RI 9382

REPORT OF INVESTIGATIONS/1991

Evaluation of Solid-Block and Cementitious Foam Seals

By N. B. Greninger, E. S. Weiss, S. J. Luzik, and C. R. Stephan

UNITED STATES DEPARTMENT OF THE INTERIOR

MARCH 3, 1849

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Library of Congress Cataloging in Publication Data:

Evaluation of solid-block and cementitious foam seals / by N.B. Greninger . . . [et al.].

p. cm. — (Report of investigations; 9382)

Includes bibliographical references

Supt. of Docs. no.: I 28.23:9382.

1. Concrete stoppings (Mining)—Testing. 2. Mine explosions—Prevention. I. Greninger, Nevin. II. Series: Report of investigations (United States. Bureau of Mines); 9382.

TN23.U43 [TN313] 622 s—dc20 [622'.82] 91-16546 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot
ft^2	square foot
ft^3/min	cubic foot per minute
gpm	gallon per minute
h	hour
hp	horsepower
in	inch
in H_2O	inch of water (pressure)
lb	pound
lb/ft^3	pound per cubic foot
lb/yd^3	pound per cubic yard
m	meter
ms	millisecond
pct	percent
psi	pound (force) per square inch
psig	pound (force) per square inch, gauge
psi-s	pound (force) per square inch-second
s	second

EVALUATION OF SOLID-BLOCK AND CEMENTITIOUS FOAM SEALS

By N. B. Greninger,[1] E. S. Weiss,[2] S. J. Luzik,[3] and C. R. Stephan[4]

ABSTRACT

The U.S. Bureau of Mines conducted explosion tests on various full-scale cementitious bulkheads used in abandoned mine areas to evaluate the ability of the bulkheads to withstand gas explosion overpressures of 20 psig.

Tests were performed on 120-ft^2 solid-concrete-block seals of varying thicknesses and designs. Of the seven solid-concrete-block seals tested, only the standard-type seal, having a 16-in thickness, keyed at the floor and ribs, all joints mortared, wedged at the roof, and a center pilaster, maintained its integrity when subjected to a 20-psig pressure wave. After being subjected to repeated explosions, the standard seal only showed a small hairline crack and had an air leakage of 87 ft^3/min at a pressure differential of 1 in H_2O.

Tests were performed on cementitious foam seals of varying thicknesses and compressive strengths. Explosion tests have shown that 200-psi strength, 4- and 8-ft-thick seals can withstand a 20-psig pressure wave. At a pressure differential of 1 in H_2O, no air leakage was detected through the 200-psi, 8-ft-thick foam seal.

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INTRODUCTION

BACKGROUND

Abandoned areas of a mine must be either ventilated or isolated from active workings through the use of explosion-proof seals. As part of its safety program, the U.S. Bureau of Mines has conducted explosion and hydrostatic tests on a concrete-block bulkhead to evaluate its ability to function as both an explosion-proof bulkhead and a water seal for the isolation of abandoned coal mines.[5,6] This masonry bulkhead has withstood explosion and water pressures up to 40 psi, providing a fair degree of explosion isolation for abandoned areas and fire zones.

According to Bureau research,[7] "a bulkhead may be considered explosion-proof when its construction is adequate to withstand a static load of 20 psig, provided that the area to be sealed contains sufficient incombustible to abate the explosion hazard in that area and that adequate incombustible is maintained in the adjoining open passageways." With adequate incombustible and minimal coal dust accumulations, it is doubtful that overpressures exceeding 20 psig could occur very far from the explosion origin. This report[8] also states that "gas-air exchanges between sealed and open areas must be controlled."

Before seals can be erected in an operating mine, they must be incorporated into the mine's ventilation plan, which must meet the approval of the local U.S. Mine Safety and Health Administration (MSHA) district manager. Title 30 of the U.S. Code of Federal Regulations (CFR) identifies the current requirements for the construction of seals or bulkheads in Part 75.329-2 as follows: "Pending the development and publication of definitive specifications for explosion-proof seals or bulkheads, such seals or bulkheads may be constructed of solid, substantial, and incombustible materials such as concrete, brick, cinder block, or tile, or the equivalent, sufficient to prevent an explosion which may occur in the atmosphere on one side of the seal or bulkhead from propagating to the atmosphere on the other side; provided, however, that upon publication of definitive specifications, all such seals or bulkheads, including those in place at the time of such publication, shall be required to meet or exceed those specifications."

The MSHA-Bureau program was developed to evaluate seal construction in underground coal mines. This program primarily evaluated the "substantial" qualities of proposed seals. MSHA has identified 10 solid-block cementitious seal configurations that merit investigation during the initial stages of this research program. All of these seals utilize 6- by 8- by 16-in solid concrete blocks. In most of the configurations tested at the Pittsburgh Research Center's Lake Lynn experimental mine (LLEM), the seals were keyed to the ribs and floor and wedged at the roof. Two of the seal configurations, 2 and 8, (listed below) were installed with no keying at the floor. In operating mines, the keying of the seal is achieved by digging into the ribs and the floor before erecting the seal. The LLEM realistically simulates modern coal mine widths and heights and was constructed in a limestone formation to reduce the fire and explosion damages to the entry roof and ribs. To facilitate the removal of dust and debris between explosion tests, each of the entries in the LLEM has a concrete floor. To provide keying in the LLEM without damage to the floor or ribs, a 6-in steel angle was used on the floor and along the ribs on both sides of the solid-concrete-block seals. The steel angle was secured with 1-in-diam bolts of 2-ft length with a spacing of about 1.5 to 2 ft. The steel angle along the ribs was bolted and grouted into solid rock. When floor keying was used, the steel angle was bolted to the floor and a concrete ramp was built with a 6-in elevation. This technique could also be used in operating mines to augment keying where associated strata do not provide adequate key strength. The 1/8-in-thick coatings that were applied to some of the seals utilized a fiberglass-reinforced portland cement. The solid-block cementitious seal configurations are as follows:

1. Seal configuration 1.—Standard-type thick wall (wetwall), 16 in thick with mortared joints with a center pilaster of 32-in thickness; keying to the floor and ribs;
2. Seal configuration 2.—Thick wall (wetwall), 16 in thick with mortared joints with a center pilaster of 32-in thickness; keying at the ribs, but no keying at the floor;
3. Seal configuration 3.—Thin wall (wetwall), 8 in thick with mortared joints; center pilaster having a 24-in thickness; keying to the floor and ribs; 1/8-in coating on the inby[9] side of the seal;
4. Seal configuration 4.—Thin wall (wetwall), 8 in thick with mortared joints; center pilaster having a 24-in thickness; keying to the floor and ribs; 1/8-in coating only on the outby[10] side of the seal;
5. Seal configuration 5.—Thick wall (wetwall), 16 in thick with mortared joints; keying to the floor and ribs; no pilaster;

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[5] Mitchell, D. W. Explosion-Proof Bulkheads. Present Practices. BuMines RI 7581, 1971, 16 pp.

