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SHEAR STIFFNESS DEVELOPMENT AND PORE WATER PRESSURE DISSIPATION IN CEMENTED PASTE BACKFILL

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INTRODUCTION

The backfilling of an underground mine stope using a paste (or hydraulic fill) is a complex geotechnical process; which has been largely overlooked in past research. As the current resources boom forces underground mines to become deeper, and pillars between stopes to become smaller (to allow for greater ore extraction,) the need to quantify the paste backfilling process has become increasingly important. A better understanding of the geotechnical process that occurs when a stope is backfilled is also necessary to improve safety in underground mines. Between December 2003 and December 2004, there were six reported instances of stope filling accidents, which stemmed primarily from lack of knowledge of paste behaviour (Helinski, 2005.)

THEORETICAL BACKGROUND

An underground stope is a large void which has been excavated in order to allow for removal of an ore body. The backfilling process involves filling the stope with a pumpable slurry, consisting of mine tailings, water and General Portland cement. The paste is then left to 'set' and when it has achieved a required strength, an adjacent ore body can be mined, and a new stope created.

The aim of this paper is to examine the effect the tailings properties have on the processes of 'stiffness development' and 'pore water pressure dissipation' within the stope. A series of laboratory tests were carried out on three significantly different paste fills, in an attempt to quantify the progression of the above interactions with regard to the tailings properties.

Stiffness model

The addition of cement to a paste will obviously have significant affects on the strength of the paste, particularly as hydration of the cement proceeds. An empirical model has been developed by Helinski to predict the development of the shear stiffness of a paste over time. By measuring the stiffness of the paste samples in the laboratory, the validity of Helinski's model is able to be verified, and a relationship between the tailings properties and the stiffness development may hopefully be determined.

Helinski's model states that:

$$K = K_o + K_{\max} \exp\left(\frac{-d}{\sqrt{t}}\right)$$

Where K_o and K_{max} are the initial and final bulk moduli of the sample. The d term is a maturity constant which reflects the rate of stiffness development, and t is a measure of time (in days) from the initial set of the paste.

Pore Water Pressure reduction model

Paste fills used in the backfilling of an underground stope, are assumed to experience undrained loading conditions. This assumption is based on the rapid loading rate, the relatively impermeable stope boundaries which encase the paste, and the low permeability of many of the hydraulic pastes. If the system is assumed to be undrained, then the self-desiccation process caused by the cement within the paste will result in a reduction in pore water pressure. This reduction in pore water pressure will then lead to an increase in effective stress. As the effective stress increases, vertical stresses within the fill are reduced and arching proceeds. Arching is a stress redistribution, which results in the mobilisation of the surrounding interface strength; allowing stresses within the paste to reduce as they are transferred to the surrounding stope interface.

Helinski also developed a model which predicts the drop in pore water pressure due to the self-desiccation process caused by the hydration of the General Portland cement. The model is as follows:

$$\frac{\Delta V_{water}}{C_{cement}} = E_h \exp\left(\frac{-d}{\sqrt{t}}\right)$$

This model predicts the volume of water dissipated per gram of cement, where d is a maturity constant, and t is again a measure of time (in days) from the initial set of the paste. The E_h term predicts the 'efficiency' or rate of cement hydration.

In the same way that the laboratory tests were used to verify the accuracy of the stiffness development model, the laboratory tests were also used to validate Helinski's model as an accurate way of predicting the dissipation of pore water pressures, and in turn the stress redistribution process.

LABORATORY TESTING

The three different types of tailings used were from mine sites located at Kanowna Bell, Leinster and Broken Hill. The three tailings are shown in figure 1 below.

FIGURE1. Leinster, Kanowna Belle and Broken Hill tailings (from left to right)

A table outlining the properties of each of the tailings is shown in figure 2 over the page.

Tailings	Kanowna Belle	Leinster	Broken Hill
Description	Silty tailings, uniform composition throughout tailings	Highly silty to silty tailings, with signs of clumping	Coarse tailings, large loose soil particles
Relative Particle Size Ranking (1=small, 3=large)	2	1	3
Specific Gravity	2.78	3	2.79
Moisture Content	19.3%	0	20.0%

FIGURE 2. Table outlining the physical properties of each tailings type

It was decided that the three tailings should be mixed into pastes with a void ratio (e) of 0.9, and a General Portland cement ratio of 3% by mass. By maintaining uniform paste properties between the three laboratory tailings samples, it is possible to more clearly and accurately measure the effect of the tailings properties on the paste properties, namely the 'stiffness development' and 'pore water pressure reduction.'

