Advances in In-Situ Testing of Ventilation Control Devices for Underground Mines

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ABSTRACT: As underground mines increasingly face the challenge of maximising production without losing focus on safety excellence, the ability to predict the effectiveness and identify defects in mine seals and stoppings plays an increasingly important role in mine ventilation management. While technologies for sample testing installed seals provides significant assurance, the difficulty of conducting tests in operational environments, combined with the production impact of destructive testing procedures, has led to the development of a new method for non-destructively testing ventilation control devices (VCDs). This paper addresses the challenges of in-situ testing and reviews the approaches previously employed to verify the quality of VCD installations. It then describes a new testing methodology jointly developed by Aquacrete and Parsons Brinckerhoff (PB) and the range of tests that have been carried out in the laboratory, above ground, at trial underground sites and in active coal mine operations.

Over a three year period, Aquacrete and PB have co-operatively developed a method for in-situ, non-destructive testing of ventilation control devices. Although a new approach to testing underground VCDs, the method employs recognised testing equipment in a new application. The aim of the new non-destructive technology is to not only verify the thickness, and therefore overpressure rating compliance, of new VCDs, but to allow mine operations to identify and locate defects in installed VCDs without causing damage to the material structure. It is difficult, time-consuming and costly to carry out physical sampling and testing of every VCD. Therefore, a reliable and accurate means of non-destructively testing concrete and plaster seals in-situ will provide substantial operational and safety benefits to the underground coal mining industry.

1 Introduction

The key objective of underground mine ventilation is to provide and maintain an adequate supply of fresh air to the work face while efficiently exhausting stale and contaminated air. In addition, unused and worked-out sections of the mine need to be effectively closed off from ventilation to minimise the risk from spontaneous combustion and manage goaf gases.

Devices used to control air flow and isolate sections of underground mines are termed stoppings and seals respectively and are collectively referred to as Ventilation Control Devices (VCDs) in this paper.

Stoppings are typically designed for differential air pressures up to 35 kPa (5 psi) while seals are typically designed to resist blast pressures of 140 to 345 kPa (20-50 psi).

VCDs have traditionally been constructed using a variety of materials and methods to address specific mine site conditions. However, as many installations have been temporary in nature, specific research into the construction requirements and performance measurement of VCDs has been limited

More recently, greater attention has been placed on the risks of lost production or even loss of life should a stopping or seal fail prematurely. Once a VCD has been installed, there is currently no accepted means for verifying its condition.

2 Factors Affecting VCD Performance

The effectiveness of a VCD relies on many factors and each factor is the responsibility of a different party. This means that a VCD is only as good as the "weakest link" in the chain of planning, design, supply, construction and maintenance.

In summary, the factors affecting the finished strength of a VCD include:

- Geology
- Siting
- Design
- Materials
- Construction, and
- Maintenance

While the first three items in the above list can be independently checked with reference to maps, reports, plans and calculations, physical inspection and testing is essential to verify the last three items on the above list.

Some types of VCDs lend themselves to testing during construction. For example, concrete for VCDs can be sampled and tested in exactly the same way as for above ground construction. Manufacturer's certificates can also be used to verify the material quality. At present, however, there is no way to easily verify that the material quality has not deteriorated over time, due to exposure to underground conditions, for example.

3 Background to Aquacrete VCDs

The in-situ, non-destructive testing described in this paper was developed specifically to enable testing of Aquacrete VCDs and this section provides an overview of that product.

Aquacrete is a specialised gypsum-based product that is sprayed onto a backing board to form stoppings and seals in underground mines. It has been successfully used in underground mines in Australia for over 20 years. In 1998, Aquacrete undertook full-scale blast testing of VCDs varying from 100mm up to 500mm thickness using peak blast pressures up to 520 kPa (75 psi). The tests were conducted in an underground operational mine in Western Australia and were fully instrumented with pressure sensors providing time/pressure histories at five locations on each VCD.

Figure1: Full scale blast testing simulation of Aquacrete VCD showing blast pressure

Due to the variable pressure results recorded over the face of each VCD during the tests, and the fixed size of the test VCDs (approx. 4.5m x 4.5m) these test results could not be directly used to certify VCDs for use in underground coal mines where roadway sizes are more typically 3.2m high x 5.5m wide. Also, the Queensland regulations stipulate that VCDs must be able to resist a uniform pressure across the entire face and the test results showed varying pressures at different locations. A final complication was that the tests used a commercial high explosive (gelignite) to produce the explosive blasts and in coal mines, either methane or coal dust are usually responsible for underground explosions.

