Development of new protocols to evaluate the transverse loading of mine ventilation stoppings

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ABSTRACT: The Code of Federal Regulations (CFR) requires that the transverse load capacity of stoppings be equal to or greater than traditionally accepted in mine controls, which for block stoppings is generally accepted as 39 psf as referenced in the preamble to the CFR standard. This measure is based on physical testing of a freestanding wall in accordance with ASTM E 72 specifications, where our past research has shown that the dominant parameter is the tensile strength of the sealant. A new protocol based on rigid arch loading of the structure is proposed to determine the true transverse load capacity of block stoppings. Arching is achieved by the restraint of the stopping against the mine roof and floor, whereby compressive forces are developed within the wall. A laboratory procedure using the NIOSH Mine Roof Simulator (MRS) to simulate rigid arching of block stoppings was developed and results verified through full-scale in-mine tests. The rigid arch tests have demonstrated transverse load capacities more than an order of magnitude higher than the ASTM E 72 evaluation method from which the 39-psf requirement is derived. More importantly, the rigid arch tests have shown that the load capability is dependent on the physical properties of the block and geometric properties of the wall and not the sealant.

1 INRODUCTION

In mining, stoppings are used to direct and separate ventilation air courses and are designed primarily to withstand air pressure differentials generated by the mine fan that exert transverse loading against the high-pressure side or face of the stopping. These pressures can range from as low as 0.25 psi in the working sections of the mine to over 1 psi near the area of a bleeder fan. Air blasts from roof falls, gas ignitions, and other potential sources can generate localized areas of significantly higher pressure that can destroy stoppings. As a result, it is critical that the ultimate transverse loading capability of stoppings be given consideration in their design and evaluation.

There are no full-scale tests required for stoppings to determine their load capacity. The current Code of Federal Regulations (CFR) requirement is to test 4x8-ft sections of freestanding walls in accordance with ASTM E-72 specifications (30 CFR, Part 75.333, July 2005). This test inadequately determines the transverse load capacity of actual in-mine stopping constructions when the mine the 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. As a result, the true transverse load capacities of mine ventilation stoppings are not known using the current evaluation testing methodology.

Recently, a new generation of low strength, lightweight blocks has been developed for mine ventilation stopping constructions. While stoppings utilizing these blocks have all passed the current CFR criteria, it is believed that their true transverse load capacity varies considerably. This is because the material strength of the block types varies by as much of an order of magnitude, and the material strength of the different blocks correlates to the arching capability of the restrained wall in the mine during transverse loading. Without such knowledge, the design of mine ventilation systems using these lighter-weight, but lower-capacity alternative constructions can be misleading, potentially exposing the mine to inadequate ventilation control under some circumstances.

The objective of this paper is to describe a new protocol to determine the transverse load capacity of block stopping constructions. Using the unique biaxial loading capabilities of the National Institute for Occupational Safety and Health's (NIOSH) Mine

Roof Simulator (MRS), rigid-arch conditions for stoppings are simulated in the laboratory. Verification of the procedure has been done through full-scale testing of stoppings in a pressure chamber in the NIOSH Experimental Coal Mine and in the underground Longwall Gallery from stopping failure data gathered during full scale explosion testing at the NIOSH Lake Lynn facility. Ultimately, this should lead to more appropriate design criteria and allow regulatory statutes to be developed that will ensure a more accurate evaluation of stopping transverse loading capability.

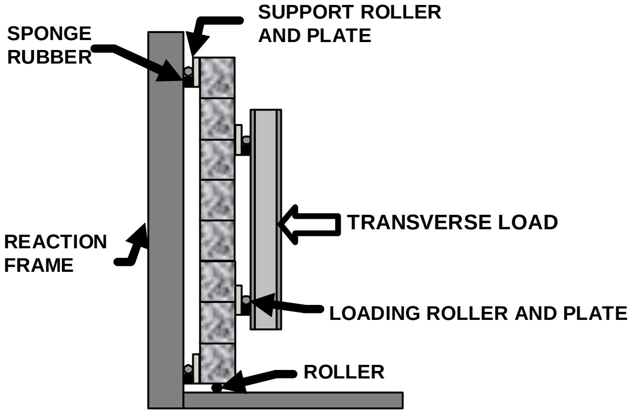

Figure 1. Diagram of test apparatus for conducting E-72 testing of stopping walls.

2 CURRENT CFR CRITERIA FOR STOPPINGS

Part 75.333 Ventilation Controls of the CFR requires that stoppings be tested in accordance with ASTM E 72 specifications.

