

CEMENTED PASTE BACKFILL LEACHATE CHARACTERISTICS - SNAP LAKE DIAMOND MINE¹

Ken DeVos,² and Rens Verburg²

Abstract. A geochemical study was completed as part of an Environmental Assessment Report for De Beers Canada Inc. Snap Lake diamond mine located in the Canadian Northwest Territories. The deposit will be mined using underground methods and consists of a diamond bearing planar kimberlite dyke dipping at about 15 degrees, hosted in metavolcanic and granite rock. Processing will include grinding of the kimberlite ore and a gravity separation circuit on this ore which will result in processed kimberlite waste including a coarse fraction and a finer fraction which will be used to produce a cemented paste backfill material. The cemented paste composed of processed kimberlite, dilution rock, and cement is thickened to a paste-like consistency and will be used to fill the mine voids.

The study discussed in this paper was completed to evaluate potential leachate chemistry of the alkaline cemented paste backfill material slated for use underground. The laboratory test program included solids testing, short-term leach testing, and longer-term kinetic testing on a variety of cemented paste blends and additives. Results show that the pH of the leachate remained alkaline for subaqueous test cells and decreased over time for sub-aerial test cells. Geochemical speciation modeling using PHREEQC that was completed to further evaluate leachate chemistry for site specific conditions indicated probable solubility constraints due to secondary mineral precipitation for parameters calcium, chromium, manganese and nickel.

Additional Key Words: kinetic, alkaline, PHREEQC, cement, paste, backfill, kimberlite.

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² Ken DeVos, Associate, Golder Associates Ltd., Mississauga, ON, L5N 5Z7, Canada, Rens Verburg, Principal, Golder Associates Inc., Redmond, WA. USA. 98052.

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Introduction

The use of cemented paste as backfill material has become an accepted method to promote physical stability within underground mines (le Roux et al., 2005; AGC, 2003; Gay and Constantiner, 1998; Mitchell et al., 1982). This type of backfill is typically composed of fine grained processed materials, dilution rock, and cement, is thickened to a paste-like consistency, and is used to fill remaining underground voids after mining. The use of cemented paste backfill has added environmental benefits through lowering the quantity of mine wastes placed on the surface, thereby reducing surface exposure and the potential for environmental impacts, especially with respect to water quality. Further benefits are often achieved during operation due to reduced requirements for fresh make-up water for processing.

The De Beers Canada Inc. Snap Lake underground diamond mine, located in the Canadian Northwest Territories, will use a cemented paste backfill material for structural stability in the underground workings. The deposit consists of a diamond bearing planar kimberlite dyke dipping at about 15 degrees, hosted in metavolcanic and granite rock and will be mined using underground methods. Processing of the kimberlite ore will include grinding and gravity separation which will produce a minus ¾ inch (coarse) fraction, a coarse sand (grits) fraction, and a finer sand (slimes) fraction which will be combined with dilution rock and cement to produce the cemented processed kimberlite (PK) paste backfill for use underground.

A critical component determining any long-term environmental impacts from the proposed underground mine at the Snap Lake Project is an understanding of how water quality may be affected following mine closure. The chemical stability of uncemented paste materials is generally similar to that of traditional, saturated tailings (Newman et al., 2001). That is, the high degree of saturation of paste typically acts to reduce sulphide oxidation. Furthermore, water present in paste tends to be effectively retained in the paste matrix, thereby significantly reducing potential release of chemical constituents from the paste. However, due to cement addition the backfill will be alkaline in nature and will require an assessment of potential implications with respect to the overall mine water quality during operations and after closure.

This paper discusses the geochemical testing completed on samples of the cemented PK paste backfill and the results of the testing. The results are further evaluated using the geochemical speciation model PHREEQC.

Objectives

The specific objectives of the geochemistry program for the Snap Lake PK paste backfill project were to:

- develop more reliable estimates for water quality from the PK paste and an understanding of the mechanisms that control release of pertinent chemical components;
- develop an understanding of attenuating mechanisms that may operate along the flow path between the mine and the surrounding lakes such that these findings can be incorporated into refinement of the estimates of groundwater quality; and
- assess at a preliminary screening level, possible amendments that might be applied to the PK paste backfill.

The goal of the geochemical modelling was to estimate post mining closure water quality near the mine workings following leaching from PK paste.

Geochemical Test Program

Test Materials and Preparation

The material for the test program was selected to represent the PK paste backfill that is to be deposited underground. The components of the PK paste were provided by De Beers and prepared by Mine System Design (MSD) of Kellogg, Idaho. The paste consisted of 29% kimberlite slimes, 35% grits and 36% coarse fractions. Where necessary, the minus 3/4 inch crushed kimberlite was ground by MSD to create the particle size distribution that will be generated during operations. Dilution rock consisted primarily of granite, as this is the predominant host rock for the kimberlite deposit. Additives provided for mixing with the paste included: Type 10 Portland cement; fly ash, and Rheomac UW 450, an anti-washout agent to reduce loss of fine material from the paste surface supplied by Master Builders.

The following cemented paste mixtures were prepared:

- Standard cemented paste. PK with 2.5% cement (type 10 Portland) by weight;
- Amended paste #1. PK with 2.5% cement/fly ash by weight consisting of a 70:30 ratio of type 10 Portland cement: flyash; and
- Amended paste #2. PK with 2.5% type 10 Portland cement by weight with anti-washout additive.

