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Laboratory Assessment of Alternative Longwall Stabilization Materials

By Deno M. Pappas

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Donald Paul Hodel, Secretary

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David S. Brown, Acting Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	lb/yr	pound per year
ft^2	square foot	min	minute
ft^3	cubic foot	P	poise
h	hour	pct	percent
in	inch	psi	pound (force) per square inch
in^2	square inch	yr	year
lb	pound		
lbf	pound (force)		

LABORATORY ASSESSMENT OF ALTERNATIVE LONGWALL STABILIZATION MATERIALS

By Deno M. Pappas[1]

ABSTRACT

The objective of this Bureau of Mines investigation was to identify and evaluate alternative binder materials for use in stabilizing and consolidating highly fractured roof along longwall faces and gate roads. The desirable characteristics of a stabilization material were defined, and an extensive search was conducted to find materials satisfying these characteristics. Of 20 materials originally scrutinized, 9 were chosen for laboratory analyses. The laboratory tests evaluated bond strength and tensile strength under both dry and wet conditions. An optimum material was not found. The laboratory analyses indicated two possible candidate materials for longwall stabilization: high-aluminous cement and two-component epoxy; however, the tensile strength of the high-aluminous cement was mediocre, and the epoxy cement is toxic, flammable, and fairly expensive. The potential market demand for an effective and economical stabilization material is discussed in the appendix.

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[1] Civil engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

Highly fractured roof strata and bad roof associated with geologic anomalies such as clay veins, sand channels, and faults can fall quickly and unexpectedly before the roof can be adequately supported. In the past 6 yr, nearly 200 underground workers have died and 6,000 workers have been injured in accidents directly related to the fall of roof or rib (1).[2] Approximately 400 of the injuries and 4 of the fatalities occurred along longwall faces and gate roads. In addition to creating health and safety hazards, ground control problems have also seriously inhibited and/or halted longwall production of coal and increased operating costs.

During the development of a longwall panel, bad roof may be encountered, sometimes resulting in the formation of large cavities above the longwall support shields. These cavities cause the shields to lose contact with the roof. Correction of this problem often requires the building of cribs on top of the shields to reestablish roof contact. However, this type of construction subjects workers to extremely hazardous roof conditions (2). Another common problem with bad roof is that rock chunks fall from the roof in front of or between supports as the supports are advanced. Often these rock chunks jam the armored face conveyor, stage loader, and/or belt conveyor, which temporarily halts production.

If the roof is extensively fractured, there is very little that the coal mine operator can do to avoid roof failure using traditional roof support practices. However, there are three basic presupport techniques that have been used in Europe for many years to reinforce and/or consolidate fractured roof prior to mining (3):

1. Strata reinforcement--The strata are reinforced with wood and/or steel dowels grouted with resin contained in cartridges and installed on an angle through the coal face and into the roof rock strata. This method is used when the strata are relatively unfractured but could become more fractured by subsequent mining operations.

2. Strata consolidation--A binder material is injected into the strata ahead of the face to consolidate and stabilize fractured roof. This method is used in very weak or intimately fractured strata.

3. Strata reinforcement and consolidation--A binder material is injected through dowel rods to fill the large fractures and to key the strata blocks together. This method is used to reinforce or consolidate strata that fracture into large blocks with relatively wide fractures.

The presupport technique most widely used by U.S. longwall mining operators is the strata consolidation technique (4). Although this technique is often very effective, the polyurethane used as binder material may have serious health and safety drawbacks in addition to being very costly (5). Because of these drawbacks, the strata consolidation technique is used only when all other support methods have been exhausted. Therefore, to encourage the use of this successful technique by making the binder material less hazardous and less costly, the Bureau is attempting to identify and evaluate alternative types of binder materials that are equally as effective as the polyurethane but are cheaper and have minimal health side effects.

Previous work on stabilization materials includes an extensive study on the state of the art of longwall face and roof stabilization techniques (4). The investigation identified, surveyed, and field-tested resin injection and resin doweling techniques that had been used to prevent or stabilize ground control problems associated with longwall mining. In other work, a potential stabilization material known as magnesium oxychloride

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[2] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

cement was refined by the Bureau (6). This material was inexpensive, nontoxic, and nonflammable. However, it has a slow set time and deteriorates in strength when subjected to water. In spite of these disadvantages, the magnesium oxychloride was included in this study so that the physical strength properties could be determined and the material's characteristics equitably assessed.

SELECTION OF BINDER MATERIALS

A comprehensive study was conducted to determine the required properties of a successful stabilization material, and specifications were written that detailed these characteristics. Stabilization materials used in other countries were examined, as well as many grouts, resins, cements, and adhesives, even if there was only a remote possibility that the material could be used as a stabilization material. Subsequently, a list was made of the nine binder materials that met most of the specifications for a successful stabilization material.

