# Development of a Fire-Resistant Cardboard Compressible Block for Use in Stopping Construction in Underground Mines

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## Abstract

An engineering study was undertaken to develop a cost-effective compressible block for use in stopping construction in areas of underground coal mines exposed to convergent ground and roof conditions. A cardboard block consisting of 1 .25-cm hexagonal cells with a nominal 0.4-mm face coating of intumescent paint was judged to be a viable solution to this problem and met the important performance characteristics of high fire resistance at low pressure differentials, low flame spread, resistance to air leakage, and relatively low compressive strength. These units may not perform well in areas of high humidity (above 90%).

A special block, treated with 18% by weight of phenolic resin. displayed excellent resistance to moisture and adequate fire-resistance characteristics. It may be considered an attractive alternative to untreated blocks for use in mines experiencing high humidity (above 90%).

## Introduction

Stoppings are walls built in underground mines to separate adjacent airways. They are used principally to control the direction of air for the purpose of providing adequate ventilation at the working faces where the coal is being extracted.

Stoppings are frequently constructed of concrete or cinder blocks. These blocks may be held together with mortared joints (wet wall), or they may be dry-stacked and coated on both sides with a fiber-reinforced surface-bonding mortar. The dry-stacked wall with mortared surfaces has been shown to have flexural strength that exceeds that of the wet wall. 1

Some mines experience ground and roof control problems, such as floor heave or roof sag. Stoppings constructed with solid masonry units do not perform very well when subjected to these types of conditions. Due to the nonresilient nature of masonry units, fracturing occurs, which results in partial or complete destruction of the wall. This allows air to leak through, which compromises the ability of the stopping to separate adjacent airways.

This problem can be resolved by incorporating a compressible block, or “squeeze block,” into the stopping in strategic locations. Normally, one or two courses of

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compressible material approximately 10 to 20 cm high and 20 cm thick are placed between two courses of masonry block to relieve the load taken on by the stoppings and to preserve the integrity of the wall. The number and location of courses depends upon the type and magnitude of convergence anticipated. In some cases, where severe floor heave is being experienced, a large block of compressible material is centered on the floor, and masonry blocks are laid over and around it. This arrangement is depicted later in this report.

In the past, materials exhibiting a flame spread index of 25 or less, as determined by the American Society for Testing and Materials (ASTM) E-84[2] or E-162,[3] were permitted for such use. Flame-retarded polystyrene (EPS) and polyisocyanurate (PIC) were commonly used in such squeeze block applications. Their excellent compressibility, their moisture resistance, and their air-impermeability properties made them attractive materials for stopping constructions exposed to convergent conditions.

Unfortunately, the poor performance of these materials at elevated temperatures has caused the Mine Safety and Health Administration (MSHA) to develop new policies concerning their use." Heat from a fire in one airway may cause squeeze blocks to melt or otherwise thermally degrade, allowing smoke and toxic gases to contaminate the parallel, adjacent airway, which may serve as a designated escapeway for the miners working in the mine.

MSHA now requires that squeeze blocks be able to provide ventilation separation under fire conditions in a manner consistent with incombustible masonry building blocks, tile, or similar materials. Materials used in mine stoppings that do not meet this criterion must be removed and replaced with suitable alternatives or coated with fire-resistant coatings designed to protect the blocks against fire for extended periods.

One commercially available phenolic foam product, used primarily as a roof insulation board, has been favorably evaluated for squeeze block applications.5 This product demonstrates excellent fire-resistant properties, exhibiting char depths of less than 5 cm when exposed to a flammable liquid test fire generating temperatures between 700° and 900°C for one hour. Unfortunately, it tends to be rather friable and not as resilient as its EPS and PIC counterparts. Its performance in mines exhibiting more than 5 to 10% convergence has been disappointing.

As a result, this study was undertaken to develop a cost-effective alternative that would incorporate the important performance requirements necessary for this type of application.

## Performance Requirements

Selection of a suitable replacement material for EPS and PIC blocks w-as based on performance requirements in several important areas. The six most important parameters considered when evaluating the candidate materials are:

1. High fire-resistant qualities,
2. High compressibility,

3. Low surface-flammability characteristics,
4. High resistance lo moisture absorption,
5. High resistance to air transmission, and
6. Cost.

The main factor controlling the selection of candidate materials was the cost. Many products available would obviously meet the proposed design performance requirements. However, their cost would be prohibitive. High-tech ceramic fiber and heat-resistant polymers typically cost several dollars per kilogram and would not be economically feasible for in-mine squeeze block applications.

## Fire Resistance

Probably the most important factors in the selection of a squeeze block are the block's ability to maintain the structural integrity of the stopping and to resist the passage of flame and smoke in the event of afire. There are standard test methods used to measure the fire resistance of building materials, the most common of which is ASTM E119.[6] This test is used to determine the fire resistance of floor and roof assemblies, walls, and columns, and it provides an indication of the time a given assembly would be able to contain a fire and maintain its structural integrity. However, this test neither investigates the tendency of' an assembly to leak smoke under the test conditions nor incorporates a pressure differential across the assembly being tested.

Smoke leakage is an important parameter when evaluating mine stoppings because there is always a potential for leakage through such stoppings due to the pressure differentials that exist between adjacent underground airways. This means that when a fire occurs in one airway, combustion products leaking through a stopping may contaminate the adjacent airway. If the adjacent: airway serves as an escapeway, toxic gases will be a threat to those attempting to escape, and the presence of heavy smoke will delay or prevent escape.

The Industrial Safety Division (ISD) of MSHA has developed an informal test to assess the fire resistance of proposed stopping constructions.[7] A 2- by 2-m stopping is exposed to a nominal 500 KW flammable liquid tray fire. The velocity of ventilating air past the stopping is normally adjusted to 2.5 m/second, and the pressure drop across it is set for 37.5 Pa. These values can be changed by adjusting regulator doors on the northernmost end of the test gallery. Smoke leakage through the test structure can be qualitatively observed in this test. This test is often used to evaluate proposed materials and to perform final design tests on favorable candidates.

A stopping should exhibit at least a l-hour fire rating when tested under these conditions. One hour is considered a reasonable amount of time for miners working underground to exit the mine via an escapeway in the event of a fire.

## Compressibility/Compressive Strength

An ideal squeeze block material has enough strength to support the weight of the masonry units above it but yields to the ground or roof forces at a pressure below the compressive strength of the masonry blocks themselves-about 55 MPa. As the squeeze block begins to compress, it should continue to act as an air seal and should not spall, fracture, or otherwise lose its integrity. Polystyrene exhibits these ideal properties, having an initial compressive strength of about 173 kPa and compressing to a fraction of its initial height while maintaining an air-tight seal.

Compressive strength and block behavior under squeezing conditions was measured and observed using a Tinius Olsen test apparatus. The adhesive and cohesive properties of the various protective coatings investigated were also noted during these experiments.

## Surface Flammability

Surface flammability is a measure of the rate of flame propagation along the surface of a solid material. Materials with low flame spread rates are desirable to prevent a localized ignition source in contact with a squeeze block from spreading fire to other areas. As previously mentioned, MSHA requires that sealant materials used on stopping constructions exhibit a flame spread index of 25 or less.

## Moisture Resistance

Many mines in which convergent conditions necessitate the use of squeeze blocks also experience extremely high humidity. In some cases, relative humidities of 95% may exist continuously. Closed-cell plastic materials, such as EPS and PTC, have excellent moisture resistance and will not be adversely affected by highly humid conditions. Porous materials, such as cellulose, may absorb moisture, which could reduce the strength and overall integrity of the blocks under conditions of high humidity. Samples were conditioned in a controlled-temperature-and-humidity chamber to determine the effects of these parameters on their strength and integrity.

