Resource Operators Conference

Faculty of Engineering and Information Sciences

2023

The optimisation of ground consolidation practices in longwall mining

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THE OPTIMISATION OF GROUND CONSOLIDATION PRACTICES IN LONGWALL MINING

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ABSTRACT: The Australian longwall mining industry spends millions of dollars per year on both proactive and reactive ground consolidation methods from time to time across most of the underground operations currently in production. The design and effectiveness of the applications and products used are often variable and based on past experience at each site or what was considered successful at other sites in similar situations.

This paper discusses the current product testing data and proposes an industry-standard testing regime that will provide mine site-based geotechnical engineers with a standardised set of data for product selection and geotechnical design.

In addition, the preliminary results of an underground *in situ* testing program designed to provide quantitative data relating to the improvement in rock mass condition as a result of polymeric ground consolidation are presented and discussed. The results provide a measurement of changes in permeability, the material strength of the coal seam, and the migration of the injected material.

INTRODUCTION

Ground consolidation to improve the rock mass conditions has been used for centuries to resolve poor rock and soil mass conditions in civil and mining engineering. But in the narrow context of longwall mining, consolidation methods have been used for at least 60 years. Longwall ground consolidation methods have generally evolved and improved over the years in terms of application systems and materials used, with the improvements often gained by trial and error.

The use of polymeric chemical resins was adopted rapidly in the coal industry across Europe, the USA, and China as a means of sealing water inflows, consolidating weak rock masses, and aiding in the recovery of strata failures in front of powered supports and at the corner of the longwall face and the gate roads. Schaller and Russell (1986) reported on the first application of Polyurethane (PUR) in Australia at Angus Place Colliery in 1986 to aid in the recovery of a large fall of ground on a longwall face.

From the initial and ongoing successful deployment of PUR, several other materials have come into common use, such as Urea Silicates (URS) and Alkaline Phenolic Resins (APR), all of which are marketed and applied by various service providers in Australia as ground consolidation products.

The design and effectiveness of the applications and products used are often variable and based on empirical experience at each mine site or what was considered successful at other sites in similar situations. The ability to apply a scientific and engineering design basis to consolidation programs has been lacking.

The Queensland Coal Mining Board of Enquiry's findings that the explosion event at Grosvenor Mine on 6th May 2020 was likely due to thermal runaway from PUR injection causing spontaneous combustion of coal which in turn led to ignition of methane which caused the explosion. Since these findings were published, there has been a significant focus by the Queensland Coal Inspectorate - Resources Safety & Health Queensland (RSHQ) and industry on the application and design of ground consolidation practices.

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Underground testing of consolidated ground has been proposed as part of the RSHQ's revision of Recognised Standard 16 (RS 16) for quantifying the temperature and migration characteristics of consolidation products. The testing regime has been completed at one mine site in the Bowen Basin and the relevant results are discussed in detail.

The requirements are summarised in the RSHQ Coal Inspectorate Alert No.387 which requires all ground consolidation plans using polymeric chemical application to be designed and authorised by an experienced Registered Professional Engineer of Queensland (RPEQ) qualified Geotechnical Engineer.

As with all geotechnical assessments and RPEQ level designs, there is a minimum requirement for:

1. Data and assumptions on the rock mass and stress conditions.
2. Assumptions on the deformation and failure mechanisms.
3. Assumptions on the design performance requirements.
4. A set of specifications for the ground support products to be used.
5. A defendable design methodology which can be applied to a recommended ground support plan.
6. Methods to assess or quantify the improvement in the rock mass condition gained in the ground that has been treated.

While the understanding of longwall face behaviour, stress changes, rock mass strength, and deformation caused by the mechanics of longwall mining and caving are reasonably understood in normal operations, little work has been done on roof falls on longwall faces. Despite the potential health and safety risks and production risks, and actual monetary cost of the work involved, there are currently no detailed, quantified methods to assess the characteristics of the products used or of the improvement in the rock mass condition gained in the ground that has been treated by consolidation. As such, there is little quantitative or qualitative basis for the geotechnical engineering design and assumptions of what is needed for a successful consolidation program. The lack of research and analysis has resulted in an acceptance of a lack of the application of geotechnical engineering fundamentals in the design of consolidation programs.

In an attempt to address the gaps in the design knowledge base, the Australian Coal Association Research Program (ACARP) has funded a PhD research project titled "The Optimisation of Ground Consolidation Practices in Longwall Coal Mining Applications". This paper presents a portion of the initial research findings for research project C34067.

MATERIAL PROPERTIES

The initial literature review and discussions with various suppliers and industry representatives have confirmed a lack of standardised testing methodologies applied to ground consolidation materials used in longwall mining. The majority of testing has been undertaken to satisfy the NSW Mines Department licencing system and pertains to chemical hazards, exothermic reaction temperature, Fire Retardant Anti-Static (FRAS) properties, and fire and electrical characteristics, as per "MDG 3608 - Non-metallic materials for use in underground coal mines" (NSW Government TIMS, 2012).

There are three main types of polymeric consolidation chemicals commonly used in Australian Longwall operations, these being:

- Polyurethanes (PUR).
- Urea Silicates (URS).
- Alkaline Phenolic Resins (APR).

Bolesta and Ruppel (2001) provide a background to the history of ground stabilisation and the key performance, design, and geotechnical considerations for mining applications. Each chemical has properties that are stated by the suppliers, which they claim can make them more or less applicable to strata consolidation.

It is common sense and generally accepted that the aim of ground consolidation is to improve the rock mass strength by infilling the fractures, providing increased cohesion/friction or mechanical interlock between blocks of strata, and increasing confinement applied to the rock mass.

The limitation of laboratory testing in geomechanics is relating the results to the performance of the rock mass, and this limitation is magnified when considering a consolidated rock mass. The testing methods should be aimed at providing comparable performance criteria which can be related to the expected improvement in rock mass performance.

The geomechanical properties of importance when selecting ground consolidation products to achieve the aims of a consolidation program are:

- Compressive Strength (MPa).
- Modulus of Elasticity (GPa).
- Tensile Strength (MPa).
- Flexural Strength (MPa).
- Shear Strength (MPa).
- Adhesive or Bond Strength (MPa).
- Viscosity (for pumping distance and migration of the product into the fissures).
- Foam Factor (ratio of starting volume to final volume – for economic and pressure of injection reasons).

It is also critical to understand that the properties of the resin products alone do not represent the behaviour of the treated rock mass. Bolesta and Ruppel (2001) provide laboratory data from a synthetic rock mass of shale pieces with a 50% void space, treated with various resin (and grout) products. The data show that the rock mass strength is not dominated by the strength of the injection product, but rather it is limited by the strength of the shale pieces. Essentially the weakest component of the rock mass will control the strength.

A review of the available geomechanical specification data from the various Australian and two American product suppliers was undertaken to compile the data to allow a like-for-like comparison. The data set was gathered from publicly available technical data sheets provided by the supplier companies.