2.1 *ASTM E 72 Test Specifications*

The procedure requires testing of a nominal 4x8-ft section of wall (ASTM E-72, 1981). The wall is to be constructed in the manner it will be used in the mine, including the application of sealant when specified. The test apparatus is shown in the diagram illustrated in figure 1. The wall is placed on a steel channel which rests on a cylindrical roller to *prevent restrained end conditions*. The axis of the roller is parallel to the face of the wall, allowing rotation to occur without restraint, as the wall is flexed from the application of a transverse load. Two reaction rollers and contact plates positioned at the top and bottom of the wall allow the wall to flex under the application of a transverse load from the opposite face. Again, rollers are utilized *to prevent longitudinal restraint* as the wall flexes. Transverse loading is applied across the width of the wall through a steel contact plate at quarter-height points of the wall. Rollers in the form of a steel pipe are again used to transfer the load from a central I-beam through the contact plates, again to *prevent any rotational restraint* from occurring. As the load is applied, it is required that the load be recorded as a function of the displacement at the mid-span of the wall height. The maximum load normalized to the square foot area of the wall is then defined as the transverse load capacity for the wall. It is also required that three separate walls be tested. The average transverse load capacity from these three tests must exceed 39 psf to comply with the CFR statute.

2.2 *Inadequacies of Current CFR Specifications*

Examination of the mechanics of the wall response to transverse loading reveals the inadequacies of the CFR test procedure. First, it is seen that great care is taken to ensure that there is no longitudinal restraint provided to the wall as the load is applied. Essentially, the wall is considered freestanding and unrestrained from vertical movement as it flexes or bends from the application of the transverse load. The objective of the test is to evaluate the flexural strength of the wall. Any structure that is subject to bending produces tensile stresses on one side of the structure and compressive stresses on the opposite side of the structure. Typically, the tensile strength of the material, being weaker than the compressive strength, controls the capability of the structure to withstand loads that produce bending. Concrete has relatively low tensile strength, but a *dry-stacked* block stopping has no effective tensile strength because the joints are not bonded. Theoretically, the transverse load capacity of a freestanding, dry-stacked stopping would be provided only from the weight of the block, which acts to provide a superimposed vertical load on the structure. Even the heaviest typical blocks, which weigh about 55 lbs, would not provide enough axial loading to meet the 39-psf criteria.

The tensile strength for stoppings constructed in the mine is actually provided by the application of sealant to the face of the wall. First, this is obviously not the primary function of the sealant. In order for the sealant to be effective for controlling the transverse loading, it must be applied to the anticipated low-pressure side of the stopping or the face opposite the side where the transverse load will be applied. If the ventilation pressure could be reversed either intentionally or unintentionally, then the sealant should be applied to both sides of the stopping under these criteria. Since several sealants are available, each with different material properties, then the stopping should only be certified with the specific sealant used in the evaluation test. Furthermore, for a given sealant, the thickness of the sealant contributes significantly to the effective tensile strength and resulting transverse load capacity of the stopping. How thick the sealant is applied in the test program compared to the thickness normally applied to such stoppings in the mine is another issue of concern. The test program should exclude abnormally thick sealant applications, since in-mine constructions are not likely to apply the sealant any thicker than is necessary to prevent air leakage.

3 RIGID ARCH LOADING MECHANISM

In the mine, stopping walls are not freestanding structures as evaluated by the ASTM E 72 test referenced in the current CFR criteria. Stoppings, as constructed in the mine, bridge the distance between the mine floor and the mine roof and are typically wedged in place at the roof interface to provide a tight fit during installation. They also span the full entry width, butted against and typically trenched into the un-mined pillars on both sides. Hence, if the mine stoppings are restrained by the mine roof and floor and pillars, this restraint allows for a completely different loading mechanism to occur, namely arching.

3.1 *Description of Arching*

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 of the wall 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 where the external moment caused by the transverse loading (w x ρ x $L^2/8$ term in equation 1) is resisted by the internal force couple (P x r), where r is defined as the width of the arch and P is the thrust force generated by the arching. This condition is illustrated in the free-body diagram in figure 2 and expressed mathematically by equation 2. This equation can then be solved for the transverse pressure (ρ) as shown in equation 3.

$$\int_0^{L/2} w \times y \times \rho \times dy = w \times \frac{y^2}{2} \times \rho \Big|_0^{L/2} = \frac{w \times L^2}{8} \times \rho \qquad \textbf{(1)}$$

