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The Backfilling Research Being Conducted by the U.S. Bureau of Mines

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The U.S. Bureau of Mines is currently investigating the engineering aspects of tailings used as backfill material. Backfilling with mine wastes can reduce surface subsidence through the filling of underground voids, the enhancement of miner health and safety, and the achievement of more efficient and environmentally sound mining methods. The backfill material studied by Bureau researchers includes cemented-paste fill and cemented rock-and-alluvial-sand fill. The work includes the determination of material properties, the transportation and placing of backfill, instruments to monitor the backfill, and computer modelling.

This paper presents laboratory data about the effects of particle-size gradation on the unconfined compressive strength of tailings backfill. Fine tailings (100 per cent minus 0,074 mm) were added to varying amounts of coarse silica sand to alter the fineness modulus. It was found that the unconfined compressive strength increased for the mixes containing finer tailings and sand when the water/cement ratios and slumps were held constant. Another test series showed that the temperatures of cold material decreased the unconfined compressive strength of the mix.

An overview is given of the Bureau's 'Mining With Backfill' research programme, which studies the effective use of backfill material. Continuing research includes investigations of the strength of backfill containing total-gradation tailings, the development of a paste-pump simulator, the field instrumentation of backfill and pillars, and the computer modelling of backfill stability.

Introduction

The 'Mining With Backfill' project of the U.S. Bureau of Mines consists of four interconnected tasks involving the determination of

(1) backfill properties
(2) design fundamentals of paste-backfill transport
(3) deformation and strength of rock and methods of measuring pillar loads
(4) pillar and backfill interaction models.

The goals of the project are directed towards improving the strength of mine backfills, defining the deformation properties of backfills and rock pillars, determining the mechanics of gravity loading of backfill-pillar support systems, assessing stability by numerical and/or physical models, comparing results with actual behaviour during the extraction of mine pillars, and improving systems to deliver fill materials underground.

The personnel working on the project have investigated methods of improving the strength and transportability of low-slump backfill of low cement content developed from mill-tailings material. *In situ* test methods were devised to determine the stress–strain properties of the backfill and pillars in massive rock formations. The results of laboratory and analytical modelling were compared with data obtained from instrumented mines to verify the models as reasonable predictors of actual mine behaviour.

This paper presents the results of tests on specific backfill properties to determine the effects of particle-size variability and cold material temperatures on unconfined compressive strength. The tests were conducted on dewatered, total-gradation mill tailings. In addition, the paper gives an overview of current progress in the Bureau's 'Mining With Backfill' project.

Backfill Properties

Effects of Particle Size

The results of previous tests using total-gradation mill tailings have been presented in conference proceedings[1] and Bureau publications[2]. These studies describe a range of relationships among three sources of tailings materials, as well as the effects of different water/cement ratios and the use of additives, such as superplasticizers, fly ash, slag, and cement, on unconfined compressive strength.

The purpose of the study presented in this paper was to determine whether the basic relationships found in concrete testing could also be generalized to cemented mill tailings. For mortar and concrete, it had been found that wide variations in sand grading have no effect on the compressive strength[3]. For example, in tests by the Bureau of Reclamation, the fineness modulus (FM) for mortar was found to range from 2,54 to 3,29, and that for concrete from 2,70 to 3,10. (Mortar is technically defined as a mixture of cement, sand, and water. Concrete, in addition to cement, sand, and water, includes gravel, crushed rock, or another form of aggregate.) FM is defined as follows:

$$FM = \frac{\text{Cumulative percentage retained on U.S. sieve screens 4 to 100}}{100},$$

where the screen sizes are Nos. 4, 8, 16, 30, 50, and 100.

As a comparison, the FM for tailings ranges from 0,00 to 0,65—much finer than the FM for standard mortar and concrete materials. Although the FM does not reflect the sand gradation, it does indicate the coarseness or fineness of the material.

Table I summarizes 17 mixes and test results, and Table II summarizes a subset of tests in which the slumps and water/cement ratios were kept constant for four mixes but the FM was changed.

