Comparison of the transverse load capacities of various block ventilation stoppings under arch loading conditions

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ABSTRACT: Stoppings are required to resist lateral forces on the face of the structure to control pressure differentials created by ventilating air. The design criteria in other parts of the world, including Australia, exceed this requirement by specifying over pressurization control to as much as 14 kPa (2 psi) in the active sections and 35 kPa (5 psi) in the main ventilating control areas. This is done to provide protection to the mine workers from explosive or air blast events within the mine that can create this over pressurization. The National Institute for Occupational Safety and Health (NIOSH) has been conducting research to develop a new testing protocol for rating mine ventilation stoppings. The premise of this work is that arch-loading conditions more accurately reflects the transverse load capabilities of stoppings in underground coal mines than the freestanding flexural strength test specified in the current Code of Federal Regulations (CFR). This work clearly shows that the transverse load capabilities of dry-stacked, mine ventilation stoppings are dependent upon the material strength of the block and the height and thickness of the wall, none of which are part of the current CFR criteria based on ASTM E-72 specifications. This paper compares the transverse load capabilities of several block materials and wall dimensions commonly used in stopping constructions based upon simulated three-hinge, rigid-arch loading tests of half-wall constructions in the NIOSH Mine Roof Simulator. The results indicate a wide-range of transverse load capacities, ranging from as low as 21 kPa (0.3 psi) to as much as 117 kPa (17 psi) for the conditions evaluated in this study. The current CFR criteria do not distinguish between applications of these stopping designs despite their wide variance in transverse load capabilities, which is not conducive to employing ventilation control strategies that isolate certain sections of the mine to prevent injury to mine workers.

1 Introduction

Stoppings are required to resist lateral (transverse) forces on the face of the structure to control pressure differentials created by ventilating air. These pressures can range from as low as 2 kPa (0.25 psi) in the working sections of the mine to over 7 kPa (1 psi) near the area of a bleeder fan. The design criteria in other parts of the world, including Australia, exceed this requirement by specifying over pressurization control to as much as 14 kPa (2 psi) in the active sections and 35 kPa (5 psi) in the main ventilating control areas (Lyne B, 1996). This is done to provide protection to the mine workers from events such as large roof falls, face ignitions or other explosive events within the mine. Although these requirements appear to be somewhat arbitrarily chosen, they are consistent with forces that can cause harm and serious injury to a human being. The force from a 14-kPa (2-psi) blast of air will cause a standing person to be thrown hard enough to cause incapacitating injuries and above 35 kPa (5 psi) fatalities are likely (>50% fatality rate). A 95% fatality rate is expected with pressures of 48 kPa (7 psi) (Cornwell and Marx, 1997).

There are no full-scale tests required for stoppings to determine their load capacity under U.S. mining regulations. The current Code of Federal Regulations (CFR) requirement is to test 1.2 x 2.4-m (4 x 8-ft) sections of freestanding walls in accordance with ASTM E-72 specifications (30 CFR, Part 75.333, July 2007). For dry-stacked stopping constructions, the transverse load capacity under the ASTM E-72 criteria is primarily determined by the tensile strength of the sealant. Under the freestanding load condition, 2 kPa (39 psf) is designated in the preamble to the CFR as the minimum required transverse load capacity. Any block material, regardless of its physical properties, can be made to pass this test criterion for use in underground coal mines provided the sealant is strong enough and can adhere to the surface of the block. This test does not determine the transverse load capacity of actual in-mine stopping constructions when the mine roof and floor and ribs of un-mined areas restrain the stoppings. This restraint creates significantly greater transverse loading capability by taking advantage of the compressive forces that are generated as the wall arches between the mine roof and floor.

A protocol to evaluate the transverse load capacity of block stopping constructions under arch-loading conditions using the unique biaxial loading capabilities of the National Institute for Occupational Safety and Health's (NIOSH) Mine Roof Simulator (MRS) has been developed and verified with in mine experiments (Barczak and Batchler, 2006). Using this protocol, this paper documents the transverse load capacities of stoppings constructed from various block materials that have been acceptable for use in U.S. underground mines. It is shown that a wide range of transverse loading capacities exist, not only because of the introduction of light weight, low strength block materials, but also due to the impact of mining height and wall thickness. It is imperative that the true transverse load capability of the stoppings be determined if the design requirements are to extend beyond the loading levels induced by ventilating air pressure differentials to provide protection to mine workers in the event of over pressurization from roof fall blasts or explosive events within the mine.