## Air Leakage

Since the primary purpose of a stopping is to direct air to the working faces, the importance of maintaining air-tight stoppings cannot be overemphasized. The pressure differential across a stopping can vary between 2 or 3 Pa to several kPa (approximately 0.01 inch to several inches of water gauge).

The ideal squeeze block material will not leak any appreciable air during any stage of the life of the stopping in which it is incorporated. Small leakage rates can be tolerated without compromising the overall performance of the stopping construction. The leakage rates through candidate squeeze block materials were measured at various pressure differentials.

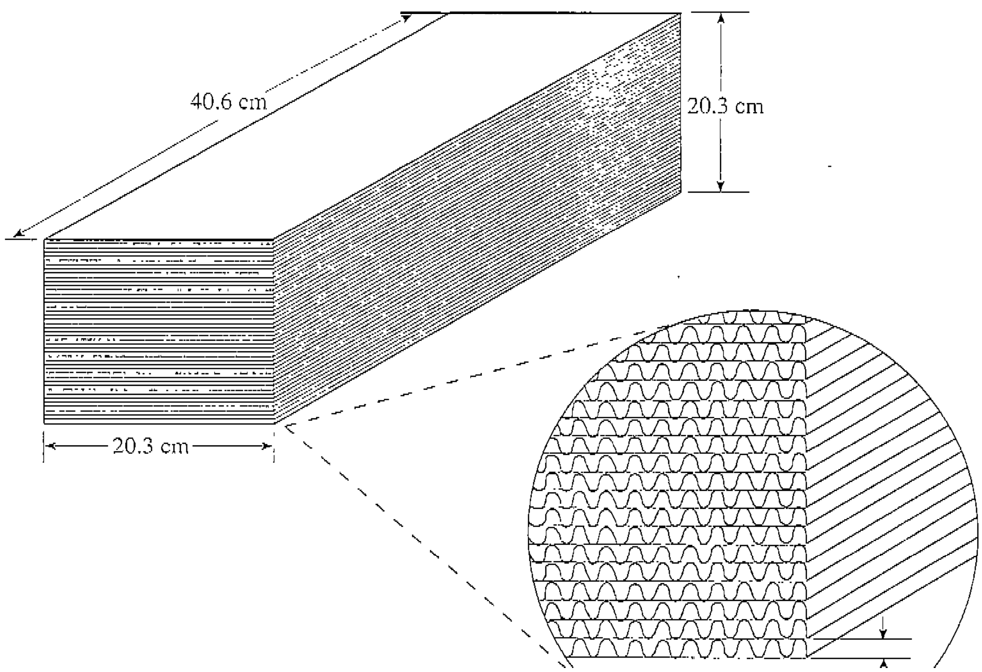
## Economics

The economics of a potential squeeze block material are probably the overriding consideration in the final selection process. Many materials meet or exceed the minimum performance requirements developed in this study. However, high cost would probably negate their use in the underground environment. Ceramic fiber materials and high-molecular-weight, heat-resistant polymers developed for the space industry are attractive candidates, but their high cost-$500 to $1000 per cubic meter-would prohibit their widespread use for this application. EPS and PIC products sell for about $50 to $100 per cubic meter; these figures are based on 1992 market quotes.

## Candidate Materials: Corrugated Cardboard Blocks

The compressible nature and low cost of corrugated cardboard made it a likely candidate for this application. Problems of poor moisture resistance, questionable fire-resistance, and high flame spread behavior were among the obvious potential problems that had to be addressed.

Initially, various types of corrugated cardboard were investigated. These preliminary investigations were concerned primarily with the fire resistance of various construction designs using the corrugated cardboard. Three sizes of cardboard were selected, based upon the number and size of openings or flutes within the cardboard. The standard sizes selected were designated as "A," "B," and "C" flutes. The A flute is the largest commercially available flute and consists of Kraft paper folded into alternating patterns of ridges and furrows with an opening size of about 4 mm. The openings of the B and C fluted cardboards were 3 mm and 2 mm, respectively. Pieces of cardboard measuring 20 cm by 40 cm were glued together with a polyvinyl acetate glue to form solid blocks with a nominal height of 30 cm, as shown in Figure 1. This




Note: Layers Cemented Together with Polyvinylacetate Glue.

Figure 1. Corrugated cardboard squeeze block.

size approximates the normal size of a standard masonry unit. The flutes in these blocks are oriented such that the open ends are parallel to the floor in these designs. Compressive forces act to close the flute openings.

Blocks were also prepared using two commercially available corrugated products, one of' which had been treated with a Flame-retardent formulation and the other with a moisture-resistant formulation developed for shipping containers for the U.S. Navy. Furthermore, the faces of some of the blocks were coated with commercially available intumescent paints to study the effect of the coatings on fire resistance. In one block, the intumescent paint was applied between each layer and on the exposed face.

## Compressibility Tests on Candidate Corrugated Blocks

The various corrugated cardboard block designs were compressed in a compressibility test apparatus to document the behavior of the block under heavy loading. The tests were continued until the load/deflection curve began to rise very rapidly. At this point, further loading of the block did not produce any further decrease in block height. These tests also provided an indication of the adherence of the coatings, where applicable, to the fact of the blocks as they were being squeezed.

## Fire-Resistance Tests on Candidate Corrugated Blocks

Tests were conducted in the ISD's fire gallery to investigate the fire resistance of various candidates. The fire zone was modified to accommodate four specimens per fire exposure. A view of the fire zone used for these experiments is shown in Figure 2. Blocks were instrumented with Type K thermocouples to indicate temperatures at various locations on and within the blocks. Small-scale elevated temperature exposure tests, conducted on cardboard materials, revealed that decomposition would occur at a temperature of about 200°C. At this temperature, the cardboard would char and ultimately loose its strength. Based on the results of this test, it was decided to use 200°C as an indicator of decomposition at any point within the block.

Specimens were exposed to the flammable liquid test fire for one hour. Thermocouple recorders were allowed to remain on for 34 hours after the test to provide information concerning the tendency of the blocks to undergo afterglow, or glowing combustion after the test exposure.

Temperatures developed across the wall were not uniform. The hottest temperatures were developed on the right side of the wall due to vortexes created by the ventilating system. Temperatures ranged from about 400° to 900°C during the final 30 minutes of each test.

Test results are reported as the time that it took to reach 200°C at various locations within and on the backside of the block.

## Summary of Testing of Candidate Corrugated Blocks

All of the corrugated blocks tested exhibited very good compressibility properties. The waterproof block compressed to about 40% of its original height before a sharp increase on the load-versus-deflection curve was observed. Other designs exhibited even better compressibility before heavy loading took place. The compressive strength values calculated ranged from 68 to 181 kPa. This range allows the blocks to support the weight of several courses of masonry units that may be installed **above** them, but it is low enough to allow squeezing (as roof or ground forces act on the wall) without compromising the masonry blocks, which have a much higher compressive strength (approximately 55 MPa).

These tests also demonstrated that flame-retardant face coatings would compress along with the block to which they were affixed without significant spalling, chipping, or delamination. These coatings remained affixed to the blocks after they were allowed to rebound following removal of the load. The block crushed one layer at a time until no voids remained, at which point the load-versus-deflection curve underwent a steep rise.