Table I
Summary of slurry compositions and properties

Sample no.	Tailings %	Sand %	Cement %	Slurry density† %	W/C*	FM	Unit wt kg/m³	Air %	Average strength MPa
FM–0	100,0	0,0	0,0	70,0	0,00	0,00	1730,0	2,4	0,00
FM–00	100,0	0,0	0,0	80,0	0,00	0,00	1864,5	6,4	0,00
FM–1	100,0	0,0	4,0	70,0	11,14	0,00	1579,4	11,2	0,26
FM–2	100,0	0,0	6,0	70,0	7,57	0,00	1579,4	11,3	0,36
FM–2A	100,0	0,0	6,0	80,0	4,42	0,00	1739,6	13,2	1,36
FM-3	75,0	25,0	4,0	70,0	11,14	0,16	1489,7	16,2	0,14
FM-4	75,0	25,0	6,0	70,0	7,57	0,16	1489,7	16,3	0,25
FM-4A	75,0	25,0	6,0	80,0	4,42	0,16	1906,2	4,9	1,07
FM-5	50,0	50,0	4,0	70,0	11,14	0,38	1742,8	2,0	0,07
FM-6	50,0	50,0	6,0	70,0	7,57	0,38	1736,4	2,5	0,14
FM-6A	50,0	50,0	6,0	80,0	4,42	0,38	1912,6	4,6	0,93
FM-7	25,0	75,0	4,0	70,0	11,14	0,50	1630,7	8,4	0,06
FM-8	25,0	75,0	6,0	70,0	7,57	0,50	1678,7	5,8	0,15
FM-8A	25,0	75,0	6,0	80,0	4,42	0,50	1665,9	17,0	0,47
FM-9	0,0	100,0	4,0	70,0	11,14	0,65	1707,6	4,1	0,06
FM-10	0,0	100,0	6,0	70,0	7,57	0,65	1707,6	4,2	0,24
FM-l0A	0,0	100,0	6,0	80,0	4,42	0,65	1553,8	22,6	0,54

* W/C = Water/cement ratio
† Percentage slurry density = weight of solids/(weight of solids + weight of water) x 100

Table II
Test results when the slump and water/cement ratio* were held constant

Sample no.	Tailings %	FM	Slump cm	Cement %	Slurry density† %	28-day strength MPa
PS–1	100,0	0,00	7,62	14,0	67,1	1,10
PS–2	75,0	0,16	6,35	8,6	75,9	0,92
PS–3	50,0	0,38	6,35	7,2	79,0	0,72
PS–4	0,0	0,65	7,62	8,0	77,0	0,46

* Water/cement ratio = 4
† Slurry density = weight of solids / (weight of solids + weight of water) x 100

Grab samples of tailings were taken from a mine storage bunker. They were then oven-dried prior to the mixing. The cement used was Portland cement type I,II; the mix water was taken direct from the tap. All the material preparation, batch mixing, sample storage, and testing were conducted at the Bureau's laboratory at the Spokane Research Center in Spokane, WA. Figure 1 illustrates grain-size gradations for the tailings, No. 70 silica sand, and three synthetic mixes representing ratios of 25, 50, and 75 per cent tailings to sand.

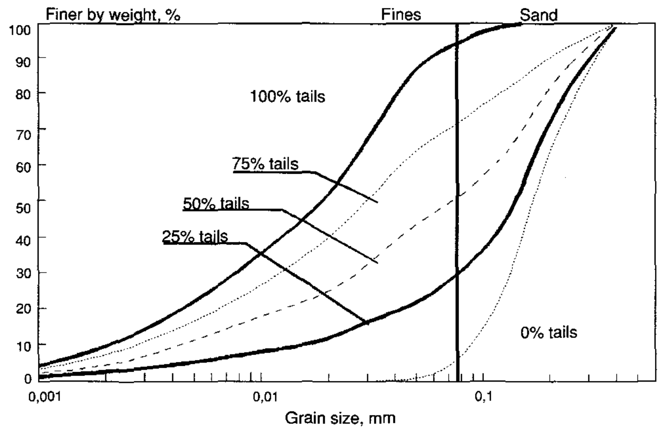


Figure 1. Gradation curves for the tailings and sand mixes

Each mix batch was cast in triplicate into waxed cardboard cylinders 7,6 cm by 15,2 cm in size, and allowed to cure for 28 days in a room of 100 per cent humidity equipped with misters. The triplicate samples allowed the sample properties and unconfined compressive strengths to be averaged. In the case of mixes with constant slump and constant water/cement ratios, enough material was mixed to allow the use of the cone for the ASTM concrete-slump test[4].

After 28 days of curing, the samples of mix were stripped from the cardboard cylinders and, after being capped with sulphur to produce flat, parallel ends, were tested for unconfined compressive strength. For the mix containing 4 per cent cement, the strengths increased with increased amounts of fine tailings (Figure 2), as opposed to a 100 per cent classified sand. For the mix containing 6 per cent cement, the strength decreased before increasing. Although, on the surface, this finding is contrary to conventional expectations, two major differences preclude direct comparisons. First, the dense or paste-type tailings backfill is based on the use of more fines (with a particle size of minus 0,074 mm). Second, the paste-type backfill requires less water (having a slurry density of 80 per cent) than classified, hydraulically conveyed tailings sandfill (at a slurry density of 70 per cent). Slurry density, although not a true density property, is defined as

$$\text{Slurry density, \%} = \frac{\text{Weight of solids}}{(\text{Weight of solids + weight of water})} \times 100$$

Because of the increased fines content, and therefore the greater surface area, more water is needed to wet the surfaces of the particles. The mix protocol kept the water constant and varied the amount of tailings (fines within the total mix). As the amount of fines increased, the effective consumption of water for particle wetting and cement hydration increased. There was less 'free' water because it was trapped within the material mass. Excess pore water can cause the cement and particles to segregate before the cement hydrates and hardens, and also results in higher pore pressures, which reduces the shearing resistance during compression tests.