Plastic cement forms were used to shape cylindrical moulds. Once the moulds had cured, they were placed in a cell for kinetic testing. Several large and small cylinders were poured; four of the larger cylinders were used for kinetic testing and the smaller cylinders were used for static testing. The large moulds had dimensions of 16 inches (40.6 cm) diameter by 1.75 inches (4.44 cm) in height such that they fit snugly in the kinetic testing cells, with dimensions of 16.5 inches (41.9 cm) inner diameter by 6.5 inches (15.9 cm) in height (Fig. 1 and 2). The moulds were allowed to cure for 28 days prior to initiating the static or kinetic test work.

Table 1 summarizes the materials used for tests; the leach testing completed on each, and provides an overview of the testing program. The test procedures are described in more detail below and in Price (1997).

Test Methods

Static Tests

Static testing was completed for confirmation of material properties. Static tests are short-term tests designed to provide a rapid assessment of material properties. All test samples were characterized for solids elemental composition (elemental metal analyses), acid generation potential through acid base accounting (ABA), and short-term leach potential Special Waste Extraction Procedure (SWEP) test following common industry standard guidelines as presented the Price (1997) and DIAND (1992) guideline methods.

The SWEP is a short-term leach test used to assess the short-term chemical stability of a material. This type of test was conducted on each of the standard and amended cemented PK

paste mixtures in duplicate. The test that was used for the PK cemented paste was modified slightly from the standard test to better simulate the conditions that might be expected at the mine site. Distilled water was used as the lixiviant in a 4:1 liquid to solid ratio. The resulting leachate was analysed for general parameters and metals, with metals being analysed by ICP-MS. Cold-temperature SWEP tests were identical in methodology, but conducted under low-temperature (3°C) conditions to evaluate the influence of colder temperatures on the short-term leaching characteristics and water quality.

Table 1. Overview of test materials

Mix Type	Material Use / HC Cell #	Purpose	Cell (inches)		Paste Cylinder (inches)	
			Height	Width (ID)	Height	Width
2.5% Portland Cement	HC 33	Standard Kinetic	6.25	16.5	1.75	16
2.5% Portland Cement	HC 34	Standard Kinetic	6.25	16.5	1.75	16
2.5% Portland Cement	HC 35	Subaqueous Kinetic	6.25	16.5	1.75	16
2.5% Portland Cement	HC 36	Subaqueous Kinetic	6.25	16.5	1.75	16
2.5% Portland Cement	broken up for testing	Static Tests	N/A	N/A	6	3
2.5% (Cement/Flyash Binder)	broken up for testing	Static Tests	N/A	N/A	6	3
2.5% Cement (Anti-washout)	broken up for testing	Static Tests	N/A	N/A	6	3
Granite	HC 37	Attenuation Testing	8	4	N/A	N/A
Metavolcanic	HC 38	Attenuation Testing	8	4	N/A	N/A

Notes: N/A = Not applicable

Kinetic Tests

Kinetic tests are repetitive leach tests designed to determine long-term leachate characteristics from a geologic material or mine waste. Kinetic testing for 20 weeks with a weekly flush was completed on four sub-samples of cemented PK paste material, all of which consisted of the expected standard mixture of PK paste with 2.5 wt% cement. Two tests were completed using a standard subaerial leach cycle (Price 1997). The other two kinetic tests were conducted sub-aqueously whereby the sample remained saturated for the duration of the testing and the waters saturating the materials were replaced on a regular seven-day cycle. These two cells were used to evaluate cemented paste leaching under submerged conditions, as well as to generate leachate for the attenuation testing. Two cells were set up to evaluate attenuation potential of the rock types. Leachates were all analysed weekly for general parameters pH, temperature, conductivity and sulphate, and less frequently nutrients and metals. Metals were determined using ICP-MS. Each of these three types of kinetic tests is described below:

Standard subaerial kinetic testing (2 cells; HC 33 and HC 34). The standard kinetic test cells consisted of a cylinder of cemented PK paste of approximately 41 cm diameter by 4.5 cm thickness (Fig. 1). The cemented PK paste was subjected to a weekly leach cycle. A standard

seven-day leach cycle was used, but modified such that humidified air was passed over the sample for the first six days (the humidified air was considered more typical of what would be expected underground). This six-day interval was followed by a one-day flush whereby liquid was added to the cell at a 0.5:1 liquid to solid ratio and allowed to saturate the sample for 24 hours. The rinse water was collected and analyzed for a suite of chemical parameters.

Subaqueous kinetic testing (2 cells; HC 35 and HC 36). Subaqueous kinetic test cells had the same dimensions as the standard kinetic test cells. A seven-day leach cycle was still used; however, the water was added to the cell on the first day at a 0.5:1 liquid to solid ratio and allowed to soak the sample for the entire seven days. At the end of the seven days, the water was removed from the cell and analyzed for the same suite of chemical parameters. A sub-sample of this water was used in the attenuation testing described below. The water removed from the cell was replaced with fresh water immediately after removal.