Working together with Aquacrete, PB used these test results to develop an engineering model to predict the performance of VCDs for a range of sizes and uniform pressures. By developing a finite element computer model of the test VCDs and calibrating the model's behavior using the test results, the authors were able to show that a reliable prediction of required VCD thickness could be made for any specific combination of size, pressure rating and requested factor of safety.

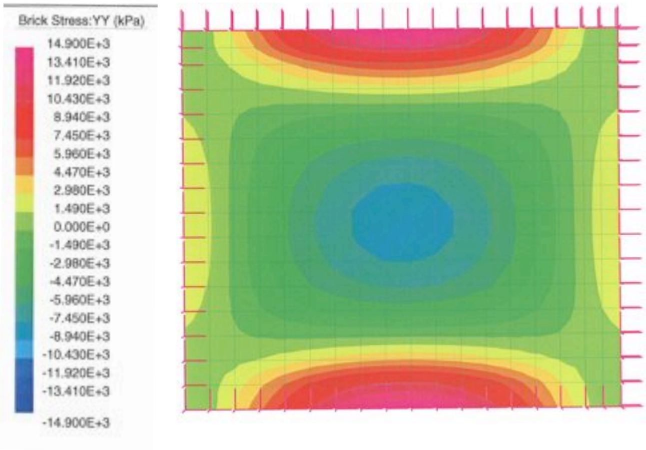

Figure 2: Shear stress distribution – blast loading

4 Requirements for Testing VCDs

There is currently no Australian Standard for design or construction of VCDs and information available internationally is of limited use. Some useful research work was carried out by ACARP between 2000 and 2004 and those studies provide a useful snapshot of the "state of the art" at that time. Regrettably, there appears to have been little progress on adopting any of the recommended next steps from those reports.

Within Australia, the two main coal-mining states of NSW and QLD have their own and different requirements for design, construction and certification of VCDs. As the Queensland regulations are currently the most stringent, Aquacrete and PB have adopted those as the basis for the design of all Aquacrete VCDs.

The Mines Inspectorate in Queensland has issued various industry communications over the years, the most recent being Safety Bulletin No. 107 in March 2011. This communication suggested that, among other measures, mine managers should ensure that construction materials were tested and not to rely on manufacturers' documentation. It also recommended that mine managers should "validate the integrity of a seal by an engineering review". The ambiguities contained in Bulletin 107 have not clarified the official position regarding the structural requirements for VCDs in Queensland. The authors' experience is that mines are making their own interpretations, resulting in inconsistency and wasted effort as suppliers and contractors attempt to meet the mines requests.

Nevertheless, ongoing monitoring of VCDs is important, as is verification that construction of a VCD has met the design requirements.

5 Testing of VCD Materials

The two most common construction materials used in VCDs are concrete and mining plaster. Concrete has a long history of use in construction and reliable methods for production and quality assurance have been developed over time. Concrete testing as typically carried out in the above ground construction industry is often cited as the model that should be used for testing both concrete and plaster for underground VCD applications.

In practice, there are a number of physical and practical reasons why such testing is impractical. Therefore, alternative methods need to be developed specifically to suit underground mining.

As an example, consider the process of testing concrete above ground on a construction site and compare that with the situation underground.

1. Concrete is sampled on site by a concrete tester
2. The tester is a qualified (ticketed) and experienced technician who uses specialised equipment and follows strict Australian Standard guidelines to sample and slump test the concrete
3. The concrete tester, in accordance with Australian Standards, casts concrete cylinders on site in a very precise manner
4. The cylinders are left on site for 24 hours in a protected location
5. The next day, the cylinders are collected and transported to a testing laboratory, where they are stripped from the moulds and transferred to a curing water bath where the temperature is maintained at a specified value
6. A set number of days after casting, the test cylinders are first checked for defects, then capped to ensure that they fit perfectly straight into the testing machine
7. The testing proceeds and the strength of each cylinder is recorded in a report, which is provided back to the client

On the surface, a concrete tester can easily visit many sites in a day and the following day the test cylinders can easily be collected. Underground movement is much slower and more difficult than on the surface. Transportation of the test cylinders from the mine to a NATA-registered testing facility is also not easy as many mines are located remotely from testing facilities. Concrete cylinders that are damaged in the process before testing cannot be used to provide test results.

The physical characteristics of mining specialised gypsum-based products, such as Aquacrete, present certain challenges that are discussed in the next section.

