POST-PEAK RESPONSE OF UNCONFINED CEMENTED ROCKFILL

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ABSTRACT
Cemented Rock Fill samples, 450 mm diameter by 900 mm high, were tested using a very stiff loading frame which allowed the detailed post-peak response of the samples to be captured. Such post-peak response is generally not appropriately captured by commercial test frames, which are too soft and fail the sample uncontrollably in the post-peak regime. The samples demonstrated surprising ductility, which has important implications for geomechanical design of underground mines.

RÉSUMÉ
Les échantillons cimentés de roches, diamètre de 450 millimètres par 900 millimètres de haut, ont été examinés en utilisant une armature très raide de chargement qui a permis à la réponse détaillée de post-crête des échantillons d'être capturée. Une telle réponse de post-crête généralement n'est pas convenablement capturée par les armatures commerciales d'essai, qui sont trop molles et échouent l'échantillon incontrôlablement dans le régime de post-crête. Les échantillons ont démontré une ductilité étonnante, qui a des implications importantes pour la conception géotechnique des mines souterraines.

1. INTRODUCTION

Cemented Rock Fill (CRF) is one technique for supporting mined-out openings in underground mining. The Unconfined Compressive Strength (UCS) test is the most common basis for comparing strengths of lab-prepared CRF samples, owing to the logistical complexities of attempting to conduct triaxial tests on such samples. A common heuristic used in strength testing is that the sample diameter should be at least 10 times the largest aggregate size. The CRF samples are generally 450 mm diameter by 900 mm height, even though aggregates exceeding 45 mm diameter are common (Figure 1). As a result it is likely that a 450 mm diameter sample still incorporates some size effect, and is probably generally stiffer and stronger than a larger sample would be.

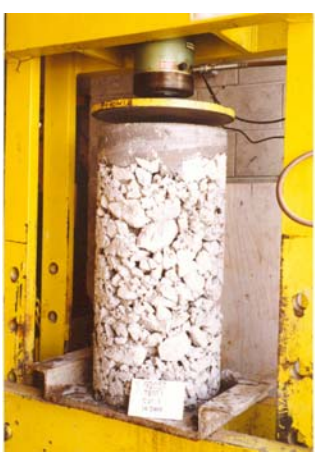

Figure 1. A typical 450 mm diameter by 900 mm high Cemented Rockfill Sample being tested for Unconfined Compressive Strength using a commercial test frame.

Even a 450 mm diameter CRF sample, however, requires considerable total load for failure in uniaxial compression. The few frames that are available in commercial testing facilities are generally constructed from steel sections and the load is applied using a hydraulic jack (Figure 1). Although these frames may appear substantial, they in fact can be relatively soft compared to the stiffness of the sample being tested. It is well established in materials testing that such frames store appreciable strain energy prior to the peak load of the specimen, and that when the specimen goes into the post-peak regime the frame can unload its strain energy into the sample in an uncontrolled manner, such that the true post-peak response of the sample is not adequately captured. Therefore, the commercial test frames are generally suitable for evaluating the UCS of the CRF specimen (which is their primary purpose, of course), but they do not provide useful information regarding the post-peak behaviour of the CRF, which may also be important in geomechanical design. This paper examines the behaviour of some CRF specimens that were tested using a much stiffer loading system. Detailed post-peak response of the CRF specimens is captured and shows a surprisingly ductile response. This can have positive implications for geomechanical mine design.

2. DESCRIPTION OF CEMENTED ROCK FILL TESTED IN THIS STUDY

The mine's CRF is comprised of aggregates, binder, and a hydration retarder to prevent setting of the mix during transport underground. The aggregate is produced from a surface quarry operation that passes material through crushers at 6" maximum clearance (Table 1).

Table 1. Typical Particle Size Distribution for Aggregates in the Mine's CRF

SEIVE	Cumulative Weight kg	Cumulative % Retained	Cumulative % Passing
6"	0.00	0.0%	100.0%
3"	55.95	17.1%	82.9%
2"	113.55	34.7%	65.3%
1"	207.35	63.4%	36.6%
¾"	235.25	71.9%	28.1%
½"	260.50	79.6%	20.4%
3/8"	272.75	83.4%	16.6%
# 4	289.20	88.4%	11.6%
#8	297.35	90.9%	9.1%
Pan	327.15	100.0%	0.0%

For this study, the crushed rock was cemented with 4.2 wt-% binder (weight of dry binder components divided by weight of dry crushed rock). The dry binder components were mixed to form a 54 wt-% slurry (weight of dry binder components divided by weight of binder and water), and Delvo, a hydration retarder, was added at a rate of 200 ml per 100 kg of binder.

2.1 Sample Preparation Procedure

The following procedure was used to prepare the CRF at a remote site, prior to casting at the University of Toronto laboratories:

1) Mix slurry in a separate container for 6-7 minutes, using the following quantities: binder, 6.30 kg; Mix Water, 5.40 kg; Delvo Admixture, 12.6 ml.
2) Load the mixer with 150 kg rockfill material.
3) Spray the slurry on the surface of the rockfill material.
4) Tumble and mix the rockfill material and the slurry mix to simulate the mixing action used in the mine's standard operating procedure. One minute in mixer was used to simulate 11 minutes in the mine's operation.
5) Load the containers for delivery to the University of Toronto laboratory (approximately 45 minutes in transit).

