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PUMPABLE ROOF SUPPORTS: DEVELOPING DESIGN CRITERIA BY MEASUREMENT OF THE GROUND REACTION CURVE

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ABSTRACT

Pumpable roof supports provide an alternative longwall tailgate roof support and have grown in usage during the past few years. Heintzmann Corporation has been installing pumpable roof supports at the RAG Resources Emerald Mine in western PA since 1998, where they have provided effective roof control in their longwall tailgates. Despite the success of these supports in this application, questions remain regarding critical design issues for optimizing the use of this support technology. The support loading profile is characterized by a high initial stiffness with peak loading occurring at less than one inch of convergence, followed by significant load shedding with a post failure capacity comparable to that of wood cribbing. Therefore, the key to optimizing the support utilization is to provide sufficient load density to prevent convergence from occurring beyond the peak loading capacity. This requires an understanding of how the supports interact with the ground conditions, hence measurement of the ground reaction curve. In order to obtain this information, pumpable roof supports were instrumented to measure support loading. Roof deformation and roof-to-floor convergence measurements in the vicinity of the instrumented supports were also made. The experimental parameters for the installation were the support spacing and water-to-solids ratio of the grout, which controls the grout strength and ultimately the maximum capacity of the support. The study clearly shows that at this mine a 24-inch diameter support is fully capable of providing adequate ground control under depths of cover of 750 ft as only 50 pct of the available support capacity was utilized outby the longwall face. It was also shown that the 2.00 to 1 water-solids ratio, despite providing a slightly softer support response, is sufficient for maintaining the same degree of roof control provided by the traditional 1.75 to 1 grout mix. The 10-ft spacing of the supports did not cause any ground control problems outby the face. However, inby the face the performance of the support is degraded once the peak capacity of the supports is exceeded. It appears that the large load shedding behavior, which is characteristic of this support following peak loading, allows the immediate roof to separate. When this happens, the support is unable to regain control of the roof in time to prevent failure of the immediate roof beam.

INTRODUCTION

Conventional wood cribbing has been the traditional form of secondary roof support in longwall tailgates. In recent years, several alternative support technologies have been developed, including pumpable roof support systems. As the name implies, a pumpable roof support is one in which the support is formed in place in the mine entry by pumping material, such as a cementitious grout, into some form of a containment structure, typically a bag that is hung from the mine roof (figure 1). One major advantage of the pumpable roof support system is that it reduces the material handling difficulties that are common with most other forms of standing roof support, thereby expediting the installation process as well as reducing material handling injuries which are prevalent with many other support systems (1-2).

Figure 1. Pumpable roof support being installed in a longwall tailgate.

Heitech[1], an affiliate of Heintzmann Corporation, has been installing pumpable roof supports in the Emerald and Cumberland (RAG American Resources) mines near Waynesburg, PA for the past four years. The Heitech pumpable roof support uses a two-component grout that has successfully been pumped for distances of over 15,000 ft through surface boreholes at these mines. The key ingredient in the grout is a calcium sulfo-aluminate (CSA) component that provides a fast set up time with a high yield solution of cementitious material with a compressive strength of approximately 1,000 psi after cementation. The CSA material is not available domestically and is currently imported by Heitech from England. This has prompted an effort to optimize the design

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

and utilization of this support system, both to improve its performance and reduce the installation cost. Efforts to optimize the bag design, reduce the diameter of the support from 30 to 24 inches, and improve the logistics of the support installation have helped to reduce the costs to its current level of about $120 per meter of entry when the supports are installed in a single row on 8-10 ft center-to-center spacings. At this cost, the support system is competitive with other alternative support technologies that are used to replace conventional wood cribbing in longwall tailgates in several other mines. The goal of this study was to focus on the performance aspects and to provide data that will help to further optimize the support design.

Figure 2 illustrates the loading characteristics of the Heitech pumpable roof support from full-scale testing conducted in the National Institute for Occupational Safety and Health's (NIOSH) Mine Roof Simulator. The support loading profile is characterized by a high initial stiffness with peak loading occurring at less than one inch of displacement, followed by significant load shedding with a post failure capacity comparable to that of wood cribbing. Hence the key to optimizing the support utilization is to prevent convergence beyond the peak loading capacity from occurring in areas where critical roof support is needed. Control of the roof depends on a certain level of support capacity. The question then becomes "what needs to be done to ensure that the peak loading does not occur?" If the loading environment is bad-controlled within the realm of the available support capacities, meaning the equilibrium of the roof and floor is related to the support resistance, then this can be accomplished by installing the proper number of supports to provide a support load density that will establish equilibrium of the rock mass before the convergence reaches a level where peak support capacity will occur (3). However, all longwall mining operations have some degree of displacement-controlled loading, meaning that some convergence will occur regardless of the support system in use. For example, pillar yielding cannot be prevented by any man-made standing support. Hence, pillar yielding produces roof-to-floor convergence of the tailgate, which induces displacement on the pumpable support, regardless of its size, design, or the number and arrangement of supports installed in the longwall tailgate (4). Floor heave and compressional (buckling) failures of the bolted roof beam due to horizontal stress may also have elements of displacement-controlled loading. A critical question then becomes, "how much displacement-controlled loading is occurring in a particular longwall tailgate?" If it is more than 1 inch, then the pumpable roof supports will be pushed beyond their peak capacity, leaving only their residual capacity to support the mine roof, and this may not be adequate in all circumstances.

Another issue is "how far inby can the pumpable roof supports maintain stability of the immediate roof in gassy mines that require ventilation be maintained in the active tailgate to the first open cross cut alongside the caved gob?" Does the roof fail once the peak loading capacity of the support is exceeded or does the post failure support capacity help to maintain roof stability and form an open air course to the first open cross cut alongside the caved gob?

In an effort to answer these questions and establish design criteria for pumpable roof supports, a study was conducted at the Emerald mine where support loading, roof deformation, and roof-to-floor convergence were measured. This paper documents the results of this study, assesses the degree to which the supports are loaded relative to their peak loading capacity, and draws conclusions regarding the overall design requirements necessary to provide effective roof support with this support technology.