Attenuation testing (2 cells; HC 37 and HC 38). The attenuation test cells consisted of columns containing screened (grain size of 0.5 to 1 inch diameter) and washed rock (HC 37 contained granite rock; HC 38 contained metavolcanic rock) (Fig. 2). A seven-day leach cycle was used. On the first day, rinse water generated by the subaqueous kinetic testing of cemented PK paste was added to the cell (water from HC 35 was added to HC 37 and water from HC 36 was added to HC 38) at a 0.5:1 liquid to solid ratio and allowed to soak the attenuation material for the entire seven days. At the end of the seven days, the leachate was removed from the cell and analyzed for the comprehensive suite of chemical parameters. The water extracted from the cell was replaced with new rinse water from the subaqueous kinetic testing immediately upon removal. This set-up was designed to allow evaluation of interaction between leachate from cemented PK paste and the host rock material, since leachate will be transported through the host rock after closure. This testing component emphasized the evaluation of processes that could result in attenuation of certain leachate constituents through mineral precipitation and/or adsorption.



Figure 1. Top view of cemented paste in kinetic test cell.



Figure 2. Columns used for attenuation testing.

Test Results

Paste pH

Values for paste pH in the cemented paste samples are approximately 9.0. These values are higher than in uncemented PK samples; however, they are not as high as those measured in leachates from the SWEP testing (> 11 , Table 3). The pH values in excess of 11 are consistent with equilibrium between a common cement-forming mineral, portlandite [$\text{Ca}(\text{OH})_2$], and the leaching solution. This equilibrium likely was not achieved during the paste pH measurement.

Acid Base Accounting Results

Results show that the acid-generation characteristics of the cemented PK paste and the fly ash amended samples are similar to those of unprocessed kimberlite. That is, they are non-acid generating due to low sulphur content and very high neutralization potential.

The ABA results for cemented processed kimberlite are presented in Table 2. The results show that the cemented PK paste samples are typical of kimberlite samples with respect to total sulphur as they contain very low amounts of total and sulphide sulphur (less than 0.3 percent by weight). Conservatively, the total sulphur value was used to calculate the acid production potential (AP) in this study. However, the sulphide sulphur constitutes only slightly more than half of the total sulphur content.

The bulk neutralization potential (bulk NP) and carbonate neutralization potential (CaNP) values generally are very high relative to the acid production potential. Bulk NP is generally considerably higher than the CaNP, suggesting that not all NP is present in the form of carbonates (dolomite and calcite), as discussed in De Beers (2002 and 2003), but also in other mineral forms.

The NP:AP range for the cemented paste samples is between 89 and 238, while the CaNP:AP range is between 21 and 56 (Table 2). This demonstrates that the cemented paste samples have significant excess NP both in carbonate and non-carbonate form.

SWEP Test

Table 3 summarizes the results from the SWEP testing on kimberlite, and uncemented and cemented processed kimberlite. The results show that the pH of SWEP leachate from the cemented PK paste is approximately 11.4, whereas the pH for uncemented samples is approximately 9. In general, the concentrations of most major ions in leachates from the cemented PK paste sample are elevated with respect to the uncemented processed kimberlite samples (Table 3). Concentrations of the trace metals Al, Cr, Cu, and Mo are also elevated with respect to uncemented sample averages, likely due to the alkaline pH conditions in the cemented PK paste. In general, the results for the standard ambient-temperature and cold-temperature SWEP tests are very similar. Concentrations of alkalinity, SO₄, Al, Ba, Ca, Cr, Mo, K, Na, and Sr are slightly lower in the cold-temperature tests.

Table 2. Summary of ABA results

Processed Kimberlite Samples	Number of Samples	Paste pH	Sulphide (wt.%)	NP	CaNP	AP	NP:AP	CaNP:AP
Average Uncemented Processed Kimberlite	12	8.07	0.06	309	113	2.1	147	54
Cemented PK (EAR Sample)	1	11.3	0.12	221	53	2.5	89	21
Cemented PK (2.5 % Cement - Sept 02)	1	9.1	0.07	310	73.3	1.3	238	56
Cemented PK (Flyash Amendment – Sept 02)	1	9	0.08	287	66.1	1.6	179	41

Notes: * units expressed in kg CaCO₃/tonne
 EAR = Environmental Assessment Report
 NP = neutralization potential of the bulk sample
 CaNP = Neutralization potential due to carbonate minerals
 AP = Acid production potential
 PK = Processed Kimberlite

Paste Consolidation Pore Water

A small amount of pore water is generally released as paste consolidates. This paste consolidation water, or pore-water, was collected during the initial curing phase of the paste cylinders (within 24 hours of pouring). The volume of this water was measured and a composite of the pore water from the cells was submitted for chemical analysis, while the remaining static and kinetic testing was conducted on cured, less-leachable material.

Table 3. SWEP water quality test results for selected parameters.