The resultant data in **Tables 1** to **3**, for PUR, URS, and APR respectively has been de-branded and illustrate the range in the stated properties. The data set is highly variable, non-standardised, non-comparable and non-auditable across the different suppliers. In most cases, no standardised testing methodology is recorded, or testing methods and testing time frames are brand specific and non-comparable or there is no data provided at all.

Table 1: Material property specifications for PUR resins

Brand	Resin Type	UCS	Tensile Strength	Adhesive Strength	Flexural Strength	Shear Strength	Viscosity	Foam Factor	Elongation
A	PUR	>69 MPa (ASTM D-1621)	42 MPa (ASTM D-638)	N/A	69 MPa (ASTM D-790)	38 MPa (ASTM-D732)	N/A	N/A	2% (ASTM D-638)
B	PUR	20	45 MPa	>3 MPa	90 MPa	N/A	A 280+/-40 mPas B 210+/-70 mPas	1.0-5.0	N/A
C	PUR	70	30 MPa	>3 MPa	40 MPa	N/A	N/A	1.0-5.0	N/A
D	PUR	8 MPa at 10% deformation	N/A	>2 MPa after 3 hrs	N/A	N/A	N/A	1.5-2.0	N/A
E	PUR	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

For all strata control and geotechnical engineering design, especially where RPEQ or equivalent standards are to be maintained, there is a requirement for factual, credible, and auditable product specification, such as one would see for roof bolts, cable bolts, and the associated resins and grouts. The current industry data set does not provide this level of technical specification.

As such, there is currently no quantitative or even qualitative basis for the engineering design and assumptions for the geotechnical engineering of consolidation programs.

The lack of industry standardisation of specification requirements has resulted in an acceptance of a lack of the application of geotechnical engineering fundamentals in the design of consolidation programs, with a reliance on experience-based guidance for longwall face rock mass consolidation design.

Table 2: Material property specifications for Urea silicate resins

Brand	Resin Type	UCS	Tensile Strength	Adhesive Strength	Flexural Strength	Shear Strength	Viscosity
A	US	47 MPa (ASTM D-695)	15.7 MPa (ASTM D-638)	N/A	28.3 MPa (ASTM D-790)	16.6 MPa (ASTM D-790)	Part A 200 CPS Part B 300 CPS (ASTM D1638)
B	US	30 MPa	N/A	5.8 MPa	24 MPa	N/A	Part A 260 +/-40 mPas Part B 150 +/-30 mPas
C	US	30 MPa (at 50% deformation)	N/A	6 MPa on concrete after 30 mins	14 MPa	N/A	Part A 260 mPas Part B 150 mPas
D	US	40 MPa	N/A	5.5 MPa	18 MPa	25 MPa	N/A
E	US	Approx 34 MPa (Approx 20 MPa after 15 mins;Approx 24 MPa after 30 mins; Approx. 33.7 MPa after 24 hours) (EN12190)	N/A	41 MPa (to dry concrete (ENISO 4624)	Approx 24 MPa after 24 hrs	N/A	Part A 230 CPS Part B 110 CPS (ENISO 3219)
F	US	N/A	N/A	N/A	N/A	N/A	N/A

Table 3: Material property specifications for Phenolic resins

Brand	Resin Type	UCS	Tensile Strength	Adhesive Strength	Flexural Strength	Viscosity	Foam Factor	Elongation
A	APR	N/A	N/A	>1 MPa after 3 hrs (bond strength)	N/A	Part A 100 mPas Part B 250 mPas	N/A	N/A
B	APR	N/A	N/A		N/A		1.0	N/A
C	APR	30 MPa	N/A	7.3 MPa	24 MPa	Part A 260+/- 40 mPas Part B 150+/-30 mPas	1.0-5.0	250 MPa after 7 days

PROPOSED STANDARDISED TESTING METHODS

For a consolidation program to be competently designed it is necessary to have a thorough understanding of the target strata, stress, deformation and failure modes, as well as the operating properties of all the available injection products. Only when this knowledge is at hand, and supported by appropriate product testing, can the geotechnical objectives be achieved.

It is proposed that the industry adopts a set of standardised, commonly available, repeatable, immediately comparable, and auditable geomechanical property testing methods, to provide the geotechnical engineers with a set of baseline data for comparable design. The proposed testing methodologies are described below by the three Australian Standards.

1. Standard UCS Testing as per AS 4133.4.3.2:2013 “Determination of the deformability of rock materials in uniaxial compression - Rock strength less than 50 MPa”. Testing should be conducted at curing stages of 30 minutes, 3 hours, 12 hours, and 48 hours.
2. Indirect tensile strength as per AS 1012.10-2000 “Determination of indirect tensile strength”. Testing should be conducted at curing stages of 30 minutes, 3 hours, 12 hours, and 48 hours.
3. Flexural Strength (modulus of rupture) as per AS 1012.11-2000 “Determination of the modulus of rupture”. Testing should be conducted at curing stages of 30 minutes, 3 hours, 12 hours, and 48 hours.

The intent of the testing at the four curing stages (30 minutes, 3 hours, 12 hours and 48 hours) is to provide mechanical performance curves over the typical design life of a longwall face consolidation program. Where the typical process is to inject and then resume production as fast as possible.

As stated previously, the index testing above is intended not as a direct comparison for the expected rock mass behaviour when treated, but will provide comparable performance criteria which can be related to the expected improvement in rock mass performance.

A fourth novel testing method for assessing bond strength or adhesion is proposed following a review of the available standards, literature, and consideration of the mechanics of the behaviour of the longwall face during mining.

In general terms the rock mass on a longwall face will be experiencing a combination of the following deformation stresses:

- Bending.
- Shearing.
- Compression.
- Tension.

The imposed stresses will act to mobilise existing discontinuities such as cleats and joints, bedding planes, and roof and floor contacts. When the magnitude of stresses is not high enough to cause fracturing, only elastic deformation occurs. When the magnitude of the stresses is such that fracturing and shearing occurs through the intact rock mass, then loss of confinement and failure occurs.

Gale (2005) provides an insight into the failure mechanisms and the use of numerical modelling tools to characterise and understand the dynamic changes occurring on a longwall face. The process describes the transition from an intact rock mass strength to a residual rock mass strength condition. Typically, as each successive shear is taken, a longwall face will be in a dynamic situation where the immediate face will be at or near a residual strength condition, transitioning at some depth into the face to an intact rockmass strength condition. The depth of failure and deformation will be dependent on many factors, such as coal properties, longwall shield performance, roof and floor contacts and strengths, and caving mechanics. An example of the types of failure modes and numerical modelling used for the analysis of the depth of rock mass damage and failure is illustrated in **Figure 1**.

Any bond strength testing needs to replicate the deformation modes the coal face experiences and the injection characteristics, in some manner. A review of ASTM International methods which may be suitable came up with two tests that will provide data on the adhesion properties of the resin product when applied to a standardised material. These methods are:

1. **ASTM D4541-22** “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers”, as depicted in **Figure 2**, commonly used for thin skin liners. This test method is the most widely used procedure used by researchers for testing the adhesion of a thin layer of a material to a substrate due to its ease of application and accuracy of results.

   The coating is applied by pouring over the substrate such that application under pressure cannot be simulated. Tests can be conducted in situ or in a laboratory.