Most important, the addition of fines resulted in a better-graded aggregate mix. The grain-size gradation curve

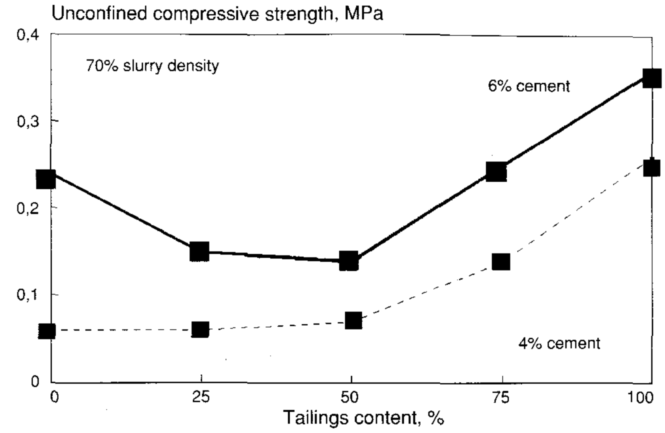


Figure 2. Comparisons of unconfined compressive strengths

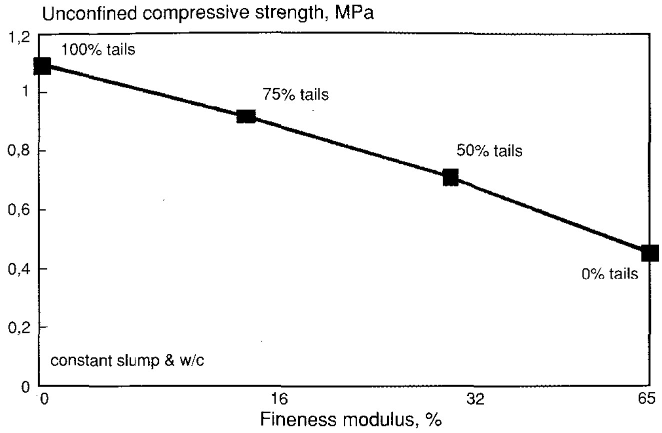


Figure 4. Effect of FM on 28-day strength

extended over a wider range of particle sizes, resulting in better packing of the smaller particles within the voids left by the larger particles and in increasing frictional resistance during compression tests.

During cement hydration, calcium hydroxide, calcium aluminate, and other crystalline calcium composites and compounds are formed[5]. This chemical process physically alters the concreted mass in that the original void ratio is no longer correct. Pore water is taken up during chemical hydration, and, to a lesser extent, the air voids are filled with formations of concrete fibres. Figure 3 demonstrates that the air volume is not a good predictor of compressive strength for fine tailings materials; the expected increase in strength is not related to decreasing air volume, which is defined as

$$\text{Air, \%} = (\text{Volume of air/volume of batch}) \times 100.$$

However, there does appear to be a range of grain-size gradations (between 25 and 50 per cent tailings) where decreasing air volume has the expected effect of increasing the compressive strength. This can probably be attributed to an effective void ratio in a particular mix. However, the determination of the void ratio of a concreted mass is not a wholly quantitative exercise, as noted above.

Figure 4 illustrates an inversely linear relationship between the FM and the unconfined compressive strength of backfill material when the slump and water/cement ratio are held constant. As the particle size of the material became finer and the FM decreased, the compressive strength increased. In tests of structural concrete, when the water/cement ratio and slumps were held constant, this was not found to be the case[3]. In those tests, changes in sand grading within the aggregate material had no effect on the compressive strength of the mortar or concrete. However, the mortar contained no more than 16 per cent minus 0,074 mm fines. In the present tests, the fine gradation of the tailings, even when altered to include 100 per cent sand, did not produce results that reflected previous findings about mortar characteristics; that is, the compressive strengths of total-gradation mill tailings changed when the slump and water/cement ratio were held constant.

In tests to increase the unconfined compressive strength of a total-gradation tailings material, there appeared to be an optimum water/cement ratio and grain-size gradation (Figure 5). At higher water/cement ratios (7 to 11), material gradation had little effect on the unconfined compressive strength. When the water/cement ratio was decreased to 4,42, the unconfined compressive strength more than doubled. At a water/cement ratio of 4,42, there was little significant effect except in that instance where the mix containing 50 per cent tailings represented an FM of 0,32, or a particle size of 50 per cent minus 0,074 mm.