All the designs tested exhibited relatively good fire-resistant properties. No burn-through was observed during the l-hour test exposure. Uncoated, untreated corrugated blocks of A and C fluted designs did not burn through during the l-hour exposure, either. These blocks did exhibit afterglow, however, and they were

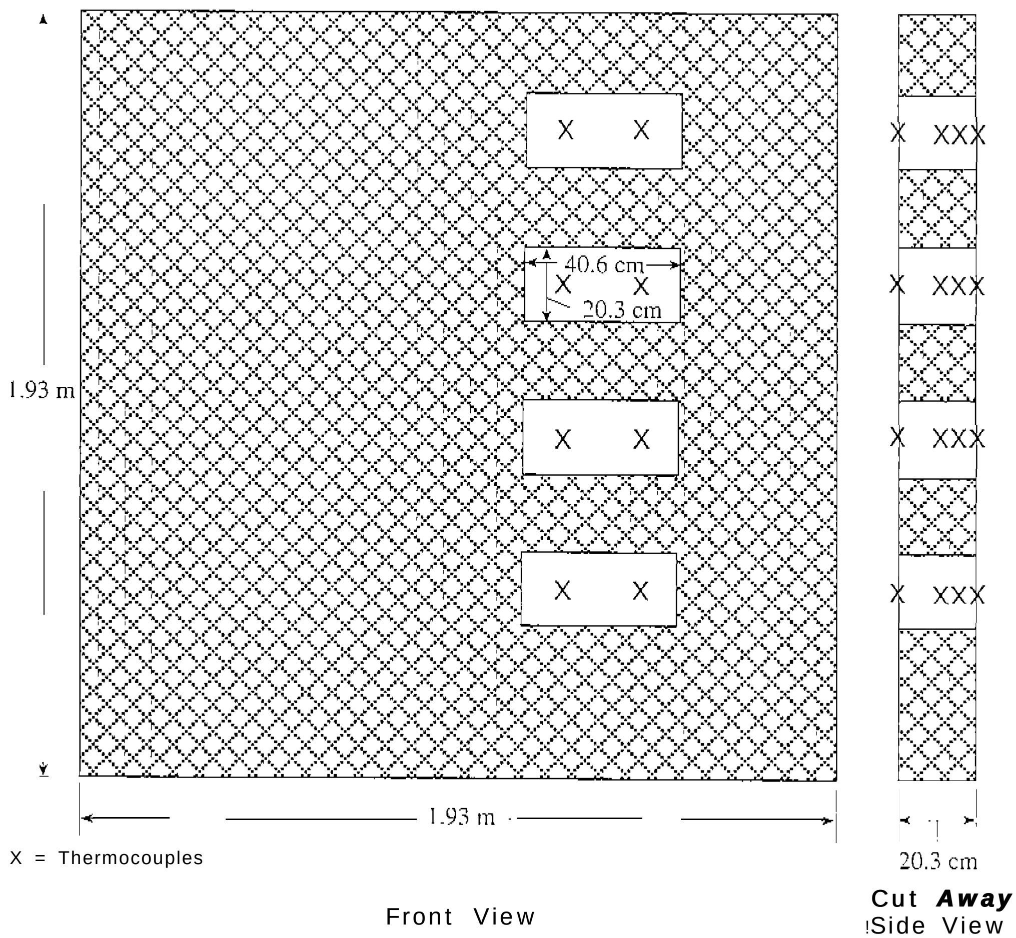



Figure 2. Wall construction for corrugated cardboard fire-resistance tests.

completely destroyed within 24 hours after the test. The flame-retardant design did not display appreciably better fire resistance than its nonflame-retarded counterparts. The presence of an intumescent coating significantly slowed the initial rate of charring. Complete details of this phase of the project can be found in an ISD open-file report.[8]

## Candidate Materials: Honeycomb Cardboard Blocks

The cost of a corrugated cardboard block of A, B, and C fluted design is on the order of a $200 to $250 per cubic meter of raw material. Since the fire resistance of these units was much greater than the minimum anticipated performance standard, it was felt that a cardboard material of larger flute would be less expensive and could possibly meet the other goals of the project, as well.

An extensive search revealed a product manufactured from natural Kraft cellulose fiber made into corrugated ribbons and nested together to form hexagonal cells of various sizes. Face sheets of Kraft paper are glued over the open cells on both sides of the block to stabilize the unit and to provide additional strength.

There are currently many uses for this product, including protective packaging for fragile and expensive products during shipping, re-usable dunnage, energy absorption pads, and wall partition filler. These honeycomb blocks possess a very high strength-to-weight ratio and were deemed to be worth further consideration for squeeze block applications. It is important to note that the proposed cell orientation of these blocks, with respect to the wall in which they are placed, would be perpendicular to the floor. This is in direct contrast to the corrugated blocks in which the flutes were parallel to the mine floor.

Three different size honeycomb blocks were investigated. Figure 3 shows a 1.25-cm-celled block. The cell size is the dimension between two parallel faces of the hexagon voids formed by the Kraft paper walls. In addition, tests were conducted on blocks coated with intumescent paints and filled with vermiculite, mineral wool, and perlite. A description of the various designs tested is given in Table 1. The 2.54-cm cell blocks consisted of 95% air and 5% cardboard on a volume basis and cost roughly $30 per cubic meter. The 1.25-cm cell blocks contained 90% air and 10% cardboard, and they sell for about $55 per cubic meter.

## Compressibility Tests on Honeycomb Cardboard Blocks

Tests were continued until the load/deflection curve began to rise very rapidly. At this point, further loading of the block did not produce any further decrease in height.

The honeycomb blocks exhibited excellent compressibility properties. Specimens could be compressed to a small fraction of their initial height with no noticeable tearing, fracturing, or other sign of compromise. The compressive strengths of 1.25- and 2.5-cm uncoated and unfilled cell-size blocks averaged about 345 and 145 kPa, respectively. These values increased slightly with the addition of face coatings and/or inert fillers.

These tests also provided an indication of the adherence of coatings to the face of the blocks as they were being compressed. Face coatings adhered well upon squeezing, and significant spalling and delamination did not occur. The inert fillers remained within the individual cells when the block was compressed.

## Fire-Resistance Tests on Candidate Honeycomb Cardboard Blocks

Fire-resistance testing was conducted on the candidate blocks using the test parameters and char guidelines employed for the corrugated block tests. The solid masonry block frame that housed the test specimens was modified to accommodate the 10-cm-high honeycomb blocks by partially filling the 20-cm openings with 10-cm incombustible concrete blocks. Test results are shown in Table 2.

A number of observations were made about the performance of the blocks in the fire-resistance tests:

1. The 2.5-cm honeycomb blocks exhibited poor fire-resistant properties, but their performance could be improved by coating them with an intumescent paint or by filling the cells with mineral wool, vermiculite, or cellulose.

