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Bolt Anchorage With Gypsum-Plaster Water Capsule Cartridges

By J. E. Fraley and M. O. Serbousek

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm^3	cubic centimeter	m^3	cubic meter
cm^3/cm	cubic centimeter per centimeter	min	minute
°C	degree Celsius	mL	milliliter
g	gram	mm	millimeter
g/cm^3	gram per cubic centimeter	mm^3	cubic millimeter
g/L	gram per liter	μm	micrometer
h	hour	MPa	megapascal
kg	kilogram	N·cm	newton centimeter
kN	kilonewton	pct	percent
L	liter	s	second

BOLT ANCHORAGE WITH GYPSUM-PLASTER WATER CAPSULE CARTRIDGES

By J. E. Fraley[1] and M. O. Serbousek[2]

ABSTRACT

Full-column anchored resin bolts were first used in underground mines in 1972. These bolts appear to improve support in many roof bolt applications, as indicated by the use of about 30 million resin bolts in 1980. In the mid-1970's, Bureau of Mines investigators began looking for a substitute for resin because of its short supply and rapidly increasing price. The investigators selected accelerated gypsum plaster ($CaSO_4 \cdot 1/2H_2O$), which becomes gypsum ($CaSO_4 \cdot 2H_2O$) when mixed with water. Gypsum makes an effective alternate grout material because it hardens quickly, is readily available, and is inexpensive in comparison with other cementitious materials. The Bureau received a patent (U.S. patent 4,096,944) for a system combining water capsules (wax-encapsulated water) with plaster into cartridges resembling resin cartridges.

This report presents the results of tests conducted by the Bureau on the plaster, the water capsules, and their combined use in cartridges. The tests were designed to determine how the gypsum-plaster water capsule bolting system performs and what happens in the hole while the bolt is being inserted through the cartridge. The test results indicate that water capsule plaster cartridges are a workable alternative to resin cartridges under normal or dry conditions.

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INTRODUCTION

The Bureau of Mines gypsum-plaster full-column anchored bolting system uses gypsum plaster to bond the roof bolt to the bolthole surfaces in the mine roof. This is the same function resin performs in a resin bolt. Cartridges similar in shape to those used in resin bolting contain a mixture of powdered gypsum plaster and small wax capsules that contain water for hardening the plaster.

The water capsules are produced by a patented process (*5*).[3] Their shells are made of petrolatum wax and additives, as described in a report by the Southwest Research Institute (*4*). The average diameter of the capsules is approximately 1,700 µm. The encapsulated water is combined with the plaster in a cartridge for subsequent use.

This report describes the gypsum-plaster anchoring system, presents the results of tests of the system, and discusses its commercialization.

GYPSUM-PLASTER WATER CAPSULE BOLTING SYSTEM

Figure 1 shows the components of the Bureau of Mines gypsum-plaster roof bolting system: the plaster, the water capsules, a cartridge, and a short length of rebar (reinforcing steel for concrete, the bolt). The water capsules and plaster remain in the cartridge until the bolt is installed, at which time rotation of the bolt causes the water to be released from the capsules. When the water mixes with the gypsum plaster, it forms gypsum. The gypsum hardens in the hole, forming a bond along the length of the bolt. One difference between the gypsum-plaster bolts and resin bolts is that the gypsum-plaster cartridge length equals the bolthole depth. For example, a 1,219-mm hole would require two 610-mm-long cartridges. The gypsum-plaster bolting system uses Hydrocal White[4] gypsum plaster, which was chosen because of its fast set and strength development.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

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

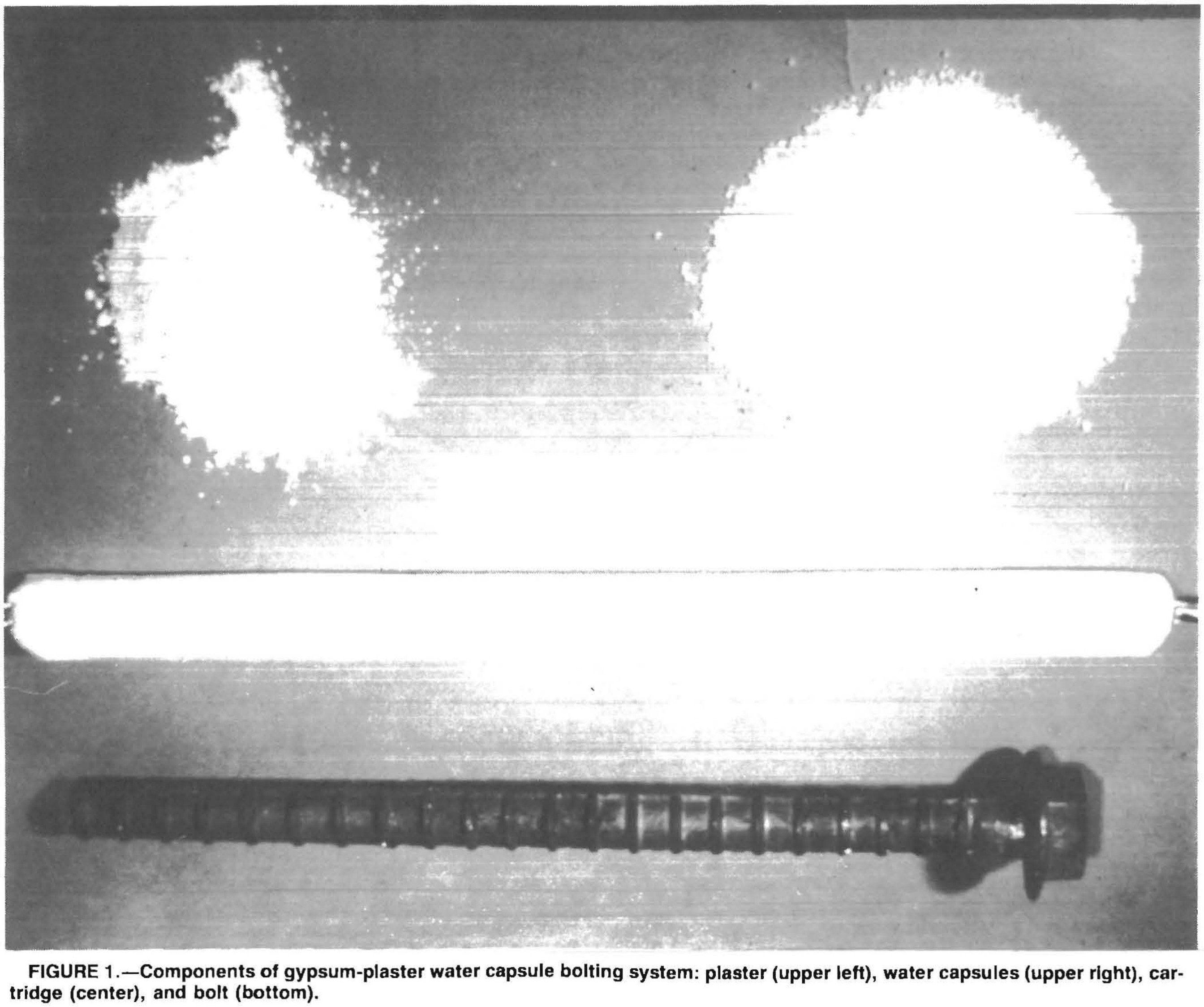

FIGURE 1.—Components of gypsum-plaster water capsule bolting system: plaster (upper left), water capsules (upper right), cartridge (center), and bolt (bottom).

GYPSUM PLASTER

Several nonstandard tests were conducted to determine how well the gypsum plaster would perform as a bolt grout. Pull tests performed on bolts installed in concrete blocks were among the more informative tests. The results of these tests are reported in a later section.

COMPRESSIVE STRENGTH

Because gypsum plaster requires a water-to-cement (WC) ratio of only 0.186 for the complete hydration necessary to form gypsum, WC ratios of 0.30 to 0.40 also provide free water to produce a material of workable consistency that is capable of being mixed.

Compressive tests of gypsum plaster were made to determine the effects of the WC ratio and the amount of free water present on the plaster's strength. Tests showed that increases in free water adversely affected the compressive strength of Hydrocal White gypsum. This is significant because a humid environment, as is typical in underground coal mines, will encourage free water retention.

The tests for compressive strength were conducted according to American Society for Testing and Materials (ASTM) standards (*1*) using standard 50.8-mm cube specimens. The 50.8-mm cubes generally had a 10- to 15-pct higher strength than the 76- by 152-mm cylinders (fig. 2) because of their shape. Figure 2 shows the compressive strength of Hydrocal White with retained free water at WC ratios from 0.28 to 0.42. Each data point represents the average strength of either two or four samples. The compressive strength increased as the WC ratio decreased because gypsum with lower WC ratios contains fewer open pores and a smaller crystal structure. The 0.28 WC ratio produced grout with a consistency that was too stiff to make a uniform test specimen. Air entrapment was greater in these samples, even though a vibratory table was used in their preparation.

Figure 3 show the compressive strength of Hydrocal White at WC ratios of 0.28 to 0.42 where the free water in the pore structure had been removed by placing the samples in an oven at 43° C. The specimens were dried to constant weight in approximately 7 days. As in the previous tests, the compressive strength increased as the WC ratio decreased. The samples made using the 0.28 WC ratio had lower strength than expected because the stiff consistency of the grout led to greater air entrapment when the samples were molded. It is difficult to produce uniform and consistent specimens at the lower WC ratios. Inconsistent data, such as the compressive strength at WC ratios of 0.30 and 0.38 (fig. 3), probably resulted from laboratory or sample-testing errors.

Compressive strength comparison between the samples, with and without free moisture (figs. 2-3), showed that the samples without free water were about twice as strong. Therefore, a meaningful discussion of gypsum strength should include taking note of the amount of free water present. Typically, the temperature of an underground coal mine is between 7° and 15° C, and the seasonal humidity is rather high. These conditions allow hardened gypsum to retain large amounts of free water. Therefore, the underground gypsum strength should not be assumed to be any greater than the gypsum strength with free water retained at a given WC ratio. As expected, the testing showed less gypsum compressive strength as the WC ratio or the amount of free water increased.

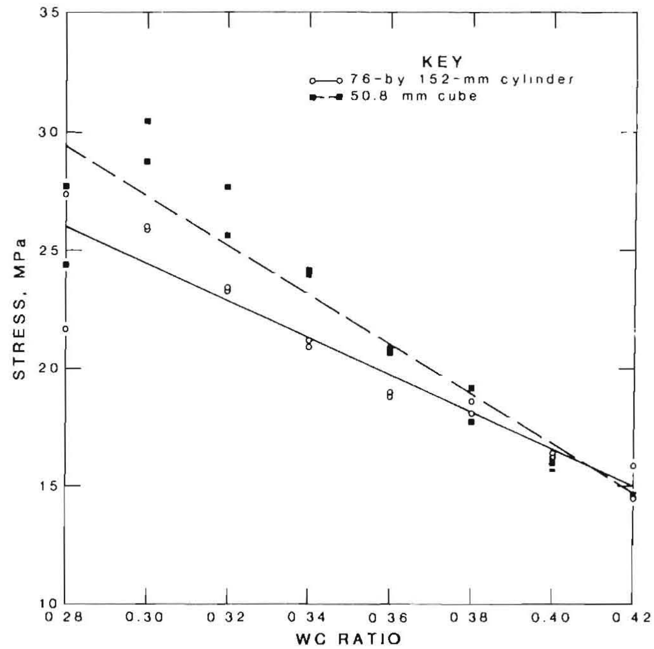

FIGURE 2.—Compressive strength versus WC ratio for Hydrocal White gypsum with free water.

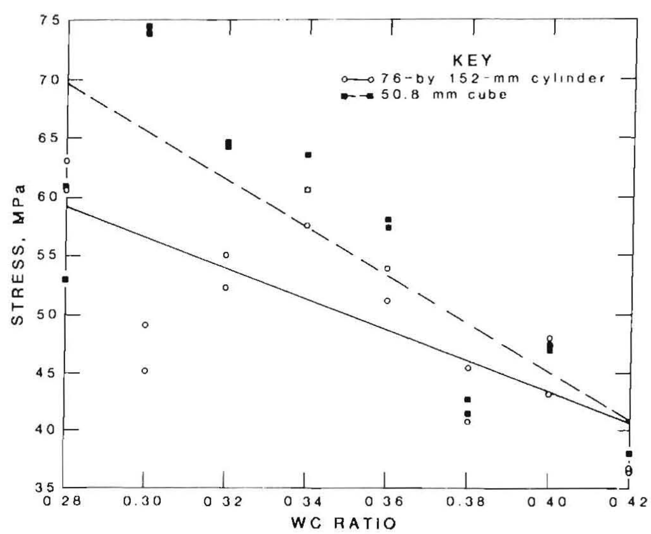

FIGURE 3.—Compressive strength versus WC ratio for Hydrocal White gypsum without free water.

SPECIFIC GRAVITY

The specific gravity of Hydrocal White gypsum also varies with the WC ratio. Because gypsum with a lower WC ratio is less porous, its specific gravity is greater than gypsum with a higher WC ratio. Figure 4 shows the relationship between specific gravity and WC ratio for gypsum with free water. Figure 5 shows the relationship between specific gravity and WC ratio for gypsum that was dried to a uniform weight and was without free water in the matrix. The specific gravity of the gypsum with free water was higher than that of the dried gypsum because water has a higher density than air.

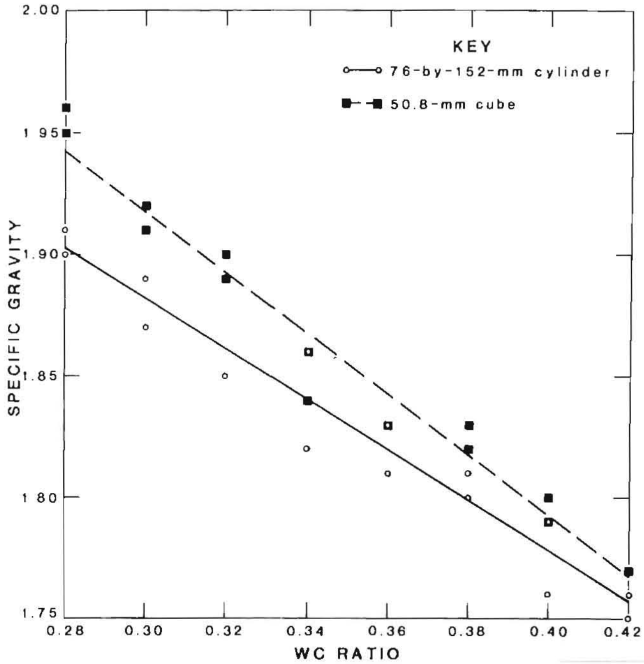

FIGURE 4.—Specific gravity versus WC ratio for Hydrocal White gypsum with free water.

