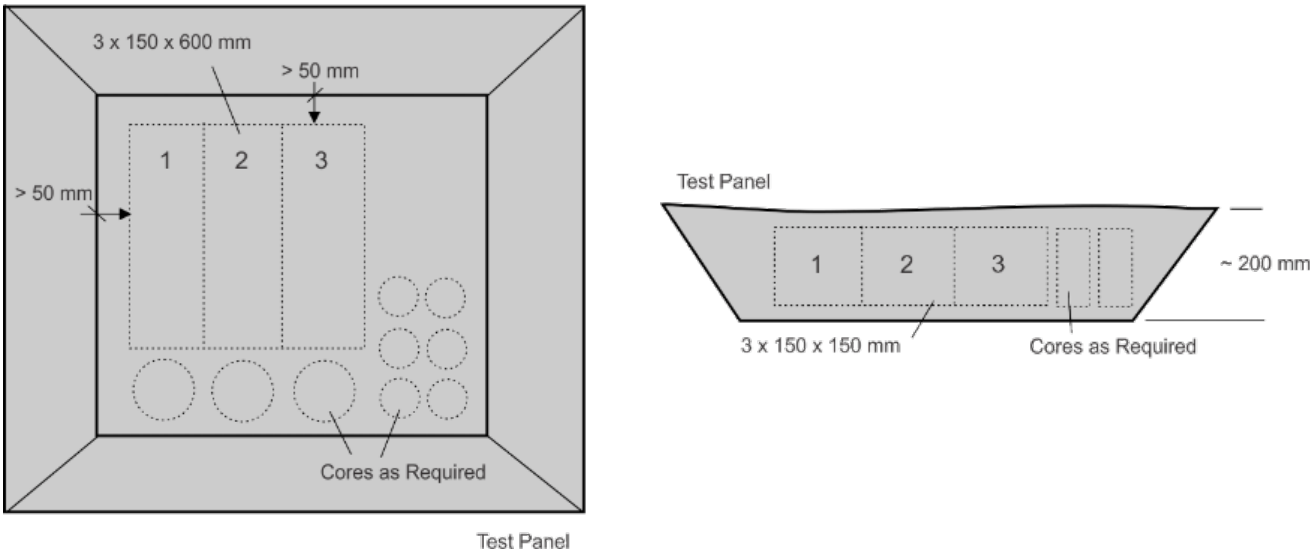

Figure 3 Recommended location of cut flexural beams and cores from within a sprayed test panel

6.2.5 Finishing of Samples

Some types of test specimen, especially ASTM C1550 and EN 14488-5 panels, require screeding to obtain a flat finished surface. Once the application of shotcrete is completed such samples should be finished to a flat, closed surface. This is done by "cutting" the panel with a cutting straight edge or builders' level in a left to right sawing/zig zag motion from top to bottom whilst applying downward pressure (Figure 4). Once the shotcrete is level with the mould it is then closed over by using a trowel or magnesium float to produce a smooth finish to the surface. This should also be done for beam end samples, so they have a uniform finish to fit easily into the testing equipment. Splashing or spraying water as a finishing aid to the specimen surface is unacceptable as this will affect the water/binder ratio and produce distorted results.



Figure 4 Screeding and floating round panels immediately after spraying

For specimens such as ASTM C1550 round panels that require screeding to final thickness while fresh, screeding can be difficult when the full in-situ accelerator dosage is used. A trial should therefore be undertaken to establish the highest accelerator dosage that still allows satisfactory specimen production. This dosage should ideally not be less than 80% of the dosage used for the in-situ shotcrete. All subsequent panels used for post-crack performance assessment should then be sprayed at that consistent dosage, and the dosage adopted should be recorded. Cast panels should not be used as a substitute for sprayed panels.

6.2.6 Curing and Storage

All concrete specimens, whether sprayed or cast, should be carefully cured and stored to ensure reliable test results. Immediately after spraying or casting, specimens should be wet cured for at least 24 hours by covering them with a double layer of continuously damp hessian or burlap, overlaid with plastic to lock in moisture and humidity and prevent airflow from evaporating the moisture. It is critical that the hessian or burlap never dries out, as this would act as a wick and draw moisture from the specimen; simply covering with plastic alone is insufficient. After the initial 24-hour curing period, specimens can be carefully moved to a facility where they are submerged in lime water, ideally protected from direct sunlight and freezing temperatures, and should remain in water curing for a minimum of six additional days. On site, sprayed test panels and related specimens should be stored for at least three days before transport to a laboratory to allow adequate strength gain, with longer periods required in cold climates where strength gain is slower.

Cutting or coring of specimens should only be undertaken once the shotcrete has reached a compressive strength of at least 10 MPa so that the concrete can withstand the sawing or coring process without cracking. Once prepared, the finished specimens should be returned to a damp state—either by immersion in water, wrapping in cling film, or covering with damp cloth—to promote hydration, prevent drying shrinkage, and preserve their integrity until laboratory testing.

6.2.7 Handling and Transportation

Handling and transport can materially affect whether specimens remain fit for testing. Mining and tunnelling environments may make transport difficult, particularly where testing facilities are remote and access roads are uneven. Panels are often too heavy for individual manual handling and should therefore be moved using suitable mechanical aids (the typical mass of hardened panels in forms can range from 200–1200 kg). Lifting arrangements should keep the specimen level and minimise impact, vibration and local damage.

Transport vehicles should have adequate load capacity, and panels should be supported in a way that minimises vibration and concentrated restraint. Stacking should generally be avoided unless the specimens are light enough and suitable cushioning and separation are provided (Figure 5). Tie-downs should secure the load without introducing cracking, local crushing or bending of the specimen.

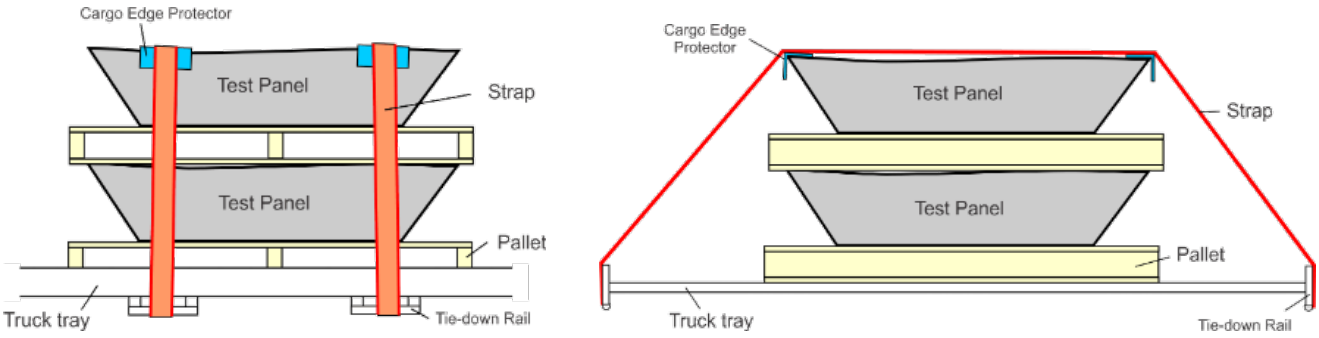

Figure 5 Illustrative methods of strapping shotcrete panels for transport

Finished panels should be kept damp during transport to minimise premature drying. Covered transport is preferable where practicable to reduce exposure to sun and wind. After delivery, moulds and reusable equipment should be inspected, cleaned and prepared for subsequent use.

6.2.8 Record Keeping

Comprehensive records are essential for traceability. Records should document the production, storage, handling and receipt of specimens so that the causes of non-conforming results can be investigated if required. Each specimen or specimen set should be linked to a paper or digital record that follows it through production, curing, transport and testing.

Key details to record include:

- Batch record number or docket number of the concrete load.
- Time and date of supply.
- Name of the sprayer responsible for producing the specimens.
- Machine used for spraying, including pump stroke rate and air pressure/volume.
- Dates of spraying and first movement of panels.
- Accelerator dose rate as well as the in-situ dose rate (should it differ).
- Fibre type and dosage.

Additional information should cover how specimens were stored on site including the maximum and minimum ambient temperatures, how they were stacked, and the method of transport. The record may also include the date of dispatch, the carrier, and the date of receipt at the laboratory. For specimens requiring cutting or coring, the date of preparation should be noted. The date of testing is typically reported on the test certificate accompanying each result.

Any deviations from recommended practice should be documented, along with the reasons for such deviations. Photographic records of specimens prior to transport are strongly recommended, as they provide visual evidence of conditioning and handling.

7. Frequency of Testing

The required frequency of testing depends on the property being assessed, the importance of the structure and the consequences of non-conformance. Major transport tunnels and other high-consequence infrastructure generally require more intensive testing than lower-consequence works. Mining applications often form a separate category because of their strong emphasis on worker safety and the different balance between structural and serviceability requirements.

The recommendations in Table 4 are intended as indicative guidance only. They draw on established sprayed concrete practice and have been adapted to reflect Australian conditions and project delivery methods. Where possible, related tests should be performed on concrete from the same batch before and after spraying so that the relationship between as-supplied and as-sprayed performance can be understood.

A reasonable starting point for selecting testing frequency is the guidance in EN 14487-1, adjusted as necessary for the project risk, production rate and consequences of non-conformance. It is also common to begin production testing at a relatively high frequency and reduce it once consistent results have been demonstrated over an appropriate volume of work.

For example, EN 14487-1 recommends one set of flexural strength or toughness tests for every 100 m3 of shotcrete used for ground support in higher-consequence projects. In practice, a project may start at a higher frequency, such as one set for every 25 m3 for the first 200 m3 and then reduce to one set for every 100 m3 once consistent compliance has been demonstrated.