SPECIFICATIONS FOR A SUCCESSFUL BINDER MATERIAL

The following characteristics are desirable for a binder material; they are based partially on a report by Subramanian (7) and on other articles on stabilization materials and installation procedures (4, 8).

1. Nontoxic--The binder material's components should not contain ingredients and/or emit any vapors that could cause short- or long-term health and safety problems.

2. Nonflammable--The binder material should be flame resistant and should not emit any toxic fumes when burned.

3. Economical--The cost of the stabilization material should be equal to or less than $38/ft^3$ or $1.25/lb, based on the 1987 cost of polyurethane.

4. Competent strength properties--Usually, the binder material's weakest mechanical property is its ability to adhere securely to adjacent surfaces, which is known as the bond strength or shear strength. Since this is usually the weakest property, it is important to know the approximate strength value at which the bond may fail. The tensile strength of the binder material is another important property because the injected binder material has to be able to hold the mine roof, which is usually in tension, together. Typically, the material's compressive strength is several multiples higher than either the shear strength or the tensile strength, and therefore, it is not necessary to evaluate this property. The material's mechanical properties should equal or exceed the strengths listed below. These values are based mostly on averaged strength values of polyurethane, which has proven itself to be effective:

Bond strength..........	≥700 psi.
Tensile strength.......	≥1,000 psi.
Compressive strength...	≥3,500 psi.

5. Quick set time--The binder material should reach a minimum of 10 pct of its ultimate bond strength in 10 to 15 min, 50 pct in 3 h, and 90 pct in 8 h. A quick set time is very important because the material should quickly begin to provide structural strength to the mine roof to prevent the roof from sagging. The specified time limits were determined to provide an acceptable support strength before start of the next mining cycle.

6. Low density--The binder material should have a low density in order to keep the weight that the material adds to the roof at a minimum.

7. Deformable--The grout should be able to undergo a 25-pct elongation prior to failure. Ability to deform is a desirable characteristic for a binder material because it allows the roof to flex without immediate failure.

8. Minimal shrinkage--Shrinkage should not cause the binder material to pull away from the bonded surface.

9. Low viscosity--The viscosity of the binder material should be between 10 and 20 P, so that it can be injected into the roof at pressures not exceeding 1,500 psi. Also, a low viscosity is necessary in order for the stabilization material to penetrate the minute fissures in the roof strata.

10. Water tolerance--The presence of water should not greatly affect the strength of the material since water in the mine strata is a common occurrence.

11. Minimal exothermic heat--The rate of heat generation within the material should be low enough so that the heat can be dissipated quickly, to prevent the adjacent coal from reaching its ignition temperature.

These are ideal characteristics for a roof stabilization material to possess; however, in reality, probably no material exists with all these characteristics.

BINDER MATERIALS CHOSEN FOR EVALUATION

The initial 20 binder materials identified as possible alternative materials for stabilizing fractured roof strata were narrowed down to 9 binder materials using the specifications stated above. The binder materials selected for further evaluation were those that satisfied more than half of the specifications (table 1). Although comparable strength properties and water tolerance were unknown for most of the materials, the phenolic resin, the high-aluminous cement, the magnesium phosphate, and the acrylic resin met most of the important criteria (table 1).

ASSESSMENT OF PHYSICAL STRENGTH PROPERTIES

All of the listed specifications play an important role in the makeup of an effective stabilization material. Physical strength properties are essential characteristics of a binder material since success depends mostly on the material's ability to bind the fractured roof strata together. Since the physical strength properties and water tolerance were not available for most of the binder materials (such that the materials could be equitably compared), the materials were laboratory-tested to obtain these quantitative and comparable test results.

LABORATORY TESTS

Three series of laboratory tests were utilized to evaluate the bond strength, tensile strength, and water tolerance. For the first series, a bond strength test was chosen to measure the least competent property of the binder material--its ability to adhere and fuse to the adjacent fracture surfaces. The bond strength test measures, for the most part, the material's shear strength. The second series of tests examined the tensile strength of the binder material, another important property since the material has to be competent enough to withstand tensile forces resulting from the sagging of the mine roof. The last series of tests repeated the previous two series, but with the binder material exposed to water, to measure the degree of adverse effects that water has on the binder material's strength. This is a major concern because of the common occurrence of water in most underground mines.