Parameter	Uncemented Kimberlite Group Averages (EAR Samples)			Averages for Cemented Paste PK		
	Unprocessed	Processed: Tails and Grits	Processed: Thickener and Underflow	Standard Cemented PK Paste (2.5% cement, 23 °C)	Cemented PK Paste Cold Temperature (2.5% cement, 3 °C)	Cemented PK Paste Amendment # 1 (Binded with 2.5% Flyash/Cement, 23 °C)
No. of Samples	4	3	1	2	2	2
pH	8.8	8.7	8.7	11.41	11.32	11.70
Alkalinity (mg/L as CaCO ₃)	24	32	30	350	320	685
TDS (mg/L)	98	130	174	507	683	757
SO ₄ (mg/L)	29.5	36.0	59.6	37	18.5	10.5
Cl (mg/L)	0.24	0.22	0.73	3.88	4.03	7.99
Total P (mg/L)	0.02	0.01	0.07	<0.01	<0.01	0.026
NH ₃ (mg/L- N)	0.04	0.01	0.01	<0.01	0.82	3.21
NO ₃ (mg/L- N)	0.01	0.04	0.01	2.01	1.93	1.91
Al (mg/L)	0.019	0.005	0.009	0.69	0.50	0.49
As (ug/L)	0.63	<i>0.50</i>	1.00	<1	<1	<1
Cd (ug/L)	<i>0.05</i>	<i>0.05</i>	<i>0.05</i>	<0.5	<0.5	<0.5
Co (ug/L)	0.08	0.08	0.36	<1	<1	<1
Cr (ug/L)	0.31	0.42	<i>0.25</i>	97.5	75.5	14
Cu (ug/L)	0.70	0.43	1.00	2.0	2.0	4.0
Fe (mg/L)	0.05	0.04	0.13	<0.03	<0.03	<0.03
Hg (ug/L)	<i>0.5</i>	<i>0.5</i>	<i>0.5</i>	<0.05	<0.05	<0.05
K (mg/L)	2.90	3.48	7.05	26.25	23.05	34.95
Mn (ug/L)	0.94	1.08	2.70	<1	<1	<1
Mo (ug/L)	10.73	18.53	43.80	77.5	67.0	51.5
Na (mg/L)	2.00	1.00	2.20	13.7	12.7	21.6
Ni (ug/L)	2.95	4.93	10.00	<5	<5	<5
Pb (ug/L)	<i>1.00</i>	<i>1.00</i>	<i>1.00</i>	<1	<1	1
Zn (ug/L)	1.06	<i>0.25</i>	<i>0.25</i>	<5	<5	<5

Notes: Values reported as less than detection are entered as 1/2 the detection limit for calculated averages in the italicized cells; dissolved metals reported; “ug” = micrograms.

Paste pore water represents a snapshot of the porewater quality at the time of paste deposition. Very little pore water was released due to consolidation. The total amount of pore-water retrieved from the cemented paste corresponded to less than 1% of the initial water content. This low volume of water is consistent with the specific retention characteristics of paste and its general ability to retain its moisture without appreciable loss. Since the cemented material has not yet set or cured, this water generally represents a worst-case quality. Concentrations for key parameters from the pore water sample are provided in Table 4. Given the low volume of water collected, it was not possible to conduct a comprehensive analysis, including measurement of pH. For parameters, K, Mo, Pb and Na the concentrations in the pore water are much higher than those from both the SWEP testing and the kinetic testing; Mn concentrations were similar, and Al values were lower in the pore waters. For other parameters comparison was not possible due to elevated detection limits in the pore water resulting from the small sample volume.

Table 4. Summary of paste consolidation pore water quality analysis

Parameter	Paste Consolidation Water (Uncured Pore-water)
Al (mg/L)	0.025
As (mg/L)	<0.0025
Cd (mg/L)	<0.00125
Co (mg/L)	<0.0025
Cu (mg/L)	<0.0025
Fe (mg/L)	<0.075
K (mg/L)	80
Mn (mg/L)	0.0025
Mo (mg/L)	0.395
Pb (mg/L)	0.005
Ni (mg/L)	<0.0125
Na (mg/L)	88
Zn (mg/L)	<0.0125

Note: Due to the small volume of water obtained, it was only possible to conduct a single composite ICP-MS analysis at elevated detection limits.

Kinetic Test Program

Four humidity cell tests were completed on the cemented paste materials, two (duplicate) subaerial tests (HC 33 and 34) and two (duplicate) subaqueous tests (HC 35 and 36). Selected kinetic test results for the complete 21-week testing period are summarized in Fig. 3 and 4. Parameters of particular interest included Al, Cr, and molybdenum, as these constituents are known to demonstrate enhanced mobility under alkaline conditions. Good reproducibility is found for the duplicate cells within each set.

The results from the kinetic testing show that in all kinetic test cells pH decreases over time and that the pH trends for each duplicate set of cells are very similar. In the subaerial humidity cells the pH stabilized between 8.5 and 9.5 (Fig. 3). In the subaqueous cells, the decrease is less

pronounced (Fig. 4). However, in both subaqueous cells, the values decrease from greater than 11.5 to less than 10.8 over the 20-week course of testing.

