A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Department of Civil Engineering
University of Toronto

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Abstract

Underground mining can be summarized as the removal of economically viable volumes of rock which creates underground voids. In order to optimize ore extraction, a material is used to backfill these openings prior to creating any adjacent openings. The use of cemented paste backfill (CPB), a mixture of mine tails, water, and cement binder, has gained prominence as it not only provides a material that has engineered strength and can be deployed rapidly, but also decreases the surface storage volume of the mine tails.

There is limited knowledge about the behavior of the stresses within the CPB during the filling of an underground opening, particularly during the early curing ages of the hydrating CPB which is critical to the design of fill barricades. This thesis presents a design procedure which can be used to determine the in situ stresses within the CPB.

Three methodologies were used in the development of this design procedure. The first was to develop a laboratory testing method that determined the time-dependent consolidation characteristics and strength parameters of the hydrating cemented paste material. The second was to collect several field-data sets. The third methodology was
to numerically model the CPB using Itasca’s FLAC3D, which incorporated the underground void’s geometry, backfilling strategy, and time-dependent backfill parameters in order to determine the in situ stresses of the CBP. This simulation allowed for the prediction of both total and effective stress throughout the stope.

The model and the laboratory results were used to model the stresses in several test stopes so that a comprehensive comparison could be made between the model and field instrumentation results. Four case studies were examined using a total of six different field instrumentation datasets. The results from these case studies showed that the modeling approach, given some model calibration, is capable of quantitatively representing the important geomechanical aspects of paste filling and curing.
Acknowledgements

John Donne once wrote “No Man Is an Island unto Himself” and no truer words have ever been spoken, especially as regards the completion of a research PhD. An enormous debt of gratitude is owed to many. Let me begin with my thesis supervisors, Dr. W.F. Bawden and Dr. M. W. Grabinsky, because, without their advice, assistance, and support, this project and my particular research contribution might not have been possible. Thank you, Will, for encouraging me to apply to graduate school and for being an extraordinary sounding board. Your pragmatic design approach to both field and academic work is an inspiration. Thank you, Murray, for your assistance, reviews, and suggestions and for providing me with reality checks along the way.

To the graduate and post-doctoral students at the University of Toronto, you have been wonderful colleagues. Thank you as well to Dr. A. Coulson for taking me under his wing when I first arrived at UofT and to Dr. D. Simon for her dedication and assistance in the geotechnical lab. A great deal of the laboratory testing of this thesis would not have been possible without my summer students, Mr. R. Malik and Ms. M. Moore, who spent many long hours working with the shear box.

Field work comprised another critical and labour intensive component of this research and for his cheerful and constant assistance, I am grateful to Dr. B. Thompson.

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<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>BC</td>
<td>Boundary Conditions</td>
</tr>
<tr>
<td>C_a</td>
<td>Preconsolidation Index</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Assisted Drawing</td>
</tr>
<tr>
<td>CBI</td>
<td>Çayeli Bakır Isletmeleri A.S.</td>
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<tr>
<td>C_c</td>
<td>Compression Index</td>
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<td>CMS</td>
<td>Cavity Monitoring Survey</td>
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<td>CNS</td>
<td>CBI Non-Spec Ore</td>
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<tr>
<td>CNS 6.5</td>
<td>CBI Non-Spec Paste with 6.5% Binder</td>
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<tr>
<td>CPB</td>
<td>Cemented Paste Backfill</td>
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<td>C_r</td>
<td>Recompression Index</td>
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<td>CRF</td>
<td>Cemented Rock Fill</td>
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<td>CBI Spec Paste with 6.5% Binder</td>
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<td>CS 8.5</td>
<td>CBI Spec Paste with 8.5% Binder</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
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<tr>
<td>C_v</td>
<td>Coefficient of Consolidation</td>
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<td>DSB</td>
<td>Direct Shear Box</td>
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<tr>
<td>e</td>
<td>Void Ratio</td>
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<tr>
<td>Fe</td>
<td>Iron</td>
</tr>
<tr>
<td>g</td>
<td>acceleration of gravity (9.81 m/s²)</td>
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<tr>
<td>G</td>
<td>Shear Modulus</td>
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<tr>
<td>hrs</td>
<td>hours</td>
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<tr>
<td>HS</td>
<td>Horizontal Stress</td>
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<tr>
<td>K</td>
<td>Bulk Modulus</td>
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<tr>
<td>k</td>
<td>Coefficient of Permeability</td>
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<tr>
<td>KIDD</td>
<td>Kidd Mine</td>
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<tr>
<td>KIDD 2.5</td>
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<td>KIDD 4.5</td>
<td>Kidd Mine Paste with 4.5% Binder</td>
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<tr>
<td>kPa</td>
<td>Kilopascals</td>
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<tr>
<td>LDT</td>
<td>Linear Displacement Transducer</td>
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<tr>
<td>LHS</td>
<td>Left Hand Side</td>
</tr>
<tr>
<td>log-σ_n</td>
<td>Lognormal Scale of Normal Stress</td>
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<tr>
<td>M</td>
<td>Confined Compression Modulus</td>
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<tr>
<td>M-C</td>
<td>Mohr Coulomb Failure Criterion</td>
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<tr>
<td>m</td>
<td>meters</td>
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<tr>
<td>min</td>
<td>minutes</td>
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<td>m_v</td>
<td>Coefficient of Volume Compressibility</td>
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<td>m</td>
<td>Lead</td>
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<td>m</td>
<td>Portland Cement</td>
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<td>PP</td>
<td>Paste Plant</td>
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<td>PWP</td>
<td>Pore Water Pressure</td>
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<td>PZ</td>
<td>Piezometer</td>
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<tr>
<td>RHS</td>
<td>Right Hand Side</td>
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<tr>
<td>RRA</td>
<td>Rise Rate A (or B etc.)</td>
</tr>
<tr>
<td>s or sec</td>
<td>seconds</td>
</tr>
<tr>
<td>SD</td>
<td>Specific Discharge</td>
</tr>
<tr>
<td>SG</td>
<td>Specific Gravity</td>
</tr>
<tr>
<td>S</td>
<td>Degree of Saturation</td>
</tr>
<tr>
<td>TEPC</td>
<td>Total Earth Pressure Cell</td>
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<tr>
<td>UCS</td>
<td>Unconfined Compression Strength</td>
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<tr>
<td>UG</td>
<td>Underground</td>
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<td>University of Toronto</td>
<td></td>
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<tr>
<td>VS</td>
<td>Vertical Stress</td>
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<td>VWT</td>
<td>Vibrating Wire Transducer</td>
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<td>Zinc</td>
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<tr>
<td>γ_w</td>
<td>Unit Weight of Water</td>
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<tr>
<td>ν</td>
<td>Poisson's Ratio</td>
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<tr>
<td>ρ</td>
<td>density</td>
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<tr>
<td>φ</td>
<td>Friction Angle</td>
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CHAPTER 1
Introduction

Underground mining can be summarized as the removal of economically viable volumes of rock. This removal, in turn, creates underground voids, but different mining methods will produce different types of voids. In this thesis all voids will be referred to as stopes. Stopes are typically designed to maximize size while retaining stability, i.e. the stope is made the biggest size possible while remaining stable until both the mucking and backfilling operations are completed. See Figure 1.1 for a simplified schematic of a primary-secondary sequence stope panel in a steeply dipping, long, tabular ore-body. Primary stopes are removed before the secondary stopes. Once the primary stopes are removed, it is inadvisable to remove the secondary stopes unless the primary stope walls are supported by some form of backfill. There are several types of backfill, including hydraulic fill and cemented rockfill (CRF), but this thesis will concentrate on cemented paste backfill (CPB).

The use of CPB has become a popular backfilling method and has started to replace both CRF and hydraulic fill as the preferred backfill material for underground mining operations. This popularity is due to its high delivery rate, versatility, engineered strength, and its usefulness for reducing the amount of tails that need to be stored above ground. At its most basic composition, CPB consists of thickened mine tails, binder, and water. However, there are
A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

1.0 INTRODUCTION

STOPE SCHEMATIC

Figure 1.1
numerous options for binder types, binder additives, and additional aggregates, all of which can allow the mining engineer to customize the design of CPB as needed.

CPB fulfills several functions. As stated above, once it is in place, it provides ground support and allows for maximum ore recovery. An additional benefit is the disposal of mine tails underground decreasing the area needed for, and the amount of risk associated with, surface disposal. This backfill has to be self-supporting and able to remain standing when the backfill loses its confinement when the secondary stopes are removed. This confinement will only be regained once the secondary stopes are backfilled.

There is limited knowledge about how the CPB behaves during the filling of an underground opening, particularly during the early curing ages of the CPB. This lack of understanding poses several problems for mining engineers, including how to design backfill barricades and how to define backfilling procedures. For instance, most mines use a two staged pour which is divided into a plug pour and a stope pour. This pouring strategy is a holdover from the use of hydraulic sand-fill. When backfill is poured into a stope, a barricade prevents the backfill from entering the rest of the mine through the undercut. The plug pour is created by filling the stope to a height that is typically two meters above the brow. The brow is the where the back of the undercut drift and the stope body meet. Once the plug is placed, the pour stops, usually for 3 to 7 days, to allow the plug to cure and gain strength. This delay and subsequent backfill strengthening is used to protect the barricade when the rest of the stope is filled (stope pour). Figure 1.1 depicts the location of the barricade, the plug pour, and the stope pour. There is a significant potential for cost savings if mines can reduce their cure times or, ideally, move to a continuous pour procedure (i.e. do not pour a plug). However, this is not possible unless two things are known: the pressure that the barricade can withstand and the pressure the barricade will experience.

The pressure at the barricade is dictated by a range of parameters including: binder content, binder type, tailings type, additional aggregates, rise-rate, stope geometry, etc. With an increased understanding of how early CPB behaves, barricade designs can be refined and made more cost effective, and pouring strategies can be streamlined. However, these cost savings cannot be realized unless there is a practical and reliable method for determining what stresses the backfill barricade will experience.
1.1 Economics of Cemented Paste Backfill

As many mining decisions are based on economics, a basic economic analysis comparing staged and continuous pours was devised based on a fictional gold ore-body. This section will present only the conclusions from this analysis. For more information, including assumptions and input parameters, refer to the economics memo in Appendix 1.

In this theoretical ore body, the basic difference between the continuous and staged pour for a two-stope sequence was that the continuous pour needed only 12 days to complete the sequence whereas the staged pour needed 18 days. Note that this analysis assumes serial mining, meaning that only one stope can be mined at a time. This means that, over a year, a mine using continuous pouring methods could access 60 stopes while a staged pour system could access 40 stopes. If there were 600 stopes available to mine, the continuous pour mine would have a mine-life of 10 years while the staged pour mine would have approximately 15 years of life.

Each mining method generated the same amount of non-discounted revenue, as the same ore body is being mined. In this example the amount is around $350 million. However, when the revenue from the stopes is discounted, it is found that the continuous pour mine’s revenue is around $215 million while the staged pour revenue is $175 million. This is a difference of $40 million.

This simple example demonstrates the advantage of continuous pouring: by decreasing the discounting time, more revenue is made faster.

1.2 Purpose of Thesis

The purpose of this thesis is to develop a design process which would help mining operations predict the stresses that early age CPB exerts on a barricade during the backfilling process. Mining engineers could then use this process to determine which stopes could be poured continuously and which stopes need to be poured in stages. Even if a staged pour was necessary, this approach would allow the mine engineer greater control over the curing times of the staged pour.

This thesis is part of a larger research project being conducted by the University of Toronto, involving three different mine sites. This project involved the installation of in situ instrumentation in a series of test stopes. This instrumentation was monitored as the stopes were
filled. More detailed information for each mine site is presented in Section 1.3 of this chapter while instrumentation details are presented in Chapter 5.

1.2.1 Thesis Objectives

The overall thesis objective, to develop a means for determining the in situ stresses within the CPB, can be broken into sub-objectives:

- Conduct a review of the past and current methods for modeling CPB or CPB-like materials.
- Quantify the time-dependent strength and deformation behaviour of seven different CPB streams by conducting a laboratory program consisting of modified consolidation and direct shear box tests.
- Develop a numerical model using an established commercial numerical analysis code with the following capabilities:
  - be able to account for the time-dependent behaviour of the paste,
  - have the ability to replicate different filling rates,
  - have the ability to use complex 2D and 3D geometries, and
  - have the ability to model multiple paste mix designs within a stope.
- Conduct a validation exercise of the model using the laboratory results to demonstrate the model’s capacity to meet the four criteria mentioned above.
- Conduct stope scale numerical modelling of six instrumented test stopes. Each stope will be modelled using its individual input parameters (physical and laboratory). The model results will then be compared to the test stope instrumentation results to determine the predictive capability of the model.

1.2.2 Outline of Thesis

Chapter 1 provides an introduction of the project and presents background information on each participating mine.

Chapter 2 provides background data on current knowledge dealing with time-dependent behaviour of CPB and both analytical and numerical modelling approaches for determining CPB behaviour.
Chapter 3 presents the results from the laboratory testing program, including comparisons between the different pastes used at each mine as well as a project-wide comparison. The methodology and procedures for the testing are also presented in this chapter.

Chapter 4 contains the methodology for the creation of the model and presents and discusses the results of the model validation.

Chapter 5 presents the modelling results for five case-study stopes. The geometry, instrumentation, and rise-rate for each stope will be presented and discussed. Each stope will be modeled both in 2D and 3D.

Chapter 6 provides a brief summary of the conclusions and provides recommendations for future work arising from this thesis.

### 1.3 Background Information

This section presents the details of each mine including the locations, number and type of stopes, and binder types. There are six case-study stopes from three mines involved in the study. The mines involved are the Çayeli Bakir Mine, the Williams Mine, and the Kidd Mine. The naming convention for different paste stream is the name of the mine and the binder percentage (e.g. Williams Mine paste with three percent binder is WILL 3). For more details pertaining to the individual stopes refer to Chapter 5.

#### 1.3.1 Çayeli Bakir Mine

Çayeli Bakir Isletmeleri A.S. (CBI) is owned by the Inmet Mining Corporation. The mine is located near the town of Çayeli in the Rizé Province of Turkey. Figure 1.2 shows the location of the mine. Çayeli is located on the Black Sea coast, about 60 km east of the provincial capital of Rizé and 90 km west of the Georgia/Turkey border. The mine is located about 10 km southeast of Çayeli.

CBI is an underground mine producing primarily copper but it also produces some zinc. The ore body consists of two different ores, spec and non-spec, with the spec ore being less zinc rich and non-spec being zinc rich. These two ores meant two different tailings and paste types. The abbreviation for Çayeli Spec paste is CS while the abbreviation for non-spec tailings is CNS.

Four test stopes were instrumented at CBI: two were completed in 2008 while two were completed in 2011. The first stope filled was designated 685 N22 and contained two paste types:
A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

1.0 INTRODUCTION

LOCATION OF ÇAYELI BAKIR ISLETMELERİ A.S.

Figure 1.2
CS 8.5 for the plug pour and CS 6.5 in the remainder of the stope. The other stopes were designated 715 N18, 715 N22, and 745 N5. All of these stopes contained only CNS 6.5 paste.

1.3.2 Williams Mine

The Williams Mine is owned by the Barrick Gold Corporation. It is located in the Hemlo mining camp and is about 30 km east, from the Northern Ontario town of Marathon. The location of Marathon and the mine are shown on Figure 1.3.

Williams Mine produces gold from both underground workings and an open pit operation. It produces one type of tailings which consists mainly of processed ore from the open pit. One stope (9500 L70-5) was instrumented and filled at the Williams Mine during 2010.

1.3.3 Kidd Mine

The Kidd Mine is owned and operated by Xstrata Copper Canada. It is located about 30 km north of the Town of Timmins in Northern Ontario. The location of Timmins and the mine are shown on Figure 1.4.

Kidd Mine is a copper/zinc producer with all production being obtained from underground workings. However, the mine originally started as an open pit, which was exhausted in the 1980s, after which mining operations went underground. Kidd is the one mine in the project that does not use its own tailings as a constituent of the CPB used underground. This is due to the distance between the mine and processing plant. The mine uses tailings from an abandoned gold mine located closer to the mine site. Kidd’s paste recipe also calls for sand from a nearby esker added to its CPB. The ratio of sand and tails is 55:45. A long-hole stope (67 SL1) was filled during 2008 using KIDD 4.5 in the plug pour and KIDD 2.5 in the remainder of the stope.
A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

1.0 INTRODUCTION

LOCATION OF WILLIAMS MINE

Figure 1.3
1.0 INTRODUCTION

A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

LOCATION OF KIDD MINE

Figure 1.4
Cemented Paste Backfill (CPB) arose from combining traditional hydraulic fill methodologies and thickened tailings technology. The use of thickened tailings for surface deposition was started by Robinsky in the late 1970s (Robinsky, 1975; 1976; and 1978). The first use of cemented thickened tailings occurred in Germany in 1979 (Grice, 1998). Research on CPB started at the same time, mainly in Canada and Australia, in order to help this method become a viable backfilling option.

All CPB consists of thickened tailings, water, and cement, though it has become common-place to use additives common in concrete such as flyash, slag, or other add-mixtures. Occasionally, the mining operation may incorporate additional aggregates, such as sand, into the paste in order to achieve the required material performance (Counter, 2006). The usual composition of CPB is around 70-85% (wt % solid) mine tailings, 2-9% (wt % solid) binder, and water (25-40% water contents) (Brackebusch, 1994). The CPB is typically produced at a surface paste plant and is moved, on surface, by a positive displacement pump until gravity moves it to the stope. This filling process has been found quicker at several mining operations, such as Kidd Mine and the mines at the Hemlo Camp, than the CRF or hydraulic fill methods that preceded it. CPB also has advantages over hydraulic fill as CPB does not have the drainage issues associated
with hydraulic fill (Sivakugan, 2008). For more detailed information on the rheology and design of CPB refer to Archibald and Hassani (1998) and Potvin et al. (2005).

The initial CPB research focused on the stability of the paste when a confining wall was removed. This loss of confinement is caused by the blasting and mucking of the stope next to a previously backfilled stope. An example of this work was the research by Mitchell at Queen’s University (Mitchell et al., 1982).

Interest in paste continued and mining operations continued to develop and operate paste plants, but it was not until the mid-1990s when several large-scale paste plants were brought online in Canada and Australia, that CPB was considered a viable option to the more established hydraulic or CRF methods.

When dealing with any backfilling operation there are two main questions to be dealt with. The first has already been touched on and deals with whether or not the backfill will remain stable if a supporting wall is removed. Note that this is not limited to the removal of a sidewall but also can refer to the undercutting of the fill due to mining operations below the backfilled stope. The second question deals with the backfill barricade and can be divided into two sub-questions:

1. What pressure the barricade can withstand before failure?
2. What stress will the barricade experience during the backfilling operation (and potentially after that operation)?

Several researchers have reported barricade failures both in hydraulic and CPB filled stopes (Revel and Sainsbury, 2007a; Yumlu and Guresci, 2007; Helinksi and Grice, 2007; and Sivakugan, 2008). These failures pose a serious potential hazard to the underground mine workers, and, even if this risk can be mitigated, there are still the economic issues posed by the cleanup costs and the resulting down time. This thesis will attempt to answer the second sub-question by determining the in situ stresses within the CPB during the time when potential barricaded failures are most likely to occur.

An idealized backfilling instrumentation curve is shown in Figure 2.1. This figure contains three curves: a vertical total stress curve (dark blue), a horizontal total stress curve (red), and a pore-water pressure (PWP) curve (light blue). During the initial stages of filling, the stresses are hydrostatic due to the fluidic nature of the CPB at this time of curing. Note that in Figure 2.1 the isotropic total stress curve is shown as a black line. This line is a product of the
A design procedure for determining the in situ stresses of early age cemented paste backfill.

2.0 Cemented paste modelling

Idealized backfill instrumentation curve

Figure 2.1
fluid density, the height of the paste above the measurement point at that time, and gravity. The
duration of this isotropic behaviour depends on the type of paste and the depositional
environment. After this period of isotropic behaviour the stresses start to deviate indicating that
the paste is starting to generate shear strength.

There are several processes by which this shear strength can develop. The first is the
reduction of pore water pressure (PWP) and the corresponding net-volume reduction of the paste
due to cement hydration (Grabinsky and Simms, 2006; Helinski et al., 2007b; Simms and
Grabinsky, 2009). The second is the gain of effective stress due to consolidation. While
consolidation is more pertinent to hydraulic fill, it has been shown to have some impact on the
strength of CPB (Belem et al., 2004; Yilmaz et al., 2009; Fahey et al., 2011). Once the CPB has
developed enough shear strength, it will also start to exhibit soil arching behaviour where the
stress within the CPB is transferred to the boundary between the CPB and the stiffer surrounding
rockmass (Mitchell, 1992).

The following sections will consider how the in situ behaviour of CPB is currently being
investigated. These methods have been separated into four categories: soil arch modeling, PWP
reduction modeling, laboratory testing, and in situ stress monitoring.

2.1 Soil Arch Modeling

Soil arching is due to the frictional interface created between a yielding mass and the
static material surrounding it. This interface creates an arch which allows the weight of material
above the arch to be transferred to the abutments. This transfer means that the material below
the arch and closer to the interface will experience less vertical stress than material that is further
away from the interface and that there will be an overall reduction of stress at the base of the
yielding mass. The next section will present a history of arching methods while the subsequent
section will show how some of these methods have been adapted for use with paste backfill.

2.1.1 A Brief History of Soil Arch Modeling

The first mention of soil arching was in the early 1800s when French military engineers,
asked to design magazine silos, found that the base of a silo only supported a fraction of the total
load from the material above it, while the side walls carried considerably more stress than
anticipated. This research was further expanded by Janssen (1895), who looked at grain silos.
The first major research of arching within soil was conducted by Marston (1930), who was looking at protecting buried conduits. This work was followed by Terzaghi in his trap-door experiments in 1936 and his arching theory work (1943). His work looked at the effects of arching on tunnel construction. A further continuation of Marston’s work was carried out by Handy and Spangler (Spangler in 1964 and both in 1973), as part of a review looking at the failure of conduits throughout the US.

2.1.2 The Use of Soil Arching with CPB

The method developed by Marston is the primary arching method that has been applied to CPB. As mentioned above, Marston developed his method to estimate the loads on buried conduits, but the methodology can be modified to estimate the vertical and lateral loads within a stope. The theory uses the weight of the fill and the shear forces that are developed between the vertical sides of the stope and the fill. Results from this method have been compared to numerical or laboratory modelling results using hypothetical paste and stope parameters with reasonable success (Aubertin et al., 2003; Li et al., 2003; Pirapakaran and Sivakugan, 2007a and 2007b). However, there are limitations to this method, mainly that it is only a two dimensional solution, does not incorporate either cohesion or pore-water pressure, and is only applicable to simple, vertical stopes. The above authors compared a modified Marston method for inclined stopes with numerical modeling but had little success. The Marston method’s approach is also limited as it does not incorporate the time-dependent aspect of cemented paste backfill. Furthermore, it is typically not used to show how the stope stresses develop with time but is used only when the stope is completely full, although the above researchers have recently started to incorporate staged filling into their models (Li and Aubertin, 2009a, 2009b, 2009c, 2009d, and 2010).

Additional research using the Marston method has led to further developments, including a three-dimensional formulation (Li et al., 2004 and 2005), the inclusion of PWP (Li et al., 2009a, 2009c, 2009d, and 2010), and another attempt to adapt the model to inclined stopes (Ting et al. 2011, Sing et al., 2011). These new developments have shown some promise when compared to numerical models, but there are still limitations to the method, mainly the lack of cohesion, limited variation of geometry, and lack of time-step applications.


2.2 Consolidation Modeling

The other primary method for determining the in situ stope stresses consists of modelling the PWP reduction. This reduction is generally caused by either a desiccation effect caused by the hydrating binder or by the drainage and subsequent consolidation of the paste.

Most consolidation research looking at CPB involves building on previous work carried out by Gibson (Gibson, 1958 and Gibson et al., 1967). In these papers Gibson developed a one-dimensional consolidation model which dealt with the large deformation consolidation of saturated clay. One important aspect of this model was that it allowed additional material to be placed on top of previously placed and consolidated layers. Gibson’s model was then used to develop a finite-element code called MinTaCo by Seneviratne et al. (1996). These authors used MinTaCo to model consolidation of slurried mine tails. Further researchers have used this code to study a variety of tailings filling operations (Fahey and Newson, 1997, and Fahey et al., 2002).

The MinTaCo code was further modified by Helinski et al., (2007a and 2007b) to incorporate the effects associated with cement hydration, renaming the model CeMinTaCo. The same authors did additional work on the code in order to model consolidation in two dimensions (Helinski et al., 2010). The new two-dimensional model was then used to look at two case study stopes (Helinski et al., 2011). These studies produced some promising results but the authors were hampered by the lack of a 3D code. The other drawback of this modeling approach is that there are complicated input parameters which require sophisticated laboratory tests.

2.3 Laboratory Testing

The laboratory testing of CPB is generally completed for two reasons. The first is to provide researchers with input parameters for their modeling studies (Pierce, 1997; Helinski et al., 2007b). The second reason is to study and quantify the difference between the in situ field samples and laboratory-created samples (Oullet et al., 1998; le Roux et al., 2005; Sivakugan et al., 2006; Rankine and Sivakugan, 2007). These comparisons have led to the use of increasingly sophisticated laboratory testing aimed at answering specific questions about the behaviour of CPB, as well as to try and replicate how the paste is actually behaving in the stope (Helinski et al., 2007b; Yilmaz et al., 2009; Moghaddam, 2010; Abdeltaal, 2011; Fahey et al., 2011). However, the complexity and cost of these sophisticated tests means that it is difficult for a mine
site to replicate the test and makes large testing programs prohibitively expensive. Therefore, the testing methods used for this thesis need to be widely available and cost effective for a typical mine site.

2.4 In Situ Stress Monitoring

Both Sections 2.1 and 2.2 have shown different methods by which the in situ stresses within backfilled stopes can be modelled. However, there was a lack of data available pertaining to the behaviour of the in situ stresses within the CPB. This lack of data prevented the comparison of the results obtained from the previously discussed models to actual field measures. A stope instrumentation program was started at the University of Toronto (UofT) in 2007 to rectify this gap in knowledge.

The UofT program was not the first attempt to instrument a stope. There have been several previous attempts to monitor the in situ stresses within a stope. Hassani et al. (1998) and Oullet et al. (2005) lowered instrumentation clusters, containing total earth pressure cells (TEPCs), into the upper volume of an open stope prior to backfilling. These instruments were then monitored as the stope was backfilled. Belem et al. (2004) installed two orthogonal TEPC clusters at different heights in a test stope. Yumulu and Guresci (2007) instrumented a series of three stopes. Each stope had an instrument cluster, containing horizontally and vertically oriented TEPCs, a thermistor, and a piezometer (PZ), placed near the center of the open stope at ground level. Additional stope instrumentation consisted of a horizontally oriented TEPC was mounted on the barricade fence. Other studies have only installed instruments on the barricade fence (Dehn et al., 2007 and Hughes et al. 2010). Xtrata’s Kidd Mine also installs TEPCs on all of their fill fences as a part of their backfill protocol (Counter, 2006).

Note, however, that only one of the previous studies included the installation of a PZ. This omission means that the PWP within the stope was not monitored and that the effective stress in the stope could not be determined. This limits the type of model calibration exercises that can be completed and limits the understanding of how the effective stress behaviour of the CPB affects its overall behaviour in the stope (Fourie et al., 2007).

The UofT instrumentation program was initiated in 2007. The goal of this program was to build on the previous instrumentation programs, using more types of instrumentation at more monitoring locations and in more stopes. At the publication of this thesis, a total of nine stopes
have been instrumented at the three partner mines: Barrick Gold Corporation’s Williams Mine, Inment Mining Corporation’s Cayeli Bakir Mine, and Xtrata Copper Canada’s Kidd Mine. The instrumentation for each stope varies but all include TEPCs and PZs at various locations within the stope. For further information on this instrumentation, refer to Chapter 5 or to Thompson et al., 2009, 2010b, 2011a, and 2011b. The UofT CPB stress dataset provided the necessary comparison point for modelling back analysis presented later in this thesis.

2.5 Summary

As stated in Chapter 1, the aim of this thesis is to develop a procedure that a mining engineer could follow in order to determine the stresses within the CPB as it fills a stope. The stope filling process involves two filling time-steps. The first is the filling time (i.e. the time to fill the stope). The second is the curing time of the cement within the CPB. This means that the behaviour of different ages of paste will be different. Several authors have looked at CPB parameters with time (Pierce, 1997; le Roux, 2004; le Roux et al., 2005; Moghaddam, 2010). Unfortunately this data is usually for cure times 28 days or greater, making it of limited use for a filling process that usually takes no longer than three days. In order to rectify the absence of data on early cure-time behaviour, it was necessary to generate a dataset showing the relationship between CPB parameters and early age cure-times.

There were many testing methods that could be used to obtain this cure-time data. However, the testing method of choice had to be accessible enough for a mine site to undertake similar work. To this end, it was decided testing would use a direct shear box testing apparatus (DSB) as this type of testing is widely available and is both relatively easy to use and inexpensive.

After reviewing the current methods being used to model CPB and, again, with a desire to keep methods applicable for a mine site, it was also decided to use an existing commercial software package to develop a paste filling model. The benefit of this was two-fold: the first benefit was that the development and coding of the basic models was already done and the second benefit was that, as a commercial code, the software was widely available and could be easily purchased by a mining operation. The selection of an appropriate software package could fill some of the research gaps mentioned above. These gaps include the inability to model 3D
geometry and the lack of integrated time-dependent CPB behaviour. See Chapter 4 for more
details about the numerical modeling code chosen for the thesis.

Therefore, the research presented in this thesis will develop a process that a mine
engineer on a typical mine site could follow using relatively simple laboratory testing and a
commercially available software tool to determine how the in situ stresses within a backfilled
stope develop as the stope is filled.
CHAPTER 3

Laboratory Investigation

The purpose of the laboratory investigation was to determine starting input parameters for the numerical modeling. This section presents the following:

- the testing methodology,
- the background material data obtained by the larger research group that the author was part of, and
- the testing results obtained from the author’s own laboratory testing program.

3.1 Introduction

This laboratory testing program involves the investigation of the strength and consolidation properties for seven different paste streams from three different mines. These streams, summarized in Table 3.1, differ in binder content, type of binder, tailings material, and cement additives. A total of 504 tests were carried out during the testing program. The focus of the testing was to generate input curves for numerical modelling as well as to determine what type of data could be generated using a direct shear box testing apparatus (DSB).

There were several reasons why the DSB was used. The first reason was that this testing method was relatively quick and allowed a large volume of samples to be tested in a short period
### TABLE 3.1

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A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

#### 3.0 LABORATORY TESTING

**PASTE STREAMS**

<table>
<thead>
<tr>
<th>Mine</th>
<th>Number</th>
<th>Tailings Type</th>
<th>Aggregate</th>
<th>Binder Composition</th>
<th>Paste Solids Composition by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cayeli Bakir</td>
<td>1</td>
<td>Non-Spec</td>
<td>None</td>
<td>100% Turkish Cement</td>
<td>6.5% Binder</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Spec</td>
<td>None</td>
<td>100% Turkish Cement</td>
<td>6.5% Binder</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Spec</td>
<td>None</td>
<td>100% Turkish Cement</td>
<td>8.5% Binder</td>
</tr>
<tr>
<td>Williams</td>
<td>4</td>
<td>NA</td>
<td>None</td>
<td>50% Portland Cement</td>
<td>3% Binder</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>NA</td>
<td>None</td>
<td>100% Portland Cement</td>
<td>5% Binder</td>
</tr>
<tr>
<td>Kidd</td>
<td>6</td>
<td>45% Tails</td>
<td>55% Sand</td>
<td>100% Pre-Mix</td>
<td>2.5% Binder</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>45% Tails</td>
<td>55% Sand</td>
<td>100% Pre-Mix</td>
<td>4.5% Binder</td>
</tr>
</tbody>
</table>

Notes:

1. Pre-Mix = PC and Slag
of time. The second was that the methodology for interpreting DSB results is well-known. Finally, it is a testing technology that mine personnel are familiar with and the testing apparatus can be found in most geotechnical laboratories, making it an easy test to conduct if a mine decides to conduct a testing program. To this end it was decided to maximize the testing potential of the DSB by conducting several tests on each sample. These testing methodologies will be discussed in more detail in subsequent sections.

