EVALUATION OF NEW METHODS AND FACILITIES TO TEST EXPLOSION RESISTANT SEALS

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ABSTRACT

The Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) has conducted full-scale explosion experiments to evaluate the strength characteristics of several seal designs for isolating worked out areas in underground coal mines. The PRL is currently pursuing the development of improved seal evaluation methods and facilities based on pneumatic and hydrostatic testing that would lend themselves to in-situ seal testing in an operating mine. Two chambers were constructed and instrumented within PRL's Lake Lynn Experimental Mine (LLEM) for the evaluation of seals. Two solid-concrete-block seals, 13.5 and 40.3 square meter cross-section and 406 mm thick with a central pilaster, were constructed in both the small and large chambers and tested to failure with a series of methane explosions producing loading pressures ranging from 386 to 688 kPa.

A preliminary size-scaling relationship is presented for estimating the ultimate strength of masonry block seals built with rib and floor hitching. Testing seal designs in the chambers shows promise as an alterative evaluation method to that of full-scale explosion testing within the LLEM.

INTRODUCTION

Since 1993, seven documented explosions of methane and/or coal dust occurred within sealed areas of underground U.S. coal mines. These explosions, believed to be initiated by lighting strikes on the surface, destroyed numerous seals and caused considerable damage in the active areas of the mines. Fortunately, these explosions did not cause fatalities or injuries. One explosion that shows strong evidence of being caused by lightning occurred at the Mary Lee No. 1 mine in Alabama on August 22, 1993 (Hurren et al., 1993). From all indications, the explosion occurred at 4:40 pm. At the same time, the National Lightning Detection Network (NLDN) observed a 21.7 kA lightning flash in the vicinity of a fan shaft that vented the area where the explosion occurred. Subsequent investigations at the fan shaft indicated electrification of the 4.5 m high metal vent pipe extending from the concrete shaft cap; this cap was destroyed during the explosion.

Three explosions occurred in the gob at the Oak Grove Mine, Alabama (Scott et al., 1996). In each instance, severe thunderstorms and lightning occurred above the sealed gob. With each of these events, the NLDN documented scores of lightning flashes within the vicinity of a 114 mm diameter steel cased hydro-geological test hole connecting a surface pumping station to the gob. Several 1.2 m thick pumpable cementitious seals were destroyed, including one that was rebuilt after a previous gob explosion. Analysis of the fractured seal material showed compressive strengths less than that required by the Mine Safety and Health Administration (MSHA), except the rebuilt seal which was stronger than required. These gob explosions, initiated by lightning, forcefully demonstrate the need for adequate seals and sealing procedures to protect mine workers against explosions.

Title 30, Part 75.335 of the Code of Federal Regulations (CFR) (1995) states that abandoned areas of a mine must be either ventilated or isolated from active workings through the use of seals capable of withstanding a static horizontal pressure rise of 20 psi (138 kPa). Seals are also used to isolate fire zones or areas susceptible to spontaneous combustion. To effectively isolate areas within a mine, a seal should be designed to control the methane and air exchange between the sealed and open areas so as to prevent toxic and/or flammable gases from entering the active workings. A seal must be capable of preventing an explosion from propagating into or out of the sealed area. Early U.S. Bureau of Mines (USBM) research indicated that it would be unlikely for overpressures exceeding 138 kPa to occur very far from the explosion origin, provided that the area on either side of the seal contained sufficient incombustible and minimal coal dust accumulations (Mitchell, 1971). Pressure balancing across the seals plays a key role in seal deployment strategies by minimizing the exchange of gases and limiting the resulting volume of flammable gas in the gob.