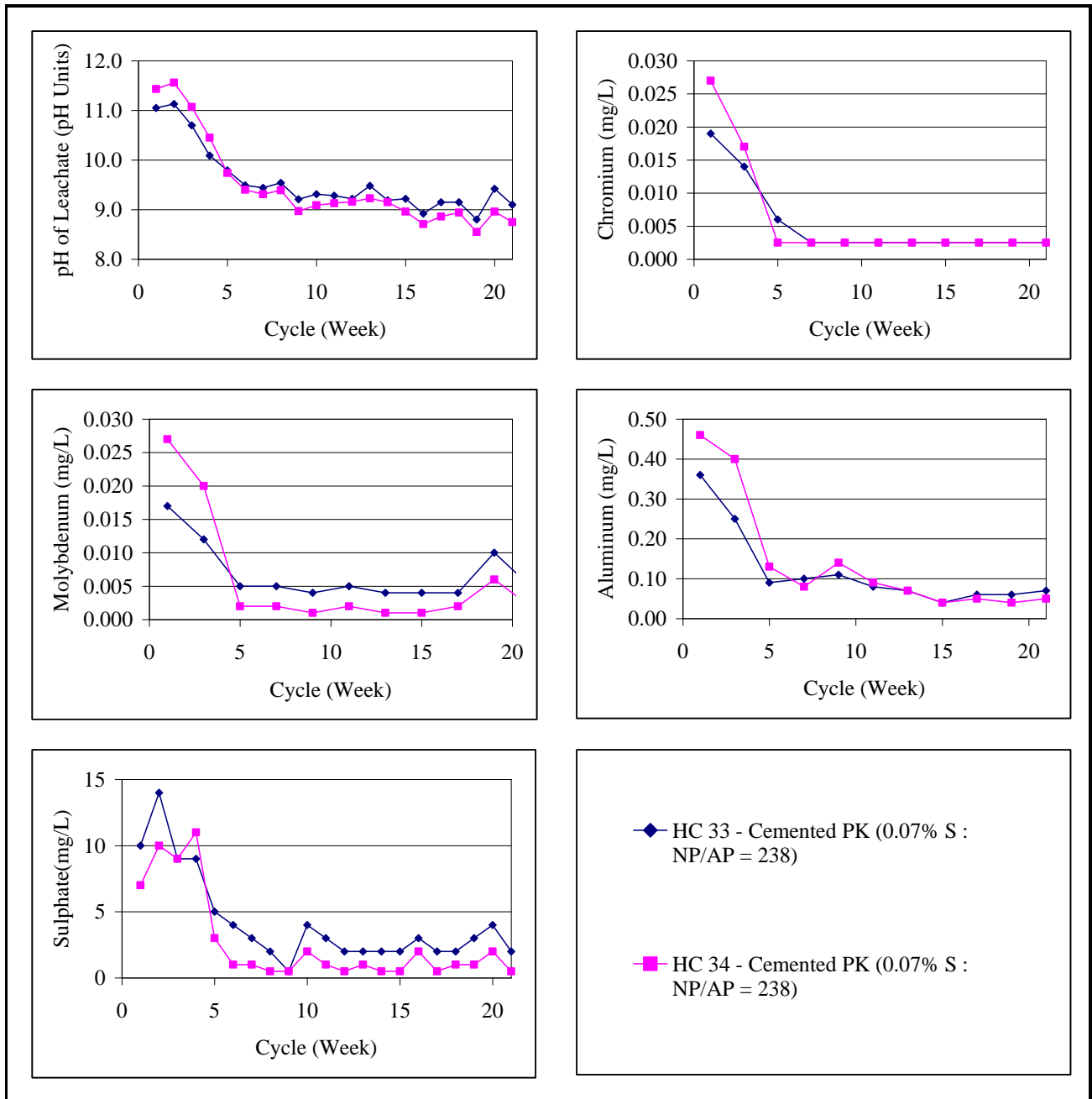


Figure 3. Results for kinetic testing on duplicate subaerial test cells

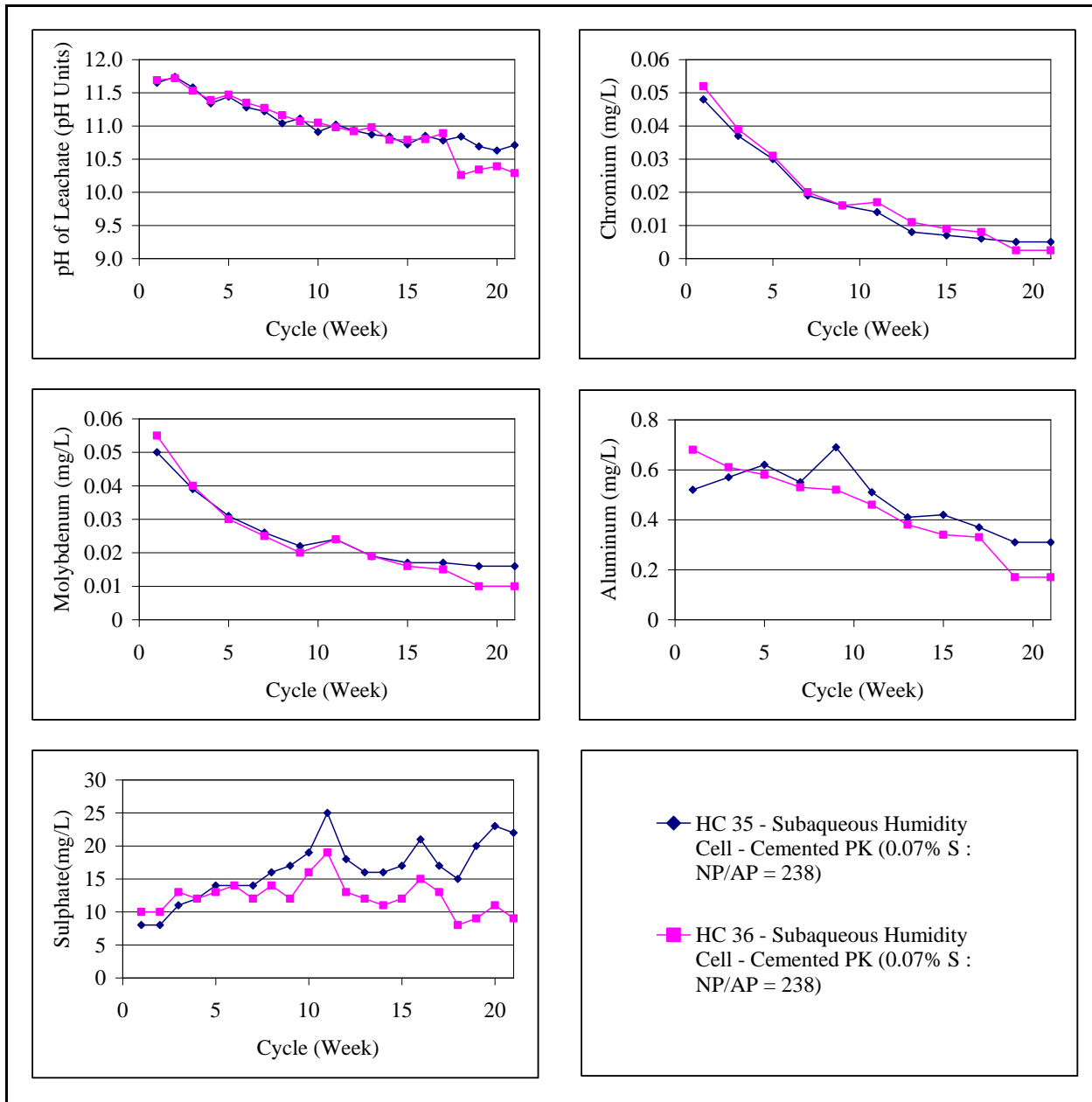


Figure 4. Results for kinetic testing on duplicate subaqueous test cells

In the subaqueous test cells, the Cr, Al and molybdenum concentrations show a consistent downward trend. However, in the subaerial humidity cells, their concentrations decrease more rapidly within the first few weeks of testing. Sulphate concentrations in the subaerial cells show a sharp initial decrease as well, whereas in the subaqueous cells they remain approximately constant at low levels.

Geochemical Modelling

Geochemical speciation and mixing modelling was conducted to evaluate geochemical controls on paste leachate composition and to estimate the potential for changes in the pH and long-term concentrations of key parameters following mine closure. A discussion of several of the considerations used in defining the model setup is provided in the Conclusions and Discussion section. The model setup is described below.

Model Methodology

Geochemical modeling was conducted according to the following general approach:

- Definition of Input Water Qualities - definition of paste pore water, groundwater and flood water quality. Leachate chemistries from the kinetic testing program were used to define the paste pore water quality (Table 5). Early leach test results were selected representing initial flushing of the material, resulting in peak loadings as a worst –case estimate. The quality of the mine flooding water was based on the predicted mine water inflow concentrations at the time of flooding. The groundwater quality applied was the median granite groundwater established during the baseline study for the Snap Lake Project.
- Geochemical Mixing Modeling - Mixing of paste backfill pore water with mine flood water and groundwater in appropriate proportions. Geochemical speciation and mixing modelling was conducted using PHREEQC Version 2.8 (Parkhurst and Appelo 1999) with the MINTEQA2 database (Allison et al., 1991). PHREEQC is an equilibrium mass transfer code developed by the United States Geological Survey (USGS). It is widely accepted by both the regulatory and scientific community. The model has been used to simulate many geochemical conditions, including cement-clay systems (Jacques 2002).
- Evaluation of geochemical controls on constituent concentrations - Mineral dissolution and secondary mineral precipitation were evaluated as potential geochemical controls.