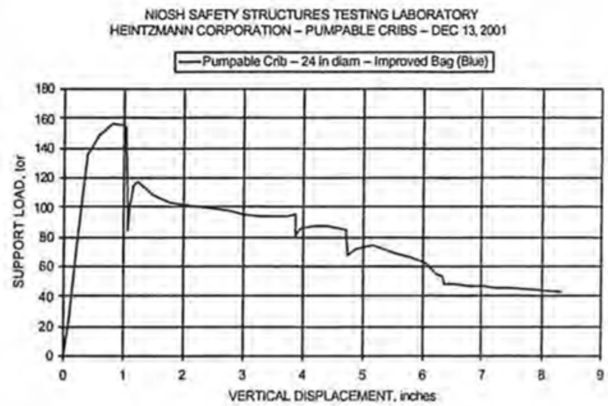

Figure 2. Loading profile of 24-inch diameter (Heitech) pumpable roof support.

PROJECT DESCRIPTION

Objectives

The focus of this investigation was to evaluate the interaction of the pumpable roof support with the strata in the longwall tailgate, both outby and inby the longwall face. The specific objectives of the underground monitoring were: (1) to determine the loading of the support as a function of face position relative to the capacity of the support, (2) evaluate the roof deformation and roof-to-floor convergence and resulting stability of the immediate mine roof in the longwall tailgate, (3) determine the difference in behavior in the intersections compared to the entry areas adjacent to the pillars, and (4) determine trends in loading profiles and roof control relative to the three instrumented test sites where the grout strength and support spacing were varied.

Support Specifications and Control Parameters

Three test sites consisting of a single row of 24-in-diameter, Heitech pumpable roof supports spanning over a distance of three pillars were evaluated in the study. The supports were located in the center of the longwall tailgate. The locations of the instrumented supports for each of the three test sites in the study area are illustrated in figure 3. As shown in figure 3, both pillar areas as well as intersections were evaluated in the study, with a sufficient transition zone between the instrumented supports to ensure that the impact of the experimental parameters was properly observed. The experimental parameters for the roof support system were the water-to-solids ratio, which controlled the grout strength, and the spacing of the supports. The specifications for the individual study areas are defined as follows:

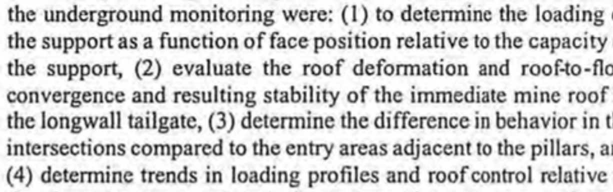

Figure 3. Location of instrumented tailgate supports in the study areas.

- Site A (conventional design) – 24 in diameter supports – 1.75 to 1 water-solids ratio – 8 ft center-to-center row spacing.
- Site B (lower strength and softer design) – 24 in diameter supports – 2.00 to 1 water-solids ratio – 8 ft center-to-center row spacing.
- Site C (lower support density) – 24 in diameter supports – 1.75 to 1 water-solids ratio – 10 ft center-to-center row spacing.

Mine and Tailgate Description

The Emerald mine, where the study was conducted, is located in Greene County in western Pennsylvania where it is mining the Pittsburgh coal seam. The immediate roof in the study area was typical for the Pittsburgh seam consisting of thinly interbedded rider coal and weak shale or claystone layers with a CMRR of 40. The seam height varied from 6.5 – 7.0 ft in the study area under a depth of cover of approximately 750 ft. The goal was to select the area with the highest depth of cover to evaluate the worst case overburden loading. The pillars in the three-entry gate roads were on 184-ft cross-cut centers and 100-ft entry centers (figure 3) providing an ALPS stability factor of 1.82, compared to the minimum recommended stability factor of 1.2 for these conditions. The location of the study site was at blocks 15, 16, and 17, positioning the instrumented supports approximately 2,700 ft from the end of the 10 North longwall panel. Site C was mined through first, followed by sites B and A respectively as the longwall advanced.

Instrumentation Description

The instrumentation arrangement for each of the three study areas is shown in figure 4. Instrumentation was at the mid-pillar and intersections. A permissible Campbell Scientific multiplexor and data logger was used at each of the three test sites to provide continuous recording of the instrumentation. The cables for the sensors were run outby to allow monitoring of the instrumentation inby the face on Sites B and C while site A was monitored until the face area reached the intersection. The cables were laid against the coal pillar and covered with the grout used to fill the pumpable supports. This grout layer would protect them from damage due to rock falls and pillar sloughage. In the intersections, the cables were covered with a foaming agent, typically used to seal around the perimeter of ventilation seals and stoppings, to provide protection to the cables in these areas.

Load was measured on five supports at each of the three study sites: (1) two adjacent supports at the mid-pillar area, (2) two adjacent supports in the entry at the intersection, and (3) one support in the crosscut corner at the intersection. Loading was measured by a 26-in-diameter hydraulic flatjack cell. The flatjacks were filled with water and calibrated to a pressure of 600 psi in the NIOSH Mine Roof Simulator. The flatjack was placed on top of the support prior to being fully filled with grout, and then it was pushed tightly against the mine roof as the support was completely filled. The flatjack was instrumented with a 1,000 psi pressure transducer and gage to record the pressure as the support load developed.

Roof-to-floor convergence was measured at each of the supports that were instrumented to measure support loading. The convergence was measured approximately 1 ft from the pumpable roof support. Twelve-inch-long rebar bolts were grouted into the mine roof and floor to provide anchors which would eliminate movements of the skin of the mine roof and floor in the convergence measurements. A displacement transducer was mounted to the plate on the roof anchor and connected to a floor anchor by a wire to measure the roof-to-floor convergence. Roof-to-floor convergence was also measured between the two, flat-jack-instrumented supports located at the pillar area and intersection to help evaluate the zone of influence of the pumpable support.

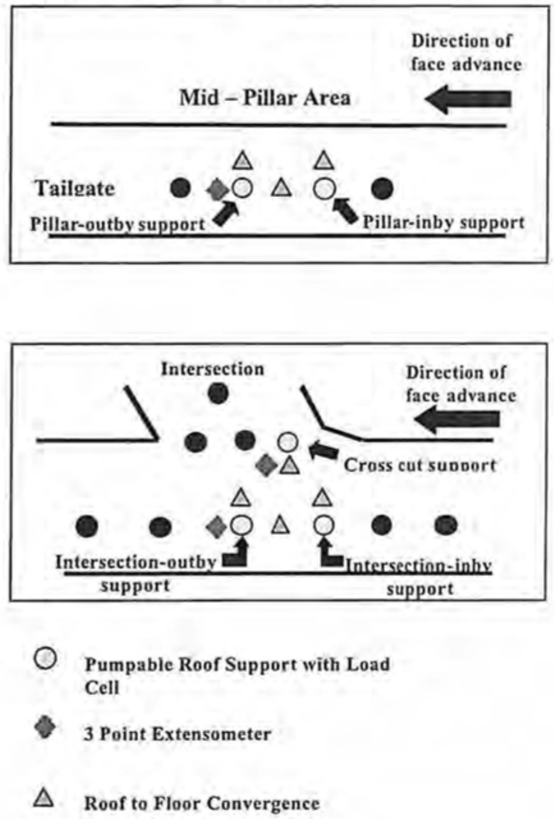

Figure 4. Instrumentation arrangement for each pumpable roof support area of study.