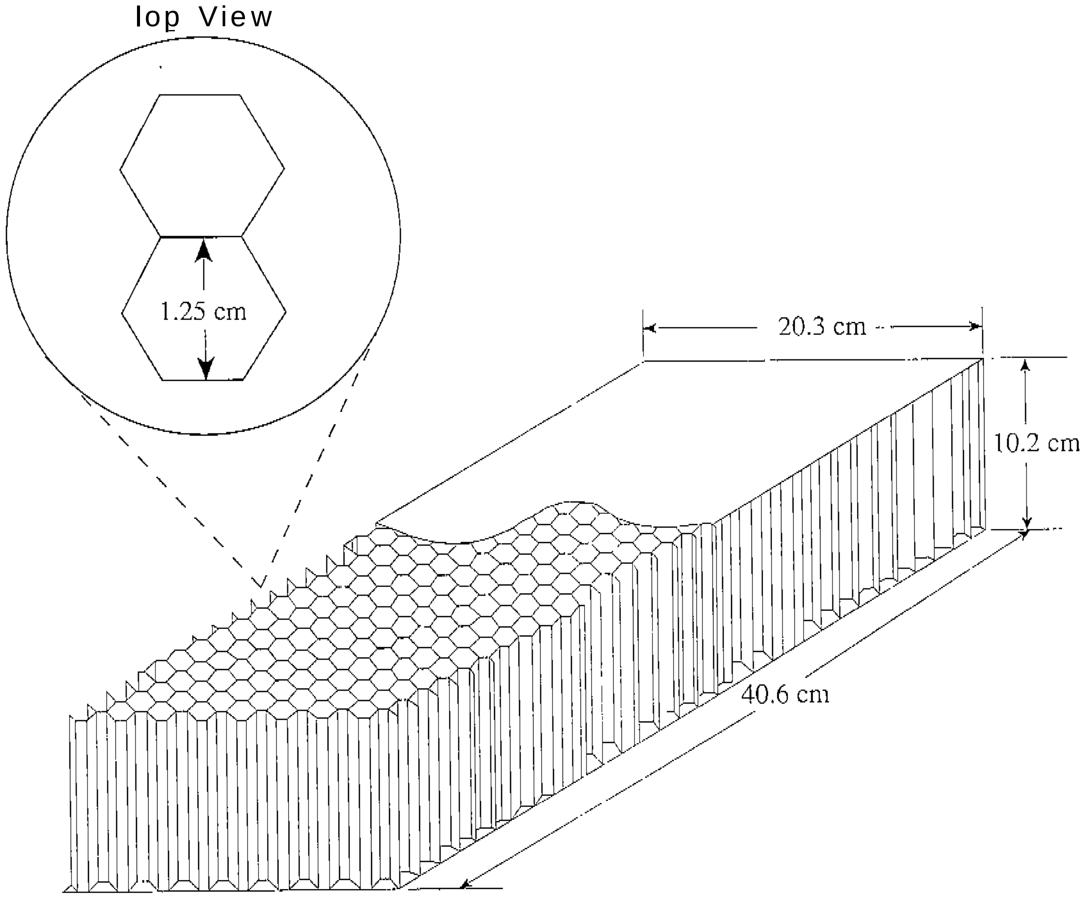



Figure 3. Cardboard honeycomb block (1.25=cm cell).

TABLE 1
Description of Various Test Designs

| Sample No. | Cell Size (cm) | Coating | Filler | Weight (kg) | Comments |
|---|---|---|---|---|---|
| 1B | 2.50 | **NONE** | None | 0.18 | untreated/uncoated |
| 2B | 2.50 | 2 Cts CIear Intum. | None | 0.17 | 0.3-0.5 mm casing |
| 3B | 2.50 | 2 Cts White Intum. | None | 0.16 | 0.3-0.5 mm coating |
| 4B | 2.50 | None | Cellulose | 0.55 | loose-fill cellulose |
| 5B | 2.50 | None | Vermiculite | 0.94 | 144 $kg/m^3$ masonry grade vermiculite |
| 6B | 2.50 | None | Rock Wool | 0.85 | 120 density rock wool |
| 7B | 1.90 | None | None | 0.12 | flame-retardant paper |
| 8B | I .25 | None | None | 0.35 | untreated/uncoated |
| 9B | 1.25 | 2 Cts Clear Intum. | None | 0.30 | 0.3-0.5 mm coating |
| 10B | 1.25 | 2 Cts White Intum. | None | 0.30 | 030.5 mm coating |
| 11B | 1.25 | None | Rock Wool | 3.00 | 120 $kg/m^3$ density wool |
| 12B | I .25 | None | Vermiculite | 1.20 | 144 $kg/m^3$ density vermiculite |
| I3B | 1.25 | None | Perlite | 0.97 | horticultural-grade perlite |
| 14B | 1.25 | 2 Cts White Intum. | Vermiculite | 1.20 | 0.3 mm coating/vermiculite filled |
| 15B | 1.25 | None | None | 0.35 | block rotated for fire resistance text |

TABLE 2
Fire-Resistance Test Data for Candidate Honeycomb Blocks

| | Sample Number | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1B | 2B | 3B | 4B | 5B | 6B | 7B | 8B | 9B | 10B | 11B | 12B | 13B | **14B** | **15B** |
| Block Depth | Time to Reach 200°C (min) | | | | | | | | | | | | | | |
| 5 cm | 3 | 16 | 20 | 4 | 2 | 7 | 3 | 5 | 16 | 21 | 22 | 7 | 8 | 20 | 5 |
| 10cm | 6 | 19 | 27 | 23 | 10 | 11 | 9 | 14 | 27 | 41 | 95 | 50 | 32 | 59 | 10 |
| Burn-Through | 7 | 29 | 47 | 73 | 54 | 68 | 26 | | | | 265 | -- | | | 30 |

Note: Blocks measure 20 cm by 40 cm by 10 cm.
When time to reach 200°C exceeds 60 min., combustion is due to airflow.

2. Limited tests on 1.90-cm flame-retarded honeycomb cardboard blocks indicated less-than-desirable fire-resistant properties, and burn-through occurred in 26 minutes.

3. The 1.25-cm honeycomb blocks exhibited much better natural fire-resistant properties than the 1.90-cm celled units and did not burn through during the 1-hour exposure. Between 2.5 and 10 cm of unburned block remained after the test. The addition of a 0.3- to 0.5-mm coating of an intumcscent paint on the exposed face significantly improved the time it took to char to a depth of 5 cm and resulted in an overall increase in the percent of undamaged block remaining at the conclusion of the test.

4. Afterglow was not observed in any of the unfilled, unsqueezed blocks after exposure to the test fire.

5. The addition of granulated perlite and vermiculite to the cells reduced the overall char rate and thus improved the fire resistance of the honeycomb blocks when compared to their unfilled counterparts.

6. When rotated so that the cell openings were parallel to the floor, the 1.25-cm cardboard honeycomb blocks exhibited poor fire-resistant qualities. The reason for this is not yet well understood: but it may be due to inefficient heat transfer between horizontally oriented cells during fire exposure, which results in aggressive burning into the block.

Based on the results of these preliminary tests, it was decided that cardboard honeycomb blocks of 1.25-cm cell size with face coatings of intumescent paint were worth investigating further. In conjunction with their economic attractiveness, their excellent compressibility and fire-resistant characteristics made them the final choice for further testing.

## Moisture Absorption of Cardboard Honeycomb Blocks

The manufacturer of the cardboard blocks indicated that, at relative humidities above about 75%, the strength properties of the cardboard might be significantly reduced. Since many mines experience very humid conditions, the effect of high humidity on the block was investigated by exposing them to controlled conditions of 90% and 98% relative humidity at 21°C for extended periods. A treated honeycomb block consisting of 18% impregnated phenolic resin was also investigated for possible application in high-humidity mines.

At 90% relative humidity, the treated and untreated cardboard blocks reached an equilibrium moisture content of about 10% and 14%, respectively. Under these conditions, the treated blocks experienced a 35% reduction in original, dry compressive strength. The untreated units displayed a 60% reduction in compressive strength. In both cases, the final values are believed to be adequate for their proposed application. (The compressive strength of 32 $kg/m^3$ density polystyrene is about 136 kPa. )

At 98% relative humidity, both treated and untreated honeycomb blocks experenced equilibrium weight gains of about 30X. Reductions in compressive strength for treated and untreated units were 39% and 79%, respectively. The untreated units became very soft and literally fell apart. The compressive strength of the untreated units-312 kPa-remained relatively high. These treated units did not fracture or otherwise lose their integrity when compressed in their saturated state.

Based on these test results, the use of a paper block treated with phenolic resin appeared to be a viable approach in mines experiencing very high humidity.

## Air Leakage Tests on Cardboard Honeycomb Blocks

Leakage tests were performed on untreated and face-coated cardboard honeycomb blocks, uncompressed and compressed to fractions of their original height. Tests were also performed on phenolic-impregnated blocks squeezed 25% and 50%.

The test results indicate that the leakage rates through uncoated units are minimal and of the same order of magnitude as chose of uncoated masonry block units. The presence of a 0.4-mm intumescent face coating significantly reduces the leakage when compared to an unsqueezed, uncoated counterpart. As the block is compressed to within 2.5% of its original height, the leakage increases by a factor of about five. The overall increase in leakage that would occur is not considered significant since the exposed area of the block is reduced by 75%. Leakage rates at various pressure drops are shown for coated and uncoated blocks in Figures 4 and 5.