[6] Work done by Foster-Miller Associates, Inc., under Bureau of Mines contract H0166015.

[7] Work cited in footnote 5.

[8] Work cited in footnote 5.

[9] In this report, the term "inby" refers to that side of the seal that is closest to the face area where the explosion is initiated.

[10] In this report, the term "outby" refers to that side of the seal that is farthest from the face area where the explosion is initiated.

6. Seal configuration 6.—Thin wall (drywall), 8 in thick; drywall construction (no mortared joints); center pilaster having a 24-in thickness; full face coating on both sides of seal; keying to the floor and ribs;
7. Seal configuration 7.—Thick wall (drywall), 16 in thick; drywall construction (no mortared joints); center pilaster having a 32-in thickness; full face coating on both sides of seal; keying to the floor and ribs;
8. Seal configuration 8.—Thin wall (wetwall), 8 in thick with mortared joints; center pilaster having a 24-in thickness; keying at the ribs, but no keying to the floor; 1/8-in coating on the outby side of the seal;
9. Seal configuration 9.—Thick wall (drywall), 16 in thick; drywall construction (no mortared joints); center pilaster having a 32-in thickness; keying to the floor and ribs; 1/8-in coating only on the inby side of the seal; and
10. Seal configuration 10.—Thick wall (drywall), 16 in thick; drywall construction (no mortared joints); center pilaster having a 32-in thickness; keying to the floor and ribs; 1/8-in coating only on the outby side of the seal.

Explosion tests were not conducted on the last three configurations listed above since they were of weaker design than some of the other configurations that were tested first and failed. Following the testing of seven of the above solid-block designs, similar tests were conducted with several cementitious foam seal designs to evaluate their effectiveness against the 20-psi explosion overpressures.

PURPOSE

The objective of this research is to determine whether the solid-block cementitious and the cementitious foam seal designs can withstand a 20-psig methane-air explosion without losing their structural integrity. Not only must the seal be physically strong, but it also must effectively control gas-air exchanges between sealed and open areas. The tests conducted on these seals will also assist MSHA in characterizing an acceptable leakage rate across a seal. A safety and cost benefit may also result from this program in that some of these new seal designs require fewer worker-hours and less materials handling to install than the standard-type seal.

Full-scale explosion-proof seal research provides input to MSHA for setting adequate standards and useful information to industry for the improvement of mining safety and economics. MSHA is currently reviewing the regulations for explosion-proof seals and needs performance data from full-scale dynamic tests for seals. The LLEM can be used to provide these data, and MSHA has requested Bureau assistance in this area.

ACKNOWLEDGMENTS

The computer analysis of the pressure pulses acting on the seals was performed by Dr. Glenn Grannemann, physicist, Pittsburgh Research Center's Theoretical Support Group. Randolf Lipscomb, physical science technician, and Kenneth Jackson, electronics technician, of the Bureau's Lake Lynn Laboratory, arranged the instrumentation for the tests, conducted the tests, and performed the initial evaluation of the condition of the seals following the explosion. The leak-rate tests on the standard and foam seals were conducted by George Triebsch, facility superintendent, Lake Lynn Laboratory, and John Perry, supervisor SSI.

EXPERIMENTAL PROCEDURE

All of the configurations tested were made either of cementitious foam or solid-concrete blocks. All the tests were conducted in the LLEM.[11,12] Figure 1 shows a map of the LLEM. The seals were erected in the crosscuts between C drift and B drift and subjected to an approximate 20-psig methane-air explosion. B and C drifts (fig. 2) of the LLEM are 1,700 ft long, 20 ft wide, approximately 7 ft high, and closed at the inby end. Mixtures of natural gas and air are prepared at the face (closed end) in C drift and confined by a thin plastic diaphragm. The 47-ft-long gas zone contained about 6,600 ft^3 of near stoichiometric methane-air mixture. The mixture was ignited by electric matches, which were placed at the face in three locations. Barrels filled with water were located in the gas zone to act as turbulence generators to achieve the 20-psi pressure wave. The ignition of this gas zone results in a reproducible 20-psi overpressure. The instrumentation in C drift included pressure transducers and flame sensors (refer to figures 1 and 2 for the location of the

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[11] Triebsch, G., and M. J. Sapko. Lake Lynn Laboratory: A State-of-the-Art Mining Research Facility. Paper in Proceedings of International Symposium on Unique Underground Structures (Denver, CO, June 12-15, 1990). CSM Press, v. 2 , 1990, pp. 75-1 to 75-21.

[12] Mattes, R. H., A. Bacho, and L. V. Wade. Lake Lynn Laboratory: Construction, Physical Description, and Capability. BuMines IC 8911, 1983, 40 pp.

