Citation:

Mohajerani, A, Rodrigues, D, Ricciuti, C and Wilson, C 2015, 'Early-age strength measurement of shotcrete', Journal of Materials, vol. 2015, 470160, pp. 1-10.

Link to Published Version:
http://dx.doi.org/10.1155/2015/470160

Hindawi Publishing Corporation
Journal of Materials
Volume 2015, Article ID 470160, 10 pages
http://dx.doi.org/10.1155/2015/470160

Review Article

Early-Age Strength Measurement of Shotcrete

Abbas Mohajerani, Daniel Rodrigues, Christian Ricciuti, and Christopher Wilson

School of Civil, Environmental and Chemical Engineering, RMIT University, 124 La Trobe Street, Melbourne, VIC 3000, Australia

Correspondence should be addressed to Abbas Mohajerani; dr.abbas@rmit.edu.au

Received 6 June 2015; Revised 11 October 2015; Accepted 12 October 2015

Academic Editor: Te-Hua Fang

Shotcrete or sprayed concrete is a special concrete designed for spraying onto a surface, as a construction material. With shotcrete application as a ground support system ever-present in both mining and tunnelling sectors, a major requirement of drive progression is to determine when it is safe to reenter beneath freshly sprayed concrete. Accurately determining this time is of paramount importance. Generally, this reentry time is based on measuring the developing strength of shotcrete until an adequate strength value is reached. The issue with current practice is that there is no widely accepted or generally preferred method that accurately assesses the shotcrete lining's true early-age strength. However, there are a number of strength tests that are commercially available and used in the industry; these include the soil penetrometer, needle penetrometer, bolt screws, beam end testers, and drilled core samples. This paper researches into these testing methods and their characteristics in order to determine their accuracy, testing ranges, and suitability for in situ use in the tunnelling and mining industry. The investigation ultimately reveals that current methods all have substantial shortcomings. Based on these findings, recommendations are proposed for the applicable use of the current testing methods and recommendations for future improvements.

1. Introduction

Shotcrete, also known as sprayed concrete, is a material that is frequently used in the construction industry and has become a prevalent lining technique in the tunnelling and mining sectors. Shotcrete has been used for many years, since 1930s, for rock reinforcement and other applications in mining and civil constructions [1]. The ability of shotcrete to form on most shapes and its ability to bond to uneven surfaces make it a highly versatile material that provides effective and economical ground support with the benefit of quick and easy application [2]. The capacity and bond strength of an early-age shotcrete lining are dependent on the adhesion and interaction between the shotcrete and the surface it is sprayed on. It is also reliant on the strength of the shotcrete very early after spraying. Movements in the rock mass and vibrations from equipment and construction work may cause failure of the shotcrete (e.g., [3, 4]).

Shotcrete application in recent times is mainly through remotely controlled spraying machinery, thereby negating the safety concerns of labourers working under potentially unsafe, unsupported rock. However, machinery and labourers must still be able to continue the drive progression before the shotcrete has reached full strength. Therefore, the need to determine when the shotcrete has gained adequate strength for drive progression to recommence is of paramount importance. This illustrates the need for and importance of accurate shotcrete strength testing methods. Authorising reentry is not, however, purely based on safety and is largely driven by the demand and goal of efficient and expedited drive progression. For this reason, it is common that shotcrete is at a very early age when reentry occurs. It is also common that adequate shotcrete strength needs to be determined in order to authorise effective rock-bolt installation without degradation of the shotcrete lining [5]. Currently, there is no widely preferred method or technique for measuring the early-age strength of shotcrete lining, which is largely due to the limitations of the available testing methods. This presents an issue in which measurements may suffer with accuracy and could result in workers entering potentially unsafe zones, or, alternatively, if measurements underestimate strength, the projects could then suffer from diminished efficiency and drive progression. The aim of this paper is to critically review the dominant testing methods and techniques currently being used and report on their operation, limitations, and advantages to ultimately provide a recommendation on their use. Through this review, recommendations for advancement in testing techniques may be presented. In assessing the testing methods, it has also been deemed important to determine the failure modes that are most prevalent in early-age shotcrete linings. This is important as it signifies what strength parameters would be most beneficial for testing. This paper's criterion for what constitutes a successful testing method is one that is accurate, has a suitable testing range, is reliable, and is easy and practical to use.

Definition of Early-Age Shotcrete. In order to determine how appropriate a test method may be, it is important to define the timespan over which the strength of shotcrete can be classed as "early age." Because there are so many factors that can affect shotcrete strength, compounded by the broad variance between each site and mix design, it can be difficult to define an exact time. In fact, there are no worldwide guidelines for classifying when shotcrete is considered "early age" [6, 7]. Shotcrete of ages under 24 hrs is generally considered "fresh shotcrete" or "green shotcrete." Early-age shotcrete is then described as shotcrete that is 1–3 days old after application. Yet, testing shotcrete during these early periods is only necessary until it is deemed safe to reenter, or the strength of the shotcrete is at a level that would permit construction to continue underneath or in nearby locations. The former is particularly highlighted in the case of Kidd Creek Mine, where reentry occurred as quickly as 30 minutes, corresponding to a measured unconfined compressive strength (UCS) of 0.8 MPa, which was suitable for bolting to take place without damaging the shotcrete [5]. Duffield and Singh [8] show that by changing admixture concentrations in shotcrete mixtures, the strength gain even in the first four hours can be substantially altered. Moreover, it is important to note that different places have different standards for a safe reentry strength [5]. This review will focus on testing methods that are suitable for shotcrete that is 0–3 days old and the failure modes corresponding to the mentioned ages.

Understanding Failure Mechanisms. The aim of testing shotcrete early-age strength is to determine safe reentry times for tunnelling and mining drive progression. Therefore, rather than just determining a strength value that is deemed adequate, it is important to understand what types of failure early-age linings are subjected to in order to better understand and develop testing techniques. Through experimental work, Bernard [2] determined that there are two main types of failure mode for early-age shotcrete. These are shear punching failure and flexural delaminating failure. Shear punching failure, where wedges present, from converging faults, punch through the lining, has been determined to be the dominant failure mode over the first few hours after spraying. Similarly, Ding and Kusterle [9] identify the failure mode as shear fracture. Failure can later progress to delamination failure but only if there is relatively poor bond strength between the shotcrete and substrate [2].