TABLE 1. - Characteristics of selected binder materials, in order of importance

Material	Nontoxic	Nonflammable	Economical	Strength properties	Quick set time	Low density	Deformable	Minimal shrinkage	Low viscosity	Water tolerance	Minimal exothermic heat
Magnesium phosphate........	Y	Y	M	U	Y	M	N	Y	Y	U	Y
Epoxy.............	N	N	N	U	Y	M	Y	N	Y	U	M
High-aluminous cement..........	Y	Y	Y	U	M	M	N	Y	Y	U	Y
Acrylic resin.....	Y	Y	Y	U	Y	M	N	Y	Y	U	Y
Magnesium oxychloride......	Y	Y	Y	U	N	M	N	Y	M	N	Y
Phenolic resin....	M	Y	Y	U	Y	Y	Y	M	Y	U	M
Sodium silicate with limestone...	Y	Y	Y	U	Y	Y	N	N	Y	U	Y
Magnesium oxysulfate.......	Y	Y	Y	U	N	M	N	Y	Y	U	Y
Ultrafine cement..	Y	Y	Y	U	N	M	N	Y	Y	U	Y

M Marginally meets given criteria.
N No; does not meet given criteria.
U Unknown.
Y Yes; meets given criteria.

Bond Strength Test

The bond strength test, specifically known as the composite cylinder test or Arizona slant shear test (ASTM standard C-882) (9), evaluates the ability of the binder material to bond to fracture surfaces. The test specimen consists of two concrete cylinder wedges 6 in by 3 in. in diam, with the binder material sandwiched in between and bonding both concrete components together into a composite cylinder (fig. 1). These cylindrical wedges are formed according to ASTM standards and are cured for 28 days in a humidity chamber to ensure that the concrete has reached its maximum strength. Subsequently, the binder material is applied (approximate thickness 0.015 to 0.030 in) on the elliptical surface of the wedges, and the wedges are bonded together to form a composite cylinder. The ends of each composite cylinder are finely ground to ensure uniform loading. Once the specimens are prepared, a universal testing machine is used to uniaxially load the bonded cylinder (fig. 2). Failure of the bonded cylinder usually occurs in one of two ways:

1. When the applied load exceeds the bond strength of the binder material, the cylinder fails directly along the elliptical bonded surface, as shown in figure 3.
2. When the strength of the binder material approaches or exceeds the strength of the concrete wedges, the concrete will start to fail in compression until it weakens the bond. Consequently, the bonded cylinder fails partially within the outer layer of concrete and partially along the elliptical surface (fig. 4).

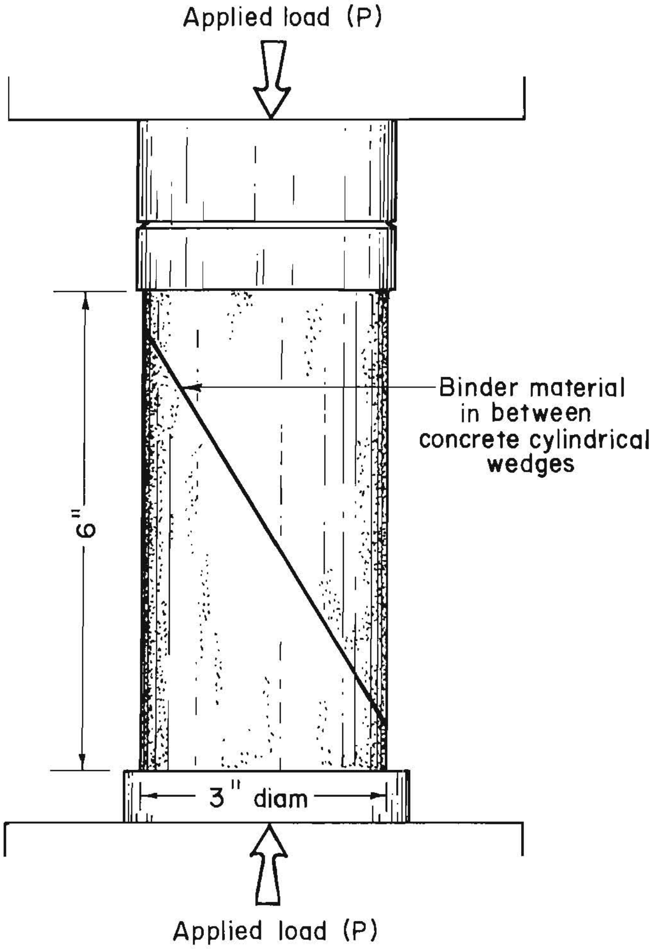

FIGURE 1.—Schematic of bond strength test.