LABORATORY TESTING APPARATUS

Triaxial Compression Chamber

The triaxial compression tests were carried out in a purpose built chamber; which was capable of applying uniform stress over the entire surface of the sample. The triaxial chamber was used to replicate the in situ, undrained loading conditions that a typical paste is subject to.

Below is a schematic of a typical triaxial compression chamber, along with a view of the triaxial cell used in the laboratory.

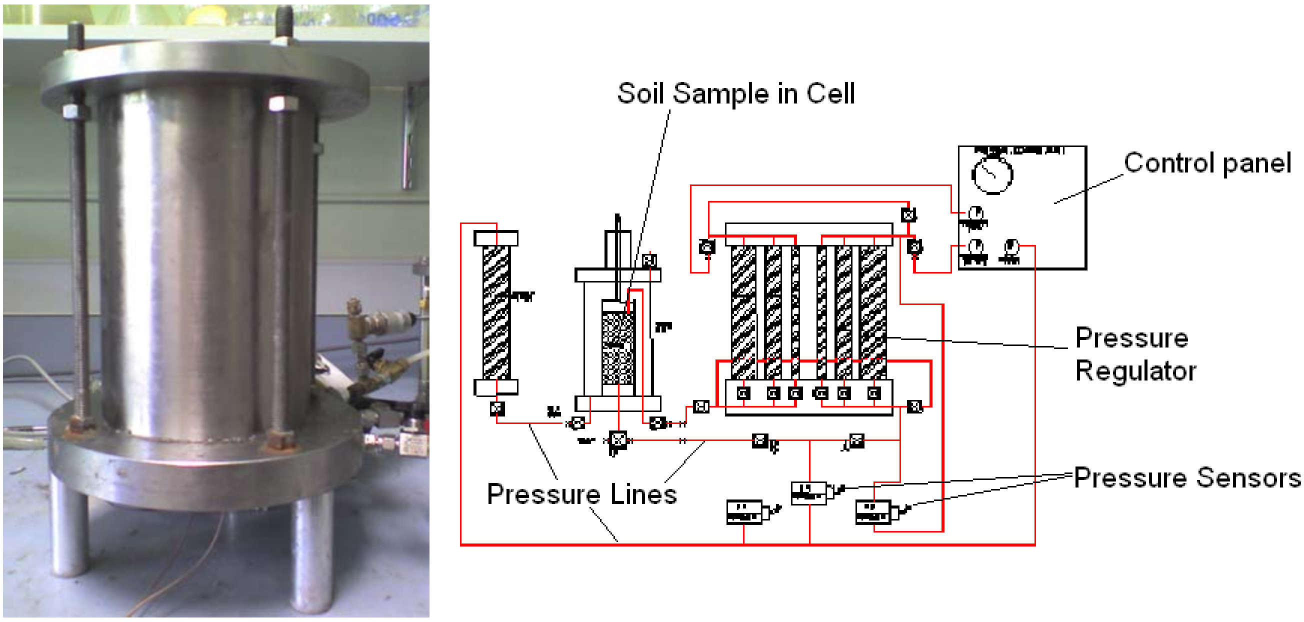


FIGURE 3. Left, the triaxial compression cell actually used. On the right a schematic of a standard cell

The paste was placed in a rubber membrane which is centrally located within the cell. The two pressure lines into the sample (located at both the top and bottom of the sample) allowed for a back pressure (or pore water pressure) to be recorded. The water which fills the cell, is also connected to a pressure line, which allows for a cell pressure (equal to the in situ confining stress) to be applied. The three pressure lines are controlled by a central control board, shown in figure 4 below.

FIGURE 4. The control board for the triaxial cell, showing dials for cell pressure and pore pressures

Bender Elements

A Bender element simply consists of a tiny piezoelectric plate which deforms when subjected to an electric current. Under an alternating current the piezoelectric plate continually deforms in opposite directions as the current oscillates.

In the laboratory, each bender element was coated in an epoxy resin before being mounted in the top and bottom caps of the soil sample. The bottom Bender element is connected to a sine wave generator, which transmits a single electric pulse to the piezoelectric plate of the bender element. The Bender element then undergoes a tiny deformation, which results in the propagation of a shear wave up through the soil sample. When the shear wave reaches the top receiving Bender element, it is converted back to an electrical pulse.

