LOAD AND DEFLECTION RESPONSE OF VENTILATION STOPPINGS TO LONGWALL ABUTMENT LOADING - A CASE STUDY

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ABSTRACT

Few studies have specifically measured and documented the large-scale loading behavior and durability of ventilation stoppings to mining induced movements, particularly from longwalls. Ventilation stoppings are more commonly the concern of ventilation engineers, and ventilation stopping response to ground movement has only been documented in an incidental manner. This paper presents the investigations of underground measurements that have been conducted to determine the loading response of stoppings constructed from lightweight aggregate concrete masonry units (CMU). These investigations have produced some interesting results that may prove beneficial, not only for developing and assessing alternative stopping construction techniques, but also for designing and selecting standard construction methods for use in varying mining conditions. For instance, the interface friction that results from wedging a CMU stopping during construction plays a substantial role in its ability to resist both lateral and vertical loads. Although they are not intended for ground support, the study showed that block stoppings can resist vertical loads of at least 2,700 to 3,000 kN. Asymmetric loading of a stopping may result in localized failure of blocks within a stopping, which, depending on the severity, can be a precursor of impending stopping failure. In addition to measurement results and implications, the paper will also present details of field measurement methods used to assess stopping response. Stopping stiffness and material strength characteristics will also be presented.

INTRODUCTION

In conjunction with a project designed to evaluate alternative stopping construction materials, CONSOL Energy (CONSOL) recently initiated an underground field study to assess the behavior of concrete block ventilation stoppings at a southwestern Pennsylvania mine. With the assistance of the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH), several gateroad stoppings were instrumented with convergence sensors and load cells. The data collected from the field study are being used, along with test data from the NIOSH's Mine Roof Simulator (MRS) and from CONSOL=s modified E-72 test apparatus, to provide insight into the response of concrete block ventilation stoppings to mining-related ground movements, particularly those that occur during longwall retreat. This study will primarily discuss the field study and is intended as a first step toward improving understanding of the strength and deformation properties of ventilation stoppings. Ultimately such understanding could lead toward the development of design criteria to help maximize the efficiency of stoppings with respect to ventilation, ground control, economic, and safety considerations.

UNDERGROUND STUDY SITE

The study site is located in a southwestern Pennsylvania coal mine operating in the Pittsburgh coalbed. The site, as shown in figure 1, is located between crosscuts 33 and 35 of a longwall gateroad, approximately 485 m from the panel startup room and 2,700 m from the panel recovery area. The gateroad is the first headgate of a new block of panels being developed. It was driven utilizing three entries, with the track situated between the belt and return (future tailgate) and crosscuts driven at right angles to the entries. Entries and crosscuts were both driven 4.9 m wide by 2.1 to 2.4 m high. Entry centers were 18.3 and 42.7 m and primary crosscut centers were 84 m. Development was oriented at a 23° angle clockwise from the east west direction.

A total of four stoppings were instrumented at the study site, two between the headgate (belt) and track entries and two between the track and (future) tailgate entries. Two of the instrumented stoppings were constructed of trial alternative lightweight concrete blocks and two of lightweight aggregate concrete masonry units (CMUs) commonly used at the mine. Due to logistical problems and proprietary considerations, the alternative concrete block stoppings will only be discussed to a limited extent in this paper. In addition, and as anticipated, the stoppings between the headgate entry and track entry were removed 30 to 80 m ahead of the face, thereby limiting their value toward this study.

The most useful data collected were from the lightweight CMU stoppings built successively between the track and tailgate entries at crosscut 33 (figure 1). Although the original project plan was to leave all instrumented stoppings between the track and tailgate entries in place through both phases of longwall mining, mining logistics made it necessary to remove these stoppings slightly less than 100 m before the first longwall pass. They were subsequently replaced with new stoppings several days after the face passed beyond their respective crosscuts.