Approximately 10 batches (+1,500 kg) of material was required to create five specimens.

Five samples were created as follows. First, the bottom 75 mm (approximately) of each of five sonotubes were cast with a concrete mix of about 25 MPa. The purpose of this mix was to form a bottom loading cap for each specimen. Truckload of CRF mix were delivered to the University of Toronto laboratories in 20 litre pails. For each specimen, two pails of mix at a time were dumped into the sonotube and rodded for two to three minutes to ensure consolidation representative of probable field conditions. About four or five lifts per specimen were required. Concrete top caps (with the same concrete capping mix as the bottom caps) were cast on all 5 specimens (Figure 2). Specimens were then left to cure with polyethylene sheets placed over them after setting. The top caps were approximately 100 mm thick, with one being about 150 mm thick (the general thickness depending on the amount of stone that was cast into the sonotube and their arrangement within the sample).

Figure 2. Top: Preparing specimens for top capping. Middle: A specimen just before top capping applied. Bottom: A specimen just after top capping applied.

The casting frame (shown in Figure 2) was carefully constructed so that the axis of each specimen would be perpendicular to its base, to within about 0.2° (or 1/8" horizontally over the sample's 36" height). However, in order to ensure as close a match as possible between the top of the sample and the loading plate, the following procedure was used. The load frame was fitted with a loading plate fixed to the frame through a spherical seat, which ensures that the applied load will remain vertical even if the top of the sample is not perfectly horizontal, either at the start or at any point during testing. Each sample was moved into position under the loading plate and capped with a Plaster of Paris thincoat (Figure 3(top)). The loading plate was lowered to just bear on the thincoat during setting (Figure 3(middle)), thereby ensuring the most exact contact possible between the loading plate and the specimen's top end cap. Curing of the thincoat takes about one-half hour. The sonotube was then removed, and the specimen was tested.

Figure 3. Top: Placing Plaster of Paris thincoat about ½-hour prior to loading. Middle: Placing loading plate on thincoat before setting. Bottom: A specimen ready to be tested.

3. DESCRIPTION OF TESTING FRAME

The testing frame used is a load-controlled Baldwin-Lima-Hamilton Universal Testing Machine (S/N 044-1943) with 1,200,000-pound maximum capacity. It is equipped with a load transducer in the loading head, and a displacement transducer which measures changes in the clearance between the loading head and the floor of the machine on which the specimen sits. For data recording purposes, the machine was set to the 240 kip load range (except for specimen 5 when it was switched to the 1200 kip range partway through the test) and 2" displacement range.

The loading head can be rapidly raised and lowered using large diameter threaded transfer rods. During testing, however, these rods do not actively move the loading head, rather, hydraulic rams apply thrust through the rods which then transmit load to the head and, finally, to the specimen itself. This configuration results in an anomaly in the generated load-displacement curve, discussed in the next section.

3.1 Key Load-Displacement Characteristics

Before the specimen is put into place, the threaded transfer rods carry the entire weight of the loading head. As the specimen is loaded, however, the weight of the head is gradually transferred from the rods to the specimen. When the specimen carries the entire weight, the threaded transfer rods travel a distance equal to the clearance between the threaded portions of the rods and the corresponding portions of the head – about 0.04” (1 mm) (Figure 4). This travel is accompanied by no change in the load cell, and the load cell reading corresponds to the weight of the loading head – about 45 kips (200 kN). A final presentation of the load-displacement curve (or corresponding stress-strain curve) should therefore be modified to correct this known anomaly.