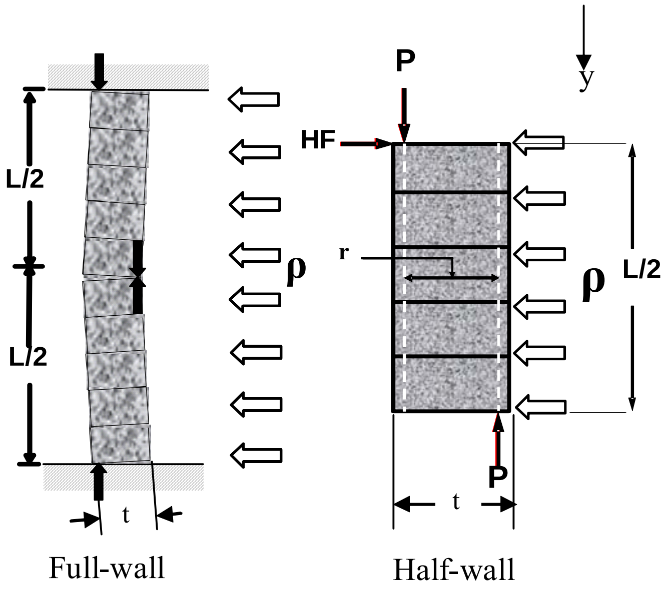

Figure 2. Three hinge arch illustration and free body diagram of half-wall.

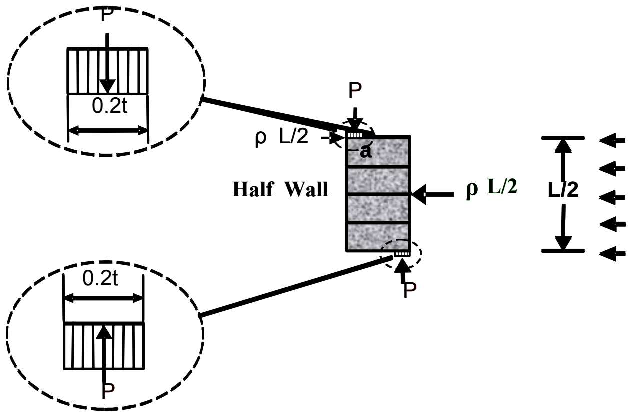

Figure 3. Examination of the thrust force developed in rigid-arching loading conditions.

$$\frac{w \times \rho \times L^2}{8} = P \times r \qquad \textbf{(2)}$$

$$\rho = \frac{8 \times P \times r}{w \times L^2} \qquad \textbf{(3)}$$

Where ρ = transverse load, psi,
L = height of the wall, in,
w = width of the wall, in,
P = resultant thrust force at the hinge points, lbs, and
r = width of the arch, in.

If it is assumed that the arching thrust (P) is controlled by the compressive strength of the block material and the "crush zone" is acting over an area of the block equal to 2/10 the thickness of the wall (see figure 3), then an expression for P can be derived as given in equation 4. As shown in figure 3, this assumption also results in the width of the pressure arch (r) being equal to 0.8 x t. Substituting this expression for r and the expression for P from equation 4 into equation 3 yields a solution for determining the transverse load capacity of a stopping wall (equation 5).

$$P = 0.2 \times t \times f_c \times w \qquad \textbf{(4)}$$

Where ρ = transverse load, psi,
P = arching thrust, lbs,
t = thickness of wall, in,
L = wall height, in, and
f_c = compressive strength, psi

$$\rho = 1.28 \times f_c \times \left(\frac{t}{L}\right)^2 \qquad \textbf{(5)}$$

An example is considered using a 6-in-thick wall that is 72 in high and constructed from concrete blocks with a compressive strength of 1,000 psi. The term $f_c \times (t/L)^2$ equates to 6.94 psi for this example, which computes a predicted transverse load capacity of 8.9 psi or 1,279 psf.

Using these same relationships, it can be shown that the transverse pressure acting on a full-scale stopping can be computed from the measured horizontal force (HF) at the base of a half-wall as used in the MRS laboratory testing from equation 6, where w is the width of the wall and (L/2) is the half-wall height.

$$\rho = \frac{2 \times HF}{w \times (L/2)} \qquad \textbf{(6)}$$

3.2 *Implications of Rigid Arching To Stopping Design*

Rigid arching indicates that the physical properties of the block and the size of the mine opening must be considered to evaluate the transverse loading capability of a stopping for design purposes. 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. These relationships are illustrated in figure 4 for conventional concrete masonry units that have historically been used to construct stoppings. These solid blocks measure nominally 6x8x16 inches and have a unit block compressive strength of 1,330 psi. As seen in the figure, using the 8 in-wide construction nearly doubles the transverse load capacity of the stopping for a

