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THE EFFECTS OF FRICTION ON THE PERFORMANCE OF A CONCRETE BLOCK MINE SEAL WITH PRESSURIZED GROUT BAGS

WPŁYW TARCIA NA ZACHOWANIE TAMY USZCZELNIAJĄCEJ WYKONANEJ Z BLOKÓW BETONOWYCH ZE SPRASOWANYMI WORKAMI ZACZYNU

Mine seals are necessary in nearly every underground coal mine to isolate mined-out areas from the ventilation network. Many seals are already in place in active mines and more need to be constructed to keep up with the development of underground coal reserves. The accidents involving seal failures at Sago and Darby prompted MSHA to create and implement new regulations regarding the strength of the seals. These regulations require the design and construction of seals that are larger and stronger than ever before. Structural seals capable of withstanding the new required design loads are now designed by an engineer and no longer approved through explosion testing.

Prior to the seal failure accidents, a solid-block wall with pressurized grout bags at the wall/ribs and wall/roof interfaces was a popular design which met the 137.9 kPa (20 psi) requirement. After implementation of the new 344.7 kPa (50 psi) or 827.4 kPa (120 psi) design regulations depending on whether the atmosphere is kept inert inby the seal, a re-design of the seal was necessary. This paper discusses the quantification of the coefficients of friction which are then implemented into finite element modeling.

Keywords: coal mining, mine seals, explosions, finite element modeling

Tamy uszczelniające niezbędne są prawie w każdej kopalni podziemnej do oddzielenia obszarów wybranych od sieci wentylacyjnej. W kopalniach aktywnych znajdują się już liczne tamy a coraz większa ich ilość zostanie zbudowana w miarę udostępniania kolejnych złóż węgla. Wypadki spowodowane przez awarie tamy w kopalni Sago i Darby stanowiły bodziec dla urzędu górniczego MSHA do stworzenia i wdrożenia nowych regulacji odnośnie wytrzymałości tam. Przepisy te wymagają projektowania i budowania tam większych i bardziej wytrzymałych niż kiedykolwiek w przeszłości. Tamy strukturalne zdolne do przenoszenia na nowo określanych obciążeń obliczeniowych muszą być obecnie projektowane przez inżynierów a procedura ich odbioru nie obejmuje badań w warunkach wybuchu.

Przed wypadkami spowodowanymi przez awarie tam, popularnym rozwiązaniem były ściany z jednolitych bloków ze sprasowanymi workami zaprawy umieszczanymi na styku pomiędzy ścianą, żebrami oraz stropem. Rozwiązanie to było szeroko stosowane i zapewniało spełnianie kryterium przenoszenia obciążeń na poziomie 137.9 kPa (20 psi). Po wdrożeniu nowych wymogów określających obciążenia obliczeniowe:

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344.7 kPa (50 psi) lub 827.4 (120 psi) w zależności od tego, czy atmosfera w rejonie zamkniętym tamą uszczelniająca ma pozostawać obojętna czy też nie, niezbędne okazało się przeprojektowanie tamy. W pracy tej zbadano w ujęciu ilościowym współczynniki tarcia, a wyniki badania zaimplementowano z wykorzystaniem metody elementów skończonych.

Słowa kluczowe: górnictwo węgla, tamy uszczelniające, wybuch, metoda elementów skończonych

1. Introduction

Seals have been commonplace in underground coal mines in the United States for many years. In areas where the reserves have been depleted yet mining is active in other parts of the mine, the operator has the choice to either continue ventilating the mined-out area or sealing it off (United States, 2007). Typically, a series of seals are constructed in the entries which access the depleted part of the mine as it is the cheaper solution. Seals have two purposes. The first is to isolate the atmosphere inby from the active mine and the second is to resist any explosion that may occur. The seal must be able to withstand an explosion force from either side. If an explosion happens on the active mining side, leakage of methane from behind the seals to the active part of the mine may provide fuel for additional explosions. If an explosion happens behind the mine seals, they must be able to resist the forces generated so that the atmosphere does not become explosive within the active part of the mine. A example scenario in which mine seals are utilized can be seen in Figure 1.