Roof deformations were also made near three of the instrumented supports: (1) one in the pillar area, (2) one in the intersection area, and (3) one in the crosscut. Three-point extensometers were installed at levels of 2, 7, and 10 ft from the roof horizon in each location. These measurements were also made approximately 12 inches from the support.

MATERIAL PROPERTY TESTS AND FULL-SCALE LABORATORY SUPPORT TESTS

Laboratory tests were conducted on 3 x 6 in grout samples collected during the pumping of the supports. The samples were tested by NIOSH approximately 28 days from the pouring of the supports and by an independent laboratory a week prior to the time the instrumented areas were mined through (approximately five months from the time when the samples were taken during the pumping of the supports). The averages of the three-sample test results are shown in table 1. As expected, the material in Site B exhibited the least strength because the water content in these supports was higher. Since Site A and C had the same water content, it was expected that they would produce similar compressive strengths. This was true in the 28-day test conducted at NIOSH, but in the tests conducted when the longwall mined by the instrumented areas, Site C exhibited a 21 pct higher strength than the average of Site A. Another unexpected result was that the material apparently lost strength from the tests in November, 2002 to March, 2003. Since the tests were conducted at different labs, the difference in results may be due to sample preparation (i.e., sample size and end conditions).

It is expected that the grout with the higher water content would not only lower the compressive strength of the grout, but also reduce its modulus of elasticity, thereby reducing the initial stiffness of the full-scale support. Figure 5 illustrates the load-displacement response of full-scale supports tested in the NIOSH Mine Roof Simulator. It can be seen from this graph that the initial stiffness of the support with higher water content was lower. The lower support stiffness indicates that the support with a 2.00 to 1 water-solids ratio would require more roof-to-floor convergence to provide the same load as the support with a 1.75 to 1 water-solids ratio. The supports with the higher water content also produced lower peak loads in this full-scale test, which is expected since the grout strength was lower. However, the water content does not influence the post failure characteristics of the support, since the bag confinement controls the post failure response.

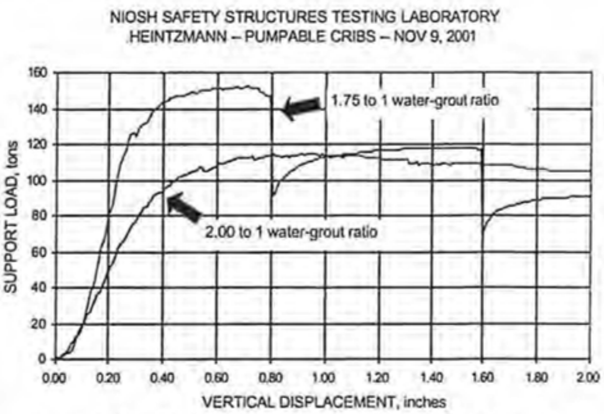

Figure 5. Loading profile of 1.75 to 1 and 2.00 to 1 water-solids ratio showing reduced stiffness and peak capacity of support with the higher water content.

Table 1. Summary of grout compressive strength tests for tailgate performance inby and outby the face.

Site Identification	Cure time is 28 days		Test at time of longwall passing (Cure time is approx. 5 months)	
	Avg Compressive strength, psi	Standard Deviation	Avg Compressive strength, psi	Standard Deviation
Site A	1126	108	852	79
Site B	912	88	758	50
Site C	1272	64	1032	76

Table 2. Summary of support loading for all three instrumented support sites.

Support ID (see fig. 4)	SITE A				SITE B				SITE C			
	Face loading, tons[2]	Pct of peak load[3]	Peak load, tons	Peak load (distance Inby, ft)	Face loading, tons	Pct of peak load	Peak load, tons	Peak load (distance Inby, ft)	Face loading, tons	Pct of peak load	Peak load, tons	Peak load (distance Inby, ft)
Pillar Area Supports												
Pillar Inby	36	30	N/A		49	42	116	39	18	15	121	26
Pillar Outby	62	52	N/A	43[4]	53	55	97	42	12	10	N/A	
AVG	49	41			51	49	106	40	15	13	121	26
STD	18	16			3	9	13	2	4	4		
Intersection Area Supports												
Intersection Inby	18	15	N/A		N/A		N/A		4	5	78	49
Intersection Outby	38	32	N/A		30	25	N/A		17	14	N/A	
Xcut	25	21	N/A		17	29	58	67	17	16	108	53
AVG	27	23			24	27	58	67	9	12	93	51
STD	10	9			9	3			7	6	21	3
Summary of All Instrumentation												
Overall AVG	36	30		43	35	38	90	49	12	12	102	43
Overall STD	17	14			21	14	30	15	6	5	22	15

[2]Face loading refers to the support loading when the support is at the longwall face as it is being mined. This represents the maximum outby loading on the supports.
[3]Peak loads a re the maximum loads measured underground, which always occur inby the longwall face. Peak loads were not obtained at Site A. The pct of peak load values for Site A are an approximation using an assumed peak load of 120 tons which is representative of the maximums observed in this underground study.
[4]Loading was approaching peak load of other supports at this distance inby the face.

MINE TEST RESULTS AND ANALYSIS

An assessment of the underground study is broken down into the following areas: (1) tailgate performance outby the face, and (2) tailgate performance inby the face. Table 2 provides an overall summary of the support loading and figures 6a, 6b, and 6c show the support loading as a function of the face position for each support in Sites A, B, and C respectively. Table 3 summarizes convergence measurements taken at the longwall face. The study applies only to the active tailgate loading, with inby and outby referenced to the face position (inby referring to the mined out or gob area and outby referring to the un-mined section of the panel). In all figures referring to face position, inby is denoted as a positive tailgate location and outby is denoted as a negative tailgate location with the face being represented as 0. The supports were not instrumented in time to collect data during the first panel mining prior to the entry becoming an active tailgate for the study panel.