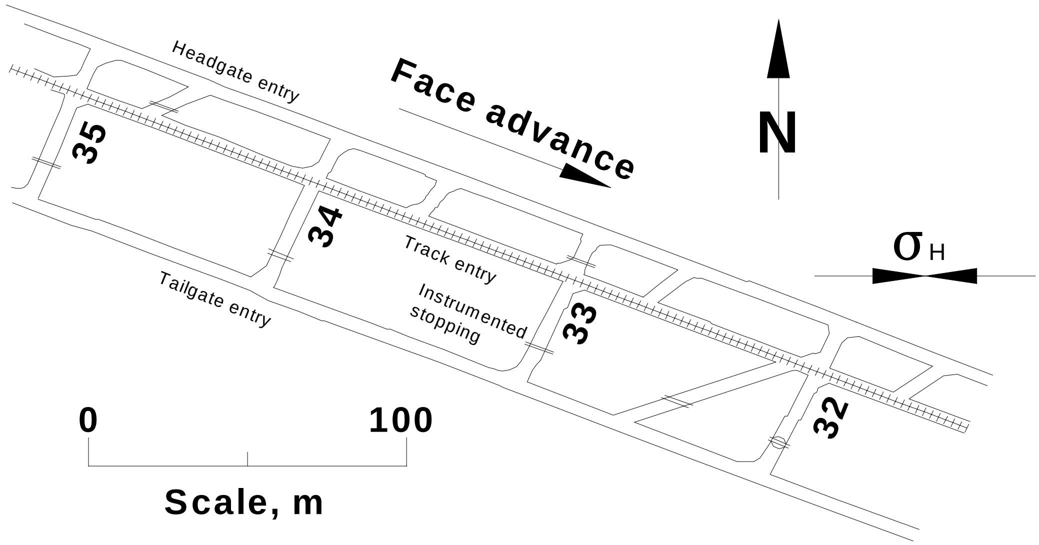

Figure 1. Study site

GEOLOGY, STRESS AND GROUND CONDITIONS

The Pittsburgh coalbed averages approximately 2.1 m in the study area, including a 0.2 m parting and a 0.3 m upper split. The roof rock generally consists of 1.8 m of thin-bedded silty shale overlain by interbedded sandstone and sandy shale. The floor geology at the site was not directly observed, although nearby corehole data suggest that the immediate floor consisted of 0.15 to 0.6 m of shale and fireclay underlain by 0.3 to 1 m of limestone and limey shale. The study site lies below a stream valley, with overburden ranging from 190 to 240 m. The maximum principal horizontal stress direction at the study mine had been previously measured at approximately N90°E.

Although the entries and crosscuts, which were oriented at N23°E within the study site, were generally observed to be in good condition, cutters were observed in many of the crosscuts,. In most instances, these cutters migrated toward the outby rib of the crosscuts and occasionally progressed into the tailgate entry, where they soon terminated. Cutters were found to have a strong influence upon the convergence and loading patterns observed in the stoppings at this site. Some spalling was noted on highly stressed ribs near the study site, typically initiated at the parting. As indicated by the apparently competent floor geometry, little to no floor heave was observed in the vicinity of the study site.

STOPPING CONSTRUCTION

The instrumented stoppings were built by mine masons using dry-stack methods considered standard practice at the mine (figures 2 and 3). The only significant deviation from normal dry-stack practice was the installation of the flatjack load cells above the ninth block course. The stoppings were built by laying an initial course of blocks lengthwise and flat (shortest dimension perpendicular to the floor) across the entry in a previously leveled area of the crosscut. Rock dust was used to help provide an even bed for the blocks. The remaining courses were laid upright, without mortar. A 50 mm thick crush block, made of phenolic foam, was placed above the fourth course. As construction proceeded, the stoppings were periodically wedged along the ribs and eventually at the roof line. Wood blocks and wedges were used as needed to fill the remaining openings. After the stopping was in place, it was sealed on one side with an appropriate thickness of sealant, in this case a surface sealant that, in part, contained fiber and latex. All exposed wood was also covered on both sides with sealant. At the study site the stoppings were approximately 2.5 m high, 4.8 m wide and required 11 or 12 courses of block.

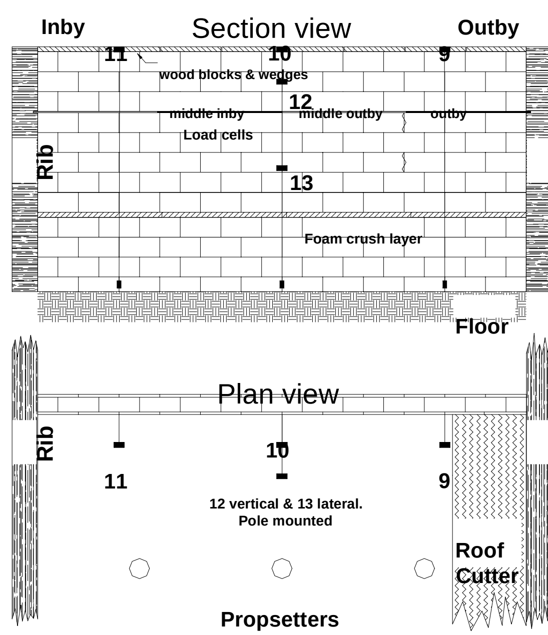

Figure 2. Stopping at crosscut 33 showing construction and instrument locations

Figure 3. Photo of the replacement stopping at 33 crosscut

CONCRETE BLOCK PROPERTIES

Three of the lightweight aggregate CMUs used in the stoppings were tested in the laboratory to determine their dimensions, density, water absorption, and strength characteristics. The blocks, collected from the mine, were tested as per ASTM procedure C140 - 96b for testing Concrete Masonry Units (1). The block dimensions, weights, densities, and moisture absorption characteristics are shown in table 1. Compressive strengths, stiffness values, and maximum loads are also shown in the table, along with their averages.