Effects of Cold Material Temperatures

The effect of cold material temperatures on the unconfined compressive strength of cemented backfill was studied after questions arose as to the quality of the backfill that had been placed during the winter months at a particular mine site. Specifically, the mine uses partly deslimed, vacuum-filtered tailings for backfill material. The tailings average 8 per cent moisture and are stockpiled in a storage building

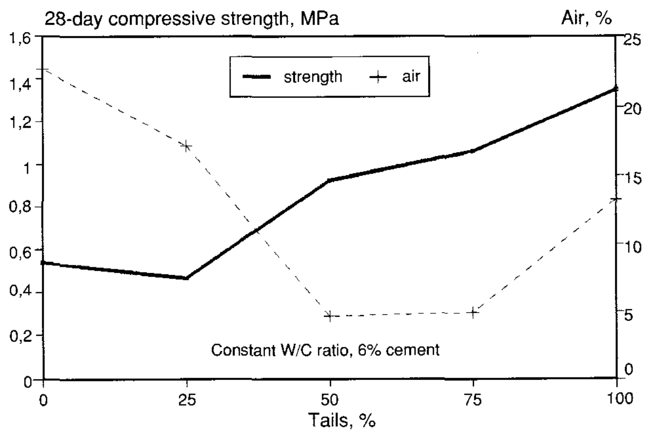


Figure 3. Effects of air volume on 28-day strength

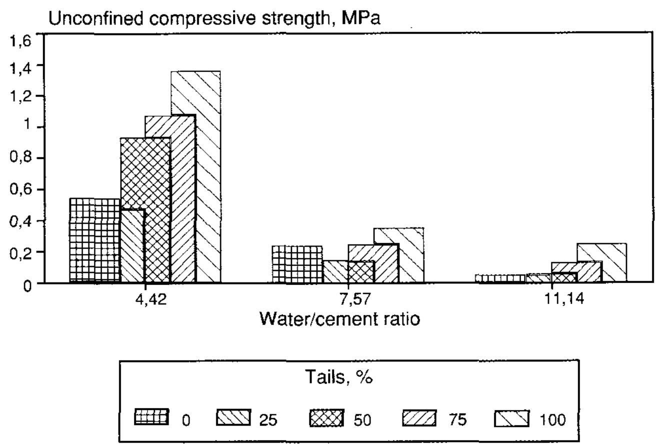


Figure 5. Effect of gradation changes on 28-day strength

until needed. Type I,II Portland cement is stored in an adjacent unheated silo on the surface. During the backfilling operations, cement is added to the stockpiled tailings in a batch mixer prior to being pumped underground; approximately 6 per cent cement is added to achieve the consistency of paste. Mix water from a nearby surface stream is added at the backfill plant in an amount equalling 15 per cent by weight of the total dry mix. During the winter months, the ambient air temperature may stay below 0°C for weeks at a time, and the stream is covered with ice.

Grab samples from the stockpile of mine tailings were brought to the laboratory, oven dried, and then stored with the cement in a freezer to simulate winter conditions prior to mixing. Type I,II Portland cement was used in this series of tests, and the mix water was iced prior to mixing. A backfill mix was batched using 10 per cent cement and a slurry density of 75 per cent, or 33 per cent moisture (weight of water/weight of solids).

Waxed cardboard cylinders, 7,6 cm by 15,2 cm, were used as test moulds. Six cylinders were filled with the backfill mix to provide two samples for unconfined compressive strength tests after 3, 7, and 28 days of fogroom curing. A seventh cylinder was also filled, and a thermistor was placed inside. The probe, as well as an ambient thermistor in the fogroom, was attached to an Endex data-acquisition module. Temperature readings of the sample and the ambient air in the fogroom were taken every 15 minutes for the first 24 hours, and then every 4 hours for 28 days. Figure 6 shows the rapid rise in sample temperature until it reached ambient conditions about 24 hours after being placed in the fogroom.

The results of the unconfined compressive strength tests are shown in Figure 7.

The control samples had been mixed at the same ratios as the cold-affected samples, but the materials were not frozen. Also, the control tailings, although gathered from the same covered stockpile at the mine site, had not been collected during the same sampling trip. There remains some concern that the tailings may have been different, either as a result of differences in gradation and/or source, since previous tests had confirmed that tailings from waste rock and ore produced different compressive strengths. The difference could also be due to the difference in the relative density of the tailings.

