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FULL SCALE EXPLOSION TESTING AND DESIGN OF GYPSUM PLASTER VENTILATION SEALS

Verne Mutton[1] and Michael Salu[2]

ABSTRACT: This paper describes recent research to evaluate Gypsum plaster seal designs in the full-scale pressure test facility at Londonderry, NSW. After the Moura Number 2 Mine explosion a review of the safety of coal mine operations resulted in changes to mining legislation where ventilation control devices (VCDs) were required to be tested in an internationally recognised mine testing explosion gallery to achieve over pressure ratings of 14, 35, 70, 140 or 345 kPa. Since this disaster, Minova has live tested all VCD designs to provide validation test data for design purposes. In recent years validation and certification of seal designs has been undertaken by Queensland Registered Professional Engineers (RPEQs) using laboratory measured seal material properties as input to 3-dimensional numerical models. As an engineering material, mining plaster has properties that approximate to those of a low-strength concrete. Unlike concrete, mining plaster gains strength extremely rapidly and this makes it ideal for constructing seals where downtime while waiting for material strength literally costs money. As a result of these properties, Sprayplast UW VCDs can be rapidly brought into service as explosion rated and/or water holding seals and stoppings. Previous full-scale explosion testing carried out in Australia at Testsafe's Londonderry Explosion Gallery (Pearson, 1999) has shown that mining plaster stoppings can resist significant blast pressures.

This paper describes a recent series of full-scale explosion tests carried out at the Londonderry Testing facility in NSW, which were intended to build on experience gained from earlier tests carried out at the Lake Lynn experimental mine in the USA and at Londonderry, NSW in 1999. The testing process and instrumentation layout will be described in which each seal design was subjected to a series of explosions progressively increasing in intensity until seal failure resulted. Two seal designs at 100 and 150 mm nominal thickness were constructed and instrumented to provide time-related overpressure and wall deflection response during the controlled series of explosions in separate test programs. Suppliers worked to develop reliable engineering designs, with results of the testing used to calibrate a numerical engineering model for Sprayplast UW mining plaster that can be used to design seals for overpressures up to the maximum currently legislated in Australia. The model can also be used to design bulkhead thicknesses for water retention. In addition to theoretical analysis, this paper also considers some of the practicalities of seal location, design, construction and maintenance.

INTRODUCTION

After the Moura No 2 Mine explosion in 1994 there were changes to mining legislation in Queensland that required all Ventilation Ccontrol Ddevices (VCDs) to have been tested in an internationally recognised laboratory. Although most VCDs are now designed by registered professional engineers in Queensland, there is a variation in design practises and outcomes with no design methodology common to the coal industry in Australia.

In contrast the coal industry in the United States now has a set of guidelines, the “final rule” for mine seals issued in 2008. This replaced historic requirements set in 1992 where seal design only required a seal to survive a 20-psi test explosion at the National Institute for Occupational Safety and Health (NIOSH) Lake Lynn Experimental Mine (LLEM) without any visible structural damage and within certain leakage bounds. Seal design strength was increased and there are specified new requirements for the engineering and construction of mine seals (MSHA seal reference). New seal designs (Zipf, *et al.*, 2010) must resist a design pressure-time curve, remain elastic to withstand repeat overpressures, have adequate anchorage to the surrounding strata, and consider roof-to-floor convergence.

In Australia there is a variation in both software being used by designers and in their ability to design structures that are subject to transient loads. Characterisation of seal construction materials provides important input for design using Finite Eelement Numerical Methods (FEM). Gyspum plaster products

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used in VCD construction must be "fit for purpose" in the range of conditions they will be subject to over their life.

The Queensland Mines Inspectorate stipulates (Taylor, 2011) now that designs are to be examined using numerical computer models by registered engineers. Parsons Brinckerhoff believes that valid designs with a greater degree of confidence are possible when numerical (FEM) models are calibrated from the results of live seal testing in controlled experimental conditions.