There has been a wide range of materials used for coal mine seals. From traditional block/mortar and reinforced concrete to fiber-reinforced OMEGA block seals which can be cut to size

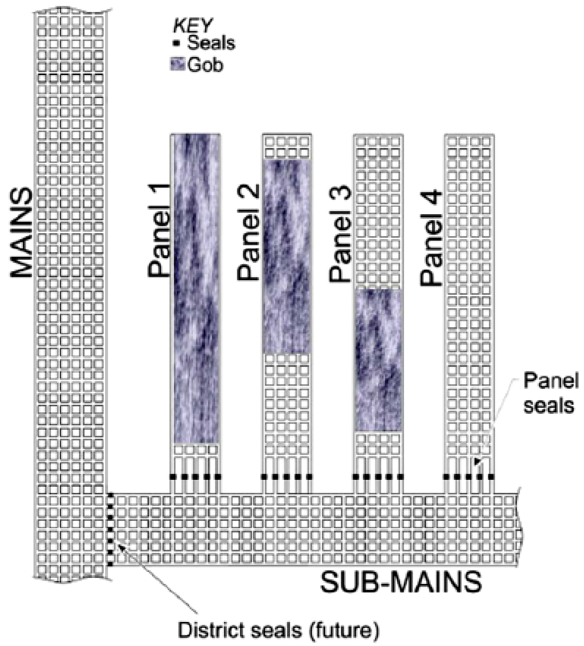

Fig. 1. Typical layout of room and pillar retreat mine with seal locations shown (United States, 2007)

with a hand saw (Twedt, 2006). Regardless of the material used in the seal, each design implements a way to transfer the loads (shear, moment, etc.) generated during the explosion to the surrounding rock strata. This can be achieved through steel bars imbedded in the roof and floor, cutting a slot in the roof and floor (hitching), or creating a pseudo-hitch using pressurized grout bags around the perimeter of the seal.

After the tragic explosion accidents in which many coal miners died due to seal failure, MSHA (Mine Safety and Health Administration) raised the seal design standards from 137.9 kPa (20 psi) to either 344.7 kPa (50 psi) or 827.4 kPa (120 psi). A 344.7 kPa (50 psi) seal may be constructed in areas where the atmosphere behind the seal is kept inert (not susceptible to explosion) whereas a 827.4 kPa (120 psi) seal may be constructed in areas where the atmosphere behind the seal may be within the explosion range, 5-15% methane (Federal Register, 2008). Each pressure versus time waveform has an instantaneous rise time to the prescribed pressure, held constant for four seconds, and then released instantaneously. Seal approval has gone from surviving an explosion at a testing laboratory to calculations and modeling which are reviewed by MSHA.

Seal designs today stem from modeling programs and calculations which are based on engineered structures. In a mining environment, this is seldom the case for seal construction. Engineered foundations and connection types are often assumed to be applicable in mine seal designs, but these can potentially end up being incorrect and dangerous assumptions. Each mine is unique and each seal construction location is different. Models today, such as SBEDS (Single-degree-of-freedom Blast Effects Design Spreadsheet) and finite element programs, are based on engineered structures resisting loading, not structures affixed to the earth in novel ways. The purpose of this paper is to either prove or disprove some of these assumptions and how it can affect calculations, modeling, and the overall design of a seal to the required pressure loading.

In a block wall which utilizes pressurized grout inside grout bags, the bags function as the energy transfer medium between the blocks and the surrounding rock strata. Instead of mechanically creating a channel in the rock material at the desired seal location which takes many man hours and equipment utilization, grout bags are placed around the perimeter of the seal and then pressurized with a grout material. This creates an assumed hitched surface similar to that of a mechanically removed channel.

A grout bag alone consists of four layers of materials surrounding the internal bag void where grout is pumped. There are three layers of a rough nylon material with a smooth plastic layer within the three nylon layers to hold grout pumped into the bag. On the outside of the bag, a threaded nipple is exposed for grout hose attachment. The nipple passes through all four layers so the inner plastic bag can be filled with grout. Figure 2 shows two typical grout bag sizes.