6 Early Attempts at Site Testing Aquacrete

As Aquacrete is superficially similar to concrete, many mines have requested that the Aquacrete specialised gypsum-based product should be tested in the same way as concrete (refer Section 5 above). A number of methods have been trialed with varying results:

6.1 Coring

The Australian Standards for concrete testing permit the use of cored cylinders of hardened concrete in lieu of cast cylinders. This has the advantage that material in the VCD itself is sampled. Coring underground is difficult however, as the electrically-powered corers used on the surface are not permitted and trials using air-powered, hand-held machines have resulted in poor quality cores. To meet Standard requirements, the cores must have a set height to diameter ratio. Usually, coring a hole through a VCD is not acceptable and the hole needs to be reliably sealed afterwards. Also, the core top and bottom surfaces often need to be sawed off site, to achieve a surface suitable for capping and testing. The difficulties associated with coring means that it is not practical to be used on a regular basis.

Figure 3: Coring samples

6.2 Test Cylinders from Sprayed Material

Aquacrete is sprayed using a dry spray technique. The dry Aquacrete product is blown by compressed air through a hose and mixes with water injected by a hose at the nozzle. The mixed wet material is then sprayed onto a backing as previously described. Attempts have been made to spray Aquacrete directly into cylinders, but that has proved unsuccessful due to the large amount of rebound and relatively small cylinder diameter (100mm).

Trials have also been conducted by spraying the Aquacrete into a pile and then scooping it into the test cylinders. It was found that the material could not be compacted properly in the cylinders due to the product's rapid setting properties, and without proper compaction, cylinder compression strength test results were highly inaccurate.

6.3 Test boxes, Cored

A third method trialed was to spray boxes approximately 600 x 450 x 250mm full of Aquacrete in a location adjacent to the sprayed VCD. In this way, the same material as is being sprayed was being sampled and it proved to be much easier to spray a box rather than a narrow cylinder. However, the issues with coring and timing still remained and getting access back to the VCD site 24 hours later, then taking a heavy awkward box to the surface proved to again be impractical as a regular method.

Figure 4: Coring test box

6.4 Cylinders Sprayed in a Box

The most successful method found so far is a combination of 6.2 and 6.3 above. Disposable plastic cylinders are placed in a box, which is fixed to a rib adjacent to the VCD to be sprayed. The operator then sprays into the cylinder group using the same sweeping motion as for spraying the VCD. The result is that all cylinders are filled together and properly compacted by the spraying action. Aquacrete's rapid setting property means that the cylinders can be transported to the surface at the end of the shift and then immediately transported to a testing laboratory. In practice, the spraying has to be carefully coordinated to ensure that transportation of the cylinders to the test station can occur and that testing is carried out within the specified time limit (typically 48 hours).

The above trials demonstrate the difficulties in applying standard concrete test methods to Aquacrete in particular. This was one of the reasons for developing an alternative testing methodology.

7 Non-Destructive In-situ Testing of VCDs

The problems with site testing as described in Section 6 above required a solution and several non-destructive in-situ tests were considered.

The Schmidt Hammer uses a well-known relationship between surface hardness and concrete strength to test hardened concrete in-situ. The equipment is inexpensive and readily available but there is no current information on a relationship between plaster strength and hardness. The reliance on surface properties and the large inherent variability of the results also made the Schmidt Hammer a less than ideal choice for further investigation.

Ground penetrating radar (GPR) has been used extensively for sub-surface investigations and for some concrete investigations of suspect concrete construction. However, the equipment is very expensive and the results require extensive interpretation due to the very "noisy" signals that natural materials like soils and concrete generate. Those two reasons were sufficient to not further consider GPR.

A third testing technology known as echo impact testing was selected for further evaluation, as trials using self-contained, hand held equipment on other surfaces had previously shown promising results.

Echo impact testing uses sound waves to test a material for integrity and strength properties. It works by striking a surface with a hammer and then measuring the elapsed time for the sound waves to reflect off the far surface. If there are any defects within the material such as voids, the sound waves will not transmit through and the instrument will record the sound waves bouncing off an apparently thinner section.

If the thickness of a section is known, then the speed of sound in the material can be measured. The speed of sound in concrete has been shown to correlate well with compressive strength.

If the speed of sound in a material is known, then the thickness can be directly found by measuring how long echoes take to come back from the far surface.

The echo impact tester as used for testing VCDs is known as the Aquacrete Thickness Gauge (ATG). Using it provides a number of advantages over other test methods:

- Access is only required to one side of a VCD
- No damage occurs to the VCD during testing
- Multiple readings can be easily taken to get a good representation across a VCD
- Results can be uploaded by cable directly into a spreadsheet computer
- Results can be available immediately to assess a pass/fail test for a VCD
- Equipment can be calibrated to either a known thickness for quality testing or a known material for thickness verification
- An accuracy of up to +/-10% is achievable under field conditions
- Portable, self-contained test equipment that can be approved for use in underground coal mines.