This method is sensitive to the:

- Strength of the substrate material.
- Surface roughness of substrate material.

- Thickness of the layer of product.

This test does not replicate the modes of deformation or failure experienced on a longwall face.

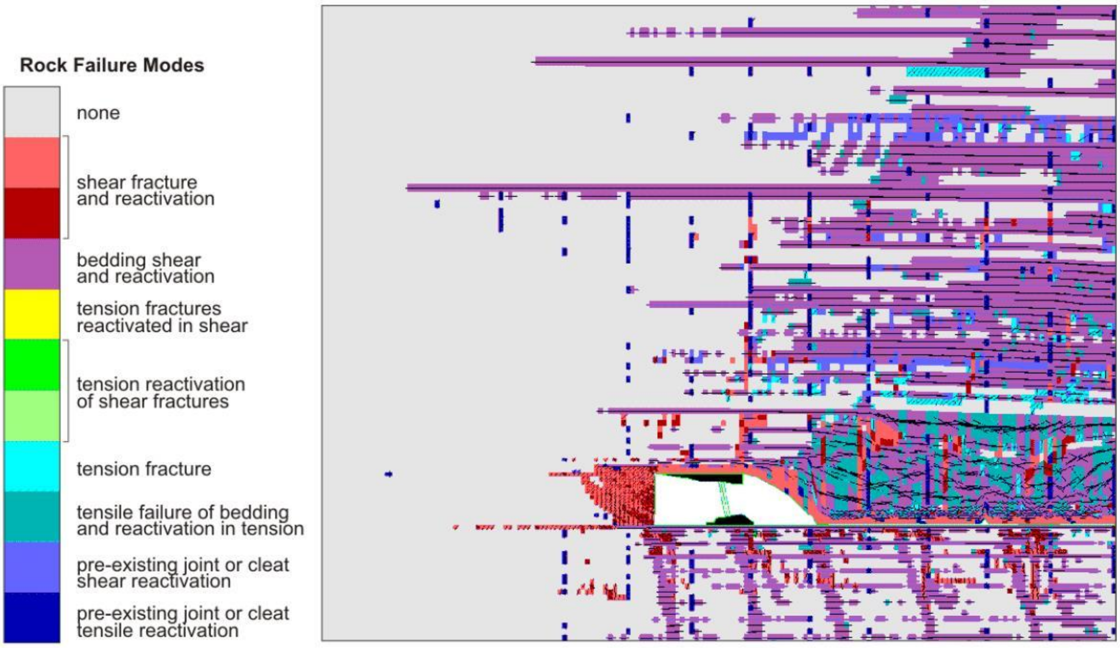


Figure 1: Longwall face failure mechanics and depth of failure characterised by numerical modelling tools (from Gale, 2011)

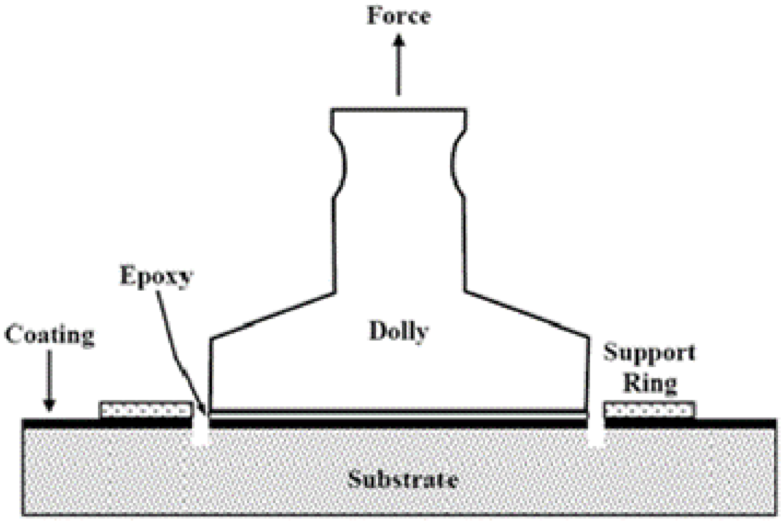


Figure 2: ASTM D4541 glued dolly test method (from Saydam and Decrat 2007)

2. **ASTM C882/C882M-20** “Standard Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete By Slant Shear”. The slant shear test method is a widely employed test procedure to determine the bond strength for the selection of repair material for durable concrete repair. In this test procedure, the repair material is bonded to a substrate mortar specimen on a slant elliptical plane inclined at an angle of 30˚ from vertical. It assumes that the failure of the composite cylinder occurs preferentially on the slanted surface to calculate the bond strength. **Figure 3** depicts a slant shear test.

> This method is designed to test how a repair material will bond to an existing specimen – the aim is to understand what will fail; the new material, the old material, or the bond surface between the two.

This test does replicate the shearing deformation on a longwall face, but not the other modes of deformation or failure experienced.

Figure 3: ASTM C882 Slant Shear Test methodology (from Yates pers com 2022)

Further discussions around the need for a method that better represents the actual failure modes on a longwall face and application pressures of resin products were undertaken with industry representatives and geotechnical engineers. The result was the identification of the “Modified Gap Injection Method” that was developed and used by DMT Germany in the early 2000s (Yates pers comm 2022).

The modified gap injection method uses a standardised engineered material such as grout/concrete pavers of a designed dimension. A gap is created between the blocks at a standard thickness, typically 3 mm. The surface roughness of the gap can be sawn with a concrete saw, or 2 separate moulded blocks, or moulded to a standard representative joint roughness characteristic or range (JRC moulds), as shown in **Figure 4**.

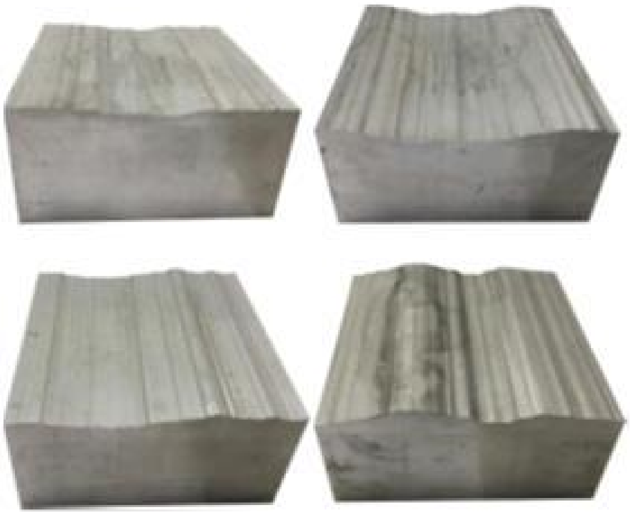


Figure 4: Examples of standardised representative joint roughness characteristic (JRC) moulds

The consolidation product is injected with the standard pumping, hose, and gun equipment, with a flow rate limiter on the inlet side. The resin material is injected at normal injection pressure – 40-60 bar, through a mixer and packer, but at a reduced flow rate due to sample size (not 6-8 m long drill hole) into the specimen – which can be heated to replicate the in situ temperature of a coal seam, and have thermocouples included to record the reaction temperature of the resin.