2 Review of Test Protocol for Arch-Loading Evaluation

Arching is the mechanism that occurs when the curvature of the stopping, specifically the extension of the tension face of the stopping, as it bends under the application of transverse loading is prevented by the rigid contacts of the mine roof and floor. This arching of the wall produces a thrust force that acts at the mine roof and floor interface, and produces compressive forces within the wall that can dramatically increase the transverse load capacity compared to a freestanding condition. In the unloaded or minimally transverse loading condition, the ends of the wall are in full contact with the mine roof and floor and the individual horizontal joints between the courses of block are in full contact with each other. As the transverse loading increases, the wall will begin to flex or bend. Associated with the bending will be the opening of the block joints along the mid height span of the wall (location of the maximum positive moment), and the opening of the interfaces between the blocks and the mine roof and floor (location of the maximum negative moment). A three-hinged arch is formed, which is simulated in the NIOSH MRS load frame by examination of the half-wall section as illustrated in Figure 1.

The half-height section of a stopping wall is placed in the load frame in a typical vertical orientation, as it would be in the mine. The upper platen position is adjusted to the height of the block column and is hydraulically clamped to maintain its position. The vertical position of the lower platen is commanded to remain constant. Hence, the fixed positions of the upper and lower platen allow them to act as rigid restraints. The lower platen is then moved horizontally at a constant velocity causing the wall to rotate (Figure 1). As the base of the wall is forced to move horizontally, crush zones are created at the ends of the wall on opposite sides, consistent with the three-hinge-arch loading mechanism. The horizontal force (HF) applied to the base of the half-wall by the MRS is measured and is equated to the transverse pressure (ρ) acting on a stopping wall using equation 1, where (w) is the width or thickness of the wall and (L/2) is the half-wall height.

$$\rho = \frac{2 \times HF}{w \times (L/2)} \qquad (1)$$

3 Stopping Materials Examined in this Study

Using the established protocol, the transverse load capacity of various stopping constructions under arch-loading conditions was determined through a series of half-wall tests in the NIOSH Mine Roof Simulator (MRS) load frame. The block materials chosen for the study represent the full spectrum of materials that have been determined as suitable for mine use by the Mine Safety and Health Administration (MSHA) using the current CFR freestanding wall assessment criteria. The block materials can be categorized as follows. Table 1 documents the relevant material properties for the blocks used in this study.

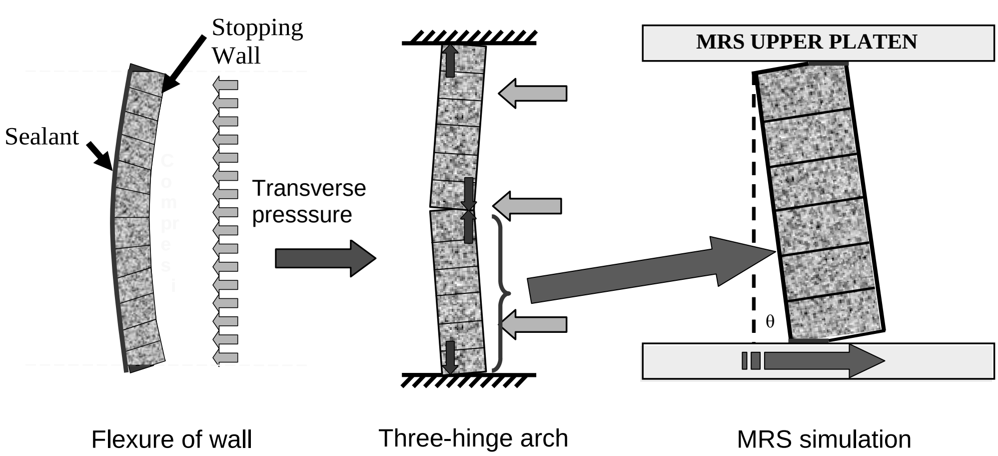

Figure 1. Simulating rigid arching in the NIOSH Mine Roof Simulator (MRS).

Table 1. Summary of the properties of the various stopping block materials evaluated in this study.