Using an oscilloscope, and plotting the transmitted and received shear wave pulses on an ‘amplitude vs. time’ axis, the total return time for the electrical pulse was determined. In order to determine the exact time taken for the shear wave to propagate through the soil sample (To), ‘Bender lag’ was accounted for. ‘Bender lag’ is the time delay inherent in the apparatus due to resistance in the wiring; it was measured by touching the two bender elements directly and observing the pulse return time. The time delay due to ‘Bender lag’ was then subtracted from the total return time of the electrical pulse in order to yield the exact time taken for the shear wave to propagate through the soil sample. Accounting for ‘Bender lag’ within the system led to an increase in the accuracy of pulse return time measurements, which was in the order of 10%.

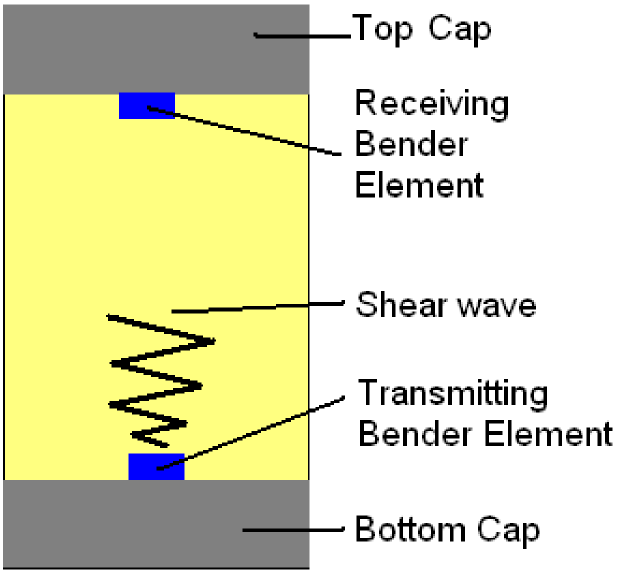


FIGURE 5. A schematic showing the propagation of a shear wave through a soil sample by a Bender element

Laboratory Testing Procedure

In order to ensure the accuracy of the data obtained from the laboratory testing, it was deemed necessary to implement a strict laboratory test procedure. The experimental procedure was designed to eliminate variations within the input variables; with the aim of producing a data set which was dependent only on the physical properties of the paste, and not on any other factor.

Laboratory Test Procedure for Triaxial Test

- Ensure all apparatus (particularly seals and o-rings) are clean
- Measure the ‘bender lag’ by touching the two bender elements and recording the time delay on the return wave
- Stretch the membrane onto the bottom bender cap, and secure in place with two o-rings
- Assemble the sample mould around the membrane, and then stretch the membrane tightly over the mould, being careful to avoid pinching or puncturing of the membrane.
- Prepare the paste sample, ensuring the quantities of tailings, cement, and water used will yield the desired void ratio; also ensure a representative sample of the tailings is used
- Record the time the water is added to the cement and tailings, and then begin mixing sample thoroughly.
- When sample is fully mixed, place the paste into the mould, ensuring that membrane is completely full. Then vibrate sample to remove any trapped air.

- Place the top bender cap onto the sample (ensuring that the top bender element is aligned with the bottom bender element) and secure the membrane to the cap with two o-rings.
- Record the weight of the left over paste, which can then be used to calculate the sample weight.
- After filling the triaxial cell completely with water, secure the lid of the cell. (By removing the plug on the cell lid, and applying a small cell pressure, any trapped air within the cell can be expelled)
- Begin logging the results using the Rowe Cell software.
- Ensure all valves are open, and apply a cell pressure of 40 KPa, and a back pressure of 20kPa
- When pressures become constant, slowly increment both the cell and back pressures by 20KPa until a cell pressure of 420KPa, and a back pressure of 400kPa are achieved. These cell pressures are designed to replicate the in situ stresses the paste experiences
- When the pressures again become constant, isolate the sample within the cell by closing off all valves to the sample

After the sample has been isolated and, and the self-desiccation process has begun, the bender elements are used to monitor the development of the small strain shear stiffness (Go).

As the self desiccation process progresses, a drop in pore water pressure within the soil sample occurs. The pore water pressure within the soil sample must be ‘backed up’ to its original level whenever it falls by more than approximately 20% of its initial value; this prevents dissolved air in the paste from precipitating out.