In 1997 at Lake Lynn Experimental Mine, Tecrete Industries (Weiss, *et al.*, 1999) designed an explosion seal and stopping test program in which instrumentation was introduced for the first time to measure the structural response of VCDs when subject to transient loads. Using linear variable transducers, accelerometers and carefully situated overpressure monitoring, live test data was captured that would be useful to enable the design of VCDs in a wide range of roadway sizes and pressures ratings ranging from 14 kPa (2 psi) to 345 kPa (50 psi). With this data numerical models were constructed.

Parsons Brinckerhoff designed a series of explosion tests that would provide 138 kPa (20 psi) and 345 kPa (50 psi) Gypsum plaster seal designs around the testing facility available at Londonderry, NSW.

Thus thinner seals were modelled that could replicate a normal mine sized seal. Nominal thickness seals of 100 and 150 mm were chosen as they were found to provide sufficient data to be able to predict the performance of high pressure rated seals. As per the MSHA requirement it could be seen how the seal designs reacted under multi explosions. Natural gas was used to replicate an explosion in a coal mine as opposed to using high explosive charges or water pressure as in the LLEM hydraulic test facility. The pressures generated in the tunnel gas enclosure subject the VCD to rapid load. Even pressure is experienced across the structure at any given time, making structural response more easily simulated with a FEM model. There is a possibility that acceleration and additional loading of the VCD could occur under rapid loading, which cannot be simulated by applying hydraulic pressure to a seal. Materials when subjected to rapid loads exhibit higher strength capacity over and above their capacity under static loading. Seal displacement data during these tests showed that the pressure across the seals was uniform. Hysteresis (permanent displacement) was measured for each seal design during successive testing.

USE OF GYPSUM BASED PLASTERS IN MINE SEALING

Gypsum based plaster materials have been widely used for dry application spraying of stoppings and seals within Australian coal mines since the mid 1990s and these are intermediate in strength and stiffness between Portland cement based shotcrete and high yield grouts. Gypsum based products can either be manufactured from naturally occurring crystal Gypsum deposits, desert sand or synthetically from industrial processes such as a by product from the lime scrubbing of sulphur from power station flue gases (Germany).

Mitchell (Mitchell, 1971) reports studies in 1968 to develop bulkheads for mines in the United Kingdom and in the Ruhr and Saar districts of Germany. These studies resulted in the Gypsum bulkheads which withstood 1480 kPa (215 psi) and failed at 1790 kPa (260 psi) in explosion trials that developed impulses of up to 100 psi-seconds. At this time Gypsum was preferred by British, Czechoslovakian, and German coal miners who believed it to be the most effective, easiest to use, and least costly seal material. British miners used "Hardstem" and "Hardstop," which are proprietary products made by heating ground Gypsum under controlled conditions, mixed with water and wet pumped in between two form walls.

These materials have fast set times allowing high-speed building. Strength gain is rapid with 70% of the 28 d strength being gained in the first 24 h. Unlike cement based materials, Gypsum based plasters expand on setting. Sprayplast UW used in the explosion tested seals is highly resistant to wet-dry cycles with only 3% water absorption measured in 28 d of submersion. Uniaxial compression tests on six 50 mm diameter x 100 mm length cores (Refer to Figure 1) show the average strength of Sprayplast UW is significantly stronger than Gypsum plaster product live tested by Tecrete Industries (Pearson, 1999).