The reason that most early-age shotcrete failures are shear failures is due to the nature of tunnelling and mining, and the role of shotcrete is primarily a lining designed to protect from rock-falls. It is reported by Bernard [2] and Clark et al. [10] that the majority of shotcrete failures are the result of individual loose rocks and small blocks of fractured zones punching through the lining and that it is seldom the case that shotcrete linings fail in total collapse. Empirically it has been determined that a UCS of 0.5–1.0 MPa is deemed an adequate strength for shotcrete to protect against rock-fall [11]. Particularly apparent in a number of techniques is a conversion into equivalent UCS values for which Jolin and Beaupré [12] recommend careful attention.

It can be quite difficult to determine shear strength experimentally, and, consequently, it tends to rely on its relation to compressive or tensile strength [13]. Although there is a reasonably well defined relationship between UCS and shear strength for mature-age concrete [14], studies into shotcrete early-age shear strength and compressive strength relationships are less clearly defined. Studies by Bernard [2, 15] investigated this relationship and, through testing, have developed a correlation that has a coefficient of variation in shear strength that is estimated to be 25% at early ages. With the early-age dominant failure mode of shotcrete known to be shear punching failure, this gap in standardised early-age strength relationships highlights the importance of being able to accurately determine the shear resistance of a lining, as this governs the majority of its early performance. Based on this information it seems appropriate that a direct testing method of shotcrete shear strength would be the most relevant and beneficial for the mining and tunnelling industry. However, nothing satisfactorily currently exists.

2. Shotcrete Strength Testing Methods

Typically, in order to assess the concrete strength, measurements are performed on cylinders or drilled core specimens. These are then crushed in order to obtain a UCS value, usually after 28 days of setting time. The issue with early-age shotcrete and concrete is that cylinders should not typically be demoulded before 48 hours' setting time, as this is considered bad practice and can lead to damage of the very young concrete [16]. Needless to say, waiting 48 hours to test the shotcrete specimens becomes impractical and inefficient, especially as two-hour reentry times are now regularly being achieved [5]. Similarly, coring of in situ specimens is equally as futile as it is suggested by Clements [16] that coring should not take place until a compressive strength of at least 5 MPa is attained or between 8–10 MPa, as Jolin and Beaupré [12] suggest, to avoid coring damage. The inability to obtain direct UCS values for shotcrete strength presents the issue that the testing methods currently being used in the industry make use of a correlation factor to convert their measured data to UCS values [12]. Unless care is taken when converting measured values to UCS equivalents, the accuracy of results could be further affected. The inapplicability of the typical compressive strength methods is the precise reason for the need and development of other measurement tools and procedures. However, the issue in the industry is that determining safe reentry times (based on strength measurements) is currently determined on a case-by-case basis, which

Figure 1: Beam end tester, showing the moulds and the hydraulic tester [18].

changes from project to project. The assessment of testing methods by Clements [16] is that although many methods of testing early-age strength development exist and are used, the accuracy of these tests is not well understood. This statement highlights a significant gap in the understanding of strength development and of the subsequent testing methods, pointing out the need for further research in the area. Based on the available literature, case studies, and author opinion, various methods will be reviewed in the following sections. Unlike many reviews of early-age shotcrete strength, which focus on the accuracy of these testing methods, this paper will analyse them more extensively with the criteria that a successful testing method is one that not only is accurate, but also has a suitable testing range, is reliable in its consistency, and is easy to use and simple in its application.

3. Beam End Testing

3.1. Description. The beam end test involves the crushing of sprayed beams, usually 75 × 75 × 400 mm in size by the use of a small hydraulic pump which applies direct compression until failure occurs through platens of a certain dimension [17, 18]. The device is illustrated in Figure 1. The peak failure load is then divided by the area of the platen in order to provide a strength value in MPa [16]. The device is similar in design to many compression testing machines but is portable in size. The beam sits under the platen with a single point load applied from a fixed platen underneath. The process is detailed by the spraying of shotcrete into an open-ended mould; the open ends prevent the collection of uncompacted rebound accumulating in the testing specimen. Generally, the shotcrete can be demoulded at strengths of 0.5 MPa, which is usually determined by using a needle penetrometer [5]. This strength value generally provides the lower limit of the testing range. However, it has been reported in some cases that its testing range can start as low as 0.1 MPa [18]. The upper limit of the strength range is said to be as high as 10 MPa UCS [5].

3.2. Advantages. Bernard and Geltinger [18] and Clements [16] have undertaken separate investigation studies into the comparison of various early-age strength testing methods including the beam end tester. Testing by Bernard and Geltinger involved comparing beam tests with UCS testing of cored samples with strengths greater than 5 MPa. In this study, it is claimed that the beam end tester's correlation with direct UCS testing provided a close enough relation to allow the beam end tester's measurements to be taken as true UCS values. In fact, the corresponding UCS values are used to calibrate other test methods. However, no equation of the graph or coefficient of correlation has been provided for this claim. Clements' studies state that the method provides the most reliable way of determining in situ early strengths. These studies indicate that the device is generally believed to have an excellent accuracy in terms of strength measurement. In addition to this, the hydraulic operation of the device ensures that there is little operator dependency in running the test, and, for this reason, repeatability of the results is considered satisfactory. Earlier studies [19] describe the test as a robust, simple, and low cost method that can be used in underground environments and in laboratory situations, with which the abovementioned studies tend to agree.

3.3. Disadvantages. However, despite the consistency of the testing device, there are distinct limitations in its use. Although operator dependency is reduced, there is still dependency related to spraying the test beams, and, for this reason, care must be taken to achieve well-compacted specimens. For example, it is important to ensure that spraying is perpendicular to the mould to prevent any accumulation of uncompacted shotcrete [16]. It is also very important to understand that this testing method does not directly measure the early-age strength of the shotcrete *lining* but rather gives an accurate strength indication of sprayed beam specimens. This can cause argument as to whether the testing is in fact in situ as Clements [16] suggests. Another issue related to this is that temperature variances between the lining and the specimens can cause alternate strength gains between the two (Bernard, 2005). This necessitates that the specimens be tested on site with temperature conditions closely matching that of the lining. It is also the opinion of this paper that sprayed linings that are immediately subjected to high stress conditions could possibly have alternate strength development compared to the unstressed specimens. In addition, other factors such as groundwater ingress could affect the lining strength. Lastly, while the testing device is not exactly heavy machinery, on-site tests favour more portable, easier, and simpler methods. Beam end tests take time, labour, and resources to spray enough shotcrete specimens (for every single drive progression), presenting issues with efficiency in both time and resources. For a combination of these reasons, Clements [16] believes that the device is too unwieldy to be used as a daily quality assurance tool.