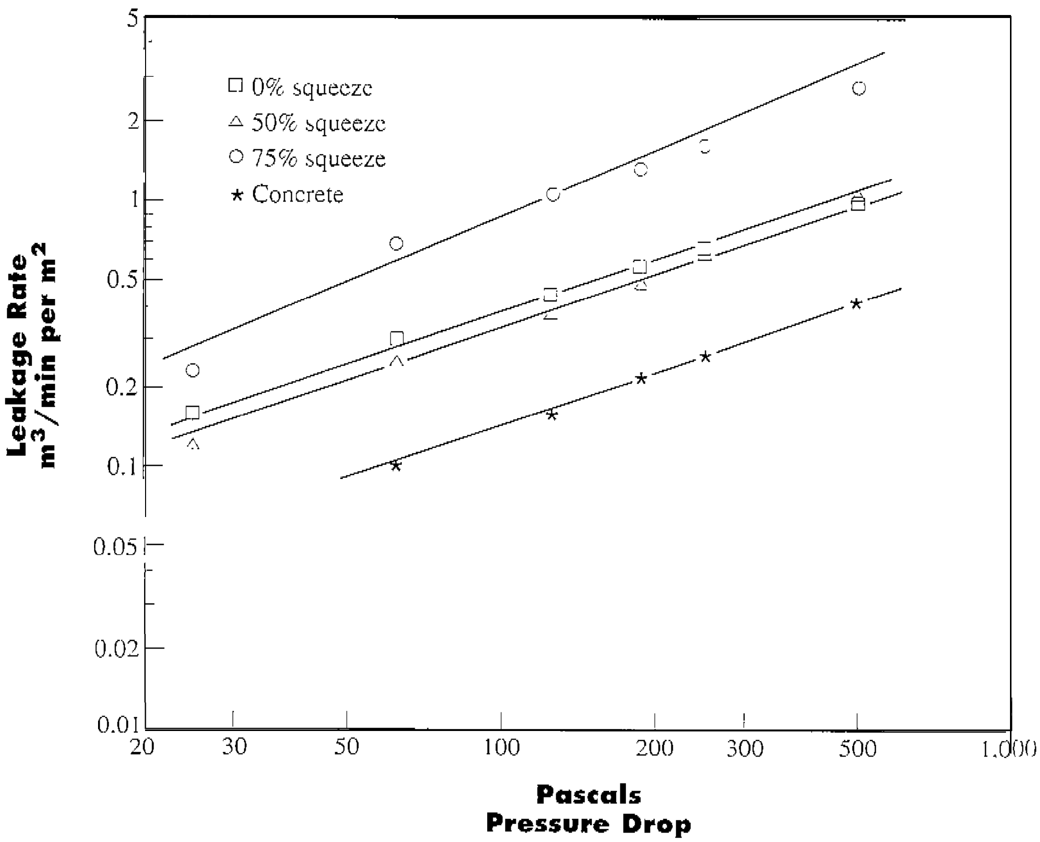



Figure 4. Leakage rates through uncoated 1.25cm honeycomb blocks.

Air leakage tests on phenolic-impregnated blocks were conducted after conditioning at 90% relative humidity for two weeks. The leakage rates through the squeezed units at any given pressure were about twice the rate of an untreated unit.

Examination of units that had been squeezed down to 25% of their original height revealed that the individual cells had bellowed like an accordion and did not tear or rupture. The overall cell structure remained uncompromised and intact.

## Surface Flammability of Curdboard Honeycomb Blocks

ASTM E-1.62 tests were performed on Kraft paper coated with the two intumescent paints used in the test program. The flame spread index of this paper treated with a 0.2-mm coating of these products was 0.

## Summary of Testing on Cardboard Honeycomb Blocks

Test results indicated that the 1.25cm cardboard honeycomb blocks with intumescent face coating and optional phenolic treatment displayed all the important properties desired in a product used in squeeze block applications. The fire-resistant behavior of the blocks in a full-size fire test had yet to be determined.

Fire resistance is one property that cannot always be predicted based upon a scaled-down version of a test. Experience has shown that products that have demonstrated certain fire-resistance ratings when tested in a scaled-down configuration behave quite poorly when tested in a geometry more closely approximating their proposed end-use. For this reason, large-scale tests were conducted on various wall designs to

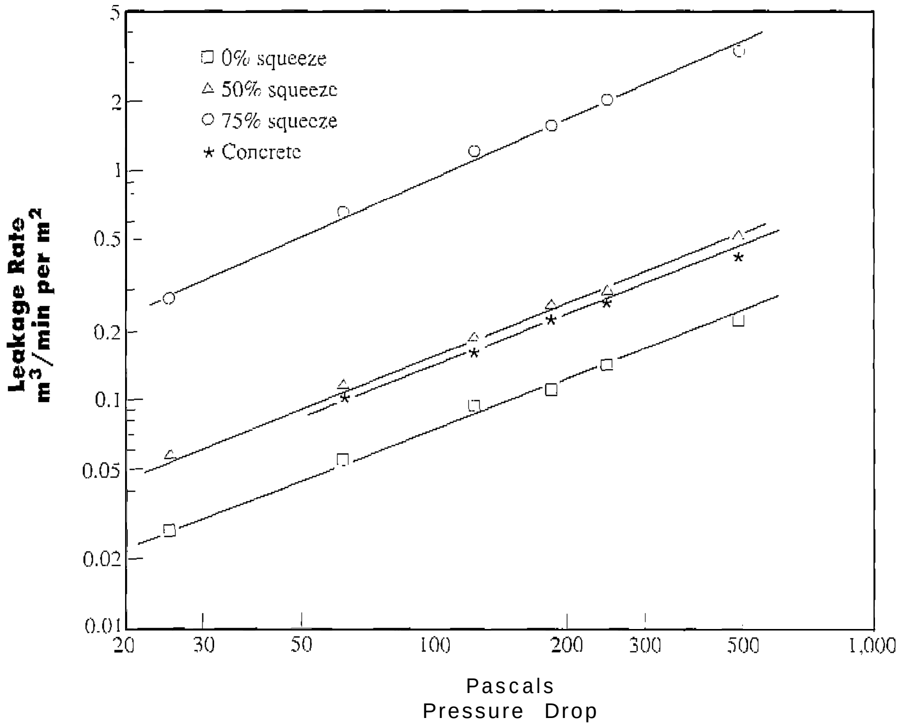



Figure 5. Leakage rates through intumescent coated 1.25-cm honeycomb blocks.

determine the overall fire resistance of the wall as a function of block design, degree of squeeze, placement, and pressure differential.

## Fire-Resistance Testing of Stopping Designs Containing Cardboard Honeycomb Squeeze Blocks

Seven tests were conducted to investigate the fire-resistant behavior of honeycomb squeeze blocks as a function of block design, placement, and pressure differential. Test configurations for these tests are shown in Figure 6. In addition, two tests were conducted on full-size wall assemblies constructed entirely of the cardboard blocks. Figures 7 and 8 show thermocouple locations for all tests.