Table 4 Recommended shotcrete testing frequencies (blank indicates testing usually not required)

Property	Test Method	Civil Ground Control[1]			Mining Applications		n[a]
		Low	Med	High	Temporary	Life of Mine	
Workability/ consistency[2]	AS1012.3 or EN12350-5	Daily / every 5th truck	every 5th truck	every batch	Daily / every 5th truck	Daily / every 5th truck	1
Fibre Content	AS1012.25.1/ RC 377.01	At least once	1/200 m^3	1/100 m^3	–	–	1
Early-age Strength[3]	Needle pene. or ASTM C116	1/month	2/month	1/week	1/250m^3 or 2/month	1/250 m^3 or 2/month	3
Compressive Strength[b]	AS1012.9 and AS1012.14[4]	1/1000 m^3 1/2000 m^3	1/500 m^3 1/1000 m^3	1/100 m^3 1/500 m^3	1/500 m^3	1/500 m^3	(c)
Density of hardened concrete	AS1012.12.1	When testing compressive strength					
Resistance to water penetration[5]	EN 12390-8	1/1000 m^3	1/500 m^3	1/250 m^3	–	–	3
Post-crack performance of FRS	ASTM C1550 or EN 14651	1/1000 m^3	1/500 m^3	1/100 m^3	1/1000 m^3	1/500 m^3 or 1/week	(d)
Durability[6]	ASTM C1202	–	–	1/2500 m^3	–	–	1
	AS 1012.21	–	–	1/500 m^3	–	–	1
	ASTM C1012	Pre-const. trial only			–	–	1
	NT Build 492[8]	–	–	1/2500 m^3	–	–	1
Drying shrinkage[9]	AS 1012.13		1/2000 m^3	1/1000 m^3	–	–	3
Freeze/thaw resistance[10]	ASTM C666 or ASTM C1262	–	–	1/1000 m^3	–	–	1
Bond Strength[11,12]	AS 1012.24 or SS 137342	1/1000 m^3	1/1000 m^3	1/1000 m^3	–	–	6

Notes to Table 4:

1. Consequence or importance of element or structure, to be determined in consultation with Owner and Designer based on risk for element/structure
2. Concrete load acceptance test per face or cutting
3. Need to develop strength development curve at least once per mix

4. Cores to be taken from test panels at same frequency as cast cylinders, cores to be taken from works at reduced frequency as indicated to check test panels.
5. Usually not done for temporary shotcrete
6. Test method to be selected on basis of assessed durability risk
7. Check for over-dosing of set accelerator
8. Only relevant for steel bar reinforced shotcrete
9. One set of prisms to be cast as per AS 1012.13, one set of prisms to be cut from same batch of shotcrete sprayed with set accelerator and tested in parallel with cast prisms.
10. Only for shotcrete exposed to freezing conditions
11. Bond should not be relied upon for long term (5+ year) support
12. Bond testing is only required to ground, bond to relatively young shotcrete can be considered sound provided it is kept clean and moist.

a) All test frequencies are to be specified by the project designer, and to consider the consequences of test failure. Test frequencies provided in this table are a guideline and the frequency can go up or down in accordance with the considered opinion of the project-specific designer.

b) A high entrained air content can reduce the compressive strength of concrete as delivered. It is therefore suggested that the air content of the delivered concrete be checked regularly.

c) One at 7 days, two at 28 days & two at 90 days if required

d) Three at 28 days and three at 90 days if required

8. Test Methods

The test methods described in the following sections are of particular relevance to shotcrete quality control and performance verification. The full titles of all standards cited in this section are listed in the reference list at the end of the document.

8.1 Consistency/Workability

8.1.1 Description of Property

Workability describes how fresh concrete behaves during mixing, transport, placement, compaction, and finishing. It is not a single physical property. Rather, it encompasses consistency, flowability, cohesion, internal friction, viscosity, resistance to segregation and compactability. No single test measures all these characteristics. The slump test captures only one slice of this behaviour being the concrete's deformation under its own weight, which essentially reflects its consistency and not its full workability.

Historically, slump became the default field test because traditional concretes were simple, normal-strength, low-admixture, coarse-aggregate mixes where water content largely controlled ease of placement. Under these conditions, a higher slump correlated reasonably well with more workable concrete. Modern concretes break that relationship with the use of superplasticisers, viscosity-modifying agents, fibres, fillers, and varied paste volumes, which can produce mixes with high slump but poor workability, or low slump but excellent workability, and even mixes with identical slump but completely different pumpability. For this reason, slump is best understood as a consistency check used to verify whether concrete is too stiff, too wet, or consistent with the mix design, rather than a true measurement of workability.

8.1.2 Existing Test Methods

8.1.2.1 Slump Test (AS 1012.3.1)

Methods of testing concrete: Determination of properties related to the consistency of concrete — Slump test. This well-known test involves filling an inverted cone with concrete, tamping it to consolidate the concrete, and lifting the cone to measure the fall in height. This test is suitable for relatively low workability mixes, but it is less suited to highly workable mixes.

Australia does not have a dedicated Australian Standard for the flow table or the slump flow test for concrete covered by EN 12350-5. Instead, Australian practice commonly adopts the European standard.

EN 12350-5- Testing Fresh Concrete Part 5: Flow Table Test

EN 12350-8-Testing Fresh Concrete Part 8: Self-Consolidating Concrete / Slump-Flow Test

8.1.2.2 The Flow Table Test (EN 12350-5)

Measures how far fresh concrete or mortar spreads when a filled mould is lifted allowing the sample to spread on the hinged table which is then raised 40 mm and repeatedly dropped 15 times. That height is fixed by the mechanical stop on the table, ensuring every drop delivers the same energy. The introduced energy reduces the influence of static internal friction and gives a more representative indication of the flow behaviour of highly workable or fibre-reinforced mixes.

8.1.2.3 The Slump Flow Test (EN 12350-8)

Requires the lifting of a slump cone and measures the gravity-driven spread of highly workable concrete without external energy. Flow tables suit mortars and very fluid mixes; slump flow is the standard for self-compacting concrete, with no jolting applied.

8.1.2.4 Preferred Test Method

EN 12350-5- Testing Fresh Concrete Part 5: Flow Table Test

8.1.2.5 Summary of EN 123505 – Flow Table Test

EN 12350-5 Part 5 specifies the method for determining the flow (consistence) of fresh concrete using a flow table. It is intended for high-workability concretes, particularly where slump testing is not sensitive enough. This test assesses workability, consistency, and cohesion, and is suitable for concretes with flow values between 340 mm and 620 mm. In general, greater spread indicates higher flowability. A circular, uniform spread also indicates good cohesion. Segregation shows as a noncircular shape or visible paste separation. A ring of clear water may also appear if the mix is prone to bleeding.

8.1.3 Discussion

Concrete slump is influenced by the many factors that affect how easily the mix can deform under its own weight, mainly water content, paste volume, aggregate shape and grading, admixtures, and the presence of fibres. Increased water content or paste volume generally increases slump, while angular aggregates, low paste content, or high friction within the mix reduce it. Fibres, whether steel or synthetic, tend to lower slump because they increase internal friction, create a physical network that resists flow, and trap a small amount of free water along their surfaces. This makes the mix appear stiffer in the slump test. However, fibres do not necessarily reduce workability in the practical sense: with proper admixture use and mix design, fibre-reinforced concrete can still pump, place, and finish well.

The slump test only measures vertical deformation, not cohesion, pumpability, or overall ease of handling, so a fibre mix can show a lower slump while still being highly workable on site. The danger of specifying a slump is that, all too often, to pass the "slump test" there is an excessive use of admixtures which are expensive, chemically change the mix and are not beneficial to the mix performance itself. The truth is that the simple slump test is often the wrong test for conformity and quality control of fibre reinforced concrete or shotcrete.

A Flow Table Test, where energy is introduced to the mix by repeatedly dropping the flow table as specified in the procedure, is a far more appropriate method for assessing a shotcrete mix as it better reflects real-world conditions where fibre-reinforced concrete is subjected to significant energy as it is loaded into the hopper, pumped, and placed. Using the correct test ensures the mix is genuinely fit for its intended purpose, rather than being artificially adjusted simply to pass a test that is potentially misleading and does not replicate its actual placement method.

8.2 Compressive Strength Testing

8.2.1 Description of Property

The material property most commonly specified for plain, bar-reinforced and fibre-reinforced shotcrete is compressive strength. Compressive strength is the resistance of a material to an axially applied crushing force. The unconfined compressive strength (UCS) of hardened shotcrete is one indicator of material quality and may also be used as an indirect indicator of other properties. However, it should not be treated as the sole measure of performance. It is only indirectly related to parameters such as compaction, permeability and durability, and therefore often needs to be interpreted together with other test results.

It is important to distinguish between the compressive strength of shotcrete as supplied and the compressive strength of shotcrete in place. The strength of the as-supplied mix is normally assessed using cast cylinders. The in-place strength is normally assessed using cores drilled either from the works or from a test panel sprayed adjacent to the works. During placing, the material may be affected by factors such as temperature, set accelerator dosage, spraying quality, compaction, storage conditions and curing. Verification of design strength should therefore be based on the performance of the shotcrete as sprayed, with cores drilled from the in-situ structure representing the most direct measure. Because coring from the works requires repair, cores from production test panels are widely accepted as a practical substitute. The compressive strength of shotcrete as supplied should be sampled from the delivery chute of the agitator truck or the pump hopper and cast into cylinders. It should never be assessed by spraying into cylinder moulds, as rebound accumulation will significantly degrade specimen quality.

The magnitude of the difference between as-cast and as-sprayed performance should be considered during design and should be established through pre-construction trials. A difference of about 20% is often observed between a standard test cylinder cast from the shotcrete mix and a core taken from a sprayed test panel produced with the same mix, including any set accelerator. This difference reflects both the effect of the accelerator on density and the differences between the standard testing methods for cylinders and cores. For example, if a specification requires a characteristic in-situ strength of 32 MPa, it is common to specify a characteristic cylinder strength of 40 MPa for the concrete as delivered.

Excessive reductions in compressive strength between the as-supplied and as-sprayed conditions, for example a reduction greater than about 20%, may indicate an adverse impact on quality caused by poor spraying technique, curing conditions or other production factors. For non-accelerated shotcrete, the difference between the strength of the concrete as-delivered and as-sprayed will generally be less than for accelerated shotcrete. The compressive strength of shotcrete as sprayed should therefore be determined by spraying a large panel and extracting cores after hardening. Correction factors for core strengths are listed in AS1012.14.

If a relationship between the strength of cast cylinders representing shotcrete as supplied and cores representing shotcrete as-sprayed is required for a project, then it should be developed by conducting tests on cast cylinders using shotcrete as-supplied and cores representing shotcrete as-sprayed.

The compressive strength of hardened shotcrete is highly dependent on the water-to-cementitious-materials ratio. The water-to-cementitious-materials 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 using High-Range Water Reducers but such mixes may be challenging to spray. The water-to-cementitious-materials ratio typically lies 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. Addition of an accelerator can reduce this by several megapascals. For higher compressive strengths of more than 50 MPa at 28 days, potential embrittlement of post-crack residual strengths in fibre-reinforced shotcrete should be considered. Many permanent civil infrastructure projects specify a minimum strength of 32–50 MPa at 28 days depending on the design role, exposure and asset class. Typical strengths encountered in various applications are listed in Table 5 below.