3.4. Recommendation. Notwithstanding the limitations, advantages, and disadvantages of the beam end tester, it is deemed to be an effective tool for accurate strength estimations, at least for ranges above 0.5 MPa. In terms of being a tool that would be generally accepted and preferred in the tunnelling and mining industry, the device has some substantial drawbacks. Notably, the process of having to spray numerous testing samples, demoulding the samples, and then destroying them requires substantial resource allocation, particularly when the process has to be restarted

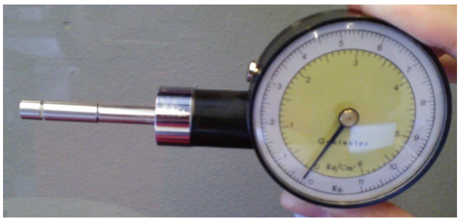


Figure 2: Soil penetrometer.

for porous or poorly compacted specimens [16]. Ultimately, this overly time-consuming process renders the method inefficient and cumbersome for in situ measurements. Nevertheless, the device can be very useful in assessing the accuracy of the strength measurements of other testing devices through the direct comparison of results and cover their shortcomings in range. Its use can be very beneficial in the further development of other testing methods, as it can be used as to calibration.

4. Soil Penetrometer

4.1. Description. The Australian Shotcrete Society (AuSS) describes the soil penetrometer as a device consisting of a sprung flat-ended steel plunger calibrated to indicate the approximate compressive strength of the soil/concrete when forced into the surface a distance of about 6 mm. The AuSS states its application in tunnelling and mining as follows: the device is used at approximately 6–10 locations across the surface of freshly sprayed shotcrete at each age of testing, and readings are taken at 10–20 minutes' intervals until the required strength is achieved. Although there are various types of soil penetrometer, for the following discussions the soil penetrometer's attributes and application will be assumed to follow AuSS's description. Figure 2 shows a typical soil penetrometer.

4.2. Case Studies. Rigorous testing of the soil penetrometer has been undertaken by Clements [16]. This included tests done at Perseverance Mine at Leinster, Western Australia, and at Freeport Mine in Irian Jaya, Indonesia. In Clements' investigation, 12 readings of a ST315 soil penetrometer (a specific and popular model of soil penetrometer) were taken for each set of time measurements, and then the highest and lowest results were discarded allowing for the exclusion of outlying results and a more accurate average to be taken of the other values. This was done in order to minimize the effect of any extraneous readings that may be given by the soil penetrometer. These results were then compared with early-age strengths found by the Meyco needle penetrometer and beam end testing. The comparison with the other two methods illustrated that, in general, the soil penetrometer gave much higher readings than both the beam end tester and the Meyco needle penetrometer, as illustrated in Figure 3. For example, it is stated that the soil penetrometer could indicate the strength of 1.4 MPa, while the Meyco needle penetrometer only showed a value of 0.5 MPa or even less for the same age. Not only did the soil penetrometer tend to overestimate the compressive strengths, it is stated that even when comparing soil penetrometer results to each other, there are significant variables that can largely be attributed to a high operator dependency and that care that must be taken to avoid striking aggregate. Furthermore, it is identified that the penetrometer's method of testing produces largely inaccurate results. The process of forcing the apparatus into the specimen would require displacement of the material. As such, it is the confined compressive strength that is determined rather than the unconfined compressive strength. Ultimately, Clements deems the device unsuitable for compressive testing of fibre-reinforced shotcrete due to its unreliability and comparatively high readings. Despite this condemnation, Clements still believes that the soil penetrometer has certain uses in shotcrete measurement, specifically limited to comparing the performance of different accelerators in the very early stages after spraying. It is stated that it is important that these comparisons would only be between one accelerator and another and that these values should not be taken as UCS values.

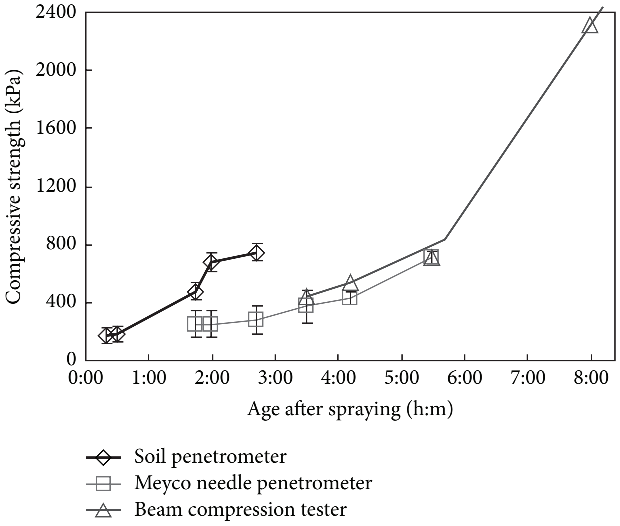


Figure 3: Comparison of early strength results using the Meyco needle penetrometer, sprayed beams, and soil penetrometer [16].

A more recent assessment of the soil penetrometer has been undertaken by Bernard and Geltinger [18] with similar results. The study involved over 1000 tests on approximately 30 sprayed and cast batches of shotcrete. By comparing various testing methods, Bernard and Geltinger established the beam end tester as the true UCS values and then compared other test results with these values. As with previous findings by Clements [16], the soil penetrometer was found to substantially overestimate the strength values. The significance of the strength overestimation is said to be by a factor of 1.5–4.1 across all capable strength ranges of the device. Despite the seemingly grave overestimates of the device, the study does, however, attempt to improve the accuracy and usability of the device through the use of the following formula [18]:

$$\sigma_c = \frac{\sigma_s}{1.5 + 2\sigma_s}, \tag{1}$$

where σ_c is a more conservative compressive strength, MPa (a value that more closely matches beam end testing/needle penetrometer testing). σ_s is the compressive strength reading of the soil penetrometer, MPa.

This was obtained by using linear regression of shotcrete's true compressive strength (according to beam end testing and the Meyco needle penetrometer) and relates this value to soil penetrometer readings. There is no coefficient of correlation given for this relationship.

4.3. Discussion. The capability of the standard device is in the range of 0–1.4 MPa [5, 16]. However, although this may be the capability of the device, it is reported that its useful strength range for shotcrete testing is only a fraction of this, with the useful range limited to 0–0.2 MPa [18]. With adequate shotcrete strength for safe reentry widely reported as 1–1.5 MPa, this strength range has some obvious deficiencies.