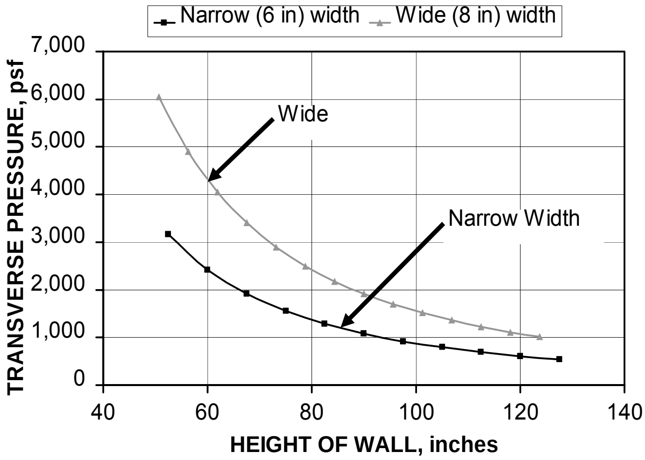

Figure 4. Impact of wall thickness and height on transverse load capacity of a conventional concrete block stopping.

specific construction height. For comparison, for a stopping constructed in a 16 ft-wide by 8 ft-high opening, the wide-side construction would require 192 blocks while the narrow-side construction would require 144 blocks. In other words, for a 33 pct increase in the number of block, the transverse load capacity can be increased by 100 pct. Also, note that the transverse load capacity would drop by a factor of four if the construction height were doubled.

4 SIMULATING RIGID ARCHING THROUGH BIAXIAL LOADING IN THE MINE ROOF SIMULATOR

NIOSH has a unique load frame that was designed to simulate the behavior of rock masses in underground mining operations. It is called the Mine Roof Simulator (MRS). This unique facility's capabilities provide an ideal framework in which to conduct rigid-arch testing of stopping walls.

Since the load frame platens are 20 ft x 20 ft and with a maximum vertical opening of 16 ft, the MRS can accommodate full-scale stopping constructions. The MRS is capable of providing controlled biaxial loading in the vertical as well as one horizontal axis. Up to 3 million lbs of vertical force can be applied through a 24-in vertical stroke of the lower platen and up to 1.6 million lbs of horizontal force through a 16-in horizontal stroke of the lower platen. The loads or displacements in these two axes can be applied individually or simultaneously if desired.

4.1 *Test Protocol for Simulating Rigid Arching*

In order to simulate rigid arching, a half-height section of a stopping wall was placed in the load frame in a typical vertical orientation as it would be in the mine. The upper platen position was adjusted to the height of the block column and was hydraulically clamped to

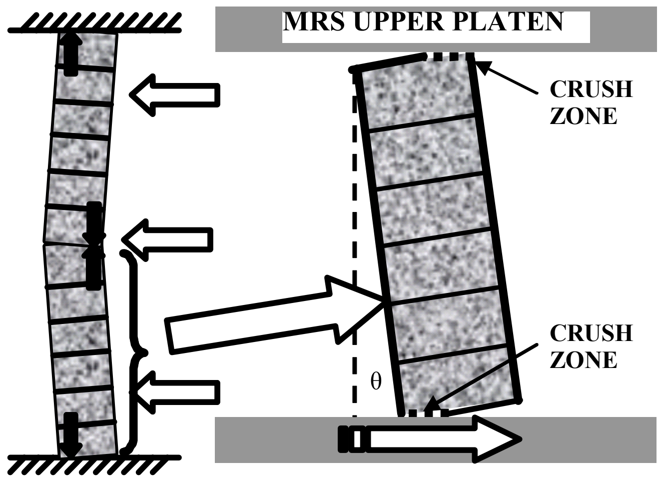

Figure 5. Simulating rigid arching in the NIOSH Mine Roof Simulator.

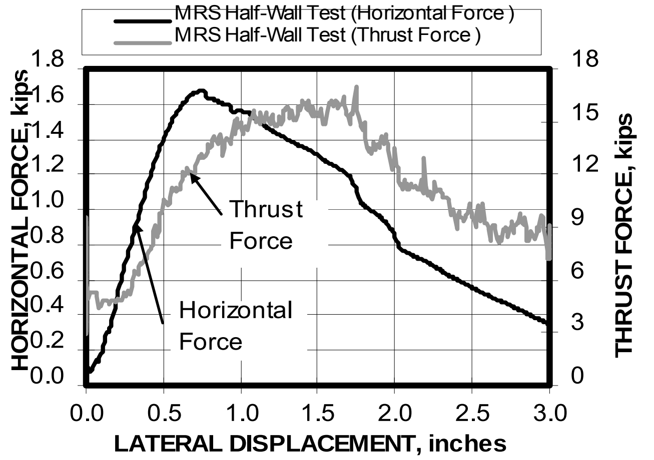

Figure 6. Example test result of 4 course half-wall arch test of Kingsway block stopping wall in the MRS.

maintain its position. The vertical position of the lower platen was commanded to remain constant. Hence, the fixed positions of the upper and lower platen allowed them to act as rigid restraints. The lower platen was then moved horizontally at a constant velocity of 0.5 in/min, causing the wall to rotate (figure 5). As the base of the wall was forced to move horizontally, crush zones were created at the ends of the wall on opposite sides, consistent with the rigid-arch loading mechanism. The horizontal force applied to the base of the half-wall by the MRS was measured and was equated to the transverse pressure acting on a stopping wall using equation 6.