The initial temperature of the sample of backfill material was 5°C (Figure 6). Within the first 5 hours, the sample

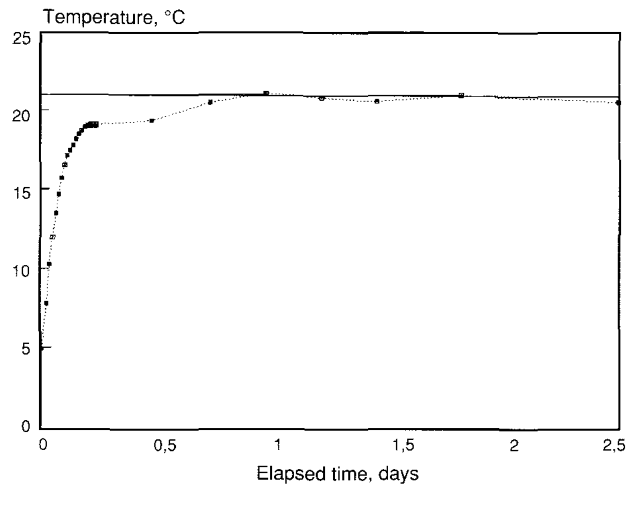
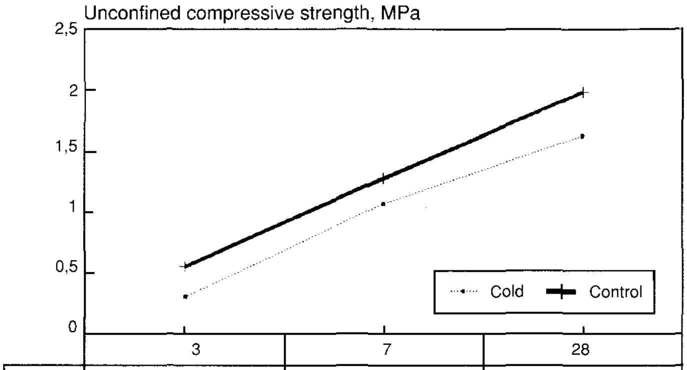


Figure 6. Sample and ambient temperatures



	3	7	28
Cold	0,3	1,07	1,63
Control	0,55	1,28	1,99

Elapsed time, days

Figure 7. Effect of cold material temperatures on the compressive strength of tailings mixes containing 10 per cent cement

temperature reached 90 per cent of the ambient room temperature and, between 5 and 20 hours, the sample reached equilibrium with the ambient room temperature. It is interesting that, even with 10 per cent cement in the mix, it was not sufficient to show elevated temperatures, which had been observed in the regular concrete samples during the entire 28 days of hydration.

When tested, the cold-affected samples produced lower compressive strengths than the control samples for all the curing days. The 3-day sample showed the most dramatic difference in that it gained only 54 per cent of the control sample's 3-day compressive strength. By 7 days, however, the cold-affected compressive strength increased to 83 per cent of the control sample's 7-day strength, which did not change during 28 days.

The rate of increase in compressive strength remained the same for both the cold and the control samples (approximately 35 per cent) during the period 7 to 28 days. This means that, even with tailings from different sources, the rate of increase for both tailings types was the same between 7 and 28 days. However, the rate of increase in compressive strength in the cold sample between 3 and 7 days was much greater than in the control sample (72 per cent for the former versus 57 per cent for the latter). This would indicate that, when materials are cold, the cementing process is retarded during the 3-day setting time. By the 7th day, the effects of cold are diminished but still produce lower strengths during 28 days.

Cold air and material temperatures are typically avoided in structural-concrete pours. If necessary, the mix water is heated and added to the cold aggregate before the cement is added. However, the heating of cement or the addition of hot water to cement can cause flash sets or premature hardening of the concrete[3].

Overview of Research on Mining with Backfill

The previous section detailing the test results obtained on tailings backfill describes one of four tasks funded by the Bureau's 'Mining With Backfill' project. The research in mining with backfill attempts to develop improved mining technology to maximize resource recovery by the use of improved backfill-transportation and -placement technology, backfill-pillar design, stress-monitoring instruments, and mine-system evaluations. The individual tasks associated with the 'Mining With Backfill' project are described in the following sections.

Transportation of Paste Backfill

The maximum delivery distance for paste-consistency backfill containing total mill-gradation tailings is limited by friction loss, which is a consequence of several variables, including tailings type, grain-size gradation, slurry concentration, aggregate and binder additives, pipeline diameters, and flowrate. Studies of backfill transportation have included full-scale pump-loop tests and, more recently, the development of a laboratory-scale pump-loop simulator.

The Bureau conducted six full-scale pump-loop tests on tailings from two mine sources representing two different gradation curves[2]. The pipeline, 149,4 m in length, utilized a positive-displacement pump to move material through pipe sections of 11,4 cm, 12,7 cm, and 15,2 cm diameter. These six tests included slumps ranging between 11,4 and 17,8 cm, representing slurry densities of 74 to 80 per cent. The cement concentrations ranged from 0 to 6 per cent.

Using friction-pressure gradients and experience gained from a study of the mechanics of pumping backfill materials, a prototype paste-pump simulator (PPS) was constructed and tested (Figure 8). The PPS requires only 0,11 m^3 of material as compared with 5,35 m^3 for the full-scale pump loop. The PPS consists of four short lengths of schedule-40 steel pipe 11,4 cm, 12,7 cm, 15,2 cm, and 20,3 cm in diameter. A four-piston plunger assembly with diameters corresponding to the pipe sections is attached to a crossframe mounted onto one end of a double-rod hydraulic cylinder. The paste 'plug' is contained within opposing pistons, which are computer-controlled. Differential pressures are measured against the programmed velocities. To maintain constant velocities during pressure measurements, the piston assemblies are allowed to accelerate, maintain a constant velocity, and then decelerate through each stroke.