A block wall seal is constructed in the desired location and then grout bags are placed around the perimeter of the seal. No bags are placed below the seal, but the two lower bags on either side of the seal are placed so that 15.24 cm (6 in) of the bag is underneath the first layer of blocks. The bags are then placed around the sides and top with a minimum of 15.24 cm of overlap. Each bag is pumped to a range of 250-300 kPa (36-43.5 psi) which is read from the inline pressure gauge starting with the top center bag. From there, the two bottom sides are pumped, then the top corners, and then the remaining bags in a symmetrical fashion. The bags are pumped with a grout material designed to have limited shrinkage with a hand pump.

To fully define the effects of the grout bags on a solid block wall subjected to blast loading, three experiments were performed. Complete definition of all effects is necessary for a proper design to be performed.

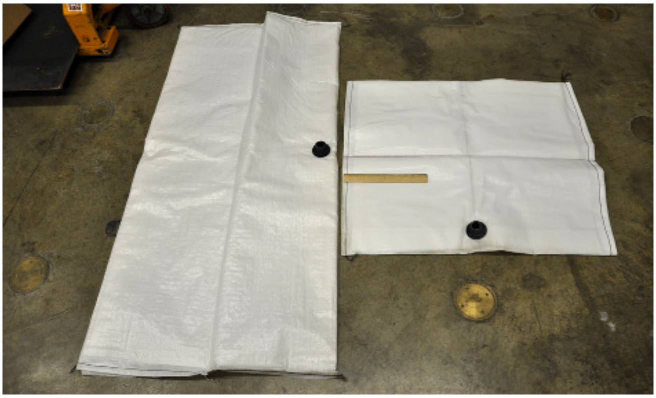

Fig. 2. Photograph of two typical grout bags

2. Friction Analysis

2.1. Static Friction

Since the grout bag serves as the medium of load transfer between the block wall and surrounding strata, a coefficient of friction between the materials involved was necessary. A block of coal was used as this would be on the sides of the wall. A block of sandstone was used to simulate the roof material and a concrete block for the wall material. To determine the coefficients of friction, a test apparatus was constructed by affixing a flat plywood sheet to a wooden beam using two hinges as shown in Figure 3. From there, a protractor was placed just outside the plywood board with the center point on the same axis as the hinge point. The plywood board with a grout bag attached was lifted until the block began to slide with a camcorder capturing the reading at the protractor. The wooden beam base was secured on two threaded poles with washers and nuts to assure no undesired movement of the testing apparatus. By knowing the weight of the block

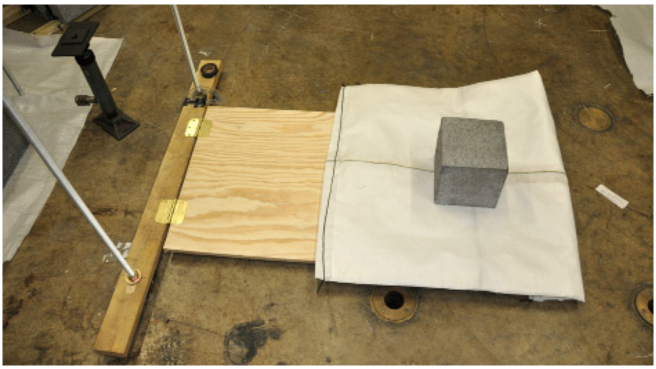

Fig. 3. Testing apparatus consisting of a secured wooden beam hinged to a plywood sheet which is raised on one end to determine angle at which movement of subject occurs

and the angle at which it started to slide, a simple static analysis was performed to calculate the frictional force, normal force, and friction coefficient.

Two test sets were run with the variable between the two being the bag material attached to the plywood board. The first set utilized a single, outer layer of the nylon material from the grout bag. The second used a complete empty bag. Through each set, five tests were performed on all three materials. The concrete block tests consisted of three different series in which the block size or block orientation was changed as shown in Figure 4. The sandstone block tests consisted of two series in which a smoother and rougher side of the block was put in contact with the bag material. The coal block tests were similar to that of the sandstone tests, in which a smoother and rougher side was placed against the bag. The smooth and rough sides of the sandstone and coal blocks can be seen in Figures 5 and 6, respectively.