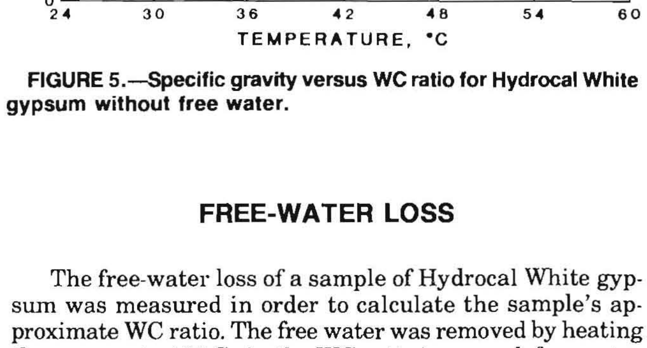

FIGURE 5.—Specific gravity versus WC ratio for Hydrocal White gypsum without free water.

FREE-WATER LOSS

The free-water loss of a sample of Hydrocal White gypsum was measured in order to calculate the sample's approximate WC ratio. The free water was removed by heating the gypsum to 43° C. As the WC ratio increased, free water filled more voids within the gypsum. Therefore, the free-water loss increased as the WC ratio increased. Figure 6 shows this relationship. By measuring the free-water loss, the approximate WC ratio of a sample can be calculated.

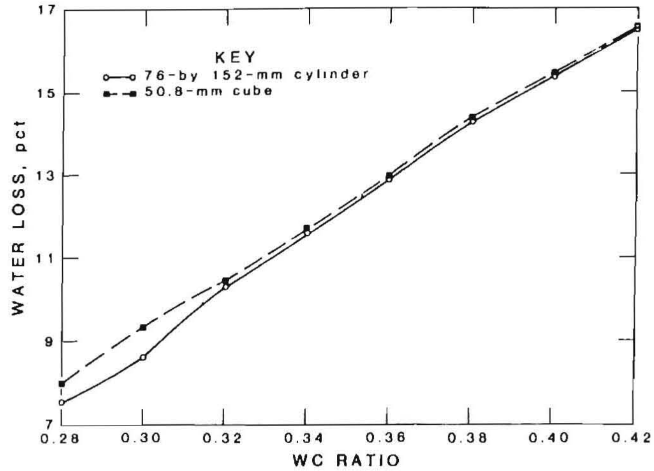

FIGURE 6.—Free water loss at 44°C versus WC ratio for Hydrocal White gypsum.

CARTRIDGE WEIGHT TO FILL ANNULUS

The cartridge weight required to completely fill the annulus between the bolt and hole was calculated to insure better bolt anchoring. As the WC ratio of the plaster decreases, the density of the hardened gypsum increases, because there are fewer pores in the material. Because the density of gypsum plaster is variable depending on the amount of entrapped air, it is important to have enough plaster in the cartridge to ensure complete filling of the annulus.

The annulus volume of a No. 6 rebar (19 mm diam) in a 26.2-mm-diam hole (drilled with a new bit) is about 2.56 cm^3/cm. A typical gypsum density is 1.8 g/cm^3. Therefore, the cartridge weight required to fill a 1,219-mm length of annulus, including a 25-mm overdrill of the hole and 15-pct material excess, would be 330 g. Table 1 shows the cartridge weights necessary to fill the 1,219-mm annulus (including a 25-mm overdrill and allowing for 15-pct excess material) using gypsum of various densities. The grout density is lowered by the wax in the water capsules.

Table 1.—Cartridge weight needed to fill 1,219-mm-long annulus

(Including 25-mm overdrill of the hole and allowing for 15 pct excess material)

Gypsum density, g/cm³	*Cartridge weight, g*
1.8	339
1.9	358
2.0	377
2.1	395

SET TIME

A spring-loaded penetrometer (Soil Test model CL-700) was used to compare the set times of the plaster at different WC ratios. The penetrometer with an adapter point is shown in figure 7. By depressing the penetrometer to the same extent in all tests, roughly the same force was applied to each sample. Therefore, a larger penetration-hole diameter indicates a softer material. The test allows quick comparison of sample setting times. Figure 8 shows the

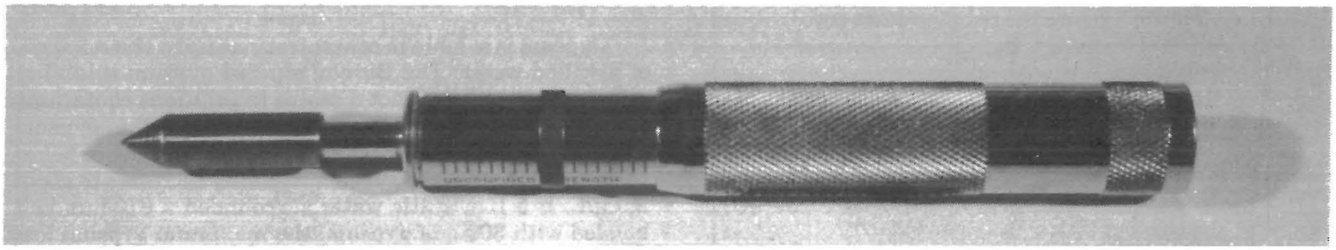

FIGURE 7.—Penetrometer with special point.

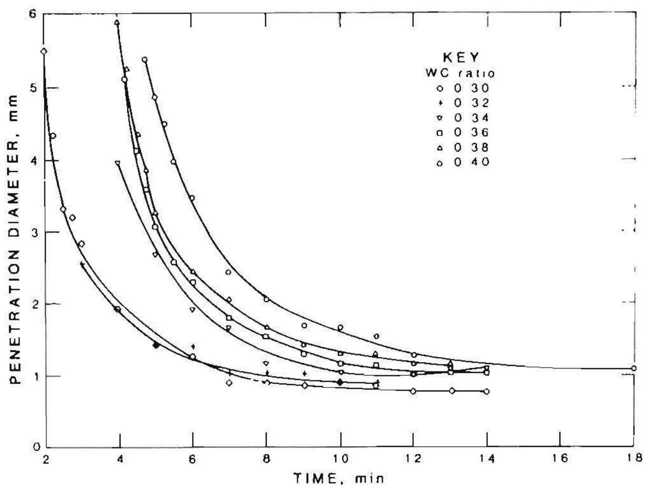

FIGURE 8.—Penetration diameter versus WC ratio for Hydrocal White gypsum.

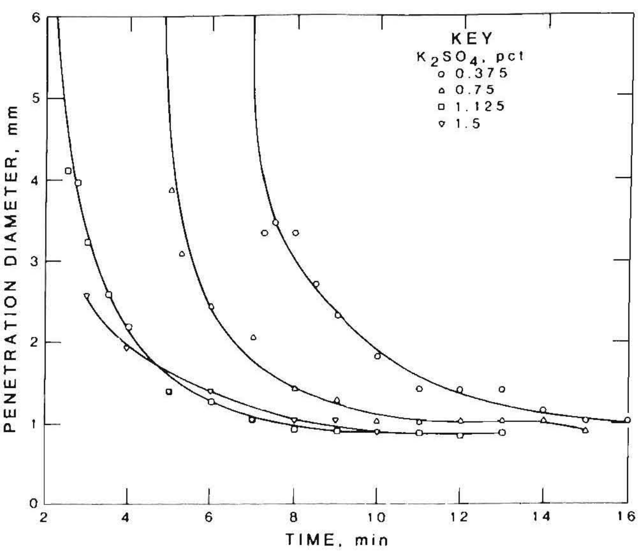

FIGURE 9.—Penetration diameter versus percent K_2SO_4 for Hydrocal White gypsum.

penetration-hole diameter versus time for the various WC ratios. Lowering the WC ratio decreased the set time of Hydrocal White and lessened the time required to obtain a constant penetration-hole diameter. Some irregularity in the data occurred when the 0.32-WC-ratio samples set more quickly than those made using a WC ratio of 0.30. This was probably due to the stiffness of the slurry produced using the 0.30 WC ratio, which resulted in more difficult mixing.

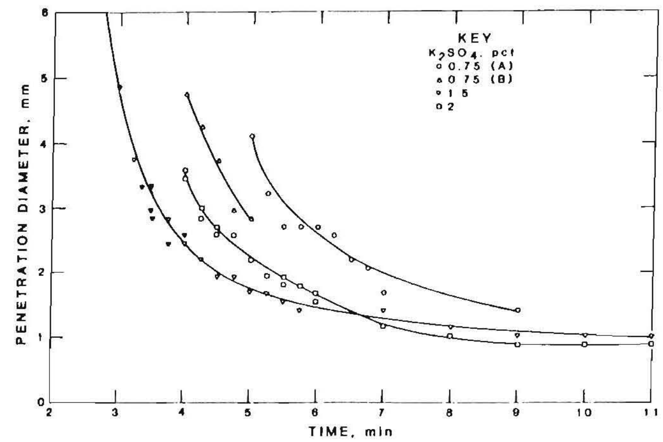

FIGURE 10.—Hydrocal White gypsum penetration diameter versus percent K_2SO_4.

Set times were also measured using various amounts of potassium sulfate (K_2SO_4) accelerator with Hydrocal White. Figure 9 illustrates the decreased set time with increased K_2SO_4 up to about 1 pct, as shown by the smaller penetration diameters. All tests used a constant WC ratio of 0.32.

Figure 10 shows penetration tests at a WC ratio of 0.32 and K_2SO_4 percentages of 0.75, 1.5, and 2. The fastest set occurred using between 1 and 2 pct K_2SO_4. Inconsistent results occurred using 0.75 pct K_2SO_4, as shown by the data for samples A and B (fig. 10). Higher percentages of K_2SO_4 reduced the uniaxial compressive strength. This effect was quite pronounced at K_2SO_4 values above 2 pct.

TEMPERATURE RISE

As plaster hydrates to become gypsum, the chemical reaction is exothermic, and heat is released. The amount of heat liberated depends upon the amount of plaster hydrating to gypsum. A more rapid evolution of heat from a sample indicates a faster set time. The time for samples to reach their highest temperature during hydration was measured to obtain more data on the effect of K_2SO_4 on acceleration of the set. Figure 11 shows the time from plaster mixing to the maximum temperature versus the percentage of K_2SO_4 accelerator. A temperature probe was used in a cup half full of freshly mixed plaster. As illustrated, the maximum plaster acceleration occurred using slightly over 1 pct K_2SO_4.

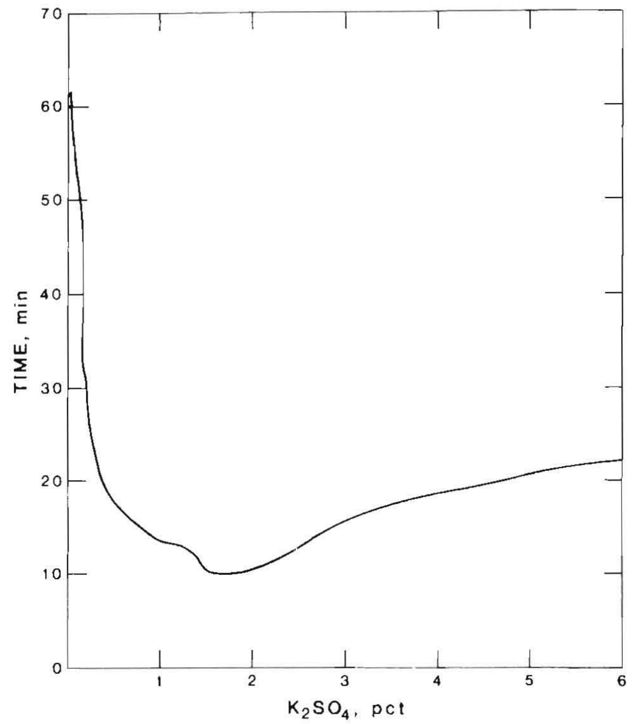

FIGURE 11.—Time to maximum plaster reaction temperature versus percent K_2SO_4.

SOLUBILITY

Gypsum is soluble in concentrations up to about 2.0 g/L of distilled water. The Bureau studied gypsum solubility and found that it will not dissolve in solutions containing Ca^{+2} or SO_4^{-2} ion concentrations above the gypsum solubility limit. When these concentrations decrease below the solubility limit, the gypsum solubility increases to about 2.0 g/L. If 5 L of static water surrounded a 610-mm bolt bonded with 300 g of gypsum, the maximum gypsum loss would be 10 g, or 3.3 pct of its total weight.

A water seepage of one drop per minute is equal to over 2 L per month. As a worse case, if the initial ion concentration of the seeping water is assumed to be zero, 4 g of gypsum per month, or 48 g/yr, will be lost from the bolt. If the initial cartridge weight is about 339 g, the weight of plaster in the cartridge would be about 226 g (for a WC ratio of 0.325 and a capsule water content of 65 pct). A gypsum loss of 48 g/yr is equivalent to more than 20 pct of the initial cartridge plaster weight. This suggests that the performance of gypsum-bonded roof bolts under wet ground conditions should be evaluated. The Bureau reported the results of its gypsum solubility tests in greater detail in a previous report (*3*).

WATER CAPSULES

As is true for other cartridges such as resin bolts, plaster water capsule cartridges must have a shelf life long enough to allow them to be stored at the mine site until they are used. If the water capsules release some of their water during storage, areas of partially hardened gypsum will result. Cartridges may become too dry for easy bolt insertion; or, hardened balls of gypsum may act as aggregate, entirely preventing insertion of the bolt. Initial water content and ability to retain encapsulated water over time were measured to determine the water capsule quality.

WATER CONTENT

To ensure adequate water for easy mixing of the gypsum water capsule cartridge and adequate cartridge shelf life, the water capsules were checked for water content. Good-quality water capsules contain from 60 to 65 pct water and can withstand handling in cartridge preparation and installation. Table 2 shows how water capsule payload affects the WC ratio for a mixture of 50 g of water capsules and 100 g of gypsum plaster. It is necessary to have a minimum payload of 60-pct water to yield a WC ratio of 0.30 or higher.

Distillation tests were conducted using 5 g of water capsules placed in toluene. The toluene was heated to boiling, causing the wax capsule shell to melt and dissolve. The water was carried by the toluene as vapor into a condenser, where it cooled and collected in a receiver. The water, being denser, collected below the toluene. This water, the water content of the capsules, was then measured. Table 3 shows the water content for several lots of water capsules

Table 2.—Water-to-cement ratio for various water capsule payloads

(Based on a mixture of 50 g of water capsules and 100 g of plaster)

Payload, pct	*WC ratio*
66	0.330
65	.325
64	.320
63	.315
62	.310
61	.305
60	.300

Table 3.—Water content of various water capsule lots, percent

Lot[1]	*Water content*
SWRI:	
7-135	65.0
7-142	56.3
7-152	63.6
7-178	62.7
7-179	59.5
7-180	63.5
7-181	62.3
7-284	63.9
MED:	
11-01-A	60.9
12/7/79	64.1
1A	68.3
2A	66.0
2B	59.3
3A	57.3
3B	67.7
4A	63.5
4B	66.9
5A	67.9
5B	67.9
6A	66.7
6B	66.0

[1]Water capsule suppliers: SWRI—Southwest Research Institute, MED—Mine Equipment Development Corp.