To date, 13 PPS tests have been completed. The results of these experiments have been correlated with the findings of the full-scale pump-loop series and PPS shake-down tests. It must be stressed that the PPS is not a proven test apparatus. Tests are being conducted to determine the correlation between the PPS and full-scale pumping results. Future tests are planned to more accurately characterize and increase the pumpability of paste backfill and to improve the techniques for the characterization of the materials.

Methods of Measuring Pillar Loads

This task of the 'Mining With Backfill' project focuses on the determination of the accuracy and reliability of existing types of *in situ* instruments placed specifically within the abutments or pillars of a mine. Laboratory tests to date include a 30-day creep test of a CSIRO HI stress gauge. (Note: Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.) The gauge's mechanical properties and the effects of glue creep over time within a limestone block subjected to controlled axial loadings (Figure 9) were investigated. The purpose is to determine the gauge's suitability for long-term stress

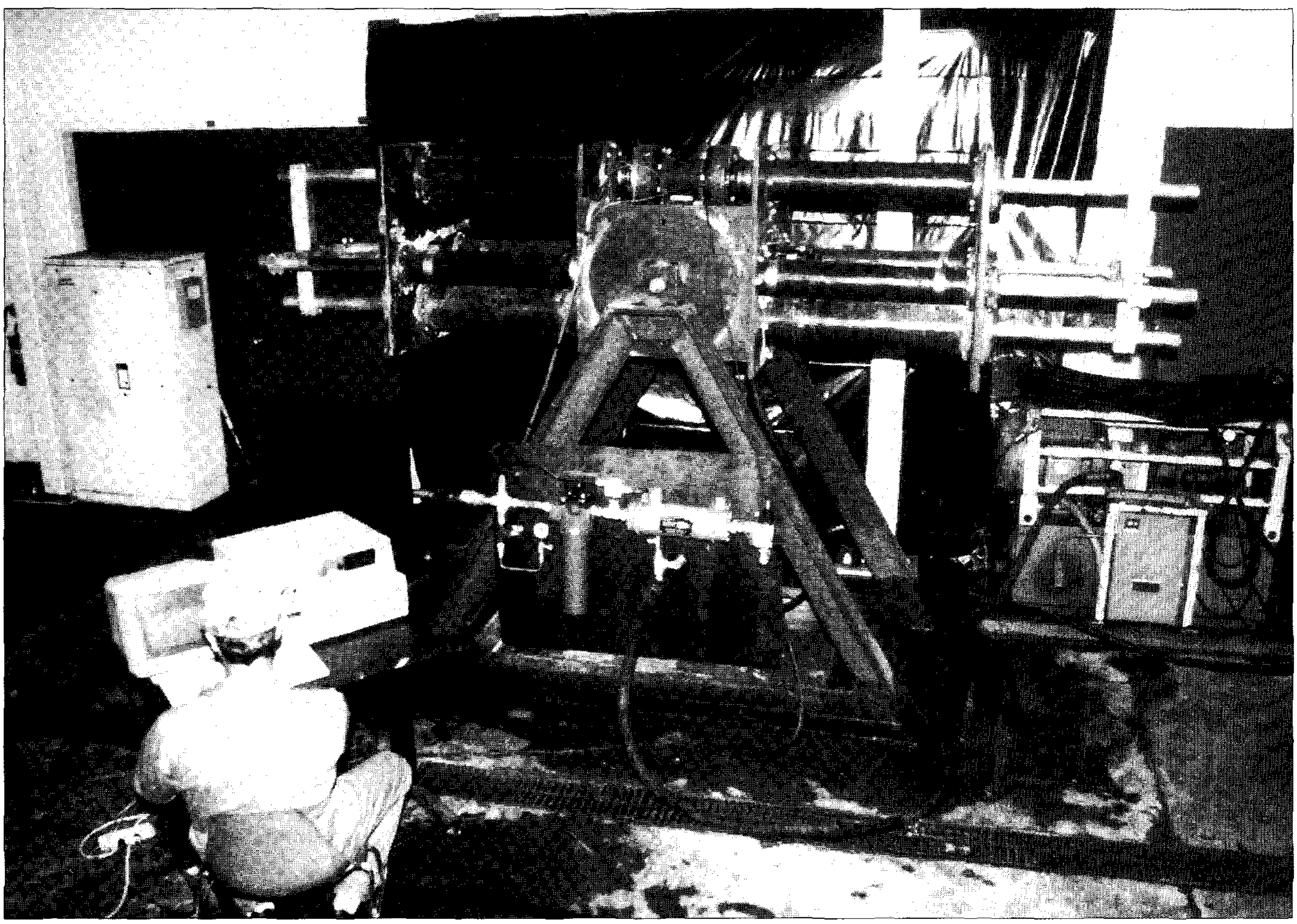


Figure 8. Paste-pump loop simulator