Figure 5: Aquacrete Thickness Gauge – Testing Head

8 Calibration and Utility Testing of the ATG

The ATG has been subjected to a thorough testing program to confirm its performance and suitability for use underground.

Initial testing was conducted on 100mm diameter test cylinders that had been cored from Aquacrete test walls of known strength. The speed of sound was recorded across several specimens, based on measurements of the core lengths being between 199 and 203mm. The natural variability of velocities in these carefully sprayed walls was found to be less than 2% in each sample.

The next round of testing was carried out at the Mines Rescue Station in Newcastle, NSW. Several Aquacrete VCDs have previously been sprayed there and these were tested in two ways. Firstly, the thickness was estimated using the ATG and assuming that the material was Aquacrete. These thicknesses were then compared with holes that had been drilled through the VCDs. The results showed that the estimated thickness and the actual thickness were within 10% of each other, which is within the design allowance.

Finally, the ATG was taken into an operating underground coal mine in the Illawarra region and trialed on a number of previously sprayed Aquacrete VCDs. One of these VCDs had depth gauges installed during construction. This allowed both quality testing and verification of thickness testing to be carried out. The test results showed that the thicknesses predicted by the ATG were within 15% of the actual thickness of the VCD.

8.1 ATG Testing Procedure

Using the ATG in an underground mine is quite different to using it in a laboratory or to test a concrete wall on a building site.

The main difference is the requirement for surface preparation to ensure a "clean" signal is generated. This requires a minimum surface approximately 200 x 200mm to be smoothed off prior to using the ATG.

The ATG provides a visual indication of the echo signal shape as well as a "Q-number" to assist with interpretation of the results. The Q-number is a measure of the strength and hence reliability of the primary echo signal. The wave shape shown on the ATG viewing screen can indicate if there are defects or voids within the VCD as well as giving another means of assessing the accuracy of the echo signal.

9 Calibration Results for the ATG

Table 1. Results From Testing Cored Samples

Material	Average Cylinder Height (mm)	Average Velocity (m/s)
Aquacrete OPR2	199	2250
Aquacrete Wet-Repel	203	2550

Table 2. Results from Mines Rescue Station

Location	Material	Tested Thickness	Actual thickness	Ave. Velocity (m/s)
Stopping 1	OPR2	218	200	2200
Stopping 2	OPR2	150	155	2150
Stopping 3	Wet-Repel	216	209	2420

Table 3. Results from Underground Mine Testing

Location	Stopping/Rating	Tested Thickness	Minimum Thickness	Pass/Fail
Site 1 c/t	OPR2/2psi	86	75	Pass
Site 2 c/t	OPR2/2psi	93	75	Pass
Site 3 c/t	OPR2/5psi	162	100	Pass
Site 4 c/t	OPR2/5psi	138	100	Pass

10 Other Applications for the ATG

Although the trials covered in this paper have been conducted to test Aquacrete VCDs, the ATG may also be used to test dams and bulkheads, including those that are already holding water. Some additional testing may first be required to ensure that a suitable signal is received when the far surface is underwater.

VCDs constructed with other materials may also be tested using the ATG, but would be dependent on establishing appropriate calibration curves.

11 Use of the ATG for Acceptance Testing

The ATG will enable a mine manager or ventilation officer to get immediate confirmation of the “health” of a VCD, even if the original construction records are not available and with or without previously installed thickness gauges. The process will be:

. Identify the VCD to be tested
. Assess visually or by scratch test the VCD construction material e.g. concrete or plaster
. Set the ATG to the relevant material velocity
. Test the VCD and read off the VCD thickness

If the thickness meets the original design thickness (within +/-10%) the VCD passes. If it doesn’t pass, further investigation will be required. The ATG should also register a high Q number, say 7 or higher. Consistently low Q numbers can indicate deterioration of the far surface of a VCD.

Alternatively, if the VCD has depth gauges installed, steps 3 and 4 change to:

3. Measure the depth and set the ATG to test that thickness
4. Test the VCD and read off the velocity

If the velocity matches within 10% of the required tabulated velocity, then the VCD passes.

For both types of testing, a minimum of five sets of results, but preferably 10 sets, should be taken so that a statistically significant and therefore relevant result is obtained.

12 Summary and Conclusion

The requirement for on-going quality assurance testing of Ventilation Control Devices in underground coal mines and the practical difficulties in carrying out those tests, has led to the development of a new non-destructive test procedure using echo impact technology. This procedure is faster than current methods and more reliable than alternative non-destructive methods. It can be applied equally well to new or existing VCDs.

The ATG gives mine managers and ventilation officers a means of verifying VCD thicknesses independently of thickness gauges. It also allows the material integrity of a VCD to be checked at any time following the initial installation of the VCD.

13 References

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