The goal of the geochemical modelling was to estimate post mining closure water quality near the mine workings following leaching from paste backfill. Modelling therefore simulated the mixing of groundwater, mine flood water and paste pore water to determine the resultant chemistry. Because leaching of pore water is expected to be a slow process, the effect of this leaching on mine water quality was simulated assuming that all of the porewater in a given “skin” thickness would mix with the nearby groundwater or mine flood water.

Use of an equilibrated solution in mixing simulations is considered a reasonable assumption due to the long residence time of the paste pore water, much longer than the period of the kinetic test. Model input water qualities were adjusted based on equilibration with a select number of solid phases. These phases are generally accepted as being geochemically credible (i.e., they are capable of rapidly establishing equilibrium with an aqueous solution and are commonly found in systems that include mining materials). Portlandite and calcite, minerals are present in the paste backfill and therefore were allowed to dissolve if undersaturated.

Table 5. Input chemistry for mixing waters

Parameter (mg/l)	Unit	Paste Pore Water	Mine Flood Water	Groundwater
pH	(i.u.)	11.41	8.10	8.10
Aluminum	mg/l	0.685	0.06	0.005
Arsenic	mg/l	0.0005	0.001	0.0006
Calcium	mg/l	142	121	60
Cadmium	mg/l	0.0003	0.0001	0
Chloride	mg/l	3.9	172	154
Chromium	mg/l	0.098	0.005	0.001
Copper	mg/l	0.002	0.002	0.001
Iron	mg/l	0.015	0.12	0.01
Potassium	mg/l	26	10.5	3.5
Magnesium	mg/l	0.02	12.6	8.0
Manganese	mg/l	0.0005	0.01	0.009
Sodium	mg/l	13.7	22	49
Ammonia	mg/l	-	3.2	25.2
Nickel	mg/l	0.0025	0.008	0.0008
Nitrate	mg/l	-	5	0
Sulphate	mg/l	58	10	9
Zinc	mg/l	0.003	0.014	0.001
Alkalinity (as CaCO ₃)	mg/l	350	162	90

Mixing proportions for the various model scenarios were selected to represent possible combinations of short-term, and long-term contributions from the cemented PK paste to the overall groundwater system. The range of potential mixing proportions was estimated taking into consideration the volume of the paste backfill and the volume of the remainder of the flooded mine workings. Five mixing scenarios were modeled. Case 1 and Case 2 involved mixing of only backfill porewater and mine flooding water. These scenarios were assumed to be representative of conditions immediately following flooding. Cases 3 through 5, representative of later conditions, simulated mixing of paste porewater, mine flooding water, and groundwater. Table 6 shows the mixing proportions for the various simulations.