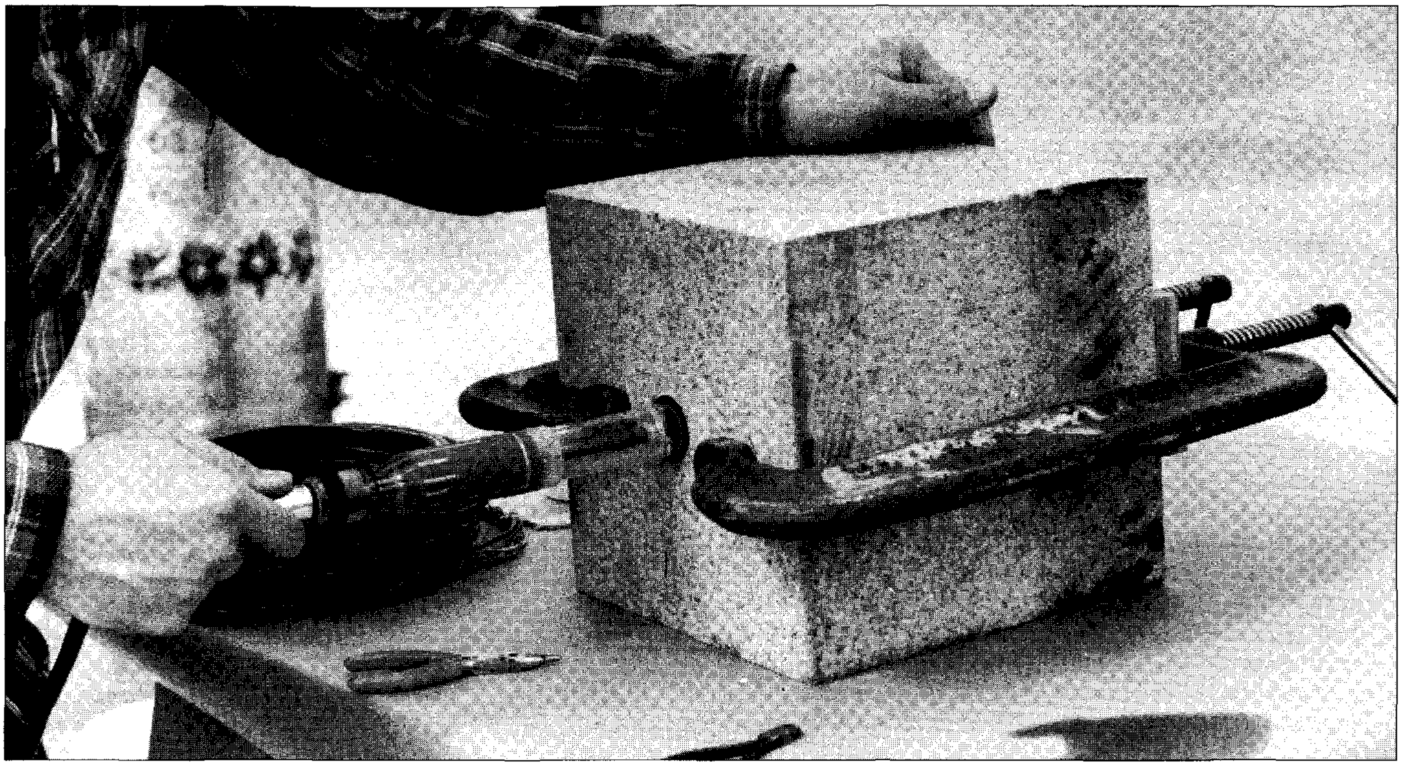


Figure 9. Installing the gauge for the glue-creep test

monitoring. The HI cell was originally developed to measure *in situ* stress during the brief time that a gauge is overcored.

Another area of interest has been the determination of the installation protocol and modifications required when *in situ* instruments are used within the constraints of an operating and dynamically evolving mine environment. Such constraints include the need to hand-cast cemented rockfill around pressure cells installed within a stope that is being backfilled. The *in situ* hand-casting procedure assured that materials of the correct modulus surrounded the cell and protected the instrument and cable from the backfilling operation. This function is especially critical when stopes are backfilled with rock.

Modifications have also been made to enhance the survivability and long-term reliability of extensometers after they have been installed. By the use of polyvinyl (PVC) casing and steel couplers, slip joints are created that allow the vertical extensometer's protective casing to become compressed during loading of the backfill. As the stope is backfilled, fill material is hand packed around the casing for stability[6].