Table 4.—Water capsule drying data[1]

Drying time, min	Sample weight, g	Water loss g	Water loss pct
0	118.71	0	0
8	67.64	51.07	43.0
30	56.82	61.89	52.1
51	50.42	68.29	57.5
80	47.99	70.72	59.6
108	47.23	71.48	60.2
134	47.03	71.68	60.4
173	46.80	71.91	60.6
199	46.74	71.97	60.6
258	46.63	72.08	60.7
290	46.59	72.12	60.8

[1]Data for oven drying of capsules from lot SWRI 7-379 after initial heating in microwave oven.

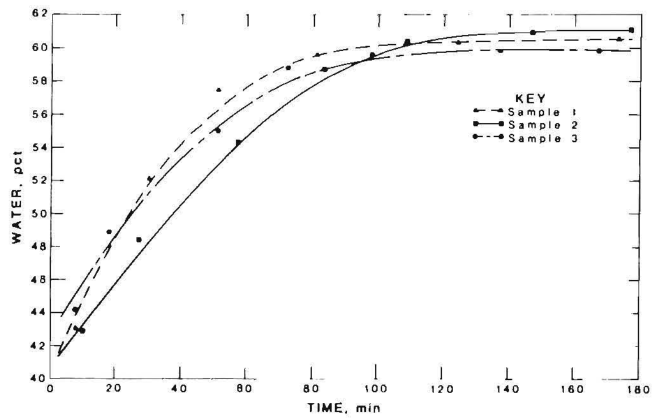

FIGURE 12.—Drying rates for SWRI 7-379 water capsules in microwave oven.

and illustrates the typical 60- to 65-pct water content of the capsules.

As stated, each distillation test used only 5 g of water capsules. By increasing the size of the collected sample, a more accurate water-payload value was obtained. A heat-resistant plastic container was lined with absorbent towels to separate the wax and water as the water capsules were melted. After weighing the container and absorbent liner, approximately 100 g of capsules was placed in the lined container, and the container was heated in a microwave oven for about 8 min. The wax and water mixture foamed and allowed separation. The container was placed in a drying oven at approximately 94° C for about 2 h to allow the water to evaporate from the absorbent liner. The container, liner, and wax were then weighed, and the container and liner weight subtracted to give the wax weight. By subtracting the wax weight from the capsule sample weight, the water payload in the capsules was determined. Typical data are shown in table 4. The 2-h water payloads for three samples were 61.4, 61.9, and 60.4 pct; the average was 61.2 pct. All dried samples reached nearly constant weights after 2 h (fig. 12.)

WATER LOSS UNDER AMBIENT CONDITIONS

Ninety-day pan-drying tests can be used to measure capsule water retention. About 500 g of capsules is placed in a pan and weighed each day. The initial water loss is usually greatest, and it varies because different amounts of water remain on the outer capsule surfaces after

Table 5.—Slope 2[1] for good-quality water capsules, percent

Lot (all SWRI)[2]	Slope 2[1]	Total water loss
90-DAY DATA		
7-152	0.040	5.8
7-152	.048	5.1
7-152	.032	3.6
7-135	.037	4.4
7-182	.042	4.9
7-178	.016	3.2
7-179	.020	4.7
7-180	.020	4.9
7-181	.020	4.9
DAY 10 TO DAY 90 DATA		
7-284	0.022	4.9
7-379	.013	1.1

[1]Average steady-state water loss per day.
[2]In order listed in appendix.

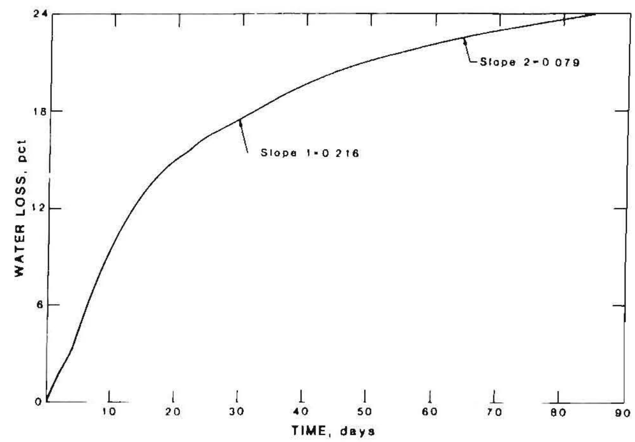

FIGURE 13.—Ninety-day water loss for 500 g SWRI 7-178 water capsules.

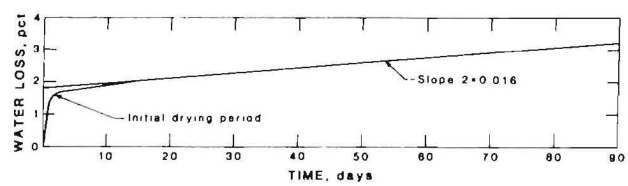

FIGURE 14.—Ninety-day water loss for 500 g MED 3B water capsules.

manufacture. After the surface water has dissipated, the water loss slows. Eventually, with good-quality capsules, the water loss settles to a constant value per day. Poor-quality water capsules require a longer time to reach a constant rate of water loss. The lower the water loss per day, the better the quality of the capsules. Cartridges containing good-quality capsules will have a longer usable shelf life.

The water-loss data for all the capsules tested are listed in the appendix. The lot number identifies either Southwest Research Institute (SWRI) or Mine Equipment Development Corp. (MED), the two companies that supplied the capsules. Also listed are the test starting date, type of wax, and percentages of wax modifiers. Boler wax with picolyte, epolene, and polybutane modifiers. Boler wax with picolyte, epolene, and polybutane modifiers produced the best-quality water capsules. Slope 1 is the average water loss per day (as a percentage) after the surface water has evaporated. Slope 2, the average loss per day during the period of constant loss, is more important. The total 90-day loss (also given as a percentage) is listed for the first 28 capsule samples. For the other capsules (tests 29-94), the water loss (percentage) from day 10 to day 90 of each test is shown. The 10- to 90-day data are more meaningful with regard to actual capsule quality. The amount of surface water on the capsules varied, as reflected in the 90-day water loss data. The initial drying period, in days, is the time required for the capsules to lose most of their surface water.

An important indicator of good capsule quality is a steady-state water loss per day (slope 2) of 0.045 pct or less. Table 5 shows slope 2 for high-quality capsules. (Additional drying data for the capsule lots listed in table 5 are included in the appendix.) The water losses listed in table 5 are 90-day losses, except for capsule lots SWRI 7-284 and SWRI 7-379. For these two lots, slope 2 was based on the 10- to 90-day losses, because after 10 days, the effect of varying amounts of surface water is eliminated. Good-quality capsules will generally have a 90-day (total) water loss of 6 pct or less.

A typical 90-day drying curve for good-quality capsules (SWRI 7-178) is shown in figure 13. The initial drying period is well defined at 6 days. For comparison, figure 14 shows the water-loss curve for capsule lot MED 3B. For this lot, the initial drying period is not well defined until 17 days. Slope 1 extends to 40 days, indicating a large number of poorer quality water capsules. Slope 2 extends to 80 days, and if the curve were continued past 90 days, it would have shown a third slope as the water loss from poorer quality water capsules decreased.

WATER LOSS DUE TO ELEVATED TEMPERATURES

Because mine site storage of water capsule cartridges could involve elevated temperatures during the warmer months, the capsule water loss at elevated temperatures was measured. Good capsules (total water loss of 6 pct or less in 90-day pan-drying tests) were measured for water loss when heated for 24 h at various temperatures (fig. 15). As the temperature was increased from 37.8° to 48.9° C, the water loss doubled. Increasing the temperature from 48.9° to 54.4° C again doubled the water loss, as is shown by the increasing slope of the loss curve. Figure 16 shows the water loss versus time for good capsules at 48.9° C.

Figure 17 shows the water loss versus time for good capsules at room temperature. After evaporation of the capsule surface water, the loss per day equaled 0.0156 pct, or 0.156 pct in 10 days. The 10-day water loss at 48.9° C was 0.98 pct (fig. 16). Short-term exposure of the capsules to 48.9° C increased the water loss by 6 times. The water loss of the capsules doubled from 48.9° to 54.4° C, indicating that 48.9° C is the approximate maximum temperature to which the capsules should be exposed.

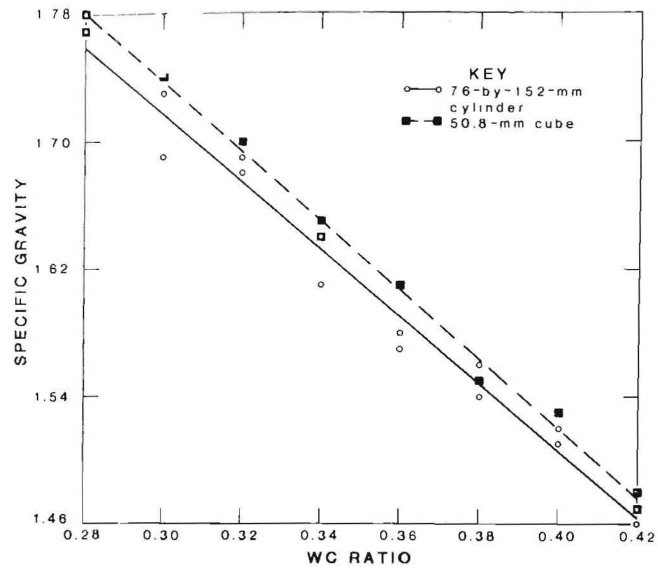

FIGURE 15.—Twenty-four-hour water loss for 100 g of SWRI 7-178 water capsules versus temperature.

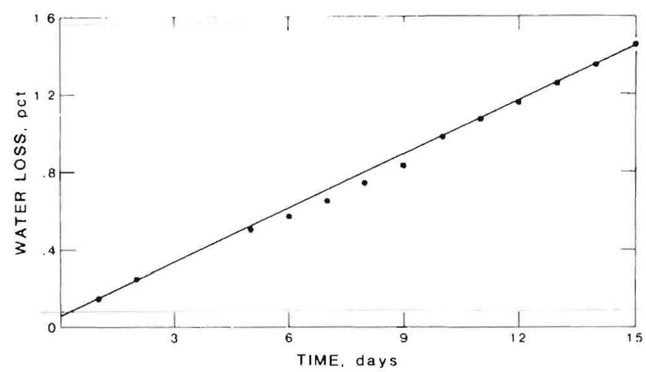

FIGURE 16.—Water loss for 100 g of SWRI 7-178 water capsules at 49 °C.

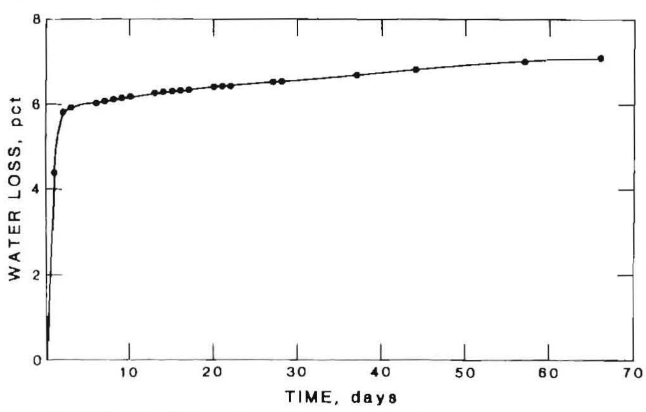

FIGURE 17.—Water loss for 100 g of SWRI 7-178 water capsules at room temperature.

GYPUM-PLASTER WATER CAPSULE CARTRIDGES

In addition to tests of the gypsum plaster and the water capsules, the plaster and capsules were tested in combination in cartridges.

SHELF LIFE

Gypsum water capsule cartridges were placed in an environmental chamber at 48.9° C and at varying relative humidity for 2 weeks. As previously discussed, tests on water capsules showed 48.9° C to be the upper practical limit for short-term water capsule exposure. It is not likely that cartridges stored at a mine would be subjected to such a high temperature for long periods.

Bolts were installed using the cartridges that had been exposed to high temperature and compared to bolts installed using cartridges stored at normal room temperature. The data are listed in table 6. Bolt 1, stored at room temperature, was the control. It was hard to insert at 200 mm out, but was completely inserted in 26.2 s. Bolts 2 through 5 had the same style wrapper as bolt 1 but were stored at 48.9° C. Bolt 2 was hard to insert at 380 mm out. Bolt 3 required excessive wrench installation time. Both required 49 s for insertion. Bolt 4 completely inserted in 19.2 s, after having fallen in at 150 mm out when the block cracked. Bolt 5 completely inserted in 38.5 s, but required excessive wrench installation time. The time required for complete insertion, after the wrench was installed, was nearly the same for bolts 1 and 5, at 12.5 and 12 s respectively.

Bolts 6 and 7 had 0.076-mm cartridge wrappers and were stored at 48.9° C and varying relative humidity. Their insertion times after wrench installation were 12.4 and 10.3 s, respectively. These times were similar to the time required using the thinner (0.028-mm) wrappers. The data in table 6 indicate that cartridges remain usable after 2 weeks exposure to 48.9° C.

Table 6.—Cartridge shelf life tests at 48.9° C

Bolt[1]	Wrapper thickness mm	Wrench-on time, s	Full insertion time, s	Comments
1[2]	0.028	2.8-13.7	26.2	Hard insertion at 200 mm out; excess at 150 mm out
2	.028	2.8- 9.8	49.0	Dry material before wrench. Hard at 580 mm out.
3	.028	2.2-21.8	49.0	Bolt in too far before wrench on.
4	.028	1.6-11.2	19.2	Fell in when 150 mm out as block cracked.
5	.028	1.6-26.5	38.5	Hard at 150 mm out.
6	.076	1.6-10.7	23.1	Hard at 100 mm out.
7	.076	1.3-16.0	26.3	Hard at 300 mm out; fell in at 150 mm out as block cracked.

[1]Bolt was spun before wrench installation.
[2]Control; stored at room temperature.

VOLUME REDUCTION DURING MIXING

In addition to the gypsum plaster and water capsules, the gypsum cartridge contains entrapped air. This air causes the plaster to have a variable dry density, depending on the degree of compaction of the plaster in the cartridge. Because the entrapped air occupies cartridge volume which is lost after mixing, it is important to produce sufficiently dense cartridges to ensure having enough mixed material to fill the annulus between the bolt and bolthole surfaces. The gypsum-plaster system will provide adequate roof support only if it is properly designed for the specific combination of hole diameter (which changes slightly with drill bit wear and resharpening) and bolt size encountered in each bolt installation. There is a relationship between the weight of the cartridge, the hole diameter, and the bolt size that may be used to ensure that the annulus between the bolt and the bolthole will be filled with gypsum of adequate strength. This relationship is illustrated in the calculations below, where

Length of bolthole (L) = 1,219 mm,
Diameter of drillhole (D_h) = 26.2 mm (for a new bit),
Diameter of roof bolt (D_b) = 19.0 mm, and
Density of hardened grout ($_p$) = 1.75 g/cm³.