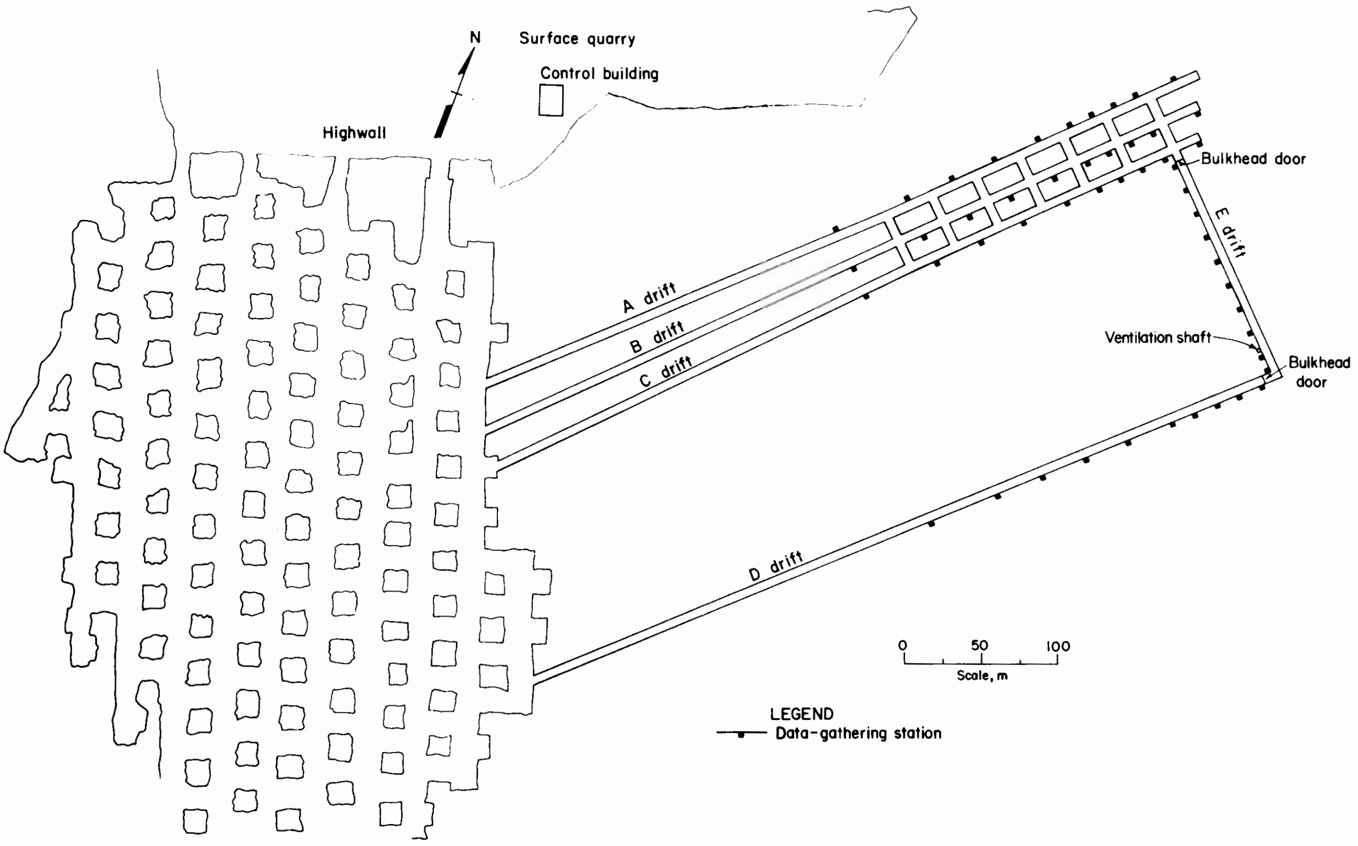

Figure 1.—Plan of LLEM.

data-gathering stations that house the instruments). Signals from the instruments were recorded on a Microvax II[13] computer. The computer collected and prepared the data. Figure 3 shows a typical pressure versus time trace for a station located 134 ft from the face near crosscut 2. This diagram shows the signature for the pressure acting on the seal between 260 and 1,100 ms. The calculated impulse per area for this event is 3.17 psi-s.

The seals, erected in the crosscuts, typically were 5 to 8 ft from C drift. The ability of each of the various seals to withstand an approximate 20-psig methane-air explosion has been determined and compared with that for the standard seal. The standard seal (fig. 4) is a 16-in-thick wetwall with a 32-in pilaster and a cross-sectional area of about 140 ft^2. It was constructed using approximately 450 8- by 16-in solid-concrete blocks. The standard seal is keyed to the ribs and the floor using steel angle (6- by 6-in) and wedged at the roof. In all the comparison tests, the standard seal was located in crosscut 1 (first outby) between C drift and B drift.

For each of the cementitious foam seals, two sets of lattice structures were constructed. Vertical wooden posts were first erected (figure 5, top). Additional support boards were added in a horizontal orientation to form a wooden network (figure 5, middle). The top horizontal board on the C-drift side had injection ports. Brattice material was attached to the inside of each of the wooden lattice structures (figure 5, bottom). A four-person Celtite team took about 4 h to construct the forms for each seal. It took about 2 h to set up the mixing machine and couple in the feed and transport lines.

The feed, mixing, and pumping system selected for use in erecting the foam seals included a Langley skid-mounted mixing machine (model 1), powered by a 10-hp

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[13] Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

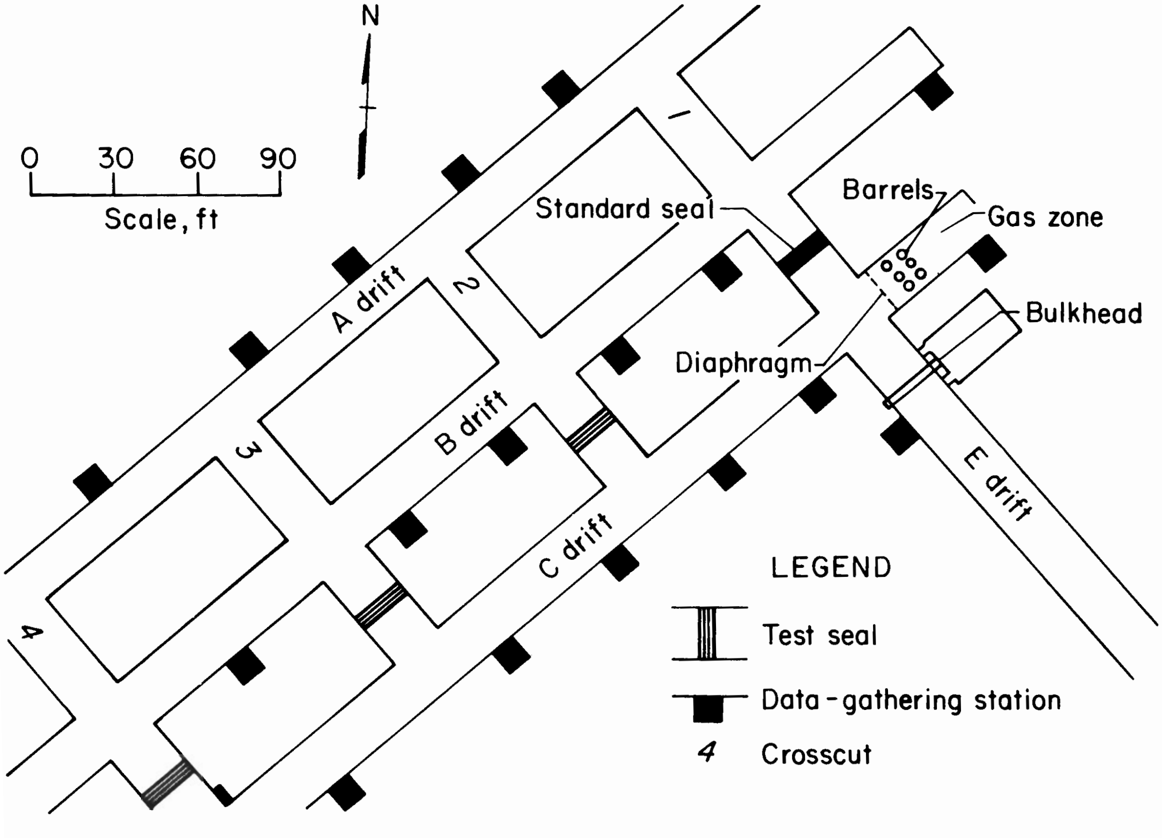

Figure 2.—Diagram of seal test area in LLEM.