All the tests were conducted on UofT’s research DSB. This apparatus was a constant vertical load/velocity controlled lateral shearing type of machine, with digital linear displacement transducers (LDTs) in the horizontal and vertical directions, and a digital load cell in the horizontal direction. The interior dimensions of the shear box were 6 cm by 6 cm in plan and 5 cm depth. The box consists of an upper half and a lower half; each half being 2.5 cm deep. Figure 3.1a is a photograph of the DSB used while Figure 3.1b is a schematic of the machine.

### 3.1.1 Methodology

This section provides a background for the laboratory program and the testing methodology. A complete test procedure is available in Appendix 2. Note that the testing procedure evolved as the testing continued, with the procedure in Appendix 2 presenting the final iteration of the testing procedure.

Five normal stresses were used ranging from having no normal stress (0 kPa) to a normal stress of 400 kPa (0, 50, 100, 250, and 400 kPa). The maximum stress expected in any of the stopes is around 400 kPa, with the other normal stresses being chosen to provide suitable range of testing points (Thompson et al., 2009a, 2010b, 2011a, 2011b).

Six different curing ages were generally used: 4, 12, 24, 48, 96, and 168 hours. However, due to delays in stope pours it was necessary for some of the paste streams to be tested at ages ranging up to 550 and 1344 hours. These longer cure ages were chosen to encapsulate the length of time each paste stream was placed in its respective stope to provide a continuous picture of how the paste strength is changing, particularly during the first 48 hrs, and to allow comparison between results obtained by the author and the results obtained by other laboratory researchers.

It should be noted that it was difficult to test the paste samples at exactly the stated curing age. An example is paste at the 4 hour curing age. All of the samples were mixed in the same batch with the first sample being tested as soon as the paste was mixed. However, as each test
a) Photograph of Direct Shear Box Apparatus

b) Schematic of Direct Shear Box
Each sample was tested in two ways. The first was a consolidation test with the normal load being applied incrementally or instantly. Each test was carried out in the DSB. The vertical displacement due to the applied load was recorded by the vertical LDT. After the sample was consolidated it was submitted to a direct shear test. During the test, the horizontal load on the sample and its horizontal and vertical displacements were recorded.

The initial void ratios were determined by the water content and mass of the samples before the testing began. As the vertical displacement was recorded during the consolidation and shear testing, it was possible to observe how the void ratios of the samples changed during testing. The initial and final densities were also measured, with the post-consolidation density being calculated from the vertical displacement during the consolidation phase of the testing.

The consolidation testing was based on American Society of Testing and Materials (ASTM) D2435-04. During this testing, incremental loads were applied to the sample. At each load increase, the change in void ratio could be calculated and plotted on a void ratio (e) versus log normal stress (log-σn) plot. From these curves, the Coefficient of Volume Compressibility (mv), the Compression Index (Cc), the Recompression Index (Cr), and, in the case of over-consolidated samples, another compression index called Ca were calculated. The values of the Ca index should be similar to Cr. Note that the stress at which the consolidation curve changes from Ca to Cc is called the pre-consolidation pressure (Pc). The Coefficient of Consolidation (Cv) was calculated using the root time method. Figure 3.2 shows a schematic of a compression curve with the above indexes labelled. Note that the inverse of mv is the confined modulus (M).

Finally, the Coefficient of Permeability (k) was calculated using the equation:

\[ k = C_v m_v \gamma_w \]  

where \( \gamma_w \) is the unit weight of water. It is recognized that this method for calculating permeability is not ideal as it deals with the relationship between permeability and the reduction of void ratio due to consolidation. It does not take into account any hydration products which clog the pore spaces or increase the viscosity of the fluid within those pore spaces.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPRESSION CURVE SCHEMATIC

FIGURE 3.2
Nevertheless, this equation was used because it is a common method of determining permeability and is easy to calculate as all of the necessary parameters are determined during the data analysis of the consolidation testing.

The direct shear testing was based on ASTM D3080. During each shear test, the horizontal load was recorded in kilograms and was used to calculate the shear stress in kilopascals. This stress was plotted against the horizontal displacement so that the peak and residual shear strengths for each test could be determined. These values were then plotted on a normal versus shear stress plot to determine a Mohr-Coulomb failure envelope for that particular paste at that particular curing age.

3.2 Chapter Organization

The laboratory results will be presented as comparison plots or tables, and will be organized by mine. The results from Çayeli Bakir (CBI) will be presented first, followed by Williams Mine (WILL), and then Kidd Mine (KIDD). There are four types of data presented:

1. The initial material properties, including void ratio, density, and water content.
2. The consolidation results, including consolidation parameters, discussed in Section 3.1.1, and an average consolidation curve.
3. The third type is average permeability versus normal stress, and
4. the fourth is Mohr-Coulomb (M-C) parameters and envelopes.

Each section will also have a brief discussion of the results. The raw laboratory testing results are available in Appendix 3.1. The processed laboratory results that were used to create the charts shown in this chapter are available in Appendix 3.2.

3.3 CBI Laboratory Testing

Two different types of tails are generated by CBI, Spec (CS) and Non-Spec (CNS), because two different types of ore are present at the mine: CS is generated from the less zinc-rich ore and the CNS which is generated from the zinc-rich ore. The main difference between the two types of tails is that the CNS contained more clay than the CS. In this thesis, the binder contents of the CS tailings were 6.5% and 8.5%, while the CNS tailings only used a binder content of 6.5%. The binder material used at CBI is a Turkish manufactured cement.
A total of 230 tests were carried out on CBI paste, with 78 samples made from CNS 6.5, 75 from CS 6.5, and 77 from CS 8.5. The curing ages tested were 4, 12, 24, 48, and 96 hours in all pastes. CNS 6.5 and CS 6.5 were tested to 168 hours. The normal stresses that were used in the testing were no load, 50, 100, 250, and 400 kPa.

### 3.3.1 CBI Initial Material Properties

The two tailings streams at CBI have different chemical, mineralogical, and physical compositions. Tables 3.2 and 3.3 compare the chemical and mineralogical properties of each tailings type.

The bolded text in Table 3.2 shows chemical compounds that, with the exception of Copper (Cu), show a large concentration difference between the tailings types. Of particular interest is the much higher Zinc (Zn) concentration in the CNS tailings indicating that this is Zn rich ore. The higher concentrations of the heavier chemical compounds (Iron (Fe), Zn, and Lead (Pb)) show why the CNS tailings have a Specific Gravity (SG) of 4.52 compared to the Spec tailings SG of 4.18. Note that the concentration of copper in both tailings streams is more or less equal. Table 3.3 shows that there is a larger concentration of clay minerals in the CS tailings (7.8%) than in the CNS (3.9%). This difference is due to higher concentrations of both Kaolinite and Dickite in the CS tailings, and the addition of a new clay mineral, Chlorite. It is important to note as these differences affect the behaviour of the two paste streams.

Figure 3.3 shows the grain size analysis curves for both tailings types. Three different analyses are shown: sieve, hydrometer with deflocculant, and hydrometer without deflocculant. There is very little difference in the grain sizes between the two tailings types. This is not surprising as both materials need to go through a similar milling process. Both tailings types are poorly graded sandy silt with trace clay.

Table 3.4 summarizes and compares the initial material properties of the three CBI pastes. All of the average material property values of the two CS pastes are relatively equal. The CNS paste properties differ from the CS paste properties. This stems from the difference in SG for the two pastes. The CNS paste has a higher initial density than the CS paste which is due both to its higher SG and its lower water content. The difference in initial void ratio is also due to the higher SG and low water content of the CNS paste.
## TABLE 3.2

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A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

**LABORATORY TESTING**

**CHEMICAL COMPOSITION OF CBI TAILINGS**

<table>
<thead>
<tr>
<th>Element</th>
<th>Compound</th>
<th>Non-Spec Concentration (%)</th>
<th>Spec Concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>Na₂O</td>
<td>0.143</td>
<td>0.193</td>
</tr>
<tr>
<td>Mg</td>
<td>MgO</td>
<td>2.181</td>
<td>5.965</td>
</tr>
<tr>
<td>Al</td>
<td>Al₂O₃</td>
<td>3.002</td>
<td>6.19</td>
</tr>
<tr>
<td>Si</td>
<td>SiO₂</td>
<td>8.533</td>
<td>15.572</td>
</tr>
<tr>
<td>P</td>
<td>P₂O₅</td>
<td>0.026</td>
<td>0.031</td>
</tr>
<tr>
<td>S</td>
<td>S</td>
<td>43.098</td>
<td>37.258</td>
</tr>
<tr>
<td>K</td>
<td>K₂O</td>
<td>0.217</td>
<td>0.379</td>
</tr>
<tr>
<td>Ca</td>
<td>Ca</td>
<td>2.593</td>
<td>2.616</td>
</tr>
<tr>
<td>Ti</td>
<td>TiO₂</td>
<td>0.059</td>
<td>0.098</td>
</tr>
<tr>
<td>Cr</td>
<td>Cr</td>
<td>0.008</td>
<td>0.012</td>
</tr>
<tr>
<td>Mn</td>
<td>Mn</td>
<td>0.092</td>
<td>0.052</td>
</tr>
<tr>
<td>Fe</td>
<td>Fe</td>
<td>36.306</td>
<td>32.027</td>
</tr>
<tr>
<td>Ni</td>
<td>Ni</td>
<td>0.012</td>
<td>0.007</td>
</tr>
<tr>
<td>Cu</td>
<td>Cu</td>
<td>0.455</td>
<td>0.434</td>
</tr>
<tr>
<td>Zn</td>
<td>Zn</td>
<td>2.182</td>
<td>0.989</td>
</tr>
<tr>
<td>As</td>
<td>As</td>
<td>0.143</td>
<td>0.099</td>
</tr>
<tr>
<td>Se</td>
<td>Se</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>Sr</td>
<td>Sr</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>Mo</td>
<td>Mo</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>Ba</td>
<td>Ba</td>
<td>0.71</td>
<td>0.646</td>
</tr>
<tr>
<td>Pb</td>
<td>Pb</td>
<td>0.163</td>
<td>0.066</td>
</tr>
</tbody>
</table>

**Notes:**
1. Non-Spec concentration an average from 2 tests
2. Only in-common elements are shown

E:\[Cayeli Figures&TAbles.xlsx]Table 3.2

25-Nov-12
### TABLE 3.3

UNIVERSITY OF TORONTO
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY
AGE CEMENTED PASTE BACKFILL
LABORATORY TESTING

MINERALOGICAL COMPOSITION OF CBI TAILINGS

<table>
<thead>
<tr>
<th>Compound Name</th>
<th>Non-Spec Concentration (% wt)</th>
<th>Spec Concentration (% wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrite</td>
<td>82.1</td>
<td>77.1</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>5.4</td>
<td>5.9</td>
</tr>
<tr>
<td><strong>Kaolinite</strong></td>
<td><strong>2.1</strong></td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>Biotite</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Dickite</strong></td>
<td><strong>1.8</strong></td>
<td><strong>2.2</strong></td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Quartz</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Barite</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Chlorite</strong></td>
<td><strong>3.0</strong></td>
<td></td>
</tr>
<tr>
<td>Smithsonite</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td><strong>Total Clay</strong></td>
<td><strong>3.9</strong></td>
<td><strong>7.8</strong></td>
</tr>
</tbody>
</table>

Notes:
1. Bolded text indicates clay compounds

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3.0 LABORATORY TESTING

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

GRAIN SIZE ANALYSIS OF CBI TAILINGS

Figure 3.3
### TABLE 3.4

**UNIVERSITY OF TORONTO**

**A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL**

3.0 LABORATORY TESTING

**CBI PASTES - INITIAL MATERIAL PROPERTIES**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unit</th>
<th>CNS 6.5%</th>
<th>CS 6.5%</th>
<th>CS 8.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder Type</td>
<td>100 % TC</td>
<td>100 % TC</td>
<td>100 % TC</td>
<td></td>
</tr>
<tr>
<td>Tails Designation</td>
<td>PG Sandy Silt</td>
<td>PG Sandy Silt</td>
<td>PG Sandy Silt</td>
<td></td>
</tr>
<tr>
<td>Aggregate Designation</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Initial Void Ratio - Average</td>
<td>1.34</td>
<td>1.53</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>Initial Void Ratio - Standard Deviation</td>
<td>0.11</td>
<td>0.08</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Initial Density - Average g/cm³</td>
<td>2.29</td>
<td>2.18</td>
<td>2.18</td>
<td></td>
</tr>
<tr>
<td>Initial Density - Standard Deviation g/cm³</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Initial Mining Water Content - Average %</td>
<td>24</td>
<td>26</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Initial Mining Water Content - Standard Deviation %</td>
<td>1.38</td>
<td>0.9</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Average %</td>
<td>31</td>
<td>35</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Standard Deviation %</td>
<td>2.35</td>
<td>1.6</td>
<td>3.1</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. TC = Turkish Cement
2. PG = Poorly Graded

E:\Cayeli Figures&TAbles.xlsx|Table 3.4
25-Nov-12
3.3.2 CBI Consolidation Testing

Figure 3.4 shows a series of age-related normalized average consolidation curves for each paste type. All of the plots show that the younger pastes consolidate more than the older pastes, with the largest difference in the amount of consolidation being between the 4 hour and 12 hour pastes. There is less difference between each subsequent paste and no difference between the 96 and 168 hr pastes. The 4 hour curves show only normally consolidated behaviour whereas the rest of the age curves show both over and normally consolidated behaviour.

The CS 8.5 paste shows the most initial consolidation, followed by the CNS 6.5, and then the CS 6.5 paste. The CS pastes have a very sharp change in consolidation particularly between the 4 and 12 hour curves. The CNS paste has a more gradual change, with each curve being spaced slightly apart from each other. However, by the later curing ages, the CNS paste experiences the least consolidation of the three CBI pastes, followed by CS 8.5 and then CS 6.5.

Figure 3.5 is a comparison between the average values of Cc, Ca, Cr, and Pc. This shows that the Ca and Cr values for each paste are generally similar, except for a blip between 24 and 48 hours in the CNS paste. All of the Cc curves show a similar trend: they all rise and reach a peak value between 24 to 48 hours, after which all of the curves start to decrease. A reason for this decrease is the strength gain of the paste. As a paste gains strength, it consolidates less, shown in Figure 3.4, meaning that the older pastes, for the normal stresses tested, experience less consolidation. This causes the Cc slope to flatten or decrease.

It was expected that the Pc values would increase with curing age and eventually plateau reflecting the strength gain of the CPB. All of the pastes show this trend. The most interesting observation is the difference between the two paste types. The two 6.5% pastes initially have lower Pc values than the 8.5% paste. However, the Pc of the CNS 6.5% increases quickly, surpassing both CS pastes by 48 hours.

Figure 3.6 shows the C_v, m_v and k values for all three pastes from different curing times. All of the C_v results, except for the 4 hour curing age, show the same trend of the C_v decaying with increasing normal stress. The 4 hour results show that the C_v increases slightly with normal stress due to the increased consolidation time involved with the lower normal stresses. Note that over time, the C_v values increase and the decay curves straighten.
COMPARISON OF CBI PASTES: AVERAGE CONSOLIDATION CURVES

A. DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF CBI PASTES: AVERAGE CONSOLIDATION CURVES

Figure 3.4
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF CBI PASTES: CONSOLIDATION PARAMETERS

Figure 3.5
Figure 3.6

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF CBl PASTES: \( C_v, m_v \), and \( k \) RESULTS
The $m_v$ results show that the early age paste is the least stiff, but that its stiffness increases with normal stress. As the curing age increased, the stiffness of each paste also increased.

All of the $k$ results, for all three pastes, show a decrease in $k$ with increased normal stress. This was expected as the increased normal stress increased consolidation, decreasing the void ratio, and, hence, the $k$ value. Note that all of the $k$ result clusters are very similar, indicating that increased curing time did little to decrease the $k$ of the tested paste.

### 3.3.3 CBI Shear Testing

Figure 3.7 contains the paste specific plots for the cohesion changes with time. These plots show that the CS 8.5 paste has the highest initial cohesion and gains cohesion the fastest. The CNS 6.5 paste has the least cohesion for the first 24 hours, followed by a period of rapid cohesion gain, while the CS 6.5 paste initially has slightly more cohesion than the CNS paste, but gains cohesion very slowly. It should be noted that the CS 6.5 paste does not show significant differences between peak and residual behaviour, whereas the other two pastes do. It should also be noted that the residual values seen in the CNS 6.5 and CS 8.5 pastes are similar to the cohesion values seen in the CS 6.5 paste.

Figure 3.8 is similar to Figure 3.7 but shows the changes in Friction Angle ($\phi$) with time. The curves from each paste show a similar shape, with the $\phi$ increasing over the first 24 hours, peaking at 24 hours, and then decreasing with time. The CS 8.5 paste has the lowest $\phi$ values, followed by the CNS 6.5 paste, and then the CS 6.5 paste. The CS 6.5 paste shows similar peak and residual behaviour, whereas the CS 8.5 and CNS 6.5 paste show a marked difference in peak and residual $\phi$ behaviour. Both of these pastes have similar $\phi$ values up to 48 hours, after which the residual $\phi$ decreases less rapidly than the peak $\phi$ values. As a result, the residual values are higher than the peak values.

The reason for this behaviour is shown on the plots in Figure 3.9. These plots show the M-C envelope plots for each curing age. At longer curing ages, the difference between the peak and residual cohesion in the CS 8.5 and CNS 6.5 pastes is large. The M-C envelope needs to maintain the shear stress at the largest normal stress increment. The shear stress in this case is approximately 310 kPa. As the peak cohesion increases, the $\phi$ must decrease in order to
Figure 3.7: Laboratory Testing A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

3.0 Laboratory Testing

Comparison of CBI Pastes: Cohesion

Figure 3.7
A design procedure for determining the in situ stresses of early age cemented paste backfill.

3.0 Laboratory Testing

Comparison of CBI pastes: Friction angle

Figure 3.8
## 3.0 Laboratory Testing

### Comparison of CBI Pastes: M-C Envelopes

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Shear Stress (kPa)</th>
<th>Normal Stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96 hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>168 hr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A design procedure for determining the in situ stresses of early age cemented paste backfill.
maintain this value. However, as the residual cohesion does not increase as much (particularly for the CNS 6.5 paste) the $\phi$ can remain lower.

### 3.3.4 Comparison with other Testing Methods

This section compares the strength results obtained by the DSB testing with a series of unconfined compressive strength (UCS) tests carried out during the pouring of the instrumented test stopes. These tests were carried out on both underground and surface pastes and were tested at 7, 14, and 28 days. Unfortunately, only the 7 day testing age can be directly compared to the 6.5% binder paste results and there are no ages that can be directly compared for the CS 8.5 binder paste. In order to compare UCS with DSB tests the following equation was used to convert the M-C parameters into UCS results, where $c$ is cohesion:

$$UCS = \tan\left(45 + \frac{\phi}{2}\right) \times 2c$$

(3.2)

Figure 3.10 shows the results from the UCS and converted DSB testing. This figure shows that there is some similarity between the UCS results determined from the two different testing methods. At the 7 day comparison point the CNS 6.5 DSB value is between the paste plant (PP) and underground (UG) UCS points, but is much closer to the PP value. The CS 6.5 DSB value is below both the PP and UG UCS values, and has a difference of 80 kPa between it and the PP UCS value. The UCS results show that the UG UCS values for all paste types are higher than the PP values. This difference is a common occurrence in this type of testing and is attributed to the changes caused by the transportation of the paste from the plant to the stope.

It is difficult to compare the CS 8.5 results as there is no common curing age. However, if the CS 8.5 curve was to follow a similar trend to that of the CNS 6.5, its 7 day DSB value would be within the underground and surface UCS values. There appears to be some relationship between the UCS and DSB testing. However, more testing would help validate the relationship.

### 3.4 Williams Laboratory Testing

Williams Mine generates one type of tailings which consists of material from its open pit and underground operations. Two different paste configurations were tested. The first consisted
Notes:
1) Note that UCS values for CS 8.5%, CS 6.5%, and CNS 6.5% were determined from DSB results
of 5% binder containing 100% Portland cement (PC) while the other consisted of 3% binder with a 50:50 mix of PC and fly ash.

It should be noted that Williams Mine does not use the Williams 5% (WILL 5) in its mining operation. Will 5 was the first type of paste examined during the laboratory testing process in order to determine preliminary laboratory testing procedures. However, this meant that the quality of results and record keeping from this testing were not as good that was obtained during the later testing. Due to some missing records, no initial material property data and limited consolidation data will be presented for the Will 5 paste. Data that will be presented for this paste is the normalized void ratios, permeability, and shear testing results. These results have been included in order to provide a comparison point for the Williams 3% (WILL 3) paste.

A total of 135 Williams paste samples were tested. Out of the total number, 85 tests were carried out on WILL 3 and 50 tests on WILL 5. WILL 5 paste was tested at 4, 24, 48, and 96 hours, while WILL 3 was tested at 4, 12, 24, 48, 96, 168, 384, and 1344 hours of curing. The normal stresses that were used in the testing were no load, 50, 100, 250, and 400 kPa.

### 3.4.1 Williams Initial Material Properties

Figure 3.11 shows the grain size analysis of the Williams tailings. This shows that the tailings consist of approximately 80 percent silt and 20 percent fine sand. The silt is generally coarse with some medium and fine grained silt. This classifies the tailings as uniform, slightly sandy, medium to coarse silt. Table 3.5 shows the initial material parameters of WILL 3.

### 3.4.2 Williams Consolidation Testing

Figure 3.12 contains the normalized average consolidation curve (e versus log-$\sigma_n$) plots for WILL 3 and WILL 5 pastes. Each plot contains multiple curves representing each curing age. All of the plots show that the younger pastes consolidate more than the older pastes, with the largest difference in the amount of consolidation being between the 4 hour and 12 hour pastes. The WILL 3 plot shows that the 12 to 384 hour curves are relatively clustered but that the 1344 hour curve is above the cluster. The WILL 5 plot shows that all the hour curves are spaced apart. The 4 hour curves of both pastes show only normally consolidated behaviour whereas the rest of the curves, in both plots, show both over and normally consolidated behaviour.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

GRAIN SIZE ANALYSIS OF WILLIAMS TAILINGS

Figure 3.11
<table>
<thead>
<tr>
<th>Criteria</th>
<th>WILL 1</th>
<th>WILL 2</th>
<th>WILL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder Type</td>
<td>1:1 PC</td>
<td>P.G.</td>
<td>NA</td>
</tr>
<tr>
<td>Tails Designtation</td>
<td>Flyash</td>
<td>Sandy</td>
<td>Silt</td>
</tr>
<tr>
<td>Aggregate Designation</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Void Ratio - Average</td>
<td>1.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Void Ratio - Standard Deviation</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Density - Average</td>
<td>1.82 g/cm³</td>
<td>0.03 g/cm³</td>
<td>0.03 g/cm³</td>
</tr>
<tr>
<td>Initial Density - Standard Deviation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Mining Water Content - Average</td>
<td>26%</td>
<td>18%</td>
<td>37%</td>
</tr>
<tr>
<td>Initial Mining Water Content - Standard Deviation</td>
<td></td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Average</td>
<td></td>
<td></td>
<td>37%</td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Standard Deviation</td>
<td></td>
<td></td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Notes:
1. PC = Portland Cement

The table compares the initial material properties of WILL 1, WILL 2, and WILL 3, including binder type, tails designation, aggregate designation, initial void ratio, initial density, initial mining and geotech water content, with averages and standard deviations.
Figure 3.12

A Design Procedure for Determining the In Situ Stresses of

3.0 Laboratory Testing

Comparison of Williams Pastes: Average Consolidation Curves

Figure 3.12
The WILL 3 paste always experiences more consolidation, given the same conditions, than the WILL 5 paste. For example, the 1344 hour (56 day) WILL 3 curve shows similar consolidation with the 96 hour WILL 5 curve. This is due to the differences in initial strength and each paste’s respective strength gain.

Figure 3.13 shows the consolidation parameters for WILL 3. It should be noted that the 168 and 384 testing ages did not contain enough data points to make it possible to determine consolidation parameters. The $C_a$ and $Cr$ values are similar which was expected. The $Cc$ rise over the first 4 curing ages, peaked at the 96 hour curing age, and then decreased till the 1344 curing age. Unfortunately, the lack of parameters between the 96 and 1344 curing ages does not allow for a better understanding of what happens during this time interval. The $Pc$ plot curve showed the expected $Pc$ increase with time. It was expected that the $Pc$ values would plateau during the later curing ages. However, this plateau was not observed due to a lack of results from these curing ages.

Figure 3.14 shows the $Cv$, $mv$ and $k$ values for both pastes from different curing times. Veenstra (2012) results are from WILL 3 paste. Note that there is an additional group of results labeled UofT (2012) on all plots. These results were obtained from standard oedometer testing of WILL 3 paste.

The 24 through 1350 hour $Cv$ plots show the same trend, with the $Cv$ decaying with increasing normal stress. The 4 hour results show that the $Cv$ increases slightly with normal stress, while the 12 hour plot shows both types of behaviour. Note that over time the $Cv$ values increase and the decay curves straighten. All of the $Cv$ results show decent correlation.

The $mv$ results show that the early age paste is the least stiff, but that its stiffness increases with normal stress. As the curing age increased, the stiffness of each paste also increased. Note that the two WILL 3 pastes results (Veenstra 2011 and UofT 2012) are very similar but that the WILL 5 results are significantly higher, indicating that this paste is less stiff than the WILL 3 paste even though WILL 5 has a higher binder content. The most likely reason for this discrepancy is the early laboratory techniques used to test the WILL 5 Paste.

All of the $k$ results, for all three pastes, show a decrease in $k$ with increased normal stress. This was expected as the increased normal stress increased consolidation, decreasing the void ratio, and, hence, the $k$ value. Again the two groups of WILL 3 results agree very well.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF WILLIAMS 3% PASTE - CONSOLIDATION PARAMETERS

Figure 3.13
**Figure 3.14**

<table>
<thead>
<tr>
<th>4 HOURS</th>
<th>12 HOURS</th>
<th>24 HOURS</th>
<th>48 HOURS</th>
<th>96 HOURS</th>
<th>~1350 HOURS</th>
</tr>
</thead>
</table>

| Veenstra (2011) denotes WILL 3 testing completed by Author |
| UofT (2012) denotes WILL 3 testing completed at UofT |

**A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL**

**3.0 LABORATORY TESTING**

**COMPARISON OF WILLIAMS PASTE: C_v, m_v, and k RESULTS**

Figure 3.14
However, the WILL 5 results are typically higher than the WILL 3 results due to WILL 5’s higher $M_\nu$ results, which were discussed above.

3.4.3 Williams Shear Testing

Figure 3.15 contains plots showing how the cohesion of the two pastes changes with time. Due to the large difference between the curing times of the two pastes, the upper plots for both pastes show the results over a large time scale whereas the lower plots show the results over a shorter time scale.

Over the first 48 hours, the WILL 3 paste has a lower peak cohesion and a slower rate of peak cohesion gain compared with WILL 5, which shows both higher initial cohesion and a faster rate of gain. However, after 48 hours, WILL 3 paste rapidly gains peak cohesion and, at 96 hours, both pastes have the same peak cohesion. The residual cohesion of both pastes is also similar over the first 48 hours, after which the WILL 5 paste gains cohesion faster compared to the WILL 3 paste. There are no comparison points after 96 hours.

The format of Figure 3.16 is similar to Figure 3.15 but shows the $\phi$ results. These results (over the curing ages that allow comparison) show very little difference between peak and residual values of the individual pastes. They also demonstrate that there is little difference between the pastes. The trends observed in both pastes show a peak of around 40 degrees at 24 hours which is followed by a decay in friction angle.

3.4.4 Comparison with other Testing work

Several studies of Hemlo Camp paste (Williams Mine is located in the Hemlo Camp) have been conducted, which means there is a large amount of information available. The first section will compare bulk properties, the second compares permeability, and the third compares strength results including a comparison of UCS results and MC parameters. Pierce (1997) and le Roux (2004) and Pierce (1997) are the primary sources of the results.

3.4.4.1 Comparison of Material Properties

Both researchers looked at the bulk properties of Hemlo paste. In both studies the authors determined initial water content ($WC$), void ratios, and degree of saturation ($S_r$). Le
A DESIGN PROCEDURE FOR DETERMINDING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF WILLIAMS PASTES: COHESION

Figure 3.15
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF WILLIAMS PASTES: FRICTION ANGLE

Figure 3.16
Roux (2004) classified laboratory samples as well as in situ paste from both core and block samples. Pierce (1997) conducted a laboratory investigation of paste. Pierce found that the average WC to be 25%, which is assumed to be determined in the standard mining method \((M_w/M_t)\). This agrees well with average mining WC of 26% found in the current study. The in situ testing, le Roux found that the WC to varied between 36% and 39%. These WC were determined by the geotechnical method \((M_w/M_s)\). The average geotechnical water content for the current testing was 37%, which also agrees well.

The average void ratio for the 1997 laboratory study was 1.0 while the in situ void ratios varied between 1.1 and 1.4. The current study had an average void ratio of 1.04 with a two standard deviation range from 0.94 to 1.14.

The 1997 study found an average Sr of 99% while the in-situ Sr ranged from 79% to 100%. The current study had an average Sr of 97% with values ranging from 90% to 100%.

3.4.4.2 Comparison of Permeability Results

A comparison between hydraulic conductivity \((k)\) results from the 1997 study and this thesis show similar results. This similarity is not unexpected as the same method was used in both studies. For 3% binder at 28 days (672 hrs) Pierce reported a change in \(k\) from \(3.5e^{-5}\) cm/s to \(1.5e^{-5}\) cm/s due to a 440 kPa normal stress increase, while for a 56 day (1344 hrs), given the same conditions, a change in permeability from \(2.7e^{-5}\) cm/s to \(1.0e^{-5}\) cm/s was measured. These values are generally within the ranges seen in the current study, where the permeability changes from \(4.0e^{-5}\) cm/s to \(1.0e^{-5}\).

3.4.4.3 Comparison of Strength Results

This section will compare UCS results measured from Pierce, results obtained by UofT personnel from UCS testing during the filling of the initial test stope at Williams, and the results from the Author’s test program. In order to compare the shear box results with the UCS results Equation 3.2, from Section 3.3.4, was used to convert the M-C parameters into UCS values.