Table 1 - Physical Properties of Lightweight CMUs

Dimensions:	CMU		
	S2	S3	S4
Height (mm)	194	194	191
Width (mm)	143	143	143
Length (mm)	396	396	396
Ambient Weight, (kg)	19.10	19.25	18.31
Saturated Weight, (kg)	20.33	20.34	19.64
Oven dry Weight, (kg)	17.63	17.62	16.76
Ambient Density (kg/m^3)	1869	1743	1756
Oven dry Density (kg/m^3)	1759	1608	1607
Ambient absorbed water (%)	8.3%	9.2%	9.2%
Max water absorption, (%)	25.0%	25.0%	26.8%
Comp. Strength, (MPa)	17.9	15.4	20.2
Tang. Stiffness, (kN/mm)	602	408	948
Secant Stiffness, (kN/mm)	397	300	423
Max load, (kN)	1015	870	1144
	AVERAGES		
Comp. Strength, (MPa):	17.8		
Tang. Stiffness, (kN/mm):	652		
Secant Stiffness, (kN/mm):	373		
Max load, (kN):	1010		

INSTRUMENTATION

Convergence sensors were installed on all instrumented stoppings, while load cells were installed only on the tailgate-side stoppings (figures 2 and 3). The convergence sensors consisted of spring-loaded string pot position transducers, which were mounted to the roof at the nearest roof strap and connected to the base of the stopping by a wire run to an eyebolt screwed into the second course of concrete blocks. Two additional sensors, measuring roof-to-floor convergence and stopping lateral movement were mounted on a vertical spring-mounted pole, which was located near the center and approximately 0.6 m laterally from the stopping.

Loads were monitored using specially fabricated steel flatjacks approximately 1219 mm long by 165 mm wide by 12 mm thick calibrated in the NIOSH ‘s. Each stopping contained four load cells, installed above the ninth course of block, and positioned end-to-end, so that the total stopping load could be measured

INSTRUMENTED STOPPING RESPONSE

During the course of the first longwall retreat, two separate lightweight CMU stoppings were built in crosscut 33, between the track and tailgate entries. The original stopping was built during gateroad development and was removed when the first longwall face was 115 m inby the crosscut to accommodate transportation of supplies to the longwall face. The replacement stopping was built three days later, in a similar manner to the first, when the face was 27 m inby. Due to the unanticipated removal and reconstruction sequence, load cells used in the original stopping had to be salvaged, recalibrated, and used in the replacement stopping. One of the cells was damaged during removal and handling. Since no replacement was available, the cell was reinstalled in the replacement stopping to preserve the symmetry of the stopping. The damaged cell was placed on the inby side of the stopping, since a roof line cutter had been observed on the outby side of the crosscut, the effect of which was considered to be significant to stopping response.

Convergence Response

The cumulative convergence of both stoppings built in crosscut 33 is graphed on figure 4. Convergence during the five day period, from October 18 to 23, after the original stopping was removed and prior to installation of instruments on the replacement stopping, was estimated from data trends. During this period, all convergence sensor locations were estimated to have converged an additional 8 mm, except inby side sensor 11, which was estimated to have moved about 1 mm.

Up until the removal of the original stopping, with the face 117 m from the center of the crosscut, convergence rates measured by sensors 9, 10 and 11 (outby, middle and inby) were approximately constant, at 0.25 mm/day. Recording of data from the replacement stopping began when the longwall face was almost even with the crosscut. At that time the convergence rates had increased to about 3 mm/day. Convergence rates began to increase rapidly when the face passed 41 m outby the site, with the outby side of the stopping exhibiting a significantly higher rate. Convergence rates peaked when the face was approximately 60 m outby the crosscut; instantaneous convergence rates for sensors 9, 10 and 11 being 68, 33 and 8 mm/day, respectively. The rates then began to decline rapidly until the face was 175 m outby (approximately 0.8 times the overburden), to approximately 1.5 mm/day across the stopping. When the face was 474 m outby the crosscut (approximately 2.2 times overburden depth) convergence rates stabilized at approximately 0.25 mm/day, which was essentially the original convergence rate prior to the first longwall pass.

Visual observations suggest that the convergence across crosscut 33 resulted from a combination of typical longwall side abutment load and the presence of a cutter roof condition on the outby side of the crosscut. It is surmised that the cutter allowed the roof to rotate, as if cantilevered about a hinge on the inby rib. Although this cutter was observed shortly after development mining, it did not show signs of significant movement until the approach of the longwall face. It is not clear from the data whether side-abutment loading or the horizontal stress concentration ahead of the face (which, because of the east west direction of the maximum stress, would not have had an effect on crosscut 33 until the face had passed) caused the increase in convergence rates. However, the large difference between the convergence rates on the inby and outby sides of the stopping suggests that the presence of the cutter had as much, if not more impact on stopping loading than did the vertical loading of the pillars. It should be noted that, although the instruments could not differentiate the floor and roof movements, few visual signs of floor heave were observed in this or the nearby crosscuts.

Lateral Movement

The lateral movement for both the original and replacement stoppings at crosscut 33 is shown in figure 4. The original stopping bowed only a few millimeters toward the tailgate. The replacement stopping began to bow rapidly toward the headgate at the same time as the stopping began to converge and take load. The bowing reached 31 mm after a week and then reversed, stabilizing around 22 mm, before increasing again in late January 2001. On April 11, with the second panel only 140 m away, the bowing reached a maximum of 36.5 mm. The instruments were then removed prior to stopping removal to facilitate tailgate ventilation.