A major issue of the device's measurements is the accuracy of the readings it produces. It is widely reported that the soil penetrometer suffers drastically in overestimating the strength parameters of early-age concrete and shotcrete [6]. This statement has been founded upon and backed up by various research, with the overestimations said to be by a factor of 1.5–4.1 [18] or in less extreme cases 50–75% overestimation [5]. In some cases, it has been found that the soil penetrometer test can show compressive strength values of 1.4 MPa, while other devices, such as the Meyco needle penetrometer, can show equal age values of 0.5 MPa or less [16]. For better strength estimates, the AuSS [6] recommends correcting the test results with the method developed by Bernard and Geltinger [18], as discussed in the case study. With wide reports of inaccuracies, especially in overestimations, the safety issues associated with using the soil penetrometer in determining safe reentry times are significant and worrying.

With any testing method, it is essential that consistent results are attainable regardless of the user. The stated ease of use of the soil penetrometer would naturally infer that repeatability of results should be relatively consistent from user to user. There are, however, two different viewpoints concerning the soil penetrometer's repeatability: one being that it does have satisfactory repeatability and the other being that its results are very inconsistent. Bernard and Geltinger [18] state that the testing method has a satisfactory repeatability, despite its overestimates. However, Clements [16] reports that the results of the device are not only inaccurate but also inconsistent, laying the blame on the high operator dependency of the device. Although these two different opinions exist, it is acceptable to assume that although one study achieved high repeatability while the other found significant inconsistencies, the differences in findings could be precisely due to the high user dependability in which one user is able to use the device more consistently than another.

Although there are numerous shortcomings in the soil penetrometer test, it does have certain advantages that account for its widespread use in Australian mines [16]. In general, these advantages tend to be related to the device being small and therefore an easily held device with a relatively simple testing process. In addition to this, the relative cost of the device is minimal, as is the labour requirements associated with its use. Perhaps its most important advantage is that the device is virtually nondestructive allowing it to test the shotcrete's lining directly without compromising the safety and capacity of the support system.


Figure 4: Meyco needle penetrometer.

4.4. Recommendation. Taking into consideration all the attributes of the device, both good and bad, it is deduced that although the device may be useful to give an *indication* of strength development, its significant inaccuracies and inconsistencies render it ineffective for the purpose of confidently measuring the lining capacity of shotcrete. Therefore, its use in helping determine reentry times is not considered effective for the purpose of maximising cycle time efficiency and creating satisfactory safety margin. This statement is based on numerous studies that show the testing method's limited useful testing range and its unconservative readings. If conducting testing with the device is necessary, it is then suggested to use Bernard and Geltinger's correction method, which is believed to output "truer" compressive strength values [6]. However, although this might provide more accurate values, it would still prove to be a tedious task to apply the correction method for every reading, especially when projects are driven by high efficiency and high progress rates.

5. Meyco Needle Penetrometer

5.1. Description. According to AuSS's [6] description, the needle penetrometer consists of a 3 mm diameter steel needle at the end of a spring that is forced into the surface of setting concrete. Its application for shotcrete testing is described as follows: the force required to drive the needle to a depth of 15 mm is used to determine the approximate compressive strength with the aid of a calibration chart. There are numerous types of needle/pin penetrometers and although other types exist, such as the Vicat needle penetrometer, they are not considered or used in shotcrete application, but rather only in assessing the setting time of conventionally cast concrete. The AuSS [6] expresses the importance of avoiding confusion concerning these different devices. The Meyco needle penetrometer is illustrated in Figure 4.

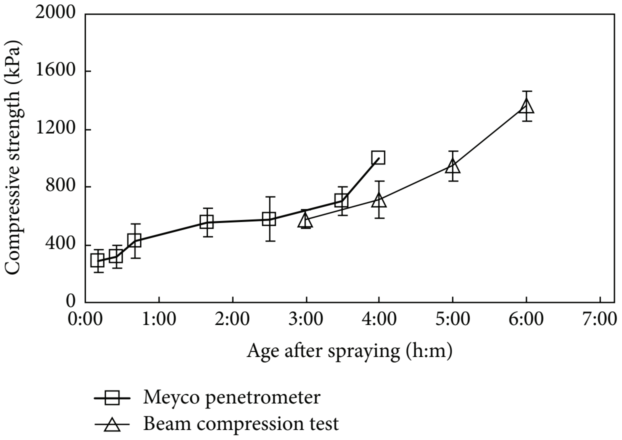


Figure 5: Comparison of early strength results using the Meyco needle penetrometer and the sprayed beams tested in compression [16].

5.2. Case Studies. A number of recent studies have been undertaken to assess the performance of the needle penetrometer with a reasonable correlation found between investigations. These investigations are detailed as follows.

Clements' investigation [16] involved the testing of the Meyco penetrometer in Perseverance Mine at Leinster, Western Australia, and at Freeport Mine in Irian Jaya, Indonesia. Similar to the soil penetrometer's readings, 12 measurements were taken with the outlying top and bottom results discarded allowing for a better average of the remaining 10 readings. Clements' general observations of the device are that it was able to avoid the aggregate and fibres more easily compared to the soil penetrometer due to its smaller penetration area. It is also stated that the manufacturers calibration curve illustrates that the device has been specifically designed for UCS strength. By a comparison of the beam end testing and the soil penetrometer, it was found that the needle penetrometer and the beam end test shared, in general, a good correlation of results. This correlation is specifically useful for the ranges of 0.3–0.9 MPa, as illustrated in Figure 5. As the beam end testing is described as a direct test of UCS strength, this indicates a good accuracy for the Meyco penetrometer. However, Clements does recognise the shortcomings of the device, stating that it is impractical to extend the device past the determined useful range, as it requires the full force of a man just to reach a strength of 1.0 MPa. This leads on to the next issue of the needle being relatively easy to snap off when subjected to high loads such as these. In closing, Clements believes the Meyco penetrometer provides a conservative and reliable option for determining shotcrete strengths up to 1.0 MPa.