The volume of the hole annulus (V_I) is given by the equation

$$V_I = \frac{\pi}{4}(D_h^2 - D_b^2)L.$$

Substituting the values given above,

$$V_I = \frac{\pi}{4}(26.2^2 - 19.0^2)(1219)$$
$$= 311{,}570 \text{ mm}^3.$$

For a 12.7-mm overdrill of the hole, the additional volume (V_o) is given by the equation

$$V_o = \frac{\pi}{4}(26.2)^2(12.7)$$
$$= 6{,}847 \text{ mm}^3.$$

The total annulus volume (V_T) is

$$V_T = V_I + V_o$$
$$= 311{,}570 + 6{,}847$$
$$= 318{,}417 \text{ mm}^3$$
$$= 318.42 \text{ cm}^3.$$

The weight (W) of the grout material required to fill the hole is

$$W = {}^{\rho}V_T$$
$$= 1.75(318.42)$$
$$= 557.24 \text{ g}.$$

Allowing for 15 pct excess material (to provide visual observation of complete hole filling), the total required weight of the grout (W_T) is

$$W_T = 557.24(1.15)$$
$$= 641 \text{ g}.$$

Because two 610-mm cartridges are needed for a 1,219-mm hole, the minimum weight per cartridge (W_c) is equal to the weight of the grout plus the weight of the cartridge wrapper.

$$W_c = \frac{641}{2} + 3$$
$$= 323.5 \text{ g per cartridge.}$$

This weight will ensure complete filling of the annulus.

MINIMIZING VOLUME REDUCTION

The gypsum water capsule cartridges in the previously described tests were as long as the bolt hole in each installation so that maximum grout was available to fill the hole. However, cartridges that are shorter than the hole length are safer for miners to install because the bolt end can be placed in the hole before machine insertion is started.

To determine if the cured volume could be increased, sand[5] was added to Hydrocal White plaster. The sand was intended to fill some of the air voids between the plaster in the cartridge, diminishing the potential for shrinkage during curing. Sand was added in amounts up to 150 pct of the plaster weight. The samples were hand mixed, and their volumes were recorded after curing. Water replaced the water capsules for easier mixing. The sand increased the sample volume as shown in table 7.

Subsequently, mixes containing gypsum, water capsules, and sand were compacted in cartridge wrappers, yielding cartridge lengths which ranged from 419 to 603 mm. These mixes contained the same amounts of sand as the cured samples from the previous tests, but used water capsules rather than water. In table 8, the cartridge volume increase is represented by greater cartridge height. Table 9 shows the ratio of the increase in hardened sample volume (from table 7) to the increase in cartridge volume (from table 8) at the various percentages of sand used in the mixes. The typical ratio is greater than 2.5, indicating an increase in the volume of hardened grout obtained per unit length of cartridge. This increased hardened grout volume is helpful in reducing total cartridge length.

[5]Wedron Silica Co. sand No. 4030.

Table 7.—Cured volume increase with addition of sand to plaster and water mixes[1]

Sand addition		Mix volume	
g	pct[2]	mL	Increase, vol pct
0	0	33.55	0
6	10	35.78	6.65
12	20	37.82	12.73
18	30	39.64	18.15
24	40	42.56	26.86
30	50	44.74	33.35
36	60	46.89	39.76
42	70	49.12	46.41
48	80	51.32	52.97
54	90	53.88	60.60
60	100	56.54	68.52
66	110	58.46	74.25
72	112	61.60	83.61
78	130	64.09	91.03
84	140	66.38	97.85
90	150	68.77	104.98

[1]Additions of Wedron Silica Co. sand No. 4030 to mixes containing 60 g of plaster and 21 g of H_2O.
[2]By weight of plaster.

Table 8.—Cartridge volume increase with addition of sand[1] to plaster and water mixes

Sand addition		Cartridge height (length), mm	Cartridge volume increase, vol pct
g	pct[2]		
0	0	425	0
15	10	425	0
30	20	[3]419	1.493
45	30	457	5.97
60	40	451	7.46
75	50	464	8.96
90	60	476	11.94
105	70	486	14.15
120	80	508	19.40
135	90	521	22.39
150	100	533	25.37
165	110	546	28.36
180	120	555	30.57
195	130	578	35.82
210	140	591	38.81
225	150	603	41.79

[1]Additions of Wedron 4030 sand to mixes containing 150 g of plaster and 82.04 g of SWRI 7-284 water capsules.
[2]By weight of plaster.
[3]Excessively consolidated sample.

Table 9.—Volume increase of cured gypsum samples and cartridges containing sand

Sand, pct[1]	*Ratio of volume increase of cured gypsum sample to volume increase of cartridge sample*
0	(2)
10	(2)
20	[3]8.54
30	3.04
40	3.60
50	3.72
60	3.30
70	3.28
80	2.73
90	2.71
100	2.70
110	2.62
120	2.74
130	2.54
140	2.52
150	2.51

[1]By weight of plaster.
[2]No increase.
[3]Excessively consolidated sample.

BOLT INSERTION

Because the gypsum-plaster water capsule cartridge contains a fine-particle solid material (the plaster) and a larger compressible solid (the water capsules), the procedure required for bolt insertion is different than the procedure used to insert resin bolts.

PROCEDURE

To install bolts using gypsum plaster and water capsules, holes are drilled with 26.2-mm bits, as is done for resin bolts. The outside diameter of the cartridges is 24.6

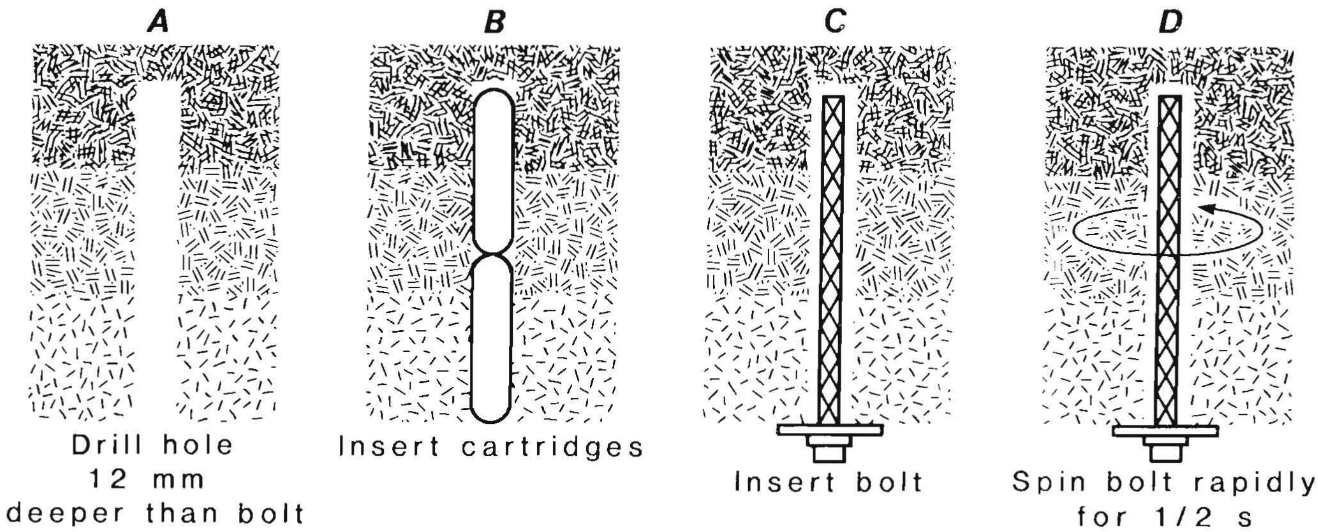

FIGURE 18.—Bolt installation procedure.

mm, which allows a clearance of about 0.8 mm between the outer surface of the cartridge and the surface of the bolt hole. This ensures easy insertion of cartridges in the bolthole. A No. 6 rebar (19 mm diam) is used so that the annulus between the hole and the bolt is completely filled with the mixed material during bolt insertion.

An ideal installation is illustrated in figure 18. The bolthole is drilled with a 26.2-mm bit, 12.7 mm deeper than the bolt lenght, so the bolt can be fully inserted (fig. 18). Cartridges are manually inserted to completely fill the hole (fig. 18). A 1,232-mm hole is filled with two 610-mm-long cartridges. The bolt is rotated and inserted to within 12.7-mm of the top of the hole to ensure adequate mixing (fig. 18). In installations at less than seam height, the bolt is inserted far enough to allow the use of a bolting wrench. The shortest usable wrench is recommended. After bolt insertion, the bolt is spun rapidly for about 0.5 s while the bolting wrench is thrust against the plate (fig. 18). The installation is finished by thrusting on the bolt. The bolter head can be withdrawn immediately, allowing the bolt to remain in place. Installed bolts should be checked after 10 min with a click-stop torque wrench (set for 2,030 N·cm) to ensure torque attainment.

Since underground conditions are rarely ideal, allowable deviations are necessary. Bits wear and are resharpened, which causes variability in hole diameters. The drilled bolthole should be checked to ensure clearance between the outside of the cartridge and the inside of the hole. A hole drilled with a 26.2-mm bit worn to 25.4-mm allows only a 0.4-mm clearance between a 24.6-mm cartridge and the hole wall. Bolt holes that are not very smooth inside and have irregularities in their inside diameters can cause difficulty during cartridge insertion.

Bolts are best installed in one continuous operation. Wrench installations should be done quickly (less than 40 s) to prevent premature hardening of the plaster. All hole drilling, bolt insertion, and bolt rotation should be done in a "hands-off" mode with respect to moving machine components.

The gypsum-anchored bolt requires less spinning than the resin bolt. Overspinning can result in acceleration of the plaster hardening rate and damage to the crystal structure of the newly hardened gypsum. However, some rotation is required to (1) ensure adequate mixing of the water capsules and gypsum and (2) tear the plastic wrapper into smaller pieces in order to reduce glove-fingering, which is discussed in a later section.

During bolt insertion, pressure builds up in the annulus between the bolt and the hole. The pressure increases the density of the newly mixed plaster, which also increases its strength. Extrusion of newly mixed paste from the hole during bolt insertion usually indicates that the hole is completely filled. The paste should appear during the last 150 to 200 mm of bolt insertion. Bolt torque should be checked after 10 min for each new section of exposed roof to be certain that a torque reading of 2,030 N·cm is achieved and to note hardening of the plaster.

Underground mines have a variety of bolting machines with different performance characteristics and bolter operators who use different techniques. Both these factors can contribute to non-uniform bolt installations. If the rotation is too fast and/or the bolter head velocity is too slow, it may be necessary to thrust the bolt part way without any rotation, followed by rotation during the final portion of bolt insertion. This change in the installation procedure would be necessary to ensure that the plaster is not overmixed. The gypsum-grouted bolt will tolerate this installation variation and provide the same performance.

A "workable" installation in a mine can be determined by the ease of repeated bolt insertions, consistent 2,030-N·cm torque readings 10 min after installation, and 89kN of pull resistance on a 1,219-mm bolt 10 min after complete insertion.

BOLT INSERTION TESTS

Because the gypsum-plaster water capsule cartridges contain solid materials rather than liquids with solid-material fillers, as are used in resin cartridges, different conditions are encountered during bolt insertion. The Bureau investigated various aspects of bolt insertion using gypsum-plaster water capsule cartridges, and the results are reported below.

Pressure in Hole

Tests were conducted to determine the pressure developed in the hole during insertion of the roof bolt because this pressure affects the gypsum density and strength. A higher roof bolt insertion pressure gives a higher density and strength. The pressures measured during bolt insertion were unexpected, based on prior underground experience.

A simple method for measuring the pressure inside a bolthole during bolt insertion was developed (fig. 19). The bolthole was drilled all the way through the block, and a pressure gauge with an oil-filled tube was inserted from the top of the block. The bottom end of the pressure tube was inserted through a wooden plug which held the tube in the center of the bolthole. The pressure-measuring apparatus was then grouted in place with fast-setting epoxy. The high hole pressure created a problem with the plastic tubing that was connected to the pressure gauge; the tubing had an unconfined burst strength of approximately 20.7 MPa. To measure higher pressures, the plastic tubing had to be completely encapsulated in epoxy grout.

All pressure-test bolts were 1,200 mm long and 19 mm in diameter. The holes were drilled to a depth of 1,219 mm. The same installation procedure was used for all the bolts. The following parameters were varied during the test: WC ratio, proportion of Lomar D (an additive to the plaster used to increase the fluidity of freshly mixed grout at a given WC ratio and facilitate grout movement within the hole during bolt insertion), and cartridge wrapper thickness.

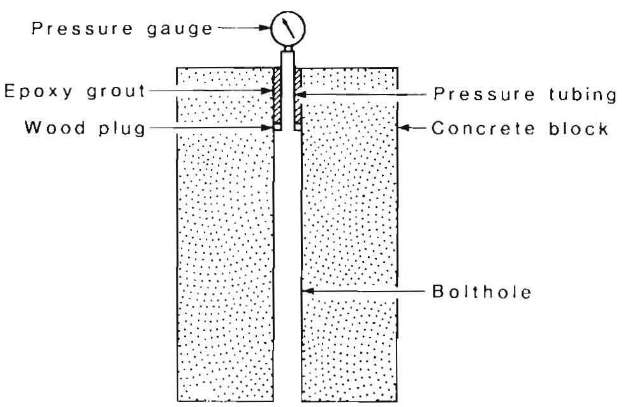

FIGURE 19.—In-hole pressure apparatus.

The tests showed that high internal pressures are developed in the hole during the insertion of roof bolts, with maximum pressures being achieved in the final 300 mm of bolt insertion. The effect of Lomar D can be seen by comparing the results of tests 1 and 2 (no Lomar D) in table 10 with the results of tests 3 through 5. The WC ratios were 0.23 with Lomar D and 0.32 without, but the hole pressures were similar. In tests in which the WC ratio remained constant at 0.32 (tests 1, 2, 6, 7, 8, 10, and 11), pressures were lowest when Lomar D was used (tests 10 and 11).

The test block was split so the bolts could be examined. No cracks were noted in the concrete block. It appeared that all of the bolt installations were normal.