Although a small portion of the bowing of the stopping could have resulted from differential convergence between the stopping blocks, wood wedges, and the floor bearing surface, the majority is believed to be the result of squeezing of the crush block layer, which was intended to protect the stopping from entry convergence damage. Most of the measured bowing (31 of 36.5 mm) took place during the period of maximum vertical convergence, which coincided with the squeezing of the crush block. Although stopping failures caused by rotation of concrete blocks about soft-inclusion layers have been observed in the field, installation of these layers near the bottom of the stopping typically minimizes the magnitude of the rotation. Since neither the stopping at crosscut 33 nor any other stopping near the study site was observed to fail as a result of instability, it may be assumed that lateral displacements on the order of 20 to 30 mm are not sufficient to cause an instability failure to concrete block stoppings.

Loading Response

Figure 5 shows the load cell data for the replacement stopping, beginning on October 23. No data are presented for the load cells in the original stopping, all of which measured loads less than 9 kN, which is only slightly greater than the zero error of the load cells. Significant loading on the outby load cells of the replacement stopping began when the first longwall face was approximately 60 m outby the crosscut, about 12 hours after the convergence rates began to increase rapidly. The outby and middle outby cells loaded rapidly, reaching loads of 500 and 400 kN, respectively, by the time the face was 175 m outby the crosscut. The middle inby load cell indicated almost no load change during this period. As with the convergence, the loading rates declined rapidly from their peaks within a short time after the face had passed.

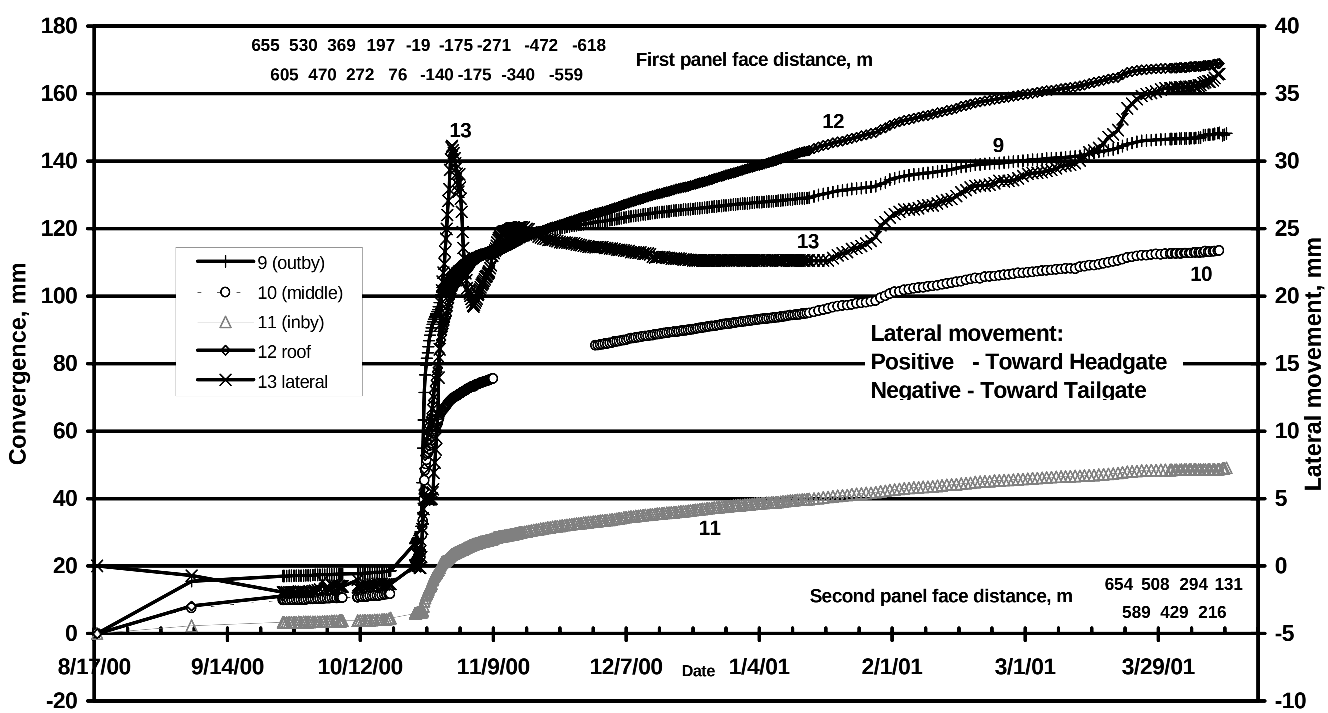

Figure 4. Total convergence at crosscut 33 location. Distances from the face to crosscut 33, in meters, are indicated.