In the early 1930's, the USBM conducted a series of tests and found that restraining the edges of a seal caused a dramatic increase in the seal strength to a much higher level than predicted by plate theory (Rice et al., 1930, 1931). Full-scale explosion experiments also showed concrete walls that were recessed into the roof, ribs and floor, and had a thickness to width ratio of at least 0.1, resisted much higher pressures than the theoretical design pressure. These results showed that recessing the ends of the concrete wall into the surrounding strata allows the wall to act as a flat arch. This arching behavior transmits a lateral thrust to the strata, which then acts as a buttress to prevent seal movement. Several efforts have been made to explain the arching behavior through various static design models. However, blast analysis of masonry and concrete structural elements has traditionally been more of an art than a science. It has been difficult estimating structural loads due to detonations and deflagrations and predicting load deformation behavior, especially for masonry walls. Early U.S. research on the response of walls to blast loads was conducted during World War II by the National Defense Committee (1946) and then later refined methods were developed to consider the load-time history and structural parameters such as material strengths and support conditions. The Department of Army, Navy, and Air Force published an important document entitled "Structures to Resist the Effects of Accidental Explosions," TM 5-1300, (1990) which is useful for predicting the ultimate strength of masonry and concrete walls. As a continuation of this work, the U.S. Army Research and Development Center, (Slawson, 1995) developed a single degree of freedom (SDOF) computer code referred to as the Wall Analysis Code (WAC). This code, which is discussed later in the paper, was used to examine the response of solid block masonry seals exposed to pressures produced from the combustion of pre-mixed methane-air concentrations.

Many countries, including the U.S., Australia, France, Germany, Poland, and China, have pursued research for developing and evaluating explosion-resistant structures for sealing sections of underground mines. Since the early 1990's, the PRL and MSHA have been jointly investigating the ability of various existing and new seal designs to meet or exceed the requirements of the CFR. Before any new seal can be deemed suitable by MSHA for use in underground coal mines, the seal design is generally required to undergo full-scale performance testing at PRL's LLEM (Triebsch and Sapko, 1990). A long-term seal research program conducted at the LLEM has resulted in the development of revised standards under CFR Title 30, Part 75 and the subsequent development of many new alternative, innovative seal designs that are now being used within the U.S. mining industry (Weiss et al., 1996).

Evaluating seals by full-scale mine explosion testing makes it difficult to determine the precise conditions for seal failure and, although not required by CFR Title 30, difficult to obtain the strength safety factor for the seal. As a alternative method to the full-scale mine explosion evaluations in the coal mine sized entries of the LLEM, NIOSH constructed two test chambers within a seldom used area of the original, high-roof workings of the LLEM. These chambers will allow for the evaluation of seal designs against static pressure loadings and will allow for the development of geometric size-scaling guidelines for use when installing seals in mine entries in excess of 2.4 m high and/or 6.1 m wide. This paper provides a brief overview of the ongoing study to evaluate the use of these chambers for pressure loading of full-scale seal designs using compressed air, water, or internal gas explosions.

TEST CHAMBERS

In 1998, PRL (Sapko et al., 1999) constructed two large-scale underground chambers within the original workings of the LLEM to conduct pneumatic, hydrostatic, or explosion pressure loading of candidate seals. Figure 1 is a schematic of the large chamber. The chamber dimensions are 9.1 m wide by 4.6 m high by 3.1 m deep with a maximum cross sectional area of 42 m^2. The smaller of the two chambers is 6.1 m wide by 2.4 m high by 3.1 m deep and can accommodate a seal design with a cross sectional area up to 15 m^2. This smaller chamber is similar in cross sectional area to the crosscuts in the multiple entry section of the LLEM where the seal designs have traditionally been evaluated using the full-scale methane and/or coal dust explosions.