RESULTS INTERPRETATION

BENDER RESULTS FOR SHEAR STIFFNESS

After the completion of each test (which usually lasted approximately 200 hours,) a table of the pulse return times over the life of the test was able to be tabulated. The shear wave velocity of the soil sample can now be determined using the below equation, where h is the sample height minus the height of the two bender elements.

$$v\,(ms^{-1}) = \frac{h}{To}$$

The formula for the small strain shear stiffness, Go, of the soil was then calculated using the following equation, where ρ is the soil density.

$$Go\,(MPa) = \rho . v^2$$

The bulk modulus K can then be determined, using Poisson’s ratio and the following formula.

$$K = \frac{2(1-v)}{3(1-2v)} . G$$

The graphs showing the observed development of stiffness over time, compared with Helinski's predicted results are shown in *Appendix 1*. Below is a summary of how the maturity term, d, related to the material property (relative particle size) of each tailings.

Tailings	**Kanowna Belle**	**Leinster**	**Broken Hill**
Maturity Term, d	-2.3	-2.5	-1.5
Relative Particle Size Ranking (1=small, 3=large)	2	1	3

FIGURE 6. Table showing the relationship between particle size and maturity term

It is evident from the table above, that a relationship exists between the particle size of the tailings, and the speed with which the stiffness of the paste develops. Helinski's model confirms that the more coarse a tailings, the faster the cemented paste will harden.

This can be explained by the higher permeability of the paste. The water within the soil matrix will flow more freely, and is able to hydrate the cement at a greater rate. This is an important relationship, because the particle size of a tailings paste can now be used to accurately predict the rate at which that particular paste will develop stiffness.

RESULTS OF PORE WATER PRESSURE DISSIPATION

At the completion of each test, the data logged from pressure sensors recording the pore water pressure drop over time, was plotted, and compared against Helinski's model. The plots showing the cumulative pore water pressure dissipation are shown in *Appendix 2.*

Tailings	**Kanowna Belle**	**Leinster**	**Broken Hill**
Maturity Term, d	-2.3	-2.5	-1.5
Efficiency, E_h	0.04	0.032	0.064
Relative Particle Size Ranking (1=small, 3=large)	2	1	3

FIGURE 7. This table shows the relationship between particle size and efficiency, E_h

The table above shows how the efficiency of pore water pressure dissipation (i.e. the efficiency of the cement hydration) varies with particle size. Once again, the particle size of the paste appears to be the major factor in determining the efficiency of the cement hydration; with the finer pastes exhibiting a smaller efficiency. Once again, this is due primarily to the reduced permeability of a paste made up of fine tailings.

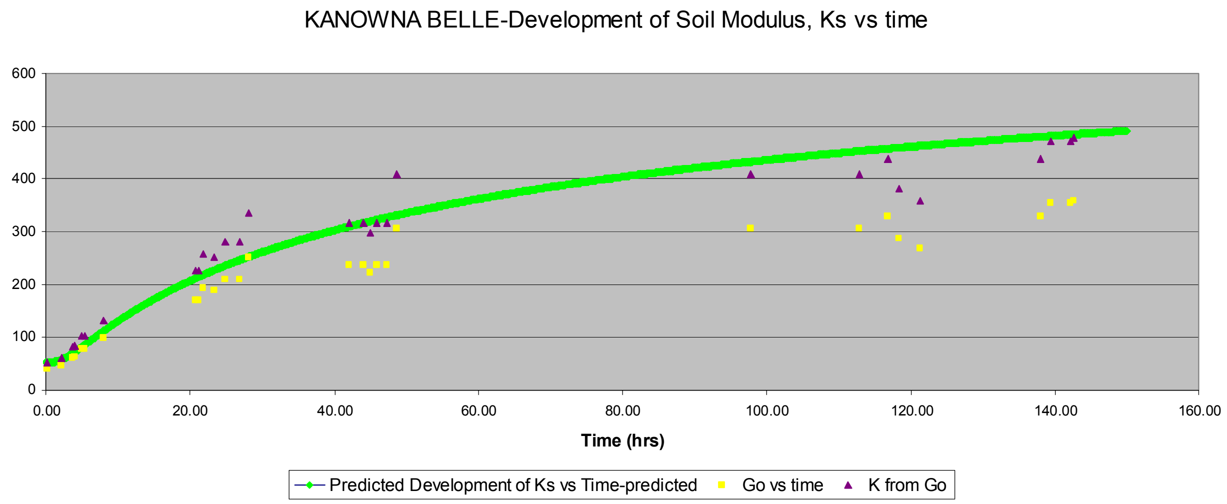
As previously stated, the rate of pore water pressure dissipation (which is positively related to the efficiency E_h) can be used to predict the rate at which effective stresses and therefore arching will develop within the stope. These laboratory experiments strongly suggest that the more coarse a tailings, the higher the efficiency, and hence the faster the development of effective stresses and arching.