4.2 *Transverse Load Determinations from MRS Half-Wall Testing*

An example of a transverse loading test is shown in figure 6[1]. The test consisted of a single column of lightweight, autoclaved concrete block, stacked four blocks high with the narrow side contact between blocks. This block measures 5.875 x 8.375 x 17.250 in with a density of 42.5 lbs/cu ft resulting in a unit block weight of approximately 21 lbs. Tests conducted on an individual block indicated that the compressive strength was 546 psi. The computed transverse pressure determined from the measured horizontal force during this test was 834 psf as computed by equation 6.

The measured vertical force is equivalent to the arching thrust (P) as defined in equation 4. The arching thrust is a function of the elastic properties of the concrete block and the contact area that develops as the wall rotates. The kinematics of the wall suggests that the contact area will decrease with increasing lateral displacement. This essentially causes an increase in the stress acting on the crushing zone until the compressive strength of the material is reached. Once the compressive (or shear strength) of the material is exceeded, the thrust force will decrease and the transverse pressure capacity of the stopping will decline.

Tests conducted on a similar half-wall constructed from block made from conventional Portland cement, sand, and aggregate material with a compressive strength of 1,330 psi produced a maximum transverse loading of 2,134 psf, or 2.6 times that of the autoclaved block used in the previous test, which is consistent with the difference in material strength. This provides additional validation for the application of arching theory to stopping wall behavior.

5 FULL-SCALE LOAD VERIFICATON TESTING

In order to confirm that arching was the proper loading mechanism controlling the transverse load capacity of mine ventilation stoppings and to verify the MRS half-wall rigid-arch testing protocol, full-scale tests of stopping walls were also administered. These tests were conducted in the NIOSH Experimental Coal Mine at the Pittsburgh Research Laboratory. Test data of full-scale stoppings was also analyzed from NIOSH's explosion testing at the Lake Lynn Laboratory.

5.1 *NIOSH PRL Experimental Coal Mine Tests*

An air pressure chamber was constructed in one of the crosscuts in the mine to provide a facility for static loading of mine ventilation stoppings. Stoppings were constructed in a crosscut measuring approximately 16 ft wide and about 80 in high. The test wall was constructed in a normal dry-stacked fashion. The top of the wall was tightened with wood wedges and the gaps were filled with mortar and sealant to prevent air leakage.

[1]Mention of company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

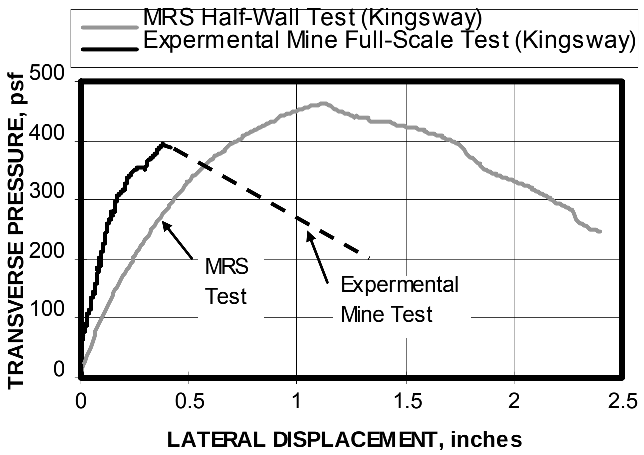

Figure 7. Comparison of MRS laboratory test and full-scale mine test of low strength block stopping.

Pressurized air was injected into the chamber between the barrier and the test wall through the air intake port. The air pressure was increased gradually in increments by adjusting a control valve on the pressure line. This process continued until the air pressure in the chamber blew out the wall. Three displacement transducers were utilized to measure the lateral displacement at the mid and quarter point heights of the wall as the pressure was applied.