Block Type	Dimensions, cm (in)	Material Density, kg/m^3 (lbs/ft^3)	Unit Block Weight, kg (lbs)	Unit Block Compressive Strength, kPa (psi)
Standard CMU	15 x 20 x 40 (5-5/8 x 8 x 16)	2,082 (130)	24 (54)	9170 – 12,273 (1,330 – 1,780)
Lightweight Aggregate CMU	15 x 20 x 40 (5-5/8 x 8 x 16)	1,602 (100)	20 (43)	14,955 (2,169)
Hollow Core Block	15 x 20 x 40 (5-5/8 x 8 x 16)	2,082 (130)	15 (32)	6,254 (907)
AAC Materials				
• Block A	15 x 30 x 60 (6 x 12 x 24)	561 (35)	16 (35)	2,903 (421)
• Block B	20 x 20 x 60 (8 x 8 x 24)	545 (34)	14 (30)	4,861 (705)
• Block C	15 x 21 x 39 (5-7/8x8-3/8x15-1/4)	689 (43)	9 (19)	3,765 (546)
Foamed Cement	20 x 40 x 60 (8 x 16 x 24)	352 (22)	18 (40)	579 (84)
Extruded Foam Cement	15 x 40 x 60 (6 x 16 x 24)	609 (38)	23 (50)	593 (86)

3.1 Standard Concrete Masonry Unit (CMU)

This block is made from conventional Portland cement and standard aggregate. These blocks can vary in compressive strength depending on the amount of cement used in the mix from 7 to 21 MPa (1,000 to 3,000 psi). They generally weigh about 23 kg (50 lbs).

3.2 Lightweight Aggregate CMU

In order to reduce the handling effort, a lighter weight block is manufactured by using lightweight aggregate. Lightweight aggregate is made by heating up certain kinds of shale. Gases in the shale expand, causing the shale to bloat, producing bubbles, making it lighter than normal aggregates. Lightweight aggregate, with a specific gravity of about 1.7 reduces the weight of the block by as much as 20 pct.

3.3 Hollow Core Block

Another way to reduce the weight is to use hollow core block. The block is made from conventional Portland cement and standard aggregate with the same basic formulation that is used to make the solid blocks. The thin webs and facing contribute to the lower strength when a full block is tested, typically less than 7 MPa (1,000 psi) compressive strength.

3.4 Autoclaved Aerated Concrete (AAC) Materials

Another approach to provide a low-density material for stopping block construction is the use of aerated cement to create pockets or air voids within the concrete mix. To manufacture AAC, Portland cement is mixed with lime, silica sand, or recycled fly ash (a byproduct from coal-burning power plants), water, and aluminum powder or paste and poured into a mold. The reaction between aluminum and concrete causes microscopic hydrogen bubbles to form, expanding the concrete to about five times its original volume. After evaporation of the hydrogen, the now highly cellular concrete (see Figure 2) is cut to size and formed by steam curing in a pressurized chamber (an autoclave). The concrete has a homogeneous cell structure, visible to the eye, not to be confused with air-entrained concrete, in which air bubbles are microscopic in size. Several AAC materials have been developed for stopping applications in coal mines.

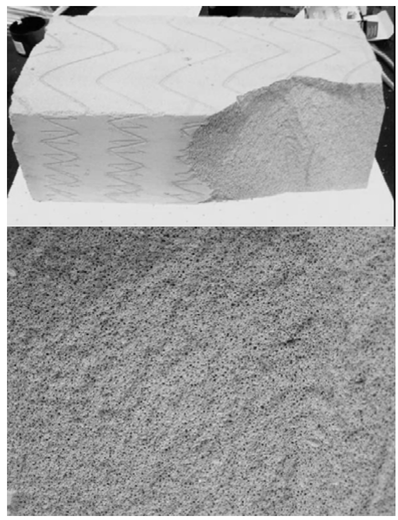

Figure 2. Cellular foam block showing void structure that contributes to light weight.

3.5 Foamed Cement

Foamed cement normally has a density of between 400 and 640 kg/m^3 (25 and 40 lbs/ft^3), compared with about 2,000 kg/m^3 (125 lbs/ft^3) for ordinary concrete. It is made of a cementitious material, filler or aggregate, and an aerated foaming agent. It is also known as cellular concrete. Foamed cements typically provide compressive strengths of less than 700 kPa (100 psi). The block is brittle and susceptible to damage from handling. Small fiberglass fibers are sometimes imbedded in the mix to help hold the material together and slightly improve its post failure loading characteristics.