CONCLUSION

The results of this paper strongly support the models (Helinski, 2005) proposed to simulate ‘stiffness development’ and ‘pore water pressure dissipation’ within a hydraulic paste. Three different tailings, each with significantly different physical characteristics (such as particle size) were combined in three different pastes. Each paste agreed with the prediction model used; showing a slower rate of hydration and hence a slower development of shear stiffness as particle size decreased. The laboratory tests also suggest that the more coarse a paste, the more quickly pore water pressures can be dissipated, the more quickly arching and effective stresses develop.

These findings are both important and relevant, as they provide a tangible link between the physical properties of the tailings, and the physical properties of the paste during the setting period. These findings have the potential to improve underground mine safety, by facilitating the more accurate prediction of the development of shear stiffness and stress redistribution within the stope.

Appendix 1


KANOWNA BELLE-Development of Soil Modulus, Ks vs time
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400
300
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100
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20.00
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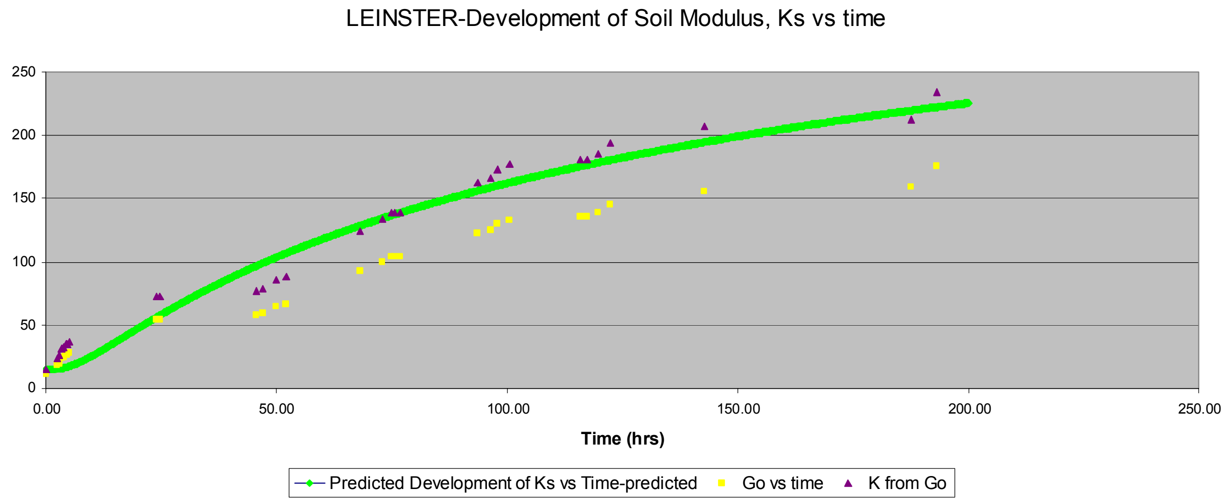
100.00
120.00
140.00
160.00
Time (hrs)
Predicted Development of Ks vs Time-predicted
Go vs time
K from Go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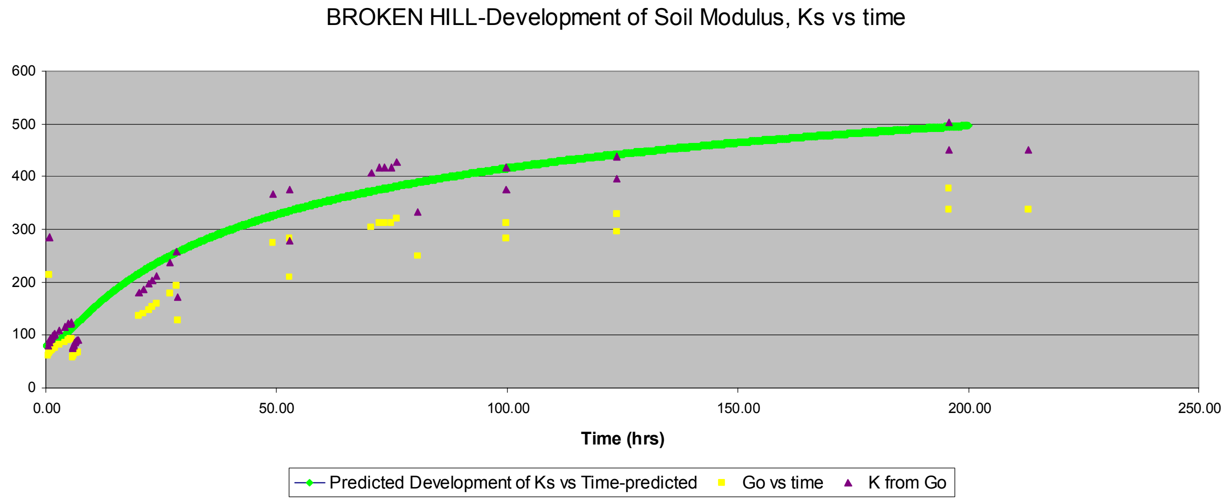
Time (hrs)
Predicted Development of Ks vs Time-predicted
Go vs time
K from Go