Table 5 Typical specified 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

Compressive strength assessment is typically determined at three key stages of a High Consequence project, namely

13. **Base Mix Phase development**, where the mix design is trialled at the laboratory stage and does not consider accelerator added at the spray rig nozzle, or pneumatic spraying effects on compressive strength.
14. **Pre-Construction Phase development**, where the field effects of spraying and accelerator at the nozzle is assessed against the base concrete mix compressive strengths and other properties.
15. **Construction Phase development**, where the inspection and test plan considers a typical sampling regime to confirm that the minimum concrete strength properties are aligned with the base mix and the pre-construction correlation assessment.

As described above, UCS values in excess of the specified minimum required at any age can have a deleterious effect on other test results, most notably the post-crack residual strength and energy absorption results for fibre-reinforced shotcrete. If the UCS test results are significantly higher than the minimum required, this will also increase the stiffness of the shotcrete structure, with the potential to invalidate the structural design calculations. The Designer should therefore specify how much over the specified minimum is permitted. As a guideline, UCS test results 20% over the specified value are typically acceptable but this is highly structure specific. To assist with concrete mix design in the early project stages, and minimise problems down the line, the Designer should state in the Project Specification how much over the minimum UCS is acceptable.

8.2.2 Existing Test Methods

Compressive strength testing is well covered by Australian Standards, and these should normally be used for Australian projects unless a project-specific requirement states otherwise.

The relevant Australian test methods include:

- **AS 1012.3.1** Sampling of fresh concrete
- **AS 1012.8.1** Method of making and curing concrete- Compression and indirect tensile test specimens
- **AS 1012.9** Determination of the compressive strength of concrete specimens (cylinders)
- **AS 1012.14** Method for securing and testing cores from hardened concrete for compressive strength (cores)

8.2.3 Preferred Test Methods

For Australian projects, the preferred methods for compressive strength assessment are those in the AS 1012 series, including sampling, specimen preparation, cylinder testing and core testing (Figure 6). These methods are well established and are generally suitable for both pre-construction and production QC, provided their limitations and the representativeness of the specimens are properly considered.



Figure 6 Freshly made cast shotcrete samples, and a crushed cylinder in a test machine

8.2.4 Discussion

Quality Control issues of concern related to compressive strength testing are typically associated with the assessment of compressive strength using cores at the pre-construction and construction phase/s of a project. Issues such as non-standard curing, or a curing history that differs for the cores compared to the test cylinders, insufficient control during sample preparation and environmental factors can distort the relationship between the two measures of compressive strength. Typically, cores are secured by drilling from sprayed test panels at variable ages, with different curing histories to the test cylinders which will typically be cast on the spray day and demoulded and cured in lime saturated water until testing. Test panels are usually covered early in their 'life', with cores drilled at variable ages and cured in air before eventual standard moist curing in a laboratory.

Another potential impact on compressive strength development is the presence of laminations or layering within sprayed panels which will manifest as layers in cores (Figure 7) but not cast test cylinders that are sampled from the agitator or spray rig hopper. It is also important that the coring contractor be aware of good practice when drilling cores such as use of a secure and sturdy core drill rig, careful operation of coring machines so as not to score the outside surface of cuts, careful handling of cores once drilled including the cutting of cores which are not perpendicular to the direction of spraying. All these factors are important regarding securing representative core samples.



Figure 7 The effect of layering during spraying on density and integrity of 75 mm shotcrete cores

Correct application of core correction factors is important given that there are appropriate correction factors in both AS 1012 (in relation to test methods) and AS 3600 (in relation to interpretation of results). AS 1012.14 considers corrections for geometry (length/height, age etc), whilst AS 3600 considers conversion of cores results

to 'equivalent' cylinder results due to 'damage' during the coring process by applying a factor of 1.15 to the core strength to obtain the equivalent cylinder compressive strength.

For example, in Section B6.4.1 of AS 3600, it states:

B6.4.1 Test requirements

Taking and testing of cores and beams from members and sample panels shall conform with the following:

The cores and beam shall be representative of the whole of the concrete concerned and in no case shall be less than three samples tested.

Cores and beams shall be examined visually before and after testing, to assess the proportion and nature of any voids, cracks and inclusions present. These factors shall be considered in the interpretation of test results.

Moreover, in Section B6.4.2 of AS 3600, it states:

B6.4.2 Interpretation of results

The strength of the concrete in the members shall be estimated as either:

a) 1.15 times the average strength of the cores or beams; or

b) by using test data from cores or beams taken from another member for which the strength of the concrete is known.

Another consideration regarding compressive strength is the concept of embrittlement of fibre reinforced concrete. In cases where the late-age compressive strength of the shotcrete continues to increase above about 50 MPa the fibre pull-out failure mode may transition from a high-performance ductile failure mechanism to a low energy brittle mode (depending on the type of fibre used) due to the anchorage strength of the fibre within the concrete being greater than the yield strength of the fibres across a crack. This can be controlled by limiting the maximum late-age strength of the concrete.

It should be noted that the curing history of cylinders and cores should be recorded if it is not in accordance with the standard moist curing conditions prescribed for concrete cylinders (AS 1012.8) or cores (AS 1012.14). Set accelerators added at the spray rig nozzle also have a damaging effect on the late age compressive strength of as-sprayed shotcrete compared to the same mix as supplied.

It is important to record factors that may affect the strength of shotcrete, including the accelerator dosage rate, air pressure, concrete pump rate, entrained air content, rebound, and interruptions to flow as these may all have an impact on the density and compressive strength of the cores relative to the as supplied concrete tested using cylinders. The use of special admixtures to minimise loss of workability (such as hydration stabilisers) may impact strength development. Internal curing compounds and Shrinkage Reduction Agents may also affect the compressive strength at various ages of the shotcrete.

8.3 Early-age Compressive Strength

8.3.1 Description of Property

Shotcrete for ground support is often required to reach a minimum strength at an early age, sometimes within the first few hours after spraying. This requirement usually arises for safety reasons, although it may also relate to structural performance requirements associated with the stiffness of a young lining and ground convergence immediately after excavation. 'Early-age strength' refers to strength requirements at ages earlier than the conventional 28-day reference age used for normal concrete supply, and most commonly refers to ages up to 3 days. Cores and cylinders are often inadequate for determining very early-age strength, so indirect or specialised methods are commonly used for this purpose.

Early-age strength development is important for limiting the excavation cycle time during advancement of a drive or tunnel and ensuring the safety of workers from rock fall and injury after re-entry. Typical requirements are a minimum compressive strength of 1.0–2.5 MPa (in combination with other project-specific measures) before

human re-entry to the workface is permitted, and in some projects (such as soft ground tunnelling or large spans) the compressive strength may be required to be greater than 4 MPa before the area can be classed as supported ground. However, it should be noted that in many circumstances shotcrete of sufficient strength alone does not render ground 'safe' for human re-entry. Ground is only considered 'supported' once secondary support installation is completed (i.e. bolting). In all cases, 'safe' re-entry must be determined by a qualified ground support engineer familiar with local conditions. It is clearly necessary to use test methods that can assess compressive strength at the work face or in-situ for relatively low strengths if these methods are to be useful and relevant.

For a typical mined tunnel, particularly in soft ground or in passive linings, there are usually requirements for early age compressive tests which are separate and in addition to the safe human re-entry requirements. These are related to the shotcrete stiffness development and the load development on the lining as the excavation face advances. A similar concept is applicable for shaft excavations. Typically, these requirements will involve specified 3-day and/or 7-day compressive strengths. Failure to adhere to these minimum requirements would potentially result in an unsafe tunnel as the tunnel face advances.

8.3.2 Existing Test Methods

Testing the early-age strength of shotcrete is challenging, partly because none of the commonly used test methods are codified and even the few that fall within 'guidelines' are frequently modified versions of an old standard (i.e. ASTM C116). Some other test methods use equipment that was originally produced by a single supplier (e.g. the needle penetrometer) but have more recently been copied by many others and the results may not be comparable.

Measurement of early-age strength development is usually undertaken to assess the ability of shotcrete to support unstable ground and to indicate suitable re-entry times for freshly sprayed shotcrete. The most suitable test depends on the strength range of interest. For indirect assessment up to about 1 MPa, the needle penetrometer is commonly used, notwithstanding potential variability between instruments (Figure 8). For direct assessment up to about 8 MPa, the ASTM C116-based beam-end test is generally the most suitable method (Figure 8). Other methods may occasionally be used, but they are less common in production QC. A minimum compressive strength of about 10 MPa is generally required before cores can be extracted without damaging the concrete.



Figure 8 Early-age test methods: a) needle penetrometer b) ASTM C116 beamlets c) beamlet tester

Many of the test methods produce results that are 'indicative' indirect measures of compressive strength for immature concrete rather than true measures of compressive strength. It is therefore difficult to apply the same standards of reproducibility for results as one would apply for cores and cylinders. Moreover, most early-age strength tests are intended to be applied by field staff and operators at the excavation-face because NATA-accredited staff are usually not available to perform these frequent tests. Further details are described in Recommended Practice for Shotcrete in Australia (2020) Clause 11.4.

8.3.3 Preferred Test Method

The two most commonly used and preferred methods of assessing early-age strength of shotcrete in Australia are the needle penetrometer and ASTM C116-based beam end test. For the needle penetrometer, results are achieved by pushing a probe or needle into a freshly sprayed test surface that is located either in a test panel or near an active face but under previously supported ground. The strength of the shotcrete is proportional to the depth of penetration. Care should be taken to calibrate the penetrometer readings with actual compressive strength values.

For many civil tunnel and mining applications the ASTM C116-based beam end test is the favoured approach as this is a direct measure of compressive strength and is able to assess compressive strength up to 8–10 MPa. It is often used early in a project to establish a correlation to the needle penetrometer results. However, it should be noted that the commonly used version of this test differs from the original ASTM C116 in that open-ended moulds are used to produce the specimens in order to avoid accumulation of rebound.

8.3.4 Discussion

The needle penetrometer tests are normally conducted on shotcrete sprayed as part of the works or on a test panel. The large size of such panels suggests that the curing conditions are typically similar to the works. However, care should be taken to prevent drying out of the surface of the shotcrete because this can produce erroneously high estimates of compressive strength.

Conversely, there is a noticeable size effect on results obtained using the beam end test in that the small size of these specimens compared to the works (or sprayed test panels) can make them susceptible to distortion if ambient conditions such as low temperatures and wind influence the rate of strength gain compared to the full-sized sprayed lining. To prevent this the beamlets should be kept next to the works (or test panel) and covered by plastic sheeting to ensure the temperature is the same as the shotcrete they represent.

Given that early age strength is typically utilised to determine safe re-entry to a work face, the typical frequency of testing for early-age strength may be 1 per 100 m3, or whenever the re-entry time is required to be checked.