Glove Fingering

Glove-fingering (glove effect) occurs when the cartridge wrapper is not shredded into small pieces during the insertion of the roof bolt. The wrapper expands and encases the grout and bolt so that the wrapper is between the grout and rock surface. Figure 20 shows glove-fingering on bolts that

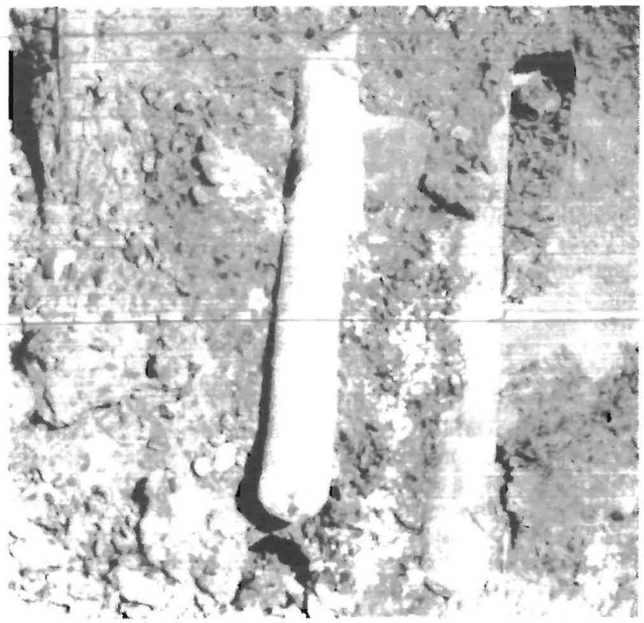

FIGURE 20.—Glove-fingering on bolts visible after breaking of test block.

Table 10.—Maximum in-hole pressures during bolt insertion

Test	Plaster, g	K_2SO_4, g	SWRI 7-379 capsules, g	Lomar D, g	Cartridge wrapper[1] thickness, mm	WC ratio	Maximum pressure, MPA	Comments
1	220.00	2.20	110.00	0	0.023	0.32	20.7	Pressure tube split.
2	220.00	2.20	110.00	0	.023	.32	20.7	Do.
3	242.76	2.42	87.24	1.65	.028	.23	17.2	Do.
4	242.76	2.42	87.24	1.65	.028	.23	NR	NR.
5	242.76	2.42	87.24	1.65	.028	.23	20.7	Pressure tube split.
6	220.00	2.20	110.00	0	.023	.32	8.3	NR.
7	220.00	2.20	110.00	0	.023	.32	24.1	Pressure tube split.
8	220.00	2.20	110.00	0	.023	.32	29.6	Pressure-tube was epoxy encapsulated.
9	229.57	2.29	100.43	0	.023	.28	37.9	Cartridges made low in water content for maximum insertion pressure.
10	220.00	2.20	110.00	1.00	.023	.32	8.3	NR.
11	220.00	2.20	110.00	.25	.028	.32	6.9	NR.

NR Not recorded.
[1]ICI wrapper used in all tests.

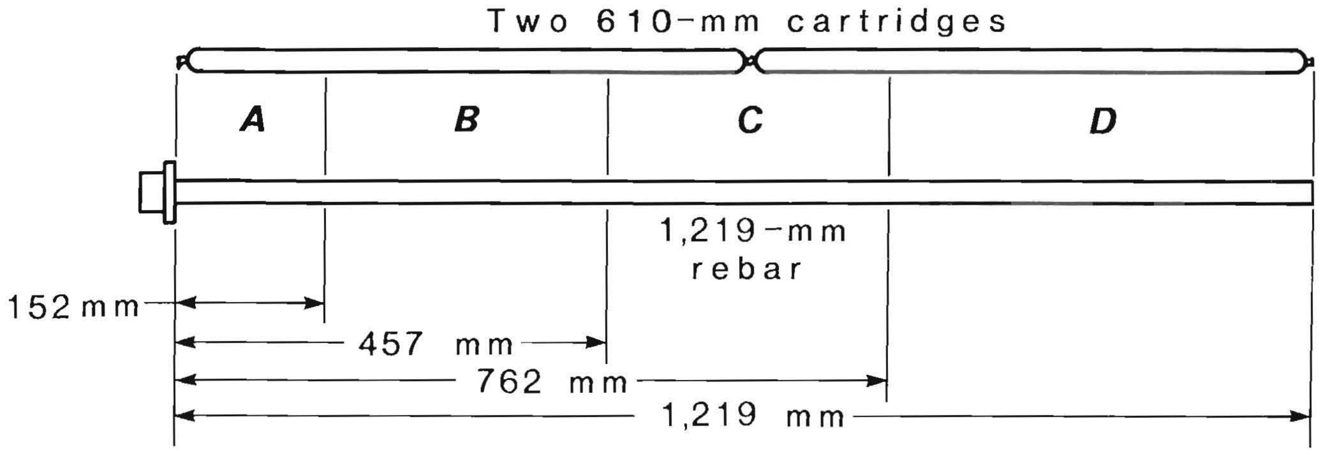

FIGURE 21.—Typical glove-fingering along 1,219-mm bolt: Along section *A*, bolt compresses cartridge end, pulling wrapper away from hole wall. Along section *C*, cartridge ends compress each other, pulling wrapper away from hole wall. Sections *B* and *D* show more glove-fingering, than sections *A* and *C*.

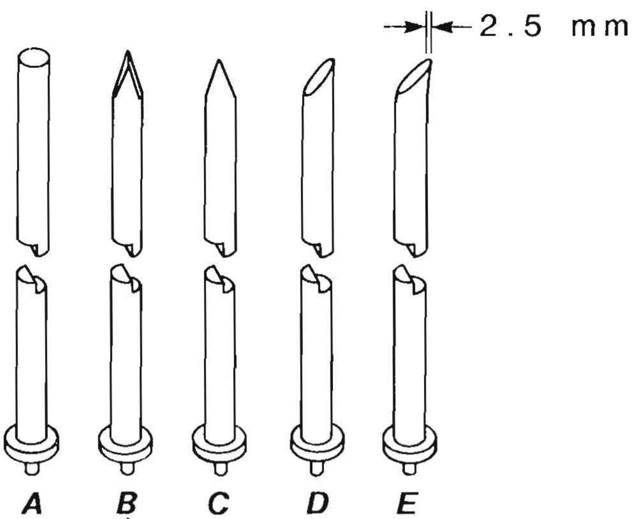

FIGURE 22.—Various rebar bolt ends. *A*, Regular square end; *B*, chisel; *C*, central point; *D*, 45° cut; *E*, 45° cut with 2.5-mm offset.

were removed by breaking the test block. All bolts used a 0.076-mm heat-sealed polyethylene-polyester-polyethylene (PPP) wrapper. Figure 21 shows bolt sections where glove-fingering typically occurs along the length of a 1,219-mm-long bolt. Typically, the 152 mm closest to the bolthead (section *A*) shows relatively little glove-fingering because the bolt compresses the cartridge and pulls the wrapper from the hole wall. At the middle of the bolt (section *C*), where the two 610-mm cartridge ends compress each other, the wrapper also pulls away from the hole wall. The other sections of an installed bolt (*B* and *D*) usually show a greater amount of glove-fingering.

Five differently shaped bolts were made in order to determine the effect of their shape on glove-fingering, using the PPP wrappers (fig. 22). No significant glove-fingering differences were observed.

Cartridges with lower WC ratios of 0.31, 0.29, and 0.28 were compared with previously tested cartridges with WC ratios of 0.32. No visible difference in glove effect was observed.

Traction sand was added as follows:
- Sand - 133.9 g (80 pct of plaster weight).
- Hydrocal White plaster - 167.3 g.
- SWRI 7-284 capsules - 88.7 g.

The resulting cartridges (WC ratio of 0.34) produced no observable changes in glove-fingering.

Use of Thinner Wrappers and Lomar D Additive

A thinner 0.034-mm heat-sealed saran-polypropylene-saran (SPS) wrapper was tested and compared with the 0.076-mm PPP wrapper. There was less glove-fingering because the thinner SPS wrapper is easier to tear. Lomar D was used to increase the fluidity of the freshly mixed grout. All tests in this series (table 11) used 584-mm-long 24.6-mm-diam cartridges containing 200 g of Hydrocal White plaster, 2.2 g of K_2SO_4 accelerator, and 110 g of SWRI 7-284 capsules.

Bolts 1 and 2, with no Lomar D, had wet grout exit from the hole when they were 406 and 305 mm from complete insertion. Bolts 5 and 6, with 0.49 g Lomar D per cartridge, had wet grout out of the hole at 610 mm from complete insertion. Bolt 8, with 0.98 g Lomar D per cartridge, slipped out of the hole during wrench installation. Lomar D significantly increases grout fluidity, as shown by these bolt installations. The more fluid grout moves out of the cartridge wrapper more quickly, helping to move the wrapper away from the bolthole surface and thereby reducing glove-fingering.

Good pull strengths were attained after 5 to 8 min using the very fluid Lomar D mixes. The average pull strength for the 9 previously tested samples was 102 kN after 10 to 13 min, while for the 15 samples in the current test series (with Lomar D in 11 samples), the average strength was 114kN after 5 to 8 min. Excess fluid grout from the hole adhered extremely well to painted metal surfaces on the bolter head. Freshly mixed grout containing Lomar D additive gives greater fluidity and allows easier bolt insertion, but does not decrease the grout strength, as happens when fluidity is increased by raising the WC ratio.

The PPP (0.076-mm) and SPS (0.034-mm) wrappers were compared using Lomar D and a WC ratio of 0.287 with bolts 19 and 20 (not included in table 11). With the 0.076-mm wrapper, no excess grout appeared during bolt insertion.

Table 11.—Effects of Lomar D additive and type of cartridge wrapper on pull strength[1]

Bolt	Lomar D, g	Full insertion time, s	Pull strength, kN	Pull time, min	Comments
			SPS WRAPPER		
1	0	21.5	108	7	Hard insertion at 127 mm out; excess at 16 mm out.
2	0	14.2	125	>6	Easy insertion; excess at 300 mm out.
3	.24	22.9	108	6	Block split on top. Hard insertion at 50 mm out.
4	.24	32.1	108	>6	Hard insertion at 200 mm out.
5	.49	18.0	125	>6	Excess from 300 mm out.
6	.49	18.8	125	>6	Do.
7	.98	15.2	116	>7	Held bolt for 25 s.
8	.98	19.4	125	>6	Bolt fell out while wrench on. Held bolt for 48 s.
			PPP WRAPPER		
9	0	19.0	125	>6	Moderate insertion; easier 200 mm out.
10	.24	24.8	125	>6	Excess from 300 mm out.
11	.49	35.1	108	>6	Hard insertion; but became easier at 200 mm out.
12	.98	26.0	125	>5	Moderately hard insertion; excess at 300 mm out.
13	.98	15.7	79	>5	Excess at 600 mm out.
14	0	32.3	100	6	Hard insertion at 200 mm out.
15	.24	35.9	108	7	Hard insertion.

PPP Polyethylene polyester polyethylene.
SPS Saran polypropylene saran.
[1]Bolt-insertion conditions: WC ratio, 0.32; SWRI 7-284 capsules; bolter head pressure, 9.0 MPa; thrust, gauge setting 8 on bolter head; and rotation, gauge setting 9 on bolter head. Bolts were spun slowly before wrench installation.

In contrast, the 0.034-mm wrapper showed grout from the hole when the bolt was 300 mm out of the hole. This excess probably resulted from a faster slurry release from the wrapper. The weight of the test equipment pulled bolt 20 from the hole at 4-1/2 min, which is evidence of the set retardation that results from the use of Lomar D. (Set retardation is discussed in detail in a later section.)

Bolts 21 and 22 (also not included in table 11) offered comparision of 0.076- and 0.034-mm wrappers with a WC ratio of 0.34, using Lomar D and 80 pct traction sand (with respect to the weight of the plaster). The bolt with the 0.034-mm wrapper showed less glove-fingering and a gypsum void for the first 737 mm from the bolthead. In contrast, the bolt with the 0.076-mm wrapper showed more glove-fingering and less gypsum adhering to the bolthole, and so it was eliminated from further tests. Insertion of the bolt was difficult because of cracks in the test block. Water from the water capsules entered the cracks before proper mixing with the gypsum plaster was accomplished, creating too dry a grout.

Comparison of Various Wrappers

Seven heat-sealed cartridge wrappers were tested to compare bolt insertion and glove-fingering. The seven wrappers are described in table 12. All wrappers were 24.6 mm in diameter and were used to make 584-mm-long cartridges. The cartridges contained approximately 220 g of Hydrocal White plaster, 1 pct K_2SO_4 (by weight of the plaster), and 110 g of good water capsules. The test results are shown in table 13. Lomar D additive was used in all installations except for bolts 12 and 15.

Bolts 1 through 7, at a WC ratio of 0.25, did not show differences in glove fingering. Bolts 8 through 13 and bolt 16, at a WC ratio of 0.32, showed no noticeable differences in glove effect with their various wrappers. However, less glove effect was observed at the 0.32 WC ratio than at the 0.25 ratio due to a faster exit of the more fluid grout from the cartridge wrapper, which disturbed the wrapper along the hole wall. Figure 23 shows bolts 1 through 7, and figure 24 shows bolts 8 through 13 and bolt 16.

Table 12.—Cartridge wrappers tested

Wrapper	Thickness, mm	Material
1.35 ICI	0.034	SPS.
1.1 ICI	.028	SPS.
0.9 ICI	.023	SPS.
1.1 HER	.025	SPS.
0.75 HER	.019	SPS.
1.0 DUP	.025	Cellophane.
0.50 DUP	.013	PPP.

DUP E. I. Dupont deNemours and Co., Inc.
HER Hercules, Inc.
ICI Imperial Chemical Industries, Inc.
PPP Polyethylene polyester polyethylene.
SPS Saran polypropylene saran.

Bolt 13, at a WC ratio of 0.32 and using Lomar D, and bolt 15, at the same ratio but without Lomar D, showed the expected effect of Lomar D: Excess material appeared earlier as bolt 13 was inserted (at 600 mm out versus 300 mm out), and the installation was easier.

Bolts 20 through 22 illustrated the effect of increasing the quantity of Lomar D at a WC ratio of 0.25. Bolt 22, with the highest proportion of Lomar D to plaster, showed excess material early during bolt installation (at 600 mm out) and required holding the bolter head against the block to keep the bolt in place. Bolt 20, with the least Lomar D of these three bolts, was the hardest to install.

Lower Water-to-Cement Ratios With Lomar D

Because Lomar D decreases the freshly mixed grout viscosity at a given WC ratio and allows the grout easier movement within the hole during bolt insertion, the WC ratio of the grout can be lowered when this additive is used, thus increasing the grout strength.