Fig. 4. Concrete block orientations. Half, full orientation A, full orientation B

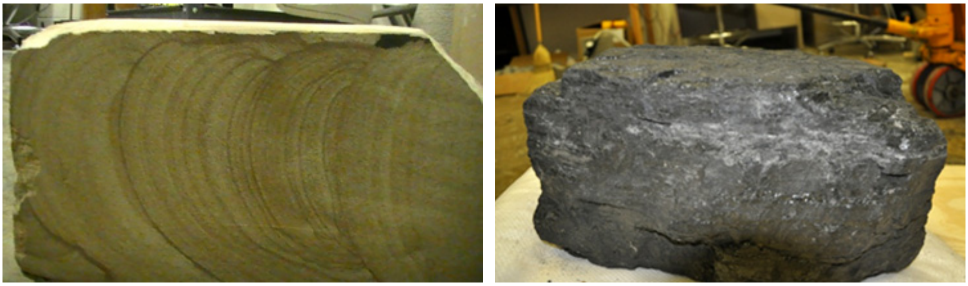

Fig. 5. “Smooth” surface (top of blocks in picture) of sandstone and coal blocks

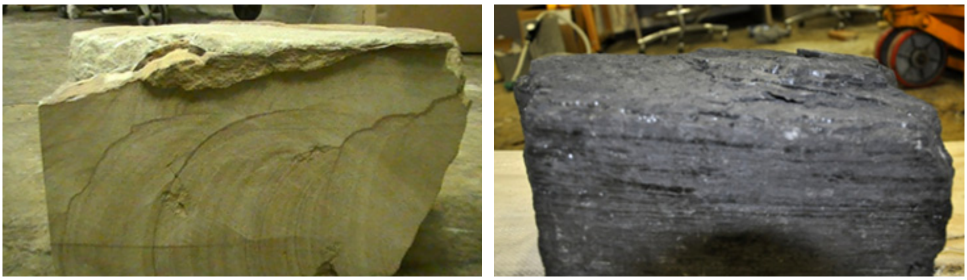

Fig. 6. “Rough” surface of sandstone and coal blocks

For each test, the block was centered in the middle of the bag material and then slowly raised on the testing apparatus. At the point which the block began to slide on the bag, the angle of the board was recorded. After determining the weight of the block and the angle at which the block began sliding, the coefficient of friction could be determined using Equations 1, 2, and 3.

$$F_N = F_G * \cos(\theta) \tag{1}$$

$$F_F = F_G * \sin(\theta) \tag{2}$$

$$\mu = \frac{F_F}{F_N} \tag{3}$$

where

F_N — normal force
F_F — frictional force
θ — angle from horizontal to angle of slippage
μ — coefficient of friction

After running each test for all the materials, an average coefficient of friction for each series was determined. The average did not vary from the range extremes by more than 10% for any individual series. The results of the static friction analysis can be seen in Table 1.

TABLE 1

Average Static Coefficients of Friction for Various Material Types vs. Bag Types

Material	**Single Layer**	**Empty Bag**
	Average μ	**Average μ**
Half Concrete Block	0.4142	0.3839
Full Concrete Block A	0.4557	0.3463
Full Concrete Block B	0.4684	0.3327
Sandstone Smooth	0.2568	0.3308
Sandstone Rough	0.3115	0.3153
Coal Smooth	0.2235	0.2699
Coal Rough	0.2849	0.3039

2.2. Simulated Pressure Frictional Analysis

The second series of experiments performed characterized the frictional properties of the grout bag when simulating differing bag pressures. The purpose of these experiments was to determine the frictional properties under differing pressures so that a fundamental understanding of the materials used for the bag could be achieved. This creates a base point for future advancements in material technologies that can then be compared to and enhancements quantified. Three different experimental setups utilizing three different bag setups were analyzed. The bags were not filled with grout but instead cut into three different configurations and one additional series with an entire empty bag. The first series utilized a single layer of the outer white nylon material. In the second series, the bag was cut in half to where three nylon layers and the smooth plastic layer were analyzed. Finally, the last series used the entire bag cross section consisting of two smooth plastic layers sandwiched between three rough nylon layers on either side.