8.4 Density

8.4.1 Description of Property

Density is the mass of a quantity of concrete divided by its volume. How these two quantities are determined varies between test methods and the method of specimen conditioning. A cubic metre of ordinary shotcrete weighs somewhere in the range 2200–2350 kg. If a batch comes out lighter than this range, something has changed relative to normal conditions: more air, more water, lighter aggregate, or the mix has not been compacted properly. If it comes out heavier, it may have lost air or picked up a denser aggregate. Density is a useful parameter that can be used to quickly identify changes to production or spraying. It is cheap, fast, and it changes when something in the production process changes.

8.4.2 Existing Tests

There are two principal test methods used for assessment of concrete density: AS1012 Parts 12.1 and 12.2. Both methods address the same parameters, mass/volume, and both assess mass the same way, by weighing. However, they differ entirely in how they establish the volume.

8.4.2.1 AS 1012.12.1 — Rapid measuring method

Methods of testing concrete, Method 12.1: *Determination of mass per unit volume of hardened concrete — Rapid measuring method*. Density is determined by measuring the specimen dimensions, calculating its volume geometrically, weighing the specimen and dividing its mass by its calculated volume.

This method is well suited to regular, well-formed specimens — principally cast cylinders and cubes. Because it needs nothing more than callipers and a balance, it can be done on a cylinder in the minute before it goes into the compression machine, at effectively no extra cost. The shortcomings to this method are attributable to the calculated volume of the specimen which is based on an assumed shape. A cylinder that is slightly out-of-round, barrelled, or has a rough or non-perpendicular end will have its volume overstated, and therefore its density understated. On a drilled core — with the saw marks, the slightly tapered profile and the ragged bottom end that drilling produces — the geometric assumption is the weak link, and the error is systematically in one direction. This method should be used for routine cylinder density, mix development, trend monitoring, or applications where a fast estimate of density is needed and the specimen is a properly made cylinder.

8.4.2.2 AS 1012.12.2 — Water displacement method

Methods of testing concrete, Method 12.2: Determination of mass per unit volume of hardened concrete — Water displacement method. Density is determined by weighing the specimen in air, then weighing it again suspended in water. The apparent loss of mass equals the mass of water displaced, which — divided by the density of water at the test temperature — gives the true volume of the specimen, whatever shape it is, calculated as:

$$V = (m^{air} - m^{water}) / \rho^{water} \quad (1)$$

$$\text{Density} = m^{air} / V \quad (2)$$

This method is best suited to cores, irregular fragments and specimens with damaged ends. The volume measurement does not rely on an assumed geometry, which makes the method appropriate where a defensible density estimate is required. The method nevertheless has limitations: the specimen must be conditioned to a defined and reported moisture state; water temperature must be accounted for; surface water must be removed consistently before weighing in air; and entrapped air bubbles must be dislodged from the specimen surface before immersed weighing. The procedure is slower than the rapid method and requires a suspension rig and stable balance. Its accuracy depends on careful specimen conditioning and execution.

This method should be used for: cores, conformance testing, compaction assessment, and any case where a core result will be compared against a cylinder result.

8.4.3 Discussion

There are four things that density indicates on site:

16. **Compaction:** Concrete that has not been adequately sprayed or vibrated may retain air voids. Because air has negligible mass relative to the concrete constituents, retained voids reduce the measured mass per unit volume. Comparing the density of a core taken from a shotcrete panel or structure with the density of cylinders cast from the same concrete provides an indication of the reduction in density associated with compaction. This is the parameter addressed in TfNSW R68 and R83.
17. **Yield:** Dividing the total batch mass by the plastic density provides an estimate of the volume delivered. If density decreases while batch mass remains unchanged, the calculated yield increases; this may indicate an increase in entrained or entrapped air, water content, or another change in the mix.
18. **Strength:** Entrapped air voids generally reduce compressive strength. A commonly cited rule of thumb in concrete technology is that each 1% increase in entrapped air may reduce compressive strength by approximately 4%; a similar relationship may apply to shotcrete, subject to the specific mixture and production conditions.
19. **Durability:** Denser concrete generally has fewer connected voids and lower permeability. But density on its own is a poor indicator of durability— it can't distinguish well-graded dense concrete from concrete with a permeable paste. Density is a compaction check that happens to correlate with durability, not a durability test.

When conducting checks on density, it must be borne in mind that the moisture state of the specimen can significantly affect the apparent density. The reason for this is that concrete is porous. A cylinder taken directly from the curing tank weighs more than the same cylinder after a week in the sun, and more again than one dried in an oven. The concrete skeleton has not changed; only the quantity of water in its pores has changed. A density figure is therefore meaningless without stating the moisture condition it was measured in. The three conditions the standards recognise are:

- **As-received:** tested in whatever condition it arrives
- **Saturated (immersed / surface-dry):** soaked to constant mass, surface water towelled off
- **Oven-dried:** dried to constant mass.

The gap between as-received and saturated is commonly 1–2%; between saturated and oven-dry it can be 3–5% for normal-weight concrete. Comparing a core density measured one way against a cylinder density measured another way is not a comparison at all.

8.4.4 Why Density Matters

In cast concrete, compaction is a separate process that can be supervised and adjusted during placement. In shotcrete, compaction is achieved through the impact velocity of the material as it reaches the receiving surface, concurrently with placement. Once the material has stiffened, further compaction is generally not practicable. Relevant variables include nozzle distance and angle, air pressure, delivery rate, accelerator dosage and operator technique, which may not be evident from the finished surface. Density therefore provides a useful indicator of the effectiveness of the spraying and compaction process and is an important component of shotcrete quality control.

The CIA Recommended Practice for Shotcreting in Australia states: "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%". For comparison, Queensland's MRTS272 shotcrete specification puts hard numbers around it, all using AS 1012.12.2:

- Trial mix approval: core density must exceed 98% of cylinder density (Cl 9.2(c))
- Production: the lot is rejected if core density is less than 95% of the corresponding cylinders (Cl 13.3)
- Four cylinders cast from the batch, four cores taken from the test panel at 24 hours or later

The 98% / 95% pairing is worth understanding: 98% is what a properly proven mix and crew should achieve under trial conditions, and 95% is the point at which production work is no longer defensible.

8.5 Post-Crack Performance Testing

8.5.1 Description of Property

Post-crack performance is an important property when load resistance is required after cracking of the concrete matrix. This property is provided by the addition of fibres to a shotcrete mixture. Post-crack performance can be assessed in terms of either the residual flexural/tensile strength or energy absorption (when it is referred to as 'toughness'). Energy absorption is typically measured 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. Post-crack performance is a property that is primarily affected by fibre design and content but can also be influenced by the strength and quality of the shotcrete matrix. The typical units of measure are Joules (Nm or kNmm) for energy absorption or megapascals (MPa) for residual flexural/tensile strength.

8.5.2 Existing Tests

The standard tests that are available to assess post-crack performance can be divided into three categories: beam-based tests, panel-based tests, and others. These test methods have evolved substantially since the 1970s due primarily to the conflicting requirements of ease of testing, low variability, and relevance of results. This evolution continues today with new test methods and variations on old methods being investigated in many countries. The list of tests described below should therefore not be taken as exhaustive or definitive. For most projects it is only necessary to conduct one type of post-crack performance test unless a correlation between performance parameters produced by different test methods is specifically required.

8.5.2.1 Beam-based Tests

The most commonly used beam-based test method for assessment of post-crack flexural performance is the EN 14651 notched beam test (Figure 9a). This test is referred to in AS3600, AS5100.5, and the Model Code 2020, making it convenient to use with existing design methods. Residual flexural strength is expressed as a function of crack width, which is directly measured using a gauge on the specimen.

A less widely used beam-based test is the ASTM C1609/C1609M third point-loaded beam test. This test uses a simply supported beam that lacks a notch, and performance is expressed as a function of central deflection rather than crack width, but if the offset of the crack from the centre is measured, then performance can also be expressed as a function of calculated crack width. Note that older third point-loaded beam tests (also known as

four-point-loaded beam tests), such as ASTM C1018 and ASTM C1399, have now been withdrawn and are no longer used despite being referred to in many older specifications.

The EN 14488-3 Method A beam test is occasionally used because it is the only standard beam test that uses a 75 × 125 mm cross-section, which is useful for thinner shotcrete linings. However, this test produces flexural strength estimates with a typical within-batch coefficient of variation (CoV, standard deviation over mean) of 30–35% so results are not particularly useful. If the performance of thin shotcrete sections is to be assessed, the ASTM C1550 round panel is generally considered more suitable.

Both the EN 14651 and ASTM C1609/C1609M tests involve a beam with a 150 × 150 mm cross-section (the actual specimen dimensions and effective depth after notiching is 125 mm) and are therefore the most appropriate tests for thicker shotcrete sections. It should be recognised that the presence of a notch distorts the performance of fibre-reinforced concrete because the stress concentration at the tip forces the crack to occur in the selected location rather than allowing the crack to find the weakest path through the cross-section. Thus, EN 14651 beams tend to produce higher estimates of post-crack residual strength (at least for steel FRC, see Foster et al., 2013; Bernard, 2022).

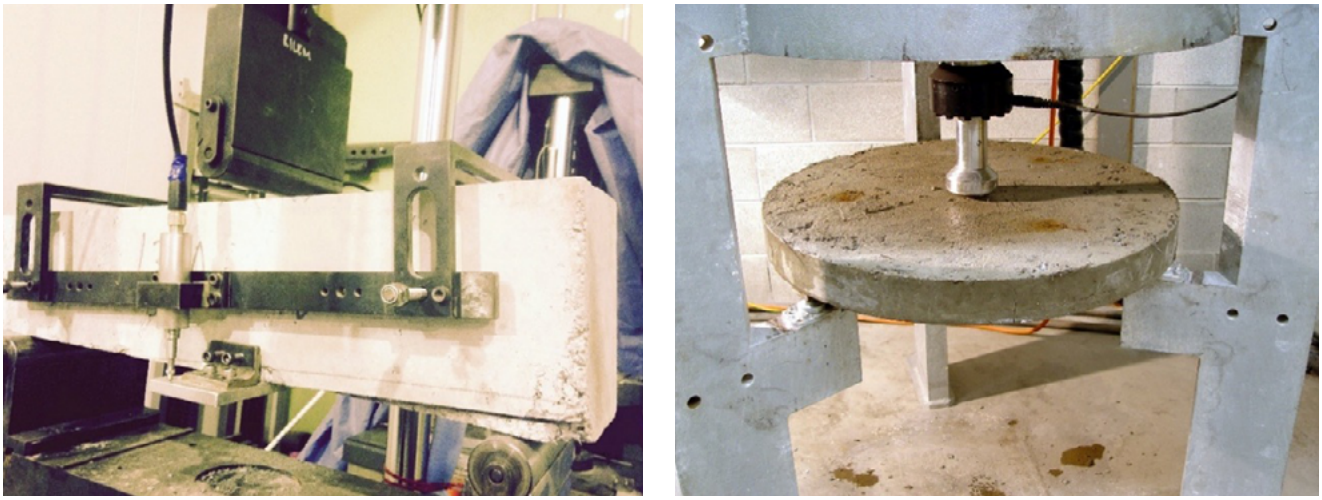

Figure 9 a) EN 14651 b) ASTM C1550 post-crack performance tests

8.5.2.2 Panel-based Tests

The most commonly used panel-based test method for assessment of post-crack performance is the ASTM C1550 round panel test (Figure 9b). This test requires a round panel 75 mm thick and 800 mm diameter to be sprayed and screeded to the required thickness while the shotcrete is still soft (see the section on finishing of samples in relation to screeding constraints). The within-batch CoV for energy absorption exhibited by this test is in the range of 10-11% for sets of three, which is the lowest of any standard test method presently available. It is also the only post-crack performance test among the many available that involves bi-axial loading in bending, making it a more relevant measure of performance than other methods in some ground-control applications. However, like the other panel tests available, it suffers from the problem that it is large and heavy and is therefore challenging to handle on-site.