Figure 3.17 is a summary plot showing the UCS results from Pierce, the UofT field study, and the current laboratory program. This figure shows that the results are relatively close and all the results follow the same trend.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF HEMLO PASTE UCS VALUES

Figure 3.17

Pierce, 1997
UofT, 2007 - UG
UofT, 2007 - PP
RLV, 2011
Both Pierce and le Roux conducted consolidated un-drained tri-axial testing in order to determine M-C parameters. Le Roux conducted tests on both field and laboratory samples, while Pierce conducted tests on laboratory samples. The M-C parameters determined by Pierce for the 3% paste at 28 days (672 hours) were a cohesion of 40 kPa and a $\phi$ of 41 degrees, while for the same paste at 56 days (1344 hours) the cohesion was 75 kPa and the $\phi$ was 39 degrees. The results from the current study were a cohesion of 50 kPa and a $\phi$ of 38 degrees at 28 day, and a cohesion of 77 kPa and a $\phi$ of 35 degrees at 56 days. These results are not equal but they are extremely close.

The samples tested by le Roux were cured for significantly longer than those tested in the current study or by Pierce. Her lab samples were tested at a curing age of 70 days and her block samples were tested at a curing age of 90 days. She found that the laboratory samples had cohesions ranging from 18 to 37 kPa and a $\phi$ between 23 and 37 degrees, while the cohesions of the block samples ranged from 47 to 98 kPa and the $\phi$ ranged from 20 to 37 degrees. The $\phi$ and cohesions for both samples have a wide range but the values from the current study and Pierce fit within those ranges.

3.5 Kidd Data Laboratory Testing

Kidd Mine does not produce the tailings used for backfilling operations due to the distance between the mine and the mill. Instead, the mine uses tails from an abandoned gold mine that is closer to the mine site. They also add an aggregate to their paste mix. This aggregate consists of sand from a nearby esker. The tails to sand ratio is 45:55. Two different paste configurations were tested. The first consisted of 2.5% binder while the other consisted of 4.5% binder. Kidd uses a pre-mixed binder combining Portland cement and slag.

A total of 183 tests were conducted on Kidd paste, with 93 tests being on KIDD 2.5 and 90 tests on KIDD 4.5. Both pastes were tested at 4, 12, 24, 48, 96, and 168 hours. KIDD 2.5 was also tested at 334 and 544 hours, while KIDD 4.5 was tested at 585 hours. The normal stresses that were used in the testing were no load, 50, 100, 250, and 400 kPa.
3.5.1 Kidd Initial Material Properties

Figure 3.18 shows the grain size analysis of the tails and sand used in the Kidd CPB. The sand can be classified as poorly graded, slightly silty, medium sand. The tailings can be classified as poorly graded, medium to coarse silt with fine grained sand.

Table 3.6 shows the initial material properties of both pastes. This table shows that both pastes have similar initial properties.

3.5.2 Kidd Consolidation Testing

Figure 3.19 contains the normalized average consolidation curve (e versus log $\sigma_n$) plots for KIDD 2.5 and KIDD 4.5 pastes. Each plot contains multiple curves representing each curing age. All of the plots show that the younger pastes consolidate more than the older pastes, with the largest difference in the amount of consolidation being between the 4 hour and 12 hour pastes. The KIDD 2.5 curves are further spaced apart while the KIDD 4.5 curves show similar separation between the 4, 12, and the other curves. This indicates that KIDD 2.5 strength gain is more gradual than the KIDD 4.5. It should also be noted that 4, 12, and 24 curves of the KIDD 2.5 paste show only normally consolidated behaviour, whereas only the 4 hour curve of the KIDD 4.5 paste shows this behaviour.

The KIDD 2.5 paste shows more consolidation at all curing ages than KIDD 4.5. Indeed, the 585 hour KIDD 4.5 curve shows negligible consolidation over all the tested normal stresses. These results suggest that KIDD 4.5 paste is both initially stronger and gains strength much more quickly than the KIDD 2.5 paste.

Figure 3.20 shows the consolidation parameters for the Kidd pastes. It should be noted that the 334 hour KIDD 2.5 testing ages did not contain enough data points to make it possible to determine consolidation parameters. Overall, the $C_a$ and $C_r$ values of both pastes are similar which is what was expected. The $C_c$ of both pastes initially rise, peak sometime between 12 and 48 hours, and then decrease with time. The $P_c$ plot curve shows what was generally expected, with increasing $P_c$ over time.

Figure 3.21 shows the $C_v$, $m_v$ and $k$ values for both KIDD pastes from different curing times. The $C_v$ curves show a very interesting comparison between the pastes, with both pastes showing the an increase in $C_v$ with normal stress at the 4 hour cure time. After this time period, the KIDD 4.5 paste shows the usual $C_v$ decay with normal stress behaviour; however, the KIDD
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

GRAIN SIZE ANALYSIS OF KIDD TAILINGS

Figure 3.18
TABLE 3.6

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A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED
PASTE BACKFILL
3.0 LABORATORY TESTING

KIDD PASTES - INITIAL MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unit</th>
<th>Kidd 2.5%</th>
<th>Kidd 4.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder Type</td>
<td>100% Pre-mix</td>
<td>100% Pre-mix</td>
<td></td>
</tr>
<tr>
<td>Tails Designation</td>
<td>PG Sandy Silt</td>
<td>PG Sandy Silt</td>
<td></td>
</tr>
<tr>
<td>Aggregate Designation</td>
<td>PG Sand</td>
<td>PG Sand</td>
<td></td>
</tr>
<tr>
<td>Initial Void Ratio - Average</td>
<td>0.77</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Initial Void Ratio - Standard Deviation</td>
<td>0.06</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Initial Density - Average</td>
<td>g/cm³</td>
<td>1.97</td>
<td>1.98</td>
</tr>
<tr>
<td>Initial Density - Standard Deviation</td>
<td>g/cm³</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Initial Mining Water Content - Average</td>
<td>%</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Initial Mining Water Content - Standard Deviation</td>
<td>%</td>
<td>1.2</td>
<td>1.09</td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Average</td>
<td>%</td>
<td>26</td>
<td>25</td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Standard Deviation</td>
<td>%</td>
<td>1.9</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Notes:
1. Pre-mix = PC with slag
Figure 3.19

Comparison of KIDD pastes: average consolidation curves

A design procedure for determining the in situ stresses of early age cemented paste backfill

3.0 Laboratory testing

Comparison of KIDD pastes: average consolidation curves

Figure 3.19
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF KIDD PASTES: CONSOLIDATION PARAMETERS

Figure 3.20
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF KIDD PASTES: $C_v$, $m_v$, and $k$ RESULTS

Figure 3.21
2.5 paste shows an increase in $C_v$ with normal stress up to the 48 hour cure time, after which it reverts to the usual behaviour. This behaviour is due to the long times necessary for consolidation at the lower normal stresses.

The $m_v$ results show that the early age paste is the least stiff, but that its stiffness increases with normal stress. As the curing age increased, the stiffness of each paste also increased. Both pastes initially have around the same stiffness, but with time KIDD 4.5 gains stiffness much quicker than KIDD 2.5. However, at the last curing stage, both pastes have similar stiffness.

All of the $k$ results show a decrease in $k$ with increased normal stress. This was expected as the increased normal stress increased consolidation, decreasing the void ratio, and, hence, the $k$ value. The results from both pastes show a scatter of results but the typical $k$ values do not change much over time although a definite decrease in $k$ is apparent at the last curing time.

### 3.5.3 Kidd Shear Testing

Figure 3.22 contains plots showing how the cohesion of the two pastes changes with time. Due to the large difference between the cohesions of the two pastes, the upper plots for both pastes show the results over the entire cohesion range whereas the lower plots show a close-up of the results.

Both pastes show little cohesive strength or change over the first 12 hours. However, KIDD 4.5 exhibits a very rapid gain in cohesion until 96 hours, after which the cohesion gain slows. The KIDD 2.5 paste exhibits a relatively linear gain over time. The peak and residual cohesion show similar trends with the residual cohesion being less than peak.

Figure 3.23 contains a plot of $\phi$ with time for KIDD 2.5 and 4.5. The KIDD 2.5 paste shows that the $\phi$ is around 35 degrees until 168 hours, after which the peak $\phi$ decreases sharply and the residual $\phi$ decreases slightly. The KIDD 4.5 paste also has an initial $\phi$ of 35 degrees but, after 48 hours, both the peak and the residual $\phi$ decrease rapidly, with the peak decreasing more than the residual.

The behaviour of both the cohesion and $\phi$ can be shown more clearly in Figure 3.24, which shows M-C envelopes for all the common curing ages except for 12 hours. These plots show the same results discussed in Section 3.3.3. In order to maintain an equal final shear strength the $\phi$ needs to decrease due to the large increase in cohesion.
A design procedure for determining the in situ stresses of early age cemented paste backfill.

3.0 Laboratory Testing

Comparison of Kidd pastes: Cohesion

Figure 3.22
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF KIDD PASTES: FRICTION ANGLE

Figure 3.23
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COMPARISON OF KIDD PASTES: M-C ENVELOPES

Figure 3.24
3.6 Comparison of All Project Pastes

This section compares all of the pastes with each other. For ease of presentation the pastes were separated into high and low binder contents, except for CNS 6.5 which is in both categories.

Table 3.7 presents a summary of each paste’s initial material properties, including grain size, void ratio, density, and water content. All values, except grain size, are expressed as average and standard deviation values. Please note that values from WILL 5 were not included as the values were not available, not calculated, or equivalent to that of WILL 3. The two CS pastes had the highest void ratios, followed by CNS paste, WILL 3, and then both Kidd pastes. It should be noted that all of the CS and Kidd pastes show very similar average values. CNS paste was the densest paste followed by the two CS pastes, then the two Kidd pastes, and the least dense was WILL 3. Again, the CS and Kidd pastes had approximately equal densities. Kidd pastes had the lowest water contents, with the next highest being the CNS paste, followed by the two CS and the Williams paste. A possible reason for the significantly lower water content of the Kidd paste is that the sand enables the paste to flow at lower water content.

Figures 3.25 and 3.26 show the average consolidation results for the high and low binder content pastes respectively. In both figures the CBI pastes show the most consolidation with the Kidd and Williams pastes being more or less equal. There is typically a sharp change in the amount of consolidation experienced between the 4 and 12 hour curing times for the CBI and WILL 3 pastes. However the amount of consolidation shown by the Kidd pastes was more spread out. The Kidd paste plots do not show the sharp transition between over and normally consolidated behaviour that was seen in the other pastes.

Figures 3.27 and 3.28 contain plots for the average permeability versus normal stress for the high and low binder pastes respectively. Figure 3.27 shows that the WILL 5 paste is the most permeable but this result may be due to the fewer data points available for analysis. The two CBI pastes were of intermediate permeability while the least permeable is the KIDD 4.5 paste. A similar trend is shown in Figure 3.28, except that the CS 6.5 paste has a lowest permeability at higher normal stresses. The permeability of these pastes is within ranges found for similar tailings (Vick, 1983). One unexpected results was the low permeability of the Kidd pastes. It was expected that, due to the inclusion of the esker sand, that these would be the more
### TABLE 3.7

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**A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL**

#### 3.0 LABORATORY TESTING

**INITIAL MATERIAL PROPERTIES FOR ALL PASTES**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unit</th>
<th>Paste Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CNS 6.5%</td>
</tr>
<tr>
<td>Binder Type</td>
<td></td>
<td>100% TC</td>
</tr>
<tr>
<td>Tails Desigation</td>
<td></td>
<td>PG Sandy Silt</td>
</tr>
<tr>
<td>Aggregate Designation</td>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Initial Void Ratio - Average</td>
<td></td>
<td>1.34</td>
</tr>
<tr>
<td>Initial Void Ratio - Standard Deviation</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>Initial Density - Average g/cm³</td>
<td></td>
<td>2.29</td>
</tr>
<tr>
<td>Initial Density - Standard Deviation</td>
<td>g/cm³</td>
<td>0.07</td>
</tr>
<tr>
<td>Initial Mining Water Content - Average</td>
<td>%</td>
<td>24</td>
</tr>
<tr>
<td>Initial Mining Water Content - Standard Deviation</td>
<td>%</td>
<td>1.38</td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Average</td>
<td>%</td>
<td>31</td>
</tr>
<tr>
<td>Initial Geotech. Water Content - Standard Deviation</td>
<td>%</td>
<td>2.35</td>
</tr>
</tbody>
</table>

**Notes:**
1. TC = Turkish Cement
2. PC = Portland Cement
3. Pre-mix = PC with slag
4. PG = Poorly Graded

E:\[Chap3 Common Fig&Tables.xlsx]Table 3.7  
25-Nov-12
FIGURE 3.25

AVERAGE CONSOLIDATION - HIGH BINDER PASTES

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

AVERAGE CONSOLIDATION - HIGH BINDER PASTES

FIGURE 3.25
3.0 LABORATORY TESTING

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

AVERAGE CONSOLIDATION - LOW BINDER PASTES

FIGURE 3.26
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

PERMEABILITY - HIGH BINDER PASTES

FIGURE 3.27
3.0 LABORATORY TESTING

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

PERMIAIBILITY- LOW BINDER PASTES

FIGURE 3.28
permeable. However, the difference between all of the pastes, with the exclusion of WILL 5, is very small.

Figures 3.29 and 3.30 contain plots showing the change of cohesion with time for the low and high binder contents respectively. In both cases the time and stress axis were limited in order for a better comparison.

The first thing that is apparent in both plots is the large difference between the Kidd pastes and the others. Figure 3.29 shows that the Kidd 4.5 paste gains more cohesion faster than the other pastes, with the two CBI pastes roughly equal, and the least cohesive strength shown by the WILL 5 paste. Figure 3.30 shows that the CNS and Kidd 2.5 pastes have very similar curves. The CS 6.5 paste is unique as it is the only paste showing negligible change between peak and residual behaviour.

Figures 3.31 and 3.32 contain plots showing the change of friction angle with time for the low and high binder contents respectively. In both cases the time and stress axis were limited in order for a better comparison.

The basic trend shown in all of the plots, on both figures, is that the $\phi$ rises until 24 hours where it peaks and then starts to decrease. The friction angles for most of the pastes range between 34 degrees and 40 degrees.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COHESION - HIGH BINDER PASTES

FIGURE 3.29
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

COHESION - LOW BINDER PASTES

FIGURE 3.30
3.0 LABORATORY TESTING

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

FRICION ANGLE - HIGH BINDER PASTES

FIGURE 3.31
FIGURE 3.32

3.0 LABORATORY TESTING

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

3.0 LABORATORY TESTING

FRICITION ANGLE - LOW BINDER PASTES

FIGURE 3.32
CHAPTER 4

Model Methodology and Validation

This chapter deals with the creation and validation of the PasteFill model, a model designed to determine the in situ stresses of early age cemented paste backfill. It will detail how the model was created and the assumptions that were made in creating it, what boundary conditions were used and why they were used, and will define what input parameters were needed. Using these input parameters, PasteFill will be run through a series of 2D and 3D stopes to show the performance of the model as well as its sensitivity to the input parameters.

Itasca’s FLAC3D was the software platform used to build the model. FLAC3D was used because it has the ability to model in 3D, model non-linear behaviour, and contains an internal programming language called FISH. Itasca has also developed mesh generation tools, such as Space-Ranger, which greatly assist the model building process.

Note that this chapter presents results in both 2D and 3D models. In order to use FLAC3D in 2D, models were created one zone thick in a horizontal direction (usually the y-direction).
4.1 Model Methodology

This section presents the criteria by which the model was designed and explains how the model meets these criteria.

4.1.1 Criteria

PasteFill was designed to meet four requirements. The first requirement was that the model needed to be able to place paste in the modelled stope in a controllable fashion and similar to how a potential mine would want it placed. This involves having a changeable rise-rate within the modelled stope as well as having the ability to model pauses in the pour due to plant shutdowns. The second requirement was for the model to incorporate the time-dependent behaviour of cemented paste backfill (CPB) as CPB gains strength with time. The third was to be able to use any sort of stope geometry, whether it be simple 2D shapes or the actual complex 3D geometry of an existing stope. The fourth requirement was for the model to be able to incorporate multiple pastes as it is common practice for mining operations to use different pastes within one stope.

Note that this is not an exhaustive list of criteria that could be examined. Other criteria that could be examined include thermal and dynamic effects, but due to time considerations only the four criteria mentioned were examined.

4.1.2 Methodology

A goal of this thesis was to model the actual rise-rate of the paste within a stope. This work builds on earlier modelling work which used both stages and changing properties, but did not account for the actual rise-rate or specific time-dependent behaviour. While the results from these older models were useful (and met the design requirements of the time), it would be more advantageous to know how these stresses change with time, due to both the stope fill-rate and the time-dependent behaviour of CPB. In particular, the actual stress rise-rate of the paste is an important parameter for pouring strategies, as the rise-rate in the paste can be slowed or stopped if the stress at the barricade is approaching the design limit of the barricade.

Ideally a continuous modelling approach, meaning that the modeled paste would be continuously added as the model was continuously being solved, would be used to model CPB.
However, this was not plausible given the modelling tool used. The solution to this problem was to mimic continuous loading by introducing the modelled paste into the stope as a series of sequential layers. The thickness of these layers is dependent on the fill-rate of the stope, meaning that a faster fill-rate would have thicker layers while a slower rise-rate will have thinner layers. Ideally, very thin layers would be used in the modelling as this more closely approximates the loading.

In practice the thickness of the layers is restrained by the number of zones within the model. A zone is the building block of the model and is its smallest piece. In all of the models in this thesis the zones used were uniform squares. The larger the model (meaning the more zones it had), the longer the model run times. The zone size was also affected by the fill-rate of the stope. The mining operations in this thesis had typical rise-rates between 20 cm to 40 cm per hour, though in some cases the rise-rate could be over a metre per hour. Stope geometry and pump rates had the greatest impact on rise-rate.

It should be noted that the model makes an assumption that paste fills in flat layers similar to the filling of a bathtub. However, this is known to not be the case, particularly when filling the bottom of a stope (Grabinsky et al. 2010). In reality the CPB flows in a similar fashion to lava, showing a “build and slump” flow pattern. The flat layer assumption was made due to both model limitations as well as lack of knowledge about how and where the paste is flowing.

PasteFill also had to deal with two time scales. The first scale deals with the pour time of the stope, which is connected to the fill-rate and is addressed above. The second is the curing time of the CPB. This was integrated into the model by assigning an initial age to a layer when it is created. After the layer is created, each additional time step of pour time ages that layer one additional step in cure time. Figure 4.1 shows a schematic of this process. The result of this aging process means that the bottom layer is oldest while the uppermost layer is the youngest. Each layer is then assigned its age-appropriate time-dependent input parameters, allowing the modelled paste to exhibit time-dependent behaviour.

The model was created so that multiple pastes types could be used. This was done by programming the model with different input tables depending on the paste type. The ability to model multiple paste types is a necessity, as most mines use at least two types of paste in any particular stope even if they are trying to pour continuously.
A design procedure for determining the in situ stresses of early age cemented paste backfill

4.0 Model Validation

Schematic for model paste fill sequence

Figure 4.1
Likewise, being able to model a pause in the pour is useful as paste plants occasionally experience problems during a pour or if the pour is intentionally staged for some other reason. Therefore, the model was designed so that the pour could be paused. Note that during this pause the model ages all of the previous placed layers appropriately.

The model contains both rock and paste, with paste being contained by a rock “mould”. This mould is built to represent the geometry of the stope. The mould is one zone thick and is fixed in all directions so that it cannot move. Note that this means there is no movement of the rock into the stope. It was assumed that the shear strength of the paste would be lower than the shear stress at the interface of the rock and paste, so the model does not contain any modelled interface or joint between the paste and the rock.

PasteFill incorporates two built-in FLAC3D model components: the basic mechanical model component and the add-on component for fluid flow. A perfectly plastic Mohr-Coulomb (M-C) constitutive model was used to model the paste. For the purposes of the model, the rock was modeled using an elastic Generalized Hoek-Brown constitutive model. However, the choice of the rock model is relatively unimportant as the rock was fixed in all directions. An isotropic fluid flow model was used to model the pore water pressure (PWP) generation.

These two model components were run in a fully coupled mode. This allowed the model to calculate both mechanical stresses as well as a PWP, and allowed this PWP to be drained with time, in essence modelling the consolidation of the paste. For further information and background on these model components please refer to the Itasca FLAC3D manual (Itasca, 2009).

Again, there are two sets of boundary conditions (BCs) for the model, one set for the mechanical model and one for the fluid model. No mechanical BCs are necessary for the paste in a full 3D stope model as the paste was contained by the fixed rock mold. However for a partial 3D (for example a ½ or ¼ model) or any 2D model (full or ½ model), a sliding boundary was necessary on any paste surface that does not contact rock. These paste surfaces include the out-of-plane surfaces in a 2D model.

It was assumed that the rock was more permeable than the paste. Therefore, the fluid BCs consisted of fixing a PWP equal to zero along the paste-rock interface as well as at the paste-air interface (the surface of the paste). This meant that water could freely drain from any of these contacts. In a full 3D model there were no further fluid BC required, but with a partial
3D or 2D model, a free PWP BC was used on all paste surfaces that do not contact rock, essentially prohibiting water flow in that direction. This assumption will be examined in more detail in Section 4.4.

There is one additional note on obtaining modelling results. FLAC3D produces a variety of results including contours, iso-surfaces, etc. However, in order for the modelling results to be useful, the model had to allow for the recording of data at particular, user-defined locations within the model. FLAC3D allows for this by allowing the modeller to monitor and record the “histories” of pre-selected modelling inputs and outputs at selected zones or grid-points within the model.

An annotated copy of the PasteFill 5.0 code is in Appendix 4.

4.2 Input Parameters

This section will discuss the input parameters required for the model. These can be broken into three different areas: the stope geometry, the stope fill-rate, and the laboratory parameters of the paste.

4.2.1 Stope Geometry

The geometry of the stope plays an important part of the model as the geometry has a major impact on how the paste in the stope will behave. However the modeller has little or no control over the shape of the stope as the shape will either be decided by a mining engineer during a planning stage or by how the rock actually breaks when the stope is blasted.

For this chapter the stope geometries were typically simple shapes and could be created using FLAC3D primitives. However, it was found that mesh creation was much easier when a CAD program called Rhinoceros (Rhino) and an in-house Itasca software program called Space-Ranger were used (McNeel North America, 2011).

In the case of the complex instrumented stopes involved in this project, which are discussed in more detail in the next chapter, the geometries were based on the cavity monitoring surveys (CMS) of the stopes. To this end, all of the stope meshes (2D and 3D) were created using Rhino and Space-Ranger.
4.2.2 Stope Fill-Rates

The fill rate of the stope is another parameter that the modeller has little control over, unless, for example, the modeller is using an arbitrary rate for a parametric study. Usually, however, the fill-rate of a stope at any one mine will fall into a standard range of values due to similar stope geometries and allowable pumping rates.

The fill-rate of the stope can be calculated from the volume of the stope, which in turn can be determined from the CMS. Using a CAD program, such as Rhino, the stope volume can be reduced into volumes per unit height. Most paste operations have the ability to monitor the volume of paste that leaves the paste plant and all paste pumps have a maximum pumping rate. By combining these variables, a fill-rate determined from volume can be calculated. However, it was usually necessary to compare these fill-rates with the actual instrumentation data to see how similar the results were and make any necessary modifications.

Note that the terms fill-rate and rise-rate are used interchangeable in this chapter and in Chapter 5. For the purposed of this thesis both terms mean the same thing.

4.2.3 Laboratory Input Parameters

The paste model requires nine input parameters and five were modelled as time-dependent. All of these parameters were calculated from the laboratory testing described in Chapter 3. The five time-independent parameters are:

- the modulus of the water,
- the saturation, the porosity of the paste,
- the density of the paste,
- and the density of water.

The fluid modulus used for all models was $2 \times 10^9$ Pascals, while the water density was 1000 kg/m$^3$. The porosity, density, and saturation of each paste were determined from the lab testing. It was found that the saturation for each paste was below one, however, for modelling purposes, the saturation of all the pastes was assumed to be 1. For porosity and density values please refer to Table 3.7 from the previous section.

The time-dependent input parameters are listed below and will be discussed in subsequent sections:
1. the bulk (K) and shear moduli (G),
2. the friction angle (φ),
3. the cohesion (c), and
4. the coefficient of permeability or hydraulic conductivity (k).

The bulk (K) and shear (G) moduli were calculated using the confined compression modulus (M) and the Poisson’s Ratio (v). The M modulus is the inverse of the coefficient of volume compressibility (m_v). Refer to Chapter 3 for details on how m_v was obtained. Figure 4.2a shows the M moduli curves for all of the paste types. This figure shows that higher binder pastes (Kidd 4.5 and CS 8.5) have the higher M moduli while the lower binder pastes have lower moduli.

Equation 4.1 shows the relationship between the M moduli, the lab testing data, and the K and G moduli:

\[
M = \frac{\sigma_n}{\delta_v} = \frac{1}{m_v} = \frac{4}{3}G + K \tag{4.1}
\]

The G and K moduli can be related to each other using v. It was assumed that realistic values of v for paste would be between 0.15 and 0.49. This means that Equation 4.1 can be solved in terms of either G or K. The other moduli can then be calculated in turn using either Equation 4.2 or 4.3.

\[
G = \frac{3K(1-2v)}{2(1+v)} \tag{4.2}
\]

\[
K = \frac{3G(1+v)}{3(1+2v)} \tag{4.3}
\]

Figure 4.2 b show different moduli curves based on different input v value curves. This figure shows that for a continuous v of 0.49, the G modulus is low and the K modulus is high. This is expected because at a v of 0.5, the material is essentially a fluid, meaning that the G modulus of the material is zero. However, as the v decreases the G moduli curve increases and the K moduli curve decreases, resulting in the curves moving towards each other.
Notes:
1) Poisson Ratio's in c were assumed
The $v$ of the paste could not be determined from the laboratory testing that was carried out. However, several methods were examined to help determine a reasonable assumption of how $v$ changes with time. The concrete and cement industries have carried out studies relating the change of $v$ with time or degree of hydration. These studies show that the $v$ changes from 0.5 during early curing ages, meaning that the paste is behaving like a fluid, to around 0.2 or lower at later curing ages. Other paste researchers have used the concept of maturity, which relates cement age to cement strength, to determine stiffness gain with time (Boumiz et al., 1996; Schutter, 2004; Smilauer and Bittnar, 2006). This method has recently been applied to CPB by Galaa et al. (2011). Both these methods, as well as CPB hydration results, similar to those obtained by Klein and Simon (2006), were used to create the $v$ curves shown in Figure 4.2c. Note that curves were for an initial curve fit only and would need to be modified with further numerical calibration.

The $\phi$ and $c$ inputs were based on the results from the laboratory testing outlined in Chapter 3. However, those results were modified to provide smoother transitions for the model. Figure 4.3 contains plots showing the baseline time-dependent $c$ and $\phi$ curves for all of the pastes. Upper and lower bounds for both parameters were also determined using the laboratory data. The model currently does not utilize the tension component of the M-C constitutive model.

Figure 4.4 shows the $m_v$ and $k$ curves for all pastes. The $k$ values were determined from the laboratory testing outlined in Chapter 3. However, the results presented in Chapter 3 were in terms of changing normal stress, whereas the $k$ and $m_v$ input parameters needed for the modelling have to be specified with respect to time. To this end, the average values for each parameter at each time interval were determined for modeling inputs.

It should be noted that FLAC3D requires an intrinsic permeability (in units of a $m^2/(\text{Pascal/second})$). In order to convert the laboratory values into a useable FLAC3D parameter, the $k$ values (in cm/s) were multiplied by $1.02e^{-6}$ (Itasca, 2009). The upper and lower bounds were also determined by looking at the minimum, maximum, and standard deviation values for all of the $k$ values for each paste at each time interval. It was generally found that order magnitude increase or decrease bounded the data scatter and was adopted as the upper and lower bound for the $k$. 
Notes:
1) Curves shown here were simplified from the Laboratory Test Results shown in Chapter 3

Figure 4.3
Notes:
1) Hydraulic Conductivities calculated from $m_v$ and $C_v$.
Figure 4.5 shows an example of how the baseline value for $\nu$, $\phi$, cohesion, and $k$ were bounded. For this example the plots are shown for CNS 6.5. The bounds were determined by the combination of parameters that would give the highest stress within the paste (meaning weaker paste) and the lowest stress within the stope (meaning stronger paste). This meant that a low $\nu$, high $k$, high $\phi$, and high cohesion should give the lowest stress values in the stope when compared to the baseline values. The modelling input parameters for the other pastes are available in Appendix 5.

4.3 Zone Size Study

As stated in Section 4.1.2, all FLAC3D models are comprised of a collection of zones. In the case of the PasteFill model, as its goal was to model a continuous pour, the use of a smaller zone is preferable to that of a large zone. However, the larger the amount of zones in model the longer the run time required. Figure 4.6 contains the results of a small study on the effect of zone size. Four zone sizes were used in a 12 m wide by 16 m high 2D model. The model was one zone thick. The zone sizes were 10, 20, 40, and 80 cm in size.

Figure 4.6 has three sections. The first is a graph showing the stress results from a location in the centre of the stope at 2 m height. The second is a table showing the number of zones in each model and their approximate run times, while the third contains the zone state plots for the final filling stage of each model. The zone state indicates the current and former failure mechanisms for each zone. Both the graph and the zone state plots show that the model results vary with zone size.

The results show that the larger zone sizes are less sensitive and show less resolution than the smaller zone sizes. This is shown in the zone state plots where the 80 cm plot shows no shear failure while the other plots do. A further example is that neither the 80 nor the 40 cm plots show the shear band that develops near the walls of the stope in the smaller zone size plots. Despite this, it appears that the 10 cm, 20 cm, and 40 cm models are all showing the same mechanics, indicated by the shear zone at the centre of the stope.

The graph shows that the z-direction stresses (VS) for each zone size are similar but that the real differences between the zone sizes are reflected in the x-direction stress (HS) and the pore-water pressure (PWP). It was observed that the HS and PWP curves are similar at lower zone sizes but deviate at the larger zone sizes. However, an examination of the relationships
1) The High Stress Bound has lower strength parameters, Poisson's Ratio, and permeability.
2) The Low Stress Bound has higher strength parameters, Possion's Ratio, and permeability.

**Figure 4.5**

**A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL**

**4.0 MODEL VALIDATION**

**BOUNDED AND BASELINE CURVES FOR CNS 6.5**
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

ZONE SIZE STUDY

Figure 4.6

<table>
<thead>
<tr>
<th>Zone Size</th>
<th>Number of Zones</th>
<th>Runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>9821</td>
<td>~16 hrs</td>
</tr>
<tr>
<td>20 cm</td>
<td>2511</td>
<td>~4 hrs</td>
</tr>
<tr>
<td>40 cm</td>
<td>656</td>
<td>~1 hr</td>
</tr>
<tr>
<td>80 cm</td>
<td>357</td>
<td>~30 min</td>
</tr>
</tbody>
</table>

Notes:
1) 10, 20, and 40 cm results generated from half models.
2) Runtimes obtained using version 5 of PasteFill
between these curves shows that the percent difference between the 40 cm curve and the 20 cm and 10 cm curves is less than 30%. The largest difference was in the horizontal stresses.

A comparison of the modeling results shows that the 10 cm and 20 cm curves and failure plots are similar, with the 40 cm model being reasonably close to them, but with the 80 cm model not capturing any similar behaviour. However, as mentioned in Section 4.1.2, a balance is needed between zone size and run time. The table contained in Figure 4.6 shows the number of zones and runtimes for the model. These numbers show that when the zone size is decreased in half (for example from 40 cm to 20 cm) the number of zones, and the resulting runtime, increased approximately four times. This increase is negligible for small models, such as the one presented, but for larger models this difference can mean a model runs for a week versus a month. Also note that the 4-fold increase is for a 2D model only; for a 3D model there is an 8-fold increase due to the extra dimension. To this end, it was decided to model the studies shown in the rest of this section using 20 cm zones but to model the larger models using 40 cm zones. Note that this means that the modeller must use a consistent zone size when comparing two models of the same stope.