The results of tests using Lomar D and cartridges with lowered WC ratios are shown in table 14. All cartridges used 0.034-mm wrappers, were 54 mm long with a 24.6-mm diam,

Table 13.—Pull-test results using various cartridge wrappers[1]

Bolt	Wrapper	WC ratio	Lomar D,[2] g	Full insertion time, s	Pull strength, kN	Pull time, min	Comments
1	1.35 ICI[3]	0.25	1.0	29.8	125	8	Excess at 250 mm out; hard at 100 mm out.
2	1.1 ICI	.25	1.08	21.4	125	>6	Excess at 250 mm out.
3	.9 ICI	.25	1.08	16.9	125	>6	Do.
4	1.1 HER[4]	.25	1.08	18.7	125	>6	Excess at 100 mm out. Easier insertion than bolt 2; harder than bolt 3.
5	.75 HER	.25	1.08	20.8	125	>6	Excess at 100 mm out. Easier insertion than bolt 4.
6	1.0 DUP[5]	.25	1.08	22.1	125	>6	Excess at 250 mm out.
7	.5 DUP	.25	1.08	20.2	125	>6	Do. Insertion similar to that of bolt 6.
8	1.35 ICI	.32	1.00	15.0	125	>6	Excess at 250 mm out. Bolter head kept on bolt to keep it in place.
9	1.1 ICI	.32	1.00	17.2	125	>10	Wet excess at 200 mm out.
10	.9 ICI	.32	1.00	18.6			Bolt installed rapidly for last 600 mm, but 40 mm short.
11	1.0 DUP	.32	1.00	14.6	125	>11	Excess at 300 mm out. Bolter head on bolt until 50.9 s.
12	.5 DUP	.32	0	17.2	125	>10	Excess at 600 mm out. Jack pulled bolt out at 1 min 51 s. Easier insertion than bolt 11.
13	1.0 HER	.32	1.00	32.8	125	>11	Excess at 600 mm out. Hard to install last 300 mm.
14	1.0 HER	.32	1.00	13.8	125	>11	Excess at 600 mm out. Dripping water during wrench installation.
15	1.0 HER	.32	0	32.8	125	>11	Excess at 300 mm out; hard insertion.
16	1.75 HER	.32	1.00	23.6	125	>10	Excess at 762 mm out.
18	1.0 HER	.32	1.00	20.7	125	>10	Excess at 600 mm out.
19	1.0 HER	.32	1.00	22.7	125	>11	Excess at 600 mm out. Bolt fell out during wrench installation.
20	1.0 HER	.25	1.62[6]	20.4	125	>6	Excess at 300 mm out; moderate insertion.
21	1.0 HER	.25	2.16[7]	21.4	125	>7	Excess at 300 mm out. Easier installation than for bolt 20.
22	1.0 HER	.25	4.32[8]	NR	116	>11	Excess at 600 mm out.

NR Not recorded.
[1]Bolt installation conditions: bolter head pressure, 9.0 MPa; thrust, gauge setting 8 on bolter head; and rotation, gauge setting 9 on bolter head. Slow spin before wrench installation.
[2]1.0 g Lomar D per 220 g of plaster, unless otherwise specified.
[3]Imperial Chemical Industries.
[4]Hercules, Inc.
[5]DuPont Co.
[6]1.5 g Lomar D per 220 g of plaster.
[7]2.0 g Lomar D per 220 g of plaster.
[8]4.0 g Lomar D per 220 g of plaster.

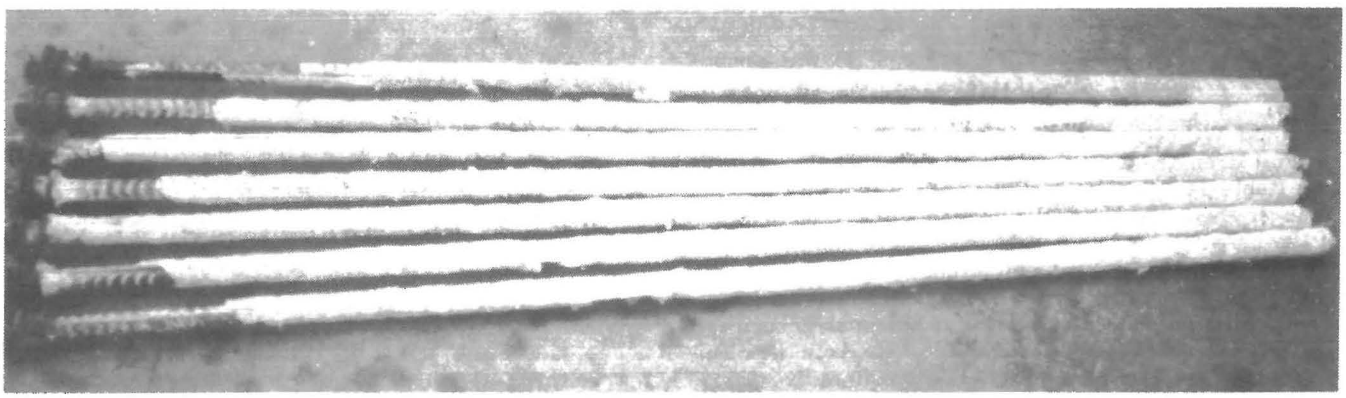

FIGURE 23.—Glove-fingering on bolts installed using 0.25 WC ratio.

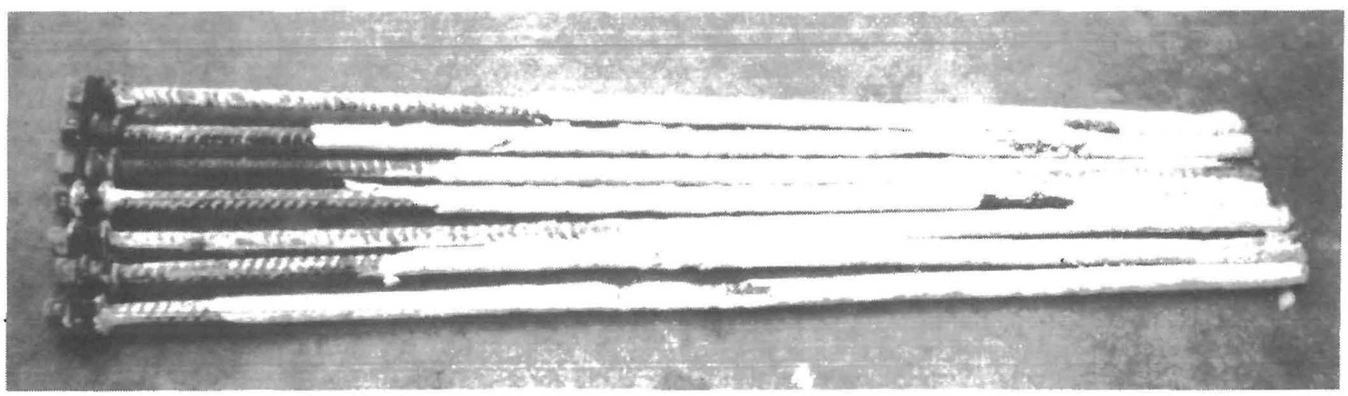

FIGURE 24.—Glove-fingering on bolts installed using 0.32 WC ratio.

Table 14.—Effect of Lomar D additive using cartridges with lowered WC ratios[1]

Bolt	WC ratio	Lomar D,[2] g	Full insertion time, s	Pull strength, kN	Pull time, min	Comments
1	0.287	1.03	13.4	125	>8	Steady insertion; excess at 25 mm out.
2	.28	1.04	14.7	125	>6	Steady insertion; excess at 51 mm out.
3	.27	1.05	23.0	125	>6	Steady insertion; excess at 76 mm out.
4	.26	1.07	22.6	125	>7	Steady insertion; but harder than bolts 1, 2, or 3.
5	.25	1.08	24.5	125	7	Steady insertion; excess at 102 mm out.
6	.24	1.08	20.3	125	>6	Hard insertion, last 406 mm; dry excess at 76 mm out.
8	.23	1.10	44.0	104	>6	Hard insertion, 203 mm out (required 20 s to complete).
9	.23	1.65[3]	22.3	125	>6	Steady insertion.
10	.22	1.65[4]	24.4	125	>7	Steady insertion, but hard last 76 mm.
11	.21	1.65[5]	25.8	125	>7	Do.
12	.24	1.09	26.4	125	>5	Steady insertion; fluid excess at 305 mm out.
13	.32	0	15.4	125	>6	Steady insertion; excess at 457 mm out.
14	.23	1.10	19.7	125	>5	Steady insertion; harder than bolt 12.
15	.24	1.09	26.2	125	>9	Steady insertion; excess at 152 mm out.
16	.23	1.10	29.9	104	>4	Steady insertion; hard 203 mm out. Block cracked badly.
17	.24	1.09	22.8	125	>4	Insertion hard at 300 mm out; bolt then fell in rapidly.
18	.24	1.09	18.7	104	4	Steady insertion.

[1]Bolt-installation conditions: bolter head pressure, 9.0 MPa; thrust, gauge setting 8 on bolter head; and rotation, gauge setting 9 on bolter head.
[2]1.00 g Lomar D per 220 g of plaster, unless otherwise specified. Adjustments were necessary in the Lomar D additions because the plaster weight varied slightly from 220 g, the standard plaster weight for these tests.
[3]1.50 g Lomar D per 220 g of plaster.
[4]1.48 g Lomar D per 220 g of plaster.
[5]1.46 g Lomar D per 220 g of plaster.

and contained 220 g of Hydrocal White plaster, 1 pct K_2SO_4 (by weight of the plaster), and SWRI 7-284 capsules. Bolts 1 through 8 used 1 g Lomar D per 220 g of plaster and WC ratios down to 0.23. A slight increase in glove effect was observed with the lower WC ratios, because a less fluid material cannot move the wrapper away from the bolthole surface as well as a more fluid material.

Bolt 9 used 1.5 g Lomar D per 200 g of plaster, which made bolt insertion easier. For bolt 11, at a WC ratio of 0.21 and using 1.46 g Lomar D per 220 g of plaster, insertion of the last 76 mm was somewhat difficult.

Bolt 12, with a WC ratio of 0.24 and 1.0 g Lomar D per 220 g of plaster, and bolt 13, with a WC ratio of 0.32 and no Lomar D, installed similarly. Assuming the water capsule cost to be 60 cents per pound, and the Lomar D cost to be 90 cents per pound, the cost savings per cartridge using the lower WC ratio would be 18.9 pct.

Pull strengths were very good 4 to 8 min after insertion (table 14). The lower WC ratios yielded a denser, stronger grout. The No. 6 (19-mm-diam) rebar used in most of the installations has a yield strength of about 98 kN, which explains the higher pull strength values shown in table 14 (compared with the values shown in table 11).

The effect of using small amounts of Lomar D (such as 1 g per 220 g of plaster) was very noticeable, as in the case of bolt 12, which showed grout at 305 mm from insertion, even though the WC ratio was only 0.24. The bolt could not be inserted at such a low WC ratio without the Lomar D.

The Lomar D additive makes bolts easier to insert over a range of conditions commonly found underground. Variations in bolt insertion techniques and cartridge storage with some loss of water sould be less likely to cause insertion difficulties.

Increased Set Time With Lomar D

Lomar D addition increases the plaster set time; it retards the hardening of the plaster while increasing its fluidity. Pull tests were done on 584-mm cartridges containing 220 g of Hydrocal White plaster with 1 pct K_2SO_4 and 110 g of SWRI 7-284 capsules, and using a 0.025-mm HER wrapper.

Bolts 1 and 2, listed in table 15, illustrate the effect of Lomar D in increasing the set time. Bolt 2, with 6.0 g Lomar D in the cartridge, had a 26-kN pull strength after a 25-min set time; whereas bolt 1, with no Lomar D, gave a 112-kN pull after 15 min. Bolt 3, with 3.0 g Lomar D in the cartridge, gave a 128-kN pull after more than 34 min. Although the 2,700-min pull time for bolt 5 was long, this bolt showed a good pull of 112kN (using 6.0 g Lomar D).

Table 15.—Effects of Lomar D additive on plaster set time[1]

Bolt	Lomar D, g	Full insertion time, s	Pull strength, kN	Pull time, min
1	0	4.2	112	15
2	6.0	5.3	26	>25
3	3.0	6.2	128	>3,434
5	6.0	5.6	112	2,700

[1]WC ratio, 0.32; bolter head pressure, 9.0 MPa; thrust, gauge setting 8 on bolter head; and rotation, gauge setting 9 on bolter head.

PERFORMANCE OF GYPSUM-ANCHORED BOLTS

The performance of gypsum-anchored bolts can be measured with pull tests conducted within minutes after bolt insertion. Both the installation procedure and variations in cartridge composition can be evaluated for their effect on bolt insertion and pull strength.

TEST APPARATUS

Concrete test blocks 610 by 610 mm square by 1,372 mm tall are placed in a test frame with sufficient headroom to allow installation of a 1,244-mm-long bolt (fig. 25). This

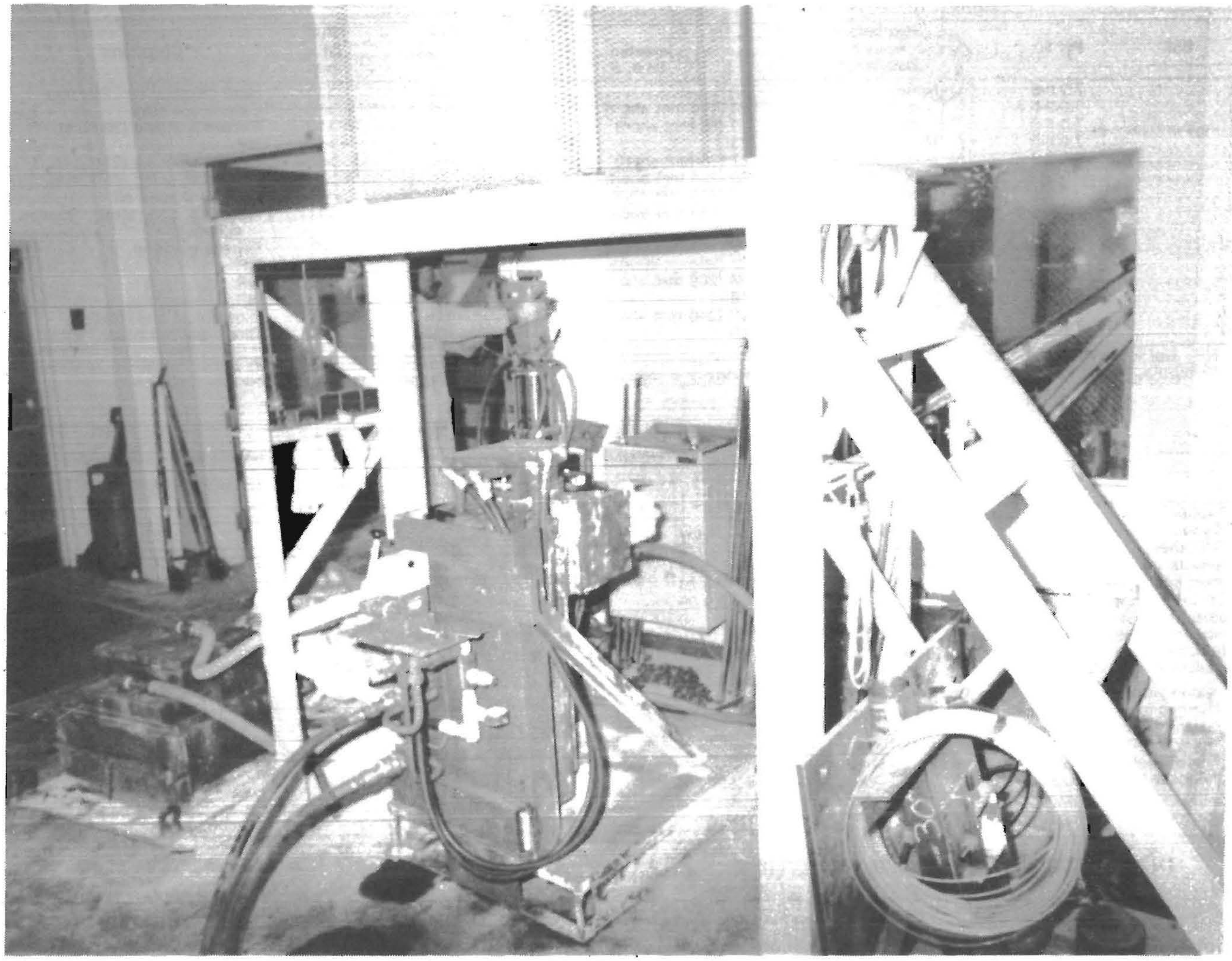

FIGURE 25.—Concrete block test frame.

height permits drilling of a 1,219-mm hole and installation of the roof bolt.