3.6 Extruded Foam Cement

An alternative approach to creating a low density material is to imbed styrofoam pellets in the concrete mix, which are easily seen as part of the block construction as shown in Figure 3. Extruded foam cement has a compressive strength of less than 1,400 kPa (200 psi) with a fairly wide range depending on the volume and dispersion of the foam pellets within the concrete structure. The low density of the material allows a large size block of reasonable weight to be manufactured.

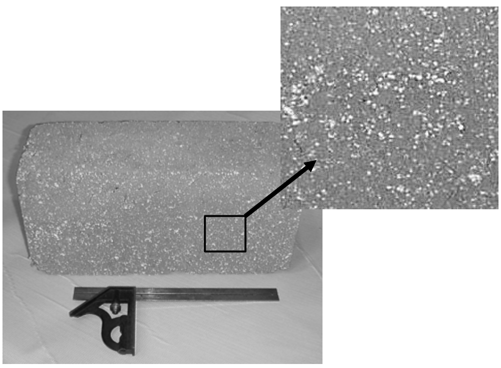

Figure 3. Extruded foam block showing close up of foam pellets (white colored areas) imbedded in a stopping block.

4 Examination of the Transverse Load Capacities

Figure 4 depicts the computed transverse load capacity of a 2.3- to 2.4-m-high (7.5- to 8-ft-high) stopping wall for the various types of block that were examined in this study based on the half-wall, arch-loading laboratory tests conducted in the NIOSH MRS load frame. The first point to be made is that all of the transverse loading is above the 2-kPa (39-psf) requirement established under ASTM E-72 freestanding wall test. The standard (solid block) concrete masonry unit and lightweight aggregate (solid block) masonry unit constructions exhibited transverse load capacity of over 19 kPa (400 psf), which is about 3 times that provided by a hollow block construction. Three different autoclaved aerated concrete (AAC) block, each of different dimensions and compressive strengths, were tested. The 20-cm-thick (8-in-thick) cellular block with a compressive strength of 4.9 MPa (705) psi provided the highest transverse load with a capacity of 32 kPa (666 psf). This is largely due to the relatively greater thickness of this block. The other two AAC blocks were of similar size to the masonry block units, nominally 15 cm (6 in) thick, but with lower compressive strengths of 2.9 and 3.8 MPa (421 and 546 psi) compared to the standard masonry units with a 9.2 MPa (1,330-psi) compressive strength. The 2.9-MPa (421-psi) block provided 8.6 kPa (179 psf) of transverse load capacity, while the 3.8-MPa (546-psi) block provided 21 kPa (429 psf) of transverse load capacity. In contrast, the weaker foam cement and extruded foam cement, both with compressive strengths less than 700 kPa (100 psi), provided only 3 and 2 kPa (63 and 50 psf) of transverse load capacity, respectfully.

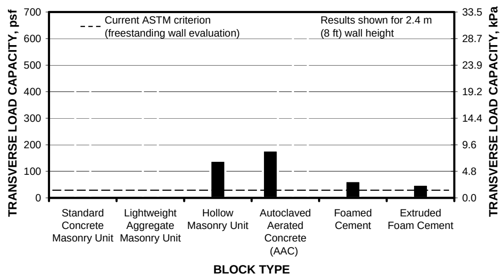

Figure 4. Transverse load capacity under arch loading conditions for various types of concrete block approved for stopping construction.

Several factors influence the transverse load capacity under arch loading conditions (Barczak and Batchler, 2006). Intuitively, higher strength block will provide greater transverse loading capability, but increasing the thickness of the block, or constructing the stopping with the wide side of the block as providing the contact area, can also greatly increase the transverse load capacity of the stopping. Likewise, it is important to recognize that, for given design parameters, the transverse load capacity will decrease as the entry height increases. Figure 5 illustrates the impact of both wall thickness and wall height on the transverse load capacity of the stopping. The graph shows wall heights of approximately 1.5, 2.3, and 3.0 m (5, 7.5 and 10 ft) comparing 15-cm-thick (6-in-thick) and 19-cm-thick (7.5-in-thick) wall constructions from the same type of block (standard CMU). The transverse load capacity dropped by nearly an order of magnitude as the wall height doubled from 1.5 to 3.0 m (5 to 10 ft). Increasing the wall thickness from 15 to 19 cm (6.0 to 7.5 in), by simply using the wide side of block instead of the narrow side of the block for contact, increased the transverse load capacity by factors of 1.8, 2.6, and 3.2 for wall heights of 1.5, 2.3, and 3.0 m (5, 7.5, and 10 ft), respectively. The strong correlation between the three critical parameters: compressive strength (f_c), wall thickness (t), and wall height (L) is shown in Figure 6, which represents data from 73 tests including eight different block materials, 4 nominal heights, 4 nominal thicknesses, and 10 compressive strengths. The term $f_c \times (t/L)^2$ is derived from the moment equilibrium requirements of the half-wall loading (Barczak and Batchler, 2006).