O'Toole and Pope [20] also undertook an investigation into shotcrete testing and part of the investigation included the comparison between the Meyco needle penetrometer and the sprayed beam compression test [17], with the aim being to determine whether the needle penetrometer is a tool that underground operators can rely on for use in determining if the shotcrete has developed adequate bolting strength. The testing involved the use of the penetrometer for ages of 0–2 hours after spraying and the beam test from 1–6 hours after spraying, giving a comparison range of one hour. These trials were conducted at a local batching plant over a two-day period. The results of the investigation revealed a reasonable correlation between the two testing methods, with the needle penetrometer generally showing higher readings at the one-hour mark. Ultimately, the paper describes the Meyco penetrometer as being an effective device in providing an indication of increasing strength but deems that it is not a sufficiently accurate device to provide specific strength values.

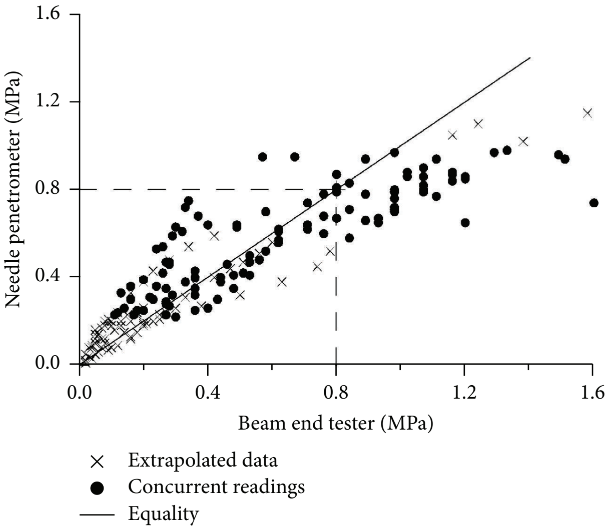


Figure 6: Indirect compressive strength as measured using a needle penetrometer compared with results obtained using the beam end tester. Solid points indicate tests done at same age and crosses indicate extrapolations in which only one of the tests was actually performed [18].

Bernard and Geltinger's testing (as described in Soil Penetrometer) found similar results to the above papers. Again, the paper determined that the beam end tester provides the truest values for shotcrete UCS and, therefore, compared these to the needle penetrometer readings. The investigation determined that the needle penetrometer, in general, overestimates readings up until 0.6 MPa and, subsequently, underestimates readings from 0.6–0.8 MPa. The paper states that the needle penetrometer is not particularly accurate after strengths of 0.8 MPa. However, despite these undulating results, ultimately, it is reported that the needle penetrometer is reasonably accurate in the strength range of 0.2–0.8 MPa, as illustrated in Figure 6. The authors define the method as currently the best testing alternative.

5.3. Discussion. The needle penetrometer is generally reported as having a maximum strength testing range of up to 1 MPa. The proprietor, Meyco, states that their device functions between 0.2 and 1 MPa. However, its useful and most accurate range is found to be less than its stated functional range. The most conservative useful range is

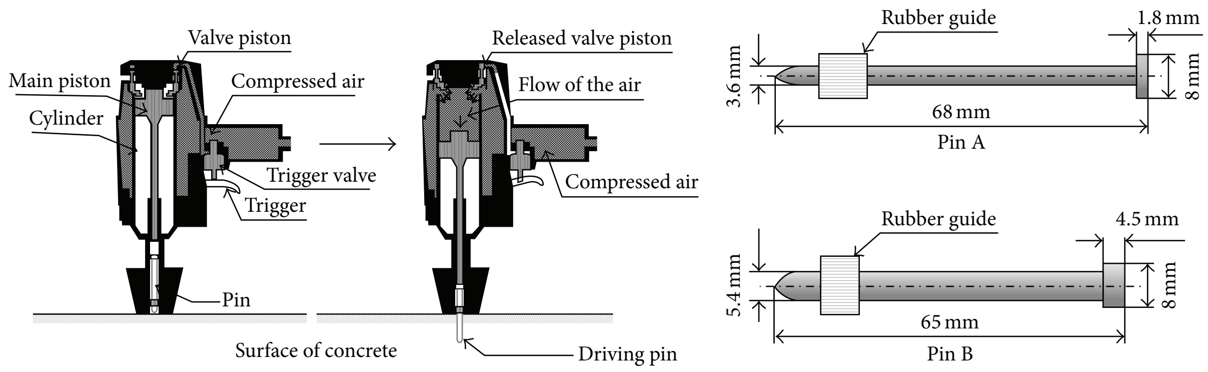


FIGURE 7: Pneumatic pin penetration nailer and specification of pins [11].

determined by a combination of two studies, Clements [16] and Bernard and Geltinger [18], resulting in a reliable accurate range of 0.3–0.8 MPa. Although this represents a reasonable testing range, for the explicit purpose of measuring early-age strength to ensure safety, it still does not satisfy the most commonly accepted adequate strength, which is usually in excess of 1.0 MPa.

The needle penetrometer's strongest attribute is its reported accuracy within its reliable range. While Clements [16] and Bernard and Geltinger [18] comment on the success of the device in accurately measuring shotcrete early-age strength, O'Toole and Pope [20] believe that the device is not accurate enough for underground measurements of shotcrete strength. Although this difference of opinion may arise due to different tolerances of accuracy between the authors, regardless of this, the needle penetrometer is still considered a relatively accurate method of determining shotcrete strength development.

The repeatability of the results is not directly commented on in the literature, but by reasoning of the testing data and general usability comments, although it can suffer from operator issues, it is evident that the device has consistent results. However, Clements' method of discarding the highest and lowest values does suggest that some unacceptable readings can occur against the general trend. The issue of repeatability may be due to the difficulties associated with the devices operation, such as the influence of striking fibres and aggregate, and the requirement that the needle must be driven *steadily* into the shotcrete surface in order to obtain reliable results.

5.4. Recommendation. In assessing the attributes of the needle penetrometer, it is evident that its application in measuring shotcrete strength certainly has some beneficial uses. Its relatively high correlation to direct compressive measurements illustrates the devices significant accuracy, which is of paramount importance when assessing shotcrete early-age strength. The problem is that this accuracy is, firstly, not widely accepted by all and, secondly, suffers from a limited accurate testing range.