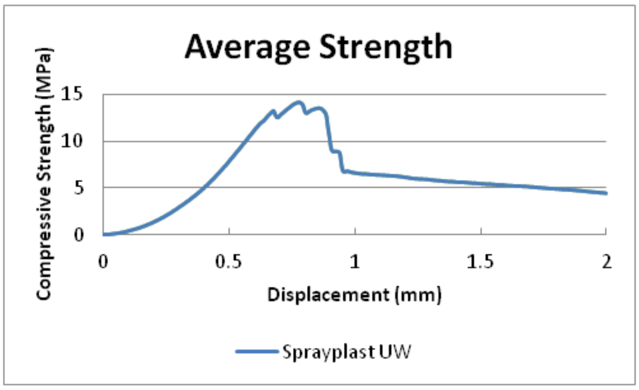

Figure 1 - Compressive strength versus displacement

EXPLOSION TESTING OF SPRAYPLAST UW SEAL DESIGNS

Two designs of ventilation seal were subjected to natural gas-air explosions inside the TestSafe Explosions Gallery to determine their ultimate explosion resistance and measure the structural response of each wall to transient explosion loads. To provide a wide enough range of data for designing 20 psi (138 kPa) and 50 psi (345 kPa) seals firstly a 150 mm nominal thickness wall was constructed and tested and then a 100 mm nominal thickness wall was built.

DESCRIPTION OF SEAL DESIGNS

The seals were erected within a circular 2.7 m diameter tunnel (Gallery) of high strength concrete pipe, about 10 m from the closed end of the Gallery. The Gallery has a flat concrete floor that reduces the maximum available height to 2.4 m. (See Figure 2 for Gallery layout).

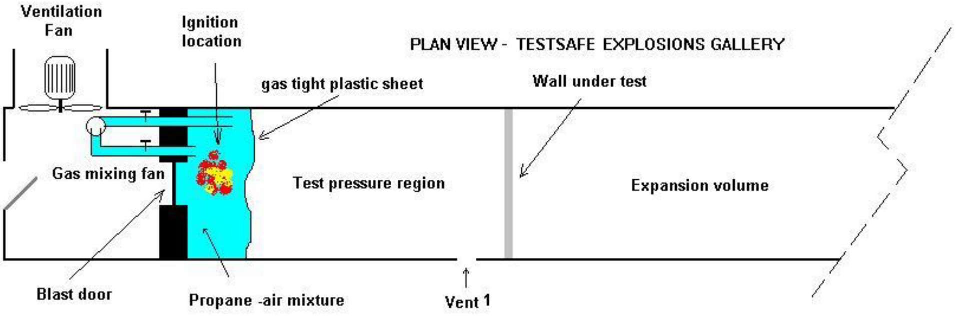

Figure 2 - Schematic plan view of test configuration (Pearson, 2012)

The inner surface of the seal site was prepared by jack hammering so as to provide a rough surface for the grout to adhere to, simulating trimming a normal roadway seal key back to solid material. Three vertical telescopic steel poles were spaced approximately 1000 mm apart (See Figure 4) and were held onto the shell of the Gallery with "Dynabolts". The 1170 mm width sheets of Tecmesh^{TM} were overlapped by 100 mm and attached to the steel telescoping poles using zip ties, forming an in-plane vertical formwork wall. The sheet edges of Tecmesh^{TM} were attached to each other by wire crimps using closing pliers.

Sprayplast UW used for both 100 mm and the 150 mm designs was sprayed onto the backing formwork with a Reed Sova pump using the dry application shotcrete process.

Nine thickness indicators were evenly distributed over the formwork for each seal using 16 mm I.D black pipe with a 40x40x3 mm steel backing plate as a guide to guarantee a minimum sprayed thickness. (See Figure 3).

Prior to testing, both seals were exposed to about 150 mm depth of water at their bases due to leakage into the gallery. Each seal was subjected to explosion pressures incrementally until structural failure occurred.

Figure 3 - Depth indicator attached to Tecmesh sheet formwork

Figure 4 - Formwork for 100 mm seal

MONITORING STRUCTURAL RESPONSE-EQUIPMENT AND METHOD

As in a previous test program at LLEM (Weiss, *et al*., 1999) both seal designs were instrumented to measure response to transient loads in order to provide data for FEM calibration.