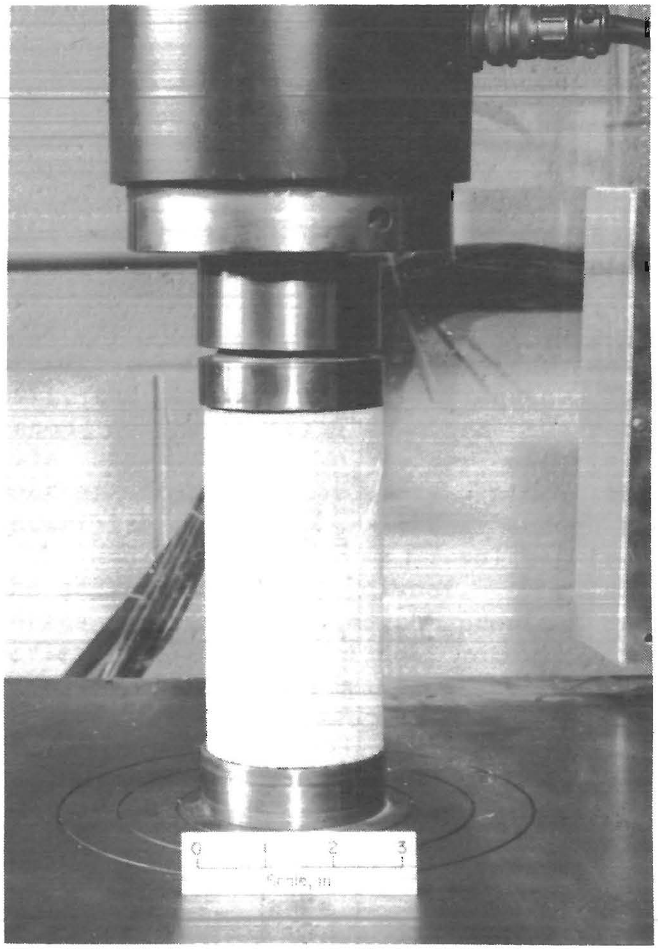

FIGURE 2.—Uniaxial loading of bonded concrete wedges.

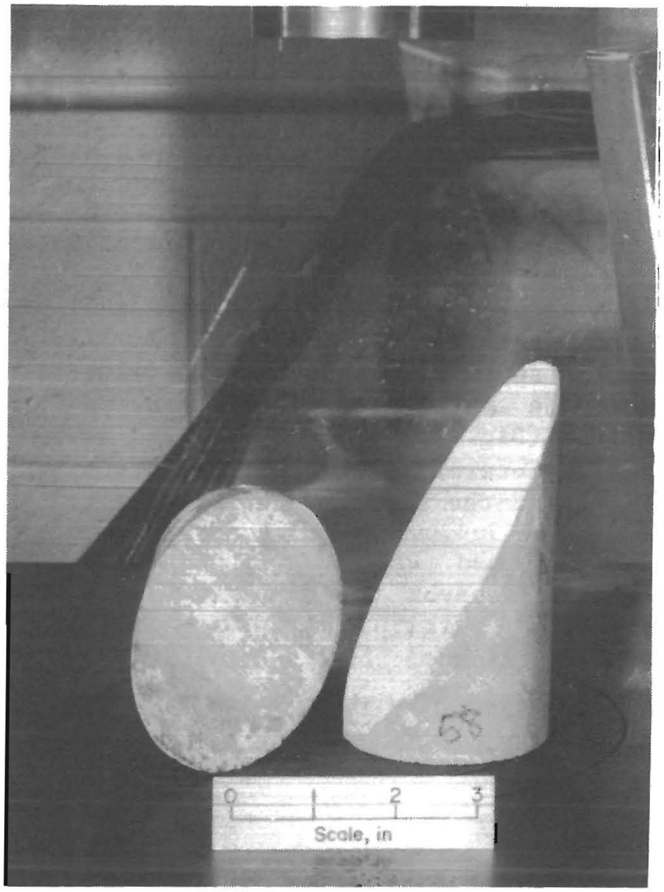

FIGURE 3.—Failure surface appearance when concrete exceeds strength of binder material.