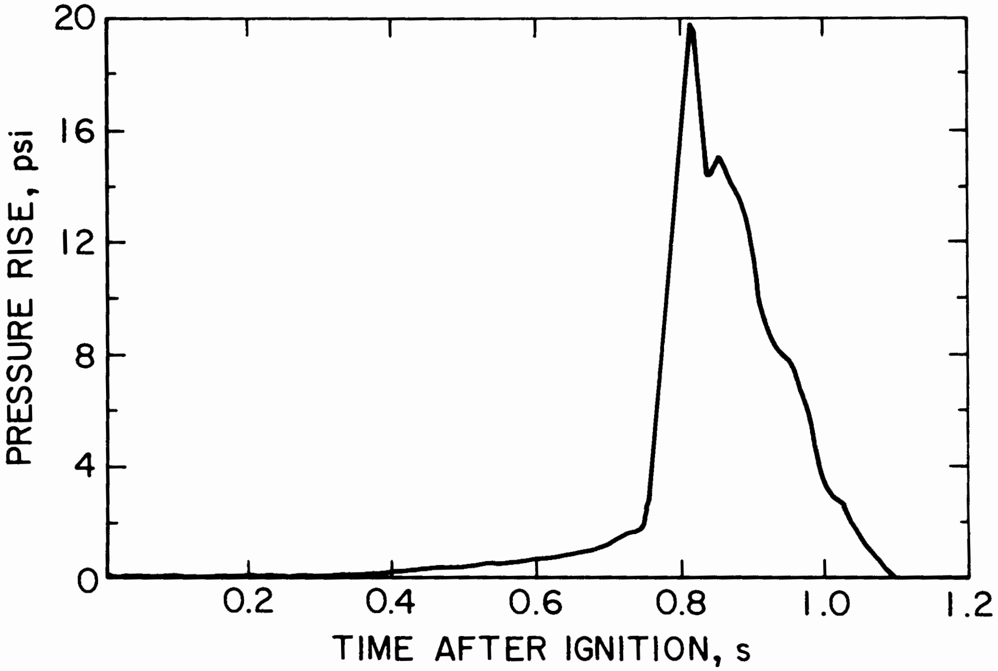

Figure 3.—Pressure trace at 134-ft instrumentation station for seal configuration 7.

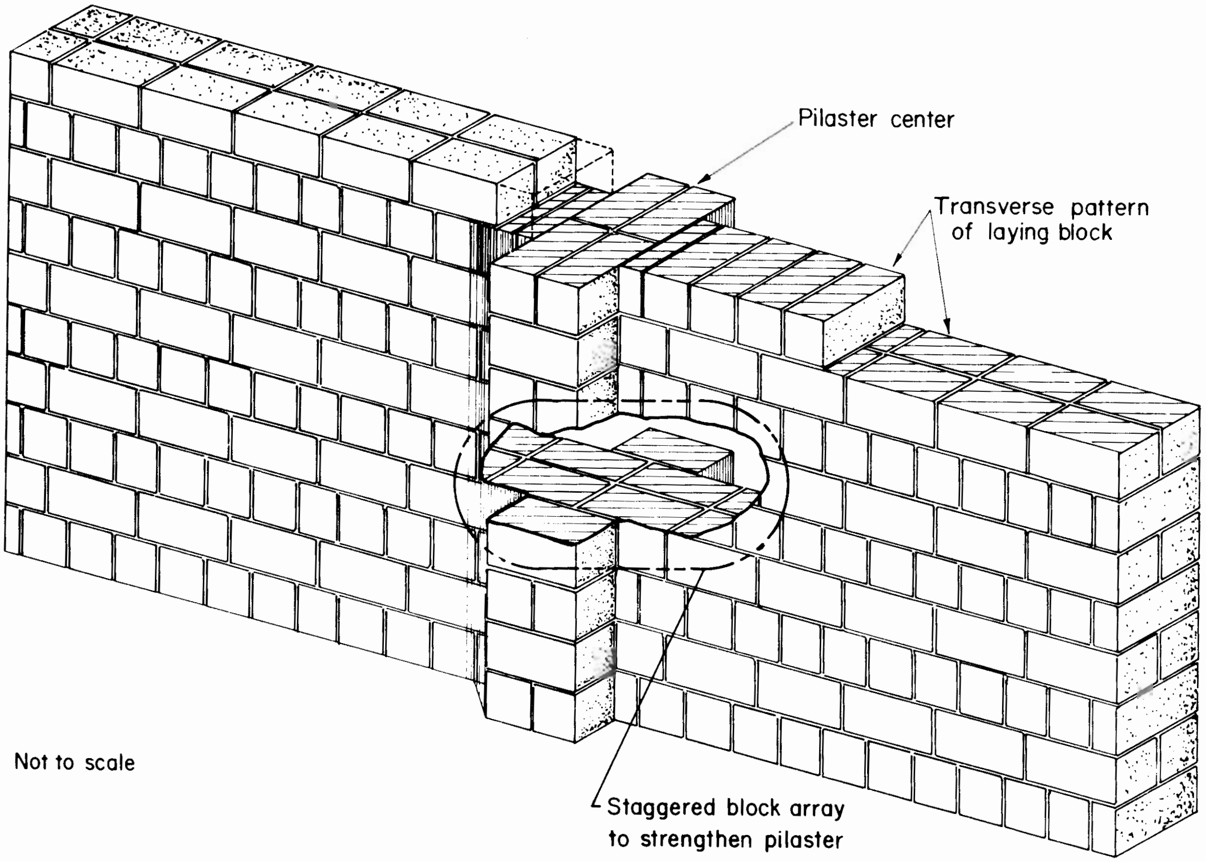

Figure 4.—Standard solid-concrete-block seal.

motor, and a slurry pump. This system was used to inject a mixture of Tekfoam[14] cementitious foam (manufactured by Celtite Corp.), water, and air into each of the lightweight construction forms of lumber and brattice cloth. Tekseal cementitious foam, a noncombustible dry powder, packaged in 45-lb bags, was added to the hopper and fed by an auger into a mixing bin where it was mixed by jets of water to form a thick slurry. Another auger drive fed the Tekseal cementitious foam-water slurry into a 2-ft-long by 6-in-diam pump whose output was then mixed with more water (typically delivered at 12 gpm with a pressure of 100 psi). In filling the form in outby crosscut 2 (8-ft-thick, 200-psi seal), the mixture was transported 150 ft and injected at the top of the form at 18 gpm, requiring about 6.5 h. In filling the form in outby crosscut 3 (4-ft-thick, 200-psi seal), the slurry was transported 80 ft and injected at the top of the form at 30 gpm, requiring 2 h. Figure 6 shows Tekseal cementitious foam being fed into the hopper of the slurry mixing-pumping unit. The slurry was pumped to the seal and injected at the top of the seal into the seal cavity (fig. 7). After a curing time of greater than 30 days, the low-density cementitious foam seals were explosion tested.

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[14] The Tekfoam cementitious foam material used in the construction of the LLEM test seals will be referred to in the remainder of this report by its new legal brand name, Tekseal.