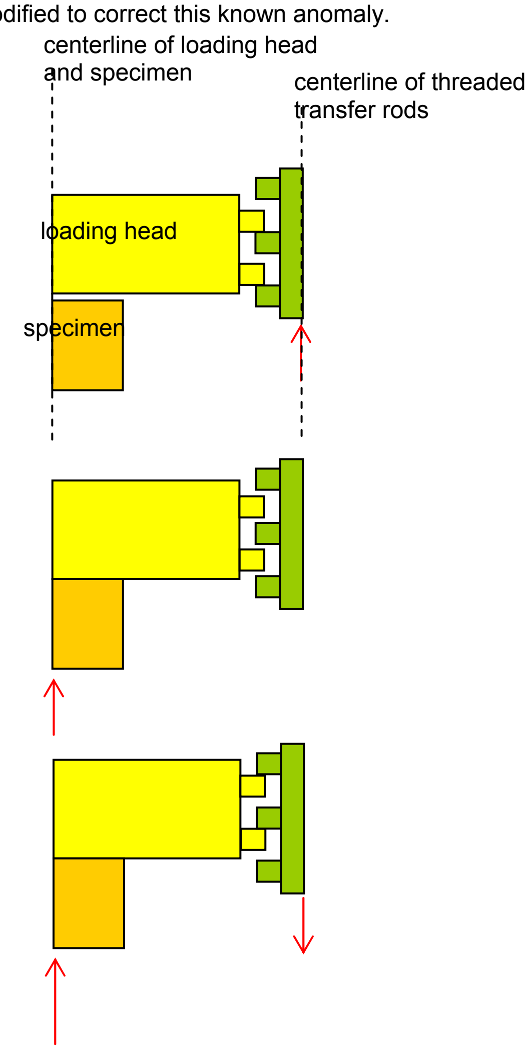

Figure 4. Simplified diagram illustrating the known “displacement anomaly” in the Baldwin 1.2M-lb frame. Top: Prior to loading, weight of loading head carried by threaded transfer rods only. Middle: When specimen carries full weight of loading head, “displacement anomaly” takes place while rods move through ~0.04” clearance. Bottom: On continued loading, specimen bears weight of loading head plus load applied by hydraulic rams through transfer rods.

Load controlled systems, such as the Baldwin frame used in this study, are generally not used to determine the post-peak response of strain softening materials (i.e., materials exhibiting a peak and subsequent decaying load-bearing capacity with continued straining). Rather, stiff servo-controlled hydraulic systems are typically employed. In this study, however, the Baldwin test frame is actually extremely stiff as compared to the post-peak response of the CRF specimens. This total machine stiffness is measured in terms of two critical components: first, the elastic stiffness of the structure; and second, the ability of the hydraulic pump to maintain pressures and flowrates sufficient to maintain any operator-prescribed load. At the start of the tests it was assumed (without rational calculation) that only the peak loads would be identified, and that the machine's stored strain energy would subsequently be released violently, destroying the sample. It turns out, however, that the samples' post-peak responses were captured rather well, probably because the machine is so much stiffer than the specimens, and because the hydraulic system apparently takes sufficient time to build up the incremental pressures and volumes in the loading rams that have been lost upon incremental specimen failure and strain increase. Given the rationale just presented, and given the apparent nature of the loading frames typically used by commercial testing facilities (Figure 1), it is unlikely that the commercial facilities' lighter frames are able to adequately capture the described post-peak behaviour.

Finally, for some of the load-displacement curves near the end of loading, a small (less than 10 kip, or 45 kN) sudden drop in load can be noted. This is where the operator has manually slowed the hydraulic pump, in preparation for rapid raising of the loading head using the threaded transfer rods.

4. TEST RESULTS

Specimens were tested at 28 days. All of the specimens exhibited an initial linear load-displacement behaviour, pre-peak nonlinearity, and post-peak ductility (Figure 5).

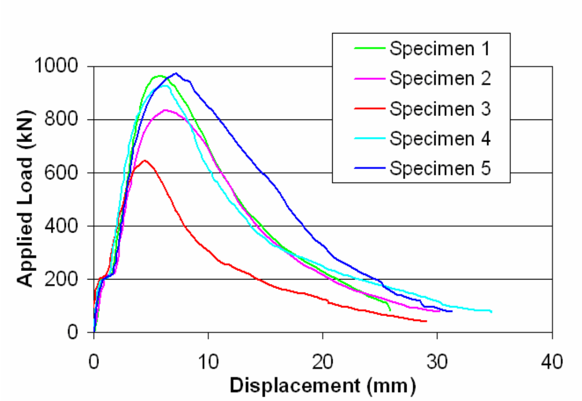

Figure 5. All load-displacement curves.

The calculated UCS values were, in rank order, 3.92 MPa (Specimen 3), 5.11 MPa (Specimen 2), 5.67 MPa (Specimen 4), 5.87 MPa (Specimen 1), and 5.97 MPa (Specimen 5), giving a range of 3.92 – 5.97 MPa with an average of 5.31 MPa.

During testing, only very minor cracking was audible at or near the peak load, and prior to the peak virtually no visible cracks could be distinguished from a distance of a few meters. All significant audible cracking, crack formation, and spalling occurred at significantly reduced post-peak load bearing capacities. Greater detail cannot be provided, however, as no formal methods were arranged a priori to quantitatively correlate post-peak load bearing capacity with observations of specimen behaviour. A composite of all load-displacement curves is given in Figure 5. Images of the post-peak response of the specimens tested are shown in Figure 6.

Specimen #1

Specimen #2

(continued on next page…)

Specimen #3

Specimen #4

Specimen #5

Figure 6. Images of samples after strength testing.

5. DISCUSSION OF POST-PEAK SAMPLE BEHAVIOUR AND SIGNIFICANCE

In underground mining, the function of the CRF is to support the host rock surrounding the mined out openings during continued stages of mining. The loading in these situations arises from two primary sources: essentially static load transfer as greater extraction ratios are achieved in proximity to the CRF filled stopes; and essentially dynamic load transfer due to rockbursting. In the case of shock loading, the ductile post-peak behaviour of the CRF is important as a mechanism by which energy may be absorbed. Under static conditions, the ability of the material to undergo relatively large strains and continue to carry load with minimal spalling is advantages in situations where the fill faces into a recently mined excavation. Here, the mining engineer wants to prevent the fill from undergoing sidewall failures that then dilute the ore being hauled from drawpoints below. The demonstrated post-peak ductility of the tested CRF is therefore seen as an important contribution of the study.

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