The testing has a product QA system inbuilt, as samples can be taken through the extraction hose for UCS testing at the same time. Each sample preparation can make three or more test specimens, such that testing at the four curing stages (30 minutes, 3 hours, 12 hours, and 48 hours, respectively) to provide mechanical performance curves over the typical design life can be easily undertaken. Details of the proposed sample preparation and injection rig are shown in **Figure 5**.

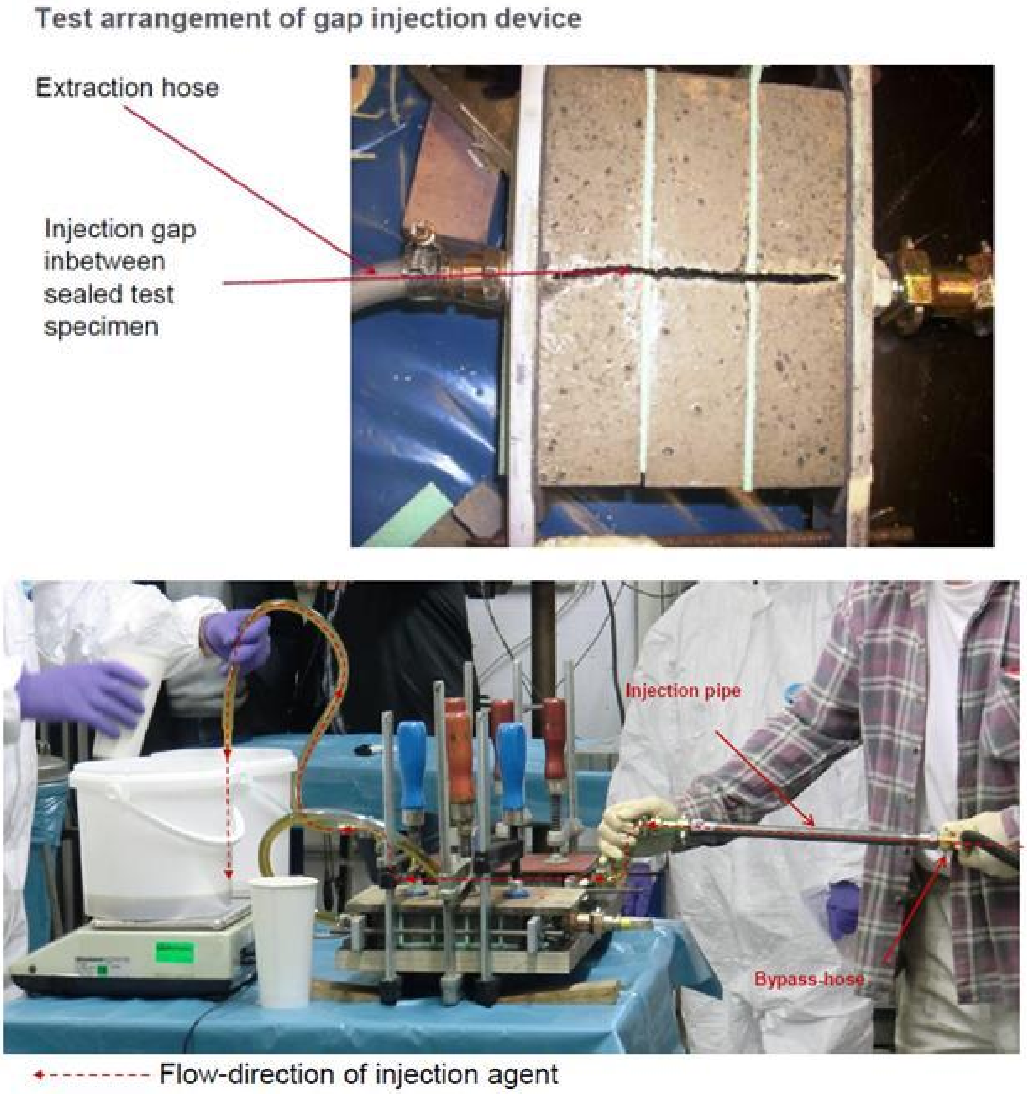


Figure 5: Typical arrangement of the DMT Gap Injection Method sample preparation (from Yates pers comm 2022)

The actual geomechanical test performed on each sample is a simple three-point tensile bending test with parallel measurement of force and displacement, simulating the different stresses that will be imposed underground when weak rock mass or fissures are “glued” together and rock mechanically-stressed due to the mining process in general. **Figure 6** shows the specimen testing equipment.

The test replicates the different stresses that can act on the rock mass:

- Bending.
- Shearing.
- Compression.
- Tension.

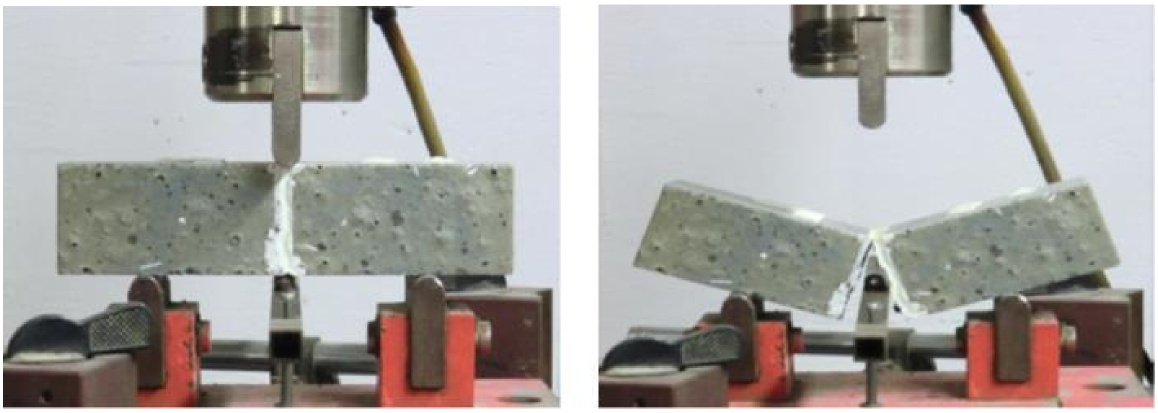


Figure 6: Three-point tensile bending test with parallel measurement of force and displacement.

Using the proposed ASTM International testing methodologies and the DMT Gap Injection Method to quantify the material performance of consolidation products would provide the industry with a set of material properties easily comparable and auditable. The data would also provide the geotechnical engineering practitioners with information that can be used in the design and justification of material selection and design of injection plans.

INITIAL UNDERGROUND IN SITU TESTING

In situ testing and characterisation of the rock mass improvement due to ground consolidation has commenced at one site in the Bowen Basin. This study is part of a wider scope of work that is informing the RSHQ's review of Recognised Standard 16 and the hazards associated with exothermic reaction risks with polymeric chemical injection. The initial results are discussed below.

A review of both civil engineering and mining case studies and practice showed very few methods for evidence-based conformance testing for assessing the actual performance or success of ground consolidation projects. As such, there is no method for assessing the success of consolidation programs.