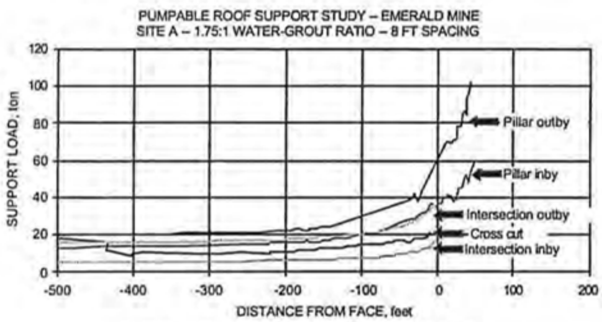

Figure 6a. Support loading for Site A.

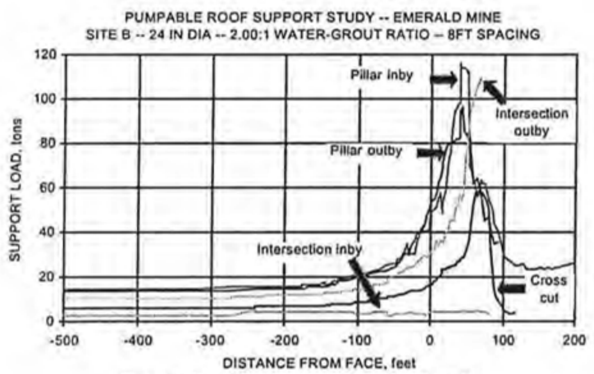

Figure 6b. Support loading for Site B.

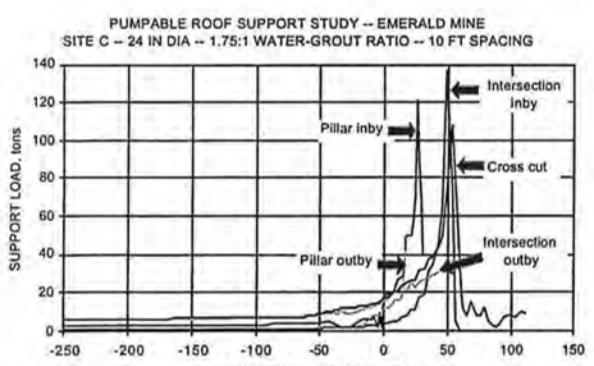

Figure 6c. Support loading for Site C.

Table 3. Summary of maximum outby convergence.

Support ID (see fig. 4)	SITE A	SITE B	SITE C
	Convergence, inches	Convergence, inches	Convergence, inches
Pillar Area Supports			
Pillar Inby	.457	.364	.209
Pillar Middle	.332	.480	.265
Pillar Outby	.392	.500	.267
AVG	.394	.448	.247
STD	.063	.073	.033
Intersection Area Supports			
Intersection Inby	.450	.639	.406
Intersection Middle	.400	.352	.155
Intersection Outby	.430	.881	.215
Xcut	.250	.500	.336
AVG	.383	.593	.278
STD	.091	.225	.114
Summary of All Instrumentation			
Overall AVG	.387	.531	.265
Overall STD	.074	.182	.084

Tailgate Behavior Outby the Face

Overall, the support loading outby the longwall face was minimal, and the tailgate conditions were excellent. The chart in figure 7 shows the average support load and convergence for each of the three test sites as the longwall face passed the instrumented supports. Site A and B had similar load developments, approximately 35 tons on average, but the convergence in Site B was on average higher than Site A. This is consistent with the pumpable crib material properties for Site B has the higher water content, which as previously shown, reduces the material modulus and initial stiffness of the support. As shown in figure 7, Site C exhibited considerably less loading and convergence outby the face than the other two sites. It is also seen that Site C felt the effects of the front abutment later (closer to the face) than did site A or B (figure 8). The response observed in Site C suggests that there was some difference in the ground conditions at Site C compared to A and B. It would be expected that Site C with the widest spacing (10 ft compared to 8 ft for Sites A and B) and consequently the lowest support density, would have the highest loading and convergence. The precise differences in conditions remain unknown. Factors that could result in less convergence would include (1) less pillar yielding, and (2) more competent roof and/or floor. Unfortunately, the uncertainty of conditions makes a direct comparison of the outby performance of Site C with Sites A and B more tenuous.

Analysis of the roof deformation data showed that there were essentially no significant separations of strata within the first 10 feet of the roof outby the face in the instrumented areas. Some movement was detected at the 2 and 7 ft horizon as the face approached to within 25 feet of the instrumented supports in a few areas indicating some local roof loading was beginning to occur. The magnitude of the deformation at the face was still less than 0.05 inches, which is not considered to be significant in terms of roof stability or pumpable support loading. Figure 9 shows the data from the mid-pillar area roof extensometer in Site

C as an example of the most severe roof deformation outby the face.

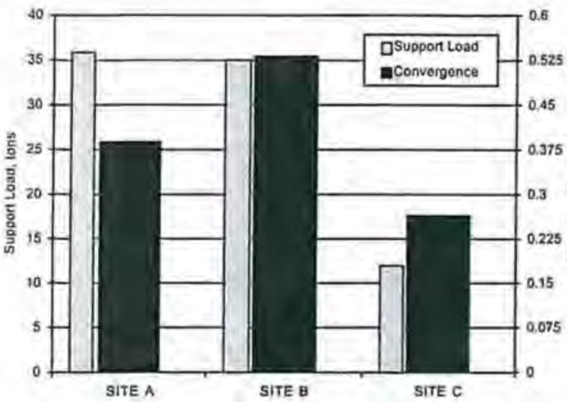

Figure 7. Average support load and convergence recorded at the three instrumentation sites.

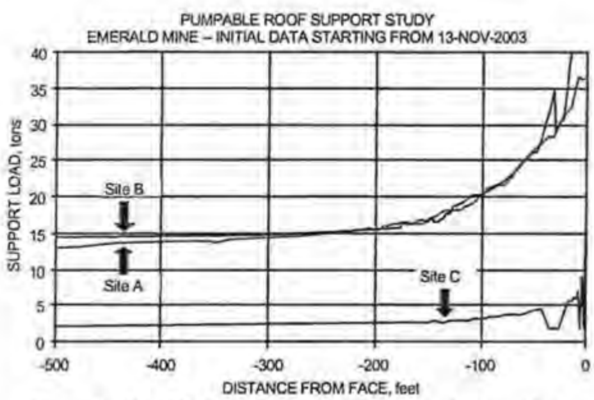

Figure 8. Site C felt the effects of the front abutment later (closer to the face) than did Sites A and B.