### 4.4 The Impact of Drainage Boundary Conditions

A brief study was undertaken to examine the effect of the assumed PWP-equal-to-zero drainage BC. This was done using a 2D vertical stope that was 6 m wide and 17 m high. The rise-rate within the stope was 0.2 m/hr and the model had a zone size of 20 cm. The total pour time was 85 hrs long.

Three different drainage conditions were looked at: none, full, and partial. The full drainage condition is what was described earlier in Section 4.1.2, while no drainage was the opposite, meaning that no drainage was allowed by the rock. The partial drainage condition had impermeable sides but had allowed flow from the bottom and the top of the paste.

Figure 4.7 presents the results from study. Both the graph and the contour plots show results from the end of the pour (85 hrs). The graph shows the stresses generated at the measurement location in the centre of the stope at 2 m height, while the contour plots show the PWP, and the total and effective stress contours.

What is observed in the graph is that increased drainage decreases the stresses in the stope. When there is no drainage the paste essentially acts as a dense fluid and the stresses stay
Notes:
1) All Plot Results Generated from Half-Models
2) The use of an apostrophe (') denotes effective stress

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WILL 3 - DRAINAGE BOUNDARY CONDITIONS COMPARISON

Figure 4.7
close to the isotropic stress line and show very little arching. This is shown particularly well in the “no drainage” stress contour plots, where the stress contours are relatively horizontal. The two effective stress plots show that there is minimal effective stress generated during the filling of the stope.

The partially drained contours show that the bottom of the stope (below the bulb of high PWP shown in the PWP plot) exhibits both arching behaviour and effective stress gain. However, above that PWP bulb, there is isotropic stress loading and little effective stress.

The fully drained contours show that both arching and effective stress gain are occurring in the stope. In particular, the effective stresses develop more rapidly near the boundaries of the stope due to the proximity of the PWP-equal-to-zero BC.

4.5 Parametric Study of Model Inputs

This section presents the results from a parametric study. The 2D test stope, with the same parameters from Section 4.4, was used for the study. All of the stress results (VS, HS, and PWP), unless stated otherwise, were recorded at the centre of the stope at a height of 2 m.

The study involved changing only one parameter at a time. For example, if one was examining the effects of changing $\phi$ on the paste, one would run a baseline model, then run a model with only the $\phi$ changed to a higher value, and finally run the model with only the $\phi$ changed to a lower value. This was done for each of the time dependent variables: $\phi$, cohesion, $k$, and $v$. All of the models in this section used the CNS 6.5 input parameters.

4.5.1 Friction Angle ($\phi$) Study

Figures 4.8 shows the results for the $\phi$ parameter study. The stope was modeled using the baseline, upper bound, and lower bound input $\phi$ values from Figure 4.5c. Two additional models for each shape were also run, one using a constant $\phi$ of 45° and one using a constant $\phi$ of 25°. Each figure contains a graph showing the stress results for each model. This graph shows the model results taken from a measurement point located at the centre of each stope and at a height of 2m. The graph also has a isotropic stress line which was calculated by using Equation 4.4:

$$\sigma_v = \rho gh$$  \hspace{1cm} (4.4)
where $\rho$ is the density of the paste, $h$ is the height of paste above the measurement point, and $g$ is gravity (9.81 m/s$^2$). Any further isotropic stress rise-rates shown on any graph presented in this chapter were calculated the same way. There are also a series of zone state plots for the 25°, 45°, and baseline models on each figure. The zone state plots show the current and past zone failure mechanisms at various pour times depending on the model.

The graph in Figure 4.8 shows that there is little difference between the baseline and the upper and lower bound curves. There was generally a slight difference between the 45° curve and the baseline curves, with the 45° model, experiencing less stress than the other models. A brief examination of the corresponding zone state plots shows that the amount of sheared zones in the baseline model is slightly greater than the amount in the 45° model but the failures are in similar areas and show similar patterns. Note that all of the stress curves, besides the 25° curves, are identical until the pour reaches a certain pour time after which the curves start to deviate (~50hrs).

It can also be observed that decreasing the $\phi$ to 25° causes the paste to experience more stress and increases the amount of shear failure that is occurring in the model. The zone state plots also show that the 25° model starts experiencing failure sooner than the other models.

This study shows that changing the $\phi$ within the range of the laboratory bounds has little impact on the stresses experienced by the stope. Increasing the $\phi$ to a realistic upper bound of 45° caused the model to have a slight decrease in stress. Decreasing the $\phi$ to 25° increased the stress within the stope. These results indicate that the model is somewhat sensitive to the $\phi$. However, an increase in $\phi$ results in only a small decrease in the in situ stress.

### 4.5.2 Cohesion Study

Figure 4.9 has the same format as Figure 4.8 but shows the results of the cohesion study. Each shape was modeled using the baseline, upper bound, and lower bound input cohesion values from Figure 4.4-b. Two additional models were also run, one using a cohesion curve five times that of the cohesion baseline curve and the other using a curve that was one-fifth of the baseline curve.

The first thing to note is that the VS results were unexpected. It was expected that the higher cohesion would produce stronger pastes which would decrease the stress the paste
Notes:
1) All Plot Results Generated from Half-Models
2) Red Dot Shows Approximate Location of Graph Measurement Point
3) Vertical Dashed lines on Graph correspond to zone state plot times

Failure State Plots shown at 10, 30, 50, and 85 hours (as labeled on Baseline plots)

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4.0 MODEL VALIDATION

CNS 6.5 - FRICTION ANGLE STUDY

Figure 4.8
Notes:
1) All Plot Results Generated from Half-Models
2) Red Dot Shows Approximate Location of Graph Measurement Point
3) Vertical Dashed lines on Graph correspond to zone state plot times
experienced. However, the graph in Figure 4.9 shows that the low cohesion pastes deviate first and initially have lower in situ VS than the higher cohesion pastes. This behaviour is reversed by the end of the pour, with the lower cohesion pastes experiencing more VS than the higher cohesion pastes. Despite the behaviour observed in the VS curves, the HS and PWP curves show what is expected, mainly that higher cohesion pastes have lower in situ stress.

There are a couple of observations to note about the stress curves. The first is that the curves generated from the paste above and below the baseline values deviate at the same time. For example, the lower cohesion pastes start deviating from the baseline at approximately 25 hrs while the higher cohesion pastes deviate at approximately 50 hrs. Note that this was the same time that the curves in Figure 4.8 started to deviate.

The second is that increasing the cohesion earlier does not necessarily decrease the amount of stress in the paste. A comparison of the zone state plots and the stress graph shows that onset of both the shear failures, if the paste experiences any, and the stress deviations occur at around the same time. This indicates that, up to that point in time, the paste in all of the models is initially strong enough to resist shear failure. Indeed, the 5x cohesion baseline model did not have any shear failures. This means that increasing the cohesive strength of the paste will only be able to decrease the in situ stress in the paste by a certain amount. In this case of this model, the in situ stress will only decrease to the 5x cohesion model curve. Decreasing the cohesion generally increases the in situ paste stresses.

This study shows that changing the cohesion within the range of the laboratory bounds has some impact on the stresses experienced by the stope. However, the majority of the sensitivity is due to cohesion decrease. There is a limit to the usefulness of increasing the cohesion as the paste will reach a point where there are no shear failures. In general, the cohesion has a slight impact on the stresses within the stope.

4.5.3 Hydraulic Conductivity (k) Study

Note that only a parameter study for k will be discussed in this chapter. The reason for this is the relationship, shown in Equation 3.1, between k, m_v, and C_v. This relationship shows that the k of a paste is directly proportional to its C_v, while the C_v is inversely proportional to its compressibility (m_v). This means is that a study changing m_v, but keeping the all the other parameters constant, would generate similar results.
Figure 4.10 shows the results for the hydraulic conductivity (k) parameter study. The stope was modeled using the baseline, upper bound, and lower bound input k values from Figure 4.5-d. Two additional models were also run, one using half the upper bound values and one using half the lower bound values. The figures follow a similar format as the ones from the previous two sections.

It was expected that the lower k parameters would produce the highest stresses as this meant that the paste was essentially a dense fluid. On the other hand, the high k parameter was expected to produce the lowest stresses as this paste would have the least amount of water in it. However, it was found that the HS and PWP curves behaved as expected, but the VS curves did not.

In Figure 4.10 the low k paste did produce the highest VS, HS, and PWP. This model’s curves also showed the highest degree of stress decay. Note that none of the zones in this model failed by shear. The next highest VS curve was the high k model followed by the mid-high k, baseline, and mid-low model curves. All of these models had zones that failed in shear.

It was noted in the previous sections that the majority of the model curves, particularly for higher strength models, deviated from the baseline curve at the same time. In the case of the baseline k value this deviation time was approximately 50 hrs. This time is shown by brown line on the graph in Figure 4.10. All of the baseline stress curves change direction where they intersect the brown line. The VS curve shows a slight increase in stress rise-rate, while the HS and PWP curves show a decrease in the amount of stress decay. This “kink” in the baseline curves also corresponds to the onset of shear failure along the edge of the stope wall and the paste. If the graphs in Figures 4.8 and 4.9 are examined, the same sort of behaviour is observed. Also, all of the curves in Figure 4.10 show the same relationship between these “kinks” and corresponding boundary shear stresses except the low k model. This repeated “kink”/boundary shear relationship shows an apparent correlation between the onset of the boundary shear and the change in the shape of the stress curve.

These “kinks” in Figure 4.10 appear at different times for each model. The high k model “kink” is the first to appear at around 30 hrs, followed by the mid-high k at around 40 hrs, the baseline at 50 hrs, and the mid-low k model “kink” at 60 hrs. Again the low k model curves do not have a “kink” as there was no shear failure in this model. Note, however, that all of these models show stress decay long before the onset of shear stress at the stope edge.
High Perm = 10x Baseline
Med-High Perm = 5x Baseline
Med-Low Perm = 1/2x Baseline
Low Perm = 1/10x Baseline

Notes:
1) Plots Generated from Half Models
2) Red Dot Shows Approximate Location of Graph Measure Point

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4.0 MODEL VALIDATION

CNS 6.5 - HYDRAULIC CONDUCTIVITY STUDY

Figure 4.10
Figure 4.10 shows that there are two different actions happening in the stope. The first is the PWP reduction phase where the change in the stress is caused by decreasing PWP due to drainage, hydration, etc. However, after this phase reaches a certain point, the shear stress phase is entered. This phase starts when the material starts shearing along the paste-rock interface. Note that shear failures located at the middle of the stope do not seem to promote this “kink” behaviour in the stress curves.

The two different stress reduction mechanisms explain the behaviour seen in the vertical stresses. The low-k model had the highest VS as it only experienced the PWP reduction phase. The high-k model has the second highest VS as it had been in the shear failure phase for the longest. However, the other models are in middle ground where they experienced both the PWP reduction and shear failure phases.

Figure 4.11 shows a further exploration of the results above. This figure presents plots of the stress paths for several zones from the low, high, and baseline k models. Three sets of zones were followed over the life of the pour. Each set had 3 zones located at the centre of the stope, halfway between the centre and the stope wall, and at the stope wall. The zone heights were 2, 5.6, and 8.6 m, shown as green, red, and blue curves respectively. Note that the green curves are for the oldest zones while the blue curves are the youngest zones. The green curves are 74 hrs old at the end of the pour while the red are 55 hrs and the blue are 44 hrs old. The results are presented in effective principle stress ($\sigma_1'$ and $\sigma_3'$) space.

There are three series of graphs on Figure 4.11. The top shows the effective stress paths for the low k model, the middle the baseline k model, and the lower shows the low k model results. The graphs on of the left hand side (LHS) of the figure are for the stope centre zones, the graphs in the middle are zones located halfway between the centre and edge of the stope, while the right hand side graphs (RHS) are for the zones located at the edge of the stope. When a zone failed in shear it is indicated by use of a diamond shaped marker outline of the same colour as the line. Note that not all of the zones shown have failed in shear and the failed zones did so at different times.

The behaviour shown in these graphs is dictated by the PWP. All of the graphs contain curves which generally follow the same basic trend. Each stress path starts out with both increasing $\sigma_1'$ and $\sigma_3'$. At some point, $\sigma_3'$ starts to decrease while $\sigma_1'$ keeps increasing, causing the curve to turn and move towards the $\sigma_1'$ axis. After this, the curve shows another increase in
Z 369, Z 377, and Z 383 = 2 m height
These zones were placed at 11 hour and were 74 hours old at end of pour
Z 997, Z 983, and Z 991 = 5.6 m height
These zones were placed at 30 hours and were 55 hours old at end of pour
Z 1425, Z 1433, and Z 1439 = 8.6 m height
These zones were placed at 44 hours and were 41 hours old at end of pour

A diamond marker of the same colour indicates that the zone had failed in shear by this point
σ₃’ which, in turn, causes the curve to turn and move away from the σ₁’ axis. The shape of the curve as it moves away depends on what is happening to that particular zone at the time. Note that not all of the curves in Figure 4.11 show the full trend described above.

The behaviour in these curves is due to the magnitude of the high PWP bulb as well as the speed by which this high pressure bulb moves upwards through the body of the stope. The high pressure bulb moves the quickest in the high-k model but has the lowest magnitude, whereas the bulb moves more slowly in the low-k model but has the highest PWP. The centre of the high PWP bulb has the lowest effective stress.

The high PWP originates at the bottom of the stope. The red and blue curves represent zones that are located above the high PWP bulb. Once the paste reaches these zones, the σ₃’ and σ₁’ stresses increases. However, as the centre of the PWP bulb moves towards a zone, the effective stress in that zone decreases, causing a decrease in σ₃’ (the first turn). Then, as the centre of the PWP bulb moves above and away from a zone, its σ₃’ starts to increase (the second turn). Note that the green curves, shown in Figure 4.11, do not show the first reduction of σ₃’.

The reason for this is that those curves represent zones that are below the origin location of PWP bulb. This means that they only show the response of the PWP bulb moving away from them.

The magnitude of the PWP also affects the response of the model. This magnitude is directly related to the permeability (k). A low k means that the rate of PWP reduction is low. A high k means that the rate of PWP is higher.

The difference between a low and high PWP reduction rate explains the rapid stress response seen in the centre and halfway model graphs for the low-k and baseline models, whereas the high k plots show a much slower and less dramatic response. This difference also explains why only the baseline model had shear failures in the middle of the stope, while the others did not.

Most of the zones that failed in the model, either at the edge or in the middle, did so at a relatively early curing age (<24 hrs). The low-k model plots, for the centre and halfway zones, show early age effective stresses that are too low to reach any of the early failure envelopes. By the time the zones start to gain effective stress, the strength in these zones is great enough to prevent shear failure. The centre and halfway zone plots for the high-k model show that the effective stresses are much higher and that the stress curves show very little response to the PWP bulb. The reason for this is that the high-k model PWP bulb has less magnitude and moves away
faster. This means that during the early curing ages, the zones never get close to reaching their failure envelope.

However, the centre zones in the baseline model have a high PWP bulb that moves slowly. This causes higher effective stresses than the low-k model but also a faster stress curve response than for the high-k model. So, in the case of the centre of the stope, this means that when the stress curve moves towards the $\sigma_1'$ axis, the paste is younger and it reaches one of the early aged failure envelopes and fails.

The shear failures at the stope edge are due to a similar response but different timing than the shear failures seen at the centre of the stope. The PWP at the edges are lower, as they are farther away from the centre of the stope and the high PWP bulb. However, due to the higher stress reductions at the edges of the stope, the overall total stresses are also lower at the edge of the stope. The shear failures typically start when a zone’s stress path curves away from the $\sigma_1'$ axis, when the PWP bulb is closest to the zone. This means that the effective stress at the zone decreases, causing a decrease in $\sigma_3'$ which brings the stress path in touch with the failure envelope. The high-k model shows the earliest response as its PWP bulb moves the fastest, while the low-k model shows the slowest response as its PWP bulb moves the slowest.

There is another difference between the failed zones in the centre and at the stope edge. The centre baseline stress path curve shows that after a zone fails, it shows a relatively linear $\sigma_1'$-$\sigma_3'$ stress increase. Note that the zone state plots in Figure 4.10 show that a zone has either failed previously (p) or is currently failing (n). These plots also show that once a centre zone fails it typically does not keep failing, hence the linear stress increase observed in the centre zone stress paths after failure. The increasing strength of the paste, the increasing distance between the high PWP bulb and the zone, and the lack of mobility of the centre zones prevent the zone from failing multiple times.

However, a typical edge zone keeps failing after its initial failure. This means that its stress path is erratic, as shown in Figure 4.11. These zones are located where the majority of the movement in the model is taking place. What this means is that even though the zone keeps gaining strength, it also keeps reaching its curing age strength envelope causing it to fail again.

Figure 4.12 shows the effective vertical and horizontal stresses measured at the zone locations mentioned in Figure 4.11. In particular, these plots provide an explanation for the shear failures that originate at the stope edge. The side plots for the baseline and high-k models
High Perm = 10x Baseline
Low Perm = 1/10x Baseline

Figure 4.12
show that the vertical stress drops to or below the horizontal stress, with the time of this drop corresponding to when the zone fails in shear.

4.5.4 Poisson Ratio (ν) Study

Figure 4.13 shows the results from five different ν models. It has a similar format to all of the previous figures in Section 4.5. For this study, the baseline ν curve was compared to three constant ν curves and one variable curve. These curves are shown in 4.13b. The three constant curves were at a ν equal to 0.49, a ν equal to 0.3, and a ν curve equal to 0.15. The other variable ν curve was modeled to show the effect of a gentler decay of ν with time. As previously mentioned, a ν of 0.5 means the material behaves similarly to a fluid while as the ν decreases a material will show decreased lateral expansion due to the same vertical compression.

The graph in Figure 4.13a shows that the model is sensitive to ν, particularly at higher values. The constant ν -equal-to-0.49 model shows the VS and HS are virtually the same while its PWP curve is substantially higher than the other values. However, this behaviour is unlikely to happen as CPB does not stay a fluid for very long.

Otherwise, the main difference shown by decreasing ν is that the HS decreases towards the PWP curve. The graph in Figure 4.13a shows that, except for the ν-equal-to-0.49 model PWP curve, the other PWP curves are very similar. However, as the ν decreases, the HS curves decrease and in the case of both the baseline and ν-equal-to-0.15 models, the HS and PWP curves trend together for longer before deviating.

The model is somewhat sensitive to this parameter. However, this is mainly a result of the large difference between a ratio of 0.5 and 0.15. As this parameter rapidly stabilizes, it has little actual impact on the model.

4.5.5 Summary of Laboratory Input Parameters

Section 4.5 dealt with a parametric study of the four main laboratory input parameters: φ, cohesion, k, and ν. This parametric study showed that PasteFill is most sensitive to changes in k, slightly sensitive to ν, but is less sensitive to cohesion and φ. The lack of sensitivity shown to the strength parameters (cohesion and φ), particularly when these parameters are increased, is due to the lack of zone failures. For example, increasing the cohesion of the paste will only have
Isotropic Stress

Figure 4.13

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

1. Plots Generated from Half Models
2. Red Dots Denote Approx. Location of Graph Measurement Point

Notes:

0.5
0.4
0.3
0.2
0.1

Pour Time (hours)

Stress (kPa)

0
20
40
60
80
100 120
140
160

0
2
04
06
08
10
12
14
16

Z
PR = 0.49
X
PR = 0.30
BL
Z
PR = 0.15
X
PR = 0.15
PP

Isotropic Stress

a)

b)

Poisson's Ratio

0
0.1
0.2
0.3
0.4
0.5

Cure Time (hours)

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

CNS 6.5 - POISSON'S RATION STUDY

Figure 4.13
a slight increase in the performance of the paste because once the paste reaches a particular strength, the model no longer experiences any shear failures. It was found that the model was not very sensitive to changes in $\phi$ unless this parameter was decreased dramatically.

Figure 4.14 compares the results of five model runs, shown both in total and effective stress space. The first model used baseline parameters, the next two models used baseline $k$ parameters but used either high or low strength parameters, and the final two models used high strength and $k$ parameters or low strength and $k$ parameters. These graphs, particularly the effective stress graph, show that PasteFill is most sensitive to the $k$ parameter, as there is little difference between the baseline curve and high and low strength curves that used baseline $k$ parameters, but there is a large difference between the these curves and the models that used increased or decreased $k$ parameters.

The other interesting observation from this section was delineation of two stress decay phases: the PWP reduction phase and the shear failure phase. During the PWP reduction phase the stresses decay due to the reduction of PWP by drainage, hydration etc. However, during the next phase, the stress decay is due to shear failures along the paste/stope wall interface. Note however, that it is possible for the material to experience both phases simultaneously.

### 4.6 The Impact of Rise-rate

One of the criteria for the model was to be able to handle variable rise-rates, including pour stoppages due either to staged pours or plant shutdowns. This section will present a series of nine theoretical rise-rates. The model stope has the same geometry as the one used in Sections 4.4 and 4.5 (unless stated otherwise). All of the graphs include an isotropic stress rise-rate shown as a black line which was calculated using Equation 4.4.

Figure 4.15 shows the first eight rise-rates used for this study. The first was the same rise-rate used in Section 4.3 and 4.4, which was a constant 0.2 m/hr and is denoted as Rise-rate A (RRA). RRB and RRC are also constant rates, with RRB being at 0.4 m/hr and RRC being 1 m/hr. RRD, RRE, and RRF have the same respective rise-rates (0.2, 0.4, and 1 m/hr), but with a 24 hour pour delay once the modelled paste reached 9 m of height. RRG has an initial rise-rate of 0.4 m/hr, followed by a 48 hour pour stoppage when the paste reached 9 m height, after which the pour continued at the same rise-rate. RRH and RRI have the same rate as RRA (0.2 m/hr) but in RRH the model was allowed to run to 300 hrs (215 hrs longer than required to fill the
The use of an apostrophe (') denotes effective stress.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

RISE RATE COMPARISON

Figure 4.15
stope) while in RRI the stope geometry was changed to allow the same rate to fill for 300 hrs. In order to allow for this increased filling time the stope height was changed from 16 m to 60 m.

Figure 4.16 shows the plots for the models that used RRA, RRB, and RRC. This graph shows that a longer pour time (or decreased rise-rate) results in decreased stresses in the stope. This stress decrease is due to increased drainage and hydration time, both of which cause the strength of the paste to increase. On the other hand, a short pour time (or increased rise-rate) does not allow for much drainage or hydration resulting in a weaker paste and increased stress within the paste. Similar stress responses, due to the variance in rise-rate, have been observed in the field instrumentation (Thompson et al., 2009, 2010b, 2011a, 2011b).

Figure 4.17 shows plots for the rise-rates that contain pour delays. Both plots on this figure show the expected stress decay during the pour stoppage and the following stress increase once filling recommenced. As in Figure 4.16, the faster rise-rate produced the highest stresses; however due to the pour stoppage, the final stresses in these models were not as high as the stresses seen in Figure 4.15. However, the difference between the continuous and paused pour model stress results decrease with increased pour time. For example, the difference in VS between the two 1 m/hr models is 42 kPa, while the difference in VS between the two 0.2 m/hr models is only 17 kPa. Similar trends are found for the HS and PWP. This indicates that a pause in the pour has less impact on the results if a small rise-rate is used.

Figure 4.18 contains plots for RRE and RRG. The only difference between the plots is that RRG had a 48 hour pour delay whereas RRE only had a 24 hour delay. Both plots show similar trends, although the RRG plot shows more stress decay due to its longer delay period.

Figure 4.19 shows the results for two of the longer running models. RRH used a rise-rate of 0.2 m/hr until the paste reached a height of 17m after which the model continued to run to 300 hrs without any additional paste being added, while RRI was also runs for 300 hrs, but continuously fills a 60 m high stope. This figure contains includes a plot of comparing the results of the two rise-rates and a set of contour plots showing VS, HS, and PWP for each of the models.

The graph in Figure 4.19 shows the model results and the vertical isotropic stress rise-rates. What is shown is that the additional loading experience in the RRI model has very little impact on the results at the bottom of the stope (i.e. the measurement point at 2 m height). The major differences between the two loading rates are that the RRH model curve decays more rapidly than the RRI curve. However, both the VS and HS curves are essentially equal after the
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

RISE RATE COMPARISON - CONTINUOUS RISE RATES

Figure 4.16

Note: All results are from Baseline Input Values
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

RISE RATE COMPARISON - PAUSED RISE RATES

Figure 4.17
Note: All results are from Baseline Input Values

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

RISE RATE COMPARISON - EXTENDED DELAY POOURS

Figure 4.18
CONTOUR PLOTS

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

RISE RATE COMPARISON - LONG POURS

Figure 4.19
PWP at the measurement point reaches zero. This indicates that after the PWP at point reaches zero the current drainage and consolidation process have finished and the stresses in the stope at that point, regardless of loading path, will follow the same path.

The contour plots help illustrate the above results. At the bottom of the stope the contours are very similar to each other whereas the upper portions of the contours are very different. This indicates that, for a given stope width, there is a height above which additional loading has very little impact on the stresses at the bottom of the stope.

Figure 4.20 shows a comparison plot between RRI and RRJ. RRJ models another 60 m high stope but fills the stope using variety of rise-rates as well as multiple pour delays of different lengths. This plot shows that, initially, the rise-rate plays an important part in determining the stresses in the stope. This is shown by how the changes in the RRJ rise-rate impact the model’s stresses, whereas the continuous RRI rise-rate does not show any changes. However, as the pouring time increases, the influence of the rise-rate decreases until the differences between the two models’ curves are minimal. Both models also show that after a certain period of time has elapsed, the bottom of the stope is not affected by what is happening above it.

4.7 The Impact of Stope Geometry

This section examines the impact of stope geometry on the modeling results. For this section only the results obtained from the CNS 6.5 paste are shown. All models were run using a rise-rate of 0.2 m/hr. The results shown in the graphs were all taken at the same measurement point, which was at the centre of the stope at 2 m of height. All of the graphs also include a isotropic stress rise-rate shown as a black line which was calculated using Equation 4.4.

The first sub-section presents the 2D modelling results, the second subsection presents the 3D modelling results, and the third subsection conducts a study examining the influence of geometry on stresses within the access drift.

4.7.1 Two Dimensional Geometry Study

There were three general shapes modelled in this sub-section. The first was a simple rectangular or vertical stope, the second was a fully inclined stope, and the third was an inclined stope but with a rectangular bottom section simulating a drift access. The width dimensions of
### RRI (0.2 m/h)

<table>
<thead>
<tr>
<th>(hrs)</th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>60</td>
</tr>
</tbody>
</table>

### RRJ

<table>
<thead>
<tr>
<th>(hrs)</th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>9</td>
</tr>
<tr>
<td>69</td>
<td>9</td>
</tr>
<tr>
<td>89</td>
<td>17</td>
</tr>
<tr>
<td>101</td>
<td>17</td>
</tr>
<tr>
<td>171</td>
<td>45</td>
</tr>
<tr>
<td>195</td>
<td>45</td>
</tr>
<tr>
<td>270</td>
<td>60</td>
</tr>
</tbody>
</table>

**Figure 4.20**

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

RISE RATE COMPARISON - RRI VERSUS RRJ

Figure 4.20
these shapes were changed so that the resulting stress changes could be compared. Three widths were used in the vertical stopes: 6, 12, and 24 m, while two widths were used in the incline stopes: 6 and 12 m.

Figure 4.21 compares three different vertical stope configurations. The dimensions of each stope model are shown in the bottom left of the figure. All of the stress curves, recorded at the measurement location, are shown in the graph. The first result that the graph shows is the dramatic increase in VS between the 6 and 12 m wide stopes, as well as the much smaller difference in VS between the 12 and 24 m stopes. Another item to note is the difference in the curve shapes. The 6 m curves show a large amount of curvature denoting a large amount of influence from the rock-paste interface, while the 12 and 24 m model curves show a much decreased curvature denoting less influence.

The PWP and VS contour plots on Figure 4.21 show what was expected: a PWP bulb in the lower half of the stope and the VS contours showing less stress with smaller widths than with the larger widths. However, the HS contours show something unexpected. The 6 m stope exhibits some stress arching in the upper portion of the stope, but there is a low pressure bulb near the bottom of the stope. As the stope width increased to 12 m, the arching in upper portion of the stope decreased and a higher stress bulb was established above a lower stress bulb. In the 24 m model, the upper stress bulb has increased and the lower stress bulb has separated into two separate bulbs situated near the lower corners of the stope. This stress development is partially due to the influence of the corner of stope as well as the change in stresses due to the arching of the vertical stress.

Figure 4.22 shows a comparison between the 6 m vertical, inclined, and inclined drift stopes. Again, the dimensions of each stope model are shown in the bottom left of the figure, the stress curves are shown on the graph, and the stress contour plots for the different geometries are shown on the right of the figure. The green line on the graph shows when the paste in the inclined drift stope moves from the drift portion of the geometry into the inclined portion. The graph shows that the stresses in the vertical stope model are the highest, followed by the inclined drift stope and the fully inclined stope.

The PWP curves shown in the graph do not represent the difference seen in the PWP contour plots. The contour plots show that the vertical stope stresses are significantly higher than the PWPs seen in either inclined stope. In this case, the PWP in the vertical stope plot is
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES

4.0 MODEL VALIDATION

STOPE SHAPE STUDY - 2D VERTICAL STOPE COMPARISON

Figure 4.21
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

STOPE SHAPE STUDY - 2D SMALL INCLINED COMPARISON

Figure 4.22
much higher than the two inclined plots. However, of the two inclined plots, the fully inclined stope generates higher stresses than the inclined drift plot as the shape of the inclined stope means there is less vertical distance to generate PWP.

The VS curves indicate that, again, the vertical stope has the highest stresses. This is also shown in the contour plots. However, the contour plots of the two inclined stopes show that the VS is being placed both on the footwall of the stope and the bottom of the stope. However, the maximum VS, in both models, is located below the largest height of paste allowed by the shape of the stope. A comparison of the two shows that there is a stress shadow along the right-hand-side (RHS) of the drift in the drift incline model.

The HS stress curves for both inclined stopes are very similar while the HS curve of the vertical stope is higher. An interesting result shown by the contour plots, for both inclined stopes, is that HS is higher on the hanging wall side of the stope. The reason for this increased stress is likely due to the orientation of the stope driving the HS in that direction.

Figure 4.23 provides the results for the 12 m wide inclined stope models in the same format as shown in Figure 4.22. There are some trend similarities between the two sets of results but, in general, the increased width reduces the arching effect within the stope and changes the geometry enough to affect the stresses. The stresses observed in the wider stope models are higher than the stresses observed in the narrower stopes in the previous paragraphs. However, similar trends are apparent between the two model types. The first is that all of the inclined models have higher VS on the footwall and lower VS on the hanging wall. The incline drift model has a VS stress shadow on the RHS of the drift due to the drift. The drift incline model also has a more centralized, higher VS than the completely inclined stope model.

The three figures presented in this section show 2D models are affected by changes in the geometry. The results show what was expected, namely, that widening a stope increases the stress within it and inclining a stope not only decreases stresses but also changes the stress patterns in the stope. This section has shown that the model can use multiple 2D model shapes and provide reasonable results for each shape.