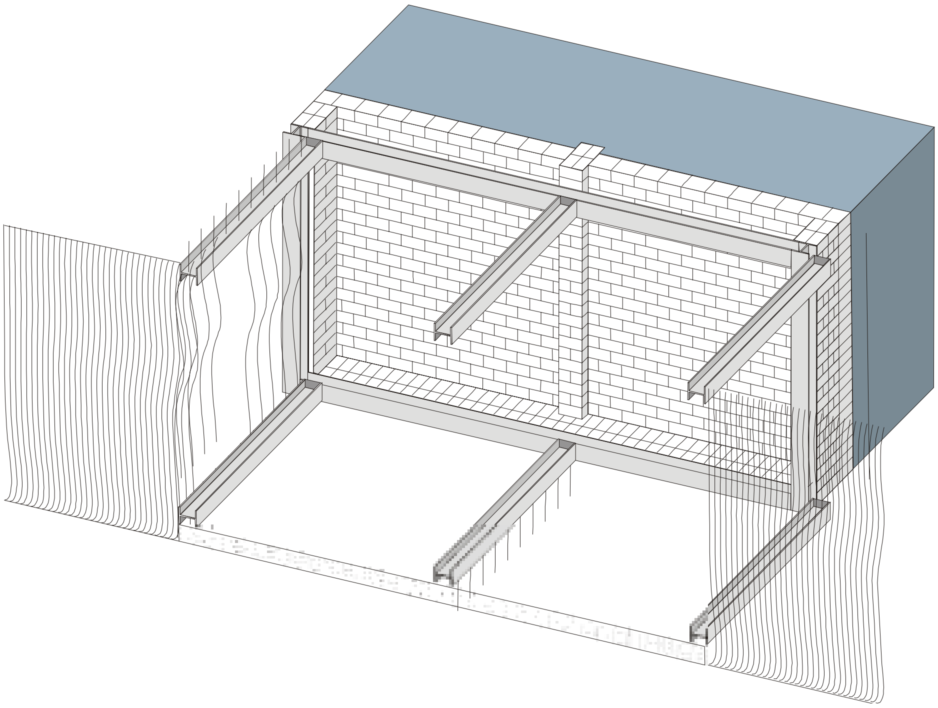

Figure 1. Large test chamber for pressure loading of seals with water, compressed air, and with the combustion of confined concentrations of methane-air

Both chambers are connected via remote controlled air valves to two diesel driven air compressors which provide 28 m^3/min (1000 cfm) of air. The air compressors were used to conduct the pre- and post-explosion leakage measurements. The seal is pressurized to about 12.7 cm of water and then as the air leaks out the pressure decay is recorded. The rate of pressure decay is then converted to an average volumetric flow rate. Parallel leakage tests were conducted to compare the pressure decay method with the conventional steady state method used during the multiple entry seal evaluations. The conventional method involved measuring, with an anemometer, the air that passes through the seal and a 0.1 m^2 opening in a nearly air-tight brattice curtain installed between the seal and the anemometer while maintaining a constant differential pressure across the seal. The two leakage methods compared favorably. The air compressors were also used to slowly pressure load the seal up to 140 kPa depending on the leakage rates through the seal.

Internal explosions of methane-air were used to characterize the ultimate failure strength of the seal. To achieve these methane-air ignitions, each chamber is equipped with methane and oxygen injection systems. The oxygen and methane are supplied by compressed gas cylinders. A pre-determined amount of methane is metered into the chamber behind the seal and thoroughly mixed with air using an explosion-proof fan located within the sealed area of the chamber. The fan generates an air flow within this area of 85 m^3/min. Uniformity of pre-test gas concentrations were determined by drawing gas through tubing and into an on-line infrared methane analyzer and a para magnetic oxygen analyzer. Samples were also collected in evacuated glass tubes for subsequent analysis by gas chromatography. The flammable gas mixture was ignited at the center of the combustible volume by a 0.5 s electrical discharge from a 30 kv luminous tube transformer across a 3.2 mm spark plug gap.

The two chambers are equipped with internal 0-1.4 MPa (0-200 psia) strain gage pressure transducers (1000 Hz) for measuring the internal explosion pressure history. Three spring-loaded linear variable displacement transducers (LVDT) were mounted around a 90° bend outside the chamber exit and connected to the test seal via lightweight nylon line. This mounting system protected the LVDTs from any projectiles that might occur. One LVDT was connected at the exact center (mid-height and mid-width) of the seal. A second LVDT was connected at a 1/4-height and mid-width point. A third LVDT was connected at the 3/4-height and mid-width point. As the seal is pressure loaded, the seal displaces outward and the LVDTs measure this displacement by generating an output signal of ~68 mv/mm. Data was recorded at 2000 samples/s per channel with a WINDAQ PC-based data acquisition system (DAS).