In this series, tests were generally continued until bum-through occurred. Temperature recording stopped at the end of the test. Figure 9 shows typical wall temperatures generated at the measurement locations during the fire exposures. These data were taken from Test 2, but other tests developed similar temperature profiles. As

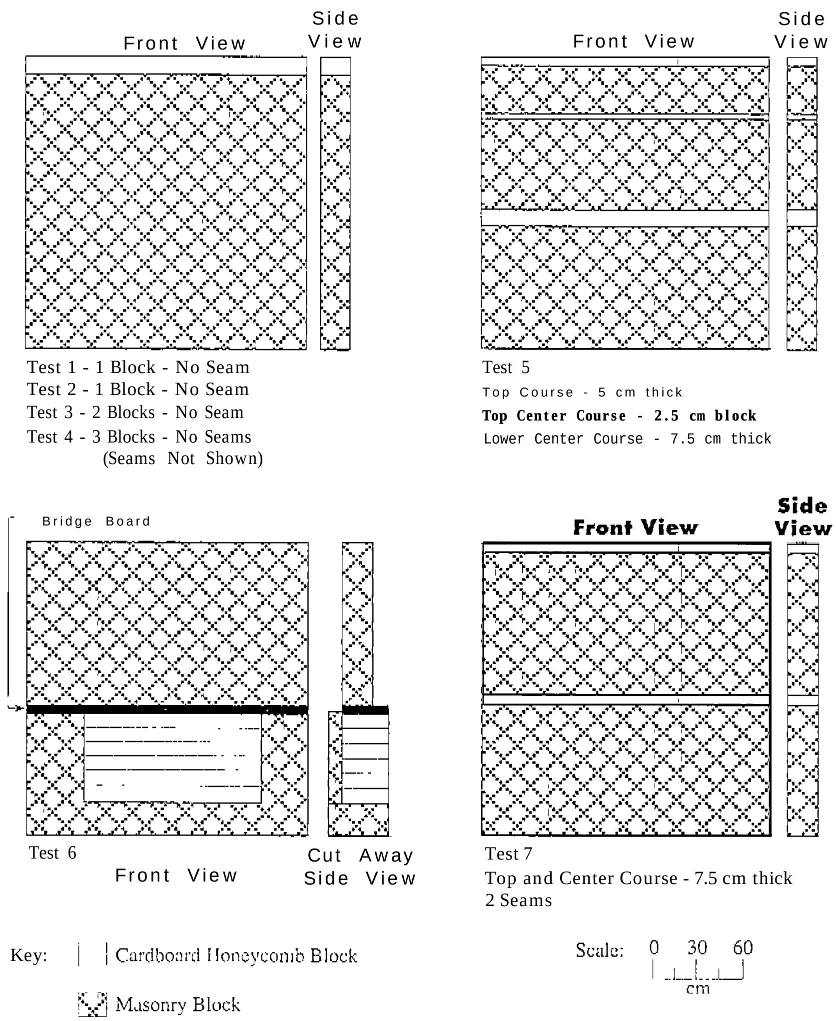



Figure 6. Cardboard honeycomb block configuration for fire-resistance tests.

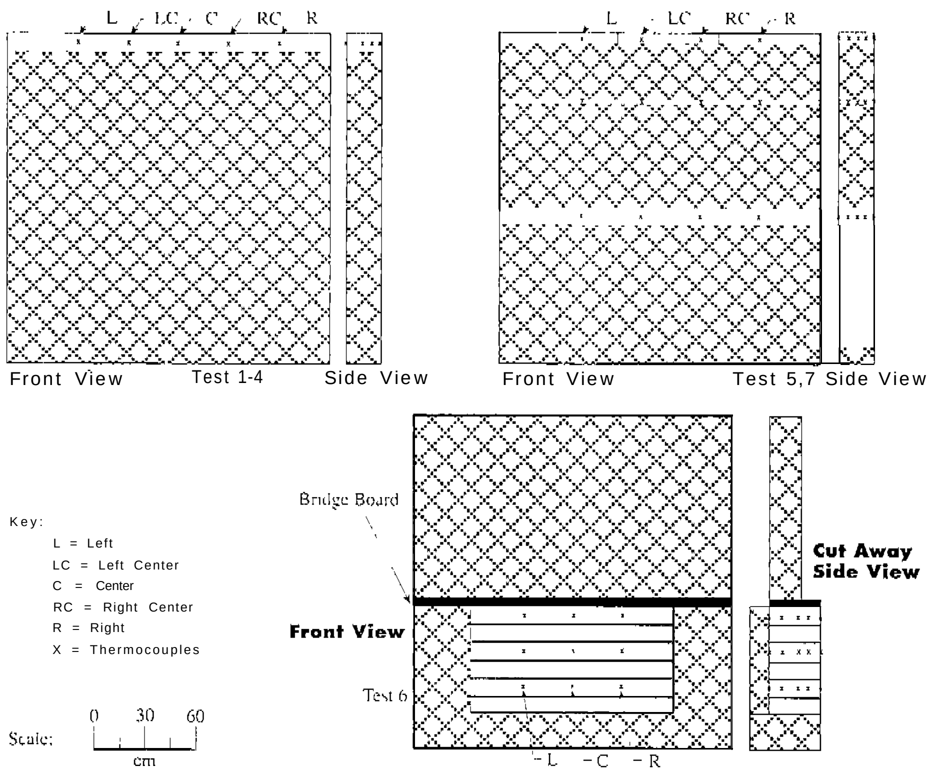



Figure 7. Thermocouple locations for fire-resistance Tests 1 through 7.

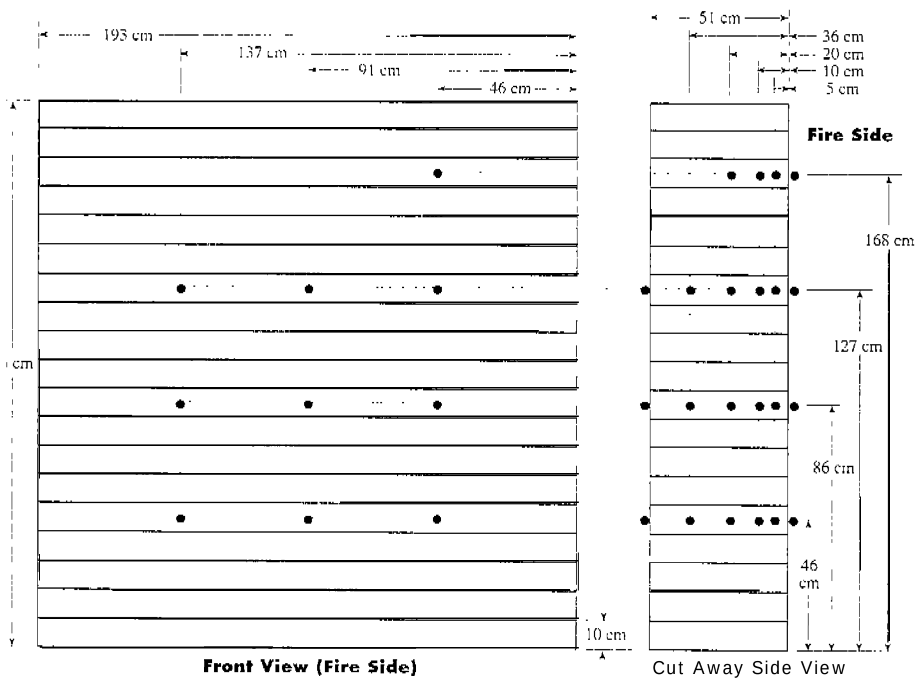



Figure 8. Thermocouple locations for full-size wall fire-resistance Tests 8 and 9.

previously mentioned, a temperature gradient existed across the wall due to ventilation patterns created by the fan, which skewed the flame plume to the right.

## Description of Tests

In Test 1, an uncoated cardboard honeycomb block 10 cm high by 2 m long by 20 cm thick was placed on the top course of a 2- by 2-m stopping constructed of dry-stacked incombustible cement blocks. The exposed faces of the cement blocks were coated with a fiber-reinforced surface bonding mortar. The pressure differential for this test was adjusted to 37.5 Pa (0. 15-inch water gauge), a pressure representative of those which would typically exist across entries on active working sections of an underground coal mine. Burr-through was observed in about 25 minutes.