4.7.2 Three Dimensional Geometry Study

Figure 4.24 contains two graphs, each showing a series of curves recorded at a measurement location that was at the horizontal centre of the stope and at 2 m height. The first
Figure 4.23

FLAC3D 4.00
2003/02/02 11:20:19 AM

Contour of Gg Pure Pressure
0.0000E+00 2.0000E+04 4.0000E+04 6.0000E+04 8.0000E+04 1.0000E+05 1.2000E+05 1.4000E+05 1.6000E+05 1.8000E+05 2.0000E+05 2.2000E+05 2.4000E+05 2.6000E+05 2.8000E+05 3.0000E+05

FLAC3D 4.00
2003/02/02 11:20:19 AM

Contour of ZZ Stress
0.0000E+00 2.5000E+00 5.0000E+00 7.5000E+00 1.0000E+01 1.2500E+01 1.5000E+01 1.7500E+01 2.0000E+01 2.2500E+01 2.5000E+01 2.7500E+01 3.0000E+01 3.2500E+01 3.5000E+01 3.7500E+01 4.0000E+01

FLAC3D 4.00
2003/02/02 11:20:19 AM

Contour of XX Stress
0.0000E+00 2.5000E+00 5.0000E+00 7.5000E+00 1.0000E+01 1.2500E+01 1.5000E+01 1.7500E+01 2.0000E+01 2.2500E+01 2.5000E+01 2.7500E+01 3.0000E+01 3.2500E+01 3.5000E+01 3.7500E+01 4.0000E+01

Note 1: Rectangular Slope Contours were generated from Half Model Contours Mirrored at Centerline of Slope

Note 2: Contours are in Pascals

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

STOPE SHAPE STUDY - 2D LARGE INCLINED COMPARISON

Figure 4.23
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

STOPE SHAPE STUDY - 3D VERTICAL STOPE COMPARISON

Figure 4.24
graph shows the results for the 6 m wide stope while the second shows the results for the 12 m wide stope. The figure also shows schematics for the seven different model configurations. The bottom row shows a series of 6 m wide models with changing lengths, while the RHS column shows a series of 12 m wide stopes. Please note that the colour of the schematics corresponds to the colour of its respective curves. Also note that the HS shown on the plots are in the x or width direction.

The first result to notice is that, as expected, increasing the length of the stope increases all of the stresses at the measurement point. In the case of the 6 m wide stope, the 6 m length shows significantly less stress than the 12 and 24 m length models. Additionally, the difference between the stresses determined from the 12 and 24 m length models is much smaller than the difference in stresses between the 6 and 12 m length models. The shapes of the curves also differ with the 6 m length curve peaking much sooner than the other two curves. Similar trends can be observed in the 12 m width models.

One unexpected result was the difference in the PWP curves. The 6 m length model shows an earlier deviation of the PWP from the HS than the other models. This indicates that additional length impacts the drainage time of the paste which is counter-intuitive. This result is more difficult to observe in the 12 m width models but can also be identified.

The stress curves for the 2D 6 and 12 m width models are also shown on the plot in Figure 4.24. The 6 and 12 m 2D model curves are very similar to the 3D model curves of the 6x24 m and the 12x24 m models. This means that for the 6 m width model, a stope length approximately four times the width would generate results similar to that of the 2D model. However, for the 12 m width, a stope length approximately two times the width would generate similar results to that of the 2D model. This implies that the model results are not dependent on aspect ratio.

Figure 4.25 presents the same sort of data presented in Figure 4.24 but the results are for fully inclined 3D models. The square vertical model’s results are also included for a comparison.

When the 6 m wide models are compared, the first result of importance is the drop in stresses between the vertical and inclined 6x6x17 m stope models. Again, this is similar to what was observed in the 2D modelling shown in Figure 4.22. However, as the length of the stope is
Figure 4.25

A Design procedure for determining the in situ stresses of early age cemented paste backfill

STOPE SHAPE STUDY - 3D INCLINED COMPARISON - INCREASED LENGTH

Note: all dimensions are in meters
increased, the stresses within the stope increase above that of the vertical model. All of the 6 m wide model stress curves show similar shapes.

The 12 m wide models show a different trend. In this case, the vertical model has higher stresses than both inclined models although the difference between it and the largest inclined model are minimal. What this reveals is that the modelling results are not consistent with aspect ratio as the 6x12x17 m and 12x24x17 m models do not show similar trends when related to vertical stopes. Again, this indicates that the model results are not dependent on aspect ratio and that there is likely a non-linear model response to aspect ratio.

Figure 4.26 looks at extending the width of the inclined stope while keeping the length the same. This figure shows similar trends to those observed in the two previous figures. In general, the stresses observed in Figure 4.26 are less than the stresses observed in Figure 4.25, even though the footprint dimensions of the models are the same. This shows that changing the stope geometry impacts the stress.

Figure 4.26 also shows the same aspect ratio behaviour mentioned above. In both the 6 and 12 m models the 2D models have the highest stresses. In the case of the 6 m long 3D stopes, even the 24 m wide stope does not have stresses close to that of the 2D model. This is different than what was observed in Figure 4.24 where the 6 m 2D vertical stope model had similar stress values to that of the 3D 6x24x17 m stope model. However, the 12 m long 2D model and the 24x12x17 m model show similar stresses.

4.7.3 Three Dimensional Drift Study

Figures 4.27 and 4.28 present the results of the drift length on stresses within the paste. These figures contain the results for a vertical stope model. Additional models were run looking at the effect of stope inclination and drift location. It was found that these geometrical changes had very little impact on what happened in the drift.

Figure 4.27 contains a series of graphs, each of which show a stress plot taken from a particular measurement location. Each stope has a measurement location at the centre of the stope, at the drift/stope boundary (also known as the brow), at a 4m drift location, and at a 10m drift location. These graphs show how the stresses change with time. Note that for all of the plots, the x-direction is perpendicular to the page, the y-direction is horizontal along the page, and the z-direction is vertical along the page. Also note that the colours of the dashed lines on
**Figure 4.26**

4.0 MODEL VALIDATION

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

STOPE SHAPE STUDY - 3D INCLINED COMPARISON - INCREASED WIDTH

Note: all dimensions are in meters

Print date: 26-Nov-12
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 REPORT VALIDATION

DRIFT LENGTH STUDY: MEASUREMENT POINTS

Figure 4.27
the stope schematic match the curve colours on the plot. The dashed line represents the edge of the barricade. For example in Figure 4.27, the green dashed line means there is no drift and the barricade would be directly underneath the brow.

Figure 4.27 shows a series of graphs which plot the PWP, the VS (ZZ), the y-direction HS (YY), and the x-direction HS (XX) curves. Each graph corresponds to a measurement location shown on Figure 4.27, taken along the y-axis centreline of the model. All of the contour plots show the stresses within the stope at the end of filling.

The stope-centre plot in Figure 4.27 shows that increasing the length of the drift has little or very little influence on the stresses at the centre of the stope indicating that, for this geometry, the measurement location is too far away from the edge of the stope to be influenced by changes at the edge. The remaining plots all show the same trends, mainly that the stresses at each measurement location are highest when the barricade is at the measurement location, whereas the stresses decay as the barricade moves further away from the measurement location into the drift. The other observed trend is that when the measurement point is at a barricade the PWP is decreased due to the proximity of the PWP boundary condition.

Figure 4.27 also contains a plot, in the top left side of the figure, which shows the stress profiles along a horizontal section at 2 m height. This plot indicates that the YY stress and the PWP are more greatly affected by the presence of the drift as these curves show the greatest difference between the no-drift model and the two drift models. It also shows that the zone of disturbance is only about 3m from the RHS of the stope wall, due to the drift.

Figure 4.28 contains a series of contour plots for the PWP, ZZ, XX, and YY for each of the stope geometries. When the 4 m and 10 m drift models are compared to the “No Drift” model, it is clear that the LHS side of the stope is not influenced by increasing the drift length on the RHS of the stope. The RHS contours, near the centre of the stope, are also unaffected by the drift, but the contours are affected by the presence of a drift as they approach the RHS side of the stope.

The PWP plot shows that when the drift is created the PWP contours enter the drift. However, there is less PWP increase at the end of the 10m drift than at the end of the 4m drift, which was expected. It should be noted that the shape of the high PWP stress bulb at the middle of the stope was not affected by the addition and lengthening of a drift in the model.
Note 1: All Stress Contours are the equal (XX-Stress = YY-Stress = ZZ-Stress)

Note 2: Contours are in Pascals

A DESIGN PROCEDURE FOR DETERMING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 REPORT VALIDATION

DRIFT LENGTH STUDY: STRESS CONTOURS

Figure 4.28
The ZZ stress contour plots also exhibits low stress area developing along the back of the drift. The size and shape of this low stress area increases with increasing drift length.

The horizontal stress plots show the most interesting results. The YY plots show that there are large changes between the no drift and 4m drift models. However, when the 4m and 10m drift models are compared, there is little change up to the 4m mark on the 10m drift. After this point, the stresses drop off rapidly as the barricade is approached. This suggests that there is an ideal drift length, dependent on drift geometry, where there is rapid drop in HS into the drift. In addition, the XX plots for the 4m and 10m drift models show something akin to the stress arching observed in the main body of the stope. However, this drift “arching” is rotated horizontally and into the stope.

### 4.8 The Use of Multiple Pastes

One of the criteria for the model was that it must be able to handle different pastes within the same stope model. As discussed previously, there are many reasons why multiple pastes may be used in a stope. In this particular project only two of the mines used pastes comprised of the same tails but different binder contents: the Kidd 2.5 and 4.5 pastes, and the CS 6.5 and 8.5 pastes.

This section will investigate how the model responds to having two pastes. The first comparison looked at the difference between a dual paste stope as opposed to stope filled completely with one type of paste. The second comparison determined how sensitive the bottom layer was to material in the second layer. Both comparisons will use the typical 6x17 m, 2D stope with a 20 cm zone size and a 20 cm/hr rise-rate.

Figure 4.29 shows the results from the first comparison, which compared the results from a stope filled CS 6.5, CS 8.5, and a mixture of both pastes. This model run filled the stope to a height of 9 m with the CS 8.5 paste and the rest of the stope with the CS 6.5 binder paste. This filling strategy reflects what actually happens at each mine site, where the stronger paste is placed below the weaker one. This figure contains three graphs and two sets of contour plots, one showing PWP and the other showing HS. The results were measured at the locations denoted on the contour plots: one at 2 m height, the second at 5.6 m height, and the last at 10.2 m height. This means that the bottom two points are within the first paste layer while the upper point is within the second paste layer.
Figure 4.29

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

TWO PASTE COMPARISON - CBI SPEC PASTES

CS 6.5 CS BP CS 8.5

CS 6.5 CS BP CS 8.5

CS 6.5 CS BP CS 8.5

CS 6.5 CS BP CS 8.5

Note: Stresses are in Pascals
Compression is negative
The graph for the bottom point shows that dual paste curve behaves similarly to that of the CS 8.5 paste, particularly for the PWP and HS curves. The dual paste curve for the middle point also follows the same trends as the CS 8.5, but with increased deviation between the two if the last 25 hrs of both graphs are compared. It should be noted that when the curves deviate, the dual curve is the higher. It should also be noted that the full CS 6.5 model curves have little similarity to the dual curves in the first two graphs. However, this pattern changes in the graph for the top measurement location. In this graph the dual curve is closer to the CS 6.5 model curve, particularly for the HS curves. This is reasonable as the behaviour at this point will be influenced more directly by the CS 6.5 paste.

When the PWP contour plots are compared, the influence of the dual pastes is readily apparent. All three of the plots contain a high PWP bulb in the top half of the stope, with the CS 6.5 model having a larger bulb than the CS 8.5 model. However, the dual paste model has a distinct transition in the blue contours around the 9 m height line shown on the plot. The HS plots also show the influence of the two pastes when the HS plots are compared. In the dual paste plot there is a definite stress change above and below the 9 m line.

Figure 4.30 contains the results showing how the upper layer affects the lower layer. There are three graphs for each of the three monitoring locations. The first location was at 2 m height, the second was at 6 m height, while the third was at 10 m height. This meant that one measurement location was well below the second layer, the second point was just below the second layer, while the third point was in the third layer. There are also three sets of PWP contours with time, one for each model.

The Location 3 graph shows how the changing the Kidd 2.5 k parameters affected the paste. This graph shows that the low k values generated larger stresses while the high k paste had less stress. The Location 1 graph, however, shows that changing the Kidd 2.5 k parameters has very little effect on the stresses at this measurement location. This is particularly true for the HS and PWP but even the maximum deviation seen in the VS curves was around 20 kPa. This is small given the weakness of the paste in the second layer. The second measurement location shows similar behaviour to that of the first location but with larger deviations.

This section shows that the model can incorporate two or more pastes within the stope. It was found that the stress behaviour at a measurement location depends on the paste in which the location is situated. It was also found that the bottom layer of a two-layered stope is
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

4.0 MODEL VALIDATION

TWO PASTE COMPARISON
- KIDD PASTES

Figure 4.30
relatively unaffected by the material in the layer above it. Note, however, that the influence of the upper layer decreases as the distance from the paste interface increases.

4.9 Discussion

This chapter presented four modelling criteria and the methodology that lead to the creation of PasteFill, a numerical stope filling simulator based in Itasca’s FLAC3D code. This chapter then proceeded to provide some parametric studies looking at how the model responded to what it was required to do, which was to incorporate changes in rise-rate including pour stoppages, incorporate the time-dependent characteristics of the paste, allow for geometries in both two and three dimensions, and allow a stope with multiple pastes to be modelled.

The laboratory input section showed that the model is most sensitive to the paste’s hydraulic conductivity, sensitive to Poisson’s Ratio, and less sensitive to cohesion and friction angle. Note that the sensitivity to Poisson’s Ratio was expected as there is a large change between ratios of 0.5 to 0.2. However, Poisson’s Ratio is a rapidly stabilizing parameter, meaning it has much less impact on the model. This section also showed that two types of stress decay mechanisms are apparent in the model. The first is due to PWP reduction while the second is due to shear failure at the edge of the stope.

Two different shear failure areas were identified, one at the centre and one at the edge of the stope. An examination of why failures start in these two areas showed that both are caused by the movement and intensity of the high PWP bulb within the stope.

The rise-rate section showed that modelled stress behaviour is greatly affected by the rise-rate of the paste. It was found that faster rise-rates generated higher stresses as there is limited time for the material to experience stress-decay. It was also observed that modelled paste, during a pause in the pour, behaves similarly to the paste in an instrumented stope during a pause in the pour.

It was found that the geometry and aspect ratio of a stope greatly affects the stress results within the stope. In general, the results show that as stopes get wider the in situ stresses increase. The addition of the third dimension also affects the stress results. However, there is a limit to this effect when, at a certain width, the 3D and 2D results were the same, indicating that any effects caused by the extra set of sidewalls were diminished. It was also observed that there is a
non-linear relationship between the stress generated in the paste and the aspect ratio of the 3D stope.

Finally, it was found that PasteFill can incorporate having a stope filled with two different pastes. The results from these models indicated that the material within the upper layer has little impact on the bottom layer, particularly as the distance from the paste interface increases.

To this point, however, all of the models run have been based on hypothetical stopes. The next step in the process would be to back-analyse an instrumented stope to see if PasteFill can match the field stresses. In order to this, PasteFill was used to model the stresses in six instrumented test stopes. The results from these models will be presented in the next chapter of this thesis.
This chapter presents the instrumentation details and model results for six of the instrumented stopes that were monitored as part of the larger University of Toronto (UofT) research project.

The first case study will include three stopes from the Çayeli Bakir Mine (CBI): 715-N22, 715-N18, and 745-N5. These stopes all use the same type of paste but have different geometries and filling rates. The second case study will present the results from the 685-N20 stope, which was also located at CBI. Even though the mine was the same, this stope was filled with two different pastes, comprised of material from a different tailings stream than the first case study. The third case study contains a long-hole stope from Williams Mine (WILL): 9500-L70-5. This stope is narrow and steeply dipping. The last case study models the 66-SL1 stope from Kidd Mine (KIDD). This stope is significantly larger than any of the other stopes presented in this thesis and is irregularly shaped. Refer to Table 5.1 for a summary of each stope. Note that each case study was written to be as stand-alone as possible. To this end some repetition between the individual case study sections is unavoidable.

The next two sections will summarize the type of stope instrumentation used and modeling process that was followed. However, each case study will present the individual stope
### TABLE 5.1

#### UNIVERSITY OF TORONTO

**A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL**

#### 5.0 CASE STUDIES

**STOPE FIELD PARAMETER SUMMARY**

<table>
<thead>
<tr>
<th>MINE</th>
<th>CASE STUDY</th>
<th>STOPE ID</th>
<th>WIDTH x-direction (m)</th>
<th>LENGTH y-direction (m)</th>
<th>HEIGHT z-direction (m)</th>
<th>INCLINATION ANGLE (deg.)</th>
<th>STOPE VOLUME (m³)</th>
<th>PASTE TYPE (type: m)</th>
<th>FILL TIME (hrs)</th>
<th>AVERAGE RISE RATE (m/hr)</th>
<th>POUR PAUSE (#:hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cayeli Bakir</strong></td>
<td>1</td>
<td>715-N22</td>
<td>17</td>
<td>8.5</td>
<td>14.5</td>
<td>NA</td>
<td>1220</td>
<td>CNS 6.5</td>
<td>114</td>
<td>0.35</td>
<td>1: 20 to 90</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>715-N18</td>
<td>8</td>
<td>24</td>
<td>15.5</td>
<td>NA</td>
<td>2250</td>
<td>CNS 6.5</td>
<td>84</td>
<td>0.22</td>
<td>1: 36 to 30</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>745-N5</td>
<td>11</td>
<td>32</td>
<td>16</td>
<td>NA</td>
<td>4170</td>
<td>CNS 6.5</td>
<td>100</td>
<td>0.16</td>
<td>1: 24 to 28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>685-N20</td>
<td>10</td>
<td>26</td>
<td>16</td>
<td>NA</td>
<td>3200</td>
<td>CS 8.5: 0m to 9m CS 6.5: 9m to end</td>
<td>68</td>
<td>0.22</td>
<td>1: 28 to 30</td>
</tr>
<tr>
<td><strong>Williams</strong></td>
<td>3</td>
<td>9500 370-5</td>
<td>9</td>
<td>20</td>
<td>53</td>
<td>65</td>
<td>6160</td>
<td>Will 3</td>
<td>66</td>
<td>0.9</td>
<td>None</td>
</tr>
<tr>
<td><strong>Kidd</strong></td>
<td>4</td>
<td>67-SL1</td>
<td>30</td>
<td>40</td>
<td>33</td>
<td>80</td>
<td>15550</td>
<td>Kidd 4.5: 0m to 6m Kidd 2.5: 6m to end</td>
<td>144</td>
<td>0.28</td>
<td>1: 36 to 48</td>
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<td>3: 96 to 104</td>
</tr>
</tbody>
</table>

Notes:
1) All Lengths and Volumes are approximate.
details such as instrument locations, stope geometry, paste rise-rate, and input parameters. These details were used to model the paste within the stope and as comparison points between the field data and the modelling results.

5.1 Stope Instrumentation

There were several types of instrumentation installed in the stopes. However, this thesis is only concerned with two of the instruments, the total earth pressure cell (TEPC) and the piezometer (PZ). Both the TEPC and PZ used were manufactured by RST Instruments of Vancouver, Canada. The TEPC used was 241mm in diameter, had a 20:1 thickness to diameter ratio, and was fluid filled. Readings were obtained from the instrument via a vibrating wire transducer (VWT). The PZ also used a VWT for readings but in this case the transducer was attached to a porous end cap that allowed water to enter but prevented the solid particles of paste from entering. For more details on both instruments please refer to the RST instrument information packages (or the UofT Paste handbook) (http://www.rstinstruments.com).

These instruments were used in two different configurations. The first configuration consisted of three TEPCs and one PZ. A wire cage was used to space and orient the instruments so that there was one instrument in each of the orthogonal directions (x, y, and z). Each instrument was given a name such as 3-1, 3-2, or 3-3. The first number is the cage number while the second number denotes the orthogonal direction in which the TEPC points. The 1- or 2-directions point in either the x- or y-direction, depending on the stope, while the 3-direction is always in the vertical or z-direction. Figure 5.1a is a photograph showing a series of these cages prior to installation in a stope. The cages were placed within a sturdier protective cage. Note that the exact instrument configuration and cage size varied from mine to mine. The cages were typically labeled C1, C2 etc., with C1 usually being the closest cage to the barricade. Any changes to this convention will be noted in the individual case study.

The second configuration was installed at the barricade. This configuration generally consisted of a TEPC mounted on the barricade with a PZ mounted nearby. Some of the mines used variations of this technique and these variations will be discussed in more detail in the appropriate section. Figure 5.1b shows a typical instrument configuration. Site specific instrumentation photographs will be included in each case study section. Each fence instrument configuration was labeled using the convention of F1 for the lowest instruments, F2 for the next
a) A series of 4 dog cages strung for installation vertically in a stope. Note the orthogonal directions of the instruments and the protective cages. Also note that the instrument configurations are not the same in each cage. The peizometers are difficult to observe.

b) Two pre-fabricated barricade wall instrumentation panels. Each contains a TEPC and a PZ. Note the Coke can hat. These were placed on the fence PZ to prevent shotcrete materials clogging the porous topcap of the PZ.
highest, F3 for the next highest etc. until all the fence instruments were named. Any changes to this convention will be noted in the individual case study section.

### 5.2 Modeling Process

The modelling conducted for this chapter includes both 2D and 3D models. It would have been ideal to use 3D models exclusively for this work as the areas of interest, mainly the barricade locations, were generally located in areas where it would be difficult or inadvisable to use 2D models. However, because of time limitations and the long run-times involved when using 3D models, both 2D and 3D models were used.

Both the 2D and 3D model geometry were developed from the cavity monitoring surveys (CMS) generated by the mines, with the 2D model geometry being cut from the 3D geometry. These geometries were then used to build FLAC3D meshes. Typically, vertical 2D models in both horizontal directions were created. Each case study section states which model geometries were developed. The 2D sections were determined by the location of the instrumentation within the stope. For example, if there was a vertical string of cages, the 2D section would intersect along that line or if there were only ground installations the section was cut to intersect the instrumentation cluster that was furthest into the stope. This allowed for multiple measurement points for comparison.

The following direction convention will be used for all of the models. The x-direction is the shortest horizontal distance of the stope or the width. This direction was also typically the same as the strike of the ore-body. The y-direction is the longest horizontal distance of the stope or the length. The z-direction is the vertical distance or the height. For more detailed information please refer to the appropriate figure within each case study.

After the model meshes were created, PasteFill model runs were created using the average laboratory input parameters. The location of each instrument cluster was inputted in the model so that the modeled stresses could be observed at approximately the same locations as the stope instrumentation. The instrument locations were determined from the field reports and photographs.

The first model that was run for any stope was a 2D model using the shortest axis (x-direction) model geometry and the average laboratory input parameters. This model was run
first because it was typically the smallest model. Each stope’s rise-rate will be presented in their individual case study sections. The results from these model runs were then compared to the instrumentation data. Several correlations were checked. The first check was the time at which the instrumentation results and the model results started. This determined whether or not the model and instrumentation started measuring stress at the same time. If both the modelled instrumentation and the field instrumentation recorded stress at the correct time, it meant that the modelled measurement point was at approximately the correct height. The second check was whether the modeled vertical stresses (ZZ) matched the input rise-rate, and the third check compared how well the model result trends matched the instrumentation trends. Note that all of the available cages for a particular stope model were checked as part of this comparison process. As mentioned above, the 2D model sections were cut so as to maximize the number of measurement locations included in the section.

The third check looked at the difference between the instrumentation and modelling results. It was generally assumed that the modelled stresses in a 3D model would be lower than a 2D model of similar geometry. This assumption was based on the results presented in Chapter 4. If the 2D model results did not match the instrumentation results, the input parameters were changed and the model was run again. The changes made to the input parameters will be discussed in more detail later in this chapter. Changes were made until the results of the x-direction (shortest axis) 2D model results generally matched the instrumentation. The modified input parameters were then used to model the other 2D and 3D models.

5.3 Case Study 1: Çayeli Bakir Stopes 715-N18, 715-N22, and 745-N5

These stopes were included in the same case study because all of the stopes were filled with the same type of paste, CNS 6.5. The 715-N22 and 715-N18 test stopes were located between the 700 and 715 mine levels and are located at the northern end of the mine. The 745-N5 test stope was located between the 730 and 745 levels closer to the centre of the mine. Figure 5.2 shows a 3D level plan of the 700, 715, and 730 levels at CBI. The locations of each test stope have been marked on the figure. Note that not all of the mine infrastructure or stopes are shown in this figure.
5.0 CASE STUDIES

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

CASE STUDY 1: LOCATIONS OF CBI 715-N18, 715-N22, AND 745-N5

Figure 5.2

Note:
1) All mine infrastructure/stopes are not shown
2) Units are in meters
Figure 5.3 contains three plots, with each plot containing four views of the geometry of its respective stope. These surfaces were created from the Cavity Monitoring Survey (CMS) taken of the stope prior to filling. These plots show that the stopes vary in size. The biggest stope was the 745-N5 stope while the smallest was the 715-N22 stope. This size difference is due to their location. The ore body decreases in size as it trends to the north causing those stopes to be smaller.

Each stope had two instrumentation locations. The first area was on the barricade itself, while the second was in the body of the stope. The approximate instrument locations are shown on the plots in Figure 5.3, with the green circles representing the barricade fence instrumentation and the red boxes representing the wire cages with the orthogonal TEPCs and a PZ. Note that the 715-N22 stope has five cages while the other stopes have only two cages. The 715-N22 stope is the only stope that had vertically strung cages.

Figure 5.4 displays photographs from the 715 level stopes. These photographs include images of the hanging cages and the “Hanging T” used in 715-N22. There is also a close-up photograph of the fence instrument installation as well as a view of the type of stope body instrumentation installed in the 715-N18 and 745-N5 stopes. This type of instrumentation consisted of a large concrete block upon which was mounted an instrument cluster inside a protective steel cage.

The backfilling strategy for these stopes was dictated by the CBI’s standard operating procedure which stated that during the first stage of the pour, which was from the start to a height of 3 m above the brow, the rise-rate should not exceed 35 cm/hr. After this height, the rise-rate could be increased to 42 cm/hr (AMC, 2004).

Figure 5.5 contains a graph showing the rise-rates from each of the stopes and shows that the 745-N5 stope was poured more or less continuously except for two short paste-plant stoppages between 20 and 30 hours. The other stopes both had extended pour stoppages; in the case of the 715-N18 stope this stop was around 24 hours, and for the 715-N22 stope this was approximately 72 hours. The reason for these stoppages was that the barricade instrumentation reached 100 kPa, which was the cutoff set by the mine management (Yumlu and Guresci, 2007). Note that this maximum barricade stress of 100 kPa was 65 kPa above what was previously recommended (Wardrop, 2001; AMC, 2004).
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 1: STOPE GEOMETRIES

Figure 5.3
CASE STUDY 1: INSTRUMENT PHOTOGRAPHS FOR TEST STOPES

5.0 CASE STUDIES

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 1: INSTRUMENT PHOTOGRAPHS FOR TEST STOPES

Figure 5.4

CBI 715-N22: Installed Hanging Cages and T

CBI 715-N22: Hanging T prior to Installation

CBI 715-N22: Hanging Cages from Overcut

CBI 715-N18: Fence Instrumentation *

CBI 715-N18: Stope and Fence Instrumentation *

* Courtesy of Dr. Ben Thompson
CASE STUDY 1: STOPE RISE RATES

A DESIGN PROCEDURE FOR DETERMING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 1: STOPE RISE RATES

Figure 5.5
The 715-N22 stope’s initial rise-rate was the fastest of the three stopes at approximately 30 cm/hour. The 715-N18 stope had an initial rise-rate of approximately 20 cm/hour, while the 745-N5 stope had an overall rise-rate of approximately 15 cm/hour. These rise-rates differ due to the volume of the stope in question; the 745-N5 stope is by far the largest and had the slowest rise-rate.

5.3.1 Modeling Procedure

Each stope in this case study was modeled using three different model geometries. The first two geometries were 2D sections running in the x- and y-directions of the stope, while the third geometry consisted of the full 3D geometry. The reason for using these different geometries was to show that different geometries could change the model results. Ideally a comparison of these model results would indicate if the use of a full 3D model was necessary. Figure 5.6 compares the three models that were created for the 715-N22 stope. The other stope meshes look similar. The intersection location of the two 2D sections was determined based on the instrumentation within the stope. In the case of the 715-N22 stope the intersection between the two 2D sections occurred where the vertical cages were strung in the stope. For the other stopes, as there were no vertical cages, the intersection took place at the installation point of the cage that was furthest into the stope.

There are some observations to note about the 2D y-direction models. It is recognized that this model configuration was not ideal due to the proximity of the end walls. One redeeming feature, however, was that the stope geometry in the y-direction changed minimally. Additionally, this model configuration allowed all of the instrumentation data to be used, although this assumed that all of the instrumentation was in the same plane. The differences between the three model configurations will be discussed in Section 5.3.2.

It was assumed that the all of the stopes were filled with the same paste, meaning that all of the stope models could use the same material properties. The modeling initially used the average values that were obtained from the laboratory testing discussed in Chapter 3 and the testing data analysis discussed in Chapter 4. Figure 5.7 shows the input parameters used in the modeling. The average values are shown as blue lines.

A comparison of the initial 2D model results, using the average input parameters, and instrumentation results showed a poor correlation. A calibration exercise was then conducted,
CASE STUDY 1: MESH GEOMETRIES

A DESIGN PROCEDURE FOR DETERMING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 1: MESH GEOMETRIES

Figure 5.6
Notes:

1) In a) and b) both the 715 Level and 745 N5 curves are equal. The 715 Level curve is hidden by the 745 N5 curve.
focusing on the consolidation parameters: \( m_v \), \( C_v \), and \( k \). Note that \( k \) is determined from the other two parameters using Equation 3.1. Cohesion and \( \varphi \) where not used as the zone state (failure) results indicated that there were limited shear failures in the paste. For the calibration study it was assumed that \( m_v \) values obtained from the laboratory testing were valid and the values used were chosen from graphs in Figure 3.6. However, since \( k \) is calculated from both \( m_v \) and \( C_v \) it was decided to vary the \( k \) inputs and determine how the \( C_v \) curves changed. In this way the \( C_v \) curve could be used as a ratio between \( m_v \) and \( k \). This allowed only one parameter to be changed as part of the study. Note that cohesion and \( \varphi \) parameters are presented in Figure 4.3.

All of the stope models were run using the same input parameters and the results indicated that, while both 715 level stope models could use the same parameters, the 745-N5 stope needed a different set of parameters. The final parameters used for the 715 level stopes and the 745-N5 stope are shown as red and green curves on graphs in Figure 5.7. Parts a) and b) show the \( m_v \) and Poisson Ratio (\( \nu \)) curves respectively while parts c) and d) show the \( k \) and \( C_v \) values respectively.

After the first 20 hours of curing, the difference between the average laboratory and calibrated \( k \) and \( C_v \) values was low, and was typically within the order of magnitude bounding discussed in Chapter 4. The graphs in Figure 5.7c) and d) both show that the calibrated parameters are lower than the laboratory values. It should be noted these results echo some of the findings from Chapter 4 where it was found that the PasteFill model is very sensitive to \( k \). However, during the first 20 hours of curing there is a large difference between the average laboratory and calibrated values for \( k \) and \( C_v \). During the calibration process it was found that in order to match the instrumentation and modeling results, a low \( k \) was necessary over the initial cure times until around the time of hydration after which the \( k \) increased rapidly. The differences between the curves for the 715 and 745-N5 stopes can be observed in Figure 5.7, but are relatively minimal. The large difference between the laboratory and calibrated \( k \) values will be discussed in more detail in Section 5.7.1.