Explosion overpressure (Pearson, 2012) was measured using RS type 461-373 pressure transducers. These had a working range of zero to ten bar and an output voltage range of zero to five VDC.

The deflection of the seal under the applied load was also measured using RS - "Miniature linear motion position sensors". These had a range of 38.1 mm and operate on the principle of variable resistance actuated by a spring loaded push rod. These were held rigidly in place on a steel frame which was itself Dyna-bolted to the interior of the gallery (See Figure 5). One sensor was located at the approximate centre of the seal and another approximately half way to the edge from the centre. Data sampling these devices for all except tests 1-3 was at a rate of 1000 scans per second. During each test, time related pressures and seal deflections were recorded at this sample rate.

A portion of the Gallery was partitioned off with a plastic sheet held in place with plastic conduit. The edges of the plastic sheet partition within the Gallery (See Figure 6) were sealed against the inner wall of the Gallery using rapid setting expanding polyurethane foam. Once the blast door was closed and sealed, natural gas was mixed into this volume with a target concentration. Once this concentration was achieved the gas supply and mixing fan were isolated and the explosive gas mixture ignited remotely.

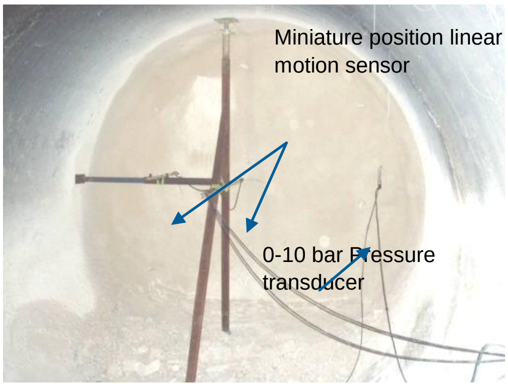

Figure 5 - Layout of instruments for measuring structural response

Figure 6 - Plastic curtain to seal gas volume

The volume of the gas/air mixture was increased incrementally over several tests on order to change the applied explosion overpressure and ultimately cause the seal to fail.

TEST RESULTS

There was no air leakage found through the seals during the test series. No discernible cracks were visible within the body of the seals before final failure. Results of the explosion testing are found in Table 2 (Pearson, 2012).

Table 2 - Explosion test data showing seal pressure and deflection

Test	Seal	Peak Pressure	Initial Side	Peak Side	Final Side	Initial Centre	Peak Centre	Final Centre
Number	Thickness	kPa (gauge)	Position	Deflection	Position	Position	Deflection	Position
5	150	66	0.40	1.20	0.40	0.75	2.35	0.80
6	150	136	0.38	2.05	0.40	0.70	3.85	0.92
7	150	175	0.38	2.55	0.45	0.88	4.85	1.00
8	150	222	0.42	3.54	0.62	1.00	7.20	1.40
10	150	250	0.76	4.50	1.00	1.70	9.40	2.30
11	150	330	0.84	NA	NA	2.10	NA	NA
12	100	50	0.00	1.47	0.05	0.00	2.05	0.06
13	100	160	0.05	6.20	0.70	0.05	9.90	1.15
14	100	214	0.50	NA	NA	0.90	NA	NA

A typical plot is shown for Test 13 of the 100 mm seal design shown in Figure 7 where peak centre deflection is 9.9 mm and final centre position is 1.15 mm indicating a minor amount of permanent deformation.