Another panel test available is the EN 14488-5 square panel test. This is an energy-based method in which a central load is imposed on a square panel up to a central deflection of 25 mm. The same type of specimen has recently been admitted as an addition to EN 14488-3 (Method B) so it now constitutes a 600 mm wide notched beam (with a 10 mm deep notch) as a 100 mm thick specimen that is deflected to 3.5 mm maximum crack width. The EN 14488-3 Method B procedure is most accurately described as centrally loaded notched beam test. Unfortunately, the standard for this test includes poor control over thickness and friction in the supporting rollers, which can result in extremely high friction at the supports, thereby distorting the apparent performance of the specimen. If this test is used the configuration of the supporting rollers should be reported and evidence that the rollers can roll during a test provided.

8.5.2.3 Direct Tension Tests

Apart from the flexural tests described above, the post-crack performance of FRC can also be assessed using direct and indirect tensile tests. There are numerous direct tension test methods available, including the Italian CNR-DT 209 method, which is referred to in AS3600. Most of these direct tension tests involve some form of 'dog bone' shaped specimen that is slender at the centre and wider at the ends so that the tensile stress is concentrated at the centre where a crack is formed and measured. Unfortunately, all these tests suffer the problem that the stiffness of the specimen falls sharply when the crack forms, leading to highly unstable post-crack behaviour even when high precision servo-displacement-controlled machines are used. This tends to erase the performance curve immediately after cracking. Moreover, the crack face is usually quite small, so the number of fibres bridging the crack is limited, and the CoV in performance is high. Direct tension tests have therefore been limited to research applications rather than QC.

8.5.2.4 Indirect Tension Tests

Due to the challenges of conducting direct tension tests, indirect tension tests have gained attention. One example is the double-punch test, a version of which is commonly known as the 'Barcelona Test' (Spanish standard UNE 83-515). In this test, a core or cast cylinder of 150 mm diameter and 150 mm length is loaded at each end using a 25 mm diameter flat plate (or 'punch') until the core/cylinder splits in tension. A conical wedge forms under each punch, driving segments of the split specimen apart. If there are fibres in the mix the load resistance to progressive splitting of the specimen is quantified as a 'tensile strength'. However, load is also resisted through friction between the conical wedges and segments so only part of the apparent 'tensile strength' is attributable to the fibres. For this reason, the method requires calibration against more direct measures of flexural/tensile residual strength before it can be used effectively.

Another type of splitting test available that can be used to quantify flexural/tensile strength indirectly is the 'Montevideo test' (Segura-Castillo et al., 2024; Garcia, 2024). In this test, a notch is cut in the side of a cube or core, and a copper sleeve is inserted. A V-shaped steel wedge is then driven into the notch at a controlled rate, causing the specimen to split apart. Since the coefficient of friction between steel and copper is well known and reproducible, the load resistance at the wedge can be converted into a flexural (or direct tensile) strength depending on whether a single or double notch is used. This method has the advantage that the peak load required is low, and a standard displacement-controlled test machine can be used.

8.5.3 Discussion

There are a number of issues of special relevance to post-crack performance testing of fibre-reinforced shotcrete. Most of these are related to the challenges of spraying specimens using set accelerated shotcrete.

8.5.3.1 Production of Specimens

The first challenge is screeding the surface of panels when a set accelerator is used. At the dosage rate of set accelerator used in many projects, especially for primary linings, the shotcrete will very quickly become too stiff to screed. This makes it difficult to achieve a smooth surface on a panel of the required thickness (Figure 10). In these conditions, it is recommended to reduce the dosage rate to the maximum level at which it is still possible to screed the surface satisfactorily. This should ideally not be less than 80% of the dosage rate used for the works and should be recorded for the relevant specimens.

A reduction in the dosage rate of the set accelerator will not be required in the production of test panels for cores and beams because these specimens are drilled or cut on all sides from an oversized panel. However, the sprayer should take care not to produce panels that are too thick for the available saws or coring rig.

A second challenge in the production of specimens is the incorporation of rebound into the specimen. In general, rebound should never be re-incorporated into the works because it usually leads to poorly consolidated shotcrete with poor performance. It is therefore vital that rebound be minimised and not be re-incorporated in test panels; this is easier to achieve if the moulds used for test panels have splayed sides as per ASTM C1140/C1140M. The mould should also be considerably larger than the minimum required for specimen production so that a margin of about 50–100 mm exists at the periphery of the mould base that needs to be cut off to produce beams and cores. During spraying of a test panel, adjacent panels should be covered with form ply to prevent accumulation of rebound and other debris.

When beams are cut from a panel, the position of each beam in the original panel should be recorded. Ideally, 28-day specimens should be taken from the central part of the panel and specimens tested at other ages from more peripheral areas. It is also prudent to produce a spare panel where feasible in case problems arise with the primary specimen set.



Figure 10 a) Spraying round panels b) layering in beams revealed during cutting

Another issue of special concern in the production of test panels is the large mass of these panels (sometimes more than a tonne). Their mass makes them not only challenging to handle but also subject to cracking if moved too early after spraying. It is recommended that, when possible, test panels be sprayed in a dedicated area with similar conditions (e.g. temperature, humidity) as close as practicable to the area to be sprayed. Use mechanised lifting equipment to minimise manual handling. Moreover, moulds should be kept in good order and oiled with form oil prior to use (do not use diesel or hydraulic oil).

8.5.3.2 In-situ Structural Tests

It should be considered that beam and panel specimens are not prototypes no matter how large they are. This is because the boundary conditions applied to these specimens during testing are very different from the boundary conditions existent in situ. The specimens will therefore yield a maximum load and post-crack performance curve quite different from the in-situ lining. Moreover, the in-situ lining is often made up of several layers of shotcrete with unknown roughness and bond characteristics between them, and follow an uneven profile, that creates a complex stress distribution within the lining. For these reasons, the standard post-crack performance test specimens commonly prescribed in specifications should be treated as tests of the consistency of post-crack performance rather than indicators of actual peak load or residual strength in situ.

If the actual in situ performance of a lining is required to be investigated, full-scale tests can be performed using, for example, pressurised bags or hydraulic actuators to apply load (Banton et al., 2004; Bernard et al., 2022). This type of test will produce a reasonable estimate of peak load and post-peak ductility capacity in FRS linings. However, they are generally expensive to perform and cannot be undertaken on a regular basis.

8.5.3.3 Testing of Beams and Panels

The principal challenge in testing post-crack performance specimens is the instability that occurs in the transition between cracking of the concrete and the residual load resistance of the fibres. This requires a closed-loop servo-control test machine, which is expensive. Test machines also need a minimum load train stiffness to control instability, even if they incorporate servocontrol. This significantly increases the cost of the testing.

A second challenge is the effect of friction at the supports on the apparent performance of a FRC specimen. All the standard beam tests require that the specimen rest on rollers to prevent friction from 'enhancing' the apparent post-crack performance of the specimen. However, only ASTM C1609/C1609M includes a specific design of support rollers with a known Coefficient of Friction (using ASTM C1812/C1812M) so that the parasitic effect of

friction can be controlled. EN 14651 and EN 14488.3 (Method B) are vague in their specification of supporting rollers with the result that 'rollers that do not roll' often end up being used. This exaggerates the flexural performance of the specimen (Bernard, 2014).

A challenge specific to ASTM C1550 is the lack of a specification for calculation of residual flexural strength in this test configuration. A suitable theoretical method (not an empirical correlation) was published but has yet to be incorporated into the standard (Bernard, 2013, 2020). If performance is to be expressed as residual flexural strength f, the load resistance P at any point in the load-deflection record can be taken and used in the following expression to obtain the flexural strength:

$$f = \frac{2rP}{\sqrt{3}t^2R} \tag{3}$$

where r is the radius to the pivots (375 mm), R is the measured radius of the panel, and t is the mean measured thickness of the panel. The mean maximum crack width w for the panel can also be found as a function of central deflection d using the following expression:

$$w = \sqrt{3}\frac{\delta t}{r} \tag{4}$$

when the neutral axis depth is taken to be zero from the top surface. If the neutral axis depth is taken to be 0.1t from the top surface, multiply this estimate of w by 0.9. Using these two expressions one can express post-crack performance as a function of calculated crack width. It is up to the designer to decide which crack widths to use such that the back-calculated central deflections can be found at which load resistance is to be specifically recorded.

8.5.4 Testing Frequency

The appropriate testing frequency depends on the project, the volume of shotcrete, the property being assessed and the consequence of non-conformance. Further guidance is provided in Table 4 Frequency of Testing.

8.6 Durability Testing

8.6.1 Description of Property

The term 'durability' describes the ability of a material to resist aggressive agents within the service environment that it is exposed to. For shotcrete the aggressive influences may include climate, extremes of temperature, seawater, chemical contact, or impact and abrasion. For underground applications, the aggressive influences most commonly include the substrate and groundwater existent within the underground environment, as well as gases and pollutants in the air such as carbon dioxide, nitrous oxide, and sulphur dioxide. Durability considerations may include resistance to freeze-thaw deterioration; although this is not a common requirement in Australia (but should be considered at higher altitudes). The presence of a set accelerator can affect the durability of shotcrete so tests of resistance to aggressive agents should be undertaken with samples of shotcrete produced using the dosage rate of set accelerator present in the works if this additive is used.