### 5.3.2 3D versus 2D Model Comparison

Figure 5.8 shows all of the modelling results, both 2D and 3D, for the third cage of the 715-N22 Stope. All y-direction results are shown in red, all x-direction results in green, all z-direction results in dark blue, and all PWP results in light blue. All of the model stress curves
CASE STUDY 1: COMPARISON OF 2D AND 3D STRESSES FROM 715-N22 CAGE 3

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 1: COMPARISON OF 2D AND 3D STRESSES FROM 715-N22 CAGE 3

Figure 5.8
show the same trend, with the y-direction curves being higher than the x-direction curves which, in turn, are higher than the 3D curves. This was an expected result. The y-direction has its side walls the farthest apart, such that these walls have the least arching affect, resulting in higher stresses. For the opposite reason the x-direction configuration model has less stress due to its closer side walls. The 3D has the lowest stress as it has four sidewalls.

The other trend shown in Figure 5.8 is that the 3D stress curves are closer to the actual results, particularly after 90 hours when the stope pour recommences. Only the 3D results will be presented during the rest of this case study as the 3D results cover the entire stope. It will also simplify the graphical presentation.

5.3.3 CBI 715-N22 Results

This section presents the results for the CBI 715-N22 stope. There are three sets of results presented: the first compares the model and instrument results from the measurement locations, the second looks at the overall stope behaviour through a series of 3D plots, while the last section looks at how the results of the model change due to changing the measurement location.

5.3.3.1 CBI 715-N22 Measurement Location Results

The results for this stope were broken up by stope area. Cages 1 and 2 were located in the drift zone and their results are shown on Figure 5.9. Cages 3, 4, and 5 were located in the body of the stope and their results are shown on Figure 5.10. The fence results are shown on Figure 5.11.

In general, the results from the cage locations show reasonable agreement between the model and the stope instrumentation. The plots from the cages closer to the centre of the stope (Cages 3, 4, and 5) show the best agreement with the instrumentation while the drift results show less agreement. The drift model results show the same trends as the instrumentation results showing that the stresses rise, decay, and rise again with the changing rise-rate. However, the model shows a faster stress decay rate than the instrumentation.

Some of the instrumentation behaviour at these cage locations is also unexpected. The instrumentation stresses start rising at around 70 hours, earlier than what the rise-rate indicates. These stresses then plateau after 80 hours. After the pour recommences some of the
CASE STUDY 1: CBI 715-N22 DRIFT ZONE - CAGES 1 AND 2

5.0 CASE STUDIES

Figure 5.9
Notes:
1) Cage 3 plot - X stress curve overlain by Y stress curve
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF

5.0 CASE STUDIES

CASE STUDY 1: CBI 715-N22 FENCE ZONE -
FENCE LOCATIONS 1, 2, AND 3

Figure 5.11
instrumentation show a slight increase, while the both the y-direction stresses show a decrease. Only the z-direction stress from Cage 1 matches the instrumentation at this point.

Figure 5.10 shows that the results from Cages 3 through 5. The results generally show very good agreement between the instrumentation and model results. There are some discrepancies, the major one being the vertical stress of Cage 3. The instrumentation in Cages 3 and 4 also show a stress drop-off at around 105 hours. The reason for this drop-off is unknown, but if one continued the instrumented stress lines, trending them the same way as prior to the drop-off, they would be very similar to the modeled lines.

Figure 5.11 shows the comparison between the fence instrumentation and model results for the fence. All of these graphs show that the instrumentation and model horizontal (y-direction) stresses are reasonably close during the first 90 hours. After this point the model responds to the pour restarting whereas the instrumentation results do not. The PWP results show that the model results are considerably lower than the instrumentation results. This is probably due to the proximity of the model measurement location to the zero-PWP boundary condition. This will be explored more fully in the upcoming Section 5.3.3.3. However, the trends shown by the instrumentation and model PWP curves are very similar despite the differences in values.

In general the results from this model match very well with the instrumentation results. There are some discrepancies but, without knowing why the instrumentation is behaving a certain way, it is hard to model that behaviour correctly. However, the results shown only represent what is happening in a small percentage of the volume of the stope. The next section will present what is happening in the stope as whole.

### 5.3.3.2 CBI 715-N22 3D Stress Contour Plot Results

This section presents a link between what is happening between the discrete measurement locations and what is happening in the rest of the stope. This is done by presenting a series of contour or zone-information plots for the stope. The three total stress contour plots are shown on Figure 5.12. The PWP, specific discharge, and zone state plots are shown on Figure 5.13. The effective stress plots are shown on Figure 5.14. Note that the specific discharge contour plot shows the magnitude of the fluid flow vector in m/s while the zone state plot shows the failure mechanism history of each zone of the model. There are seven individual plots per measurement.
Approximate Instr. Locations Shown on 10 Hour Contour Plots

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CASE STUDY 1: 715-N22 3D XX, YY, AND ZZ STRESS CONTOURS

Figure 5.12
Approximate Instr. Locations shown on 10 hour contour plots. Specific Discharge (Zone Extra 4) shown as magnitude in m/sec.

Figure 5.13
Approximate Instr. Locations Shown on 10 Hour Contour Plots

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5.0 CASE STUDIES

CASE STUDY 1: 715-N22 3D XX', YY', AND ZZ' STRESS CONTOURS

Figure 5.14
type. These seven plots each show a contour for an individual time: 10, 20, 50, 70, 90, 104, and 114 hours. At 20 hours the pour was paused, at 90 hours the pour recommenced, and the pour ended at 114 hours. Each contour plot shows a wedge cut into the paste model. The corner of this wedge is located where the instrumentation was strung vertically through the stope.

On each of the 10 hour plots there is a cluster of yellow-red dots. These are to indicate the approximate position of an instrumentation location. The legends for each plot are located at the bottom of the figure and there is a schematic denoting the location of the 3 orthogonal directions. Note that in FLAC3D, compression is negative which is why the legends for stresses contain negative numbers. Also note that all of the stress plots, both total and effective, have the same contour intervals and range.

Figure 5.12 shows the total stress plots for the three major directions: x, y, and z. All three stresses show similar contour plots up to 20 hours which is due to the paste behaving as a dense slurry.

At 50 hours all of the plots show a decrease in stress throughout the stope, but with the majority of this decay happening at the edges of the stope. The x- and y-direction stress contours show similar decreases but the x-direction contour dips more steeply inside the drift than the y-direction contour. This is due to the proximity of the 3 side walls and back within the drift. The z-direction stresses shows less overall stress decrease than the others but has a sharper decay at the edges, suggesting that the vertical stress at the centre is higher but there is less stress at the edges.

There is not much change in any of the stress plots until the pour recommences. At 104 hours all of the plots show similar trends but at different magnitudes. Each plot is showing isotropic behaviour at the top of the paste column but, below this, the previously observed stress arching is maintained. Again the vertical stress plot shows higher stresses but also more stress arching.

At the end of the pour, all of the plots show the same isotropic behaviour at the top of the stope. The vertical stress plot shows a very steeply defined stress arching shape in the middle of the stope. However, both the horizontal stress plots show a stress bulb in the middle of the stope. This bulb is a product of the cold-joint caused when the pausing of a pour allows the bottom to strengthen. Similar results were observed in Chapter 4.
The top row of plots of Figure 5.13 shows the PWP contour plots, which are related to the plots below it showing the specific discharge. Specific discharge (SD) is vector flow of fluid and is shown in meters/second. The magnitude of this vector is shown on the plots. The bottom row of plots shows the zone state or failure mechanism of the zones.

The 10 and 20 hour plots show the buildup of the PWP bulb near the bottom of the stope. Before the pour pauses, the SD is high with the majority of the flow moving to the bottom of the stope. However, after the pour pauses, the SD slows as the PWP dissipates. Note that as the PWP dissipates, the pressure bulb moves from the bottom of the stope to the middle of the stope. After the pour resumes, the PWP bulb starts to increase. The SD also increases but now the water flow goes both towards the sidewalls and the floor of the stope. Once the pour is finished the highest PWPs are in the middle of the stope with the majority of the water flow being between the high PWP bulb and the sidewalls, with only minimal flow now heading to the bottom of the stope.

The failure plots show there are no shear failures within the stope mass, meaning this stope is behaving in the PWP reduction phase identified in Chapter 4. However, some interesting correlations can be drawn between this plot and the SD plots. In the 20 hour plot there is a band of horizontal blue zones in the middle of the stope, which correspond to zones that are currently experiencing tension. These same zones are shown on the SD plot as the dark blue zones just above the much higher discharge zones below. There is a similar pattern observed in the 114 hour plots, but with a V-shaped group of zones. What this line of zones shows is how these zones are being stretched as the zones below them decrease in volume as water flows out of them.

Figure 5.14 shows the effective stress plots for the three major directions: x, y, and z. The major trend in all of the plots is the same. During the first 20 hours the effective stresses are very low, except for along the very edges of the stope. The effective stresses then increase, from the bottom up, after the pour is stopped. This increase is due to the reduction in PWP due to the flow of water away from those zones. However, after the pour recommences, most of these areas do not see their effective stresses decrease. The effective stress remains relatively constant even as more vertical load is applied. Note that at the start of the pour the majority of the SD occurs at the bottom of the stope, meaning that the effective stress increases from the bottom up. However, as the paste increases in height and the SD starts to take place along the sidewalls, in
turn causing a more pronounced increase in effective stress along the sidewalls. This same increase can be seen in the stopes drift.

### 5.3.3.3 CBI 715-N22 Measurement Location Variation

The installation position of each of the instrument clusters was determined from field reports and photographs. However, there is no guarantee that this location was correct. To this end a brief study was performed on Cage 3 and Fence 2 to determine how moving the instrument could affect the model results.

Figure 5.15 shows the results from Cage 3. It contains 4 graphs, one for each stress (XX, YY, and ZZ) and the PWP. There is also a schematic showing the orientation of the test. Essentially, the centroid of each instrument was determined and a hypothetical box was drawn around this centroid. The box dimensions were approximately ± 50 cm on either side of the centroid. The results from each corner were then determined and plotted.

The stress results show that there is an approximately ± 5 kPa difference between the model curve and the corner curves. These plots show that there are two groups of bounding curves: upper and lower. These groups denote the corners above the instrument and the corners below the instrument. Note that the PWP curves show much tighter bounding results than the other plots.

Figure 5.16 shows the how the modeled instrumentation results change when the modeled fence PZ is move away from the barricade. This figure has six contour plots, each showing the PWP along a plane moving away from the barricade fence at 20 cm intervals. These plots were taken at a 20 hour pour time. Note that the contour intervals for each plot are equal.

Each plot shows the approximate modelled location of Fence 2 with a green dot. Also shown is an approximately one meter square box located around this dot. Each corner of the box was labeled. The graph on Figure 5.16 shows the PWP results for each of the corners and the Fence 2 location. This graph shows that there is relatively steady PWP increase with PWP ranging from almost no PWP (due the PWP-equal-to-zero boundary condition) at the fence to a maximum of 80 kPa one meter away.

Two additional lines have been added to the graph, one showing the PWP generated from the model and the other showing the PWP from the field instrumentation. The model was run placing the Fence 2 PZ 20 cm away from the fence. What the chart suggests is that modelling
Note:
1) Corner 8 is hidden behind box
ALL PLOTS TAKEN AT 20 HOURS OF POUR TIME

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CASE STUDY 1: 715-N22 FENCE 2 LOCATION VARIATION
the Fence 2 PZa further 10 cm away from the fence would make the model results match the instrumentation results (at least for this time period).

### 5.3.4 715-N18 Model Results

Figure 5.17 compares the modelled cage results with the instrumentation results for the 715-N18 stope. Figure 5.18 compares the modelled fence results with the instrumentation results. This stope was modeled using the same parameters as the 715-N22 stope.

There were three measurement locations in this stope. Two instrument cage clusters were installed in the body of the stope. Cage 1 was installed in the drift (approximately 4 m away from the barricade) while Cage 2 was installed in the centre of the stope (approximately 11 m away from the barricade). The fence had two PZ-TEPC instrument clusters installed. Note that both x-direction TEPCs stopped working: Cage 1 only recorded random intermittent values while the Cage 2 instrument stopped working around 30 hours. Both of these instrument errors are attributed to cable issues.

The cage comparison shows that the model and the instrumentation have similar trends, particularly for the first cage. However, the actual model and instrumentation results are different. Some of these differences are due to unexpected instrumentation results. It was expected that the second cage would have higher stresses when compared to the first cage as the second cage was further into the stope. However, the instrumentation results show that all of the stresses in Cage 1 are higher than the stresses in Cage 2, in some cases significantly. Figure 5.18, on the other hand, shows very good correlation between the fence model and instrumentation results. Possible explanations for the observed difference in the cages’ results include a difference in the instrument elevation of the cages. However, without knowing the exact location of the instruments, it is hard to determine what caused this difference.

### 5.3.5 745-N5 Model Results

The results for the 745-N5 stope are presented in two parts. The first part compares the instrumentation and model results from the measurement locations. The second part presents a series of contour plots for the full 3D stope in a similar format to those presented in Section 5.3.3.2. These plots are presented to highlight the difference between the behaviour seen in a continuous pour of the 745-N5 stope versus a staged pour as observed in stope 715-N22.
CASE STUDY 1: 715-N18 CAGES 1 AND 2

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CASE STUDY 1: 715-N18 CAGES 1 AND 2

Figure 5.17
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CASE STUDY 1: 715-N18 FENCE 1 AND 2

Figure 5.18
5.3.5.1 745-N5 Measurement Location Results

This stope had three measurement locations that were similarly placed to those in Stope 715-N18 (Section 5.3.4). Two instrument cage clusters were installed in the body of the stope. Cage 2 was closer to the centre of the stope while Cage 1 was installed within the drift. The fence had two piezometer-TEPC instrument clusters installed. Note that all of the instruments in Cage 2 stopped working immediately after the pour commenced. This result was attributed to a problem with the cables or connections.

The fact that the Cage 2 instrumentation results were not available had a direct effect on the modeling of this stope. Typically the cages in the middle of the stope are modelled as they less influenced by stope geometry. However, having only the one set of in-stope instrumentation with this stope made calibration difficult, due both the working cage’s proximity to the drift and the lack of data from the second cage.

Figure 5.19 compares the instrumentation and modelling results for Cage 1 and provides the modelling results for Cage 2. Figure 5.20 compares the results for the fence. In both figures there are three sets of curves: the first set is the model run with the 715 level parameters, the second is with the calibrated 745 stope parameters, while the third is the actual instrumentation values. Note that Cage 2 has no instrumentation curves.

The comparison results from the cages show that there is quite a difference between the 715 level and 745 stope curves. In general the model that used the lower k curve of the 715 level showed significantly higher stress and PWP curves when compared to the results from the 745 stope. The Cage 1 plot shows that the PWP and the HS curves for the 745 stope model and the instrumentation are in reasonable agreement; however, the difference between these ZZ curves for these two models is very large.

The main reason for this difference was due to an ambiguity with the rise-rate. The usual way of determining the rise-rate for a stope is to calculate the isotropic total stress rise-rate within the stope and compare this to the ZZ rise-rate from the instrumentation. However, the best cage to do this with is the one that is at the bottom and centre of the stope. In this stope the ideal cage for determining the rise-rate did not record any instrumentation results.

Figure 5.20 shows the results for the fence measurement locations. These plots show the same large difference between the 715 and 745 parameter models. However, the 745 model
CASE STUDY 1: 745-N5 CAGES 1 AND 2

Figure 5.19
CASE STUDY 1: 745-N5 FENCE 1 AND 2

Figure 5.20
results show very good correlation to the instrumentation results, particularly for the Fence 1 results.

The trends observed between the 745 model and the instrumentation are generally similar. There are some discrepancies, mainly the large difference between the ZZ curves from Cage 1. However, given some of the ambiguities with the input parameters, in this case mainly the rise-rate, the model seems to be capturing the mechanics of what is happening in stope.

5.3.5.2 745-N5 3D Contour Plots

Section 5.3.3.2 presents the contour plots for a paused pour. This section will present results for a continuous pour. The three total stress contour plots are shown on Figure 5.21. The PWP, specific discharge, and zone state plots are shown on Figure 5.22 and the effective stress plots are shown on Figure 5.23. There are five individual plots per measurement type. These five plots each show a contour for an individual time: 20, 36, 60, 80, and 100 hours. Each contour plot shows a wedge cut into the paste model. The corner of this wedge is at the approximate centre of the stope in the y-direction, but along the approximate instrument plane in the x-direction.

Each of the 10 hour plots contains a cluster of black-red dots. These are to indicate the approximate position of an instrumentation location. The legends for each plot are located at the bottom of the figure and there is a schematic denoting the location of the 3 orthogonal directions. Note that in FLAC3D compression is negative which is why the legends for stresses contain negative numbers. Also note that all of the stress plots, both total and effective, have the same contour intervals and range.

Figure 5.21 shows the total stress plots for the three major directions: x, y, and z. Figure 5.22 shows the PWP, SD, and state plots, while Figure 5.23 shows the effective stress plots for the same directions as 5.21.

The behaviour observed in these figures is very similar to that observed in the figures from Section 5.3.3.2, but there are a few differences. The first difference is that there is no cold-joint present in this model. This means that all of the contours are smoother and that there are no HS bulbs formed at the cold-joint as shown in Figure 5.12. The other is that shear failures occur in the 745 model, shown on the 80 hour zone state plot. These are due to low effective stresses at the centre of the stope. See Chapter 4 for more details on this mode of failure.
Approximate Instr. Locations Shown on 10 Hour Contour Plots

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CASE STUDY 1: 715-N22 3D XX, YY, AND ZZ STRESS CONTOURS

Figure 5.21
Approximate Instr. Locations shown on 10 hour contour plots. Specific Discharge (Zone Extra 4) shown as magnitude in m/sec.
CASE STUDY 1: 715-N22 3D XX', YY', AND ZZ' STRESS CONTOURS

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CASE STUDY 1: 715-N22 3D XX', YY', AND ZZ' STRESS CONTOURS

Approximate Instr. Locations Shown on 10 Hour Contour Plots
5.3.6 Conclusions from Case Study 1

This section presented the results of three test stopes from the same mine that were filled with the same type of paste. Each stope had a differing geometry and rise-rate. The goal of the chapter was to see if the same paste parameters in each model would produce results that matched the instrumentation of each stope.

This was partially successful as two of the stope models produced similar results to their respective instrumentation. However, the third stope required a different k parameter curve in order to provide similar results to its instrumentation. Note that the difference between the 715 level input k parameters and the 745 stope k parameters was within an order of magnitude, a relatively small amount when dealing with k values. However, this small difference highlights the sensitivity of PasteFill to the k parameter.

Also note that there was a disparity between average laboratory and calibrated permeability values. During the calibration procedure, the k values needed to be reduced from the average values. Note that the largest reduction took place over approximately the first 20 hours of curing. This will be discussed in more detail in Section 5.7.1.

In general, it was found that the model mechanics were replicating what was being observed in the field instrumentation. There were some discrepancies but the same trends were typically observed.

Figure 5.24 compares the results for the most centrally located cages for the 715-N22 and 745-N5 stopes. Note that there are two sets of curves for the 745-N5 stope: one set denotes the model run with the 715 level parameters while the other set shows the model results for the 745 stope parameters. This comparison shows that a slow, continuous rise-rate can fill a significantly larger stope in a shorter period of time than a staged-poured smaller stope, with both stopes experiencing similar end-of-pour stresses. Note that similar results were shown in the rise-rate models presented in Chapter 4.

There were several problems encountered during the modeling. The first deals with determining the actual position of the instruments within the stope. The instrument positions used in this case study were determined from the field reports and photographs. However, the results from Figures 5.15 and 5.16 show that the model results can be changed by moving the measurement location by a relatively small amount. For future work it would be beneficial to
715 Para. means 715 Level Input Parameters
745 Para. means 745 Stope Input Parameters

745-N5 MODE
- 3D 715 Para. X
- 3D 715 Para. Y
- 3D 715 Para. Z
- 3D 715 Para. PP
- 3D 745 Para. X
- 3D 745 Para. Y
- 3D 745 Para. Z
- 3D 745 Para. PP

715-N22 MODE
- 3D 715-N22 X
- 3D 715-N22 Y
- 3D 715-N22 Z
- 3D 715-N22 PP

Note: 715 Para. means 715 Level Input Parameters
745 Para. means 745 Stope Input Parameters
establish a tighter survey control. This would position the instruments, and other important landmarks like the fill fence, more exactly. It would also allow the instruments to be tied into the mine grid.

Another survey related issue was found when attaching the CMS to the mine plans to create the paste surface for mesh creation. Typically only the inside of the stope is surveyed but it would be beneficial to have the shape of a stope’s undercut drift, as well as where in the drift the fill-fence is, in order to model the stope more accurately. The final problem was the missing instrumentation for the 745-N5 stope, where the loss of the second cage made the establishment of the correct rise-rate very difficult.

5.4 Case Study 2: Çayeli Bakir Stope 685-N20

The 685-N20 test stope was located between the 685 and 700 mine levels and was located on the north side of the ore body. Figure 5.25 shows the 685 level plan. Note that not all of the mine infrastructure and stopes are shown on this figure. The full 685-N20 stope consists of two parts. The instrumented stope was the first part or, rather, the first panel of a two panel stope to be mined. In Figure 5.25 it is shown in red, while the second stage (or panel) of the stope is shown in cyan. Both stopes were to be undercut in the future. According to CBI procedure this meant that a layer of higher strength material would be placed, with the rest of the stope being filled with a lower binder material. The mine chose to use an 8.5% binder paste for approximately the first 9 m while the rest of the stope was filled with 6.5% binder paste. Both pastes consisted of spec-type tails. The stope was filled to approximately 1 meter below the height of the stope top-cut. This unfilled volume was to be filled with waste rock to facilitate easier mucking when the stope above the test stope was mined.

Figure 5.26 shows four views of the geometry of the 685-N20 stope. This surface was developed from a combination of the cavity monitoring survey (CMS) taken of the stope prior to filling and mine level plans. The stope was approximately 12 m wide by 26 m long with height ranging from 17 m at the barricade to 15.5 m at the rear of the stope. This height difference was due to a slanting stope floor. The surface shows the remnants of the bottom-cut at the far end of the stope along the y-axis. In general the stope is fairly rectangular shaped. Figure 5.26 also contains three magenta circles and five red boxes. These denote the locations of the instruments that were installed in the stope and will be discussed in more detail in the next section.
Note that all mine infrastructure/stopes are not shown on this figure.
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CASE STUDY 2: 685 N20 STOPE GEOMETRY

Figure 5.26
There were three areas where instrumentation was located within the 715-N22 Stope. The first area was on the barricade itself, the second was in the transition area near the access drift/brow, and the third was in the main stope body at about a third of the stope length from the brow. Figure 5.27 contains two schematics of the stope geometry and five photographs detailing the instrumentation. The schematics have approximate dimensions of the instrument locations within the stope. Each photograph has been labeled and has an arrow pointing to the location where it was taken.

Traditionally, CBI would have filled this stope in two stages. The first stage would have poured the CS 8.5 paste to a height of 9m at a rate not exceeding 0.35m/hour, as per a previous study conducted at the mine (AMC, 2004). This paste would then be allowed to cure for at least three days, after which the remainder of the stope would be poured. However, as the mine was able to monitor the instrumentation results on surface, it was agreed that the stope should be poured continuously. The shutoff criterion for the pour was that the fence pressure could not exceed 100 kPa, which was 65 kPa above a previously recommended limit (Wardrop, 2001). However, the fence did not reach this stress cut-off.

Figure 5.28 contains a graph of the rise-rate used in the model. This figure shows that for the first three hours the rise-rate was at 60 cm/hr, which was significantly greater than the recommended 35 cm/hr. This large rise rate was due to the inclined floor of the stope, which caused decreased in volume near the barricade. However, after three hours the rise-rate decreased to an average of 20 cm/hr. Overall, the modeled stope was poured to a height of 14.6 m in 68 hours. There was a two hour pause in the pour, starting at 28 hours, due to a problem with the paste plant. The graph also contains two dashed lines showing the time and height where the model switched from the CS 8.5 paste to the CS 6.5 paste. The 3D plot shows the actual paste division in the model.

### 5.4.1 Modeling Procedure

This stope was modeled using three different mesh geometries. The first two geometries were 2D sections running in the x- and y-directions of the stope, while the third geometry consisted of the full 3D geometry. These meshes were similar to the ones presented in Figure 5.6. The reason for using these different geometries was to show that different geometries could change the model results. Ideally a comparison of these model results would show if the use of a
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CASE STUDY 2: 685-N20 INSTRUMENTATION DETAILS

Figure 5.27
CASE STUDY 2: 685-N20 RISE RATE

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CASE STUDY 2: 685-N20 RISE RATE

<table>
<thead>
<tr>
<th>Time (hrs)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>28</td>
<td>6.8</td>
</tr>
<tr>
<td>30</td>
<td>6.8</td>
</tr>
<tr>
<td>38</td>
<td>8.8</td>
</tr>
<tr>
<td>68</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Figure 5.28
full 3D model was necessary. The intersection location of the two 2D meshes occurred where the vertical cages were strung in the stope.

There are a couple of observations about the 2D y-direction models. It is recognized that this model configuration was not ideal due to the proximity of the end walls. One fortunate feature, however, was that the stope geometry in the y-direction changed minimally. Additionally, this model configuration allowed all of the instrumentation data to be used. Note that in order to use all of the instrumentation it was assumed that all of the instrumentation was in the same plane. The differences between the three mesh configurations will be discussed later in this section.

Figure 5.29 shows the laboratory input parameters used for the modelling. The graphs on this figure also show the average values obtained from the laboratory testing discussed in Chapter 3 and the testing data analysis discussed in Chapter 4. Note that the curves for both pastes are shown on the graphs. The average value curves are shown in light green for the CS 8.5 paste and purple for CS 6.5 paste. The calibrated input parameters are shown as blue and red curves for CS 8.5 and CS 6.5 respectively. Note that cohesion and \( \phi \) parameters are presented in Figure 4.3.

An initial comparison of the 2D model results, using the average input parameters, and instrumentation results showed poor correlation between the two. Therefore, a calibration exercise was completed focusing on the consolidation parameters: \( m_v \), \( C_v \), and \( k \). Note that \( k \) is determined from the other two parameters using Equation 3.1 in Chapter 3. Cohesion and \( \phi \) were not used as the zone state results indicated that there were minimal shear failures in the paste. For the calibration study it was assumed that \( m_v \) values obtained from the laboratory testing were valid. The values were chosen from graphs shown in Figure 3.6. However, since \( k \) is calculated from both \( m_v \) and \( C_v \), it was decided to vary the \( k \) inputs and determine how the \( C_v \) curves changed. In this way the \( C_v \) curve could be used as a ratio between \( m_v \) and \( k \). This allowed only one parameter to be changed as part of the study. Parts a) and b) of Figure 5.29 show the \( m_v \) and \( v \) ratio curves while parts c) and d) show the \( k \) and \( C_v \) values.

After the first 24 hours of curing, the difference between the average laboratory and calibrated \( k \) and \( C_v \) values was low, and as typically within the order of magnitude bounding discussed in Chapter 4. The graphs in Figure 5.29c) and d) both show that the calibrated parameters are lower than the laboratory values.
Notes:
1) Pour Time for model was 68 hours
2) In a) CS 6.5 curve and Lab. Average - CS 6.5 curve are equal
However, during the first 24 hours of curing there is a large difference between the average laboratory and calibrated values for k and Cv. During the calibration process it was found that in order to match the instrumentation and modeling results, a low k was necessary over the initial cure times until around the time of hydration after which the k increased rapidly. This will be discussed in more detail in Section 5.7.1.

5.4.2 2D versus 3D Model Comparison

Figure 5.30 shows all of the 2D and 3D modelling results for the third cage of the 685-N20 Stope. All y-direction results are shown in red, all x-direction results in green, all z-direction results in dark blue, and all PWP results in light blue. The thin vertical black line denotes the time where the modelled paste changed from CS 8.5 to CS 6.5, while the thicker black line shows the isotropic total stress stress. This was calculated using Equation 4.4. These curves show that the 3D stresses are lower than the 2D stresses. This was expected as the 3D stresses are affected by four sidewalls instead of two. It was also found that the 3D stress curves are closer to the actual results. Only the 3D results will be presented during the rest of this case study as the 3D results cover the entire stope. It will also simplify the graphical presentation.

5.4.3 CBI 685-N20 Results and Discussion

This section will present and discuss the results from modelling Stope 685-N20. Two types of results are presented. The first is a comparison between the field instrumentation and model results. The model results were recorded from measurement locations in the model that correspond to the instrumentation installation locations within the stope. The second will provide a stope-wide picture of what is happening by presenting a series of 3D plots for various stresses and other metrics of interest.

5.4.3.1 CBI 685-N20 Measurement Location Results

Figure 5.31 shows the results from Cages 1 and 2. Figure 5.32 shows the results from Cages 3, 4, and 5. Figure 5.33 shows the results from the barricade fence. The cages were separated into specific stope areas. Cages 1 and 2 are in brow-drift area, Cages 3, 4, and 5 are in the main body of the stope, and the fence instrumentation was at the barricade. Each graph
Figure 5.30

**CASE STUDY 2: 685-N20 CAGE 3 - 2D vs. 3D COMPARISON**

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CASE STUDY 2: 685-N20 CAGE 3 - 2D vs. 3D COMPARISON

Figure 5.30
CASE STUDY 2: 685-N20 CAGES 1 AND 2

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A. DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

CASE STUDY 2: 685-N20 CAGES 1 AND 2

Figure 5.31

Notes:
1) Black line at approx. 40 hours denotes break between pastes
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CASE STUDY 2: 685-N20 CAGES 3, 4, AND 5

Figure 5.32

Notes:
1) Black line at approx. 40 hours denotes break between pastes
Notes:
1) Black line at approx. 40 hours denotes break between pastes

A. DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 2: 685-N20 FENCE 1, 2, AND 3

Figure 5.33
contains a vertical black line which denotes the time when the CPB changed from CS 8.5 to CS 6.5. Additionally, the cage plots show the isotropic total stress rise-rate.

The model and instrumentation results compared in Figure 5.3.1 show that the model did a reasonable job of capturing the trends observed in the drift instrumentation. There are some discrepancies between the actual results, with the largest difference being about 40 kPa. However, the shapes of the curves are similar despite these differences.

One difference observed between the Cage 1 and 2 instrumentation needs to be highlighted. The Cage 1 instrumentation results show a 12 hour time period between when the paste first reaches the cage and when the stresses start to deviate. The model matches this trend as well. However, the Cage 2 instrumentation shows a time-till-deviation of 16 hours. PasteFill models shows a time-till-deviation of 12 hours for both cages.

Figure 5.32 shows that the model was able to capture the trends observed in the instrumentation. In particular the Cage 4 and 5 results show very good trend and result correlations. However, the Cage 3 model results, while having similar trends to the instrumentation, have different result values. The instrumentation results show a delay of 24 hours between when the paste reaches the instruments and when the stresses deviate. However, PasteFill shows the same 12 hour delay observed in first two cages.