The design of the experimental rationale was based on an attempt to quantify the effect of ground consolidation on the rock mass conditions, and product migration through the rock mass using standard methods that could be replicated across several mine sites as more testing is undertaken. The aim of this initial work program was to assess the experimental process and to make refinements as required to ensure valuable data could be obtained.

In situ testing methods deployed include:

- Pre- and post-injection Lugeon testing for measurement of the change in coal mass permeability, using the reduction in permeability as a proxy for a change in the rock mass condition.
- Pre- and post-injection coring of the coal seam for geomechanical testing (staged triaxial tests) to quantify the actual change in rock mass strength due to the application of consolidation chemicals. Cores are taken using NMLC triple tube barrels horizontally and at an angle of 15° to bedding.
- Pre- and post-injection borescope inspection of an array of holes to provide a visual inspection of pre- and post-treatment rock mass and migration characteristics away from the injection hole.
- Detailed geotechnical logging of the core to provide a semi-quantitative measure of changes in rock mass conditions post-injection. Rock quality designation (RQD) was used as an index logging method for pre- and post-treatment cores.
- Laboratory testing of suitable recovered core specimens pre- and post-treatment to compare geomechanical properties. Multi-stage triaxial tests were selected to compare intact and residual strength parameters.

- Point load index testing of core samples from cores taken pre- and post-injection to provide data on strength increases that result from resin injection.
- Rock mass temperature monitoring as a means of assessing migration from the injection hole using thermocouple devices installed in an array of holes at distances from the injection point. The temperature increases recorded are a direct measurement of the migration of resin products away from the injection hole.

It is envisaged that improvements would be identified, and some refinements will be warranted based on the results of the first round of in situ testing.

TESTING LOCATION

To date, a single in situ testing site has been completed in a mine in the Bowen Basin. The location was selected to provide a mine site that has experienced longwall abutment stresses and strata deformation but had no known significant geological structures. The mid-pillar, block-side rib of a longwall adjacent to an existing 305 m wide goaf was selected as the test site, as shown in **Figure 7**.

The testing was undertaken using a urea silicate (URS) resin which has a hole volume limit of 298 litres of resin per hole. The test site was required to comply with the ventilation standards and zone of operation exclusion areas as per the product licence.

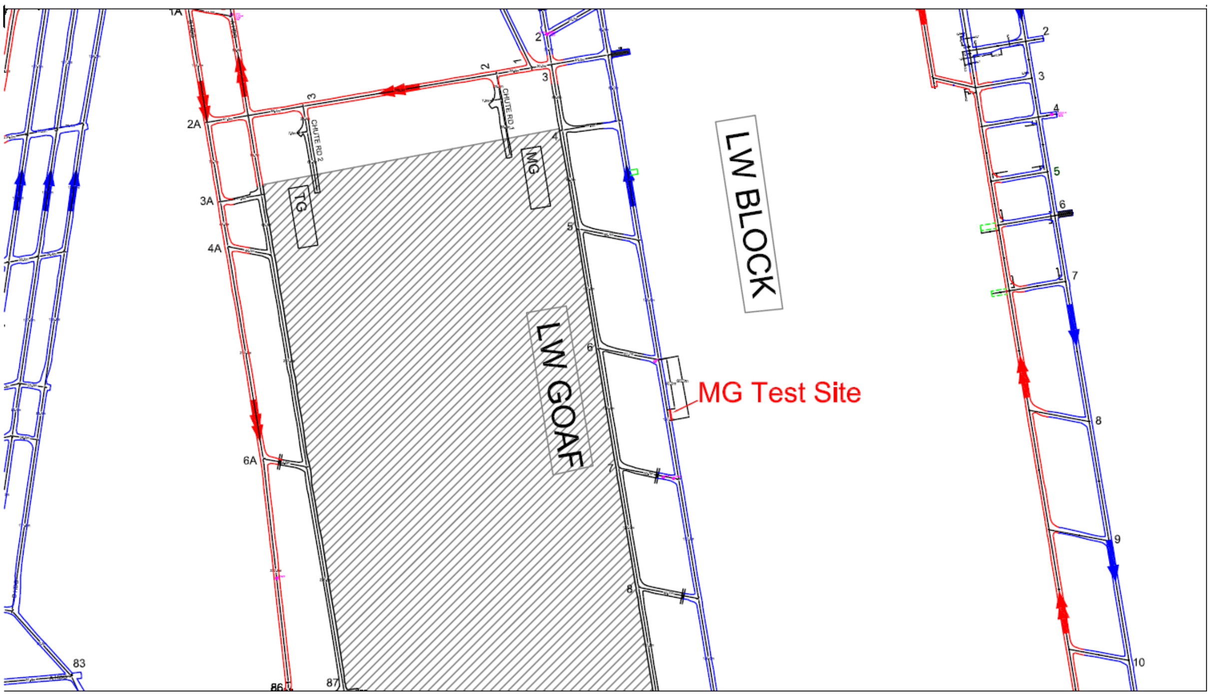


Figure 7: In situ testing site

DETAILS OF THE TESTING PROGRAM

The testing involved the following steps:

- 2 x pre-injection Lugeon tests for rock mass permeability, in two holes; one horizontal and one angled up at 15°.
- 2 x pre-injection coring of 10 m long holes for rock mass condition and laboratory testing in two holes; one horizontal and one angled up at 15°.
- 16 x pre-injection borescope inspection holes to visually inspect the rock mass condition. These holes then had thermocouples installed in them. Thermocouples were installed on dowels at 3 m, 5 m, 7 m, 9 m, and 11 m into each hole.
- All pre-injection holes were then backfilled with thixotropic cement grout at low pressure and allowed to return to the 40° ambient rock mass temperature (monitored by the thermocouples).

- 2 x resin injection holes were drilled to 7 m length, packed as normal with dowels, mixers, and a packer set at 2 m into the collar of the hole. One hole was mid-rib height and horizontal, and the second hole was in the upper rib angled up at 15° towards the seam roof. The two injection holes were located 10 m apart. Thermocouples were attached to the dowels at the packer, and at 3 m, 5 m, and 7 m into the holes.
- The URS resin was pumped as per the standard site and original equipment manufacturer (OEM) procedures, with the volume of product and injection pressures noted. Both holes took full volume and registered low pressures of between 55 and 95 bar.
- The temperature of the product and rock mass was monitored via the thermocouple arrays to measure migration until the temperatures had returned to ambient seam temperature.
- 2 x post-injection Lugeon tests for rock mass permeability in two holes; one horizontal and one angled up at 15°.
- 2 x post-injection coring of 10 m long holes for rock mass condition and laboratory testing in two holes; one horizontal and one angled up at 15°. These holes were located 200-300mm from and drilled parallel to the injection holes.
- 16 x post-inspection borescope inspection holes to visually inspect the rock mass condition and product migration (yet to be completed).

Figure 8 illustrates the site testing work program for the pre- and post-injection investigation work.