The test blocks are made with pea gravel (9.5-mm-minus aggregate) and five 42.64-kg sacks of cement per 0.76 m^3. This produces a concrete with a uniaxial compressive strength of approximately 31 MPa, which is sufficient to cause failure in a pull test at the roof-bolt grout interface. A standard roof-bolting machine head is used to drill the hole and install the bolt. The holes are drilled using a 25.4-mm finishing carbide bit. This bit drills a 26.2-mm-diam hole when new.

When the desired time has elapsed since installation of the roof bolt, the bolt is pulled from the block using a hollow-core hydraulic jacking cylinder operated by a hand pump.

PULL STRENGTH

Two 610-mm-long cartridges were placed in each pull strength test hole. The cartridges had a WC ratio of 0.32 (SWRI 7-284 capsules), contained 1 pct K_2SO_4 accelerator, and were made with a 0.076-mm heat-sealed PPP wrapper with a 24.6-mm diam. The bolt was inserted about 400 mm before wrench installation and either (1) spun slowly, (2) spun at maximum speed, or (3) not spun before wrench installation. The pressure, thrust, and rotation (P-T-R) controls of the bolter head were varied within small ranges. Table 16 shows pull-strength data for several bolt installations.

All of the bolts yielded, even though some were not completely inserted. For example, bolt 7 produced a pull over 95kN, even though it was 254 mm short of complete insertion.

Generally, the bolts showed improved insertion as the rotation and pressure increased and the thrust decreased; however, some bolts completely inserted while others did not. The water capsule quality was good, as was the quality of the cartridges. Cracks in some of the test blocks probably resulted form high insertion pressures within the holes. As previously noted, cartridge water is lost when bolts are installed in cracked holes, and the result is difficult insertion.

Table 16.—Pull strengths of bolts installed using gypsum plaster and water capsules

Bolt	P-T-R[1]	Spin before wrench installation	Insertion time, s	Pull strength, kN	Pull time, min	Comments
2	7.0-9-6	None	17	116	>10	Hard insertion last 250 mm.
3	7.0-9-6.5	..do	60 (140 mm short)	100	>13	Excess spinning.
4	7.0-8-9	..do	38 (25 mm short)	95	>10	Excess spinning (38-65 s).
5	7.0-8-9	Max	23	112	>10	NR.
6	7.0-8-9	Max	27 (25 mm short)	100	>10	Excess spinning (27-120 s).
7	7.0-8-9	Max	60 (254 mm short)	95	>10	Excess spinning (60-120 s).
8	7.0-8-9	Slow	NR (450 mm short)	NR	NR	Wrench slipped off.
9	7.0-8-9	..do	170 (450 mm short)	95	>11	Rotation too slow; excess spinning.
10	7.0-8-9	Max	210 (140 mm short)	NR	NR	Excess spinning.
11	11.0-8-9	Max	23 (25 mm short)	108	>12	NR.
14	8.3-8-9	Slow	NR (200 mm short)	NR	NR	NR.
15	9.0-8-9	..do	16	NR	NR	NR.
16	9.0-8-9	..do	NR (240 mm short)	NR	NR	Slow thrust and rotation.
17	9.0-8-9	.do	20	100	>10	Block cracked badly.

NR Not recorded.
[1]Pressure, in megapascals; thrust (gauge setting on bolter head); and rotation of bolter head (gauge setting on bolter head).

Table 17.—Insertion conditions for bolts installed in concrete test samples

	Concrete sample 1	Concrete sample 2	Concrete sample 12	Concrete sample 16
Wrapper:				
Type	Molyply	Molyply	ICI	ICI
Thickness, mm	0.076	0.076	0.023	0.023
Pressure gauge setting, MPa	10.3	10.3	[1]9.0	103
Thrust setting[2]	8.25	4.0	4.0	4.0
Rotation setting[2]	9.05	9.0	9.0	9.0
Lomar D, g	0	0.5	0.5	0.75
Installation time before wrench on, s	0-4.0	0-1.6	0-2.8	0-2.5
Wrench-on time, s	4.0-20.1	1.6-8.1	2.8-9.3	2.5-9.1
Installation time after wrench on, s	[3]66.8	[4]15.3	[5]47.6	[6]20.1

[1]Changed to max at hard insertion.
[2]Setting to control hydraulic flow to thrust cylinders and rotation motor.
[3]Hard insertion about 300 mm out; bolter jogged.
[4]Easy insertion; wet excess materal about 355 mm out.
[5]Hard insertion about 250 mm out at 18.3 s; bolter jogged.
[6]Medium to hard insertion ("pilgrim's hat" used); 10-15 g excess at 356 mm out.

PULL STRENGTH OF BOLT SECTIONS

Pull tests were conducted to determine the effect of higher insertion pressures on the strength of the upper areas of the bolts. Concrete samples for these tests were prepared by filling 102-mm-diam pipe with concrete and then drilling a 1,230-mm-deep bolt hole. Bolts were then inserted. Table 17 shows the insertion conditions for four of the test samples.

All cartridges contained 220 g of Hydrocal White plaster and 110 g of SWRI 7-379 water capsules. No accelerator was used in order to allow more time for bolt installation. For the bolt installed in sample 1, higher thrust, lack of Lomar D, and a long wrench installation time resulted in a long (66.8-s) insertion time. The bolt installed in sample 12 required 47.6 s for installation, even though 0.5 g of Lomar D was used in each cartridge. These are excessively long installation times, especially because the grout was not accelerated and would not have stiffened. The concrete quality in the test samples was suspect, because cracks in the concrete allowed the entry of excessively fluid material and made the remainder of the cartridges too dry for easy insertion.

The test samples were cut into eight 152-mm sections and adapted with an extension rod for pull-testing. Table 18 gives the pull-test data for the various bolt sections. These tests show that the half of the bolt farthest up the hole had the greater strength due to higher recorded pressures in that zone. Table 18 also shows that bolts 12 and 16 were stronger than bolts 1 and 8. This was probably because a thinner wrapper was used in installing bolts 12 and 16. (A thinner wrapper promotes grout escape from the bag and reduces glove-fingering.) The results of these tests, however, were clouded by the questionable concrete quality.

Table 18.—Pull strengths of 152-mm bolt sections, kilonewtons

Section[1]	Bolt[2] 1	Bolt[2] 8	Bolt[2] 12	Bolt[2] 16
A	22.4	20.7	16.3	39.8
B	50.3	35.8	36.8	70.3
C	39.0	32.9	73.7	71.5
D	32.8	25.4	71.6	80.4
Average (A-D)	36.1	38.7	49.6	65.5
E	55.3	27.9	78.3	67.3
F	46.7	32.9	79.9	68.3
G	24.9	24.4	85.2	72.4
H	28.9	38.7	68.7	55.3
Average (E-H)	38.9	31.0	78.0	65.8

[1]A was closest to bolthead; H was farthest.
[2]Bolt numbers correspond to those in table 13.

LOAD TRANSFER

Tests were conducted to determine the reinforcement characteristics of fully grouted roof bolts in a mine roof. This study observed the transfer of forces along the length of a fully grouted roof bolt due to induced forces from roof sag. The load-transfer characteristics for both resin and gypsum grouted bolts are presented for comparison.

The roof bolts were installed in concrete test blocks. The test blocks were made from a 5-bag pea-gravel concrete mix which yielded a compressive strength of 24.1 MPa as determined by 76- by 150-mm test cylinders. The test bolts were

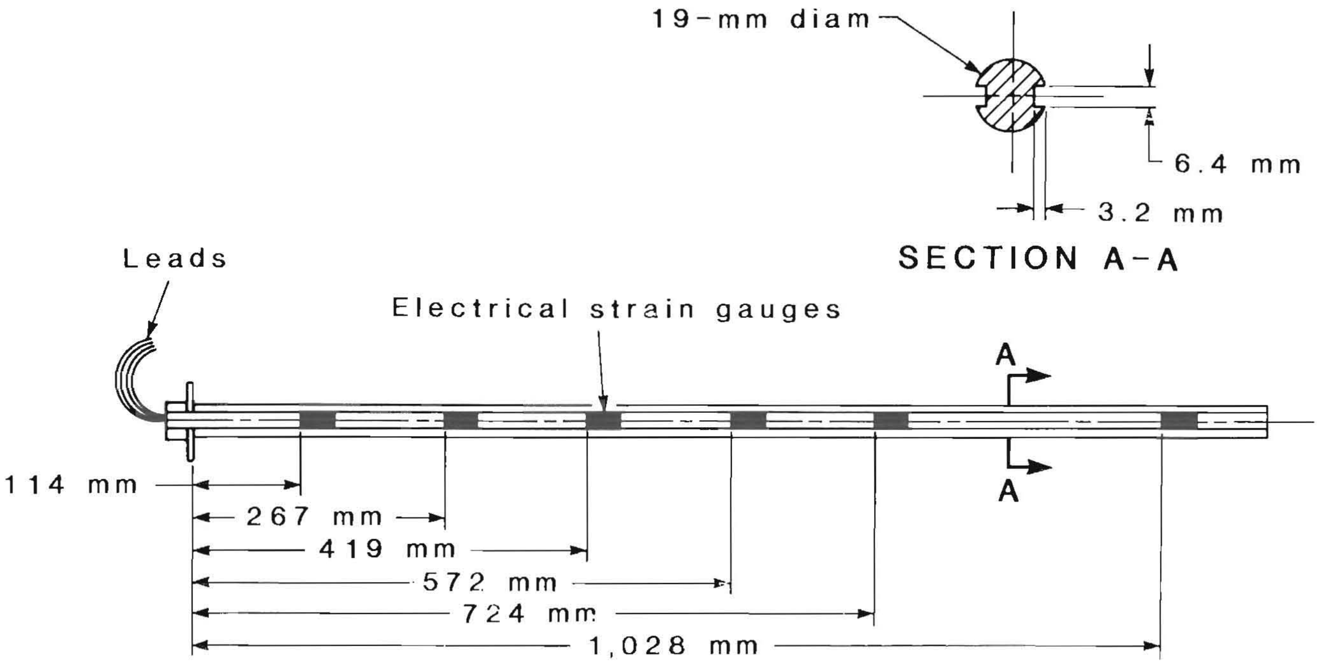

FIGURE 26.—Location of strain gauges on test bolt.

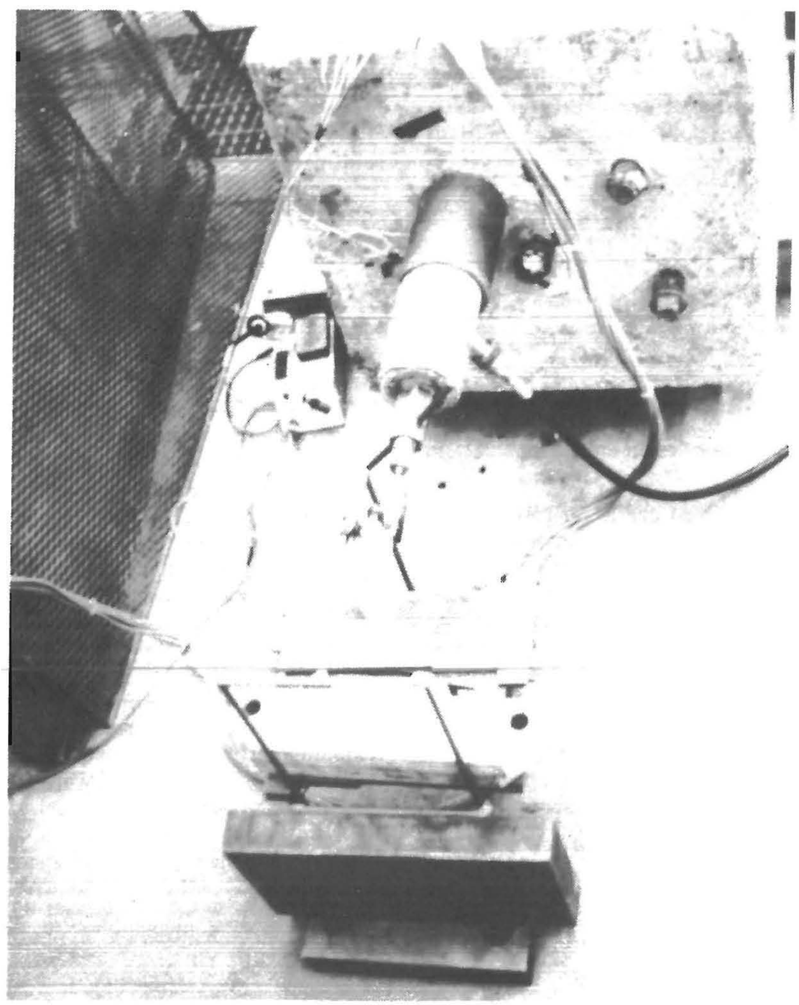

FIGURE 27.—Apparatus for determining bolt load transfer.

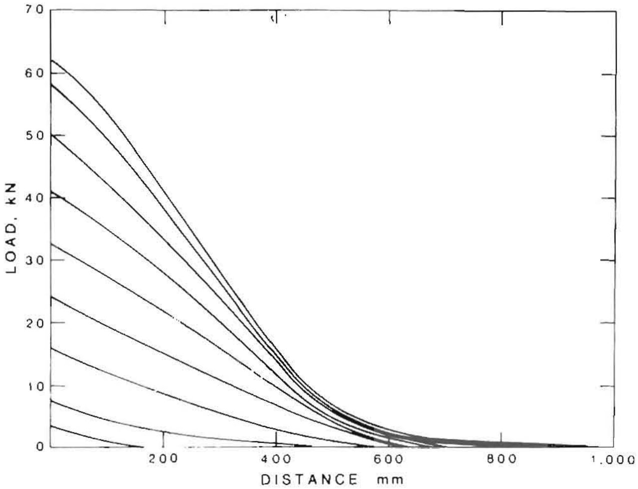

FIGURE 28.—Load transfer of gypsum-anchored bolt.