Note that the isotropic stress period for Cages 1, 2, and 3 were 12, 16, and 24 hours respectively. However, the modeled cage results all show the stresses deviating at the same time (12 hours). This indicates that current assumption of parameter equality across each modelled paste layer may be inaccurate. It also indicates that the model is consistent.

The fence results, shown in Figure 5.33, also show that the model is generating similar trends. The Fence 3 measurement location, in particular, shows a close correlation between model and instrument results. Both the modeled Fence 1 and 2 HS results are significantly higher than the instrumentation results.

5.4.3.2 CBI 685-N20 3D Stress Contour Plot Results

This section presents a link between what is happening between the discrete located instrumentation positions and what is happening in the rest of the stope. This is done by presenting a series of contour or zone-information plots for the stope. The three total stress contour plots are shown on Figure 5.34. The PWP, specific discharge, and zone state plots are
Figure 5.34 Approximate Instr. Locations Shown on 10 Hour Contour Plots

Horizontal (XX) Stress

10 hours
20 hours
40 hours
54 hours
68 hours

Horizontal (YY) Stress

10 hours
20 hours
40 hours
54 hours
68 hours

Vertical (ZZ) Stress

10 hours
20 hours
40 hours
54 hours
68 hours

Contour of XX-Stress
Wedge on Calculated by Volumetric Analysis
-2.5500E+05
-2.5000E+05
-2.2500E+05
-2.0000E+05
-1.7500E+05
-1.5000E+05
-1.2500E+05
-1.0000E+05
-0.7500E+04
-0.5000E+04
-0.0000E+00

Contour of YY-Stress
Wedge on Calculated by Volumetric Analysis
-2.5500E+05
-2.5000E+05
-2.2500E+05
-2.0000E+05
-1.7500E+05
-1.5000E+05
-1.2500E+05
-1.0000E+05
-0.7500E+04
-0.5000E+04
-0.0000E+00

Contour of ZZ-Stress
Wedge on Calculated for Volumetric Analysis
-2.5500E+05
-2.5000E+05
-2.2500E+05
-2.0000E+05
-1.7500E+05
-1.5000E+05
-1.2500E+05
-1.0000E+05
-0.7500E+04
-0.5000E+04
-0.0000E+00

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

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CASE STUDY 2: 685-N20 3D XX, YY, AND ZZ STRESS CONTOURS

Figure 5.34
shown on Figure 5.35. The effective stress plots are shown on Figure 5.36. There are five individual plots per measurement type. These five plots each show the results obtained at an individual time: 10, 20, 40, 54, and 68 hours. Each contour plot shows a wedge cut into the paste model. The corner of this wedge is located where the instrumentation was strung vertically through the stope.

On each of the 10 hour plots there are a cluster of red-black dots. These are to indicate the approximate position of an instrumentation location. Note that the y-direction limb of the wedge runs along y-plane of the vertical cages. However, the plane of the drift cages was located approximately 1 m to the left of this limb. The legends for each plot are located at the bottom of the figure and there is a schematic denoting the location of the three orthogonal directions. All of the stress plots, both total and effective, have the same contour intervals and range. Also note that in FLAC3D, compression is negative which is why the legends for stresses contain negative numbers.

One of the goals of this section is to identify how having two pastes within a stope affects the model. However, as the differences between the k-parameter curves in Figure 5.29c) are relatively small this difference may be slight.

For the first 20 hours, all of the plots show that the paste is behaving as expected. Both the total and effective stress plots show that the paste is behaving relatively isotropic throughout the stope. The SD plot shows that the water is moving towards the floor of the stope, while the PWP bulb is developing. The 40 hour plots show similar behaviour, but at this point the SD plot shows that that the main drainage direction is towards the side-walls. This movement is assisted by the relatively steeply dipping floor of the stope. At the vertical cage location the floor was 80 cm higher than it was at the barricade fence.

After 40 hours the second paste has started to be added to the stope. The 54 hour plots do not show any affects of this secondary paste. This was not unexpected as at 14 hours of curing, the differences between the pastes near the contact would be minimal. However, there are some noticeable effects at the end of the pour, after enough curing time has passed to create differences in the paste.

The difference is, unsurprisingly, the greatest in the PWP contour plot. The PWP plot shows a distinct change in the PWP above and below the paste interface, with the higher PWP
Approximate Instr. Locations Shown on 10 Hour Contour Plots
Approximate Instr. Locations Shown on 10 Hour Contour Plots
The SD plot shows the influence of the paste interface in both the 54 and 68 hour plots. This is shown by the relatively flat high SD zone in the 54 hour plot. The same thing is seen in the 68 hour plot but with another bulb of high pressure above it. This is a result of water flowing from the low-k paste of the upper level to the higher-k paste of the lower paste level in a similar way to the water flowing from the paste to the rock at the bottom of the stope. One observation to note is the absence of a high SD zone on the end-wall of the stope above the drift. If this plot is compared to the SD plot from the 745-N5 stope plot in Figure 5.22, there is a larger difference in the observed SD behaviour. The likely reason for this is that the difference in the k between the pastes, as well as the longer distance to an end-wall, prevents the water from flowing in that direction. This interpretation is supported by the PWP plot, which shows the PWP bulb closer to the side-wall than the end-wall.

These plots show the trends that were expected from the model. The paste originally exhibits isotropic behaviour and low effective stress, with the paste then gaining effective stress at the bottom and eventually at the sides as PWP reduction occurs in those areas.

The inclusion of two pastes does affect the model and this is most readily apparent in the PWP. This effect is shown by a high PWP bulb sitting on top of the paste interface. The interface also seems to reduce drainage to the end-wall of the stope.

**5.4.4 Conclusions from Case Study 2**

In general the trends observed in the model and instrumentation results are similar. The Fence and Cage 1 and 2 results show comparable PWP but the model results for the ZZ and HS are higher than the instrumentation. The stope body cages show better correlation between the instrumentation and model results.

It was mentioned previously that the model shows curve deviation at the same time in the results from Cages 1, 2, and 3. However, the instrumentation results show an increasing deviation time with the shortest being at Cage 1 and the longest at Cage 3. There are two possible explanations for this. The first explanation is that the hydration rate is faster within the drift meaning that the stress reduction will happen faster there. The second is that there may be a delay in the paste reaching the fence and drift cages due to a paste “build and slump” delivery.
It has been observed in some pastes, usually of higher binder contents, that the paste will build up in a mound at the location where the paste enters the stope. This mound will then fail and the paste will flow away (Grabinsky et al., 2010). There is some evidence of this type of behaviour, particularly in Cage 2. This behaviour would be further exacerbated due to the choking off of the brow which also occurs around this time.

The inclusion of two pastes in the stope does have an effect, particularly to the PWP and SD. However, the difference is small, probably due to the small difference between the pastes’ k-parameter curves.

### 5.5 Case Study 3: Williams Mine Stopes 9500 L70-5

This case study will present the modelling results for the Williams Mine (WILL) long-hole 9500 L70-5 (9500) stope. The stope was instrumented and filled in 2010. The actual stope was backfilled with Williams 3% (WILL 3) paste for the first six m of height after which Williams 2% paste was used. No laboratory testing was carried out on the 2% paste type nor was any instrumentation installed in it. Therefore, as no information was available for the Williams 2% paste, the model of the 9500 stope was filled only with WILL 3. It was assumed that the difference between the two pastes was minimal due to the small difference in binder content.

Figure 5.37 contains four views of the 9500 stope geometry obtained from the CMS of the stope. This stope is approximately 56 m high and 20 m long (along the strike of the ore body) and has an overall dip of approximately 65 degrees. The width of the stope varies along its height but has an overall average of around 7 m. In general the stope is shaped like an elliptical cylinder, with the long access being in the direction of the strike length. This stope had an access drift length of approximately 9 m. The access drift is located in the approximate centre of the stope body but the undercut drift runs significantly longer along the left hand side of the stope. The photograph in Figure 5.4 shows the two instrumentation clusters that were installed in the stope. The instrumentation clusters were of the cage variety discussed in Section 5.1. Two piezometer-TEPC instrument clusters were installed on the barricade fence.

Figure 5.38 shows a breakdown of the rise-rate for the 9500 stope. The rise-rate is shown in the upper left graph and has been broken into a series of filling stages. The lower left graph
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CASE STUDY 3: 9500 L70-5 STOPE GEOMETRY

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

Figure 5.37
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 3: 9500 L70-5 RISE RATE

Figure 5.38
shows the rise-rate and the instrumentation results. This was done by determining the isotropic total stress rise-rate using Equation 4.4.

These stages correspond to changes in the rise-rate. For the first 13 hours of filling the rise-rate is fairly low due to the large drift and undercut volume. Once this volume was filled, the paste started to fill into the body of the stope. The body of the stope can be broken up into a series of filling stages. These stages were called the brow and transition stage and resulted from the decrease in stope volume. The times for all of the filling stages are also shown on Figure 5.38. Note the schematic on the right showing where each transition area is in relation to the shape of the stope. This schematic shows that both the brow and the transition stage have a less steeply dipping footwall than the body of the stope forming a step. This step will play an important part in the stress development in this stope.

5.5.1 Modeling Procedure

This case study looks at a stope that has a significantly different geometry than any of the previously modelled stopes. All of the CBI stopes had a relatively uniform boxy shape making it easy to cut 2D sections in both the x- and y-directions. However, the 9500 stope is an inclined, narrow stope. This meant that the only viable 2D model would be in the y-direction. Figure 5.39 shows the 2D and 3D mesh used for the modelling of this stope. Note that the 2D mesh does not have the access drift included due to 2D modelling constraints, as the drift width is only a portion of the overall width of the stope.

The stope was initially modelled in 2D using a single comparison point of the Cage 1 monitoring location. The average laboratory input parameters were used. These parameter curves are shown in blue on Figure 5.40. Note that cohesion and φ parameters for the model were presented in Figure 4.3. These parameters were not changed in the calibration exercise.

The initial comparison of the 2D model results, using the average input parameters, and instrumentation results showed poor correlation. Therefore, a calibration exercise was completed focusing on the consolidation parameters: \( m_v \), \( C_v \), and \( k \). Note that \( k \) is determined from the other two parameters using Equation 3.1 in Chapter 3. For the calibration study it was assumed that \( m_v \) values obtained from the laboratory testing were valid and the model input values were chosen from graphs in Figure 3.14. The curves used for this model are shown in red on Figure 5.40a). However, since \( k \) is calculated from both \( m_v \) and \( C_v \) it was decided to vary the
CASE STUDY 3: 9500 L70-5 3D AND 2D MODEL MESH

A design procedure for determining the in situ stresses of early age cemented paste backfill

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CASE STUDY 3: 9500 L70-5 3D AND 2D MODEL MESH

Figure 5.39
CASE STUDY 3: 9500 L70-5 INPUT PARAMETERS

Figure 5.40
k inputs and determine how the $C_v$ curves changed. In this way the $C_v$ curve could be used as a ratio between $m_v$ and $k$. This allowed only one parameter to be changed as part of the study. Part b) of Figure 5.40 shows the used Poisson’s Ratio while Part c) and d) show the $k$ and $C_v$ curves respectively. The average laboratory value curves are in blue while the calibrated input parameter curves are in red.

A comparison between the calibrated and laboratory parameters shows a large difference between their respective $k$ parameters. The calibrated $k$ curve was initially much lower than the laboratory curve. This will be discussed in more detail in Section 5.7.1. The calibrated curve then rises above the laboratory values, peaking at around 24 hours, and then decayed below the laboratory curve.

Figure 5.41 shows a comparison between the 2D and 3D model geometry results. All of the curves provide similar results. This was expected as this is a narrow stope, meaning that the $x$-direction end walls would have limited effect. However, since this is the only cage that has both 3D and 2D results and since the 3D results more closely match the instrumentation, only the 3D results will be used on future graphs.

### 5.5.2 Measurement Location Comparison

Figure 5.42 shows a comparison of the instrumentation and modelling results for the Cage 1 and 2 measurement locations. There are some interesting observations to be made about the instrumentation. The first trend is that, after 24 hours all of the instrumentation exhibits a small, continuous increase in stress. The cause for this increase is unknown. The second is the jagged behaviour exhibited by the instrumentation during the last 10 hours of filling. Again, the cause of these jumps is unknown. The previously mentioned permeability decay was an attempt to make the model match the first observation and its success will be discussed in the subsequent paragraphs.

The Cage 1 graph shows that the modeled ZZ and HS stresses follow similar trends to the instrumentation results. However, the ZZ curve is approximately 10 kPa above the instrumentation curve, and while the YY results are fairly close the XX results show that the model curve is higher than the instrumentation curve. Note that in the YY curve is lower than the XX curve in both results. This was expected as the $x$-direction, in the drift, has the closest sidewalls. The modelled PWP is lower than the instrumentation but they show similar trends.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

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CASE STUDY 3: 9500 L70-5 CAGE 2 - 3D VERSUS 2D GEOMETRY

Figure 5.41
Figure 5.42: Stress over time for Cages 1 and 2. The graphs show the stress (kPa) against pour time (hrs) for Inst C1 X, Inst C1 Y, Inst C1 Z, Inst C1 PP, M C1 X, M C1 Y, M C1 Z, and M C1 PP for CAGE 1, and similar data for Inst C2 X, Inst C2 Y, Inst C2 Z, Inst C2 PP, M C2 X, M C2 Y, M C2 Z, and M C2 PP for CAGE 2.

**CASE STUDY 3: 9500 L70-5 CAGES 1 AND 2**

A. Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill

5.0 Case Studies

Case Study 3: 9500 L70-5 Cages 1 and 2

Figure 5.42
The Cage 2 graph shows good correlation between the stress results during the first 30 hours. After this point the instrumentation stresses start climbing while the modeled stresses plateau. The PWP curves also show similar trends for the first 30 hours but the modeled stresses are around 20 kPa lower than the instrumentation results. After 30 hours the instrumentation PWP increases while the modelled PWP decreases and then plateaus around 15 kPa.

Figure 5.43 shows the comparison results for the fence. This graphs shows that the y-direction stresses have similar trends and that the modelled results are typically 10 kPa or less higher than the field curves. However, there is almost no correlation between the modeled and instrumented PWP. This said, the PWP instrumentation does act erratically and in the case of Fence 2 actually exceeds the y-direction stress. This erratic behaviour was attributed to the PZ’s installation directly onto the barricade.

PasteFill did a reasonable job matching the trends observed instrumentation, but there was limited success in modelling the continuous stress increase mentioned above. The modeled stresses at the Cage 1 location were typically a little high whereas the modeled and instrumentation stresses at the Cage 2 location agreed well. However, in both cages the modelled PWP pressure was too low and. The fence results show good correlation between the stress curves but no correlation between the PWP curves. Some of these discrepancies are due a lack of knowledge of why the instrumentation is behaving as it is. Without this knowledge it is hard to model that behaviour correctly.

### 5.5.3 Stope Contour Plots

Several attempts were made to plot the results from this model in 3D. However, the interpretation of these plots was difficult and did not show the important relationship between the hanging wall and footwall. To this end Figures 5.44, 5.45, and 5.46 show a y-direction section cut from the 3D model. This section intersects both of the cages and the fence instrumentation. Figure 5.44 shows the total stress contours. Figure 5.45 shows the PWP contours and the specific discharge and zone state plots. Figure 5.46 shows the effective stress contour plots. These figures present a series of seven plots for the above results, each from a different time. The plot times were 4, 8, 16, 24, 32, 56, and 66 hours. Showing all of the time-specific plots as a series gives a sense of how that particular result changes with time.
Figure 5.43

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 3: 9500 L70-5 FENCE

Figure 5.43
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 3: 9500 L70-5 3D XX, YY, AND ZZ STRESS CONTOURS

Figure 5.44
Specific Discharge is calculated a magnitude and expressed in m/sec.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 3: 9500 L70-5 3D XX', YY', AND ZZ' STRESS CONTOURS

Figure 5.46
The top plot series in Figure 5.44 shows the XX, the middle plots the YY, and the bottom plots the ZZ. All of the stress plots show similar contours at 16 hours, with the ZZ showing slightly higher stresses at the bottom of the stope. Over the next 4 time plots, both the ZZ and the XX show similar trends, but with the ZZ being significantly higher. Higher stresses were observed along the footwall than the hanging wall, with the highest stresses occurring on the step in the footwall discussed in Section 5.5.1.

The YY shows a different trend with higher stresses developing along the hanging wall. The highest stresses on the hanging wall are generated at step in the narrowest part of the stope. The stress differences observed between the YY and the other two stresses are due to how the paste is loaded. In the case of ZZ and XX, the primarily vertical loading is due to gravity. Gravity is also responsible for the YY; however, the inclined nature of the stope means that this loading is forced onto the hanging wall. The previously mentioned step and constriction in the transition zone helps increase this stress as they cause a decrease in area. This stress increase is shown particularly well in the 32 hour plot of the YY stress series.

One other important observation to note is that once the paste is above the constriction (sometime between 24 and 32 hours), the stresses within the drift and undercut area do not vary much. What this indicates is that, at least from a total stress perspective, what happens in the body of the stope has little effect on the bottom of the stope. Similar behaviour was observed in Chapter 4.

Figure 5.45 shows the contour plot for the PWP, and plots for zone state and specific discharge (SD). The zone state plot shows how the zone has failed both presently and in the past while the SD plot shows magnitude of the fluid flow vector in m/s.

The 16, 24, and 32 hour PWP plots also show the importance of the constriction and the step. There is a high PWP bulb in the undercut in the 16 hour plot, but once the paste moves into the stope body, the high PWP bulb migrates to the step. After this, the high PWP bulb keeps migrating upwards into the stope body. Note that there is minimal change in the PWP bulb in the centre of the undercut after 32 hours.

The SD plots show similar behaviour, which is unsurprising as the SD is driven by the PWP. This plot shows that the drainage starts in the centre of the undercut and then migrates upwards following the high PWP bulb. Note that the footwall side of the stope typically has greater amounts of SD than the hanging wall side due to the assistance of gravity.
The zone state plots show that prior to 24 hours there is minimal shear failure. There are two zones of ongoing tension. The first is between the SD front and the bottom of the high PWP bulb while the other is along the hanging wall. Shear failures start to appear along the hanging wall and footwall after the paste moves into the main body of the stope. Note that there are no shear failures in the paste above the high SD front; it is only after the PWP decreases that shear failures can happen.

Figure 5.46 contains the contour plots for the effective XX, YY, and ZZ stresses, which show similar results to those seen in Figure 5.44. Both the ZZ and XX plots show lower effective stresses on the hanging wall while the YY plot shows lower stresses on the footwall. The reasons for this are the same as presented for Figure 5.44.

5.5.4 Measurement Location Variation

Figure 5.47 shows three PWP contour plots at 20 hours of pouring. Each plot is marked with a red dot and represents the approximate centre of the measurement location for a cage. A bounding box has then been drawn around the measurement location. PWP was examined as it was the model result curve that least matched the instrumentation in Figure 5.41. The pour time of 20 hours was an arbitrary decision.

This figure shows that varying the instrument location in the x-direction does not change the PWP; however, changing the y- and z-directions changes the PWP. The greatest difference in PWP is observed by moving the measurement location in the vertical direction. In the case of the model, the biggest vertical difference was observed at Cage 2 while the greatest y-direction changes were observed at Cage 1. However, it was found that moving the instrument location could not increase the modelled PWP enough to match the instrumentation PWP.

Figure 5.48 shows the variation of the PWP at the fence measurement locations at 20 hours of pour time. This was done by graphing the PWP changes across a horizontal line moving into the stope, at the height of the fence measurement locations. The results show that moving the instrument location in the horizontal direction had little effect on the PWP and would not allow the model PWP to reach the instrumentation PWP.
CASE STUDY 3: 9500 L70-5 CAGE LOCATION VARIATION

Figure 5.47

All contour plots for 20 hours of pour time.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

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CASE STUDY 3: 9500 L70-5 FENCE LOCATION VARIATION

Figure 5.48
5.5.5 Conclusions from Case Study 3

PasteFill model did a reasonable job of modeling the paste behaviour within the stope, especially considering the complex geometry of this stope. In particular, the model did a very good job with the total horizontal and vertical stresses over the first 30 hours. However, the PWP model results were too low. There were some concerns with the instrumentation after the first 30 hours of pouring. All of the instrumentation curves showed a slight stress increase after the first 30 hours of pouring. This was difficult to model, mainly as the mechanism behind this stress rise was unknown.

There was little difference between the 2D and the 3D model results. This was expected as the stope sidewalls were too far away to have a large impact on the results. However, the 2D model was limited as it could not be used to model the drift. This limitation meant that only one comparison point could be used and that the stress behaviour in the drift could not be modeled.

As mentioned above, the geometry of this stope was complex compared to the stopes from CBI. This complexity affected the model in two ways. The first was the inclination of the stope body which caused the stresses in the stope to act differently than stresses in a vertically oriented stope. The YY, within the stope body, were concentrated on the lower section of hanging wall due to the stope’s inclination and the constriction between the drift and stope body areas. This is compared to the ZZ and XX that were concentrated on the footwall. The second was the migration of the high PWP up the stope as the PWP below the bulb reduced. The second geometric effect was due to a step that was formed between the body of the stope and the undercut. This step helped to reduce both stress and PWP between the stope body and the undercut.

5.6 Case Study 4: Kidd Mine Stope 67-SL1

This case study will present the modelling results for the Kidd Mine long-hole 67-SL1 stope (KIDD 67). This stope was instrumented and filled in 2008. Two different pastes were used to fill the stope: KIDD 4.5 and KIDD 2.5. The higher binder paste was used as a high strength plug and the lower binder paste was placed on-top of it.

Figure 5.49 contains four views of the 67 stope geometry which were created from the CMS of the stope. This stope is approximately 33 m high, 30 m wide in the x-direction, and
Figure 5.49

CASE STUDY 4: 67-SL1STOPE GEOMETRY

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 4: 67-SL1STOPE GEOMETRY

Figure 5.49
approximately 40 m long in the y-direction. The stope had an overall dip of approximately 80 degrees in the y-direction, moving away from the barricade location. Note that the more gently dipping surface at the rear of the stope was the result of a pile of broken rock. In general, the stope has the shape of an elliptical cone that is smallest at the undercut and then extends upwards with the long axis of the ellipse at around 45 degrees between the x- and y-axis.

This stope is unique among the case study stopes as it has two access drifts. Both were approximately 5 m high, 5 m wide, and 6.5 m long. The two drifts are located at approximately right angles to each other. There is a portion of wall over-break between the two drifts as seen in Figure 5.50 c) and d).

All of the views in Figure 5.49 show 6 red squares either in the middle of the stope or in the right-hand side (RHS) of the drift. These represent the cage type instrumentation discussed in Section 5.1. The barricade fences each contain several magenta circles representing a TEPC-PZ cluster.

Figure 5.50 shows a stope schematic similar to the one seen in Figure 5.49d), as well as five photographs. The schematic shows the location of each cage and fence, while the photographs detail the instrumentation installed in the stope and provide internal views of the stope.

There were four vertically strung cages and two mounted were mounted on a “Hanging T” in the RHS drift. Figure 5.50c) shows how the hanging T allows Cage 1 to be at the brow while Cage 2 is inside the drift. Note that for this stope Cage 2 is closest to the barricade while Cage 1 is closest to the stope body.

Figure 5.50e) shows a more detailed view of the inside of the first fill fence. It had two TEPC-PZ clusters installed on the fence and one installed on a strut which placed the instruments 2 m high and 1.25 m into the stope. The instrumentation on the second fill fence was similar. There were two other instrument locations in the stope: at the brow of the Fence 1 drift and on the weight block of the vertical instrument string. The brow instrumentation is shown in Figure 5.50d) and e). The brow TEPC was oriented in the y-direction while the cement block TEPC was oriented in the vertical direction.

Figure 5.51 shows the rise-rate used for modelling the KIDD 67 stope. There were three plant shutdowns during the filling with the longest pause occurring between 36 and 48 hours. The rise-rate was determined both from physical measurements taken as the stope was filling and
**5.0 CASE STUDIES**

**CASE STUDY 4: 67-5L1 INSTRUMENTATION DETAILS**

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

**Figure 5.50**
A DESIGN PROCEDURE FOR DETERMING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 4: 67-SL1 RISE RATE

Figure 5.51
from the instrumentation. The actual stope was filled with KIDD 4.5 paste to a height of 6 m and was filled with KIDD 2.5 afterwards. Both the rise-rate graph and the 3D stope plot are divided into a KIDD 2.5, Transition, and KIDD 4.5 section. This division will be discussed in the next section.

5.6.1 Modeling Procedure

This case study stope was the largest of the stopes modeled in this thesis. It also had the most diverse geometry. All of the CBI stopes had a relatively uniform boxy shape making it easy to cut 2D sections in both the x- and y-directions. The Williams stope was somewhat uniform when cut along its y-direction. This stope, in contrast, had no regular geometry in any of the principle directions (or in any direction). This presented a problem for 2D modelling as neither an x- or y-direction section would represent the shape of the stope. To this end, sections in both directions were cut, with their planes intersecting at the vertical instrument cluster. Note that neither of the 2D model geometries were able to include the drift. Figure 5.52 shows the 2D and 3D mesh used for modelling this stope. Note that the 3D mesh near the fence locations is not smooth. The reason for this was that the mesh was setup using the vertically strung instrument cages’ axis as a basis. However, this axis was exactly lined up with the two access drifts.

The stope was initially modelled using both of the 2D models. As both model sections intersected along the vertical cages, the results from all of these cages could be used for instrument and model comparisons. The average laboratory input parameters were used. These parameter curves are shown on Figure 5.53. The average KIDD 4.5 parameters are in red, while the 2.5 parameters are in dark blue. Note that cohesion and φ parameters for the model were presented in Figure 4.3. These parameters were not changed in the calibration exercise.

The initial comparison of the 2D model results, using the average input parameters, and instrumentation results showed poor correlation between the two. Therefore, a calibration exercise was completed focusing on the consolidation parameters: $m_v$, $C_v$, and k. Note that k is determined from the other two parameters using Equation 3.1 in Chapter 3. For the calibration study it was assumed that $m_v$ values obtained from the laboratory testing were valid and these were chosen from graphs in Figure 3.21. The calibrated KIDD 4.5 and 2.5 parameter curves, used for the subsequent modelling, are shown in purple and green respectively on Figure 5.53.
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

CASE STUDY 4: 67-SL1 MODEL MESH

Figure 5.52

Notes:

2D x-direction

2D y-direction

3D
Notes:
However, since \( k \) is calculated from both \( m_v \) and \( C_v \), it was decided to vary the \( k \) inputs and determine how the \( C_v \) curves changed. In this way the \( C_v \) curve could be used as a ratio between \( m_v \) and \( k \). This allowed only one parameter to be changed as part of the study. Part a) of Figure 5.55 shows the \( m_v \) curves, Part b) shows the \( v \) curves, Part c) the \( k \) curves, and Part d) shows and \( C_v \) curves.

During the calibration process some problems were encountered in matching the model and instrumentation results, particularly for Cage 4. Due to Cage 4’s proximity to the both pastes it was decided to try using a “transition zone” between the pastes. The assumption for the creation of this zone is that there would be some mixing between the two pastes as the plant changed from one paste mix to the other. The values for the transition paste were taken to be between the KIDD 2.5 and 4.5 parameters, and are shown in light blue in the plots on Figure 5.54. The height of this zone ranged from 6 to 10 meters and is the red zone shown on Figure 5.51. This height was chosen to encapsulate Cage 4. The use of this “Transition Zone” resulted in a closer match between the Cage 4 instrumentation and model results.

A comparison between the calibrated and laboratory parameter curves shows that all of the curves have relatively similar values, particularly after 24 hours. After 24 hours all of the curves are within the one order magnitude, the limit discussed in Chapter 4. In order to calibrate the results, a decrease in \( k \) was needed at early curing ages. The assumption for this decrease is that the early age paste would act more like a fluid than a soil with little opportunity to start draining. This will be discussed in more detail in Section 5.7.1.

Figure 5.54 shows a comparison between the 2D and 3D model geometry results. All of the curves show results with similar trends. The y-direction curves show the highest stresses while the 3D model shows the lowest stresses. All of the subsequent result comparisons will only use the 3D model results. The reason for this is that 3D model could provide results for Cages 1 and 2, as well as both fences. Additionally, there was greater graph clarity when only the 3D results were used. There are three black lines on this figure. The two vertical lines denote where the paste types changed in the model and the other non-vertical line shows the isotropic stress rise-rate.
A. Design procedure for determining the in situ stresses of early age cemented paste backfill

5.0 Case Studies

Case Study 4: 67-SL1 Cage 3 - 3D vs. 2D Results

Figure 5.54

Notes:
5.6.2 Measurement Location Comparison

There were five measurement locations within the stope. The first was the drift where Cages 1 and 2 were installed, the second was the body of the stope where Cages 3 through 6 were vertically hung, the third and fourth were the instrumentation installed on Fences 1 and 2 respectively, while the fifth was the instrumentation installed on the block. This block was the concrete weight block that provided an anchor for the vertical string of cages. Each cage, fence, and the block have an individual plot. Each plot has two vertical lines denoting where the pastes in the stope changed. All of the cage plots contain a third line showing the isotropic total stress increase with time which was calculated using Equation 4.1.

Figure 5.55 shows the results for Cages 1 and 2. Note that for this stope, Cage 2 is closest to the barricade fence. There are two discrepancies that are readily apparent. The first is that the modeled stresses are much lower than the instrumented stresses after 24 hours of filling. The second is that the instrumented stresses are lower than the modeled stresses before 24 hours. The initial 24 hours will be discussed in the next few paragraphs. The discrepancy during the latter part of the pour will be discussed later on in this section.

KIDD 67 had a video camera installed its “Hanging T” which pointed towards the fill fence, allowing a view of what was happening in the stope as it was filled. This camera showed an initial paste rise in the stope followed by a 4.5 hour period where there was essentially no filling in this part of the stope. After this period of time the camera recorded a very rapid rise in the paste surface over the next hour. The rise-rate over this hour averaged around 1 m/hour. This indicates that the paste does flow through the stope and does not fill uniformly the stope like water in a bathtub (Grabinsky et al., 2010).

The two dashed vertical lines on the Cage 1 and 2 plots show the time period when the video camera showed no filling taking place. The instrumentation curves between these lines, particularly for Cage 2, also show that there is no or limited filling. However, after this period, there is a rapid increase in filling. This implies that the paste, at the bottom of the KIDD 67 stope, was showing a “build and slump” style of deposition. Since the model rise-rate could not include this sort of behaviour the model result curves do not show similar behaviour.

Figure 5.56 shows the results from the four stope body cages. Note that Cage 4 does not have any ZZ instrumentation results, due either to a damaged cable or a faulty connection. A
Notes: Solid Black Vertical Lines Denote Paste Type Transitions: KIDD 4.5 to Transition to Kidd 2.5
Cage 2 closest to Barricade, Cage 1 closest to body of stope
Notes: Solid Black Vertical Lines Denote Paste Type Transitions: KIDD 4.5 to Transition to Kidd 2.5
CAGE 5 and Cage 6 plots have Hydrostatic Stress Lines but are hidden by other result curves.
comparison of Cages 5 and 6 shows very good agreement between the model and instrumentation results. The instrumentation and model results show similar trends in Cages 3 and 4, but there are some notable discrepancies.

The first discrepancy is common between both cages. The model results for both cages show similar HS stress trends, with XX being slightly higher than the YY. However, the instrumentation results show that the XX and YY are widely separated, although the model also shows a higher XX. This comparison highlights a curious trend in the instrumentation where the YY is following the PWP for longer than is expected. None of the instrumentation from this or any of the previous case study stopes shows this sort of behaviour.