CHAMBER PNEUMATIC TESTS

The standard-type solid-concrete-block seal design was chosen for the initial evaluation since this design was extensively evaluated for several years in the PRL's Bruceton Experimental Mine (BEM) and in the LLEM. This standard-type seal was used to form the basis for the current CFR Title 30, Part 75.335. Of the solid-concrete-block seals tested in the experimental mines, only the standard-type 406-mm-thick seal with staggered and fully mortared joints, a center pilaster, floor and rib keying, and wedged at the roof successfully withstood the required pressure pulse. Figure 2 is a schematic of the standard-type solid-concrete-block seal. This same seal design was installed in both the small and large chambers. Seal keying in the chambers was accomplished by butting the seal against two 0.4 by 0.8 m solid-concrete-block rib support columns;

these columns were positioned to contact the 0.3 m wide steel H beams. Solid-concrete-blocks and mortar were placed between the base of the seal and the steel beam to simulate simple floor keying by buttressing the seal against the steel. Both sides of each seal were coated with a waterproofing sealant to help minimize air leakage. Each seal was allowed to cure for 28 days before testing. Before and after each seal test, the air-leakage across the seal was measured. Each seal was initially pressure loaded through the use of the twin air compressors. The air pressure behind the seal increased from 0 to 144 kPa (0-20.9 psig) in 290 s and then decayed to 14 kPa (2 psig) approximately 600 s after the air supply was discontinued, as shown in figure 3. Due to excessive air leakage at the higher pressures and limited compressor capacity, the maximum pressure obtained behind the seal in the large chamber was 76 kPa (11 psi). For comparison, figure 3 also shows the explosion pressure history measured at the standard-type seal constructed within a crosscut in the multiple entry section of the mine. The methane explosion in the open-ended drift produces a much more rapid dynamic loading of the seal. The seal's initial resistance to failure during the multiple entry explosion is primarily governed by the reaction of the seal's inertial mass to rapid pressure loading whereas, the resistance to failure from the long term pressure loading is primarily controlled by the strength properties of the seal.