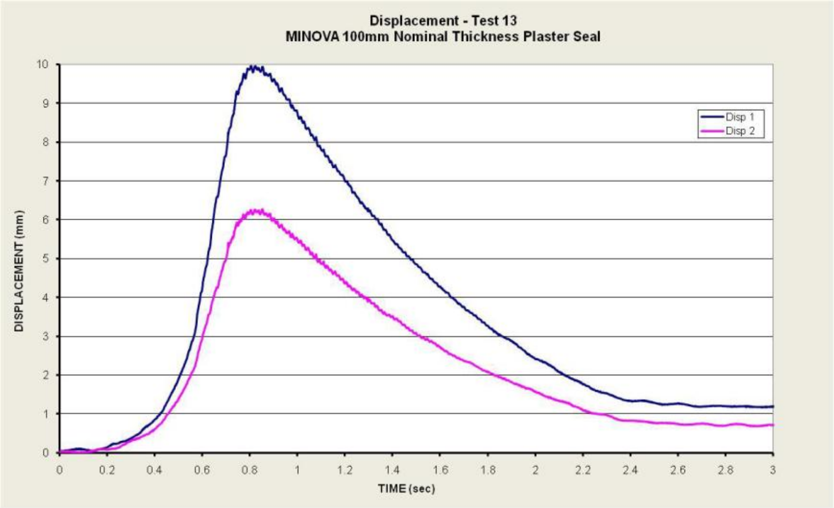

Figure 7 - Seal displacement versus time in Test 13

STRUCTURAL DESIGN ASPECTS OF SEALS

Minova Gypsum plaster stoppings have previously been full-scale blast tested at Londonderry Occupational Safety Centre (Pearson, 1999) at Londonderry, NSW using pressures up to 48 kPa (7 psi). The results from these tests together with a literature review which includes research papers from ACARP indicated that Gypsum plaster is a suitable material for construction of rated seals but unfortunately there is no recognised method for design of these seals from engineering first principles. There are no design standards such as AS3600 (Concrete structures) that give guidance on Gypsum based plasters as a construction material despite the fact that as a cost effective product it is used for low cost dwellings in developing countries of the world.

Extrapolation of low blast pressures and thin stopping thicknesses to provide designs to much higher pressures such as 140 kPa and 345 kPa (20 and 50 psi) is fraught with danger. Large factors of safety (more correctly termed "factors of ignorance") have been applied previously to Gypsum plaster seal designs and the increasing requirement of engineering Certification of stoppings and seals has lead to this Gypsum plaster seal testing program.

To keep the testing as close to typical underground mine conditions as possible within the constraints of the Londonderry testing facility, seal thicknesses of 100 mm and 150 mm were selected. These gave parametric “strength” ratios (height to thickness) of 24 and 16 respectively. Assuming that a 140 kPa plaster seal will be 200 to 300 mm thick and that a 345 kPa plaster seal will be 400 to 500 mm thick and that mine roadway heights can vary from 2.4 m to 4.2 m high, then the expected height to thickness ratios for actual mine seals will be in the range of 10 to 20, which is a reasonably good match.

The Londonderry testing setup, as previously described, was for a circular shape seal so that the maximum blast pressure available could be used for testing. Previous tests at Londonderry have tested rectangular shape seals but the asymmetric test configuration due to structural limitations in the gallery limits the blast pressures to approximately 70 kPa, which would be insufficient for the proposed tests. To convert the test results from circular seals to a useable form for the rectangular seals typical in underground mines, the approach used was to create a 3D computer finite element model of the circular seal and calibrate the material properties to those actually achieve during blast testing. The material properties could then be applied to a model with typical roadway dimension e.g. 3 m high x 6 m wide and a safe thickness determined for any overpressure as required.

One advantage of the Londonderry test and instrumentation setup was that a continuous set of pressure and deflection values were available for each test and these proved to be very interesting when plotted for each test. (Refer to Figure 8)

Only two seals were constructed, but each was subjected to multiple explosions and the results show a number of interesting features:

1. Hysteresis. The seals did not appear to exhibit classical elastic behaviour but instead showed permanent deformation after each test. This incremental permanent deformation was typically 5% of the peak deflection experienced at the centre of the seal during each blast. This possibly indicates a degree of internal damage or fine cracking that was not evident from visual inspection and is a reaction to very rapid loading during each explosion. This can be seen in the pressure-displacement data where the same seal follows different pressure-time curves in successive tests as shown in Figure 8.