5.2 *Test Results and Comparisons to Half-Wall MRS Tests*

Two full-scale wall tests were conducted in the NIOSH Experimental Coal Mine. For direct comparison purposes, these were constructed using the same block materials that were utilized in the MRS laboratory tests. The first test utilized the lightweight autoclaved concrete blocks, and the second test was a wall constructed from the conventional solid concrete aggregate block. Comparisons of the MRS half-wall rigid-arch test to the full-scale mine test are shown in figures 7 and 8. Figure 7 shows that the peak transverse loading for MRS half-wall test was higher than that observed in the full-scale mine test. Examining figure 7, it is seen that the peak transverse pressure for the MRS test occurred at a larger lateral displacement, suggesting that the full-scale mine test may have failed prematurely compared to that observed in the MRS. The full-scale mine stopping also exhibited a stiffer response than the MRS test. This may be caused by loading of the wall from convergence of the mine entry or by a shorter arching height than was considered in the MRS test. As shown in figure 8, only a 4-course and 6-course-high half-wall was tested in the MRS for the conventional concrete block, while the in-mine test was constructed with 10 courses (full-height). Therefore, a direct comparison was not provided. However, it is seen from the figure that, as expected, the full-scale mine test fits between

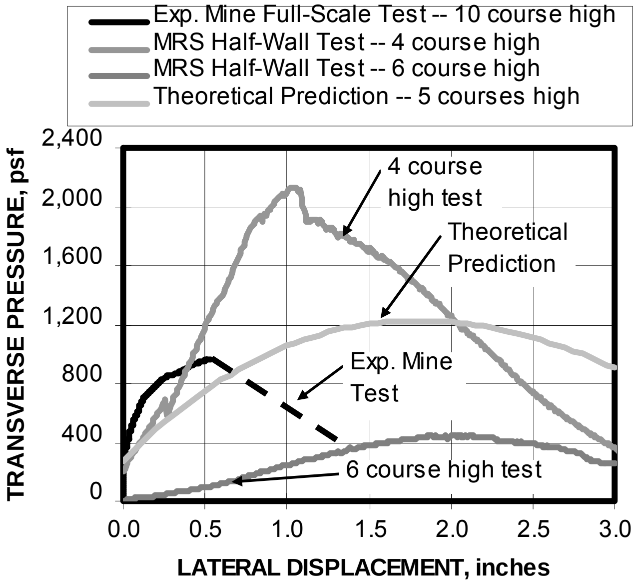

Figure 8. Comparison of MRS laboratory test and full-scale mine test of high strength block stopping.

the two laboratory tests. It is concluded that the MRS laboratory half-wall tests reasonably predict the full-scale mine tests in both cases.

These results are also consistent with the arch mechanics theory presented in the previous section, which indicate that higher walls will have less transverse load capacity than shorter walls and that weaker block materials will provide less transverse load capacity than higher strength block materials. These relationships were expressed mathematically by the $f_c \times (t/L)^2$ term (compressive strength of the material times the square of the ratio of the wall thickness to the wall height) in equation 5. Figures 9 and 10 plot the measured transverse pressure for both the half-wall laboratory tests and full-scale mine tests as a function of the $f_c \times (t/L)^2$ term. The chart shows a strong correlation of the half-wall transverse pressure measurements to this term. Also shown on the chart are the full-scale mine tests, and again, it is seen that the mine tests also fit this correlation very well. The theoretical design curve produced from equation 5 over-predicts the measured responses for the lower $f_c \times (t/L)^2$ values, and more accurately predicts the transverse pressure as the value increases. It is believed that the error lies in the arch thrust moment. The current formulation does not include the lateral displacement of the wall, which occurs throughout the loading history. Lateral displacement reduces the arch thrust moment and the resulting force couple. This topic is currently being addressed in the continuing research at NIOSH.

Additional full-scale transverse loading tests of stoppings were conducted at the NIOSH Lake Lynn Laboratory (Sapko, 2003 and Weiss, 2004). Both hollow-core and solid, high-strength, concrete block stoppings were evaluated in this study. The hollow-core block had an average material compressive