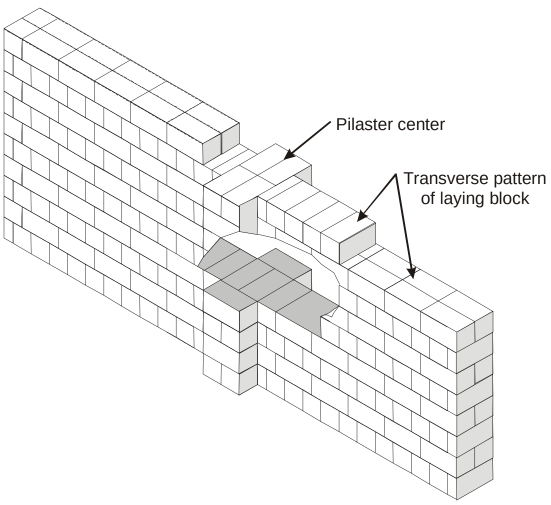

Figure 2. Standard-type solid-concrete-block seal design with center pilaster

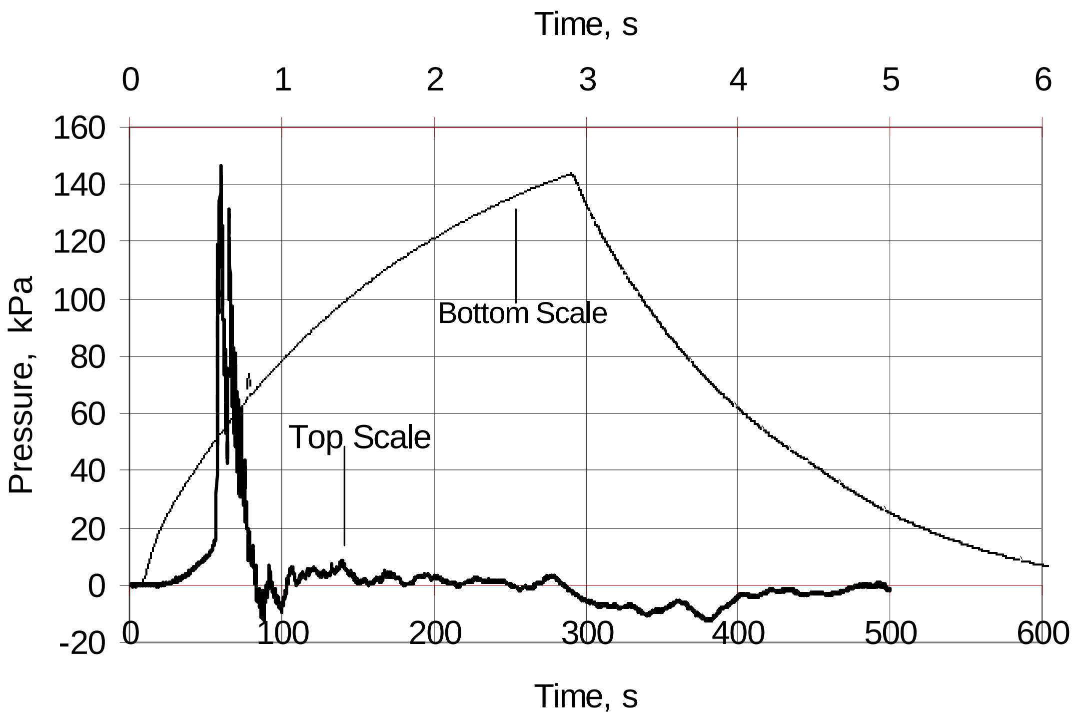

Figure 3. Comparison of standard-type seal pressure loading at 138 kPa with compressed air in the small chamber to that of a methane explosion in the multiple entries

CHAMBER EXPLOSION TESTS

In addition to the pneumatic tests, these standard-type solid-concrete-block seal designs were exposed to several internal ignitions of methane. Five such ignitions or explosions were conducted in the small chamber, exposing the standard-type seal with a pilaster, seal C1, to increasing pressures. Four explosions were conducted with the similar seal design, seal C2, without a pilaster. The standard-type seal design with a center pilaster in the large chamber, seal L1, was explosion tested to failure. A summary of the seal type, seal dimensions, and explosion test data are shown in table 1.

Table 1. Summary of small and large chamber test results for the solid block seal with and without pilaster.

Explosion Test	1	2	3	4	5	6	7	8	9	10
Seal[1]	C1	C1	C1	C1	C1	C2	C2	C2	C2	L1
Width, m	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	8.53
Height, m	2.62	.62	.62	2.62	2.62	2.62	2.62	2.62	2.62	4.72
Thickness, m	0.4	0.4	0.4	0.4	0.4	0.4[2]	0.4[2]	0.4[2]	0.4[2]	0.4
Mid line movement at Max P, mm	1.52	-	2.03	3.3	+76.2	-	-	-	-	+76.2
Max Pressure, P, kPa	390	22	651	49	688	18	24	38	669	221
Result	P	P	P	P	F	P	P	P	F	F

[1]20 x 15 x 40 cm (nominal 8 x 6 x 16 inch) solid concrete block. Average compressive strength of block =16.56 +/- 0.69 MPa (2400 +/-100 psi)
[2]No pilaster.
P=Passed post-explosion leakage
F= Failed - catastrophic rupture

The standard-type seal (C1 seal with a center pilaster) withstood four constant volume explosions before it ruptured at a peak static pressure of 688 kPa. After test 3, hairline cracks were visible primarily along the central mortar joints. The post-explosion leakage increased to about 2.7 m^3/min (97 cfm) at 0.25 kPa (1 in water gauge) which was still within the acceptable limits. For the fourth test, approximately 6 m^3 (210 ft^3) of oxygen was injected into the chamber followed by the methane injection, resulting in a near stoichiometric mixture. The pressure profile produced from the combustion of this oxygen-enriched mixture is shown in figure 4. As expected, the combustion was much more rapid as compared to the test without the oxygen injection and generated a peak static pressure of 688 kPa at 0.34 s after ignition. Prior to the fourth test, the standard-type seal design had never been destroyed during full-scale BEM or LLEM mine explosion tests which generated overpressures up to 317 kPa.