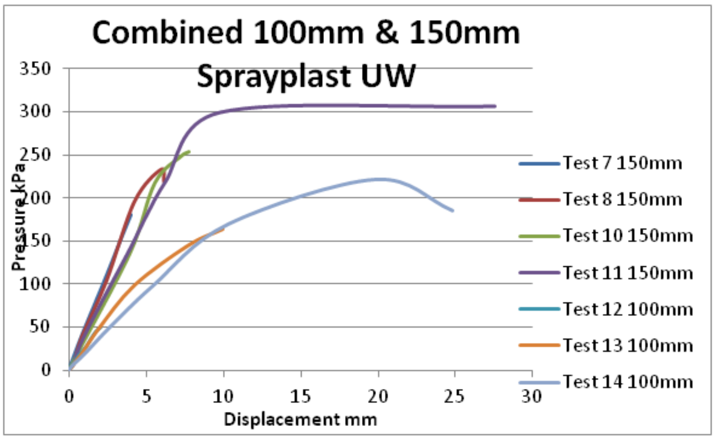

Figure 8 - Pressure versus displacement at seal centre

2. Each successive test at increasing pressure appeared to cause very little more permanent deformation when considering the increased pressure of each blast.
3. The bending mechanism is exhibited in stoppings with low aspect ratios as shown in Figure 9. The material stiffness of the 100/mm thick seal appeared to be less than the material stiffness of the 150/mm thickness seal taking into account the different bending stiffness's, which in this case differ by a factor of 3.4. The difference can be accounted for by the “arching action” of the thicker seal (Refer to Figure 9 for arching mechanism), where a proportion of the load is carried by direct compression through the seal rather than by bending (Parsons, *et al.,* 2000), as illustrated in Figures 8 and 9.

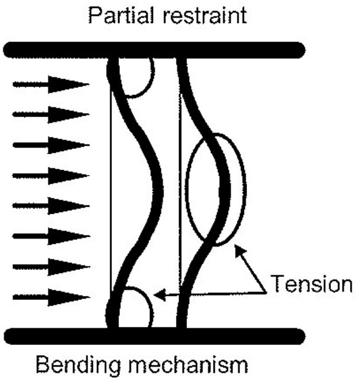

Figure 9 - Bending mechanism

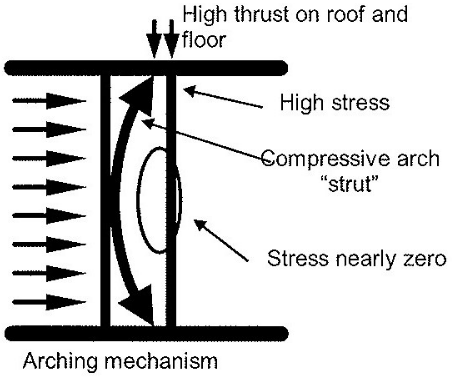

Figure 10 - Seal arching mechanism

(For Figures 9 and 10 refer to Pearson, *et al.*, 2000)

The results of the full-scale testing have allowed the development of a simple design tool for estimating thicknesses for any roadway size and for any design pressure. In order to simulate the seal test results a numerical model of each seal within the 2.7 m diameter Londonderry tunnel was compiled. Figure 11 shows a deflection plot of a seal within the gallery tunnel.

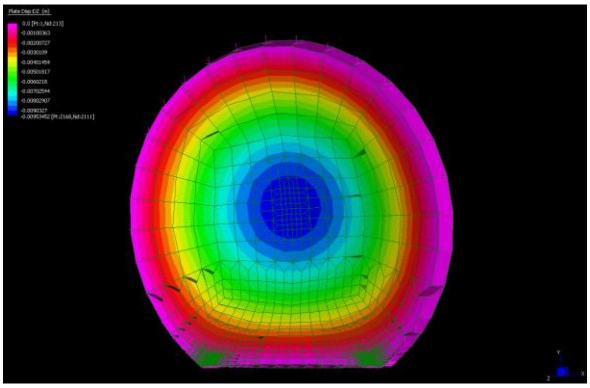

Figure 11 - Peak Londonderry seal deflection during a blast

From the calibration of this model, the designer is able to extrapolate to build a model of 20 and 50 psi explosion rated seals in a range of dimensions typically found within mine roadways. A seal displacement plot for a mine roadway with a rectangular shape is shown in Figure 12.