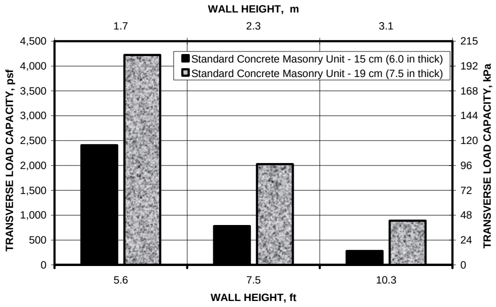

Figure 5. Impact of wall height and thickness on transverse load capacity for conventional concrete masonry block constructions.

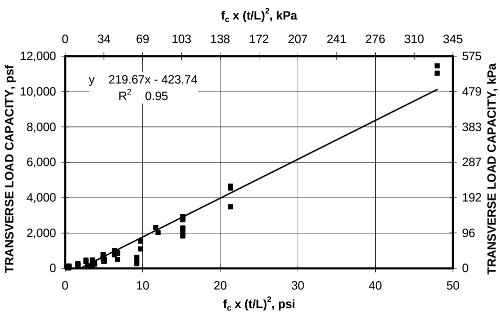

Figure 6. Correlation between critical design parameters (block compressive strength, wall height and wall thickness) and transverse load capacity.

Another factor that can influence the transverse load capacity of a stopping is the convergence of the mine roof and floor, which creates vertical pressure on the wall (Barczak, 2005). The convergence causes increased thrust on the wall that makes it more difficult for the transverse pressure to offset the moment induced by the thrust force to cause the wall to deflect outward, thus resulting in higher transverse load capacity. However, the block integrity is still limited by the stress developed from the overall loading. Therefore, in this case, the transverse pressure and stress induced from the convergence superimpose, so the benefit of the convergence will be lost once the block strength is reached. Since the two stresses superimpose, the wall will fail before the stress induced from the convergence reaches the compressive stress of the block. The example shown in Figure 7 will help to clarify these issues. Shown in the Figure are the transverse load responses from a series of half-wall tests of standard masonry block constructions in which the preload, representing the stress induced from convergence, was incrementally increased from a nominal 345 kPa (50 psi) up to 5,171 kPa (750 psi) for three half-wall heights with a constant wall thickness of 15 cm (6 in). Examining the 1.2-m (46-in) half-wall height data, it is seen that the transverse load increased from 22 kPa (450 psf) to nearly 72 kPa (1,500 psf), reaching a maximum at a preload of about 4.8 MPa (700 psi) on average, with some walls reaching maximum transverse loading at less than 4.1 MPa (600 psi). This represents about half the strength of the block. The amount of convergence required to produce this level of preload will depend on the elastic modulus of the block and the compliance between the block layers and the roof and floor contact with the ends of the wall. Tests on a 1.2-m-high (4-ft-high) half wall constructed from standard (solid) masonry block units required only 2.5 mm (0.10 in) of displacement to produce 2.4 MPa (350 psi) of stress and 3.0 mm (0 12 in) to cause 4.1 MPa (600 psi) of preload, so the amount of convergence required to produce considerable preload is relatively small.

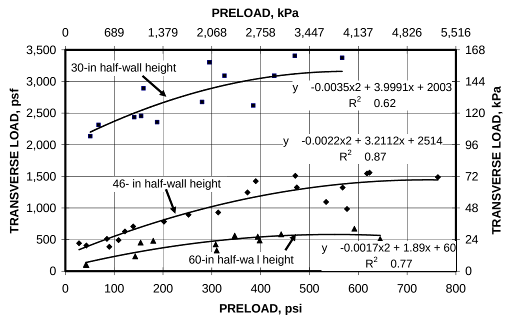

Figure 7. Impact of convergence expressed as vertical preload pressure on stopping wall on transverse load capacity of stopping walls.