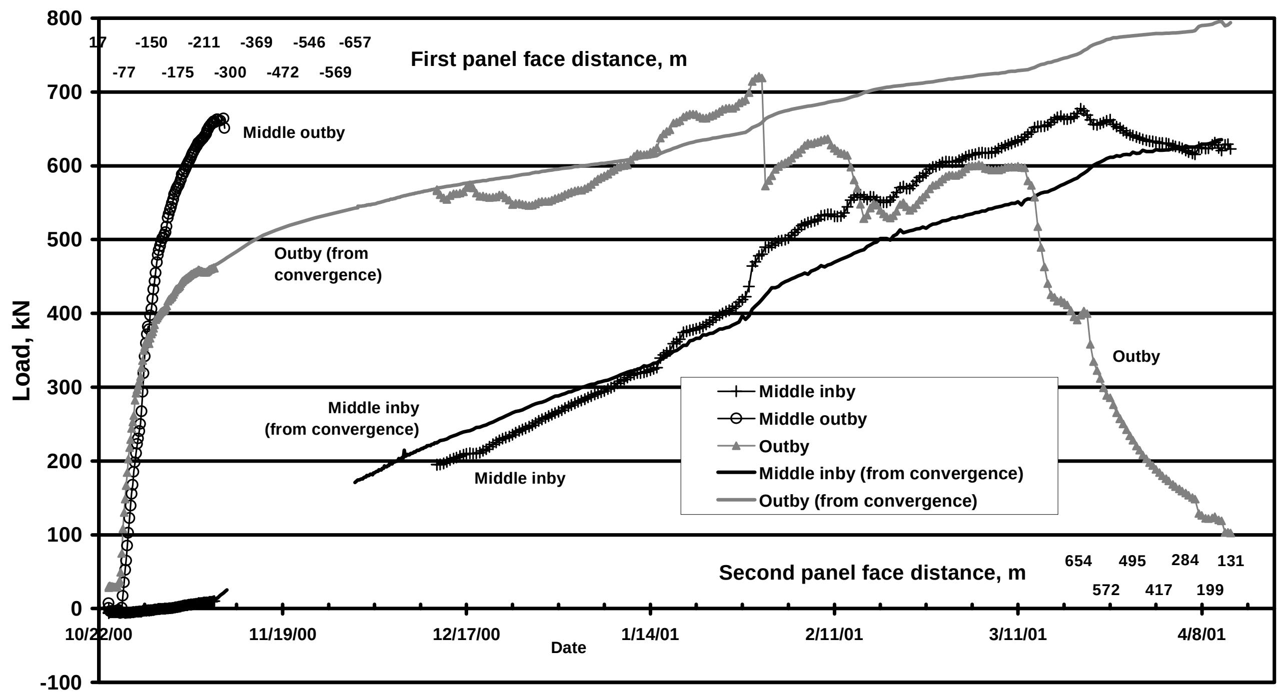

Figure 5. Loading curve for replacement stopping at crosscut 33. Distances from the face to crosscut 33, in meters, are indicated. The numbers are centered on the time when the face was that distance away. Distances to the first longwall face are at the top of the graph, to the second at the bottom. Negative numbers indicated that the face was outby the crosscut. Position numbers are staggered for readability.

The lag between stopping convergence and loading resulted from the presence of the soft crush blocks. During the lag periods the outby side of the stopping converged 33 mm and the middle of the stopping converged 16 mm. Once the crush blocks converged 55 to 60% of their original thickness, the stopping began to resist significant loads. This is consistent with laboratory tests, which show that the strength of these crush blocks is only 0.1 to 0.17 MPa, and that significant load increases occur at about 70% of the block thickness.

The loading data were complicated by damage to two cables on November 8, when the face was 260 m outby the crosscut, and by a leak in the middle-outby load cell, which appears to have begun around November 10. Data from the leaking middle-outby load cell after November 10 are invalid and are not shown in figure 5. The two power cables to the middle-inby and outby cells were disconnected by a roof fall on November 8 and were not repaired until December 12. Stiffness values calculated from the load-to-convergence ratios were combined with convergence data to estimate the loads during this period. These convergence-based load estimates are plotted for the outby and middle-outby cells. For the period after December 12, the estimates are within 16% of the measured loads.

These load data show that the stopping attained considerable load resistance without failing. Based upon the performance of the outby load cell, located where the highest loads were developed, the ultimate load capacity of the stopping appears to be in excess of 2,700-3,000 kN. This is the equivalent of about three, large (1.5 x 1.8 x 0.76 m), 4-point wood cribs loaded to maximum capacity. Note that tests conducted in NIOSH's MRS show that the strength of 6-in wide normal and lightweight aggregate CMU stoppings, constructed in a typical dry-stack manner, can reach as much as 5,000 and 3,750 kN, respectively, under ideal conditions.