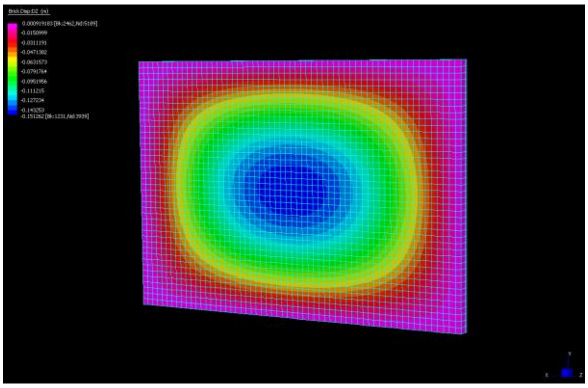

Figure 12- Peak mine seal deflection during a blast

If a mine requests a specific factor of safety to be applied to say a final seal, then this can be accommodated by designing the seal using a blast pressure equal to the design pressure of x factor of safety. For example, final seal design pressure 345 kPa and a factor of safety of three results in a total design pressure of 345 x 3 = 1035 kPa (150 psi).

ASSESSMENT OF DYNAMIC FACTOR APPLICABLE TO FULL-SCALE TESTS

The gas/air mixture used in the testing produced a relatively slow rise-time explosion, when compared with commercial high explosives. This type of explosion closely simulates actual underground coal mine gas explosions and subsequent coal dust explosions. The rise time for the explosions was in the order of 0.8 to 1 s. The natural frequency of the tested seals has been calculated as follows, for their first mode of vibration:

Seal Thickness (mm)	Blast Pressure (kPa)	Pressure Rise Time (ms)	Seal Natural Period (ms)
113	164	750	15
163*	250	1000	13

*Note that this thickness is an estimate, assuming that the 150 mm nominal seal was constructed 13 mm thicker as the 100 mm nominal seal

In both cases, it can be seen that the natural periods of vibration of the seal was substantially shorter than the rise time of the explosions. This means that the seals had time to fully absorb the pressure loading and in effect the pressure experienced was equivalent to a static load. So the pressures experienced during the tests were "actual" pressures and the "dynamic load factor" can be taken as 1.0. For the purposes of structural design, the loads are considered to be "ultimate" loads using terminology from Australian Standards and the design thicknesses derived from these test results are said to have a "safety factor" greater than 1. Using Australian Standard AS1170.0 notation the equation is:

$R^*/S^* > 1.0$

Where R* is the ultimate strength of the seal and S* is the design blast pressure.

Using a calibrated engineering model, the calculated seal thickness can sometimes be quite thin for low roadway heights. In such cases, it is recommended that minimum seal thicknesses should apply and that any design methodology should have such safety considerations included.

For example, for 140 kPa seals a recommended minimum thickness is 300/mm for all but the lowest heights and for 345 kPa, 450 mm is recommended. These minimum thicknesses provide a degree of robustness to the seals, which enables them to withstand accidental vehicle impacts and even unforeseen water pressure.

Seal thickness and type can be governed by the need to satisfy the requirement to provide an effective barrier after the effects of roadway convergence and an increased leakage path length.

Using the results from modelling of the seal explosion tests it has been possible to reduce a 20 psi explosion rated seal thickness from 450 mm to 300 mm in roadways heights up to 3.6 m within a 6 m maximum width mine roadway.