The second discrepancy is that the HS and PWP from Cage 3 do not follow the rise-rate trend even though the vertical stress does. In particular, the PWP and YY instrumentation behave unexpectedly. Both curves show a decrease during the first pour stoppage but keep decreasing after the pour resumes.

The third discrepancy is that all of the Cage 3 instrumentation shows a dramatic increase in stress around 75 hours. This increase is not seen in any of the other cages even though all of the cages were covered in paste at this time. The cause for this stress increase is unknown.

Figure 5.57 shows the results from the two fence positions and the block. The main observation from both of the fence plots is that the instrumentation results are very erratic with the possible exception of the Fence 1 brow instrumentation. The PWP results from both the model and instrumentation show good agreement although this may be a coincidence as they show low PWP hovering around zero. In general there is very little correlation between the model and fence results. However, the model curves are bounded between the fence instrumentation results indicating that the modeled stresses are in the correct value range.

The block instrumentation ZZ shows significantly less stress than the model. The PWP results are within reasonable correlation. The reason for the large difference in the ZZ is the large amount of sand that was dumped on top of the block in order to protect the cables from rockfall damage. An example of this protection sand pile is seen in Figure 5.50c). In this case, the sand piles between Fill Fence 2 and the vertical cages varied between 0.5 m to 1 m in height. It is assumed that the sand protected the vertical TEPC and prevented the full stress of the overlying paste from reaching it. However, note that same peculiar stress jump that was observed in the Cage 3 instrumentation results was also observed by the block’s TEPC.
CASE STUDY 4: 67-SL1 FENCE 1 AND 2, AND THE BLOCK

Figure 5.57

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

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CASE STUDY 4: 67-SL1 FENCE 1 AND 2, AND THE BLOCK

Figure 5.57

Notes: Solid Black Vertical Lines Denote Paste Type Transitions: KIDD 4.5 to Transition to Kidd 2.5
It has been noted that the instrumentation located in the first three cages and at the brow show that the ZZ (and some of the HS) are significantly higher than the model results particularly in the latter parts of the pour. A possible explanation for this increased load has been explored by Grabinsky and Thompson (2009) and Thompson et al. (2010a). These authors have looked at the possibility of thermal expansion generating higher than expected stresses. The next section will look at this phenomenon and apply it to the modeling results

5.6.2.1 Thermal Effect

It was noted by the authors mentioned above that, during the pour stoppages, the ZZ and HS in the paste were still rising. The rise in stress was found to be higher in the drift cages than it was in the stope body cages. This rise in stress was also more marked in the cages in the higher binder paste than those in the lower binder paste.

Figure 5.58 shows two examples of the stress versus temperature graphs: one for Cage 2 and one for Cage 3. Note that the temperatures were obtained from the thermistors contained within the TEPC instruments. The Cage 2 plot shows the curves for the ZZ and XX and the Cage 3 plot shows curves for the ZZ and YY. Each curve shows a gap where the pour stoppage occurred. For each curve the slope of the initial rise-rate, the first pause, and the third pause were determined. The second pause was not used as it was very short and was similar to the third. An examination of these slopes shows that the drift does experience higher thermally induced stress increases and the HS increases are greater than the ZZ in both cases. However, this discrepancy is much higher at Cage 3 than it is at Cage 2 where the ZZ and HS thermal increase are about the same.

Also note that the sudden rise in stress observed in the previous Cage 3 graph is also shown here. However, the plot shows that the rise is not due to temperature as there is very little temperature change during the rise in stress. A similar phenomenon is observed in Cage 2 plot due to the paste slumping noted in Section 5.6.2 and shown in Figure 5.55.

The initial slope was subtracted from the pour stoppage slope and this value was used to increase the stress according to how the temperature increased. These thermally corrected stresses are shown in plots on Figure 5.59. All four plots show that the thermally correction does move the modeled stresses closer to the instrumentation. The ZZ thermal correction for Cage 3 seems appropriate, although the increase in stress at the 75th hour makes direct
A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

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CASE STUDY 4: 67-SL1 STRESS VS. TEMPERATURE - CAGES 2 AND 3

Figure 5.58
CASE STUDY 4: 67-SL1 3D THERMAL RESULTS - CAGES 2 AND 3

Figure 5.59

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CASE STUDY 4: 67-SL1 3D THERMAL RESULTS - CAGES 2 AND 3

Figure 5.59
comparison difficult. However, the HS thermal correction seems high. However, in all cases the thermal correction generated curves matched the results much more closely than the original model, particularly in the latter parts of the pour.

5.6.3 Stope Contour Plots

This section presents a series of 3D plots over three figures for the model whose measurement point results were presented above. The goal of these plots is to identify stope wide trends. To this end, the series of plots for each result type are presented at particular times: 4, 24, 36, 48, 94, and 144 hours. The main pause in the pour occurred between 36 and 48 hours.

The results were cut by a wedge, whose fold was along the vertically strung cages and whose limbs are at 90 degrees. This means that the contours do not show results for the Cage 1 and 2 locations. All of the figures have a direction schematic. Note that no thermal correction was applied to any of these plots.

Figure 5.60 shows the total stress contours for the three principle directions. The contour legends are located at the bottom left of the figure. Note that contours for each stress are the same. The same trend is observed in all of the stresses. During the first 36 hours all three of the stress plots show similar values and distributions. However, during the pour pause between the 36 and 48 hours both HSs show a decrease in total stress while the ZZ remains the same. Note that the change between the transition and KIDD 2.5 paste occurs right before this pour pause.

The paste change becomes even more readily apparent in the 94 and 144 hour plots where both the HSs show a new area of high stress in the middle of the stope but on top of the new paste interface. Note that similar behaviour was not observed between the KIDD 4.5 and transition pastes. The paste change is less apparent in the ZZ, but a closer examination shows that there is a plane above which the ZZ contours are similar to those of the HS stresses, indicating that the stress above the plane is fairly isotropic.

Figure 5.61 shows the plot results for the PWP, specific discharge, and the zone state. The specific discharge (SD) is the magnitude of the water flow vector and is expressed in m/sec. Note that the directionality of this vector is not shown, but typically the discharge is towards the nearest stope wall. The zone state indicates if and how the zone has failed. All of the legends are at the bottom left of the figure.
Approximate Vertical Cage Positions shown as red dots in 144 hour plot.
Figure 5.61

- **PORE WATER PRESSURE**
  - 4 Hours
  - 24 Hours
  - 36 Hours
  - 48 Hours
  - 94 Hours
  - 144 Hours

- **SPECIFIC DISHARGE**
  - 4 Hours
  - 24 Hours
  - 36 Hours
  - 48 Hours
  - 94 Hours
  - 144 Hours

- **ZONE STATE**
  - 4 Hours
  - 24 Hours
  - 36 Hours
  - 48 Hours
  - 94 Hours
  - 144 Hours

Approximate Vertical Cage Positions shown as red dots in 144 hour plot.

Specific Discharge (Zone Extra 4) shown as magnitude in m/sec.

**A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL**

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**CASE STUDY 4: 67-SL1 3D PWP, SD, AND ZONE STATE PLOTS**

**Figure 5.61**
The PWP shows some interesting trends. The first is observed in the 24 and 36 hour plots where there are two PWP pressure bulbs. The lower bulb is in the KIDD 4.5 paste while the second bulb is in the transition paste. After the pause, the lower bulb has disappeared while the upper bulb has decreased. Once filling resumes, the 94 and 144 hour plots show that a new PWP bulb has formed but this bulb is within the KIDD 2.5 paste and is sitting on top of the transition/KIDD 2.5 interface. The 144 hour plot particularly shows much lower PWP in the plug section but much higher PWP in the KIDD 2.5 paste.

The SD plot also shows the trends observed in the PWP contours, as the SD is driven by the PWP and limited by the k parameter curve. The 24 and 36 hour plots show that there are large amounts of discharge happening at the bottom of the stope but only in the KIDD 4.5 paste. The transition paste shows very little discharge at either of these times. This is due to initial decrease in the k-parameter curve shown in Figure 5.53c). The 48 hour plot shows similar behaviour to the 24 and 36 hour plots but with lower SD values.

However, the 96 hour plot shows that both the KIDD 4.5 and Transition layers have high discharges while the KIDD 2.5 paste does not. Note that the broken pile of rock, mentioned in at the beginning Section 5.6, is the reason for the very high discharge bulb on the RHS of the plot. This increase is due to the rock pile’s proximity to the paste in that area. The 144 hour plot shows the relatively high SD in the bottom of the stope, but there are only relatively small high SD zones visible on the higher sidewalls in the KIDD 2.5 paste.

The zone state plot legends show that there are some zones in the model that have failed in shear but the plots do not show any large clusters of such zones. These failed zones tend to occur singly in areas where the rock mold isolates a single zone. One observation is that the currently failing tensile zones (cyan coloured zones) are located just above the SD front as it migrates up the stope. This indicates that the effective stress change caused by the movement of water away from the low SD to the high SD zone drives these failures.

Figure 5.62 shows the effective stress contours for the three principle directions. The contour legends are located at the bottom left of the figure. Note that contours for each stress are the same and are the same as the total stress contours from Figure 5.61.

The 4 and 24 hour plots for all of the effective stresses show very uniform stresses meaning that the stress is isotropic at this point. The 36 hour plots show uniform stresses
Approximate Vertical Cage Positions shown as red dots in 144 hour plot
between the HSs and a slight increase in effective ZZ. All three plots show an increase in effective stress over the pause caused by the reduction in PWP pressure during that time.

The interface between the Transition and KIDD 2.5 paste is even more apparent in the effective stress plots than it was in the total stress plots. Both the 96 and 144 hour plots show increased effective stress below the interface, while above the interface the effective stresses are still very low. Also note that the areas of the effective stress are different. In the bottom zones, the effective stress gain happened primarily from the bottom, whereas the effective stress gain in the upper portions can only come from the sidewalls. This corresponds to the SD plots where the majority of the discharge in the upper portion of the stope takes place on a relatively small section of the stope sidewall.

### 5.6.4 Measurement Location Variation

Figure 5.63 provides a close-up view of the Fill Fence 2 drift area. The approximate locations of the two cages are shown by red dots. Figure 5.56 showed that the Cage 2 model result curves were the same as the instrumentation curves, with the XX being the highest and ZZ being the lowest. However, the Cage 1 model results were reversed (the ZZ was above the XX). An examination of the contours reveals that the start of the brow is what causes the ZZ to be the lowest at Cage 2. In the case of the model results for Cage 1, the ZZ at 94 hours was approximately 158 kPa, the YY was approximately 142 kPa, and the XX approximately 125 kPa. The contour plot shows that it may be possible to obtain model results that are similar to that shown in the instrumentation, but it would require each instrument to be moved independently within the model. For example, the modeled z-direction TEPC could be moved right and the modeled x-direction TEPC could be moved down. However, while this arrangement might work for this model run, it may not work for another model run. It would be better to know exactly where the instruments are in the stope as opposed to moving them to match the instrumentation results.

### 5.6.5 Conclusion from Case Study 5

This stope was unique as it had the most diverse geometry of all the case study stopes, making it difficult to model using a 2D model. This diversity arose from the two access drifts, a slight incline, and a pile of broken rock at the base of the footwall side of the stope. It was also
Case Study 4: 67-SL1 3D Results - Cage 1

Measurement Location Variation

Figure 5.63

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Case Study 4: 67-SL1 3D Results - Cage 1 Measurement Location Variation

Figure 5.63
the largest stope, which, combined with the need to model in the stope in 3D, meant it had the longest model run times.

During the modeling it was decided to include a paste transition zone to mimic an area where KIDD 2.5 and 4.5 pastes would mix as the plant changed paste types. The parameters used for the transition zone were based on the other paste types. This zone was approximately 4 m in height and the model results from Cage 4, which was contained in the transition paste, showed that its use worked well.

The PasteFill model results were comparable to the instrumentation results, particularly in the stope body itself. The Cage 3 and 4 results show good correlation with the PWP and ZZ curves. However, there were some issues with the HS, although the instrumentation for some of these comparisons may have been faulty. The Cage 1 and 2 plots show evidence of a large paste slump in the early pour ages. The fence model results were found to be in the same range as the instrumentation, but the instrumentation also showed a very large amount of variation making comparison difficult.

An attempt was made to apply thermal loading to the modelling results in order to obtain a better match between the results in Cages 1 through 3. After determining and applying a thermal correction factor to the results from Cages 2 and 3, it was found that all of the corrected model results did match the instrumentation more closely.

The model results showed that the plug of stronger paste did protect the barricade from the influence of the weaker paste. This was accomplished by the higher binder paste gaining effective strength quickly due to its higher k parameters, as well as the proximity of discharge surfaces. This meant that the undercut areas saw little increase in stress even though the paste above the plug had very little effective strength.

There were few shear failures observed in the model results and the failures were not clustered. This indicates that the paste is still in the PWP reduction phase that was identified in Chapter 4.

An attempt was made to determine how the spatial variation of the instruments could affect the results. In general, it was found that moving the instrument location within the model could affect the results. However, these results also indicated that in order to match the instrumentation, the modeled locations would need to be moved independently. It would have been ideal to have tighter survey control over where these instruments were in the stope.
5.7 Overall Case Study Conclusions

The previous sections have presented the details for six different stopes. Three of those stopes were filled with the same paste, two of these stopes were filled with two different types of paste, four of the stopes had fairly regular geometries, and two were inclined, while one of these inclined stopes had no regular geometrical shape. All had different rise-rates. Therefore, the range of stopes presented in these case studies can be considered very broad.

The PasteFill model did a good job modeling the stress behaviour trends of the filling paste. There were some discrepancies between the model results and the instrumentation, but it was shown that the model mechanics were able to replicate the trends seen in the instrumentation and typically generated model results that were within 50 kPa of the instrumentation results. It should be noted that part of the problem with these direct comparisons is the uncertainty of the instrument locations within the stope.

All of the case studies also showed very little shear failure within the paste. However two of the stopes showed an abnormal amount of shear failures. The first stope was CBI 745-N5. This stope showed a clustering of shear failures in the centre of the paste mass. These would be similar to the failures observed in Chapter 4. The second stope was the Williams 9500 stope which showed failures along the edges of the stope. However, these are more of a function of the inclination of the stope as opposed to the shear-arching behaviour discussed in Chapter 4. In general, all of the case studies showed that PWP reduction was the controlling method for stress decay in the modeled stopes.

5.7.1 A Comment about Permeability Calibration

All of the case study models proved to be highly sensitive to the hydraulic conductivity (k) of the paste. The k of the paste is directly proportional to its C_v, while the C_v is inversely proportional to its compressibility (m_v). The laboratory m_v parameter was used in all the models and the k parameter was altered (and therefore the C_v as well). Figure 5.64 shows plots of average laboratory values for k and C_v that were used in the initial modeling stages as well as the final k and C_v parameter curves used for the previously presented models. When compared on the same vertical scales, the laboratory average values are very tightly clustered while the model values are quite scattered.
Laboratory Averages

Model Parameters

Laboratory Averages

Model Parameters

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

5.0 CASE STUDIES

$C_v$ AND $k$ COMPARISON - LABORATORY VERSUS MODEL

Figure 5.64
During the calibration process, all of the case studies required an initial reduction of permeability over a period of time ranging from 20 to 24 hours. The point of this calibration was typically to match the modeled PWP instrumentation with the field instrumentation so that the effective stress development would be equal. Basically, this initially low k assumption was meant to reflect what happens in the upper 1 to 2 metres of the CPB. This zone represents a transition of the material from a fluid to a pseudo solid. Unfortunately, not much is known about the mechanics of this zone. Instrumentation results indicate that the temperature of the paste is increasing, indicating that cement hydration has started. However, the instrumentation also shows that the effective stress is essentially zero during this time. Currently the model assumes that the material within this zone has a finite (if very low) shear stiffness. While this assumption is valid for the material below this zone, it is incorrect for material that has a shear stiffness of zero. Material with zero shear stiffness could be modeled using a pressure head boundary but determining the location of this boundary and moving it accordingly, when the new paste layers are added, would be difficult.

This raises a further concern with the current infinite permeability boundary condition that is being used. The rock is not infinitely permeable. For example, if one filled a stope with water, the water would not instantaneously disappear. However, determining what this boundary condition is and how it would change due to the addition of the paste, particularly the top 1-2 m zone, would be difficult to determine. Nevertheless, the paste can only supply a limited amount of water. Analysis of multiple in situ field samples (le Roux, 2004; le Roux et al, 2005) showed that there is very little change in the void ratio throughout the stope. This indicates limited consolidation had taken place. Additionally, there was only a slight decrease in water content between the as-prepared and the in situ samples (usually around 2%). However, this slight change in water content is enough to change the paste from a fluid to a plastic material. The modeling results presented in this chapter also indicate that the fluid discharge rates are low (the highest rate was 8e-7 m/s with typical values being around 3e-7 m/s). The higher rates were located either at the sidewalls or the floor depending on the stope. This means that the permeability of the rock is less of an issue as the paste is much less permeable and only has limited supply of water.

This fluid-pseudo solid transition zone could be modeled using a modified set of material parameters and a modified boundary condition. However, as the mechanics of this zone are not
well known, determining how to model it correctly is difficult. The calibration method described in this chapter captures the combined effects of changing material properties and moving boundary conditions that would be necessary to model this transition zone. It should be noted that changing only the k parameter, in all of the model zones, brought the model results much closer to instrumentation results at all of the modeled instrumentation zones. Therefore, while the calibration method highlighted in this chapter may not be the most theoretically correct, it is able to approximate the mechanics of the paste material and allows PasteFill to simulate a reasonable picture of what is happening in the stope.

5.7.2 Recommendations

There are two sets of recommendations dealing with problems that were encountered during the modeling. The first set deal with the model and its inputs while the second set deals with the installation of the instrumentation. Some of these recommendations are more practical than others.

There are three recommendations for the model. The first is to better quantify the input laboratory parameters, specifically the k, \( C_v \), and \( m_v \) parameters. This is particularly important for the pre- and immediately post-hydration behaviour of the paste. The second is to determine more accurate rise-rates within the paste. Note that non-horizontal layers may be necessary to capture the slumping style behaviour observed in some of the stopes. The final recommendation is to incorporate the effect of thermal loading into the model.

The installation recommendations deal with specific details of the stope and the instrumentation location. There are two recommendations. The first is to obtain CMS for the brow and undercut drift associated with the stope, preferably before and after the installation of the fill fence. The second would be to properly survey the instrumentation locations and, where possible, tie these locations into the mine grid. The first recommendation would make the transition between the stope and drift meshes into the drift more representative and the second recommendation will enable a modeller to place the stope’s measurement points more accurately.
The goal of this thesis was to provide a process that an engineer at a mine site could follow in order to predict the stresses that occur within cemented paste backfill during the early ages of curing, mainly the period of time it takes to pour a stope. This meant that every part of the process needed to be replicable at the mine site, and yield results that could be easily understood and interpreted.

In order to meet this goal, a numerical model called PasteFill, was designed using Itasca’s FLAC3D modeling software, particularly FLAC3D’s internal programming language, FISH. PasteFill was intended to meet four criteria. The first criterion was that the model had to be able to capture the time-dependent behaviour of the paste, the second was that it had to be able to model complex 3D stope geometries, the third was that it had to be able to incorporate changing paste rise-rates, and the fourth was that the model had to be able to incorporate the use of multiple paste mix designs. The model would also need to provide both total and effective stresses.

The discussions and recommendations that are presented in this section are based on the experiments and modelling conducted on the material used in this study, and may only be
applicable for similar materials and type of experiments. However, the general framework of investigation can be applied to the paste materials of other mines.

6.1 Conclusions

The following five sections summarize the conclusions drawn from the thesis, while the 6th section outlines the design lessons learned during the creation of the thesis. The conclusion sections are separated into material properties, verification, validation, model sensitivity, and behavioral sensitivity.

6.1.1 Material Properties

The developed testing methodology and the results this methodology generated were presented in Chapter 3. The conclusions determined from the testing were:

- All of the pastes showed similar consolidation trends.
  - Each paste type exhibited normally consolidated behaviour when fresh and over-consolidated behaviour after aging.
  - The higher binder content pastes have higher values of consolidation coefficient (i.e. consolidate faster) than the lower binder content pastes and typically show a faster stiffness increase.
  - There was very little difference in the hydraulic conductivities of all the pastes.

- Each paste exhibited a different increase in cohesion, although all showed a time period where there was very little cohesion increase. Typically, for the higher binder pastes the period of low cohesion was short and was followed by a rapid increase in cohesion. The lower binder pastes showed a much more modest increase in strength. The one exception was the CNS 6.5 paste, which showed very little cohesion increase for 24 hours, after which it showed a very rapid increase. The KIDD paste developed the most cohesion while the WILL 3 and CS 6.5 showed the least.

- In general, there was very little change in the friction angle ($\varphi$) over time. The $\varphi$ ranged from $35^\circ$ to $38^\circ$. Some of the pastes, usually the higher binder content pastes, could show a slight decrease in $\varphi$ over time. However, this decrease was offset by large increases in cohesion which caused an overall increase in the strength envelope.
6.1.2 Verification

During the course of the modelling, several model limitations were identified. These limitations were typically due to assumptions made during the modelling methodology.

Several of the case studies presented situations where the use of horizontal filling layers inadequately expressed how the stope was filling, due to the slump and flow behaviour exhibited by the CPB. This was particularly a problem at the drift areas of the stopes and in stopes with complex geometries. There were also problems in some of the cases in determining the actual rise-rate of the stope and whether different parts of the stope have the same rise-rate. If, for example, the hourly locations of the paste’s surface were known, then these surfaces could be pre-programmed into the model. However, as FLAC3D does not have the ability to model the flowing of paste, it could not be used to determine the location of these surfaces diminishing its use in a predictive capacity.

The model assumes that if two pastes are being modelled there is a sharp transition between them. However, this sort of sharp transition is unlikely to exist in practice. A possible solution was presented in Section 5.6 where a transition zone was used as a bridge between two different paste types.

6.1.3 Validation

The results from the case studies show that the PasteFill model can be used to match the trends and, usually, the values observed in the field instrumentation installed in the stope. In order to check this conclusion PasteFill was used to model the stresses within six instrumented test stopes. These stopes all had different geometries and rise-rates. Four of the stope models were filled with a single paste while two were filled with two pastes. In short, the PasteFill model had to deal with a large degree of complexity. There are some general conclusions that can be drawn from all of the case studies. For more specific conclusions for each case study please refer to the appropriate section of Chapter 5.

- In general, the model and instrumentation results showed very good trend correlation. The actual difference in values was usually within 50 kPa.
- All of the models proved highly sensitive to consolidation (stiffness and permeability) parameters. During the parameter calibration phase, it was found necessary to lower the
initial hydraulic conductivity in order to capture the stress deviation behaviour observed in the field instrumentation.

- It is hypothesized that this period of time represents the transition point between the paste acting as a fluid and acting as a consolidating material.

- The stope geometry can have a large impact on the stress behaviour observed in the stope, particularly if the stope is narrow and inclined. Case Study 3 presents an example of this.

- Only three stopes showed shear failures within the stope.
  - The first was the CBI 745-N5 stope, the second was the WILL 9500 L70-5 stope, and the third was the KIDD 67 stope.
  - The CBI 745 stope showed a clustering of shear failures at the centre of the stope.
  - The majority of the failures in the WILL 9500 stope occurred at the hanging wall contact and were due to the geometry of the stope.
  - The KIDD 68 stope showed isolated failures usually located where a paste zone was isolated in a “pocket” of the rock mold. These edge “pockets” are a by-product of how the model mesh was created.

- The location of these failures, particularly in the CBI stope, indicates that the primary failure mechanism is due to the migration of the high PWP bulb through the stope.

- As the majority of these stopes’s zones have not fail, it is hypothesized that this material has, by the time its PWP is reduced, gained enough strength to prevent failure.

### 6.1.4 Model Sensitivity

The following conclusions were determined from analysis of PasteFill’s boundary conditions and construction:

- It was found that the model results were dependent on the zone size. The study showed that the results were very similar when the zone size was 0.2 m or smaller.

- It was found that increasing the width of the stope increased the stresses observed in the model.

- Moving from a 2D to 3D model lowered the stresses calculated in the model. However, this difference was decreased as the stope’s aspect ratio increased (i.e. as the third dimension increased the difference between the 2D and 3D models decreased).
An exploration of the fluid-flow boundary conditions showed that the model is sensitive to where and what fluid-flow boundaries are set. For example, if the fluid-flow boundary was made highly impermeable then the modeled material behaved like a fluid (i.e. no drainage, no consolidation, and no effective stress gain). However, if the fluid-flow boundary was made highly permeable there was an effective strength gain along the edges of the stope.

6.1.5 Behavioural Sensitivity

As noted previously, the laboratory parameters obtained provided a starting point for the modeling but rarely generated results that matched the instrumentation values on the first attempt. The previous two chapters have shown that PasteFill is capable of showing the stress development trends associated with filling a stope. However, in order for the model results to match the field instrumentation, the model parameters needed to be calibrated. This limits the predictive capability of the model in the early stages of a modelling program. However, if a database of stopes filled with the same paste could be analysed and used to validate the model, then its predictive capability would be improved. Note that PasteFill does not replace field instrumentation but it can help interpret the field results.

It was also found that the strength parameters (cohesion and friction angle) had little impact on the overall stresses observed in the model. This was particularly evident in the case study stopes. The main reason for this was increasing the strength of the material would only decrease the stress slightly until a maximum strength value was reached.

6.1.6 Design Process

Figure 6.1 presents the design flow chart for the PasteFill model. Green rectangles represent non-instrumentation field data and the purple rectangle represents the instrumentation field data. Red rectangles are input parameters that rely on field data while blue rectangles represent the laboratory testing and analysis process. The orange shapes represent the iterative calibration process where the model input parameters are modified in order to obtain a closer match between the field instrumentation and model results. The final step is the analysis of and interpretation of the calibrated model results.
Figure 6.1

A DESIGN PROCEDURE FOR DETERMINING THE IN SITU STRESSES OF EARLY AGE CEMENTED PASTE BACKFILL

6.0 CONCLUSIONS

PASTEFILL FLOW CHART

Figure 6.1
Several lessons were learned during the creation of the design process. These are summarized below:

- Survey the instrument locations within the stope after they have been installed and tie these locations into the mine grid. In this thesis the approximate instrument locations were referenced to a local feature, such as the barricade fence. However, the precise location (in a survey sense) of the barricade fence within the mine was not usually known. This meant that the locations of barricades in the model meshes were placed according to field drawings, notes, and photographs.

- Arrange for a cavity monitoring survey (CMS) to be taken of a stope’s brow prior to backfilling. Also arrange for a CMS to be taken of the stope’s access drift prior to fill fence construction. If these geometries were known it would help create a more accurate model mesh for the brow area.

6.2 Design Applications, Recommendations, and Future Work

This section deals with how the current model could be used for practical design and also gives recommendations about how the model could be improved.

6.2.1 Design Applications of Research

The methodology presented in this thesis can be used in both mine design/planning and as a back-analysis tool. PasteFill can be used as part of an iterative paste design loop. This process includes the determination of the primary input parameters through desktop study or laboratory testing and some preliminary design and modeling. These designs can then be evaluated through instrumentation and used in the next design iteration. Note that this process can be used at any time during mine life. The aim of this work would be to calibrate the model input parameters so that PasteFill could be used in a predictive capacity. Examples of how PasteFill can be used as a mine planning tool include:

- Examine a mine’s proposed filling procedure in order to determine an ideal rise-rate for a particular paste and stope combination. Note that this study could include looking at the trade-offs between pouring continuously versus stage.
- Provide guidelines for the placement of the barricade fence. This would involve determining the ideal barricade location within the drift while taking into consideration mining and geotechnical concerns.
- Examine how a change in mine method or stope shape would affect the stresses within the stope. This could then be used to determine what sort of paste recipe changes may be needed.
- Examine how the loss of confining pressure, due to side-wall cutting or undercutting, affects the stability of the paste. PasteFill could be used to determine appropriate cure-times and paste designs for these situations. Note that the assumption of no rock closure would have to be re-examined for these cases.
- Part of this examination would determine if the failures that occur during the stope filling have an impact on the stability of the paste if confining pressure is removed.

### 6.2.2 Recommendations and Future Work

There are three sets of recommendations. The first set deals with the recommendations for further field work, the second deals with the laboratory testing, while the third deals with Survey Control.

The field work recommendations include:
- The establishment of survey control for the project. This would involve linking the instrument and fence locations, when possible, with the mine grid. This would allow the more precise placement of the instrument clusters within a CMS generated surface.
- Conducting additional CMS of the brow and fill access drift locations both before and after fence installation.

The laboratory recommendations include:
- Examining the behaviour of the paste during the onset of its hydration. This would involve a closer look at how the paste evolves from a fluid to a paste, as well as the how the deviation point between isotropic and effective stresses can be determined. It is likely that part of this examination would be the development of a methodology for determining hydraulic conductivity under low confining stress conditions.
- This would also examine how the assumption of an infinite permeability boundary condition affects the model.
• Determining the tensile behaviour of paste. In this thesis a tensile cut-off of zero was assumed. As most of the zones did not fail in shear but did fail in tension, it would be useful to determine how a paste’s tensile strength changes with time.

It is important to establish a link between the laboratory testing and the in situ material parameters. Therefore it is recommended that further programs of in situ material testing be undertaken. It would be beneficial to obtain results from throughout the stope, either via borehole sampling or through in situ property determination using such methods as cone-penetration. This sort of data would also be useful in order to match model results to the actual stope performances.

The model improvement recommendations include:

• Using both stress and time to select material input parameters. It has been previously mentioned that the laboratory testing looked at how a paste’s material properties changed due both to normal stress and time however, the current model only accounts for the change of material properties with time.

• An examination of the pre-hydration behaviour of paste using a flow code, such as Itasca’s PFC3D, in order to examine how to model the transition of paste from its fluid phase to its solid phase.

• The addition of thermal expansion effects into the model. FLAC3D’s thermal modeling module could be used to model theses expansions.

• An examination of the effect of saturation change on the model. Currently the model is not allowed to desaturate.

• Incorporation of barricade fence models into the overall design loop.

6.3 Summary of Contributions

The main contributions from this work are as follows:

1. A novel laboratory test was developed to efficiently determine the time-dependent stiffness, hydraulic conductivity parameters (and therefore the consolidation characteristics), and strength parameters of a hydrating cemented paste backfill material. This methodology was then used to obtain the required input parameters for seven different mix designs from three different mine operations.
2. A novel numerical modeling approach to simulate the filling process of a CPB backfilled stope was developed. This approach used the stope’s geometry, filling strategy (mix designs, fill-rates, and possible pour stages), and any pertinent material properties as determined in Contribution 1. This simulation allows:
   a. The prediction of the total pressures acting on the fill barricades,
   b. A prediction of how the effective stress develops within the backfill, and
   c. The identification of any modes of backfill failure that would occur during filling and subsequent curing.

3. Comprehensive comparisons were made between modeling results and extensive field instrumentation results from six different stopes at three different mines. From these back-analyses it was shown that:
   a. The modeling approach is capable of quantitatively representing the important geomechanical aspects of paste filling and curing,
   b. The modeling results do not necessarily correlate well quantitatively with field instrumentation results if laboratory-determined modeling parameters are used, however,
   c. With a modest amount of modeling effort, the modeling parameter values can be calibrated to provide a better fit between modeling and field instrumentation results, thereby
   d. Allowing the use of PasteFill to predict future stope filling scenarios and thereby improve geomechanical designs of cemented paste backfill systems.