Test conditions in Test 2 were identical to those of Test 1, except that the squeeze block was covered with a nominal 0.4-mm coat of intumescent paint. Burn-through was observed near the backside right thermocouple at about 63 minutes.

In Test 3, two blocks of cardboard honeycomb were placed side by side on the top of the stoppin g, as shown in Figure 6. The seam between the blocks was filled with a commercially available fire stop sealant, and the remainder of the wall was constructed as in Tests 1 and 2. The face of the squeeze block was coated with 0.4 mm of intumescent paint. The pressure differential for this test was adjusted to SO Pa (0.32-inch water gauge). Burn-through occurred within 28 minutes.

In Test 4, three 60-cm cardboard honeycomb blocks were placed side by side on the top of the stoppin g, which was constructed as in the previous tests. The joints were filled with a commercially available sealant, and the face was coated with 0.4 mm of intumescent paint. The pressure differential across the stopping was adjusted to 250 Pa (l-00-inch water gauge). Burr-through was observed in 36 minutes.

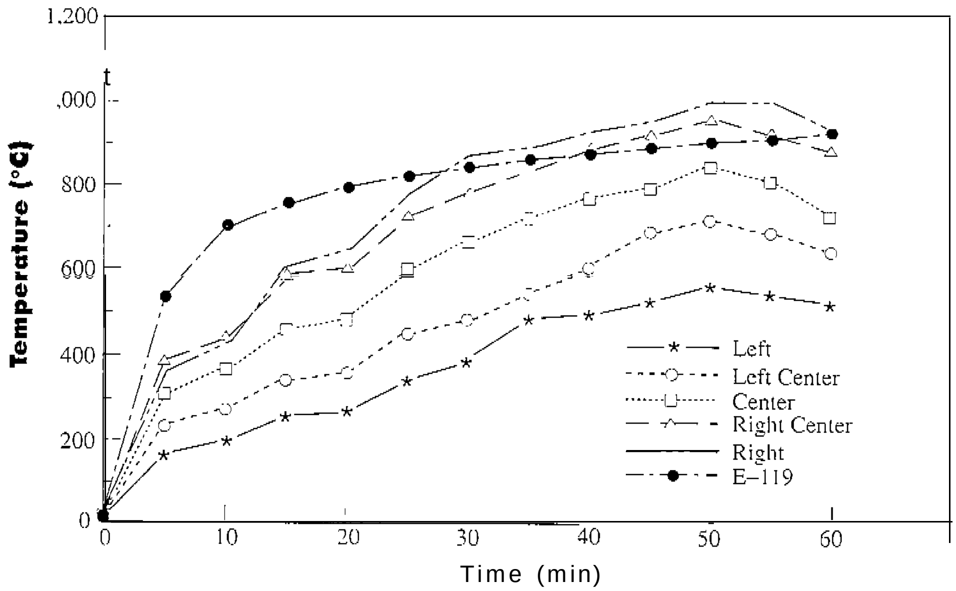



Figure 9. Fire-resistance Test 2 showing exposure temperature vs. time.

In Test 5, three courses of cardboard honeycomb block were inserted into the stopping, as shown in Figure 6. The top course had been pre-squeezed to a height of 5 cm and the course below that to a height of 2.5 cm. The course in the center of the stopping was unsqueezed, with a height of 10 cm.

The top course consisted of three blocks placed side by side with a fire barrier sealant between the joints. All blocks were covered with a 0.4-mm coating of intumescent paint. The pressure differential across the wall was set to 37.5 Pa (0.15inch water gauge), and the test fire was allowed to burn for 120 minutes. Burn-through along the top course of block, which was pre-squeezed to 50% of its original height, occur-red at 74 minutes. The course of block located in the center of the wall, which had been pre-squeezed to 2.5-cm or 25% of its original height, did not burn to a depth of 5 cm until 82 minutes into the test. At the conclusion of the test, the block was removed from the wall and examined. The maximum depth of decomposition was found to be 3 cm. The lo-cm-high course of block placed near the lower portion of the wall burned through in about 97 minutes.

In Test 6, a large crib of cardboard honeycomb block was placed in the bottom center of the wall, as shown in Figure 6. This crib consisted of individual blocks 10 cm high by 20 cm thick by 60 cm wide that had been glued together and faced with 0.5 mm of intumescent paint. A timber bridge board and masonry block was installed around the crib, and the pressure differential was adjusted to 37.5 Pa (0.15-inch water gauge). Evidence of burn-through occurred at 52 minutes, Times recorded for various depths in the block were based on the worse case for three vertically placed thermocouples at one location.

In Test 7, three 60-cm cardboard honeycomb blocks 7.5 cm thick, which had been impregnated with 18% phenolic resin, were placed side-by-side on the top of the wall, and three blocks were placed in the center of the wall. The joints were filled with a generic, non-fire-rated silicone sealant, and the faces of the blocks were coated with a 0.4-mm coating of intumescent paint. The pressure differential was adjusted to 37.5 Pa (0.15-inch water gauge). The tray fire was allowed to burn for 120 minutes. Burn-through was observed in the top course near the right thermocouple 50 minutes into the test. At the end of the test, combustion had not occurred to a depth of 15 cm in the course of block placed in the middle of the wall.

Tests 8 and 9 were conducted to investigate both coated (Test 8) and uncoated (Test 9) walls constructed entirely of honeycomb blocks measuring a nominal 1.9 m by 1.9 m by 0.51 m thick. Walls were constructed by stacking individual blocks measuring a nominal 0.10 m high by 1.90 m long by 0.51 m thick and applying a polyvinyl acetate glue over the Kraft paper facings on the top and bottom of each unit. The exposed face of the coated wall was covered with a 0.25-mm coat of intumescent paint. Char rates were measured, and the total time required to burn through in each test was also noted.

## Summary of Fire Resistance Results

Char rate data for all tests are located in Table 3.

A number of observations were made as a result of this series of fire-resistance tests.

First, untreated honeycomb cardboard blocks 20 cm thick with a nominal cell size of 1.25 cm displayed fair inherent fire-resistance characteristics. Upon heating, the blocks decomposed and formed a char and ash skeletons, which tended to insulate the virgin cells of cardboard that lay behind them and retard the subsequent decomposition rate. Fire-resistance ratings in excess of 20 minutes were observed in gallery tests with pressure differentials of 37.5 Pa across the wall.

Second, the fire resistance of cardboard honeycomb blocks can be significantly improved by applying 0.2- to 0.5-mm coatings of intumescent paint to the face of the block. The swelling, charring effect of these coatings insulates the block from the heat of the fire and limits the amount of oxygen that reaches the surface of the block, thus improving the overall fire resistance. The presence of an intumescent coating also protected unsqueezed blocks from significant decomposition at temperatures of up to about 400°C for about 30 minutes. This effect was noticed even at pressure differentials of 250 Pa.

In addition, no significant smoke was observed through the backside of the blocks during any of the tests before burn-through occurred.

The pressure differential across the stopping had an appreciable effect on the fire resistance of the cardboard honeycomb blocks. This is probably due to the fact that, at higher pressures, there is increased turbulence and leakage of hot combustion gases through the block, which causes protective ash to be swept away, accelerating the combustion process. Generally, increasing pressure differentials result in decreased fire-resistance ratings.

In terms of fire-resistance ratings, the worse-case scenario occurs when the blocks are placed in. the top course of the stopping: Test 2 displayed burn-through in 63 minutes. Heat transfer into the roof is minimal, and the highest fire temperatures appear at this location, which are probably the two main reasons for the relatively low ratings observed. A course of blocks placed near the bottom of the wall in Test 5 provided separation for an additional 34 minutes before burning through under the same conditions as the block listed in Test 2.