Another application for Gypsum plaster seals is as water-retaining bulkheads. The gypsum is typically blended with cement and other additives to make it water resistant but without losing its rapid-setting qualities. Tests have shown that this product will only absorb ≈ 3% moisture and it does not shrink during its period of strength gain. With the full-scale testing results now available, Gypsum plaster seals can confidently be designed to retain high heads of water of 30 m (equivalent to 300 kPa pressure) or more. With bulkheads and other water retaining structures such as dams, the type of load on the structure is quite different from a blast load. Water pressure is a continuous pressure that may last for the life of the mine and over time it may soften the strata surrounding the bulkhead and compromise its safety. To account for the long-term loading effects of water, it is recommended that a minimum factor of safety of two should be applied to water retaining bulkheads and some mines currently require factors of safety of up to four for combined explosion rated seals/bulkheads.

When considering the factors affecting the structural integrity of a ventilation control device such as a seal or stopping or a water control device such as a bulkhead, it is important to understand that engineering design of the device itself is only one link in a chain of requirements. Every one of those requirements is equally important because just as the weakest link determines the strength of a chain then a deficiency in any of the six factors outlined below will lead to a loss of structural strength of the seal. Particularly due to the erosion and strata softening potential of water, it is recommended that a program of pre and post injection be carried out at bulkhead sites that will be subject to ten or more metres of water head:

1. Geology. The device must be located in a region of sound material. More specifically, it should not be located in a weak or heavily faulted zone. Bulkheads should be located where the surrounding strata will be able to withstand the expected water head without piping (loss of material from the strata) or infiltration past the device.
2. Site and preparation. The device must be located away from intersections for a sufficient distance the strength is not compromise. All soft, loose, crumbly and otherwise unsuitable material must be removed to provide a sound base all around the device. For bulkheads, this generally includes cutting a "keyway" into the roof, ribs and floor to provide additional security and water sealing.
3. Design: The device must be designed by a competent engineer, experienced in design of VCDs and bulkheads and using proven methodologies. A signed design certificate should clearly state the design parameters adopted.
4. Materials: The materials used must be of the highest quality and suitable for the task. Records such as batch numbers must be provided with each consignment to provide full traceability in the event that defective material is discovered at a future time.
5. Construction: The device must be constructed strictly in accordance with the Engineering Certification and any drawings, specifications or construction notes should be provided by the designer and the material supplier. The most common construction defect of sprayed plaster devices is insufficient thickness. Depth gauges must be used to confirm the sprayed thickness and a sufficient quantity of product must be on hand before construction commences to complete the device, to provide another means of checking that the required thickness has been achieved.
6. Maintenance: Sometimes overlooked, a mine manager and ventilation officer has an on-going obligation to regularly inspect all ventilation control devices and bulkheads to ensure that they are continuing to perform as expected. Issues such as convergence, accidental damage and latent defects in the seal or strata can cause major problems if they are not picked up early.

CONCLUSIONS

The 100 mm seal that withstood a 160 kPa explosion, was destroyed during a 214 kPa explosion. The 150 mm seal withstanding a 250 kPa explosion, was destroyed during a 330 kPa explosion.

Tests have shown that Sprayplast UW seals will withstand scaled explosions within the pressure range required by Australian coal mine legislation. This explosion test program adds to a series of programs in which seals and stoppings since 1991 have been designed from the results of live explosion testing.

There is no accepted or universal guideline within Australia to assist registered professional engineers in the design of VCDs for the underground coal industry. However he "final rule" developed by MSHA provides thorough guidance.

Instrumentation showed that the seal response provided under explosion loading behaved in accordance with commonly accepted structural theories. Results from testing were consistent with the Tecrete results of 1999 testing of Gypsum based plaster stoppings. A computer model which can to be used to design seal thickness for a variety of roadway geometries and design overpressures based on results of live testing has been developed. Seal designs provided by numerical analysis have to be correctly sited, constructed and maintained in order to ensure their long-term effectiveness.

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