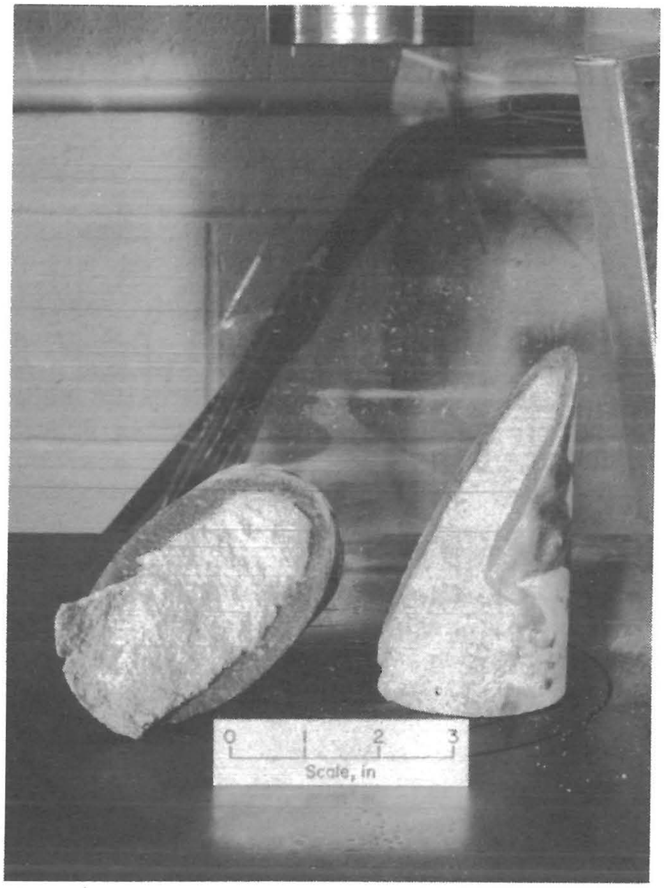

FIGURE 4.—Failure surface appearance when binder material approaches or exceeds strength of concrete.

The bond strength is calculated by using equation 1, which divides the load carried by the specimen at failure by the area of the bonded elliptical surface (approximately 14.13 in^2):

$$B = \frac{P}{A'}, \tag{1}$$

where B = bond strength,

P = maximum load carried by bonded cylinder, lbf,

and A' = elliptical surface area, in^2.

A homogenous concrete cylinder was also tested from each batch of concrete mixed. This test allowed the strength of the previously tested bonded cylinders to be evaluated as a percentage of the strength of the solid concrete cylinder. The following equation is used to calculate the competence of the bond between the two cylinder wedges as a percentage of the compressive strength of the homogeneous control cylinder:

$$M = \frac{P/A}{C/A} 100, \tag{2}$$

where M = percentage of strength of bonded cylinder with respect to control specimen,

P = maximum load carried by bonded cylinder, lbf.

C = maximum load carried by solid control cylinder, lbf,

and A = cross-sectional area of cylinder, in^2.

Tensile Strength Test

The Brazilian tensile test indirectly determines the tensile strength by loading the binder material specimen diametrically under a uniaxial load and following ASTM standards C-496 (figs. 5-6) (10). The diametrical loading generates a tensile stress at the center of the specimen in the direction perpendicular to the direction of the applied load. When the applied load reaches a critical level, the specimen splits lengthwise in tension (fig. 7) (11). The following equation determines the splitting tensile strength of the binder material samples:

$$T = \frac{2P}{\pi L D}, \qquad (3)$$

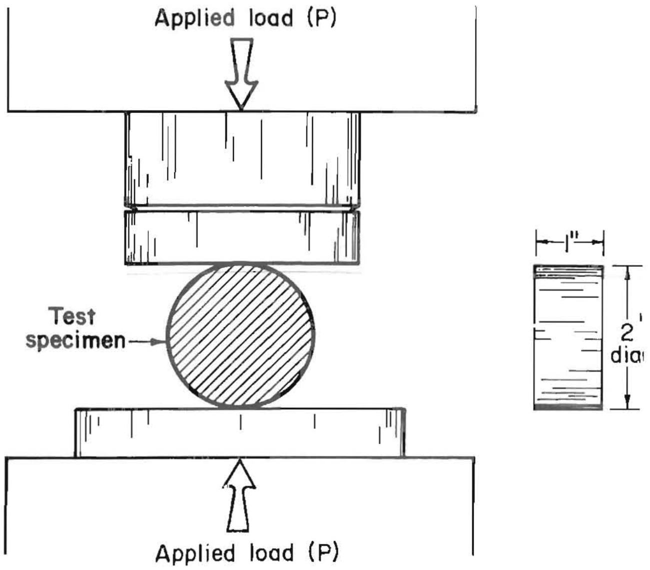

FIGURE 5.—Schematic of tensile strength test.