A concrete block was placed in a test apparatus with a certain configuration of the grout bag on top and bottom of the block. A normal force was applied downward using a 534 kN (60-tons) jack to simulate an internal pressure of the bag. Perpendicular to the normal force, a force was applied to the block until the block slid using a 267 kN (30-ton) jack. Figures 7 and 8 show photographs of the testing apparatus setup.

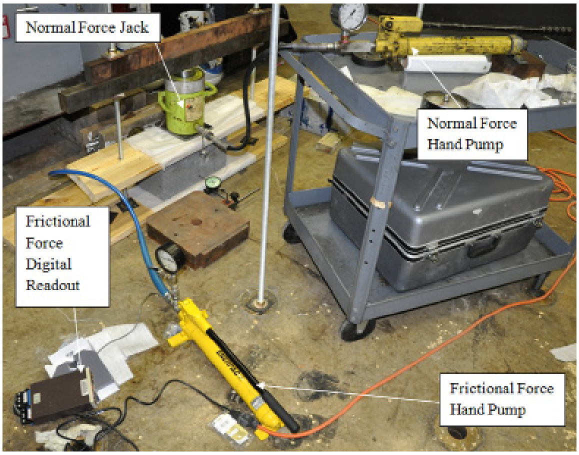

Fig. 7. Testing apparatus used for simulated bag pressure experiments

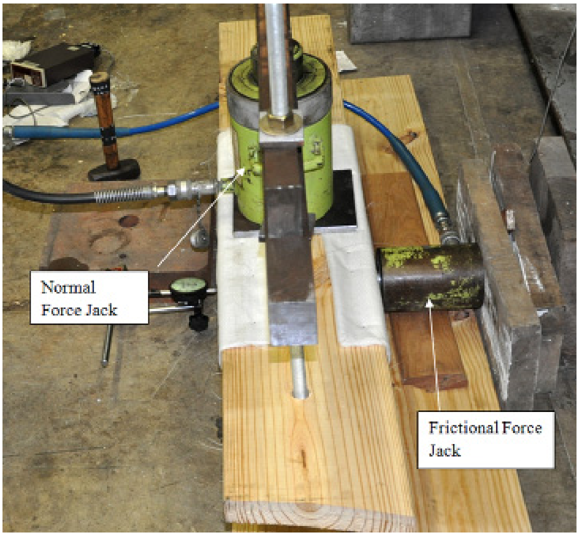

Fig. 8. Profile view of testing apparatus

Each of the three bag configurations were run through a range of simulated bag pressures ranging from 69 to 690 kPa (10 to 100 psi) in 69 kPa (10 psi) increments four times. The coefficients of friction were averaged for each simulated bag pressure and plotted for each bag setup. Figure 9 shows the results.