Several different types of rock-stress measurement devices have been installed in a room-and-pillar mine prior to pillar-recovery operations. Installation procedures, operational characteristics, reliability, data-acquisition techniques, and data-analysis methods for several types of stress-measurement devices will be evaluated over time. Borehole deformation gauges, biaxial stressmeters, CSIRO hollow inclusion stress cells, and a CSIRO yoke gauge were installed in a rock abutment near the location of the mine's backfill/pillar-recovery project. These instruments will monitor abutment stresses during the pillar-recovery operation. In addition, borehole deformation gauges and hollow inclusion stress cells were overcored for the measurement of *in situ* stress.

Pillar and Backfill Interaction Models

Data gathered from the previously described task are used primarily as an input to this evaluation and computer analysis task. UTAH2, a two-dimensional, finite-element model, is being used in an investigation of the interface between backfill and rock pillars. *In situ* instruments have been installed at a slot-and-pillar rockfilled mine; at a pillar-robbing room-and-pillar mine; and, most recently, at a mine using cemented total-tailings backfill. These three types of backfill/mining configurations allow for comparative evaluations.

Through computer analyses, the mechanics of the backfill and pillar-support systems can be determined. This task demonstrates the usefulness of numeric analysis in the development of mining sequences, as well as providing a basic understanding of rock and backfill behaviour.

Project Coordination

Another Bureau investigation directly related to the 'Mining With Backfill' project is a project on the environmental impacts of backfill. The research was initiated to evaluate the hydrochemical impacts of the placement of mine-waste backfill. Water-quality impacts that can be attributed to the placement of mine-waste backfill are being investigated in three underground sulphide-metal mines. The study includes the impacts of three different backfill materials: cemented total-gradation tailings; uncemented, classified sand; and uncemented, low-grade gob. Specific research considerations are the contamination potential of the three backfill materials in an underground environment, the mechanisms of groundwater flow through or around backfilled mine areas, and possible remedial measures to mitigate the impacts of backfill.

Chemical analyses of water samples collected underground, and assays of backfill materials and the rock surrounding backfilled stopes, constitute the data. Water samples are gathered from seepages both above and below the targeted backfilled stope. The concentrations of major ions and trace metals are compared between sites to identify differences that can be attributed to the backfill material. Interactions between backfill materials and water, and between in-place rock and water, form the basis for the development of hypotheses about the evolution of water quality at the field sites.

Summary

Several series of tests were conducted to determine whether common assumptions about concrete and mortar can be applied directly to cemented-tailings materials. In previous Bureau tests, water/cement ratios ranged between 4,0 and 10,0. Water/cement ratios for concrete are seldom more than 1,0; suggested ratios lie between 0,45 and 0,58. This great disparity makes direct comparisons between the characteristics of concrete and cemented-tailings materials questionable. A key difference between cemented tailings and concrete is the broader range of aggregate size in concrete mixes, typically minus 1,27 cm.

When the water content is kept constant, an increase in the fines content of clean sand materials decreases the strength. However, after the mixture reaches 50 per cent fines, the strength increases well beyond that of a mix containing only sand. This is probably as the result of less free water (water being taken up with the increased surface area of the finer particles) and the better gradation range of the mix.

In test comparisons of the air volume in mixes of tailings and sand, the compressive strengths tended to increase continuously with increased amounts of tailings, regardless of the volume of air. This would suggest that air voids would not be a good predictor of compressive strength.

Assumptions relating FM to compressive strength in concrete were found to be different when cemented tailings materials were used. In concrete, changes in the FM had no effect on the compressive strength. With cemented tailings, as the FM decreased (to 100 per cent fines), the compressive strength increased. In this test, as in the concrete tests, the slump and water/cement ratios were kept relatively constant, suggesting constancy in the workability or flowability of the mix.

For the gradation ranges between sand and fines, a water/cement ratio of less than 7,5 produces optimum compressive strengths. It is postulated that a water/cement ratio of more than 7,5 results in excessive bleeding and segregation of the added cement, while the lower limits of the ratio are bounded by transportation requirements such as pumpability.

The use of cold cemented-tailings materials results in decreased compressive strength. This was most evident before the mix had cured for 7 days; that is, the strengths were half those of the control mix. At 10 per cent cement content, the mix temperature rebounded to ambient temperature within 1 day, and did not rise further during 28 days of curing. This would indicate that the masses of most cemented tailings would not create heat of hydration and its associated problems. Care must be taken that heat or oxygen deprivation caused by sulphide oxidation within the backfill is not ignored[7].

The results presented in this paper were accomplished under the Bureau's 'Mining With Backfill' project. The goals of this multi-tasked project are to characterize total-gradation tailings backfill, develop a laboratory-scale paste-pump simulator, refine the suitability and installation protocol of field instruments, and improve the simulation and prediction capabilities of mathematical models.

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