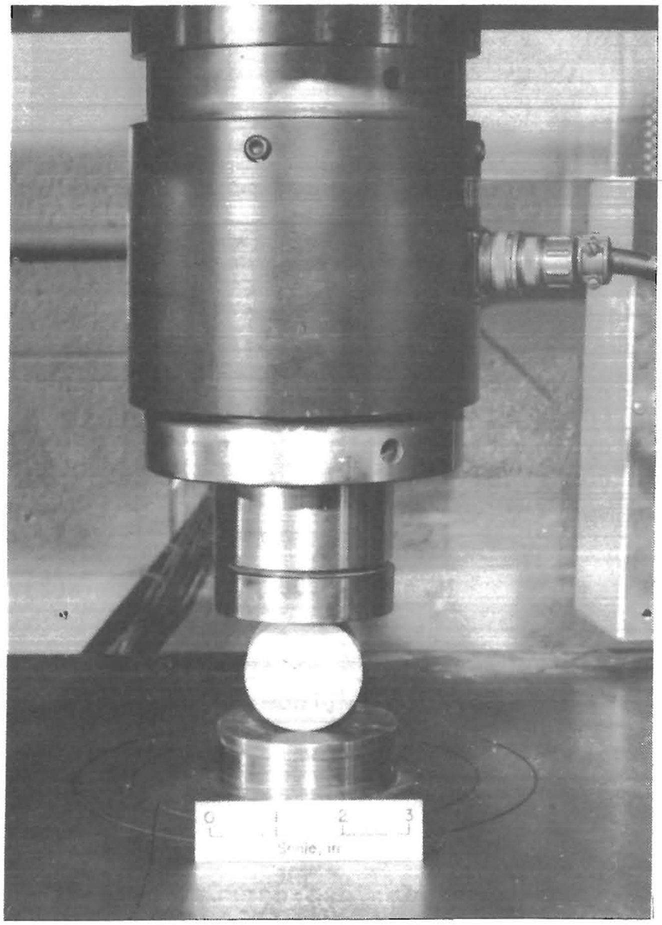

FIGURE 6.—Uniaxial loading of tensile strength test specimen.

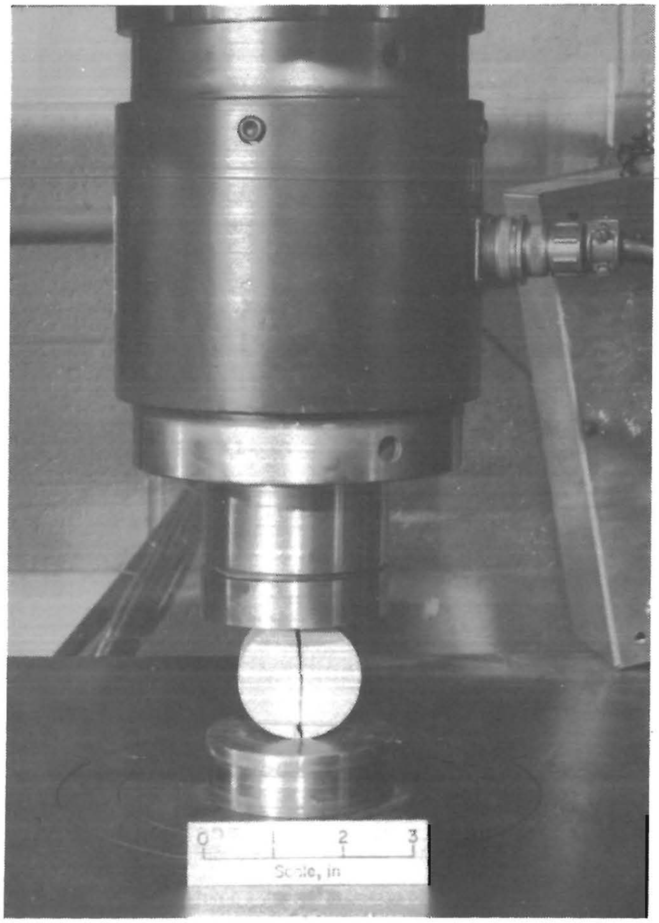

FIGURE 7.—Failure of tensile strength test specimen.

where T = splitting tensile strength, psi,

P = maximum applied load indicated by testing, lbf,

L = length of specimen, in,

and D = diameter of specimen, in.

Water Tolerance Test

Water is a common occurrence in most underground mines, usually following a path of least resistance along the joints and bedding planes of the roof strata. The water may come into contact with the binder material that has been injected into the strata and may adversely affect the strength of the material. Therefore, the bond strength and tensile strength tests were repeated under wet conditions. The bond strength samples were immersed in water for 7 days and the tensile strength samples for 4 days prior to uniaxial testing. The tensile test specimens were soaked for a shorter period because of their smaller size and greater binder material surface area exposed to water. The water used to immerse the test specimens was changed daily to simulate the effect of flowing water interacting with the binder material. If the water had not been changed, it would have reached a stage of equilibrium and prevented further dissolution of the binder material (12). Since the water used in the test would have become solution saturated, it would not have provided an accurate simulation in evaluating the water tolerance of binder materials.