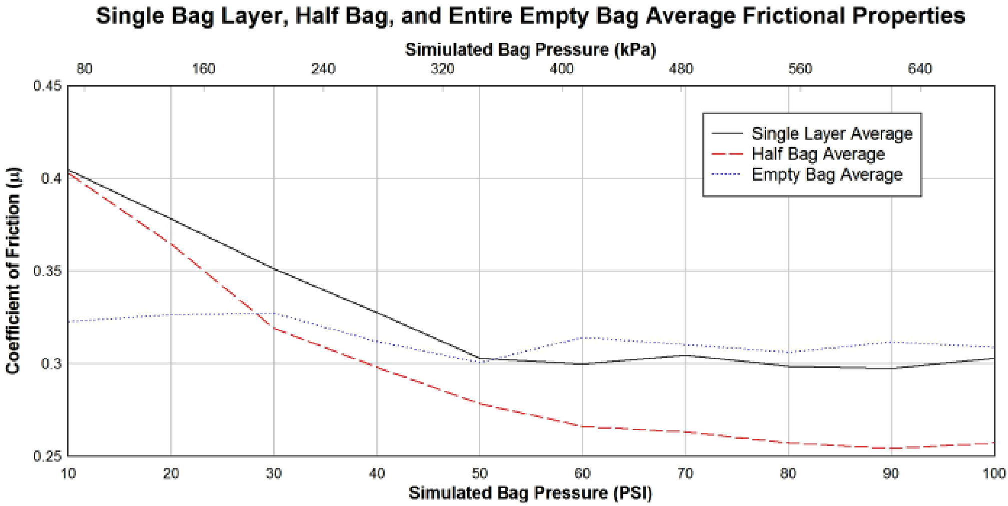

Fig. 9. Average trend lines from simulated pressure frictional test series

Figure 9 reveals several concepts. First, for the single nylon layer of the bag, the coefficient of friction has a downward trend to approximately 345-414 kPa (50-60 PSI). Each layer of the grout bag is woven out of long, thin individual nylon "threads" producing a textured surface. When uncompressed, the intersections of each thread produce small edges to react against. As compression of this layer is increased, the edges become flatter and flatter producing more of a smooth, uniform surface. Second, the same general trend occurs in the half bag as the single layer, but at lower friction coefficients. The introduction of the smooth plastic layer results in an additional surface for the innermost nylon layer to slide against. This interface has a much lower coefficient of friction than any other interface in the system. Finally, for the full bag at lower simulated bag pressures, the interface between the two plastic bags slips giving momentum to the system yielding a lower coefficient of friction. However, when larger simulated pressures are introduced, the multiple layers of the textured nylon layers begin to imbed into the plastic layers and give the plastic layers the texture. This provides additional friction to the system which ultimately results in the largest coefficient of friction for all three experiment sets.

2.3. Bulging Effects Analysis

Grout bags, which are placed on the top and sides of the block wall, must extend a minimum of 15.24 cm beyond the extents of the concrete blocks on both inby and outby of the wall. When the bags are filled with grout to a predetermined pressure, the bags bulge, or bellow, around both sides of the seal creating a pseudo hitch. These bulging effects add to the resistance of the wall without having to mechanically remove rock material on the ribs and roof to create a hitch. However, these hitch effects are only effective if the friction between the grout bag and roof is sufficient to withstand the additional resistance provided by these bulging effects.

To determine the additional resistance the bulge provides to the wall, several tests were performed. The test setup consisted of placing three concrete blocks on a oil-slicked polished concrete floor (negligible frictional resistance) and then pressurizing a bag with grout on top of the blocks. The top of the bag was in contact with a massive 23,133 kg (51,000 pounds) cannon breach which served as the dead load so that the bag would not be able to push the dead load upwards. A bulge was created around the top of the blocks and then immobilized. A jack then pushed against the blocks until the grout inside the bag failed at the bulge as shown in Figure 10. When using the width of the block, 39.7 cm (15.625 inches), in contact with the bulge and the force required to break the bulge, it was determined that the bulge length of 16.5 cm (6.5 inches) had a resistance of 1,473 N/cm (841.45 pounds per inch) of width. When dividing by the bulge length, a value of 89.22 N/cm^2 (892.2 kPa or 129.5 pounds per square inch) is found for the resistance of the bulge.

When taking into account a 0.3 coefficient of friction, the interface provided a total of 229.6 N (51.618 pounds) of frictional resistance. This equates to 3.96 N/cm (2.26 pounds per inch) in the direction of the applied load and 1 kPa (0.145 pounds per square inch) over the entire interface. Even when a higher coefficient of friction was considered, the frictional effects are very minimal when compared to the bulging effects. When subtracting these values from the bulge effect values, it is obvious that the bulge provides a majority of the resistance.

Fig. 10. Grout bag cut open to show failure surfaces

2.4. Simulated Mine Roof Frictional Analysis

In a similar test setup to that to determine the bulging effects, a test was conducted to simulate a mine roof. To simulate the potential rough surface of a mine roof created by a continuous miner, precast concrete pavers were purchased as they had a very rough surface. Each paver consists of three individual blocks but are cast together. Each individual block has a surface area of approximately 58 square centimeters (9 in^2). A photograph of the pavers can be seen in Figure 11.