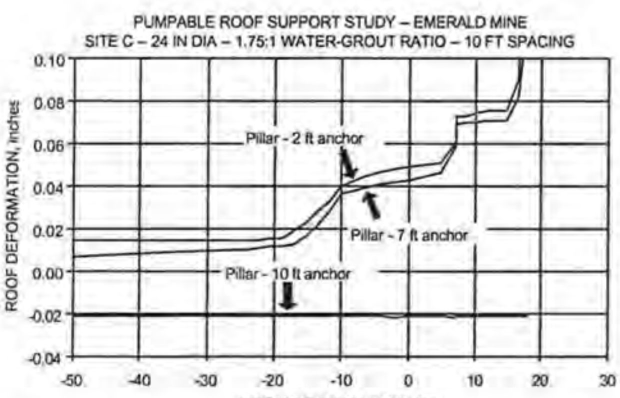

Figure 9. Example of the largest roof deformations outby the face. Overall, there were very little separations within the immediate roof.

Another trend was that the pumpable roof support loading in the mid-pillar area was considerably higher (87% on average for all three sites) compared to the support loading in the intersections. Other mine sites have reported less closure in intersections compared to the pillar line in fair to good roof conditions which would account for the lower support capacity. In these cases, it appears to be a pillar influence situation where the stresses imposed by the pillar react on the roof and floor. At mid-pillar, the close proximity of the pillar/panel generates more closure than within the intersection where the open cross cut can not generate loading and consequently less roof-to-floor closure in this area. However, in this mine, the convergence in the intersections was comparable, actually slightly higher, than that observed in the pillar line. But the support response was softer and this is what resulted in the lower support loadings for the intersection supports compared to the pillar area supports. It appears that for whatever reason, the full roof-to-floor closure was not causing displacement of the supports in the intersection areas.

Tailgate Behavior Inby the Face

As previously discussed, the inby support behavior can be important if there is a need to maintain ventilation inby the face into the active longwall's gob. While this is not always critical at the Emerald Mine, the study was designed to evaluate the inby loading behavior since this will provide valuable information for other mine sites. In addition, the inby behavior was studied to provide fundamental information about the capability of the supports to function beyond their peak capacities, which is a critical issue for this type of support system. Although an effort was made to protect the instrumentation from the coal and gob debris and falling roof rock, not all of the instrumentation survived the inby conditions.

The first question to answer was, "how far inby did the tailgate remain open?" Visual observations indicated that the tailgate remained opened for a distance of 75 to 100 ft inby the face. The peak support loading for the pillar area occurred 37 ft inby the face while the peak support loading for the intersection area occurred 56 ft inby the face. Therefore, it appears that the peak support loading occurred about half the distance that visual observations indicated that the roof had collapsed.

A related question is, "at what load were the supports failing (exceeding their peak load capacity)?" In order to determine if the supports were failing or simply unloading prior to reaching their peak capacity, the support response must be plotted as a function of convergence. Figure 10 shows data from Site B. The pillar area supports exhibited a response similar to the full-scale lab tests, suggesting that these supports were failing although at lower loads. The following discussion is intended to evaluate this conclusion. The data presented in figure 10 represents active tailgate loading only, however, there was only about 8 tons of load remaining on the supports from the first panel mining, so this is not sufficient to account for the difference between the tailgate measurements and full-scale laboratory tests. Since the support loading data were collected every 30 minutes, it is possible that the true peak loads were not captured. However, the post failure loading which occurs over several hours is also proportionally lower than that observed in laboratory testing, suggesting the measured peak loading is fairly accurate. Hence, it appears that the conditions in the mine, most likely the roof or floor contact conditions and the resulting loading conditions were responsible for the lower capacity observed in the mine. It is likely that roof is producing eccentric loading of the pumpable support inby the face due to differential closure of the tailgate between the pillar side and caved gob material on the other side. Therefore, rather than a uniform stress as would be applied to the support by a "flat and parallel" roof and floor as would occur in the laboratory, the pressure acting on the supports in the mine is most likely non-uniform with higher pressures acting on one side of the support than the other. However, while this may explain the lower peak load observed, it would be expected that the residual loading would not be as significantly affected by the non-uniform loading since once the material fractures, the residual loading is controlled by the bag confinement.

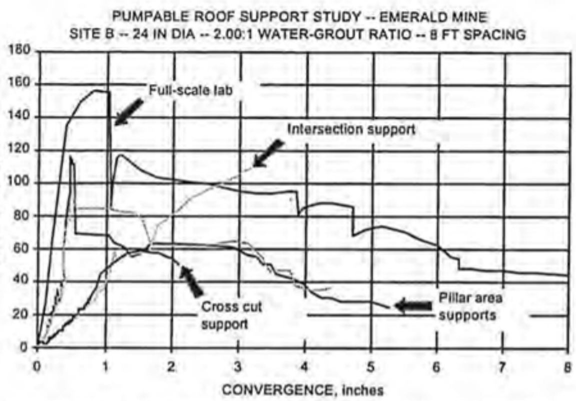

Figure 10. Load-convergence plots of supports in Site B compared to full-scale laboratory test.

The post failure loading is primarily a function of how brittle the grout is, how large the pieces are when it fractures, and the capacity of the bag to confine this fractured material. Hence, one would expect the post failure behavior in the mine to be similar to that observed in the laboratory. But here again, lower capacity was observed in the mine than was demonstrated in the laboratory. The primary difference with the laboratory test that may account for the lower observed capacity is the loading rate. The full-scale tests conducted in the Mine Roof Simulator are at a constant displacement of 0.5 inches per minute. In the mine, the loading rates are more variable and likely to be much slower a large portion of the time. Typically higher load rates of brittle materials equate to higher loads since the mechanics of the crack growth governing the material failure are altered. This may also be contributing to the lower peak loading observed in the mine compared to the laboratory. A reduced loading rate may also explain the lower post failure behavior since the bulked grout material and the bag can creep under a more statically applied load. A similar effect is seen in displacement-controlled laboratory testing, where the support load drops considerably when the displacement is held (figure 11). Without the constant pressure applied by the load frame, the bulked grout material is incapable of maintaining the same load. The other variable which has not been tested is the age of the grout. The full-scale laboratory tests have all been conducted within 30 days of the support pumping. If the material becomes more brittle with time and fails into larger more jagged pieces, the post failure capacity may be less than that observed in the lab. Rips in the bag could also be responsible for lower residual capacity. Although it was difficult to see well inby the face, no rips were seen.