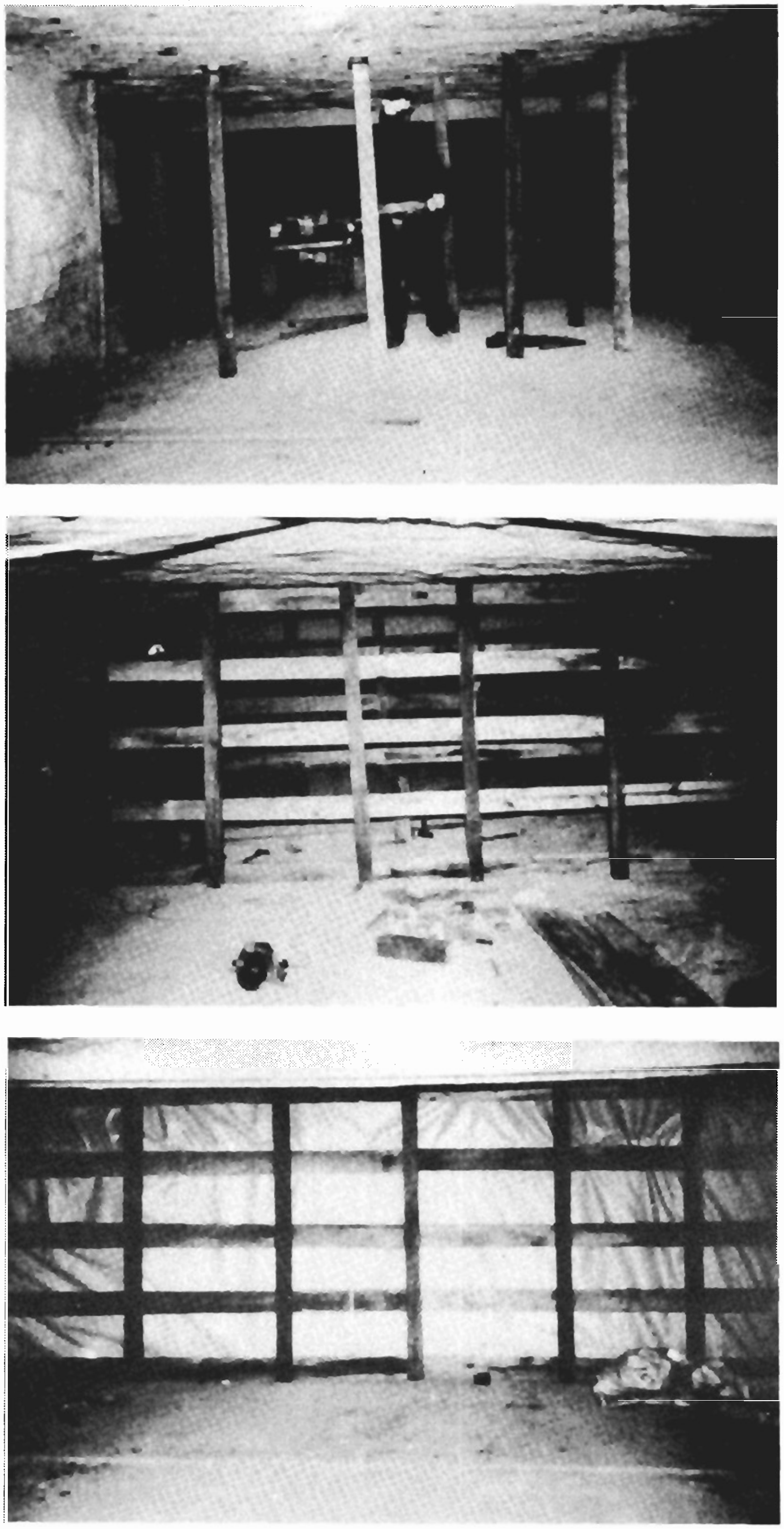

Figure 5.—Three stages in erecting wooden structure-brattice for cementitious foam seal.

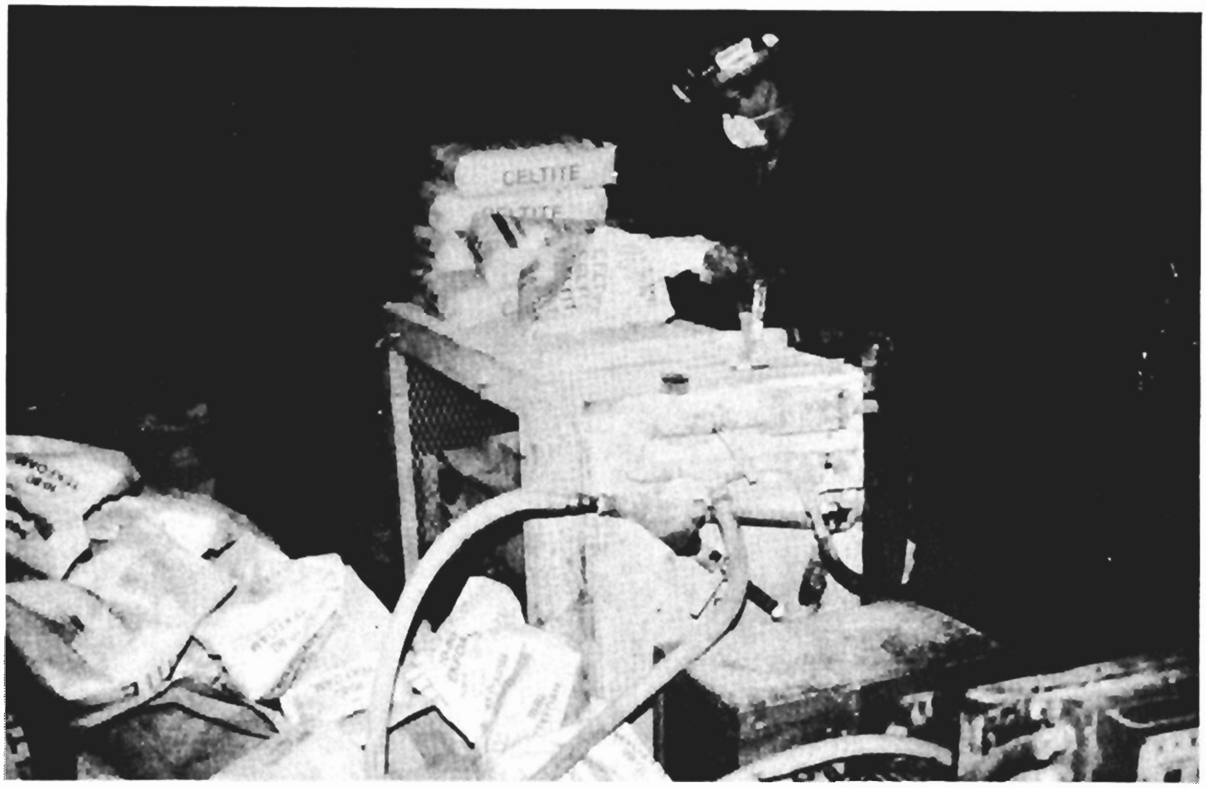

Figure 6.—Feeding cementitious foam into slurry mixing-pumping unit.