5.5. Pneumatic Pin Penetration. In response to the high operator dependencies of conventional penetrometer testing, a slight alternative has been developed by Iwaki et al. [11] and named a pneumatic pin penetration test. The author reports that a device has been created that uses a constant air-pressured penetrating needle as a simple in situ test. The device is similar to a nail gun used in the construction industry, utilizing a gun connected to constant air pressure but replacing the nails with solid steel pins. The device uses air pressure set at 1.47 MPa to drive pins of 3.6 mm diameter and 5.4 mm diameter into freshly sprayed concrete. The reason for two different diameters is to widen the range of strength estimation. The components of the testing device are detailed in Figure 7. The depth of the penetration is then the only variable and is dependent on the shotcrete strength. The penetration depth has been measured using the dedicated jig and the depths are compared with strengths determined by conventional pull-out tests. The pull-out tests follow the Japanese methods as standardised in the JSCE-G561 and JHS 702. These standardised tests measure the direct shear strength of shotcrete that has been sprayed onto forms or walls in which draw bolts have been previously attached. By recording the pull-out force required to fail the specimen, the following formulas are used to derive the shear strength and compressive strength of the shotcrete [11]:

$$F_s = \frac{P}{A} \tag{2}$$

$$F_{\mathrm{CP}} = 4F_s, \tag{3}$$

where F_s is shear strength (N/mm^2). P is pull-out force (N). A is surface area of truncated cone specimen (mm^2). F_{CP} is compressive strength (N/mm^2).

Iwaki then produces third-degree equations to plot the line of pin penetration depth versus compressive strength for two different sized pins; this equation gives a coefficient of correlation, R, between 0.94 and 0.96, indicating a close correlation between the compressive strength and the penetration depth. Although the study reveals promising results of penetration depth versus shotcrete strength, it is difficult to assess this method on its effectiveness, accuracy, and reliability. Bae et al. [21] performed further tests on the device by comparing Iwaki's predicted strength (based on penetration depth) to the actual uniaxial compressive testing and found reasonable accuracy of the method. However, the testing was only done for shotcrete, which far exceeds the adequate reentry strength of 1 MPa. Bae's testing starts 2 hours after setting time and for the specific mix design used with an average strength of 8 Mpa. Therefore, the investigation does not provide any further information on the accuracy of young shotcrete strengths. With more research into the method and testing of the device, and also the accuracy of (3), it could prove to be a useful and generally acceptable testing method.

6. Echo Testing/Shear Wave Velocity

6.1. Description. A relatively new method and technique for the measurement of shotcrete early-age strength is by using echo testing and shear (P-wave) velocities. The method uses an impact-echo system to relate P-wave velocities through the concrete material to shotcrete compressive strength values [22]. A detailed explanation of the theory behind this technique will not be discussed in this study. Rather, the results obtained and their accuracy and reliability will be reviewed and discussed.

6.2. Discussion. Gibson [23] describes echo testing as a "well-known non-destructive technique for in situ evaluation of structural concrete members." Similarly, Song and Cho [24] identify the method as successful in its evaluation of concrete structures, though they point out its limited use in shotcrete applied to complex nonuniform surfaces, such as in tunnel excavations. Ciancio and Helinski [22] and Gibson [23] undertook investigations to relate wave velocities to compressive strengths of shotcrete. They found distinct relationships between velocities and compressive strength. Although this velocity correlation exists, Gibson [23] states that this relation is mix-specific and therefore a global conversion factor would be unreliable and not recommended. This means that the relationships between shear velocities and compressive strengths are dependent on the mix design of shotcrete, such as the water/cement ratio, aggregate type, and admixture, meaning that different mix designs have different relationships to shear wave velocity. Ciancio and Helinski [22] voice this same concern with mix-specific relationships, stating that verification studies are considered necessary in order to assess the changes to the unique strength-velocity relationship to see if hydration characteristics change due to admixture additions. A recent collaboration of both authors, Gibson and Ciancio [25], resulted in in situ investigations of a novel type of disposable ultrasonic testing device. The results of this testing were reported to show good correlations between P-wave velocity and unconfined compressive strengths, specifically, those higher than 4 MPa, with a greater variability observed for strengths of less than 4 MPa. Song and Cho [24] engaged in research exploring a different perspective on echo testing through analysis of results using Fourier transform and short-term Fourier transform. Laboratory research as well as limited site testing yielded decent accuracy in determining parameters, including shotcrete thickness and the bonding state in most situations. Although this data can be important for project progression and safety assurance, it does not illustrate the strength development of the shotcrete.

Figure 8: Hilti gun.

6.3. Recommendation. Recent studies of echo testing reveal promising advancements in the area. The issue with early-age testing is that variations in mix designs can alter the readings, meaning that correlations between the shear waves and unconfined compressive strengths are mix-specific. Furthermore, the nature of echo testing necessitates consideration for additional variables that can influence results, such as surface profile variations and the impact source [24]. Apart from this, the technique requires technical expertise in understanding shear wave velocities and echo testing fundamentals. This level of expertise is not going to be common knowledge amongst most contractors. At present, it still seems that more research and development is needed in the area before the method could be widely used in the tunnelling and mining industry. Therefore, in terms of current early-age shotcrete strength, this method is only proposed as a complement to, rather than a substitute for, other direct methods [23].

7. Hilti Gun/Bolt Driving Method

7.1. Description. The Hilti gun method involves firing a steel fastener into the surface of the shotcrete, measuring the depth of penetration, and then using a separate device to pull the fastener out of the concrete surface (Bernard, 2005). The AuSS [6] describes the process of testing as a proprietary nail being shot into shotcrete using a Hilti DX450 nail gun. The penetration depth is then recorded. A nut is then screwed onto the protruding end of the nail to allow a Hilti pull-out test to be implemented. A ratio of the pull-out force to the depth of penetration is then compared against a calibration chart to determine the strength of the concrete; by taking a ratio of these two processes, scattering is reduced and more reliable results achieved. To obtain more accurate results, it is recommended that at least eight nails should be used for each testing age. The Hilti nail gun is illustrated in Figure 8.

7.2. Discussion. According to the Australian Guidelines, the Hilti nail gun testing method has a working range of 1 MPa to 16 MPa depending on the power of the cartridge being used [26]. However, it is reported that the reliable range of this technique is only upwards of 2 MPa [5, 16] with a limiting range of 18 MPa [6]. As the adequate compressive strength of shotcrete to protect against rock-fall is usually reported as an average of 1 MPa [2], with lowest ranges being

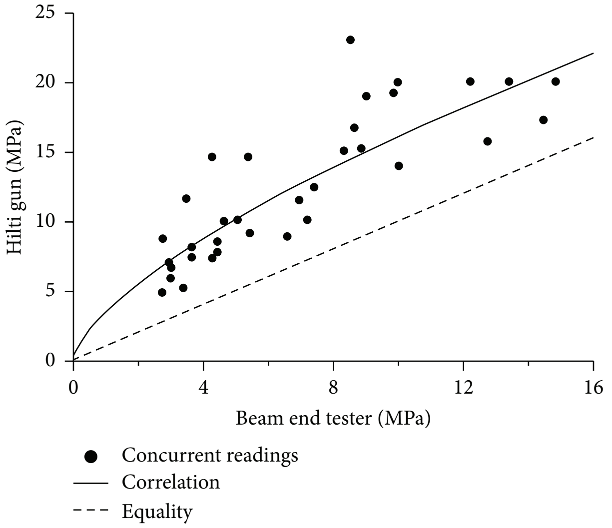


Figure 9: Indirect compressive strength as measured using a Hilti gun compared with results obtained using the beam end tester. Lines indicate equality and curve fit to data [18].