8.6.2 Existing Tests

The durability of shotcrete can be assessed according to many alternate criteria depending upon the environmental conditions prevailing. Thus, only a subset of the tests described in this section may be applicable to shotcrete used in a particular project or part of the project.

8.6.2.1 Permeability

It has been generally observed that the durability of both cast and sprayed concrete is closely related to the water permeability of the concrete matrix. Improved durability (for example, resistance to sulphate degradation)

is generally obtained when the water permeability is low. For this reason, the most commonly used means of assessing the durability of shotcrete is some direct or indirect measure of the water permeability of the material as sprayed. The most common proxy is the water penetration depth assessed using EN 12390-8 (previously known as DIN 1048 Part 5). For this test, 150 mm diameter cores drilled from a sprayed concrete panel are subjected to 5 bar water pressure on one surface which is held for 72 hours (Figure 11). The penetration depth is subsequently measured. The performance criterion deemed acceptable depends on the exposure class but typically is less than 25 mm of penetration depth (B82 Shotcrete Works, TfNSW). The most suitable direct permeability test methods which can be applied to shotcrete include AS 1289.6.7.3 (which is normally applied to soil or soft rock samples) or AS 4133 (which is applicable to hard rocks).

The Volume of Permeable Voids test as per AS 1012.21 (VPV) and the Boiled Water Absorption (BWA) test are capillary tests which measure water infiltration into a sample. The results can, however, be problematic for shotcrete, as discussed later in this guide.



Figure 11 EN 12390-8 (previously known as DIN 1048 Part 5) water penetration tests in progress

8.6.2.2 Chloride Penetration

Chloride ions are generally recognised as being aggressive toward steel reinforcement. The presence of chloride ions within concrete, and the resistance of concrete to the passage of chloride ions, are therefore the basis of durability assessment for most concrete structures reinforced with steel bars. However, steel fibres are relatively resistant to the effects of chloride ions on corrosion within intact (uncracked) concrete. This is due to the lack of continuity between steel fibres. The potential for chloride ion penetration through intact concrete is therefore only of concern for steel fibre reinforced concrete or shotcrete (SFRS) when environmental concentrations are very high (such as in a marine or chemical industry application). However, chloride ions can sharply increase the rate of corrosion of both steel bars and steel fibres in cracks that exceed a minimum threshold width. Guidelines such as the Model Code 2020 should be consulted in regard to maximum allowable crack widths for various environmental conditions.

The most commonly used standard test for the presence of chloride ions in concrete is described in AS1012.20.1. This test quantifies the amount of chloride ions present in hardened concrete. In this test a sprayed concrete sample is ground to powder and treated with nitric acid (HNO_3) to dissolve the cement paste and release chloride ions into the solution. The chloride ion concentration in the solution is then measured by potentiometric titration using a silver nitrate ($AgNO_3$) standard solution. The chloride content can be reported as the percentage chloride ion by mass of concrete, or percentage chloride ion by mass of cement.

A common test used to assess the resistance of concrete to the transport of chloride ions is ASTM C1202, but this test measures electrical conductivity as a proxy for resistance to chloride ion penetration so the results may be

corrupted by the presence of steel fibres. It is therefore only applicable to plain shotcrete or shotcrete reinforced with macro-synthetic fibres. In this test an electrical potential is applied across a sprayed concrete disk with sealed sides with only the flat end surfaces exposed. One face is in contact with a 0.3 N NaOH (sodium hydroxide) solution. The other face is in contact with a 3.0% NaCl (sodium chloride) solution. A DC voltage of 60 V is applied across the specimen, and the current flow is recorded at fixed intervals for 6 hours. From this the total charge passed can be calculated. ASTM C1202 provides a range for interpretation of the Chloride Ion Permeability based on the total charge in Coulombs, ranging from negligible to high.

An alternative approach to measuring resistance to chloride ion penetration is to place samples in a salt pond for an extended period of time and then measure chloride ion penetration by grinding and titration as a function of depth (AASHTO T 259). Bulk chloride ion content in an exposed sample can also be assessed using Nordtest NT Build 443. The problem with these methods is that they involve tests on samples that must first be cured, exposed to a chloride-rich environment, and then assessed, so they take a long time to perform (up to 100 days) and are expensive (around $4000 per sample). They are therefore problematic for QC. An alternative is the Nordtest NT Build 492 test method, which can be used to measure the chloride ion penetration rate for samples of concrete extracted from test panels or the works.

8.6.2.3 Sulphate Resistance

Sulphate ions are known to be very aggressive to hydrated cementitious materials. The susceptibility of shotcrete to sulphate attack is increased by the presence of aluminium sulphate set accelerator, particularly at high dosage rates. Certain types of ground are particularly rich in sulphate ions, and these aggressive ions can be concentrated within the surface of a shotcrete lining by evaporation of groundwater. The sulphate resistance of shotcrete is therefore of interest to designers and owners of many shotcrete structures.

The presence of acid-soluble sulphate (SO3) ions in concrete can be assessed using AS1012.20.1, which is similar to the test described for chloride penetration. The resistance of concrete to penetration and attack by external sulphate ions is most commonly assessed using ASTM C1012, which involves immersion of a bar of mortar or concrete in a bath of sodium sulphate (although alternative minerals such as magnesium sulphate can also be used). Unfortunately, this test normally takes at least 16 weeks to perform and for more durable concretes may take 12–18 months. It is therefore not suitable as a production QC test but could be used as a pre-qualification test. Resistance to sulphate attack is also improved by reduced water permeability, so water penetration tests can be used as an indirect indicator of sulphate resistance.

The penetration of sulphates and its effects on shotcrete can also be assessed using X-ray Fluorescence Mapping (XFM) or X-ray Diffraction Mapping (XDM) of cut samples. This can be achieved quickly (in about 3 days) but is very expensive (about $3000 per sample). Accurate assessment of the concentration of sulphur or sulphates also requires a known reference material (typically pure sulphur) so that the X-ray signals can be calibrated.

8.6.2.4 Freeze-thaw Resistance

Although rare in Australia, freezing conditions can occur in areas such as central Tasmania and the Snowy Mountains, and if they are frequent the freeze-thaw resistance of a shotcrete surface should be considered. Freeze-thaw resistance is achieved by incorporation of entrained air bubbles within the paste of concrete. This can be difficult for shotcrete because the spraying process usually expels air from the matrix. Special attention to air content during batching and spraying therefore needs to be paid (Jolin and Beaupré, 2003; Zhang, 2012). The most commonly used test of freeze-thaw resistance is ASTM C666, which involves cycling a specimen between sub-zero and above-zero temperatures in a climate chamber. This test is quite aggressive and is more suited to strong freeze-thaw conditions. ASTM C1262 is used for assessing freeze-thaw resistance in response to slower thermal cycling rates. Since the freeze-thaw resistance of concrete is achieved using entrained air bubbles, the resistance of a sample of shotcrete can also be assessed based on the average spacing and size of entrained bubbles using ASTM C457. This test method has been used with success for shotcrete sprayed in Scandinavia (Fonseca and Scherer, 2014; Holter et al., 2016).

8.6.2.5 Impact and Abrasion Resistance

The abrasion and wear resistance of concrete is important in many applications, particularly floors. Standard specifications such as ASTM C779 are available to assess resistance to drop weights, rotating cutter, and wear under rotating steel. There is also a sandblasting test (ASTM C418), a rotating cutter test (ASTM C994) and an underwater steel ball test to simulate waterborne erosion (ASTM C1138). All these test methods are applicable to shotcrete surfaces if the potential environmental conditions call for it.

Shotcrete in applications such as ore passes in mines may be subject to extreme levels of impact and abrasion. The resistance of a mixture to this form of aggressive loading can be assessed using a tumbling box test described by Van Heerden et al. (2005). Several documents also exist (ACI 210R-93; Yu et al., 2025) in relation to specialised testing of erosion and cavitation resistance for concrete used in hydraulic structures.

8.6.2.6 Carbonation

Carbonation is a chemical process whereby carbon dioxide in the atmosphere and in the concrete pores chemically reacts with products of cement hydration (e.g. calcium hydroxide) to neutralise the alkalinity of the cement paste, and then further chemical reactions produce calcium carbonate.

Whilst this can lead to a short-term reduction in permeability due to the voids being filled, it also leads to a decrease in alkalinity which causes corrosion of steel reinforcement. The specific problem for shotcrete (as opposed to cast in situ concrete) relates to the difference in method of application. Since shotcrete is applied in layers, there is a tendency for carbonation products and processes to form laminar microcracks in the shotcrete, thus exacerbating other issues relating to durability such as sulphate resistance.

Testing for carbonation at a specific shotcrete depth can be conducted in the same way as for cast in situ concrete i.e. applying a phenolphthalein pH indicator to either cracked core samples or an exposed section of shotcrete. The phenolphthalein changes colour in the range between pH 8.2 and 10.0 (from clear to magenta) thereby providing a visual indication of where carbonation has occurred. This test is described in EN 14630.

8.6.3 Discussion

A common factor affecting the environmental resistance of shotcrete is the presence of set accelerator. Where accelerator is used in the works, durability-related assessment should be based on specimens prepared with the relevant accelerator type and dosage. Spraying technique and curing also affect durability, so specimens should be produced and cured in a way that is reasonably representative of the intended application. Long-duration durability tests are generally better suited to pre-construction trials than to routine production QC.

8.7 Shrinkage and Shrinkage Cracking

8.7.1 Description of Property

The unrestrained drying shrinkage of a material represents 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 too complex to be determined. Drying shrinkage is caused by a contraction within the structure of hydrated cement in response to a loss of moisture. Drying shrinkage occurs slowly in response to moisture loss and a measurable change in shrinkage strain continues for many years after casting or spraying. Excessive shrinkage can lead to cracks and reduced durability and service life.

Autogenous shrinkage is a secondary form of volume loss that occurs over the first few days of hydration and is caused by a change in the volume of hydrated cement compared to un-hydrated cement as the cement consumes water during hydration and self-desiccates in the process. It is most pronounced in low water/cement ratio mixes. Autogenous shrinkage is independent of drying shrinkage but occurs concurrently over the first week of hydration. It is normally not included in measurements of drying shrinkage because it has largely ceased to occur by the time drying shrinkage measurements commence. Autogenous shrinkage occurs in-situ, but the high early-age creep exhibited by shotcrete causes most of the tensile stress generated by autogenous shrinkage to be dissipated.

However, this component of shrinkage should still be estimated and added to drying shrinkage results for the estimation of crack widths.