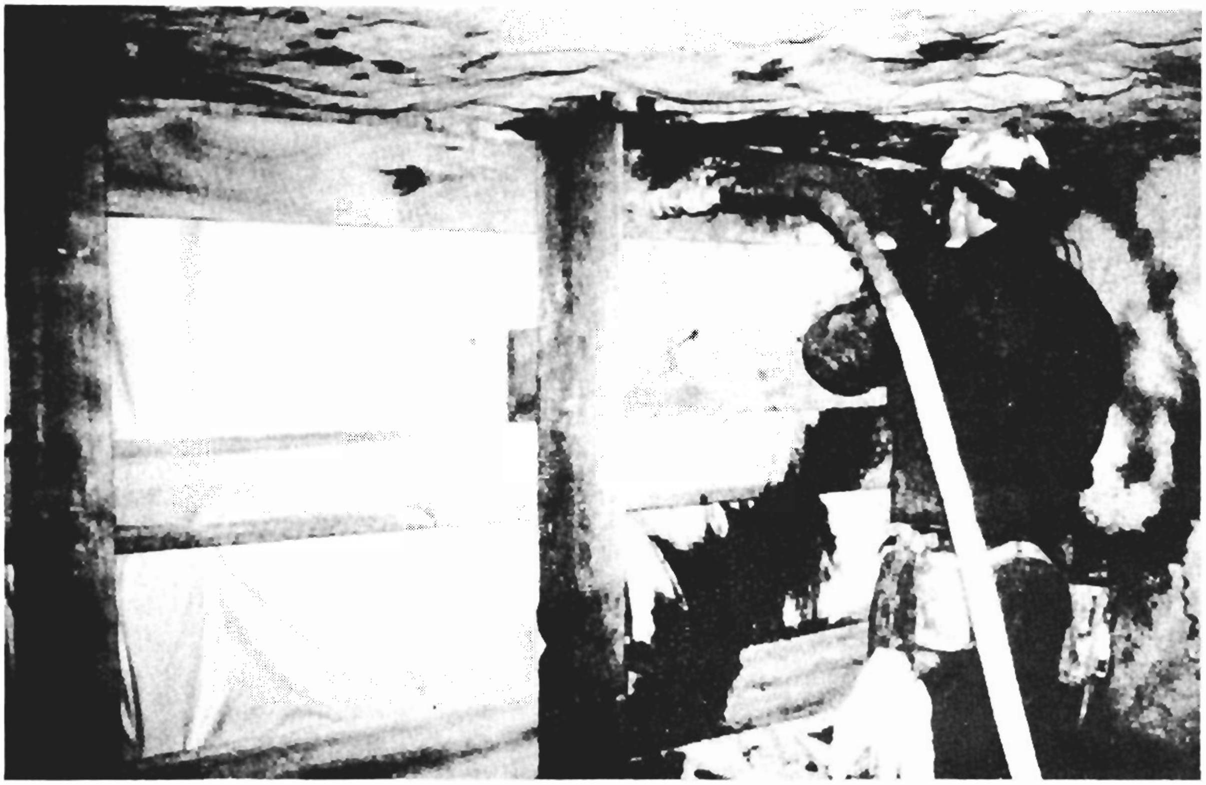

Figure 7.—Slurry injection at top of cementitious foam seal form.

DISCUSSION OF TEST RESULTS

SOLID-CONCRETE-BLOCK SEALS

In the first test series, a standard-type seal (seal 1, table 1), having a 16-in-thick wetwall with a 32-in pilaster, was positioned in crosscut 1 (fig. 2). A wetwall seal (seal 2, table 1) similar to the standard-type seal except without floor keying was in crosscut 2 (second outby). A wetwall seal of 8-in thickness (seal 3, table 1), having a 24-in pilaster and a coating on the explosion side of the seal, was keyed into the floor in crosscut 3 (third outby). A wetwall seal of 8-in thickness (seal 4, table 1), having a 24-in pilaster and a coating on the side opposite the explosion, was keyed into the floor in crosscut 4 (fourth outby). Of these four seals, only the standard-type seal in crosscut 1 maintained its integrity, clearly indicating the need for adequate keying of the seal to the floor and ribs.

The results of the first series of tests are summarized in table 1, which lists a maximum pressure of 22 psig acting on the standard seal in crosscut 1 and a pressure of 15 psig on the 8-in-thick test seal in crosscut 4.

Table 1.—Summary of test conditions and results for solid-concrete-block seals

Seal	Type	Crosscut	Location of mid center from face, ft	Maximum overpressure, psig	Impulse per area, psi-s	Degree of damage	20-psig test outcome
1 . .	Standard seal, thick wall, wetwall, pilaster, floor keying.[1]	1	60	22	4.55	None.	Passed.
2 . .	Thick wall, wetwall, pilaster, no floor keying.[1]	2	160	21	4.03	Large opening at roof, 2 large cracks at left outby side, bottom displaced about 1 in.	Failed.
3 . .	Thin wall, wetwall, pilaster, floor keying, coating on inby side.[1]	3	260	19	2.98	All blocks removed except bottom row.	Failed.
4 . .	Thin wall, wetwall, pilaster, floor keying, coating on outby side.[1]	4	355	[2]Approx 15	NA	Large crack at top, blocks missing on outby side, pilaster sheared off.	Failed.
5 . .	Thick wall, wetwall, no pilaster, floor keying.[3]	2	160	17	3.74	Minor damage, stopping intact, mortar removed at top, some half blocks removed at roof line, approx 1-ft^2 leak area formed.	Marginal at <20-psig pressure.
6 . .	Thin wall, drywall pilaster, floor keying, coating on both sides.[3]	3	260	18	2.45	Destroyed, only a few blocks remained on and near ribs.	Failed.
7 . .	Thick wall, drywall pilaster, floor keying, coating on both sides.[4]	2	160	20	3.17	All blocks removed except a few along both ribs and on floor.	Failed.

NA Not available.

[1] Data from LLEM test 180.

[2] Pressure lower at seal 4 because of venting through the opening formed when seal 3 failed at 260-ft location.

[3] Data from LLEM test 183.

[4] Data from LLEM test 187.

In the second series of tests, three seals were located in crosscuts between C and B drifts. The seals constructed from solid-concrete blocks were all tightly keyed into the ribs and wedged at the roof. The standard seal withstood the explosion without any apparent damage. A modified seal (seal 5, table 1) without a pilaster was located in crosscut 2 between C and B drifts. The explosion removed portions of the blocks in the uppermost layer, causing the seal to lose integrity. In crosscut 3, a thin drywall seal (seal 6, table 1) of 8-in thickness with a pilaster of 24-in thickness was positioned. A coating had been applied on both sides. Catastrophic failure of the seal resulted.

To measure the leakage through the standard seal after it had been subjected to numerous 20-psig explosions, a double-brattice technique utilizing a 0.5-ft^2 window in the measurement brattice was employed.[15] A centrifugal fan was used to blow air from B drift through the window and the seal into C drift. Air velocity through the window was measured with a vane-type anemometer. The pressure differential across the seal and the measurement brattice was measured.