This brings up another question, "what about the supports that exhibited essentially no residual loading?" Of the six supports in which peak loading was measured, three appear to have no significant residual loading. Data was lost on another at a post failure load about 10 tons below the residual loading observed in the two pillar area supports. This suggests that this support probably was not going to have any significant residual loading as well. The lack of residual loading must equate to dissipation of the roof loading and no residual loading most likely equates to loss of roof control by the support. This may not necessarily imply an immediate roof fall, although that would certainly explain the absence of roof loading. The roof could be breaking up to the point where it is no longer acting as a load bearing member that can transfer load to the roof support.

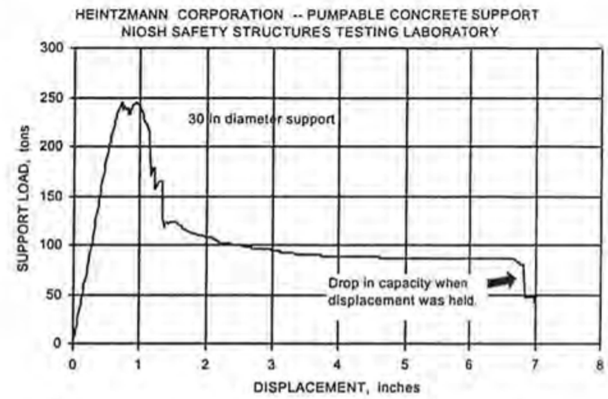

Figure 11. Load drops when displacement is held in this full-scale laboratory test.

An examination of the roof deformation data may help to resolve this issue. Figure 12 shows the roof deformation data for the pillar supports in Site B plotted in conjunction with the support loading. It is seen that the roof deformation, which was mostly limited to the lower 2 ft of roof, did not begin to occur until the peak loading of the support was exceeded. The grout in the bag fractures into blocky pieces when the pumpable support reaches its peak load carrying capacity. As the bag tries to confine the grout, the bag bulges and allows the support to compress. This can account for the lowering of the immediate roof. Once the bag develops sufficient confinement and develops some post residual load capacity, the movement of the immediate roof tends to slow down as denoted by the change in slope of the roof deformation curve as the support goes further inby the face. A different behavior was observed for the other supports which exhibited no residual loading. Two things appear to be different: (1) the roof movement occurred prior to the peak loading of the support, indicating it was contributing to the loading of the support, and (2) the separation or movement occurred higher up (to 7 ft) within the roof. Examination of figures 13 and 14 indicate that the immediate roof is delaminating prior to the supports reaching peak loading. This might also suggest that the roof had broken up and essentially lost its capability to transfer load which caused the reduction in support loading rather than the failure of the support grout. However, since there is not sufficient deformation after the support peak loading to validate this claim, and since the peak loading of the supports are similar to the supports in Site B which did exhibit a residual capacity, it is still likely that the supports were indeed failing (loaded beyond their peak capacity).

The cross cut support in Site B which exhibited the low peak loading (60 tons compared to 120 tons for the other nearby supports) shows an interesting behavior (figure 15). Here again the roof movements at the 2-ft and 7-ft anchor showed roof movement early in the support loading cycle and this movement caused an increase in the support loading. However, the support increase in support loading was not as dramatic (3 tons increase in support loading for a 0.19 inches or roof movement) as that observed in figure 12 for the pillar area support, where a very small increase in roof movement (0.02 inches) resulted in an immediate and large increase in support loading (22 tons). This most likely accounts for the low support capacity observed in this support, but why it happened in this particular support remains unknown. It may be that the sudden roof movement damaged the support in some way that degraded its capability to develop loading. The roof movement decelerated following this initial large increase, and during this period the support loading accelerated until its peak capacity was reached. Again, this suggests that the support was losing its capability to sustain loading during this period.

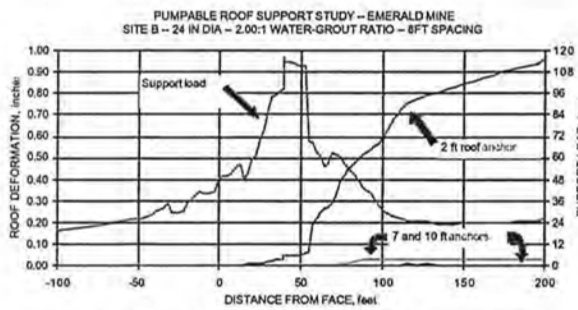

Figure 12. Roof deformation data in conjunction with support loading show that roof deformation did not begin until the peak loading of the support was exceeded.

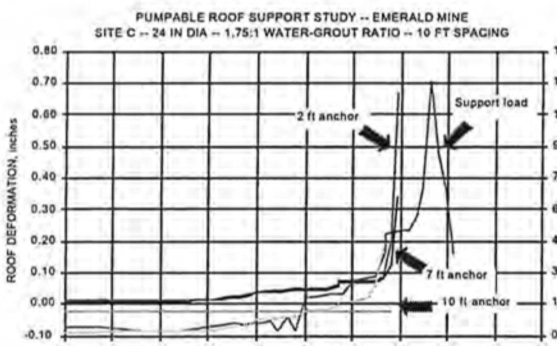

Figure 13. Roof deformation appears to be contributing to the loading of this support.

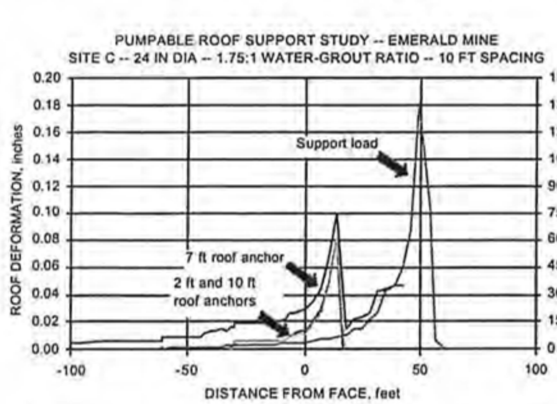

Figure 14. Another example of roof deformation occurring during the support development with no significant post failure load capacity in the pumpable roof support.