Stiffness Estimates

Figure 6 shows the load versus displacement curves for several combinations of the crosscut 33 stopping load cells and convergence sensors. As graphed, the stiffness is the slope of the curves, with the units being kN/mm. Although these curves appear quite variable, they all consist of two linear regions: an initial, near-horizontal region through 20 to 50 mm of convergence, and a second region with a much higher stiffness at larger displacements. The horizontal region indicates the initial stopping stiffness due to the presence of the crush block layer. For all practical purposes, the initial stopping stiffness, which was essentially zero, represents the stiffness of the crush block. The second stiffness, which occurred after the crush block was completely flattened, represents the stiffness of the CMUs, with a roof line wooden end constraint. After the crush blocks were completely flattened, the calculated stiffness values ranged from 6 to 32 kN/mm. For comparison, tests conducted under ideal conditions in NIOSH=s MRS produced stiffness values for 6-in wide dry-stacked normal and lightweight aggregate CMU stoppings, of 450 and 310 kN/mm, respectively. Both the wide range in the computed stiffnesses and the large difference between the field and laboratory-derived stopping stiffness estimates suggest this is a subject that warrants additional study.

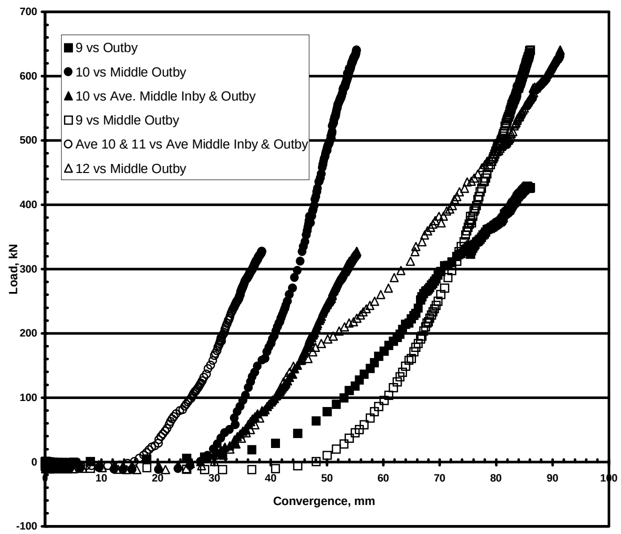

Figure 6. Load displacement graph for replacement stopping at crosscut 33. Curve slopes indicates stiffness

There are at least two likely reasons for the wide range of calculated stiffness values, both attributable to the stopping instrumentation. First, while the load cells were 1.2-m long sensors that measured average loads, the convergence sensors measured at discrete locations, not always aligned with the center of the load cells. As such, there were no pairs of convergence and load data that corresponded exactly to the same location on the stopping. Second, out-of-plane convergence measurements could also produce variations in calculated stiffness values, since the roof line convergence transducers were mounted on roof straps rather than at the top of the stopping. This is illustrated by the significant differences in convergence data from sensors 10 and 12, both of which were located near the center of the stopping, but laterally separated from it by 0.3 to 0.6 m, respectively. These data suggest that convergence close to the stopping was reduced by the presence of the stopping, the adjacent roof support, or both. The variations in the stopping convergence rates could, as a result of the placement of the instruments on the stopping, result in a wide range of stiffness estimates.

The difference between the field and laboratory derived estimates of stopping stiffness was quite large, with the laboratory estimate 10 to 50 times greater than the field estimates. One possible explanation for the disparity is that higher convergence on either side of the stopping, and in particular at the sensor locations on the straps, may have tended to underestimate the stiffness. The wide range in the computed field stiffness estimates supports this hypothesis. Another possibility is that the differences are real and that the field constraint conditions and construction methods tend to produce a much softer structure. Laboratory test walls are built on flat, stiff steel platens, which are more uniform, thus making it possible to construct walls whose stiffness more closely approaches that of the individual blocks. Both possibilities may apply.

STOPPING PERFORMANCE

Source of Loads

The primary source of stopping load appeared to have been convergence caused by cutter roof in the crosscuts, which in turn was produced by the action of horizontal stress on weak silty-shale roof. The cutters were observed during development mining and reactivated as the first longwall face passed. Side-abutment stress may also have contributed to the stopping loading, but the uneven distribution of the convergence, with the greatest convergence on the outby or cutter side of the crosscuts, suggests that the cutter played the predominant role. The headgate stoppings were removed when the face was between 40 and 100 m inby and experienced only moderate (less than 26 mm) convergence. Due to the presence of the crush blocks, loads on the headgate-side stoppings were most likely very small.

Lateral Strength Observations

Although complete data were collected only from the crosscut 33 stoppings, a significant event occurred to the alternative lightweight block tailgate stopping, located at crosscut 35, when it failed prematurely. As in the case of crosscut 33, it was necessary to remove the original stopping in crosscut 35 and replace it several days later. In this case however, a roof fall occurred between the track entry and the middle of the crosscut a few hours after the instruments were installed on the replacement stopping, between 2 and 4 days after the replacement stopping had been built. At that time, only the outby side of the stopping had begun to take load, again due to a cutter on the outby side of the entry. At the time of the roof fall, the outby side load cell indicated only a 104 kN load, the middle-outby load cell a 43 kN load, and the inby side load cells less than 11 kN. Based upon the locations of the blocks, the lack of significant convergence, and the relatively low loads, it is surmised that the force of the air blast from the fall, combined with the resulting nearby roof disturbance, pushed down the inby three quarters of the stopping. The remaining portion of the stopping stood loaded for a period of 6 hours before the load began to gradually drop to zero. The crosscut 35 stopping was rebuilt, but the instruments were not reinstalled.