The standard-type seal, which had been subjected to three 20-psig methane-air explosions and two weaker explosions, was examined for air leakage. Over the pressure range of 0.1 to 1 in H_2O, the volumetric rate of leakage was linear with the square root of pressure, as to be expected. At a pressure differential of 0.1 in H_2O, the leakage was 22 ft^3/min and at 1 in H_2O it was 87 ft^3/min. The leakage rate across the seal was not measured before the seal was subjected to the series of explosions. The other seals were not tested for air leakage since all had experienced block loss to varying degrees.

In the third series of tests, a modified drywall seal (seal 7, table 1) was located in crosscut 2 between C and B drifts. It was 16 in thick, constructed with a 32-in pilaster, and coated on both sides. No mortar was used between blocks. The explosion removed more than 90 pct of the seal, causing catastrophic failure. The standard seal still located in crosscut 1 between C and B drifts withstood the explosion without any apparent damage.

Seal configurations 8, 9, and 10, mentioned in the "Background" section, were not tested. The results from earlier tests with inherently stronger seals implied that these three seal configurations would also have failed.

CEMENTITIOUS FOAM SEALS

Following the explosion testing and removal of debris from the solid-block cementitious seals, five low-density, cementitious foam seal designs were installed and tested.

The seals were subjected to a nominal 20-psig explosion pulse on the C-drift side. The pressures obtained are summarized in table 2. The pressure in the vicinity of crosscut 2 was approximately 29 psig. The pressures at crosscuts 3, 4, and 5 ranged from 20 to 22 psig. The pressures decreased to about 13 psig at crosscut 6, located 550 ft from the closed end of C drift. Reasonable agreement between analog (oscillograph) and digital (computer) static overpressure values was obtained.

The Tekseal cementitious foam seal in crosscut 2 (8-ft-thick, 200-psi) did not show any signs of physical damage. Air-leakage tests were performed after the explosion. To measure the leakage through the cementitious foam seals after they had been subjected to a nominal 20-psig explosion, a single-brattice technique utilizing a 0.5-ft^2 window was employed. Mortar was applied around the wooden frame (along the floor, ribs, and roof) that was used to support the measurement brattice; this was done to constrain the air to flow only through the brattice window, thereby minimizing the error in leak-rate measurements. The mine's main fan was used to blow air from C drift through the seal and the window. A flow-adjustment brattice was erected outby and beyond the last surviving seal. By changing the speed of the mine fan, various pressure differentials across the seal could be obtained. Two settings of pressure differentials were used—1.0 and 4.25 in H_2O. At a pressure differential of 1.0 in H_2O, no leakage was detected through this seal. At a pressure differential of 4.25 in H_2O, only 31 ft^3/min of leakage was detected; this amount was considered by MSHA to be insignificant. Test conditions and results are summarized in table 2. Based on visual observations after the explosion and the results of the air-leakage tests, the 8-ft-thick, 200-psi Tekseal cementitious foam seal is considered to meet the criteria of Part 75.392-2 of the CFR.

The Tekseal cementitious foam seal in crosscut 3 (4-ft-thick, 200-psi) had a few hairline cracks along the side exposed (C drift) to the explosion force. At a pressure differential of 1.0 in H_2O, 52 ft^3/min of air leakage was detected. At a pressure differential of 4.25 in H_2O, 114 ft^3/min of air leakage was detected. Both these amounts are considered insignificant. Based on visual observations after the explosion and the results of air-leakage tests, the 4-ft-thick, 200-psi Tekseal cementitious foam seal is considered to meet the criteria of the CFR.

The Tekseal cementitious foam seal in crosscut 4 (4-ft-thick, 100-psi) displayed a series of cracks on both sides after the explosion. Some of these cracks appeared continuous from one face of the seal to the other near the outby end of the seal at about midheight. At a pressure differential of 1.0 in H_2O, 47 ft^3/min of air leakage was detected. At a pressure differential of 4.25 in H_2O, 114 ft^3/min of air leakage was detected. Although the leakage was considered insignificant, visual observations indicated that the seal's performance was marginal. Additional testing would be required on Tekseal cementitious foam seals of 100-psi strength to determine what thickness, if any, would be deemed suitable to meet the criteria of the CFR.

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[15] Work cited in footnote 6.

Table 2.—Summary of test conditions and results for cementitious foam seals

Crosscut[1]	Thickness, ft	Design strength,[2] psi	Location of mid-center from face, ft	Maximum over-pressure, psig	Degree of damage	Leak rate,[3] ft^3/min		20-psig test outcome
						1.0 in H_2O	4.25 in H_2O	
2	8	[4]200	160	29	None......................	0	31	Passed.
3	4	[4]200	260	22	Hairline cracks on inby side.	52	114	Passed.
4	4	[5]100	355	22	Slight cracks occurred, appearing continuous through seal.	47	114	Marginal.
5	8	[6]50	450	21	Significant cracks on both sides of seal, having about 1/4-in gap.	180	420	Failed.
6	4	[6]50	550	13	Seal was totally destroyed......	NAp	NAp	Failed.

NAp Not applicable.

[1] A standard seal made from solid-concrete blocks occupied crosscut 1 at about 85 ft from the face. The seal has a 16-in thickness and pilaster; it is keyed at both the ribs and the floor; it is wedged at the roof. Leakage tests, which had been conducted earlier, indicated that it had a leak rate of about 87 ft^3/min at a pressure differential of 1.0 in H_2O. The seal has withstood more than 5 20-psig explosions.

[2] Design compressive strengths may be slightly different than actual strengths; for example, the seal in crosscut 4 was designed for 100 psi, but testing indicated an actual strength of 78 psi.

[3] Pressure differentials across seal are in inches of water (pressure).

[4] Made using 12 45-lb bags of Tekseal cementitious foam per cubic yard, resulting in a density of about 46.4 lb/ft^3.

[5] Made using 8 45-lb bags of Tekseal cementitious foam per cubic yard, resulting in a density of about 30.0 lb/ft^3.

[6] Made using 6 45-lb bags of Tekseal cementitious foam per cubic yard, resulting in a density of about 23.1 lb/ft^3.

The Tekseal cementitious foam seal in crosscut 5 (8-ft-thick, 50-psi) displayed severe fractures on the face of the seal. These fractures appeared to extend through the entire seal. After the explosion, the air leakage at a pressure differential of 1.0 in H_2O was 180 ft^3/min, and at 4.25 in H_2O it was 420 ft^3/min, strongly indicating that crack propagation had occurred through the seal. Although a maximum acceptable leakage rate for varying pressure differentials has not been established, these values appear to be significant. Based on these leakage rates and on visual observations after the explosion, it is recommended that 8-ft-thick or less Tekseal cementitious foam seals of 50-psi compressive strength not be constructed in underground coal mines.