8.7.2 Existing Tests

Standard unrestrained drying shrinkage tests all involve measurement of dimensional change in a prism that is cast with reference studs included at the ends. The change in length over a known initial length is converted into a strain expressed as a function of time in a drying environment (usually 50% Relative Humidity and 23°C, Figure 12). The most widely used standards are AS 1012.13, ASTM C157/C157M, and EN 12390-16. The principal difference between these standards is the duration and conditions of wet curing required before the initial reference length is measured. Shrinkage is expressed as micro strain (μm/m) or % change in length.

Restrained drying shrinkage tests include a wider variety of test configurations. These configurations are all intended to induce a crack in the drying concrete, but some also involve measurement of the tensile stress present in the concrete prior to cracking. If fibres are present, the crack width and tensile stress present after cracking of the concrete matrix are also of interest. Among the restrained shrinkage tests the ASTM C1581 ring test is the most commonly used. Shotcrete is placed around a rigid steel ring which resists contraction and leads tensile stress to build up in the shotcrete. However, this specimen is too small for spraying so the shotcrete mixture is normally cast. A plate-based test, in which crack width is measured across a slab of shotcrete sprayed onto a stiff base, is also available (ASTM C1579). This test was originally developed to assess the plastic shrinkage of cast fibre reinforced concrete (FRC) but has proven useful for sprayed concrete. Various concentric or eccentric ring tests are also available (Sayahi et al., 2019; Abusogi et al., 2023) in which shrinkage strain is concentrated in a slender portion of FRC located between two rings.



Figure 12 a) AS 1012.13 unrestrained shrinkage prisms cast in mould b) stored in climate-controlled room during testing

All the restrained shrinkage tests involve assessment of the width of crack(s) generated at some point in the specimen. Unfortunately, the absolute magnitude of crack width is specific to the geometry of the test specimen and the actual restraint present in the test configuration, so extrapolations to in situ structures are difficult. Instead, these specimens are used to assess the relative effect of variations in mix design, fibre content, etc. on drying shrinkage crack widths. They are useful for developing a mix to use in shotcrete linings but are only comparative and cannot be used to predict or control potential drying shrinkage crack widths for in situ shotcrete, as none of these tests reflect the exact shotcrete lining restraint available.

8.7.3 Discussion

All of the standard restrained drying shrinkage tests available are unsuitable as quality control tests because they take too long to complete and the results are difficult to interpret. Their relevance to the in-situ tunnel lining is also difficult to determine. The tests are only meaningful as pre-production tests to assess the differences between alternative shotcrete mix designs.

In contrast, the unrestrained drying shrinkage test specimens are easy to produce and the tests easy to undertake, but they involve cast concrete rather than shotcrete. Spraying prisms using set accelerated shotcrete is difficult and produces poor quality specimens. If the drying shrinkage of set accelerated shotcrete is required to be assessed, this method is not satisfactory.

A potential solution to this problem is to cut prisms of the required size from hardened shotcrete that has been sprayed using the required dosage rate of set accelerator. This is important as the accelerator dosage will greatly influence the shrinkage results. Although the method of producing the specimens is non-standard, the measurement of strain would be the same as current practice in AS 1012.13. This has been done on site in Australia and proven to be effective. The procedure is to spray a panel of shotcrete using the mix and set accelerator dosage specified for a project, then cut three prisms of the required 75 × 75 × 280 mm size at an age of 1–2 days, attach reference studs to the ends, and cure the specimens in water until three days have elapsed since spraying. The reference length should be measured at 3 days of age after spraying and all further measurements (at 1, 3, 7, …56 days of drying) should be conducted as per AS 1012.13. Care should be taken to ensure that the reference studs are secured using epoxy at the required separation.

Note that measurement of drying shrinkage for set accelerated shotcrete samples does not negate the need to measure drying shrinkage for the same batch of shotcrete produced using cast samples from the truck (which are relevant as controls on the supply of the concrete). The set accelerated samples should be taken as additional specimens to determine the unrestrained drying shrinkage of the shotcrete as placed. This information is primarily of relevance in design but could possibly be used as a control on shotcrete as sprayed by the contractor.

Also note that environmental conditions such as temperature, airflow and humidity can significantly affect drying shrinkage. In general, lower relative humidity and higher airflow over the surface of the shotcrete increase the magnitude of shrinkage.

In general, it has been found that fibres have no measurable effect on the unrestrained drying shrinkage strain experienced by a shotcrete mixture. However, they may have some effect on the restrained shrinkage of a specimen if that specimen suffers cracking during the period of drying shrinkage. The magnitude of the effect (which is usually manifested as reduced crack widths) will depend on the dosage rate and type of fibre used. The ASTM C1579 test is quite effective for assessing this aspect of drying shrinkage behaviour. The guideline on crack control produced by CIRIA (Report C766) offers some useful advice in this regard.

8.7.3.1 Crack Width Limits

The primary reason for imposing limits on drying shrinkage strain is to preclude shrinkage cracking or limit the width of these cracks. However, the relationship between shrinkage strain in shotcrete specimens and in situ crack widths is complex. An alternative to imposing limits on drying shrinkage strains is to place limits on maximum acceptable in situ crack widths (Figure 13). Maximum acceptable crack width limits are about 0.3-0.4 mm for aesthetic purposes (depending on the project) or 0.15-0.30 mm for reasons of steel reinforcement durability depending on the exposure classification (B82 Shotcrete Works, TfNSW; Model Code 2020). A problem with this approach is that cracks take a long time to develop and there is therefore no feedback to the producer or sprayer of the shotcrete mixture that cracking may be a problem in the future.



Figure 13 Measuring the width of a crack in a core extracted from an FRS lining

8.8 Wash-out Test

8.8.1 Description of Property

The wash-out test is a fresh-state quality control method used to verify fibre content in fibre-reinforced shotcrete. Accurate fibre dosage is essential to achieving the intended structural capacity, crack control, toughness, and durability of sprayed concrete linings in tunnelling, mining, and slope stabilisation applications. In Australia, AS 1012.25.1 and RC 377.01 provide the primary wash-out procedures for determining fibre content in fresh concrete. It is primarily used as a check on fibre reinforced concrete as delivered, not sprayed. However, when applied to shotcrete, these methods can be refined to account for spray cycle variability, rebound losses, accelerator interaction, and site conditions.

8.8.2 Description of the Test

The wash-out test determines fibre content by removing aggregate, cement paste, and fines from a fresh concrete sample, allowing fibres to be recovered, dried, and weighed. Under AS 1012.25.1 and RC 377.01, a representative sample is collected, compacted to a known volume, and washed through appropriate sieve or mesh systems. Steel fibres are typically recovered magnetically, while synthetic fibres are dispersed in water and recovered before drying to constant mass. The measured fibre mass is then compared with the batched dosage to confirm compliance.

For non-accelerated sprayed concrete, sampling of sprayed concrete may be used to assess the spraying process in addition to the point of truck discharge. Sub-samples should represent early, steady, and late spray phases, as fibre distribution may vary due to pump dynamics, rebound, and accelerator interaction. Wash-out testing should remain a fresh concrete test; delayed testing allows hydration to lock fibres within the matrix and bias recovery results.

The wash-out test has limitations. Fibre loss during washing, unsuitable mesh selection, incomplete paste removal or fibre entanglement can affect recovery. The test does not measure fibre orientation, spatial distribution or structural performance in the lining. Results should therefore be interpreted as a process-control measure for fresh concrete, not as a direct measure of in-situ post-crack performance.

8.8.3 Discussion

In shotcrete applications, fibre content verification is critical because fibres frequently replace conventional reinforcement and directly influence structural capacity and toughness performance. However, sprayed concrete introduces variables which are not present in conventional cast concrete: rebound can selectively remove fibres, accelerator dosage alters matrix cohesion, and nozzle technique affects fibre distribution. Consequently, wash-out test results may confirm fibre dosage in the fresh mix but not necessarily represent the fibre content or distribution in the placed lining.

There is a need to tighten RC 377.01/AS 1012.25.1 procedures for shotcrete by specifying sieve mesh configurations, defining sampling strategies aligned with the spray cycle, increasing sample volumes for investigative testing, and recording contextual parameters such as sprayer identity, pump settings, accelerator dosage, air pressure/ volume, nozzle distance, and environmental conditions. These records improve traceability and enable meaningful interpretation of fibre recovery trends in relation to site practices.

Importantly, the wash-out test should be interpreted as a process control tool rather than a performance test. It verifies compliance with specified fibre dosage but does not assess toughness, structural behaviour, or durability outcomes. Therefore, it should be used alongside performance tests such as EN 14651 or ASTM C1550, supported by quality systems aligned with ISO 17025 and ISO 9001, and guided by best-practice documents such as EFNARC, ACI 506R, and ITA recommendations. This integrated approach ensures that fibre-reinforced shotcrete linings achieve their intended safety, durability, and long-term performance.

8.9 Bond Testing to a Substrate

8.9.1 Description of Property

Bond between shotcrete and a substrate such as rock is achieved by chemical and physical means as soon as the shotcrete is sprayed onto the surface. Long-term bond is created by hydration of cementitious components within the shotcrete paste forming tensile linkages with the substrate material, and by physical interlock between the hardening paste and the rough substrate surface. The impact between a jet of shotcrete and the substrate, combined with the relatively high strength development achieved by a shotcrete paste, typically produce a bond between lining and substrate of between 0.5-2.0 MPa in direct tension (Hahn and Holmgren, 1979). However, the actual bond strength achieved will vary with many factors, including the composition and surface roughness of the substrate, the strength of both the shotcrete and the substrate, cleanliness of the substrate, and quality of spraying as well as moisture conditions and potential groundwater flow. If bond is relied upon for effective operation of a lining, or for retention of local shotcrete features such as patch repairs, it is necessary to quantify the strength of the bond between shotcrete and substrate.

8.9.2 Existing Tests

The majority of bond test methods were originally developed to assess bond between concrete and membranes such as floor coverings and overlays. Test methods for floor coverings (such as bonded flooring materials) are more widely used than for shotcrete so the tests and equipment used for shotcrete have often been adapted from test methods originally developed for floor coverings and repair media.

8.9.2.1 Hammer Sounding

Tapping the surface of a shotcrete lining to detect hollow internal zones is a partially effective means of identifying de-bonded zones but is prone to subjectivity and error. This method was originally described in the Norwegian Concrete Association Publication No. 7 titled “Sprayed Concrete for Rock Support” (1993). The maximum lining thickness that can effectively be assessed for bond loss using this method is about 150 mm, but this will depend on the size of the de-bonded area. Despite its limitations this is the quickest and most effective non-destructive method of assessing the presence or absence of bond between a shotcrete lining and substrate.