The fire resistance of the coated cardboard blocks improved as the blocks were compressed. Burn-through times of 63,74, and more than 100 minutes were observed in fire tests exposing both unsqueezed blocks and blocks squeezed 50% and 75%, respectively, at pressure differentials of 37.5 Pa.

Joints between individual cardboard honeycomb blocks could be filled with any generic silicone sealant. Bum-through always occur-red at some point within the block itself, not at the joints when filled with these products. Listed fire barrier caulks also performed quite well, but their added expense may not be justified.

Test 5 investigated, among other things, the effect of burn-through of a cardboard block that originally supported the weight of several courses of masonry block above it. A post-test investigation of the stopping revealed that the masonry blocks above the 10-cm course of cardboard block in the lower center of the wall remained in place and did not shift significantly when the cardboard blocks below them were destroyed. If the stopping is mortared together using a fiber-reinforced surface bonding mortar

TABLE 3
Fire-Resistance Test Data for Cardboard Honeycomb Designs

| | | location | | | | |
|---|---|---|---|---|---|---|
| | | Left | Left Ctr | Center | Right Ctr | Right |
| Test | Block Depth (cm) | Time to Reach 200°C (min) | | | | |
| 1 | 5 | 12 | 11 | 9 | 6 | 7 |
| | 10 | 15 | 18 | 18 | 12 | 11 |
| | 15 | 23 | 27 | 26 | 15 | 15 |
| | BT* | -- | -- | -- | 25 | 25 |
| 2 | 5 | 43 | 25 | 26 | 15 | 18 |
| | 10 | 59 | 39 | 39 | 34 | 32 |
| | 15 | -- | 58 | 56 | 46 | 44 |
| | BT | -- | -- | -- | -- | 63 |
| 3 | 5 | 28 | -- | 16 | 18 | 17 |
| | 10 | -- | -- | 24 | 28 | 25 |
| | 15 | -- | -- | 27 | -- | 28 |
| | BT | I- | -- | 28 | -- | -- |
| 4[1] | 5 | 32 | 27 | 29 | 32 | 21 |
| | 10 | -- | 38 | 34 | 38 | 30 |
| | 15 | -- | 38 | 36 | 39 | 33 |
| | BT | -- | 39 | 36 | 38 | 36 |
| 5 Top Course | 5 | 39 | 35 | -- | 30 | 26 |
| | 10 | 56 | 54 | -- | 52 | 39 |
| | 15 | NI** | NI | -- | NI | NI |
| | BT | 83 | 74 | -- | 83 | 87 |
| 5 Mid-Wall | 5 | -- | -- | -- | -- | 82 |
| | 10 | -- | -- | -- | -- | -- |
| | 15 | -- | -- | -- | -- | -- |
| | BT | -- | -- | -- | -- | -- |

[1] Actual bum-through observed at 35 minutes near center.

***BT** - Burn-through
**NI - Not instrumented

| | | Location | | | | |
|---|---|---|---|---|---|---|
| | | Left | Left Ctr | Center | Right Ctr | Right |
| Test | Block Depth (cm) | Time to Reach 200°C (min) | | | | |
| 5 Lower Wall | 5 | 56 | 25 | -- | 21 | 15 |
| | 10 | -- | 97 | -- | 78 | 55 |
| | 15 | -- | -- | -- | 103 | 96 |
| | BT* | -- | -- | -- | 113 | 97 |
| 6 | 5 | 7 | -- | 8 | -- | 13 |
| | 10 | 16 | -- | 17 | -- | 24 |
| | 15 | 34 | -- | 37 | -- | 45 |
| | BT | 52 | -- | -- | -- | -- |
| 7 TOP Course | 5 | 62 | 41 | -- | 26 | 21 |
| | 10 | -- | 61 | -- | 41 | 34 |
| | 15 | -- | 94 | -- | 55 | 49 |
| | BT | -- | 115 | -- | 85 | 72 |
| 7 Mid-Wall | 5 | -- | 30 | -- | 14 | 17 |
| | 10 | -- | -- | -- | 66 | 60 |
| | 15 | -- | -- | -- | -- | -- |
| | BT | -- | -- | -- | -- | -- |
| 8[2] | 5 | 17 | -- | 11 | -- | 11 |
| | 10 | 31 | -- | 21 | -- | 24 |
| | 20 | 53 | -- | 43 | -- | 50 |
| | 36 | 79 | -- | 64 | -- | 89 |
| | BT | -- | -- | 88 | -- | -- |
| 9[3] | 5 | 3 | -- | 3 | -- | 3 |
| | 10 | 11 | -- | 9 | -- | 9 |
| | 20 | 27 | -- | 29 | -- | 25 |
| | 36 | 54 | -- | 62 | -- | 62 |
| | BT | -- | -- | -- | -- | -- |

[2] Actual bum-through observed in 78 minutes
[3] Burn-through observed in 68 minutes.

* BT - Burn-through

and fitted tightly into the coal ribs with a feathering of mortar, the probability of masonry block sag when the cardboard block burns through in a fire is remote.

A large crib of cardboard honeycomb block 30 cm thick by 40 cm high by 120 cm long placed in the bottom center of the stopping and coated with a 0.4-mm layer of intumescent paint demonstrated 52 minutes of fire resistance at a pressure differential of 37.5 Pa. The char rate is linear and may be extrapolated to predict the thickness of block necessary to provide a minimum l-hour burn-through. This value is estimated to be 34 cm.

The 18% phenolic-impregnated block with intumescent face coating displayed fire-resistance ratings of 50 and more than 60 minutes for top and center course configurations, respectively. Blocks would be expected to gain approximately 30% by weight in water in high-humidity environments, which should serve to improve further on the fire-resistance characteristics measured in this test. This test also investigated the concept of applying an adhesive-backed paper to the exposed face of the block and coating it with an intumescent paint. The protection this method afforded was no less effective than coating the individual vertical surfaces of the exposed cells of the block. The advantage of this tape is that it allows for the quick factory application of a more uniform coating using a smaller surface area and less paint. Several blocks were constructed in this manner and squeezed to investigate the bonding characteristics of the tape/paint under loading conditions. Excellent adherence of the tape to the face of the block was observed. The coating did not spall or delaminate when the block was squeezed to 25% of the initial height.

The 51-cm-thick honeycomb block wall whose exposed surface was coated with a 0.25-mm layer of intumescent paint in Test 8 burned through in 78 minutes. The rate of char was observed to be linear in the areas where it could be measured. The maximum measured rate of char occurred near the center of the wall and was calculated to be 6.0 mm/minute. Vertical flame propagation occurred on the backside after flame breakthrough. Evidence of deep-seated combustion was present on the face of the wall after the heat source was removed. No smoke was observed through the wall before burn-through.

The honeycomb block wall without a face coating burned through in 68 minutes in Test 9. The rate of char was determined to be linear and calculated to be approximately the same as the rate for the coated wall, or 5.8-mm/minute. The main difference observed was that the intumescent coating protected the block from initial charring for several minutes. Combustion at a depth of 5 cm into the wall occurred at 3 minutes, as opposed to 11 minutes for the coated wall. As in the case of the coated block, vertical flame propagation occurred on the backside of the wall after burn-through, and evidence of deep-seated combustion was present on the face of the wall after the test. No smoke was observed through the wall before burn-through.

## Summary

Cardboard honeycomb blocks of nominal 1.25-cm cell size, coated with intumescent paint, have demonstrated suitable performance characteristics in the critical areas of fire resistance, surface flammability, compressibility, air leakage, and cost.

Field tests are currently being conducted in selected underground mines where convergent conditions are known to exist. Preliminary results are very encouraging, and stoppings constructed using the various designs tested in the program are performing very well. The concept of a light-weight, low-cost fire barrier may have applications in other areas where fire protection is essential, including the building industry.

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