Seal C2, without the center pilaster, ruptured during the fourth explosion (test 9) at a peak static pressure of 669 kPa or ~20 kPa below the failure pressure of seal C1 with the center pilaster. Under these test conditions, both seals provide a margin of safety of about 4.8 to 5 times the CFR requirement.

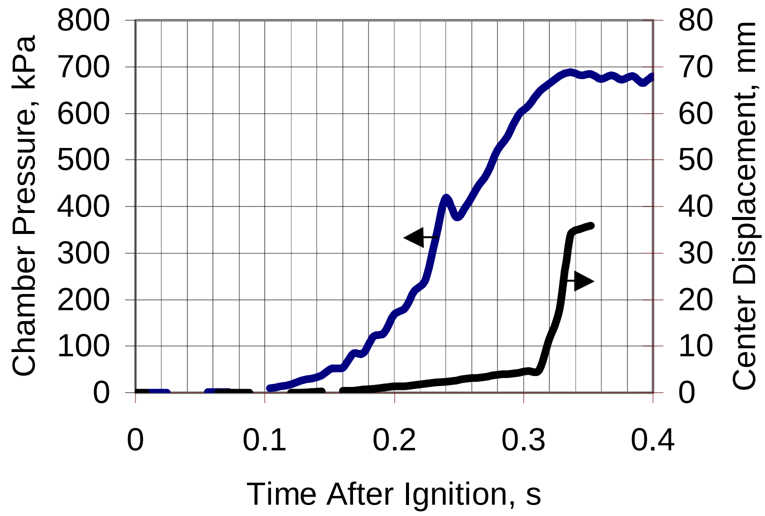

Figure 4. Static pressure profile during test 5 that resulted in the failure of the standard-type solid-concrete-block seal design in the small chamber

The second series of tests was conducted in the large chamber with the standard-type, solid-concrete-block design. The main seal wall was 406 mm thick with a 813 m thick center pilaster; the cross sectional area of the seal was 40.26 m^2. Pneumatic testing of the large seal was not as successful as with the smaller seal due to the larger seal surface area. With the two compressors operating at full capacity, the maximum attainable air pressure behind the large chamber seal was 71 kPa. At this air pressure, the LVDT indicated a maximum deflection of 2.5 mm. Post-test leakage produced an acceptable 0.7 m^3/min (25 cfm) air leakage at 0.25 kPa water gauge. No visible indication of surface cracks in the horizontal or vertical mortar joints was evident. The pneumatic testing studies indicated that, in most cases, the post-test leakage was less than the pre-test leakage measurements. It appears that, as the seal flexes from pressure loading, the fine dust kicked up by the injection of compressed air enter the small orifices and plugs them. Future studies will continue to better identify and characterize this effect.

After the pneumatic tests, methane was injected into the chamber and, when mixed with the air, produced an ~5.7% methane-air atmosphere. The flammable gas mixture was then ignited. The resulting pressure history is shown in figure 5. Based on the timing of the LVDT data, the maximum pressure peak reached 221 kPa in about 13 s at which time the seal ruptured. The displacement of the centerline of the seal as a function of pressure loading is shown in figure 6. The seal flexed nearly linearly with the pressure loading to a maximum displacement of about 11 mm at a peak static pressure loading of 207 kPa (30 psig), at which point, the seal ruptured and displaced outward.