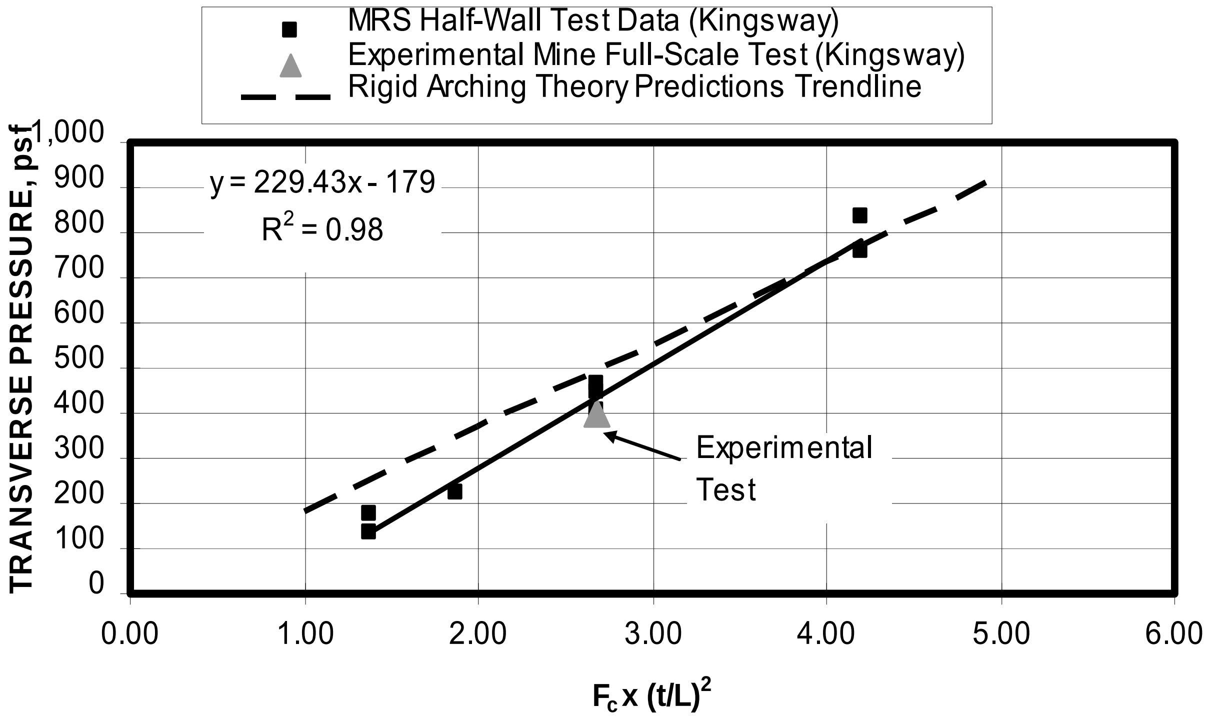

Figure-9. Comparison of MRS laboratory test, full-scale test, and theoretical predictions of transverse load capacity of various stopping constructions using low strength cellular concrete block.

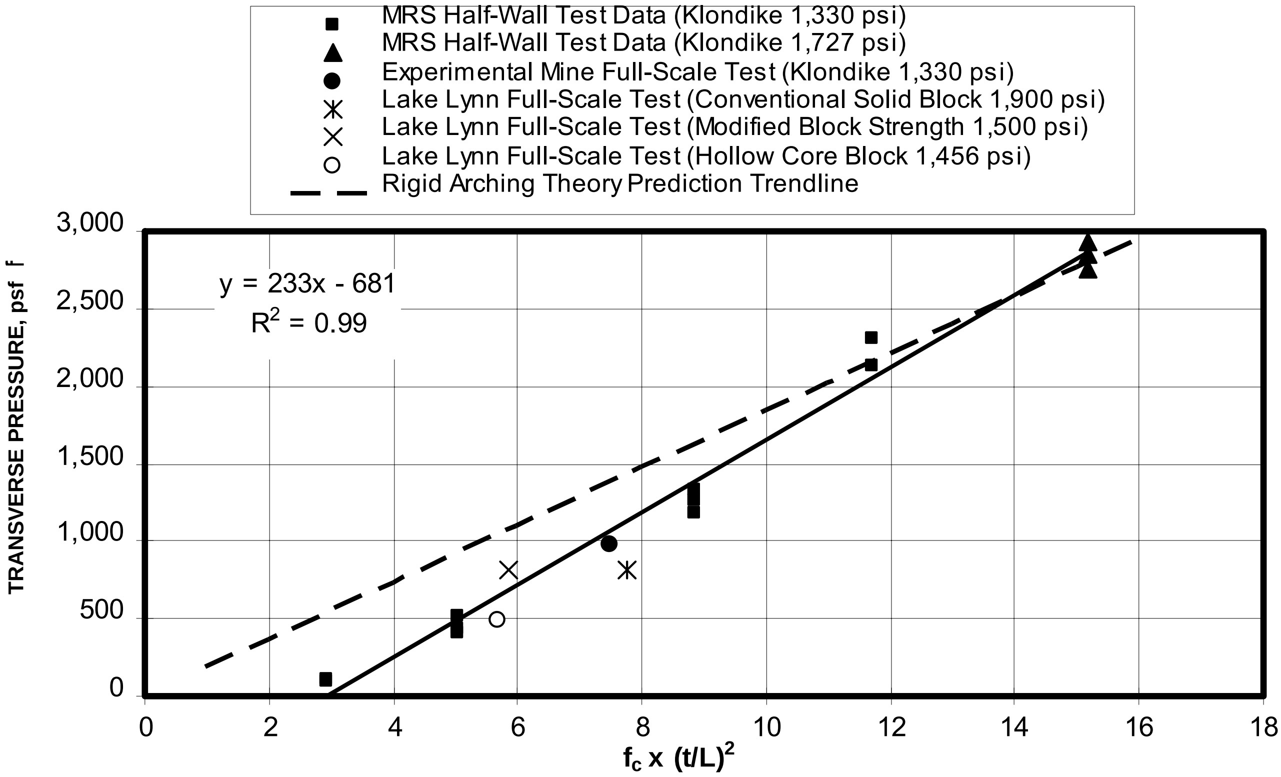

Figure 10. Comparison of MRS laboratory tests, full-scale tests, and theoretical predictions of transverse load capacity of various stopping constructions using conventional solid and hollow core block.