Up to this point, the analysis has assumed a rigid arch condition whereby the abutments do not deform. Under rigid arch conditions, the lateral displacement of the wall is controlled by the stiffness and elastic response of the block wall. The transverse load capacity will decrease as the wall stiffness decreases since more lateral displacement will occur. The increase in lateral displacement reduces the force couple provided by the arching thrust and this causes a decrease in the transverse load capacity of the stopping. If the abutments are not rigid, then the lateral displacement will increase further, resulting in a further reduction in the transverse load capacity of the stopping. The problem can be analyzed in terms of the stiffness of the system (Barczak, 2005). The system consists of both the wall and the abutments. Since the wall and the abutments act in series with one another, the system stiffness can be expressed by equation 2.

$$K_{System} = \frac{K_{wall} \times K_{abutment}}{K_{wall} + K_{abutment}} \qquad (2)$$

Where K_{system} = system stiffness,
K_{wall} = wall stiffness, and
$K_{abutment}$ = abutment stiffness.

If the stiffness of the abutment is infinity (perfectly rigid abutment), then the wall stiffness will control the lateral displacement associated with the arching thrust through the deformation of the block as described in the previous section. However, examining equation 2 shows that if the abutment stiffness was equal to wall stiffness, the system stiffness would be reduced by 50 pct. Therefore, a small change in the abutment stiffness can cause significant changes in the arching capability and transverse load capacity of a stopping.

Figure 8 shows the impact of the reduction in system stiffness to 25, 50, and 75 pct of the rigid boundary condition at 3 different wall heights. This assessment is made by relating the lateral wall displacement and arching thrust forces to the system stiffness (Barczak, 2005). It is seen from this Figure that the impact of reductions in boundary stiffness will have a greater impact in terms of absolute reductions in transverse pressure for shorter walls than it will for taller walls. For the example shown in Figure 8, the transverse pressure for the 76-cm (30-in) half-wall height was reduced from 108 kPa (2,256 psf) for the rigid boundary condition to 45 kPa (940 psf) when the boundary stiffness is one third of the wall stiffness, thereby reducing the system stiffness to 25 pct of the rigid boundary condition. This represents a 58 pct decrease in the transverse pressure capacity of the stopping.

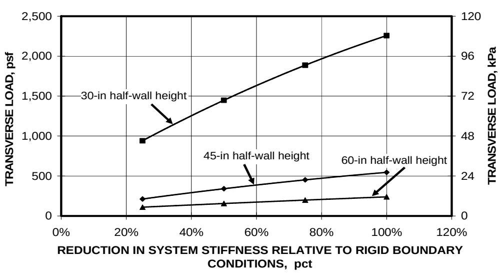

Figure 8. Impact of reduction in boundary stiffness expressed as decrease in system modulus on transverse load capacity of stopping walls.

Figure 9 shows the impact of reductions in system stiffness for a 76-cm (30-in) half-wall height as a function of preload. The Figure indicates the reductions in transverse pressure as a result of reduction in boundary stiffness are reduced as the preload increases. Using the 76-cm-high (30-in-high) half-wall as an example, the 58 pct decrease in transverse pressure which occurred by reducing the system stiffness to 25 pct of the rigid boundary condition, drops to a 7 pct reduction at a preload of 3.9 MPa (567 psi).

5 Conclusions

Stoppings are a key component of underground mine ventilation systems. Permanent stoppings are often

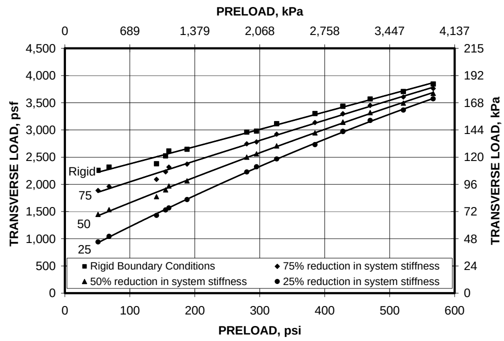

Figure 9. Impact of reduction of boundary stiffness when convergence causes an increase in vertical pressure on stopping wall.

constructed from some form of concrete block, typically dry-stacked to form a wall, equal in thickness to the narrow or wide dimension of the block, and bridging between the mine roof and floor and pillar ribs. The criteria for block stoppings to be suitable for coal mine use in the United States is a minimum of 2 kPa (39 psf) of transverse load capacity in a freestanding loading condition using the ASTM E-72. The authors do not believe that this standard provides an accurate representation of the loading conditions that occur in the mining situation. For dry-stacked stopping constructions, the transverse load capacity under the ASTM E-72 criteria is primarily determined by the tensile strength of the sealant. Any block material, regardless of its physical properties, can be made to pass this test criterion for use in underground coal mines provided the sealant is strong enough and can adhere to the surface of the block.