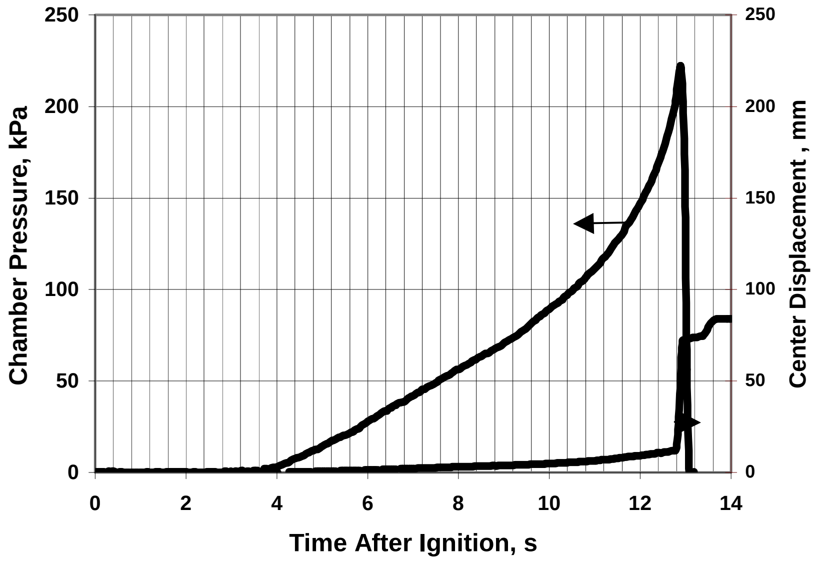

Figure 5. Static pressure profile during test 10 that resulted in the failure of the standard-type solid-concrete-block seal design in the large chamber

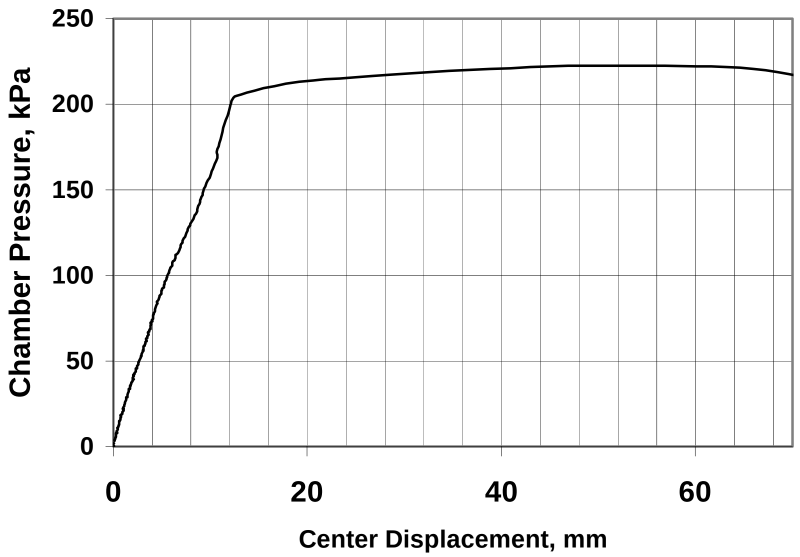

Figure 6. LVDT displacement data as a function of pressure loading on the standard-type solid-concrete-block seal during test 10 in the large chamber

SIZE-SCALING OF SEALS

Mine geometries can often vary within the mining horizon and from mine to mine throughout the U.S. mining industry. Entry height, requiring seals, can range from a low of 0.8 m to a high of 4.5 m. Major geologic faults or roof fall areas may require even larger seals. Geometric size-scaling relationships are needed to simply and reliably scale explosion performance results gathered in nominal 2.1 m high by 6.1 m wide entries to other dimensions while maintaining explosion isolation at the required 138 kPa level. The U.S. Army Research and development Center developed a SDOF computer code WAC for determining the ultimate strength of reinforced and non-reinforced masonry concrete walls. This code provides engineers with a useful tool to calculate the response of typical walls subjected to various blast loads. The WAC, calculates the resistance function (load-deflection) of a wall given construction details such as dimensions, material properties, and support conditions. The SDOF method, models the response of a structural element as a spring-mass system. The effective mass of a SDOF method is based on the deformed shape of the wall and loading distribution. The spring stiffness describes the resistance of the responding element to deformation due to the applied loading. The resistance function may be linear, bilinear (elastic-perfectly plastic), or multi-linear. The code calculates the actual SDOF equivalent loads given the explosion pressure history and solves the equation of motion to determine the response time history of a critical central point on the wall.