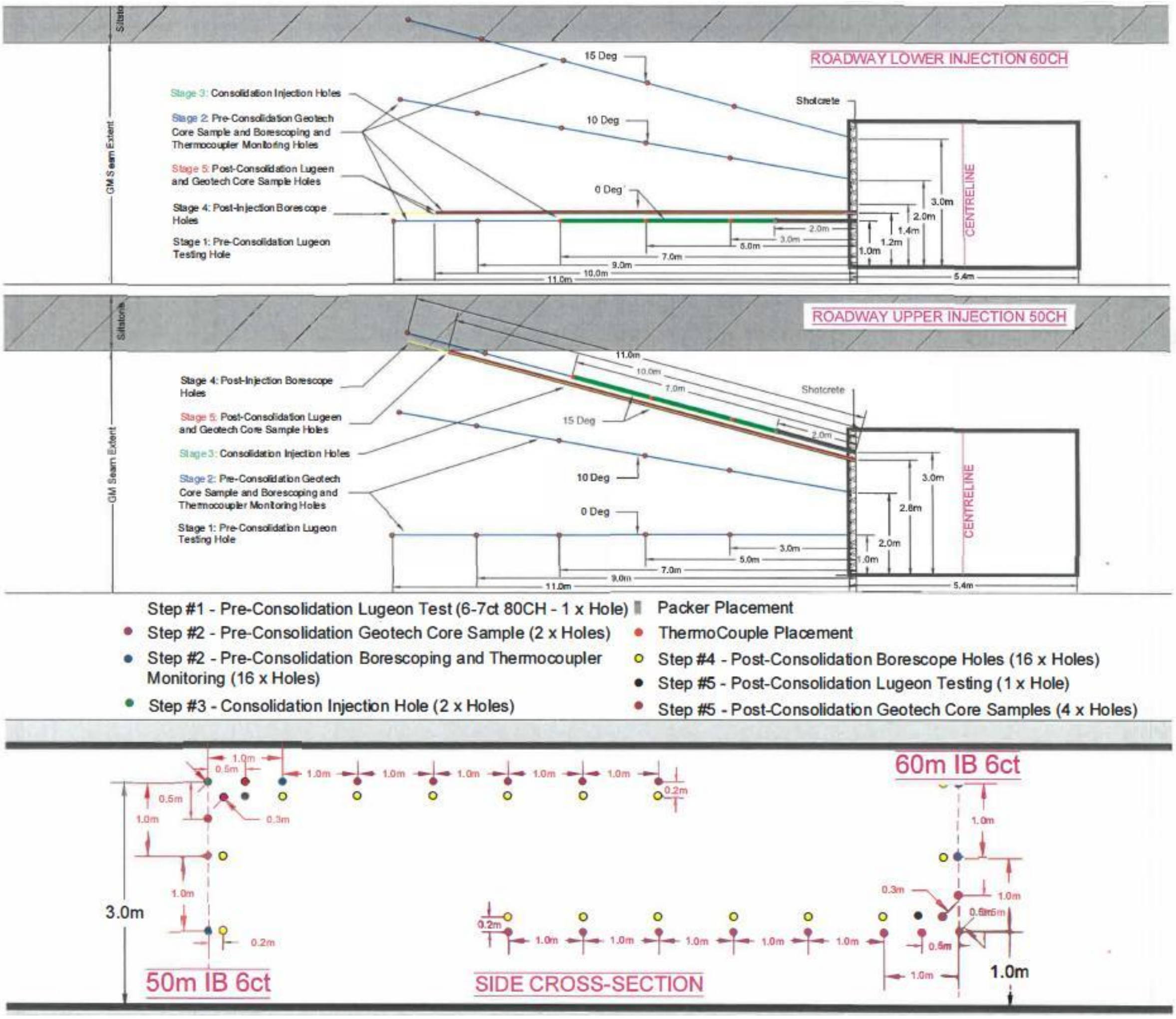


Figure 8: Details of the in-situ testing site investigation work

PRELIMINARY TESTING RESULTS

The testing program showed the collection of relevant data is feasible and the methods used are valid for the collection and quantification of rock mass permeability, geotechnical properties, improvement in rock mass condition, and product migration when a single hole injection volume is used. The details of the findings to date are discussed below.

Temperature Monitoring for Product Migration

The use of thermocouples for temperature monitoring has recorded migration of the URS resin from the injection hole outwards where a single injection hole and a single volume of USR resin are used. **Figure 9** presents the temperature data for thermocouples that detected a change in temperature during the injection of the USR product.

Of the two injection holes tested, the mid-seam horizontal hole recorded the least migration in the array design used (refer to the right-hand side of **Figure 9**) with no monitoring holes below the injection hole.

The migration in the upper angled hole showed the resin moved preferentially down with gravity, as well as radiating outwards with pressure (refer to the left-hand side of **Figure 9**). With resin-related temperature increases measured up to 2 m below and 1 m horizontally away from the injection point.

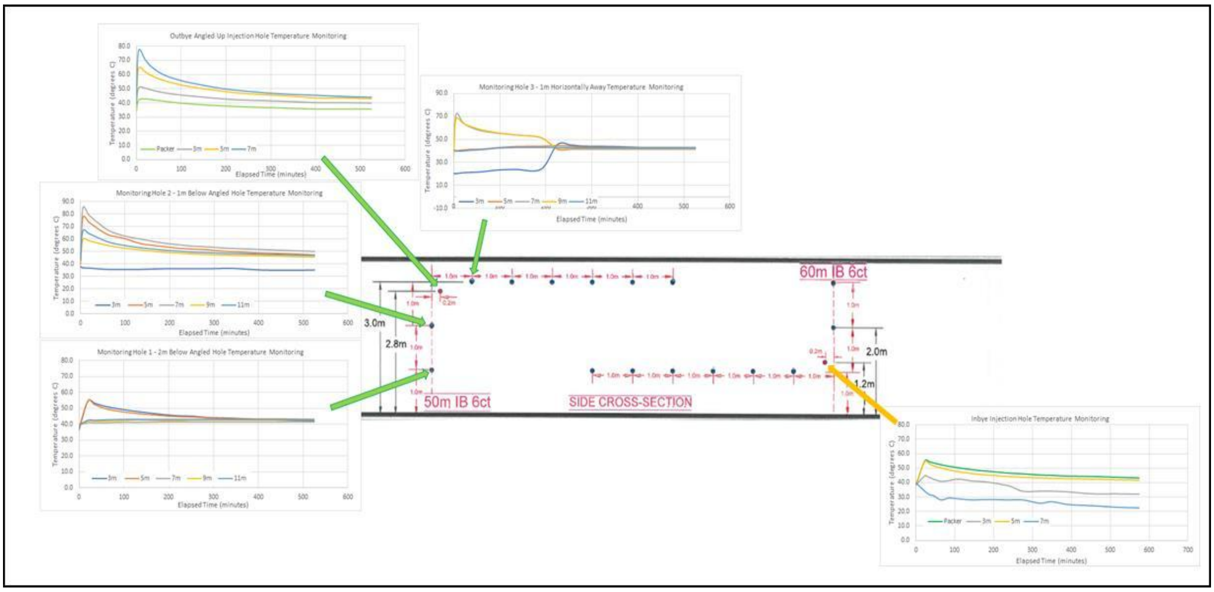


Figure 9: Temperature monitoring and migration results

Geotechnical Logging of Core

Both the pre- and post-injection cores were recovered from the NMLC triple tube barrels underground, wrapped in plastic film, and placed in core trays for transportation, photography, logging, and sampling. During drilling, run lengths and core loss were recorded.