TEST RESULTS

Under dry conditions, the magnesium phosphate and epoxy cements were found have the highest bond strengths, between 1,900 and 1,700 psi, approximately 80 to 90 pct of the strength of the solid concrete cylinder (table 2). A good bond strength property (1,000 psi) was exhibited by the high-aluminous cement. Mediocre bond strength (700 to 400 psi) were found for the acrylic resin, magnesium oxychloride, and the phenolic resin. Materials that performed poorly in the bond strength tests (below 300 psi) were sodium silicate with limestone, magnesium oxysulfate, and ultrafine cement. They were disqualified from further tests. The magnesium oxychloride was also disqualified because of its mediocre bond strengths along with other major problems (long set time and poor water resistance) that made it inappropriate for additional tests.

In the second series of tests, the tensile strengths of the five remaining binder materials were examined. Most of the inorganic materials (formed from earth minerals) produced fairly low

TABLE 2. - Bond strength test results

Material	Dry		Wet		Difference in bond strength, pct
	Av bond strength, psi	Av pct[1]	Av bond strength, psi	Av pct[1]	
Magnesium phosphate....	1,850	91	450	27	-76
Epoxy..................	1,720	83	1,600	98	-7
High-aluminous cement..	980	47	1,430	87	+46
Acrylic resin..........	710	34	420	25	-41
Magnesium oxychloride..	690	33	D	D	D
Phenolic resin.........	410	20	120	7	-70
Sodium silicate with limestone........	280	13	D	D	D
Magnesium oxysulfate...	200	9	D	D	D
Ultrafine cement.......	40	2	D	D	D

D Material disqualified from further testing.

[1] Material strength evaluated in terms of percent of strength of the homogenous control cylinders.

TABLE 3. - Tensile strength test results

Material	Av strength, psi		Difference, pct
	Dry	Wet	
Magnesium phosphate......	510	413	-19
Epoxy[1]....................	>1,000	>1,000	NA
High-aluminous cement....	410	390	-5
Acrylic resin............	455	315	-30
Phenolic resin...........	340	D	D

D Material disqualified from further testing.
NA Not available.

[1] Owing to deformation of the applied load area, the tensile strength could only be approximated. Water did not seem to affect the strength of the epoxy.

tensile strengths, between 300 and 500 psi (table 3). These low strengths are reasonable since most inorganic materials are known to be weak in tension. The epoxy cement, which is an organic material (formed synthetically using organic chemistry), produced very high tensile strengths exceeding 1,000 psi. However, specific test values could not be accurately determined because of the rapidly deforming loading area of the epoxy test specimens resulting from the extremely deformable nature of the epoxy.

The last series of tests, the water tolerance tests, were conducted on the five remaining binder materials. These tests were conducted similar to the previous test series, except that the specimens were saturated, however the results were not the same. Water significantly reduced the bond strengths of the phenolic resin, acrylic resin, and magnesium phosphate by 41 to 76 pct (table 2). However, the high-aluminous cement increased in bond strength by 46 pct. The tensile strength under wet conditions of the acrylic resin and the magnesium phosphate were reduced .by 20 to 30 pct (table 3). The high-aluminous cement decreased minimally in strength, by about 5 pct; the phe-nomenon seen in the previous test, causing the high-aluminous cement to increase in strength when subjected to water, did not occur.

DISCUSSION

Conducting these tests on strength properties and water tolerance enabled most of the unknowns shown in table 1 to be equitably evaluated, as shown in table 4. Although no material was found to be distinctively superior in all tests, the epoxy, the high-aluminous cement, and the magnesium phosphate performed noticeably better in some of the tests than the other materials tested (table 4). The epoxy outperformed all of the other materials in nearly all of the tests. Epoxy has excellent bond strengths of 1,700 psi under dry conditions and 1,600 psi under wet conditions (table 2). Epoxy's tensile strength was at least twice the tensile strength of any of the other materials. It was also observed during the tests, especially the tensile tests, that epoxy exhibited deformable qualities. Unfortunately, the epoxy has some negative characteristics that diminish its potential as a binder material for stabilizing fractured roof. As shown in table 4, it is toxic, flammable, and not economical, and some shrinkage does occur during curing.