A parametric study was conducted using the WAC to develop simplified size-scaling relationships for predicting the ultimate strength of a seal and then comparing these predictions with recent LLEM chamber data. The key scaling parameters considered for the initial study were seal width, seal height, compressive strength of the concrete or masonry units, material density, wall thickness, and the rib and floor hitching. The WAC predictions for ultimate strength were regressed and the best fit is identified as an arching theory. Figure 7 is a plot of this arching prediction model in terms of structure thickness, width, and material compressive strength as a function of failure pressure. The WAC output was correlated with a simplified formula for the arching action in transverse laterally loaded masonry wall panels (Anderson, 1984) as:

$$P=k*Fc*(T/W)^2;$$

where P is the predicted ultimate failure pressure in kPa, Fc is the material compressive strength of the block in kPa, T and W are the thickness and width respectively of the seal in m, and k is the slope. Also shown in figure 7 are the experimental results from testing the 406 mm thick standard-type solid-concrete-block seal in the small chamber and a similar seal in the large chamber, C1 and L1, respectively. The failure pressure for both the large and small standard-type seal with pilaster agree well with the SDOF code predictions and the simplified best fit approximation of:

$$P=0.35 * Fc*(T/W)^2$$

to the SDOF code. Although the agreement with experimental data is good, this preliminary approximation for ultimate seal strength should be used with caution for predicting the ultimate strength. The accuracy of the prediction relies on quality masonry construction, close contact between the seal and the rib abutments, and the abutment thrusts must be higher than the values to cause crushing of the masonry (17.25 MPa) under arching action. These results suggest that the arching theory approximation to the SDOF computer code predictions provides a reasonable method of approximating ultimate arching strengths with rigid abutments. Research continues to refine these relationships to include abutment strength and thicker seal designs with and without hitching.

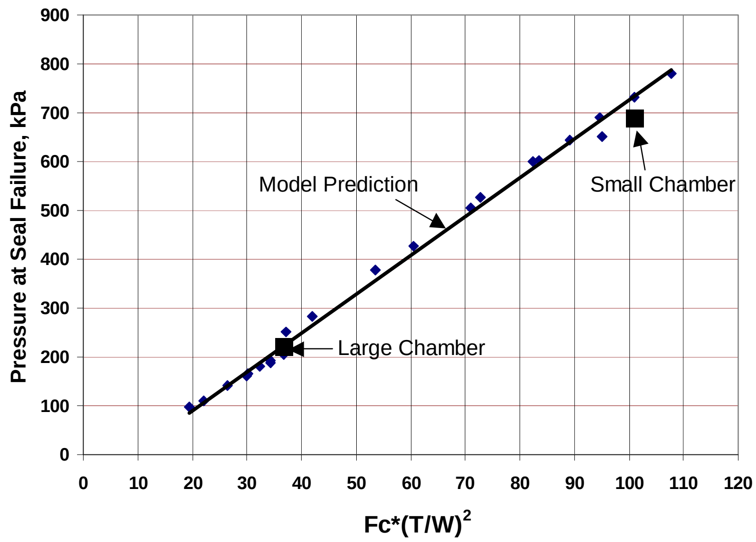

Figure 7. Comparison SDOF model predictions for ultimate seal strength with experimental failure data for the standard-type solid-concrete-block seals in both the large and small chambers

SUMMARY

Before MSHA will deem a seal design suitable for use in underground coal mines, the design has to be evaluated and, in many instances, undergo full-scale explosion testing. These new chambers show promise as a method for pressure testing of mine seals. The chambers may provide a means for evaluating hydrostatic effects, extend the duration of the pressure loading, facilitate testing to failure to determine the seal's strength safety factor, and facilitate testing the strength and leakage characteristics of seals used to impound water.

These preliminary results indicate that the explosion evaluation of seals using the chamber approach show promise as an alternative to the present full-scale explosion evaluation method. The large and small chambers will help facilitate the development of new, stronger seal designs, the development of geometric size-scaling relationships, the validation of in-situ seal performance for safe use underground, and replace the expensive full-scale performance testing at the LLEM.

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