Following mixing, solid-phase controls were applied. Phases identified as geochemically credible were allowed to precipitate upon supersaturation. Calcite was assumed present in the aquifer and therefore available to dissolve if undersaturated. Conservatively, no adsorption onto precipitated minerals (i.e., ferrihydrite) was considered due to the relatively low input conditions of Fe. The equilibrated water qualities are presented in Table 6.

Model Results

The discussion of the model results focuses primarily on the variability and groundwater characteristics (pH and redox conditions) as well as parameters most affected by potential changes in groundwater conditions (listed in Table 6).

Table 6 provides the results of the equilibrated water chemistry for these key parameters for the various mixed solutions. Geochemical controls on Ca, Cr, Mn and nickel are observed in the mixing simulations. Mixing of the porewater with mine flood water and/or groundwater results in dilution and reductions in the concentrations of Al, Ca, Fe, K, and alkalinity that are elevated in the porewater and increases in concentrations of the Cl⁻, Mg and Mn that are elevated in the groundwater.

The pH values and redox potential are significant controls on the Cr concentrations observed. Through mixing of the porewater with the flood water and groundwater, pH decreases and the solution becomes mildly reducing. This results in precipitation of Cr hydroxide, decreasing the dissolved concentrations. Additional decreases in these concentrations would be expected as the mixture migrates through the bedrock and continues to equilibrate and mix with the groundwater.

Table 6. Equilibrated water qualities from PHREEQC simulation results for various mixing scenarios.

Mixing Components	Initial Equilibrated Backfill Paste Porewater Chemistry ¹	Mixing Scenarios (proportion of component) (%)					
		Case 1	Case 2	Case 3	Case 4	Case 5	
Backfill Paste	1	90	80	45	27	9	
Porewater							
Mine Flood Water		10	20	5	3	1	
Groundwater				50	70	90	
Parameter	Unit	Concentration					
pH		12.99	12.95	12.90	12.64	12.37	11.18
Aluminium	mg/L	0.685	0.622	0.559	0.314	0.190	0.067
Arsenic	mg/L	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006
Calcium	mg/L	872	784	696	387	228	69
Cadmium	mg/L	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
Chloride	mg/L	3.9	21	37	87	114	141
Chromium	mg/L	0.097	0.088	0.078	0.044	0.027	0.005
Copper	mg/L	0.002	0.002	0.002	0.001	0.001	0.001
Iron	mg/L	0.015	0.014	0.012	0.011	0.010	0.009
Potassium	mg/L	26	25	23	14	10	6
Magnesium	mg/L	0.02	1.3	2.5	4.6	6.0	7.3
Manganese	mg/L	2.3E-07	0.0000	0.0001	0.0044	0.0061	0.0078
Sodium	mg/L	13.7	14.5	15.3	31.7	38.6	45.5
Nickel	mg/L	0.0025	0.00266	0.0024	0.0013	0.0007	0.0001
Sulphate	mg/L	58	53	48	64	68	72
Zinc	mg/L	0.003	0.004	0.005	0.002	0.002	0.001
Alkalinity (as CaCO ₃)	mg/L	2172	1936	1701	924	520	116
Solid Equilibrium Phases		MnO ₂	MnO ₂	MnO ₂	MnO ₂	MnO ₂	MnO ₂
		CaCO ₃	Ni(OH) ₂ CaCO ₃	Ni(OH) ₂ CaCO ₃	Ni(OH) ₂ CaCO ₃	Ni(OH) ₂ CaCO ₃	Ni(OH) ₂ CaCO ₃ Cr(OH) ₃

Notes: 1) Water chemistry adjusted based on equilibrium with CaCO₃ and MnO₂

Discussion and Conclusions

Results from the kinetic testing on the cemented PK paste backfill demonstrate that high pH and potentially elevated concentrations of Al, Ca, Cr, and alkalinity initially occur in the porewater of the cemented PK paste. However, during flooding of the mine at closure, the chemical composition of any porewater released by the paste will change through dilution and geochemical interaction.

Solubility behaviour within the porewater of cemented materials is a complex interaction between Ca oxides, silicates, and water (Thomas et al., 2002). Leachability and pH of the cemented material generally are a function of several minerals including portlandite, gypsum, and several Ca aluminosilicates and sulfates. Rothstein et al. (2002) found that as the cement cured, equilibrium with portlandite was obtained, buffering the pH of the porewater within the cement to a value of around 13.