0.5 MPa [11, 27], and the highest range reported as 1.6 MPa [16], this method is not suitable for the purpose of true early-age and fresh concrete testing. Thus, shotcrete would only be able to be tested when it is significantly stronger than it needs to be, thereby proving to be an inefficient method in the effort to reduce cycle times. In addition to this obvious deficiency, studies undertaken by Bernard and Geltinger [18] indicate that the method significantly overestimates compressive strength values when compared with beam end testing, as shown in Figure 9. Studies by the Technical University of Innsbruck indicate that more accurate results can be obtained by neglecting the ratio of penetration resistance to pull-out force and relying solely on the values of penetration resistance to obtain compressive strength values. This is because scattering of the pull-out test data was much greater than the scattering produced from the penetration depth data [26]. This simplification of the testing procedure by omitting the need to measure pull-out forces improves the repeatability of the testing.

In addition to having a limited working range and unreliable accuracy, the method has several other disadvantages, including the high running costs associated with the cartridges and fasteners, that it uses explosive devices, and that it is time consuming to conduct the measurements [6]. It is also stated that the device occasionally misfires the fastener. Bernard and Geltinger [18] also comment on the significant variability of available explosive cartridges, fasteners, and power settings of the guns, suggesting that this makes it difficult to ensure testing across different sites is carried out in the same manner that is prescribed for the calibration chart.

7.3. Recommendation. Although this method of compressive strength testing is widely used in the industry and included in multiple standards, when considering the limited range of the device, especially in the critical strength range for early-age shotcrete, in addition to the various limitations and difficulties the device experiences, use in the industry is not recommended for the purpose of safe reentry times. Bracher [26] attempts to simplify the method and achieve more reliable results by excluding the need to conduct a pull-out test; however this, in turn, requires manufacturers to supply updated calibration graphs for this technique. Perhaps with better calibration, accuracy, and a more relevant testing range, similar testing techniques could be successful.

8. Discussion Conclusions

The accurate early-age strength determination of shotcrete is driven by the increase in safety standards as well as the demand for cycle time efficiency in both commercial tunnelling and mining applications. With the continual improvement in excavation rates, it is important for reentry rates for machinery and miners to improve. The current literature reveals that the most common failures related to shotcrete in underground excavations occur from loose rocks and fractured blocks punching through the fresh shotcrete linings. The compressive strength of shotcrete to prevent these failures is generally reported in the range of 0.5–1.6 MPa depending on the desired factors of safety, stress conditions, and geological environment.

Following the review of the common testing methods, it seems that, currently, the best practice is to use a combination of the needle penetrometer and beam end testing, which, when combined, can give results in the range of 0.3–10 MPa. However, inaccuracies, operator dependency, and impractical use are a few of the unfavourable aspects in their application, which prevents them from being considered as "successful" methods. Other methods such as the Hilti gun and the pneumatic pin penetration method also have their inherent drawbacks. The pneumatic pin penetration tool, although a good attempt in advancing testing technology, needs more research and development to be considered for widespread use.

This highlights that although there are many testing methods available with numerous advantages in the market, all methods, even those more widely used, suffer from inherent negative aspects including very limited ranges, inaccuracies, inconsistencies, and impracticalities. The limitations of the current techniques necessitate advancements in the methods or the development of techniques to create better standards of testing for the benefit of the tunnelling and mining sectors, improving not only safety but also efficiency. Possible testing for the future would benefit by measuring the shotcrete lining directly for a specific strength parameter, such as compression, shear, or tension. A device that could directly measure compressive, shear, or tensile strength without any significant damage to the lining would surely prove to be a valuable tool in shotcrete use, representing a major benefit to the unique world of underground construction, specifically in the tunnelling and mining industries.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] ACI, “Guide to shotcrete,” ACI Report 506R-05, American Concrete Institute, 2005.

[2] E. S. Bernard, “Early-age load resistance of fibre reinforced shotcrete linings,” *Tunnelling and Underground Space Technology*, vol. 23, no. 4, pp. 451–460, 2008.

[3] L. E. Bryne, A. Ansell, and J. Holmgren, “Laboratory testing of early age bond strength of shotcrete on hard rock,” *Tunnelling and Underground Space Technology*, vol. 41, no. 1, pp. 113–119, 2014.

[4] P. Mpunzi, R. Masethe, M. Rizwan, and T. R. Stace, “Enhancement of the tensile strengths of rock and shotcrete by thin spray-on liners,” *Tunnelling and Underground Space Technology*, vol. 49, pp. 369–375, 2015.

[5] M. Rispin, D. Howard, O. B. Kleven, K. Garshol, and J. Gelson, *Safer, Deeper, Faster: Sprayed Concrete—An Integral Component of Development Mining*, Australian Centre for Geomechanics, 2009.

[6] Australian Shotcrete Society, *Recommended Practice—Shotcreting in Australia*, Concrete Institute of Australia, 2nd edition, 2010.

[7] A. Ansell, “In situ testing of young shotcrete subjected to vibrations from blasting,” *Tunnelling and Underground Space Technology*, vol. 19, no. 6, pp. 587–596, 2004.

[8] S. B. Duffield and U. Singh, “Economical mix design enhancements for FRS,” in *Shotcrete: Elements of a System*, E. S. Bernard, Ed., pp. 85–98, CRC Press, 2010.

[9] Y. Ding and W. Kusterle, “Compressive stress-strain relationship of steel fibre-reinforced concrete at early age,” *Cement and Concrete Research*, vol. 30, no. 10, pp. 1573–1579, 2000.