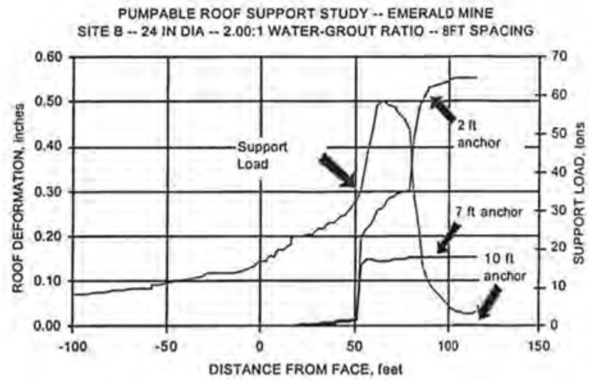

Figure 15. A different loading behavior appears to have taken place in this support which exhibited low peak loading and no significant residual load.

The roof-to-floor convergence inby the face was consistent with the load development in the support. Essentially, the convergence followed the gradual nonlinear increase that began when the abutment effects were felt outby the face, continuing inby the face for some 25-50 ft (depending on whether it was an intersection or along the pillar), and then rose sharply for about 10-20 feet of additional face advance. Measured convergence in excess of 5 inches was occurring well inby the face.

DISCUSSION OF PUMPABLE ROOF SUPPORT DESIGN CRITERIA ISSUES

The basic design requirements for any standing roof support system entail three factors (1) stiffness, (2) maximum capacity, and (3) yield and residual loading capability. A general assessment of design criteria relative to these three basic requirements will be evaluated based on what was learned in this study.

Stiffness

The pumpable roof support is one of the stiffest standing support products currently available for longwall tailgate installations (6). The 24-inch-diameter pumpable support as used in this study develops nearly 150 tons of load carrying capacity in about 0.5 inches of displacement. This compares to a four-point wood crib which would develop only about 10 tons, an order of magnitude less load capacity, at 0.5 inches of displacement. A high stiffness is thought to be beneficial in load-controlled environments where the support capacity can limit (control) the deformation of the immediate roof and associated convergence of the tailgate. Overall (average for all supports), the pumpable roof support system in this study provided a support load density of 4.38 tons per foot of roadway at the longwall face at a convergence of less than 0.45 inches. This is relatively low, indicating that not much support loading was needed to provide good roof control. However, "was the good roof control due to the high stiffness of the support?" Two observations from the study may suggest that this is true. First, it appears from the larger convergence observed in Site B with the lower modulus grout compared to Site A with the stronger and higher modulus grout, that the stiffness of the support may have had some effect in reducing overall convergence. Second, there were essentially no significant separations in the immediate roof strata outby the face in any of the pumpable roof support areas. Longwall tailgates previously supported by wood cribs were reported to have poorer ground conditions outby the face than were observed at these sites (5). Hence, it appears that the stiffness of the pumpable support may be a contributing factor improving ground control. There is some quantitative data to suggest this, but a control study on a significantly softer support system such as wood cribbing was not conducted. In the study panel, a section of four-point cribs in the tailgate at the completion of the panel approaching the recovery area also provided good ground control conditions based on visual observations. This might suggest that the loading environment was displacement-controlled and that the support was contributing little to the ground conditions, but convergence measurements were not made and since the loads were small, visual observations are not likely to be accurate enough to make this claim.

The support response inby the face is even more ambiguous and requires an understanding of the mechanics of the roof activity. As the longwall passes, the immediate roof over the longwall panel caves behind the longwall shields. The immediate roof, which was previously spanning across the tailgate to the gate road pillars, tends to shear off in the tailgate entry near the row of standing supports as the gob forms behind the face. The remaining immediate roof is acting as a cantilevered beam from the coal pillar, with additional support provided by the standing roof support. The stiffness of the pumpable roof support may be beneficial in preventing deformation of this cantilevered roof beam and separations of the laminated strata within the immediate roof. However, the intermediate or main roof is still bridging across the entry to the gob, but since the gob is significantly softer than the pillars, there is likely to be considerable ground movement, and most likely the convergence associated with this will be uncontrollable by the pumpable roof support system. Therefore, there would appear to be conflicting support stiffness requirements relative to the deformation to be controlled. The ideal design would be to match the stiffness of the support to respond to the intermediate or main roof behavior. The ideal design would allow the support to yield due to the convergence which will occur irregardless of the presence of the pumpable roof support without overstressing the immediate roof or allowing large separations in the immediate roof to occur. The pumpable support functions well until it is "pushed" beyond its peak capacity, where load shedding appears to cause the support to lose control of the roof in some cases. If the loading is displacement-controlled, then the peak loading cannot be prevented from occurring, but could be delayed if the support response was softer. However, as previously described, a softer support response outby the face may cause more problems and offset any advantage that might occur inby the face. It is also possible that high stiffness coupled with the capacity of the support may overstress the immediate roof during the load development causing it to break up or "yield" above or in the vicinity of the supports, which may contribute to the inability of the support to maintain roof control when the peak loading is exceeded.

Maximum Capacity

Historically, the maximum capacity requirement for a standing roof support system has been equated to the weight of a detached block of roof rock where separations in strata occur above the bolted horizon. Although this factor should be considered in the determination of the maximum support capacity, this study clearly indicates that such a failure may be the exception rather than the rule. The maximum load developed by the pumpable roof supports in this study outby the face was on average about 50 tons (for the pillar area supports), or about 40 pct of the available capacity of the support. More appropriately quantified, the support load density provided by this arrangement of supports was 6.25 tons/ft of tailgate. Does this mean that this is the maximum load requirement for all pumpable roof supports or for any standing support? Although the generic answer is no, this remains a difficult question to definitively answer. If the stiffness of the support is indeed helping to maintain the integrity of the immediate roof beam (meaning load-controlled roof behavior), then a softer support system that allows more roof deformation would require a higher ultimate capacity if the added deformation leads to additional roof weighting. In a purely displacement-controlled loading environment where the convergence is uncontrollable and the support is simply reacting to the closure of the tailgate, a stiffer support system would also require higher capacity since it would be more heavily loaded from convergence than a softer support. Some examples might help to clarify this discussion. If four-point wood cribs would be required to provide 6.25 tons per ft of entry support capacity at 0.45 inches convergence to control an overhead block of roof rock, ***two*** rows of cribs made from 6x6x36-inch, mixed-hardwood timbers, wedged tightly against the mine roof with hardwood wedges, would need to be installed on a center-to-center spacing of about 48 inches ***half*** the distance of the pumpable supports) (6-7). In other words, ***four times*** as many wood cribs compared to pumpable supports would be required. However, if a four-point wood crib was used to replace the pumpable roof support (i.e. same arrangement as the current pumpable roof support system at Emerald), then convergence of approximately 3.5 inches upon the wood crib would be needed to generate 6.25 tons of support capacity per ft of tailgate. If only a full displacement-controlled loading environment is assumed, then at the 0.45 inches of convergence measured in this study, four-point wood cribbing installed in the same arrangement as the pumpable roof supports would only provide approximately 1.5 tons of support capacity per ft of entry. This represents a capacity capable of supporting only the first foot of roof rock.