The Tekseal cementitious foam seal in crosscut 6 (4-ft-thick, 50-psi) was completely destroyed by the explosion. Seals constructed with Tekseal cementitious foam of less than 50-psi compressive strength are also considered unsuitable with this tested method of installation. The frictional forces between the cementitious foam seals and the mine strata may need to be enhanced to withstand the explosion pressures, especially when installing seals with materials of compressive strength less than 200 psi. These frictional forces may be increased sufficiently to withstand the explosion pressure by keying the entry ribs and floor prior to the foam injection or by installing bolts into the ribs and floor (extending into the entry) between the frame structures prior to the foam slurry injection.

The lowest seal in a set of seals must have a water pipe installed. However, water may accumulate behind the seal at a level below the water pipe if draining has occurred or at a higher level if the water pipe is closed. The long-term effects of water buildup, in general, and acidic water, in particular, against a cementitious foam seal are not known. Evaluation of the effect of water and pH level on the seal strength is merited. Personnel from MSHA are currently conducting tests to determine both short- and long-term effects of standing water of varying pH on Tekseal cementitious foam blocks of varying strengths. The blocks will be immersed in acidic water (various pH values and neutral water) for a 1- to 2-month period. Concurrent tests using regular concrete block will be conducted under similar conditions. Following the testing period, both the cementitious foam and standard concrete blocks will undergo compressive strength tests to evaluate the effect of the (acidic) water.

A significant amount of water is used during the construction of these cementitious foam seals. The long-term effects on the strength of the seal from the drying out of the foam are currently being studied by representatives of Celtite, manufacturer of Tekseal cementitious foam. Their research has shown no signs of shrinkage and only a very slight weakening of the cementitious foam in terms of its compressive strength. The recommendation is that the brattice cloth and framing be left in place for the duration of the seal's life to reduce the amount of drying and to increase the time over which drying may occur. If the brattice cloth-timber framing were removed for detailed inspection of the seal, then a suitable sealant should be applied to the exposed surface.

The seals in crosscuts 2 and 3 had been erected initially using single-point injection for the cementitious foam slurry. The single-point injection technique resulted in a rather large gap between the slurry and the mine roof. However, both seals were successfully "topped off" using a multiple-point (three-point) injection technique. Using multiple-point injection, seals were erected in crosscuts 4, 5, and 6 with good closure at the roof.

As mentioned previously, it takes about a half day for a four-person crew to prepare and erect the brattice-timber forms with multiple-injection ports; and about 2 h to set up the slurry mixing-pump system and connect the slurry lines. Injection can take 2 to 6 h, depending on the volume of the form to be filled. Less total time is required to construct a cementitious foam seal (4-ft-thick, 32 worker-hours; 8-ft-thick, 50 worker-hours) than a standard solid-concrete-block seal (using approximately 450 blocks in a 20-ft-wide by 7-ft-high entry), which may require 72 worker-hours to install, depending on the previous experience level with this type of work.

A reliable method must be developed to ensure that the construction of the cementitious foam seal conforms to the recommended installation procedures to obtain the desired strength characteristics. This entails careful monitoring of the bulk density during the slurry injection period by means of accurately controlling the number of bags of Tekseal cementitious foam and the amount of water used. Compressive strength tests on the completed seal should be conducted after the curing period.

CONCLUSIONS

Of the seven solid-block-concrete seals tested, only the standard-type seal maintained its integrity. A standard-type seal without floor keying failed. A standard-type seal with no pilaster but with floor keying failed. All the thin-walled seals of 8-in thickness made with mortar between the blocks failed; neither the use of a pilaster nor floor keying provided sufficient strength against the 20-psig explosion. The addition of coatings did not significantly augment the seal strength. When erecting solid-block seals, the technique of full-mortar bedding needs to be used; the entire solid top side and vertical contact plane of each block needs to receive mortar to maximize shear strength.

The leakage through the standard seal after the seal had been subjected to more than five severe explosions was 22 ft^3/min at a pressure differential of 0.1 in H_2O and 87 ft^3/min at a pressure differential of 1 in H_2O.

An investigation into the best method to effectively control gas-air exchanges between sealed and open areas needs to be pursued. The seal must be physically strong to effectively control gas-air exchanges between sealed and open areas. Coatings placed on high-strength seals whose physical integrity would not be impaired by a 20-psig explosion would help to minimize the air and gas leakage through the seal.

Explosion tests have shown that 200-psi strength, 4- and 8-ft-thick cementitious foam seals can withstand a 20-psig pressure wave.

RECOMMENDATIONS

Cementitious foam seals should be approved in the ventilation plan if the seals are constructed of 200-psi compressive strength Tekseal cementitious foam (or other similar product) and are at least 4 ft thick.

Additional testing should be carried out on cementitious foams in thicknesses between 4 and 8 ft and with compressive strengths between 100 and 200 psi to determine other suitable designs for underground coal mine seal construction (i.e., at 100-psi compressive strength, a 4-ft-thick seal was not proven to be totally effective and an 8-ft-thick seal of 100-psi compressive strength was not evaluated in this series of tests).

It is strongly recommended that cementitious foam of 50-psi compressive strength not be used to construct seals of any thickness at this time.

The mine companies installing cementitious foam seals should collect samples of the foam slurry materials in standard molds for processing concretes to determine, through independent laboratory analyses, the effects of aging on the seal's strength.

Multiple-injection ports (at least three) should be incorporated into the brattice-timber forms for the purpose of uniformly controlling the distribution of the foam cement within the form.

If the brattice cloth and wooden framing material are not left in place for the duration of the seal's life (to reduce the amount of drying), a face coat of a suitable sealant should be applied to the exposed surfaces after removal of the brattice cloth-timber framing.

Until further tests are conducted to evaluate the long-term effects of water buildup and acidic water against cementitious seals, cementitious foam seals should not be constructed in areas where water accumulations may occur behind a seal. Testing should be conducted to determine the effects of standing water of varying pH on Tekseal cementitious foam blocks of various compressive strengths.

Research should be devoted to determine the best method to effectively control gas-air exchanges between sealed and open areas. Practical methods for use in operating mines to measure the leak rate across newly erected and old seals need to be investigated.

Further tests on seals should be conducted in the LLEM. More specifically, it is suggested that the following be done:

- For the stronger modified solid-concrete-block seals, the pressure level at which catastrophic failure occurs should be determined;
- To increase the frictional forces between the cementitious foam seal and the entry, substantial 1-in-diam bolts should be installed into the ribs and floor on 2-ft intervals (extending about 1 ft into the entry) between the lattice frame structures prior to the foam slurry injection. These bolts should provide increased resistance to the dynamic force loadings exerted on the seal by the overpressure from the methane explosion. To what extent the frictional forces between the cementitious foam plug and the coal strata in an operating mine need to be augmented requires additional analyses;
- Various ways to augment the strength of other solid-block seal designs, such as the use of angle iron to augment keying, currently used in operating mines should be pursued; and
- Novel seal designs—such as those involving (1) foams, both reinforced phenolic and cementitious, and (2) lightweight masonry blocks—should be evaluated.

☆ U.S. GPO: 1991—511-010/42,021

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