The restraint provided by the mine roof and floor and coal pillars allows the stopping wall to arch between these abutments as the wall flexes and bends from the application of transverse loading. Arching relies on compressive forces within the wall structure to offset the bending moment induced by the deflection of the wall from the application of transverse loading. For dry-stacked stopping constructions, which have no tensile strength across the joints except for the sealant across the outer edge of the joint, these compressive forces can increase the transverse load capacity of a stopping by more than an order of magnitude compared to the freestanding condition.

A laboratory testing protocol to simulate rigid arching of stopping walls by biaxial loading in the NIOSH MRS was previously developed, verified through field measurements of stopping failures, and used in this study to evaluate several blocks used for mine ventilation stopping construction. The results confirm the theoretical analysis that both the compressive strength of the construction material and the thickness of the wall have a significant impact on the transverse load capacity of a stopping. Therefore, since most blocks are dimensionally anisotropic, constructing the wall with the wide side of the block in contact with the adjacent block layer during wall construction can significantly increase the transverse load capacity of the stopping. For example, increasing the wall thickness from 15 to 19 cm (6.0 to 7.5 in) increased the transverse load capacity of a 2.3-m-high (7.5-ft-high) wall by a factor of 2.6. Conversely, increasing the height of the stopping will reduce the transverse load capacity. Here, the impact can be even more dramatic. The transverse load capacity dropped by nearly an order of magnitude when the 15-cm-thick (6-in-thick) wall doubled in height from 1.5 to 3.0 m (5 to 10 ft). Despite their significance, none of these factors is considered in the current criteria for mine ventilation stoppings.

The full arching potential for any stopping will be realized for rigid boundary conditions, which will then establish the maximum transverse loading capacity for the stopping. Under rigid arching conditions, the lateral displacement of the wall is controlled by the stiffness and elastic response of the block wall. The transverse load capacity will decrease as the wall stiffness decreases since more lateral displacement of the wall will occur. If the abutments are not rigid, then the lateral displacement will increase further, resulting in a further reduction in the transverse load capacity of the stopping. Therefore, a small change in the abutment stiffness can cause significant changes in the arching capability and transverse load capacity. A theoretical assessment of the impact of the boundary stiffness was made by varying the system stiffness, which is the equivalent stiffness of the wall and the roof and floor acting in series with one another. The system stiffness was reduced to 75, 50, and 25 pct of the rigid boundary condition, and the transverse load capacity determined using arching mechanics formulations. An example was given where the transverse pressure for a 1.5-m-high (5-ft-high) wall was decreased by 58 pct by reducing the system stiffness to 25 pct of the rigid boundary condition.

Another important factor in considering the transverse load capacity of a stopping is the axial loading induced from the ground pressures. Even without arching, a superimposed axial or vertical load acting on a stopping wall can greatly increase the transverse load capacity of the stopping by resisting the moment induced by the transverse pressure. For arching conditions, the superimposed axial loading will act to strengthen the force couple created by the arching thrust. The result of the superimposed axial pressure will be that the transverse load development will occur at smaller lateral displacements of the wall, which results in higher transverse loading capacities. Increases in transverse loading by a factor of 5 can be attained with a 2.3-m-high (7.5-ft-high) wall constructed from conventional solid concrete block materials when the ground pressure is increased from 0 to 4.1 MPa (0 to 600 psi).

In conclusion, arch stopping design would be a radical departure from the current freestanding wall design with respect to the ASTM E-72 specifications cited by the CFR. The physical properties of the block and the size of the mine opening would need to be examined to determine the proper design for a stopping application. The sealant would no longer be considered to affect the transverse load capability of the stopping. Since the actual transverse load capacity of the stopping can be determined, the stopping can be designed based on the required transverse load capacity for a specific set of conditions in the mine, as opposed to the current system that permits stoppings of widely varying transverse loading capabilities to be employed in the same environment. This approach should lead to a safer mine environment for the tens of thousands of mine workers in underground coal mines.

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