BROKEN HILL-Development of Soil Modulus, Ks vs time
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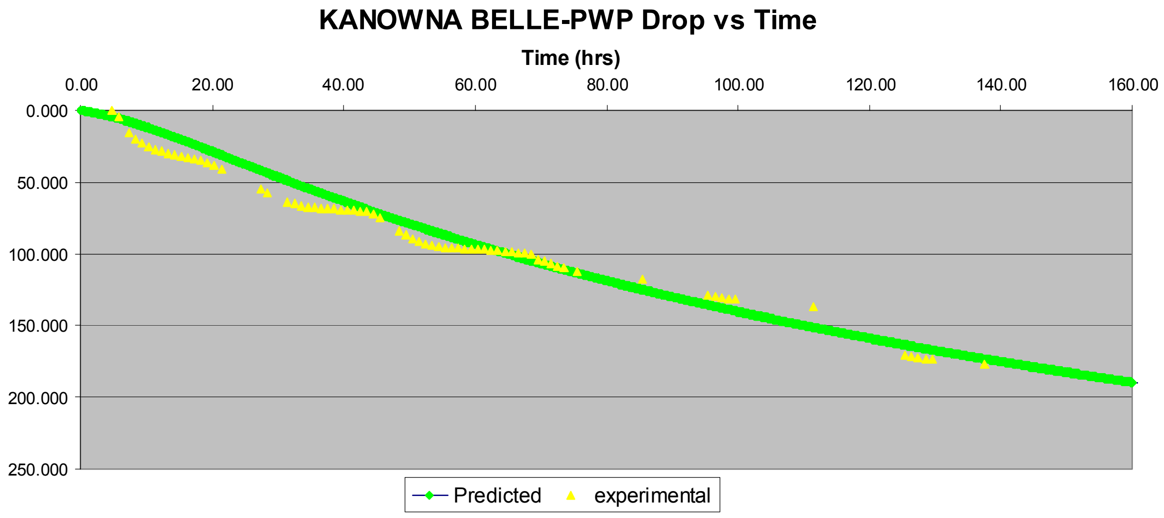
Time (hrs)
Predicted Development of Ks vs Time-predicted
Go vs time
K from Go