It should be noted that the post-injection core taken parallel to the injection holes suffered from core damage as a result of a malfunction of the core catcher that was not detected by the driller at the time. This resulted in very poor core recovery and crushing of the core. Time and access constraints resulted in not being able to regain access to take additional cores.

All cores and samples were logged as per the requirements of ASTM D6032M-17 “Standard Test Method for Determining Rock Quality Designation (RQD) of Rock Core”.

The defect spacing of the cores ranged from less than 5 mm to 100 mm in both the pre- and post-injection holes, with very little difference between the horizontal or angled holes. RQD values for all cores were between 0 and 10.

The degree of defects is not surprising given the area has been subjected to a single-sided abutment loading at around 400 m depth of cover. Further compounding the defects is the fact that the cores were taken drilling perpendicular to or at 15° to the cleat planes, hence intersecting many more defects than normal vertical cored holes. In addition, all holes had several shear or crushed zones of between 10 mm to 100 mm in thickness at various depths into the rib line. **Figures 10** and **11** show the core recovered from the horizontal and angled holes pre- injection, and **Figures 12** and **13** show the core recovered from the horizontal and angled holes post- injection.

The characterisation of the post-injection cores is inconclusive, although resin can be noted in several defect planes, as shown in **Figures 12** and **13**.

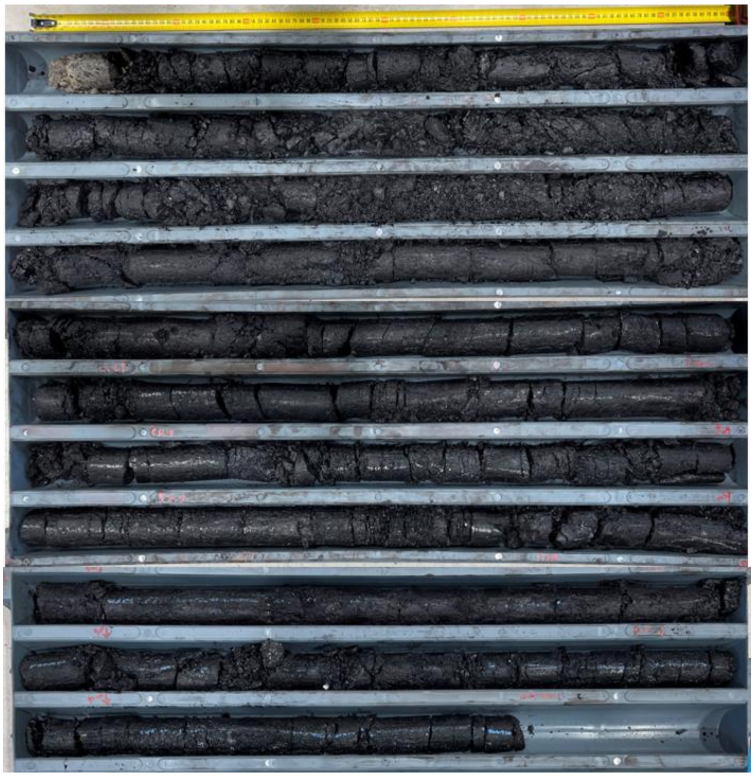


Figure 10: Core recovered from the horizontal hole pre-injection

Figure 11: Core recovered from the angled hole pre-injection

Figure 12: Core recovered from the horizontal hole post injection

Figure 13: Core recovered from the angled hole post injection

Point Load Index Testing

Point load index testing was undertaken on the two sets of coal cores taken pre- and post-injection as a means of assessing any improvement in the coal material properties. ASTM D5731-16 describes the method used for the point load testing and the point load index $Is_{(50)}$ was converted to an equivalent UCS with a conversion factor of 21.

A total of 81 point load index tests (27 axial and 54 diametral) were undertaken on the pre-injection angled core and 66 tests (39 axial and 37 diametral) on the pre-injection horizontal core samples. For post-injecting testing, a total of 53 tests (20 axial and 33 diametral) were undertaken on the angled core and 60 tests (26 axial and 34 diametral) on the horizontal core.

It should be noted that the cores were drilled either horizontally or at an angle of 15° to bedding. As such, the axial cores tended to be parallel or near parallel to bedding, and the diametral tests were parallel to or near parallel to cleating. **Figure 14** illustrates the point load testing for diametric and axial samples.

The data set generated for pre- and post-injection point load UCS equivalent for the angled and horizontal cores is shown in **Figure 15**. The results are inconclusive, predominantly due to the lack of consolidation product noted in the post-injection cores and the damage to the post-injection cores due to the malfunction of the coring equipment.

The data set does indicate that point load index testing may be a valid tool for quantifying any material difference in the coal strength pre- and post-injection, assuming the cores are recovered from a suitable location and sufficient resin is injected to saturate the defects. In addition, point load index tests are rapid, easy to perform, and can be carried out on smaller samples of coal core typically obtained when drilling perpendicular to cleating.