Yield Capability

One of the goals in the development of the pumpable roof support system was to maintain a useful residual load carrying capacity through several inches of convergence. From this study, it appears that this is not critical for roof control outby the longwall face, at least in these conditions. Less than 50 pct of the available support capacity was used outby. However, this again brings up the issue of whether the ground activity is displacement-controlled or load-controlled. Since longwall mining is likely to be a combination of both, then there are likely to be conditions where the support will be "pushed" beyond its peak capacity. While this did not happen in this study outby the longwall face, the maximum capacity is exceeded inby the face and the inability of the support to sustain its peak loading appears to have significant consequences on the supports capability to maintain roof control under these conditions.

As the previous data analysis of the support behavior inby the face showed, the load shedding of the support once the grout material fractures at the peak capacity of the support allows the roof movement to increase causing additional separations and delaminating of the immediate roof structure. Since the immediate roof is now heavily loaded by the uncontrollable convergence of the main roof deforming from the gob formation, the acceleration of the immediate roof deformation by the loss of support capacity appears to result in failure of the immediate roof beam. By the time the support is able to re-establish its residual load capacity, it is too late. The roof beam has already been destroyed and the functional capability of the support to provide roof control is now lost.

It is also important to understand that this is (assuming displacement-controlled roof activity) a yield capability problem and not just a peak capacity problem. If the convergence is uncontrollable, then the support will be "pushed" beyond its peak capacity regardless of the peak capacity. However, the support must to be able to sustain some load carrying capacity to support the immediate roof as the convergence continues. Therefore, yield capability is important, particularly in the case of the inby loading situation. In this regard, it should be noted that premature failure of stiff fiber-concrete cribs outby the face occurred at this mine at higher depths of cover (900+ ft). Unfortunately, the lack of any residual load capability in these supports resulted in tailgate ground falls outby the face (5). If the peak loading of the pumpable support was exceeded outby the face, poor roof conditions may also occur.

SUMMARY AND CONCLUSIONS

Pumpable roof supports have done a good job of providing roof control outby the longwall face at the Emerald mine. For the past 2-3 years, efforts have been ongoing to optimize the support design by reducing the size of the support, the water content in the grout mix, and most recently the spacing of the supports. This study was conducted to help provide answers to the impact of these optimization efforts and to provide insight into fundamental design issues for pumpable roof support systems.

The study clearly shows that at this mine a 24-inch diameter support is fully capable of providing adequate ground control under depths of cover of 750 ft as only 50 pct of the available support capacity was utilized outby the longwall face. It was also shown that the 2.00 to 1 water-solids ratio, despite providing a slightly softer support response, is sufficient for maintaining the same degree of roof control provided by the traditional 1:75 to 1 grout mix. The 10-ft spacing of the supports also did not cause any problems outby the face, but as noted in the paper, the load development in the 10-ft spacing area was lower than expected suggesting there may have been a difference in ground conditions at this site that prohibit a direct comparison of this site with the other two test sites.

An evaluation of the inby performance raised more questions than it answered; partly due to the difficulty in maintaining data transmission in this environment. Visual observations indicated that the tailgate remained open somewhere between 75 and 100 ft inby the face, while peak support loading occurred less than 50 ft inby the face. Several supports (at least half of those where peak loading was observed) did not develop any significant residual loading. This suggests that these supports had lost their capability to provide roof control. It appears from the roof deformation data that the large load shedding behavior of the support following peak loading allows the immediate roof to separate. When this happens, the support is unable to regain control of the roof in time to prevent failure of the immediate roof in many cases, particularly when the roof separations begin to occur during the loading of the support. If true, this has significant consequences on the support design for application in these conditions. First, considerable effort has been made to ensure that the support is capable of providing a residual loading through several inches of convergence. If the load shedding following peak loading cannot be significantly decreased, and it is unlikely that it can be with the current system, than it is unlikely that this support will provide full control of a thinly laminated weak roof inby the longwall face. Given these circumstances where the support is not achieving control of the roof, the need for any residual loading capacity is questioned. If the requirement for residual loading is dropped, then the bag can simply act as a form to fill the support and need not confine the material once it fails. Relaxation of the need for residual loading capacity may also allow other grout materials to be used. However, it should also be stated that some supports did develop residual loading and provide some degree of roof control. Hence, it is difficult to say with certainty that no residual loading capability on all of the supports would not result in poorer ground conditions than were observed here.

Perhaps the more important question is whether a support system that does not shed load when yielding would provide significantly better roof control. This question brings back the primary objective expressed in the title of the paper of determining the ground reaction curve for these conditions. Although there were some apparent differences in the stiffness of the three systems evaluated in this study, the differences were not large enough to define a ground reaction curve. In order to achieve this goal, other support systems will need to be included in such a study. One possibility would be evaluate the behavior of a Can support, which unlike the pumpable roof support has sufficient confinement capability to sustain its load carrying capacity once the peak loading is exceeded. Evaluating the performance of the Can support would determine if the unloading of the pumpable support inby the face was indeed the result of the load shedding characteristic of the support, and more importantly, if roof control could be maintained for a longer period of time or greater distance inby the face.

For the outby conditions, most people would agree that the low convergence was largely responsible for the excellent conditions that were observed outby the face in these weak roof conditions. But, how significant is the stiffness of the support in controlling the roof outby the face? With less than 0.5 inches of convergence observed in this study, the two extreme possibilities are presented. If the loading is completely displacement-controlled, then only 0.5 inches of convergence would occur no matter what support was used and it could be argued that for roof control outby the face, no standing support is needed. On the other hand, if the environment is load-controlled, then the stiffness of the support most likely played a critical role in maintaining the convergence to such a low level. Again, defining the ground reaction curve would answer these questions. Although the Can support is softer than the pumpable support used in this study, a support system softer than the Can would be preferred to evaluate the ground reaction curve outby the face. A conventional 4-point wood crib would be useful in this regard.

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