Two tests were performed to determine the frictional resistance between the grout bag and the simulated mine roof. The pressurized grout bag was oriented so that no bulge would add to the resistance of the system. The first test found a frictional resistance of 909 kPa (131.81 pounds per square inch) while the second at a higher internal bag pressure was 1,076 kPa (156.07 pounds per square inch). These values are slightly greater than the applied force that will be generated by the bulge and bag/block interface. Therefore, to generate a design which utilizes safety factors for a conservative approach, the interface between the grout bags and mine roof must be enhanced to achieve a higher level of resistance.

Fig. 11. Photograph of four sets of concrete pavers used to simulate a mine roof

3. Finite Element Modeling

In the following sections, modeling of seals in shown. Each model was constructed and run in the finite element code ANSYS Explicit Dynamics which uses Lagrangian structural solvers to calculate stress, strain, deformation, etc. (ANSYS 2014). Each model was simulated to have typical mine size dimensions and loaded with a MSHA prescribed pressure versus time waveform of 344.7 kPa (50 psi) for four seconds which is instantaneously applied and released.

3.1. Baseline – Fixed Ends

The first model created in Ansys Explicit Dynamics consisted of a concrete block wall which was 1.8 m tall, 6.1 m tall, and 40 cm thick (six feet by 20 feet by 15.75 inches). In this specific design, the blocks are glued together instead of using traditional mortar. Through multiple testing methods, it was always found that the blocks failed prior to the glue. Therefore, for simplicity, the wall was simulated as a solid concrete wall consisting of no joints between blocks. As is often assumed for designs, fixed end conditions were placed on the top and bottom surface of the wall while the sides remained free. Results of the model showed a maximum displacement of 0.092 mm (0.00363 inches) with all stresses below the strength of the concrete. A shear stress of 841.4 kPa (122.03 PSI) was calculated at the top and bottom of the wall. A screenshot of the model can be seen in Figure 12.

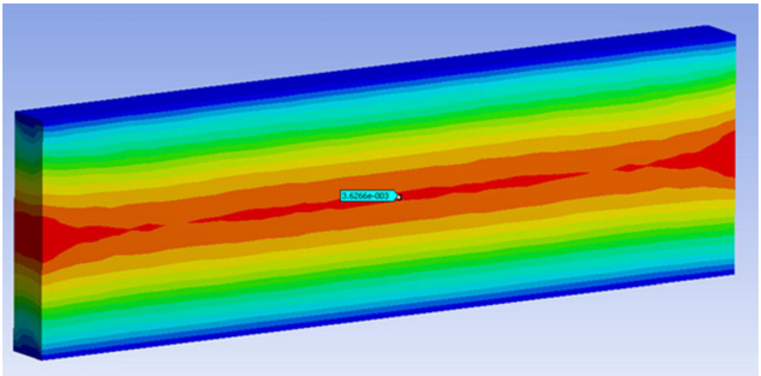

Fig. 12. Displacement on applied pressure side of baseline model

3.2. Models Using Grout Bags and Friction Coefficients

Two series of models were constructed to determine the differences in displacements when compared to the baseline model. In addition to the wall, a frame of simulated earth material was included. The coefficient of friction between the bag and the seal remained constant at 0.30 while the coefficient between the bag and the strata was varied as 0.15, 0.30, and 0.60 to simulate varying roof conditions in a mine. In addition to changing the friction coefficient, bulges were created for one series while the other did not have bulges. Figure 13 shows an image of the model without the bulges while Figure 14 shows an image of a model with bulges included. The bulge had a width of 10.48 cm (4.125 inches) and came down the face of the wall 10.16 cm (4 in).