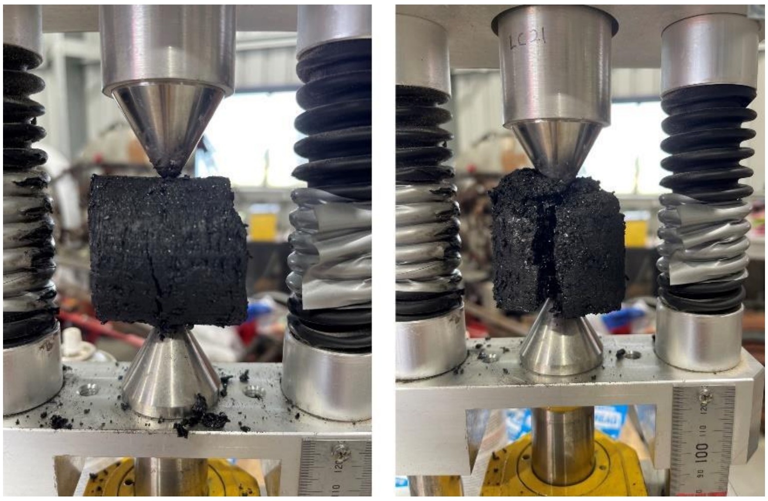
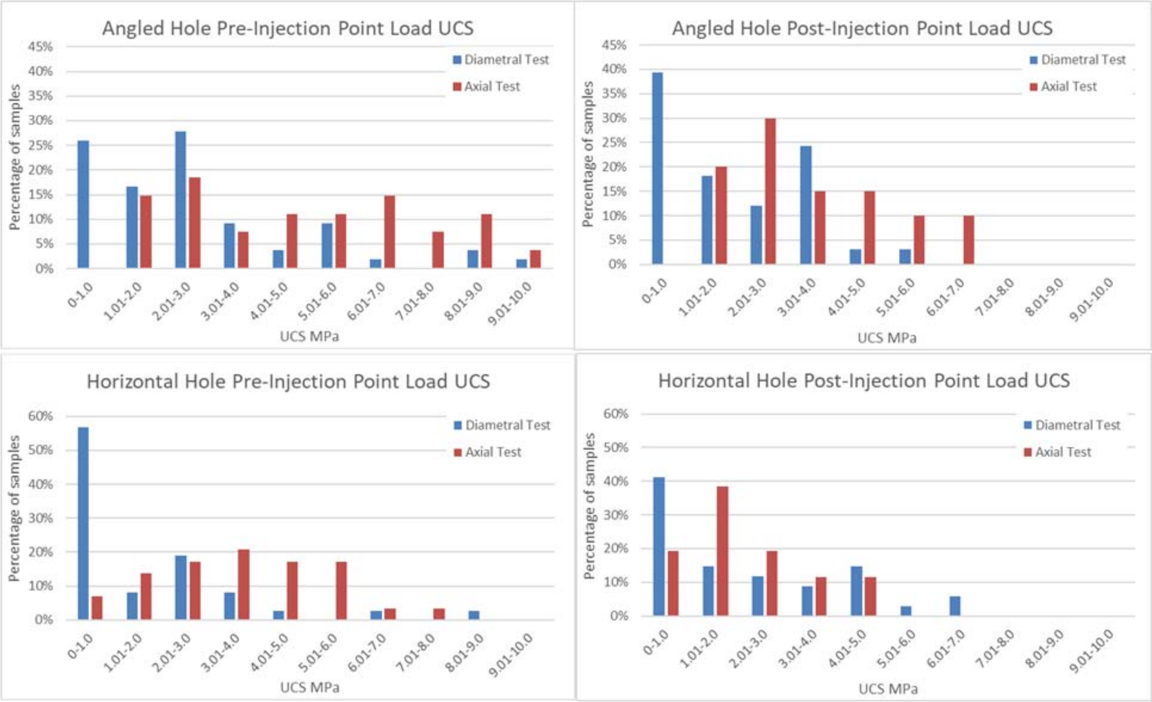


Figure 14: Diametral and axial point load testing of core samples


Angled Hole Pre-Injection Point Load UCS

Angled Hole Post-Injection Point Load UCS

Horizontal Hole Pre-Injection Point Load UCS

Horizontal Hole Post-Injection Point Load UCS

Figure 15: Point load test results for the angled and horizontal cored holes taken pre- and post-resin injection

Laboratory Testing of Core Samples

At the time of publishing, the results for the post-injection triaxial testing results were not available, but visual inspection of the cores shows very little evidence of resin in the cleat or core samples. The apparent lack of visible resin may be due to the low volume of resin injected and the location of the cores relative to the migration paths indicated by the temperature monitoring.

Lugeon Testing

Permeability or hydraulic conductivity are accurately applied to soils or materials which typically contain a regular network of connected pore spaces through which fluid moves uniformly through the soil mass.

Quiñones-Rozo (2010) correctly noted that a rock mass transmits seepage through discrete, but connected discontinuities. As such, it is more accurate to consider that Lugeon test data in a rock material reflects the ability of the intersecting discontinuities in a rock mass to transmit water.

Permeability is used in civil engineering to determine the porosity of a rock mass as a proxy for disturbance. A similar method is sometimes deployed in coal mines to assess the likely success of microfine grout injection for pre-consolidation programmes. The Lugeon test, also known as packer test, was proposed by Lugeon (1933) as a means for providing a standard unit of the transmissivity of rock discontinuities, related to a rock discontinuity condition, as shown in **Table 4**. For details of the test method and limitations, the reader is encouraged to review the original papers by Lugeon (1933) and Quiñones-Rozo (2010).

It should be noted that Lugeon values are strongly affected by the hydraulic aperture of rock fractures and also the effective radius of the borehole surface.

Table 4: Rockmass condition typically associated with Lugeon values after Quiñones-Rozo (2010)

Lugeon Value	Classification	Rock Discontinuity Condition
<1	Very Low	Very Tight
1 - 5	Low	Tight
5 - 15	Moderate	Few Partly Open
15 - 50	Medium	Some Open
50 - 100	High	Many Open
>100	Very High	Open Closely Spaced Voids

Two sets of pre- and post-injection tests have been undertaken on horizontal and angled holes. The results are shown in **Table 5**. In general, the limited results are not conclusive, except to say that the test method is appropriate and can be undertaken in situ in the coal mine with equipment that is readily available.

When the data gathered is reviewed with the migration data from the temperature monitoring, it is noticeable that the position of the horizontal hole post-injection is in a location where it is unlikely that resin-infilling of defects occurred, while the angled hole post-injection test was positioned within the known resin migration zone. Based on this review, it is considered that the method should be continued with reference to the known migration zones of the resin products.

Table 5: Lugeon test results for pre and post-consolidation product injection

Lugeon Test	Lugeon Value
Horizontal Hole Pre-Injection	Maximum 0.66, Average 0.50
Horizontal Hole Post-Injection	Maximum 0.91, Average 0.70
Angled Hole Pre-Injection	Maximum 0.79, Average 0.60
Angled Hole Post Injection	Maximum 0.53, Average 0.41

CONCLUSIONS

In the narrow context of longwall mining strata, consolidation methods have generally evolved and improved over the years in terms of application systems and materials used with improvement as a result of trial and error. The design of the consolidation application and product specification used is variable and based on empirical experience at each mine site or what was considered successful in similar situations.

Despite the potential occupational health and safety and production risks and the actual cost of the work involved, the industry lacks standardised methods to assess the geomechanical characteristics of ground consolidation products. There is little quantitative or qualitative basis for engineering design and assumptions. The lack of standardised testing and research has resulted in an acceptance of a lack of the application geotechnical engineering fundamentals in the design of consolidation programs.

This paper summarises the current geomechanical data set for products available in the USA and Australian longwall industry, highlighting the inability to compare the different products and their specifications. It is proposed that the industry adopts a set of standardised laboratory testing methods to provide geotechnical engineers with the data required for an engineering design and basis for product selection. A novel testing method is also proposed to provide an index test for the adhesion properties that is relevant to longwall face deformation and applied stresses.

Also summarised is an in situ experimental rationale based on an attempt to quantify the effect of ground consolidation on rock mass conditions, as well as product migration through the seam using standard methods. The aim of this initial work program was to assess the experimental process and to make refinements, as required, to ensure valuable data could be obtained, with the testing to be replicated across several mine sites.

The testing to date has shown that the experimental design is applicable and can successfully provide a means of capturing quantified data. The results and data gathered from the initial work provided mixed results, which could be improved by reviewing the positioning of some of the test holes, cored holes, and Lugeon test holes based on the product migration data from the temperature monitoring.

ACKNOWLEDGMENTS

The authors acknowledge the support and resources provided by the industry, both suppliers and mining companies to progress this research project, along with ACARP for the funding of project number C34067, “The Optimisation of Ground Consolidation Practices in Longwall Coal Mining Applications” and an industry PhD research project.

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