Others have investigated migration of porewater from cement-containing materials placed underground in bedrock as part of evaluations of disposal options for nuclear waste. Pfingsten (2002) calculated that in a diffusion-dominated system, high pH (>10) exists to a distance of less than 10 cm from the cement-porewater interface, and that depletion of solids from the cemented material extends less than 20 cm back into the cemented material after a period of 2,000 years. Soler and Mader (2002) investigated the interaction between hyperalkaline solutions derived from degradation of cement as they migrated through fractures in rock, and found that precipitation of secondary minerals resulted in pH reduction in the solution and corresponding reduction in the permeability of the fracture. They suggested that "...mineral reaction will tend to progressively seal the pores of the rocks and diminish the hydraulic conductivity of these systems...". Their conclusions were supported by small-scale laboratory experiments with granodiorite (a rock-type very similar in characteristics to the granitic host rock at Snap Lake).

Given the low hydraulic conductivity of the cemented paste and fracture network of the Snap Lake flow system (De Beers, 2002), and taking into consideration the results of the recent work completed on cemented materials in underground settings (Pfingsten 2002; Soler and Mader 2002), it is expected that release of chemical mass from the Snap Lake mine backfill will be governed by diffusion-dominated processes. As a result, the long-term mass depletion from the cemented PK paste is expected to occur within 10 to 20 cm of the cemented paste-groundwater interface. Further, it is expected that a pH of less than 10 will dominate the groundwater, outside of the PK porewater.

For the Snap Lake cemented PK paste backfill, based on calculations accounting for diffusion and simulation of geochemical interactions, the high pH and elevated concentrations of Al, Ca, Cr, and alkalinity observed in the geochemical test program are not expected to persist beyond the immediate vicinity of the PK paste backfill. The water quality of the overall flooded mine workings is expected to trend towards that of Case 5 as shown in Table 6, becoming less alkaline with reductions in concentrations of Al, Ca, Cr, and alkalinity.

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Literature Cited

- ACG, 2003. 2003 Seminar on Paste and Thickened Tailings. Australian Centre for Geomechanics. Melbourne, Australia. May 14-16, 2003.
- Allison, J.D., Brown, D.S., Novo-Gradac, K.J. 1991. MINTEQA2/PRODEFA2, A geochemical assessment model for environmental systems: Version 3.0 user's manual, U.S. Environmental Protection Agency, Athens, GA.
- De Beers Canada Mining Inc. (De Beers). 2002. Snap Lake Diamond Project Environmental Assessment. Document submitted to the Mackenzie Valley Environmental Impact Review Board (MVEIRB). February, 2002.
- De Beers. 2003. Snap Lake Diamond Project Cemented Paste PK Kinetic Test Results. Submitted to the MVEIRB, February, 2003.
- DIAND. 1992. Guidelines for ARD Prediction in the North. Department of Indian and Northern Affairs. September, 1992.
- Gay, F. and Constantiner, D., "Admixtures for Improving Paste Backfill Mixes", presented at Tailings and Mine Waste '98, Fort Collins, Colorado, January 26-28, 1998.
- Jacques, D. 2002. Reactive transport modelling of interaction Boom Clay – cement water: Experimental data and preliminary modelling results. In: TRePro – Workshop on Modelling of Coupled Transport Reaction Processes, Karlsruhe, Germany 2002.
- le Roux, Kim; Bawden, William F.; Grabinsky, Murray F. Field properties of cemented paste backfill at the Golden Giant mine. Mining Technology : IMM Transactions section A, Volume 114, Number 2, June 2005, pp. 65-80(16). Maney Publishing
- Mitchell, R.J, Olsen, R.S., and Smith, J.D., 1982, Model studies on cemented tailings used in mine backfill, Canadian Geotechnical Journal, 19(3) pp 289-295. <http://dx.doi.org/10.1139/t82-035>.
- Newman, P., Cadden, A. and White, R., 2001. Paste, the Future of Tailings Disposal, Proceedings of the 2nd International Conference on Mining and the Environment, pp. 594-603.
- Parkhurst, D.L., and C.A.J. Appelo. 1999. User's Guide to PHREEQC (Version 2) - A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations, U.S. Geological Survey Water-Resources Investigations Report 99-4259, Denver, CO.

- Pfingsten, W. 2002. Modelling cement-rock-water interactions – the influence of selected boundary conditions. In: TRePro – Workshop on Modelling of Coupled Transport Reaction Processes, Karlsruhe, Germany, 2002.
- Price, W.A. 1997. Draft Guidelines and Recommended Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British Columbia. Reclamation Section, Energy and Minerals Division, BC Ministry of Employment and Investment. April, 1997.
- Rothstein, D., Thomas, J.J., Christensen, B.J., and Jennings, H.M. 2002. Solubility behavior of Ca-, S-, Al-, and Si-bearing solid phases in Portland cement pore solutions as a function of hydration time. *Cement and Concrete Research*. 32 (2002) pp. 1663-1671. [http://dx.doi.org/10.1016/S0008-8846\(02\)00855-4](http://dx.doi.org/10.1016/S0008-8846(02)00855-4).
- Soler, J.M. and Mader U.K. 2002. High-pH plume reactive transport simulations. In: TRePro – Workshop on Modelling of Coupled Transport Reaction Processes, Karlsruhe, Germany 2002.
- Thomas, J.J., Rothstein, D., Jennings, H.M., and Christensen, B.J. 2002. Effect of hydration temperature on the solubility behavior of Ca-, S-, Al-, and Si-bearing solid phases in Portland cement Submitted to: *Cement and Concrete Research*. 2002.