Appendix 2


KANOWNA BELLE-PWP Drop vs Time
Time (hrs)
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60.00
80.00
100.00
120.00
140.00
160.00
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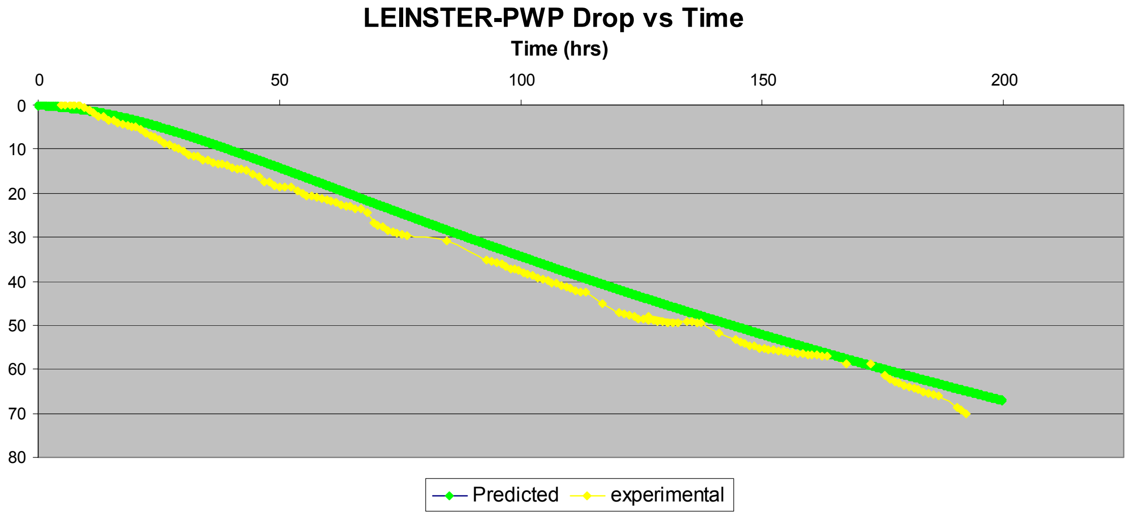
50.000
100.000
150.000
200.000
250.000
Predicted
experimental


LEINSTER-PWP Drop vs Time
Time (hrs)
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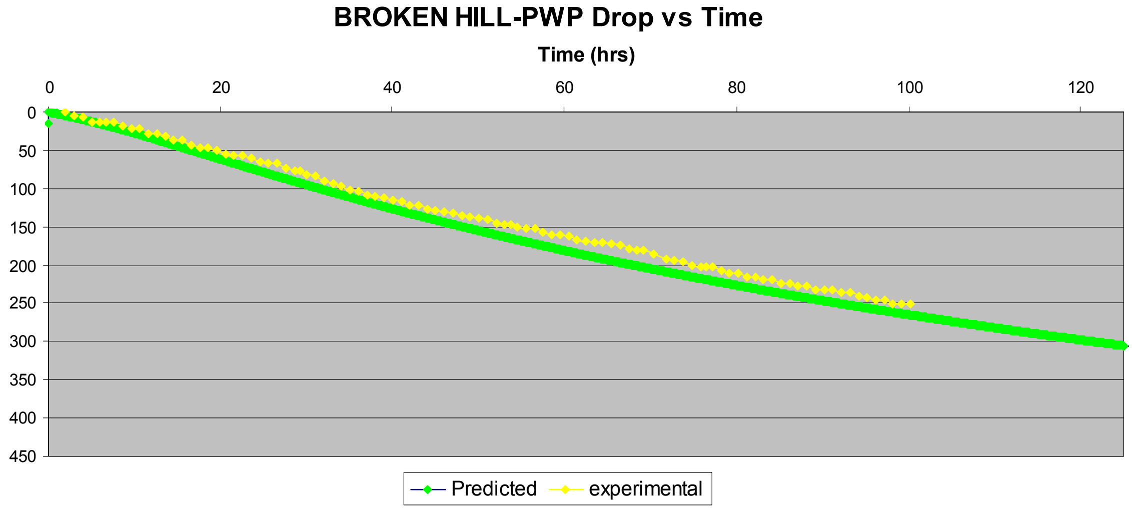
150
200
0
10
20
30
40
50
60
70
80
Predicted
experimental


BROKEN HILL-PWP Drop vs Time
Time (hrs)
0
20
40
60
80
100
120
0
50
100
150
200
250
300
350
400
450
Predicted
experimental

REFERENCES

Helinski et al (2005) Mechanics of early age cemented paste backfill paste. Limerick April 3-7, Australian Centre for Geomechanics. (In press)

Ismail, M.A., Joer,H. and Randolph, M.F. (2000) Sample preparation technique for artificially cemented soils. ASTM Geotechnical Testing Journal. Vol 23, No. 2, pages171-177

Helinski, M., Fourie, A., Fahey, M., Ismail, M., The Self Desiccation Process in Cemented Mine Backfill. November 2005 (in press)

Wood, D.M., (1990) Soil Behaviour and Critical State Soil Mechanics. Cambridge Press Syndicate, Trumpington Cambridge.