strength of 1,456 psi and the solid block an average material compressive strength of 1,900 psi. Typically, the block strength achieved in a unit block or column of block measurement is considerably less than the material strength tests that are conducted under ASTM specifications on small scale cylinders or cubes. As shown in the chart in figure 10, the mine test data is closer to the MRS laboratory tests when the compressive strengths are reduced to from 1,900 to 1,500 psi. The stopping walls constructed in the crosscuts were 12 courses high (7.5 ft), 6-in thick, and approximately 20 ft in length.

6 SUMMARY AND CONCLUSIONS

Stoppings are a key component of underground mine ventilation systems. Permanent stoppings are often 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 approval of block stoppings to be suitable for coal mine use in the United States is generally 39 psf of transverse load capacity in a freestanding loading condition. This specification is based on ASTM E 72 testing requirements. Based on the work presented, this standard does not provide an accurate representation of the loading conditions that occur in the mining situation if the restraint of the mine roof and floor is considered. 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 has long been recognized as a valid loading mechanism that can more realistically show the increased capability of jointed structures to resist loading induced by bending when end restrained. 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 on the face of the joint, these compressive forces can increase the transverse load capacity of a stopping by two orders of magnitude compared to the freestanding condition.

A static analysis of the arching condition was examined to develop a theoretical relationship for predicting the transverse load capacity of a stopping. The analysis indicates that both the compressive strength (f_c) of the construction material and the thickness (t) of the wall have a significant impact on the transverse load capacity of a stopping. Increasing the thickness of the wall will cause an increase in the force couple developed by the resultant compressive forces acting on the wall, and thereby increase its transverse loading capacity. Conversely, increasing the height (L) of the stopping will reduce the force couple, and thereby reduce the transverse load capacity of a stopping. None of these factors is considered in the current criteria for mine ventilation stoppings. A theoretical design equation to predict the transverse loading was developed using these key factors, expressed by the term $f_c \times (t/L)^2$.

A laboratory testing protocol to simulate rigid arching of stopping walls by biaxial loading in the NIOSH MRS was developed. This process is most easily simulated in the MRS by testing a half-height section of wall. The wall is restrained vertically by the fixed vertical position of the load frame platens, thereby acting as rigid end restraints simulating the mine roof and floor. The lower platen is then moved laterally, causing the base of the wall to displace with the platen and causing the wall to rotate accordingly, similar to the three-hinge theory. Crush zones are created at edges of the half-wall in the areas where these two hinges would occur in a full-height wall. By measuring the horizontal forces applied to the base of the wall by the MRS, the transverse load capacity of the wall can be determined.

Tests were conducted in the MRS on two different block types using this testing protocol. The two block types were selected for study because of their differing physical characteristics. One block was made from a low-density, autoclaved concrete material (546 psi compressive strength) while the other block was made from a more conventional material - Portland cement, sand, and aggregate (1,330 and 1,727 psi compressive strength). Tests were conducted on several wall heights ranging from 5 to 10 ft. For these tests, the transverse load capacity ranged from 138 to 834 psf for the lightweight block and 96 to 2,136 psf for the conventional block. Comparing these results to the 39-psf requirement clearly shows the disparity caused by the assumptions made in the boundary conditions, freestanding as considered in the ASTM E-72 test specification and the rigid arch conditions being proposed here as a more accurate representation of the actual in mine conditions.

The MRS half-wall rigid-arch testing methodology was verified with two full-scale tests of stopping walls in the NIOSH Experimental Coal Mine at the Pittsburgh Research Laboratory and two full-scale explosion tests at the NIOSH Lake Lynn Laboratory. Overall, good agreement was shown between the MRS tests and the full-scale mine tests.

In conclusion, rigid arch stopping design would be a departure from the current freestanding wall design assumed in the ASTM E-72 specifications cited by the CFR. For arch loading conditions, the physical properties of the block and the size of the mine opening should be examined to determine the proper design for a stopping application. The sealant would no longer be considered to impact the transverse load capability of the stopping. This approach, which will be presented and discussed with MSHA and the ASTM, could lead to a safer mine environment for mineworkers in underground coal mines by distinguishing the transverse load capacity of different stopping designs; opposed to the current system that permits stoppings of widely varying transverse loading capabilities to be employed in the same environment.

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