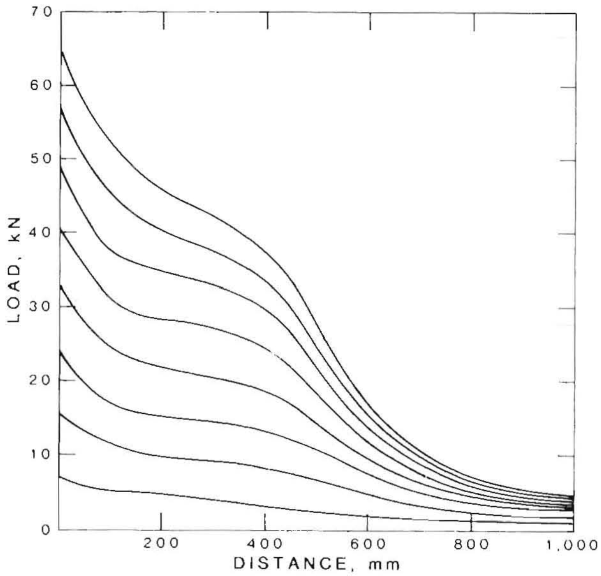

FIGURE 29.—Load transfer of resin-anchored bolt.

1,219-mm-long No. 6 (19-mm-diam) grade 50 reinforcing steel and were wire instrumented with 12 electrical strain gauges to measure the force in the bolt at a particular location. The strain gauges, in diametrically opposed pairs at six locations (fig. 26), were protectively coated before calibration. A statistical line or regression was used to determine the parameters for calculating the bolt load at particular locations.

The holes for the bolts were drilled with a typical roof bolting drill. The instrumented roof bolts were installed in the concrete test blocks using the bolt insertion procedure previously described. Figure 27 shows the load application to the bolthead with a small manual hydraulic pump. The load was applied in increments of 2.76 MPa gauge pressure (a load change of approximately 8.4kN). Data were recorded 5 min after load application to allow the load transfer along the bolt to stabilize.

The data were plotted to show bar force versus distance from the collar of the hole. The resultant graphs showed the rapid transfer of the applied force from the bolt through the grout and into the surrounding media (fig. 28). Curve shape was influenced by (1) strength and elasticity modulus of the grout, (2) strength and elasticity modulus of the host rock, (3) full versus partial grouting of the bolt, and (4) bolt size and strength.

Data for a gypsum-grouted bolt (fig. 28) defined a typical load-transfer curve for a fully grouted roof bolt. In the curve for the resin bolt (fig. 29), the relatively flat portion between 100 and 400 mm from the bolthead indicates that good bonding did not occur in this region.

Theoretically, the load transfer of forces can be calculated (2) by the equation

$$P_x = P_o e - \left(\frac{\alpha x}{d}\right),$$

where P_o = force applied on the bolthead, kN,
e = natural base for logarithms,
P_x = force at a distance x from the bolthead, kN,
α = a parameter dependent on the grouting material, determined from experimental tests,
x = distance from initial force, in,
and d = diameter of the bolt, in.

However, the preliminary results reported here did not correlate well with the equation. More tests are needed to determine a proper equation for predicting the load transfer characteristics of fully grouted bolts.

CREEP

Bolts are often installed in long-life entries where roof loads can cause long-term creep of the gypsum. Tension-creep test samples for bolts were made by filling a 102-mm-diam pipe with concrete and installing the bolts in the concrete. The samples were then put in a frame and loaded in tension to determine the creep characteristics of the cartridge system. Most of the test samples were 600 mm long, but a few were 1,200 mm long.

Bolts installed using gypsum water capsule cartridges sustained loads up to 44 kN while showing substantial creep (an inch or more), which eventually slowed to a creep rate of near zero. Creep was greatest in samples that showed relatively large amounts of grout during insertion.

Bolts were also installed with gypsum slurry (no water capsules). These bolts sustained loads in excess of 67 kN, with little or no creep, and were sensitive to the loss of grout during insertion.

COMMERCIALIZATION OF GYPSUM-PLASTER WATER CAPSULE CARTRIDGES

A usable product is required for commercialization of the technology described in this report and its adoption by the mining industry. The packaging technique for the inorganic cartridge differs from that used for the polyester resin cartridge. Resin materials are liquid, while gypsum plaster and water capsules handle as fine-particulate solids.

The Bureau issued research contract (HO202038) to develop the packaging technology for cartridge commercialization. A six-line encapsulation system for the water capsules was developed, along with the equipment to produce twenty 2-ft-long cartridges per minute.

The installation procedure previously described is based upon the experience gained in tests and through use of the Bureau's gypsum cartridge system. Any change in the formulation of materials, cartridge diameter, hole diameter, wrapper material, etc., could require modifications to the outlined installation procedure.

U.S. Steel Corp. has developed an inorganic cartridge and has done a complete section test in an Alabama mine. The company purchased the water capsules and developed packaging equipment for an inorganic cartridge at its research facility near Pittsburgh, PA. U.S. Steel examined additives to reduce the cartridge size and amount of water capsules in relationship to the gypsum plaster and developed faster bolt holding times (which are required for primary roof support). Details are not available at the present time.

Commercial Plastic Special Products, Ltd., of the United Kingdom, has purchased the patent rights to produce inorganic cartridges in the United Kingdom, Canada, Republic of South Africa, and Australia. The product has seen only limited success in the United Kingdom because of a depressed coal market. Trial shipments of the cartridges have been sent to South Africa and Australia. No information concerning these shipments and their application is available.

CONCLUSIONS

1. Gypsum-plaster water capsule cartridges provide adequate anchorage of No. 6 rebar bolts in 1,219-mm-long holes under normal or dry conditions.
2. Gypsum-plaster water capsule cartridges can provide a suitable substitute for resin cartridges under normal or dry conditions.
3. Gypsum-plaster water capsule cartridges should be further tested under wet conditions.

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APPENDIX.— NINETY-DAY WATER CAPSULE DRYING DATA

Test	Lot[1]	Wax: Type	Wax: Pct	Wax modifiers, pct: Piccolyte S-115	Wax modifiers, pct: Epolene C-16	Wax modifiers, pct: Polybutene	Water loss, pct: Slope 1 (Av per day, initial drying phase)	Water loss, pct: Slope 2 (Av per day, steady-state drying)	Water loss, pct: Total over 90 days or from day 10 to day 90[2]	Initial drying period, days
1	SWRI 7-142	Boler 1426	45	45	10	NAp	0.080	0.048	14.9	17
2	SWRI 7-152	do	45	45	10	NAp	NAp	.040	5.8	9
3	SWRI 6-961	Sunnco	60	25	NAp	NAp	.134	.060	14.5	7
4	SWRI 7-152	Boler 1426	45	45	10	NAp	NAp	.048	5.1	10
5	SWRI 7-152	do	45	45	10	NAp	NAp	.032	3.6	9
6	SWRI 7-135	Sunnco	41	41	8	10	NAp	.037	4.4	18
7	SWRI 7-142	Boler 1426	45	45	10	NAp	.101	.058	15.9	12
8	MED 11-01-A	do	45	45	10	NAp	.085	.064	17.3	19
9	MED 12-6-79	do	45	45	10	NAp	.076	.040	9.2	11
10	MED 12-7-79	do	45	45	10	NAp	.047	.030	6.6	10
11	MED 12-7-79B	do	45	45	10	NAp	.033	NAp	7.6	25
12	MED 1A	do	45	45	10	NAp	(3)	.104	19.2	50
13	MED 2A	do	41	41	8	10	.093	.082	8.96	10
14	MED 1B	do	45	45	10	NAp	(3)	.080	23.2	50
15	MED 2B	do	41	41	8	10	(3)	.076	19.5	50
16	MED 3A	C-150	45	45	10	NAp	.046	.083	8.7	23
17	MED 3B	do	45	45	10	NAp	.218	.079	[4]23.9	24
18	MED 4A	do	41	41	8	10	(5)	(6)	24.9	60
19	MED 4B	do	41	41	8	10	.094	.082	10.6	10
20	MED 5A	Indrawax 5560-j.	45	45	10	NAp	.222	.099	27.3	18
21	MED 5B	do	45	45	10	NAp	.188	.107	26.8	23
22	MED 6A	do	41	41	8	10	.136	.068	10.1	16
23	MED 6B	do	41	41	8	10	.139	.079	11.2	20
24	SWRI 7-182	do	45	45	10	NAp	.055	.042	4.9	15
25	SWRI 7-178	Boler 1426	41	41	8	10	NAp	.016	3.2	6
26	SWRI 7-179	do	45	45	10	NAp	NAp	.020	4.7	16
27	SWRI 7-180	do	41	10	10	8	NAp	.020	4.9	14
28	SWRI 7-181	Indrawax 5560-j.	45	10	10	NAp	NAp	.020	4.9	12
29	SWRI 7-284	Boler 1426	45	45	10	NAp	NAp	.022	7.3	8
30	MED 6/16/81	do	41	41	8	10	.080	.046	5.0	13
31	MED 6/26/81	do	41	41	8	10	.080	.046	5.0	13
32	MED 6/25/81	do	41	41	8	10	.064	.041	3.9	12
33	MED 6/24/81	do	41	41	8	10	.053	.030	3.3	10
34	MED 6/23/81	do	41	41	8	10	.057	.034	[7]4.1	18
35	MED 6/22/81	do	41	41	8	10	.061	.038	4.7	20
36	MED 6/19/81	do	41	41	8	10	.092	.032	5.2	17
37	MED 6/18/81	do	41	41	8	10	.080	.039	6.3	22
38	MED 6/17/81	do	41	41	8	10	.116	.038	[8]5.2	14
39	MED 6/29/81	do	41	41	8	10	.080	.0417	3.5	27
40	MED 6/30/81	do	41	41	8	10	.047	NAp	4.7	12
41	MED 7/1/81	do	41	41	8	10	.053	.037	3.3	2
42	MED 7/2/81	do	41	41	8	10	.052	.039	3.2	10
43	MED 7/6/81	do	41	41	8	10	.045	.033	2.7	7
44	MED 7/7/81	do	41	41	8	10	.057	.039	3.8	15
45	MED 7/8/81	do	41	41	8	10	.055	.035	3.2	15
46	MED 7/9/81	do	41	41	8	10	.064	.040	3.7	15
47	MED 5/10/81	do	41	41	8	10	.060	.037	3.7	17
48	MED 2/11/81	do	41	41	8	10	.112	.068	7.5	10
49	MED 2/12/81	do	41	41	8	10	.063	.033	3.6	11
50	MED 2/13/81	do	41	41	8	10	.029	NAp	3.4	35
51	MED 2/14/81	do	41	41	8	10	.065	.028	3.8	15
52	MED 5/4/81	do	41	41	8	10	.030	NAp	3.8	15
53	MED 5/5/81	do	41	41	8	10	NAp	NAp	3.8	15
54	MED 5/6/81	do	41	41	8	10	.027	NAp	3.8	15
55	MED 5/7/81	do	41	41	8	10	NAp	.029	3.8	15
56	MED 5/15/81	do	41	41	8	10	.039	NAp	3.8	15
57	MED 5/18/81	do	41	41	8	10	.097	.031	3.8	15
58	MED 5/19/81	do	41	41	8	10	.051	NAp	3.8	15
59	MED 5/21/81	do	41	41	8	10	.044	NAp	3.8	15
60	MED 6/8/81	do	41	41	8	10	.059	NAp	3.8	15
61	MED 6/9/81	do	41	41	8	10	.93	.064	4.3	12
62	MED 6/10/81	do	41	41	8	10	.72	.066	4.0	7
63	MED 6/11/81	do	41	41	8	10	.132	.089	7.1	14
64	MED 6/12/81	do	41	41	8	10	.052	NAp	3.4	16
65	MED 6/15/81	do	41	41	8	10	.106	.070	[9]5.8	16
66	MED 7/14/81	do	41	41	8	10	.047	.037	3.1	14
67	MED 8/4/81	do	41	41	8	10	.044	.035	7.1	12
68	MED 7/13/81	do	41	41	8	10	.083	.063	5.4	10
69	MED 7/25/81	do	41	41	8	10	.053	.034	3.5	12
70	MED 7/24/81	do	41	41	8	10	.053	NAp	3.9	8
71	MED 7/24/81	do	41	41	8	10	.056	NAp	3.8	13
72	SWRI 7-363	do	45	45	10	NAp	NAp	.026	2.05	7
73	MED 8/10/81	do	41	41	8	10	.100	.025	7.1	15
74	MED 8/11/81	do	41	41	8	10	.048	NAp	4.1	19
75	MED 8/12/81	do	41	41	8	10	.042	NAp	3.2	15
76	MED 8/14/81	do	41	41	8	10	.066	NAp	4.9	15
77	MED 8/17/81	do	41	41	8	10	.068	.05	4.3	8
78	MED 8/18/81	do	41	41	8	10	.067	NAp	5.0	19
79	MED 8/19/81	do	41	41	8	10	.048	.040	3.5	14
80	MED 8/21/81	do	41	41	8	10	.087	.058	6.2	21
81	MED 8/27/81	do	45	45	NAp	10	.073	.040	3.7	8
82	MED 8/28/81	do	45	45	NAp	10	.122	.076	7.3	14

See explanatory notes at end of table.

NINETY-DAY WATER CAPSULE DRYING DATA—Continued

Test	Lot[1]	Wax		Wax modifiers, pct			Water loss, pct			Initial drying period, days
		Type	Pct	Piccolyte S-115	Epolene C-16	Polybutene	Slope 1 (Av per day, initial drying phase)	Slope 2 (Av per day, steady-state drying)	Total over 90 days or from day 10 to day 90[2]	
83	MED 8/31/81	Boler 1426	45	45	NAp	10	0.070	NAp	4.1	18
84	MED 9/1/81	..do	45	45	NAp	10	.095	.031	3.0	11
85	MED 9/7/81	.do	45	45	NAp	10	.067	NAp	3.9	15
86	MED 9/7/81	.do	45	45	NAp	10	.098	NAp	[10]2.9	15
87	MED 9/10/81	..do	45	45	NAp	10	.117	0.053	5.6	15
88	MED 10/23/81	..do	45	45	NAp	10	.08	.03	3.1	9
89	MED 10/22/81	..do	45	45	NAp	10	.088	.031	3.3	12
90	MED 10/15/81	..do	45	45	NAp	10	.068	.03	3.2	13
91	MED 12/3/81	..do	45	45	NAp	10	.093	.054	5.3	15
92	MED 10/12/81	..do	45	45	NAp	12	.053	.033	3.3	15
93	MED 10/8/81	..do	45	45	NAp	10	.047	.028	2.8	8
94	SWRI 7-379	..do	45	45	NAp	10	NAp	.013	1.1	15

NAP Not applicable.
[1]Water capsule suppliers: SWRI—Southwest Research Institute, MED—Mine Equipment Development Corp.
[2]Tests 1-28: Total 90-day water loss (unless otherwise noted). Tests 29-94: Water loss from day 10 to day 90 (unless otherwise noted).
[3]Rounded; no slope.
[4]10-79 days.
[5]Rounded.
[6]No slope.
[7]10-86 days.
[8]10-68 days.
[9]10-88 days.
[10]10-53 days.

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