8.9.2.2 In-situ Bond Strength

The most common in situ methods used to measure bond strength are EN 1542, ASTM C1583, ASTM D7234, and ISO 4624 which are all primarily used to assess overlays and repairs to a concrete surface including spray applied membranes. They all involve partial coring following by bonding a dolly or pin to the exposed end of the core before it is pulled off to measure load resistance (Figure 14).

The EFNARC European Specification for Sprayed Concrete, 1996 (Section 10.6) and Swedish Standard SS 137342 were both developed specifically to assess the bond strength between shotcrete and its substrate. The EFNARC method is quite vague and primarily describes the principle of bond testing, while a later version published in 1999 introduced the requirement to conduct six replicate tests in the same general area of the works to calculate one

estimate of bond strength. The Swedish Standard SS 137342 requires concentric core holes to be drilled so that the outer hole is used to mount a pull-tester that is both concentric and perpendicular to the central tested core.



Figure 14 In situ testing of bond strength using pull-tester attached to dolly glued to end of partially drilled core using: a) hydraulic tester b) screw-activated tester

8.9.2.3 Extracted Cores

An alternative to in situ testing is extraction of a complete core that includes the boundary between shotcrete and substrate for later preparation and testing in direct tension within a laboratory, as per AS1012.24. This method is common to many national standards and may involve cores of various diameters. The common problem with this technique is that force is commonly required to remove the core and this may break the bond at the substrate boundary before it can be tested. This introduces a bias to the population of remaining test data because it removes the weakest results. There is also a risk that cores become damaged at the interface during transport and handling.

8.9.3 Discussion

There are shortcomings to all the methods described above, primarily because most of them were developed for flat surfaces of regular geometry. The SS 137342 method also requires a chuck to be used to grip the core during removal and requires the thickness of the shotcrete to be known in advance when drilling the oversized external core to mount the pull-tester.

Two methods have been developed to overcome the shortcomings of the published standard methods. The method by Seymour et al. (2010) is a recommendation produced by NIOSH in North America that is very similar to SS 137342 but avoids the use of a chuck. A further variation on the EFNARC/SS 137342 method was described by Holter (2015) that incorporated an abrasive disk to grind a flat reference surface into the shotcrete face around the core.

Many methods require that a hole be drilled through the centre of the core to secure an epoxied pull-pin before the core is drilled. This can have the effect of breaking the core if the length/diameter ratio is equal to or less than unity. In these circumstances it is better to glue a dolly to the face of the exposed core to impose the required pull force. However, this has the disadvantage that the weak shotcrete that often exists on the surface of a lining should be thoroughly removed before the dolly can be effectively glued in place.

The frequent occurrence of ‘zero bond’ results is a problem inherent to bond testing (Bernard and Braybrooke, 2026). Bond may be absent in some locations, so the coring procedure will result in the core falling out. However, the bond to the substrate may have been broken by the drilling procedure. Cores that break off during coring cannot be tested using either the in-situ or laboratory-based methods. These samples are commonly discarded and seldom recorded as ‘zero’ results. It is usually quite difficult to determine whether a core that supposedly ‘broke’ during drilling was, in fact, broken off as a result of the drilling process, or was de-bonded from the substrate prior to drilling. This ambiguity may be partially clarified by tapping the surface before drilling to detect drumminess,

or by thoroughly examining the broken surface to determine if a gap exists between the shotcrete and substrate. Even if a weak bond is present, the elimination of weak specimens by 'breakage' during drilling introduces a positive bias to the population of surviving samples. 'Zero bond' results should be investigated and recorded regardless of the suspected cause.

In general, bond between shotcrete and substrate tends to be quite good in the short term but can degrade with the passage of time due to several factors. If bond is to be relied upon in the long term the magnitude of retained bond should be checked regularly. Due to the difficulty of conducting regular tests, it is recommended that bond to the substrate not be relied upon for long term (beyond about 5 years age) load resistance in a shotcrete lining (Clark and Bernard, 2021).

8.10 Volume of Permeable Voids (VPV)

8.10.1 Description of Property

The volume of permeable voids (VPV) test is a standard method for assessing concrete durability that measures the interconnected void space in a hardened concrete sample. It is used for quality control and performance assessment because the amount of permeable void space indicates how susceptible concrete is to deterioration from water and chemical ingress. The test is performed on a sample that has been dried, saturated, and then boiled to measure its mass in various states to calculate the VPV. The AS1012.21 test method is very similar to the ASTM C642 test method but is claimed to be somewhat more reproducible.

The VPV test is claimed to quantify the volume of open pores, such as capillary pores and micro-cracks, that can absorb water through capillary suction. A lower volume of permeable voids indicates a denser, more durable concrete with better resistance to water and chemical penetration. However, critics claim that the manner in which the sample is prepared (drying at elevated temperature followed by boiling) disturbs the pore structure of the concrete and reduces the relevance of the results to the field performance of the original concrete.

8.10.2 The Test Method

The test is performed in the following manner:

- **Specimen preparation:** A hardened concrete specimen is first dried.
- **Boiling process:** The dried specimen is then boiled to fill the permeable voids with water.
- **Weight measurement:** The weight of the specimen is measured after it is dried, and then again after the boiling process.
- **Calculation:** The difference in weight corresponds to the volume of water absorbed, which is directly related to the apparent volume of permeable voids (AVPV).

In relation to quality control, the test is claimed to provide a simple, inexpensive, and quick way to ensure concrete mixes meet durability specifications. It has been shown that the results correlate with some aspects of durability, such as resistance to chloride diffusion, which is a key factor in the degradation of reinforced concrete. It has also been effective in identifying over-dosing of set accelerator when multiple batches of as-sprayed shotcrete are assessed. However, the relationship between w/b ratio and VPV (as measured using ASTM C642) is dependent on the cementitious materials present in the mix. There appears to be little correlation in apparent performance between mixtures containing different cementitious materials. This is problematic because the choice of cementitious content then has a major influence on the outcome of the test. For these reasons this test method is not recommended for use as a sole means of assessing the durability of shotcrete but instead can be used to detect variations from a baseline established through pre-qualification, especially in relation to over-dosing of set accelerator. Where VPV is contractually required, treat it as an index test only and do not use it alone to accept or reject a mix without reference to permeability, relative density and cementitious mix-design context.

9. Conclusions and Recommendations

9.1 Summary

This guideline provides a practical, risk-based framework for shotcrete quality control in Australia that prioritises in-place performance over testing for its own sake. It explains why QC is required (safety, durability, serviceability), what needs to be controlled (materials, batching, accelerator dosage, spraying technique, curing, specimen production and testing) and how those controls should be organised into a coherent QC system that links design intent, production controls, verification and acceptance. The document highlights the differences between sprayed and cast concrete, the limitations of common proxy tests (needle penetrometer, ASTM C116 beamlets, EN 14651, ASTM C1550, VPV), and the need for project-specific correlation trials. Finally, it emphasises governance and traceability: clear allocation of responsibilities, contemporaneous records and auditable evidence are essential to manage technical, contractual and legal risk.

9.2 Recommendations

9.2.1 Recommendations for practitioners

Practitioners should adopt a documented, risk-based QC plan proportionate to project importance. For high-consequence works, implement maturity-based in-situ monitoring with pre-production calibration (sensor panels correlated to cylinders at multiple ages) to support timely and defendable re-entry decisions. Specimen production should use representative sprayed panels (same mix, pump, nozzle operator and accelerator dose), splayed moulds and controlled finishing; panels should remain undisturbed for the specified hold time and follow the mandatory curing regime (initial wet-hessian cover with sealed polythene, followed by appropriate moist or immersion curing). Use the 20% cylinder to core performance loss relationship only after project-specific correlation trials and always record curing histories, accelerator dose, pump/nozzle IDs and any deviations. Adopt the Record-Keeping checklist for every specimen to ensure traceability.

9.2.2 Recommendations for contracts and hold-points

Contract documents should translate the QC framework into specific, enforceable hold points and data obligations. Example provisions include a clear early-age acceptance clause that prohibits personnel re-entry under unsupported ground until agreed early-age strength (by needle penetrometer, beamlet or maturity prediction) is demonstrated and recorded; a maturity/sensor data clause requiring calibrated maturity trials (minimum three sensor panels and three cylinder sets at standard ages), sensor-to-batch linkage and defined alarm thresholds for re-entry; and a testing frequency reduction/reinstatement clause that permits reduced sampling only after a defined run of conforming results (N samples over V m3) and requires immediate reinstatement to full testing on any non-conformance pending investigation and corrective action. Contracts should require electronic upload of QC data within 24 hours and retention for the agreed period.

9.2.3 Recommendations for digital QC adoption

Digital traceability is recommended for high-consequence or high-volume works and should be scaled to project size. Minimum data fields per batch/panel/specimen should include project and batch IDs, mix version, accelerator percentage bwc, pump and nozzle/operator IDs, panel and sensor IDs, time-stamped ambient and concrete temperatures, curing method, photographic evidence, dispatch/receipt times and laboratory certificate IDs. Data should be tamper-evident, exportable (CSV/JSON) and stored on a project server or cloud with role-based access and a full audit trail. Retain raw and processed logs, certificates and NCR records for a minimum of seven years (or project-specified term). Encourage dashboards and automated alerts to reduce disputes and speed corrective action.

9.2.4 Research and standards gaps (priority list)

Industry action is needed to close several priority gaps: develop a national shotcrete QC standard that consolidates specimen production, early-age testing, post-crack protocols and correction factors; fund research to validate the maturity/strength relationship and needle-penetrometer/beamlet/compressive strength correlations for set-accelerated shotcrete; develop an acceptable drying shrinkage test that includes the effect of set accelerators; standardise calculation and reporting methods for panel-based post-crack performance (including resolving ASTM C1550 residual strength calculation issues); investigate long-term durability impacts of accelerator types and doses on sprayed material; and define minimal data schemas/APIs to ensure digital QC interoperability between sites, laboratories and client systems. Addressing these gaps will improve defensibility, reduce ambiguity in contracts, and raise overall industry practice.

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11. Appendices

11.1 Appendix A

Acronyms Used in this Document

ACI	American Concrete Institute
AS	Australian Standards
ASTM	American Society for Testing and Materials
BWA	Boiled Water Absorption
bwc	By Weight of Cement
EFNARC	European Federation of National Associations Representing producers and applicators of specialist building products for Concrete
EN	European Norm
FRC	Fibre Reinforced Concrete
FRS	Fibre Reinforced Shotcrete
ISO	International Standards Organisation
ITA	International Tunnelling Association
LOP	Limit of Proportionality
MPa	MegaPascals
QA	Quality Assurance
QC	Quality Control
UCS	Unconfined Compressive Strength
VPV	Volume of Permeable Voids