This incident demonstrated that a moderate pre-load, in this case 104 kN, producing a vertical pressure of 0.6 MPa, effectively increased the lateral strength of the stopping. The validity of the field observation is also confirmed by theory and laboratory tests. Plate theory (2) indicates that fixed end-constraints provide greater resistance to plate rotation, and hence to lateral plate displacement, than simply supported ends, which allow rotation at the edges. It is surmised that in stoppings, as small set loads from wedges or loads produced by mine convergence are introduced, the points of contact between the stopping and the roof, rib and floor begin to act more like a fixed support, due to increases in end-support friction and stiffness (the latter as a result of gap reduction). Additionally, the interface friction between blocks will increase, thereby increasing their resistance to sliding.

Laboratory tests conducted by CONSOL using a modified E-72 test fixture also confirm the effect of this pre-loading. The E-72 test is an ASTM standard test (3) for determining the lateral strength of wall segments. It is also used to validate the strength of stopping walls in coal mines. In the standard vertical test, the wall sections are not constrained on any side. However, in tests conducted by CONSOL, the E-72 load frame was modified to allow the walls to be wedged in the frame, thereby simulating mine roof and floor constraints (Figure 7). The resulting tests indicated that 6-in wide dry-stacked walls, typically capable of supporting lateral loads of approximately 2.7 kPa in a free standing configuration, could support lateral loads as high as 5.0 kPa with tight roof line wedging (Figure 8). This indicates that end-constraint and pre-loading are important factors in controlling the lateral strength of block walls.

Figure 7. E-72 test fixture with test in progress, just prior to failure. The fixture has been modified to allow wedging to provide constraint at the top. The air bag that generates the lateral load is visible to the right of the test wall, near the center of the figure.

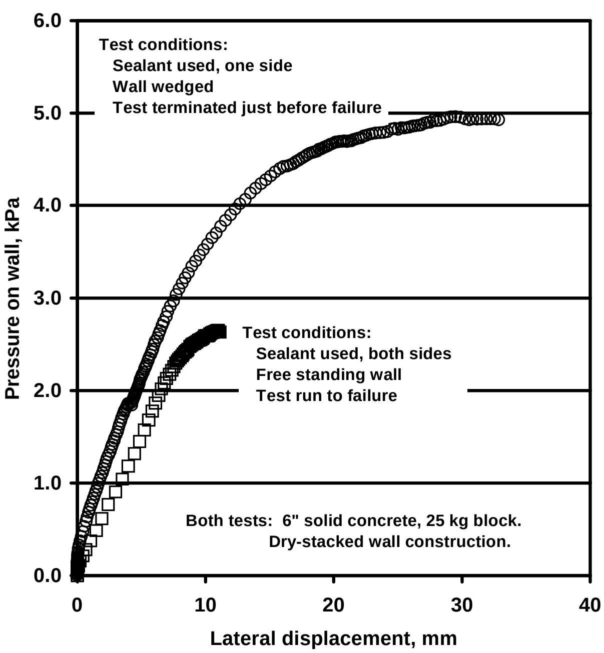

Figure 8. Comparison of the lateral strength of wedged versus free standing walls, tested in the E-72 apparatus of figure 7.

Practical Stopping Construction Considerations

The east west oriented maximum horizontal principal stress produced roof cutters in many of the crosscuts that tended to run toward and then along the outby ribs. The effect of the cutters was to produce differential convergence rates across the stoppings, with the greatest convergence on the cutter or outby side. This observed trend suggests that, in such instances, man doors could be better protected by moving the doors as far as possible toward the inby sides of the stoppings. The cutter trend also suggests that the efficiency of the secondary support occasionally installed adjacent to these stoppings for protection from the vertical loading, could be optimized by concentrating supports along the outby crosscut ribs.

Soft Inclusions

The crush blocks used in this study appeared to be fairly predictable in their effect on stopping stiffness and convergence. Generally the system stiffness was essentially zero until the convergence reached 55 to 60% of the crush block thickness, and reached a maximum when the total convergence reached 70 to 120% of the crush block thickness (the latter value indicating that convergence was taking place in stopping components other than the crush block). The effect of the crush block on the lateral stability was not determined, although it should be noted that most of the lateral movement (31 of 36.5 mm) took place during the period when the crush blocks were being squeezed. After the crush blocks were squeezed, the bowing actually decreased, possibly indicating that during the crushing process, concrete CMUs were rotating around the crush block layer, and that once this layer was crushed flat, the blocks were forced to rotate back to a more level orientation. This hypothesis is consistent with the lateral stopping measurements, which show the bowing reversing after the crush blocks were completely flattened.