[10] C. C. Clark, M. A. Stepan, J. B. Seymour, and L. A. Martin, “Early strength performance of modern weak rock mass shotcrete mixes,” *Mining Engineering*, vol. 63, no. 1, pp. 54–59, 2011.

[11] K. Iwaki, A. Hirama, K. Mitani, S. Kaise, and K. Nakagawa, “A quality control method for shotcrete strength by pneumatic pin penetration test,” *NDT and E International*, vol. 34, no. 6, pp. 395–402, 2001.

[12] M. Jolin and D. Beaupré, *Understanding Wet-Mix Shotcrete: Mix Design, Specifications, and Placement*, American Shotcrete Association, 2003.

[13] D. Diamantidis and E. S. Bernard, “Reliability-based resistance design of FRS tunnel linings,” in *Shotcrete: More Engineering Developments*, E. S. Bernard, Ed., chapter 12, pp. 109–126, Taylor & Francis, 2004.

[14] Australian Standard, *AS3600 Concrete Structures. 2010*, Standards Australia, Sydney, Australia, 2010.

[15] E. S. Bernard, “Influence of geometric factors on the punching load resistance of early-age fibre reinforced shotcrete linings,” *Tunnelling and Underground Space Technology*, vol. 26, no. 4, pp. 541–547, 2011.

[16] M. J. K. Clements, “Comparison of methods for early age strength testing of shotcrete,” in *Shotcrete: More Engineering Developments*, E. S. Bernard, Ed., pp. 81–87, Taylor & Francis, 2004.

[17] ASTM International, “Standard test method for compressive strength of concrete using portions of beam broken in flexure,” ASTM C 116-90, American Society for Testing and Materials, West Conshohocken, Pa, USA, 1990, Withdrawn 1999.

[18] E. S. Bernard and C. Geltinger, “Early-age determination of compressive strength in shotcrete,” *Shotcrete*, vol. 9, no. 4, pp. 22–27, 2007.

[19] R. Heere and D. R. Morgan, “Determination of early age compressive strength of shotcrete,” *Shotcrete*, vol. 4, no. 2, pp. 28–31, 2002.

[20] D. O’Toole and S. Pope, “Design, testing and implementation of ‘in-cycle’ shotcrete in the Northern 3500 Orebody,” in *Shotcrete for Underground Support X—Proceedings of the Tenth International Conference on Shotcrete for Underground Support*, pp. 316–327, 2006.

[21] G.-J. Bae, S.-W. Lee, S.-H. Chang, H.-G. Park, M.-S. Lee, and J.-K. Kim, “Application of pneumatic pin penetration test to estimation of compressive strength of shotcrete in Korea,” *Tunnelling and Underground Space Technology*, vol. 19, pp. 432–440, 2004.

[22] D. Ciancio and M. Helinski, “The use of shear wave velocity for assessing strength development in fibre reinforced shotcrete,” in *Proceedings of the 3rd International Conference on Engineering Developments in Shotcrete*, pp. 65–70, March 2010.

[23] A. Gibson, “Advances in shotcrete impact-echo testing,” in *Shotcrete: Elements of a System—Proceedings of the 3rd International Conference on Engineering Developments in Shotcrete*, E. S. Bernard, Ed., chapter 13, pp. 111–117, Taylor & Francis, London, UK, 2010.

[24] K.-I. Song and G.-C. Cho, “Numerical study on the evaluation of tunnel shotcrete using the Impact-Echo method coupled with Fourier transform and short-time Fourier transform,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 8, pp. 1274–1288, 2010.

[25] A. Gibson and D. Ciancio, “Early-age ultrasonic testing of concrete and shotcrete using embedded sensors,” in *Nondestructive Testing of Materials and Structures*, vol. 6 of *RILEM Bookseries*, pp. 485–490, Springer, Dordrecht, The Netherlands, 2013.

[26] G. Bracher, “Worldwide Sprayed Concrete: State-of-the-Art-Report,” Schweiz, 2005.

[27] M. Rispin, “Re-entry into a shotcreted, underground heading,” *Shotcrete Magazine*, pp. 26–30, 2005.


Journal of
Nanotechnology

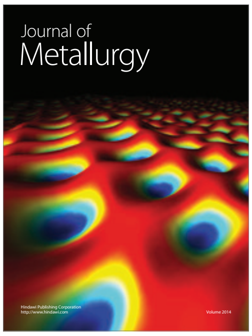

International Journal of
Corrosion


International Journal of
Polymer Science

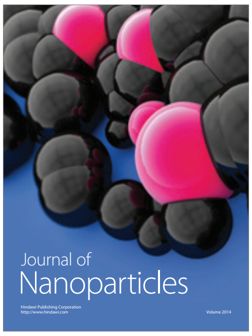

Smart Materials
Research

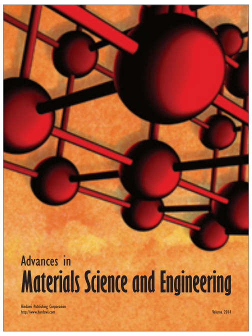

Journal of
Composites

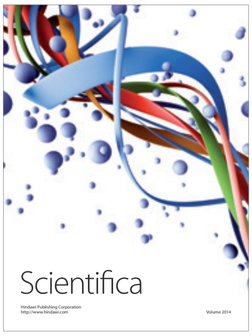

BioMed
Research International

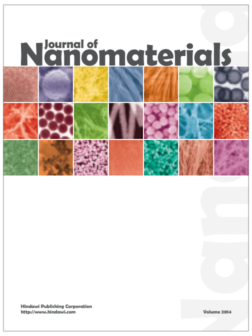

Journal of
Metallurgy


Journal of
Materials


Journal of
Nanoparticles

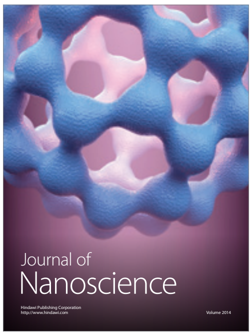

Advances in
Materials Science and Engineering


Scientifica

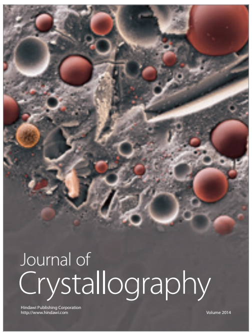

Journal of
Nanomaterials


The Scientific
World Journal


International Journal of
Biomaterials


Journal of
Nanoscience


Journal of
Coatings


Journal of
Crystallography


Journal of
Ceramics


Journal of
Textiles