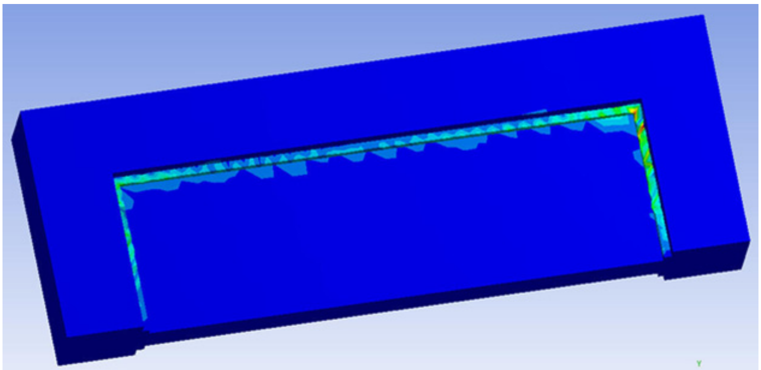

Fig. 13. Image of model without bulge

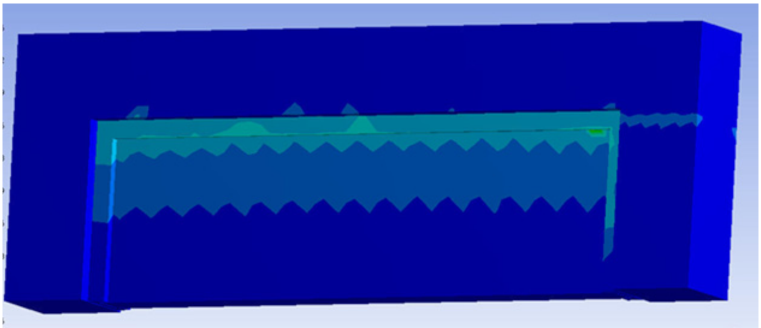

Fig. 14. Image of model with bulge around wall

After running through each model, maximum displacements of the wall and bags were tabulated. In Table 2, the displacement results from each model are shown.

TABLE 2

Displacement Results from all ANSYS Models for Block Seal

			Applied Pressure Side			
Model	**Bag / Seal μ**	**Bag / Strata μ**	**Bag Disp. (inches)**	**Seal Disp. (inches)**	**Bag Disp. (mm)**	**Seal Disp. (mm)**
Fixed Ends	N/A	N/A	N/A	0.004	N/A	0.091
No Bulge A	0.3	0.3	3.963	0.255	100.655	6.477
No Bulge B	0.3	0.6	2.576	0.239	65.420	6.058
No Bulge C	0.3	0.15	FAIL	0.648	FAIL	16.459
Bulge A	0.3	0.3	0.238	0.218	6.048	5.530
Bulge B	0.3	0.6	0.214	0.210	5.441	5.334
Bulge C	0.3	0.15	0.252	0.447	6.393	11.351

As can be seen in Table 2, the larger the coefficient of friction between the rock strata and the grout bag, the lower the total displacement. This was evident in both sets of models, both sides, and both the seal and grout bag parts. However, the largest gains in lack of displacement resulted from the models utilizing the bulging effects. When comparing the non bulging models A, B, and C with the bulging models A, B, and C respectively, the displacement is greatly reduced. The bulges add to the total resistance of the seal by creating a pseudo hitch which utilizing the strength of the material inside the grout bags. However, as the strength of the material inside the bag increases, additional forces must be resisted at the grout bag and rock interface. The grout bag and rock strata interfaces are the keys to a successful design. If that interface can be designed to withstand the forces generated by the frictional interface between the seal and bag and the effects of the bulge, the seal shows promise for approval. However, each mine seal location will vary as mines vary throughout the United States. A standardized process to assure this interface will be able to withstand the applied forces is necessary.

4. Conclusions

Current seal designs are analyzed using programs based on structural engineering calculations and conditions. While the calculations for the seal itself are valid, the supporting structure consisting of earth materials are variables that cannot be easily generalized. Each mine is different. Each mine seal location is different. Proper definition of the supporting structure must be performed so calculations can yield correct results.

As demonstrated through a thorough investigation into the frictional properties of grout bags versus several materials and then implemented into finite element modeling, simply assuming a fixed-end condition for seals is not an appropriate assumption. Since seals are installed in coal mines where geology can vary significantly, it is vital that the proper information is collected prior to the design of seals which rely on frictional resistance.

Advancements can be made in the bag material as well. Looking further into the fundamental effects may lead to additives within the material or a complete change of material. An additive to the slick nylon material, such as a fine silica embedded within the nylon, may increase the frictional resistance provided by the bag and ultimately lead to a design adequate to meet the required pressure. However, thorough testing would be required to quantify the effects of any changes made to the grout bags.

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