The crush blocks were introduced in order to protect the stoppings from convergence damage. It is likely that in many instances they perform this function, especially in places where ground movements are primarily time dependent, such as in cases of floor heave. However, in cases of roof movement, there is a question as to whether crush blocks prolong stopping life or instead permit additional movement that can be damaging to the roof, thereby accelerating roof movements, and subsequently, stopping loading. While it is recognized that CMU stoppings are not intended as roof control devices, it is obvious that they have the capacity to resist very high loads. Early development of this capacity, which is not possible when crush blocks are included in a stopping, may make it possible for them to prevent this acceleration of the roof movement, thus allowing the stoppings to protect themselves. The combination of crush blocks in a stopping, along with stiff secondary support, could produce the same effect, without causing high loading of the stopping.

The available data are ambiguous concerning the above considerations, since neither the roof nor the stoppings failed in the study. Additionally, it was not the intent of the study to assess roof conditions and roof stability. While the constant rate of convergence, beginning in December 2000 and continuing until the stopping was removed in April 2001, suggests that failure of stopping 33 was inevitable (given sufficient time before its removal), and that the soft inclusion helped to extend the life of the stopping, the data did not resolve the question of whether the use of a stopping without crush blocks could have led to a reduced initial convergence rate, that would have helped to stabilize the roof, thereby reducing subsequent convergence.

At this point the authors want to note that they recognize that yieldable stopping designs have been developed and are available to the mining industry. Some of these designs are capable of significant convergence without failure and the decision to use such products will depend upon economic, ventilation, performance and ease of construction considerations.

CONCLUSIONS AND RECOMMENDATIONS

This study has provided valuable technical data regarding the in situ response of typical dry-stacked CMU stoppings to longwall abutment stresses. The data will be useful for future reference in comparing similar type stoppings under varying conditions or alternative stopping designs and materials. The authors believe that improvement in the efficiency of ventilation stoppings, with respect to ventilation, cost and safety considerations, can best come from an improved understanding of their response to, and interaction with, variable underground loading conditions.

Of some significance is the need to reconcile the difference between the in situ and laboratory stiffness measurements, since large-scale laboratory testing has great potential for efficiently and rapidly assessing stopping designs. Toward this end, additional underground study is warranted. Such in situ testing can provide insight into the in situ loading mechanisms and the interactions between the stoppings and the ground, which, in turn, may also be of value for laboratory testing.

The study confirmed that conventional ventilation stopping designs are capable of providing substantial resistance to roof movement. The lightweight aggregate CMU stopping described in detail in this paper demonstrated a load capacity of at least 2,700 kN, without failure. Large scale laboratory simulations suggest that the maximum capacity of 6-in wide stoppings constructed of normal-weight aggregate CMUs could approach 5,000 kN. This is equivalent to three large four-point wood cribs. Although it is not suggested that ventilation stoppings can or should be considered as roof supports, it is obvious that under some conditions they do provide substantial load resistance, and therefore may be capable of controlling roof and floor weighting in order to protect their own integrity.

This study has raised the question as to how and when yielding stopping systems or soft inclusions should be designed and/or utilized in underground block stoppings. In some instances, such as in cases of floor heave, a soft inclusion may increase the longevity of a stopping. However, it is possible that in other instances, allowing such deformation may lead to accelerated roof loading that could lead to stopping failure unless additional support is used.

The study has also shown that the loads and convergence rates that stoppings may be required to withstand over the length of their operating life can vary greatly, particularly when subject to multiple longwall loading cycles. In this instance, the cutter roof conditions in the track to tailgate crosscuts, which may have been exacerbated by horizontal stress concentrations due to the longwall retreat, appear to have been the major contributor to the convergence and loading of the stoppings. Additionally, stoppings do not react to average loads, but rather entry specific loads that may vary significantly across an entry. Ultimately, to maintain its integrity, a stopping will need to resist, or otherwise deform with, the worst-case entry condition.

An unusual failure of one of the instrumented stoppings provided data that suggested the value of moderate loading to the lateral strength of a CMU stopping. This was further demonstrated by modified E-72 lateral load tests that proved the significance of wedging, or pre-loading. It is believed that such pre-loading can be as significant to CMU lateral strength as the strength of the stopping component materials and the manner of their construction.

Finally, in addition to furthering the understanding of stopping response to longwall mining, the results of this study also provided practical insight for improving stopping construction at sites under similar conditions. It was observed that cutters on the outby side of the entries lead to significantly higher convergence rates on that side of the stoppings. This suggested that critical or sensitive stopping elements, such as man doors, could be better protected by moving them to the inby side of the stopping. Additionally, it may be possible to improve the efficiency of the supplemental supports used to protect the stoppings, by concentrating the supports in the areas most likely to be affected by cutter roof or floor movements.

REFERENCES

1. American Society for Testing and Materials. Standard Test Methods of Sampling and Testing Concrete Masonry Units. C140-96b. *Annual Book of ASTM Standards: Volume 4.05*, 1997, pp 1-8.

2. Timoshenko S., Woinowsky-Krieger S. Theory of Plates and Shells. McGraw-Hill Book Company, Inc., New York, NY, 1959, pp.580.

3. American Society for Testing and Materials. Standard Test Methods of Conducting Strength Tests of Panels for Building Construction. E72 - 98 Annual Book of ASTM Standards: Volume 04.11, Building Constructions., 2000, pp 1-11.