TABLE 4. - Characteristics of tested binder materials

Material	Non-toxic	Nonflammable	Economical	Bond Strength	Tensile Strength	Quick set time	Low density	Deformable	Minimal shrinkage	Low viscosity	Water tolerance	Minimal exothermic heat
Magnesium phosphate..........	Y	Y	M	Y	N	Y	M	N	Y	Y	N	Y
Epoxy...............	N	N	N	Y	Y	Y	M	Y	N	Y	Y	M
High-aluminous cement............	Y	Y	Y	Y	N	M	M	N	Y	Y	Y	Y
Acrylic resin.......	Y	Y	Y	Y	N	Y	M	N	Y	Y	N	Y
Magnesium oxychloride........	Y	Y	Y	M	U	N	M	N	Y	M	N	Y
Phenolic resin......	M	Y	Y	M	N	Y	Y	Y	M	Y	N	M
Sodium silicate with limestone.....	Y	Y	Y	N	U	Y	Y	N	N	Y	U	Y
Magnesium oxysulfate.........	Y	Y	Y	N	U	N	M	N	Y	Y	U	Y
Ultrafine cement....	Y	Y	Y	N	U	N	M	N	Y	Y	U	Y

M Marginally meets given criteria.
N No; does not meet given criteria.
U Unknown.
Y Yes; meets given criteria.

The high-aluminious cement was found to have good bond strengths of almost 1,000 psi under dry conditions and 1,500 psi under wet conditions. This 46-pct increase in the wet bond strength may have been due to a slightly larger material thickness than used in the dry tests (>0.25 in rather than 0.015 in) and also to the presence of the moisture, which may have enabled the cement to reach its maximum strength. High-aluminous cement is also nontoxic, nonflammable, and economical. However, the tensile strength of the high-aluminous cement was found to be inadequate, at 400 psi (table 3). Other negative characteristics include its mediocre set time and its deterioration in strength over a period of time when it is subjected to high humidity and warm temperatures (13).

Magnesium phosphate was found to have excellent bond strengths of 1,800 psi under dry conditions; however, under wet conditions its strength dropped 76 pct, to 450 psi, indicating the negative effects of water. As with the high-aluminous cement, the magnesium phosphate cement had inadequate tensile strength (500 psi). Although this material is considered to be nonflammable and nontoxic, its poor tensile strength and water tolerance make it inadequate as a stabilization material.

While none of these materials meet the minimum criteria for successfully bonding fractured roof, an alternative stabilization material is definitely needed. The potential market size for such a material is shown in the appendix.

CONCLUSIONS

Although this investigation of potential stabilization materials did not clearly pinpoint an outstanding candidate, it did identify the desirable qualities and evaluate the strength properties of selected binder materials. The epoxy, high-aluminous cement, and magnesium phosphate produced good results in some of the tests, but none of the materials (except the epoxy) met the minimum strength properties for all of the tests. However, the epoxy did not meet the criteria of being nontoxic, nonflammable, and economical.

It is recommended that research be continued, to examine all avenues that may eventually lead to the development of an effective and economical binder material for stabilizing both longwall ground control problems and room-and-pillar problem areas.

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APPENDIX.--POTENTIAL MARKET SIZE FOR EFFECTIVE BINDER MATERIALS

The current market size for polyurethane, which is the prevailing material used for longwall and room-and-pillar applications, is approximately 3 million lb/yr in the United States and 35 to 40 million lb/yr in Europe (2). The volume of fractures and voids filled by polyurethane annually can be approximated at 46,000 to 100,000 ft^3 in the United States and 615,000 to 1,300,000 ft^3 in Europe. These numbers are approximated by dividing the quantity of polyurethane used by the average density of the polyurethane. It should be emphasized that use of polyurethane in U. S. mines was limited mostly to situations where extremely poor ground conditions were encountered and the polyurethane was used as a last resort when every other method of controlling the roof had failed. One factor limiting the usage of polyurethane is the cost of the material. If an effective and inexpensive material could be developed to stabilize and consolidate fractured roof strata, its potential as a method of strata control would be far reaching.

A binder material could also be used as a supplemental method of supporting the roof, along with roof bolts. The amount of material this would entail is unknown but might be millions of cubic feet.

Perhaps the binder material could eventually be used as the primary method to support the mine roof, thus reducing, or possibly eliminating, the need for roof bolts, crossbars, cribbing, etc. Based on production of U.S. underground coal, excluding longwalls, the roof area supported in 1985 is estimated as roughly 1.8 million ft^2. Two injection holes every 5 ft of entry, with an average volume of approximately 6 ft^3 of material each, yields a total volume of 241 million ft^3 that could be filled using a stabilization material. This would increase the market size to over 2,000 times its current size. It should be emphasized that using a stabilization material as the primary method of mine roof support is impossible with current materials. However, in the future, with the right material and right cost, injecting the roof with stabilization material could become as commonplace as roof bolts are in today's coal mines.

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