



uOttawa

L'Université canadienne
Canada's university

**FACULTÉ DES ÉTUDES SUPÉRIEURES
ET POSTDOCTORALES**



**FACULTY OF GRADUATE AND
POSTDOCTORAL STUDIES**

Henry Jean Claude Célestin

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

M.A.Sc. (Civil Engineering)

GRADE / DEGREE

Department of Civil Engineering

FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

**Geotechnical Properties of Cemented Paste Backfill and Tailing Liners:
Effect of Mix Components and Temperature**

TITRE DE LA THÈSE / TITLE OF THESIS

Dr. M. Fall

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Dr. Paul Simms

Dr. Baolin Wang

Gary W. Slater

Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

**Geotechnical Properties of
Cemented Paste Backfill and Tailings Liners:
Effect of Mix Components and Temperature**

By

Henry Jean Claude Célestin

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the Requirements for the degree of

Master of Applied Science

In

Civil Engineering

Ottawa-Carleton Institute for Civil Engineering
University of Ottawa

November 2008

© Henry Jean Claude Célestin



Library and
Archives Canada

Bibliothèque et
Archives Canada

Published Heritage
Branch

Direction du
Patrimoine de l'édition

395 Wellington Street
Ottawa ON K1A 0N4
Canada

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-51829-8
Our file Notre référence
ISBN: 978-0-494-51829-8

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protègent cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.


Canada

Dedicated to my family

Table of Contents

1	Chapter 1: General Introduction	1
1.1	Introduction and problem statement.....	1
1.2	Objective of the thesis.....	4
1.3	Research Methodology	5
1.4	Organization of the thesis	7
1.5	References.....	9
2	Chapter 2: Technical Background	11
2.1	Background on Cemented Paste Backfill.....	11
2.1.1	Geotechnical Design of Cemented Paste Backfill.....	15
2.1.2	Effect of mix components and proportions on Cemented Paste Backfill	20
2.1.3	Effects of Temperature on Cemented Paste Backfill	25
2.1.4	Sources of Temperature in Mines and Backfill Operations	27
2.2	Determination of Thermal Conductivity by using KD2.....	28
2.2.1	Thermal conductivity	29
2.2.2	Thermal diffusivity	29
2.2.3	Specific heat capacity	32
2.3	Background on mine geotechnical barriers (Liners and Covers).....	33
2.3.1	Mining application	33
2.3.2	Municipal waste disposal application	35

2.3.3	References	38
3	Chapter 3	48
3.1	Technical Paper I	48
3.2	Abstract.....	48
3.3	Introduction.	49
3.4	Experimental techniques and materials used.....	53
3.4.1	Materials used	53
3.4.2	Measurement device.....	56
3.4.3	Mix preparation and procedures	56
3.4.4	Experimental techniques.....	59
3.5	Results and discussion	60
3.5.1	Effect of binder types and curing time on the thermal conductivity	60
3.5.2	Effect of binder proportion on the thermal conductivity	62
3.5.3	Effect of water/cement ratio on the thermal conductivity.....	64
3.5.4	Effect of tailings characteristics on the thermal conductivity	65
3.5.5	Effect of sulphate concentration on the thermal conductivity	72
3.5.6	Coupled effect of curing temperature and water saturation degree on the thermal conductivity	74
3.6	Summary and conclusions.....	78
3.7	References.....	81
4	Chapter 4	87
4.1	Technical Paper II	87
4.2	Abstract.....	87

4.3	Introduction	89
4.4	Materials and experimental program.....	95
4.4.1	Materials used	95
4.4.2	Specimen preparation and mix proportions	97
4.4.3	Testing of specimens	99
4.4.3.1	Mechanical tests.....	99
4.4.3.2	Hydraulic conductivity tests	99
4.5	Results and discussions	101
4.5.1	Relationship of curing temperature to compressive strength development of CPB	101
4.5.1.1	Combined effects of curing temperature and mix components on UCS development of CPB.....	113
4.5.1.2	Combined effects of curing temperature and binder proportions on UCS development of CPB.....	116
4.5.1.3	Combined effects of curing temperature and tailings fineness on UCS development of CPB.....	118
4.5.1.4	Combined effects of curing temperature and W/C ratio on UCS development of CPB.....	123
4.5.2	Effect of curing temperature on the split tensile strength development of CPB	126
4.5.3	Relationship of curing temperature to hydraulic conductivity of CPB	129
4.6	Summary and conclusions	134

4.8	References	138
5	Chapter 5: Technical Paper III.....	150
5.1	Abstract.....	150
5.2	Introduction	151
5.3	Background, Transformations in natural liners.....	153
5.3.1	Natural compacted clay liners.....	153
5.3.2	Geosynthetic clay liners	154
5.3.3	Composite liners	154
5.3.4	Low permeability material research	155
5.4	Experimental program.....	156
5.4.1	Materials	156
5.4.1.1	Densified Tailings.....	156
5.4.1.2	Bentonite.....	157
5.4.1.3	Polyacrylates (SAP).....	158
5.4.1.4	Water.....	158
5.4.2	Method.....	159
5.4.2.1	Preparation of specimens	159
5.4.3	Tests conducted and characteristics of the materials	159
5.4.3.1	Sieve and Hydrometer tests	159
5.4.3.2	X-ray diffraction.....	160
5.4.3.3	Inductively coupled plasma – emission spectroscopy (ICS-ES)	162
5.4.3.4	Plasticity tests	164

5.4.3.5	Specific gravity.....	164
5.4.3.6	Compaction (Standard proctor tests).....	165
5.4.3.7	Hydraulic conductivity tests	167
5.4.3.8	Freeze-thaw tests.....	171
5.4.3.9	Cost analysis.....	174
5.5	Results and discussions	175
5.5.1	Compaction.....	175
5.5.1.1	Compaction of the reference raw densified tailings.....	175
5.5.1.2	Compaction of modified bentonite densified tailings (BDT) ..	175
5.5.1.3	Compaction of polymers densified tailings (PDT).....	178
5.5.2	Hydraulic conductivity	180
5.5.2.1	Hydraulic conductivity of raw tailings	180
5.5.2.2	Hydraulic conductivity of bentonite densified tailings (BDT) .	181
5.5.2.3	Hydraulic conductivity of polymer densified tailings (PDT)....	185
5.5.2.4	Effect of freeze-thaw on hydraulic conductivity	192
5.5.3	Cost effectiveness	202
5.6	Summary and conclusions.....	205
5.7	References.....	209
6	Chapter 6	217
6.1	Conclusions and recommendations	217
6.2	References.....	221

List of Tables

Table 1-1. General overview of the thesis organization.	7
Table 2-1. Typical containments present in hazardous landfill waste after Ehrig (1988).....	37
Table 3-1. Physical properties of the tailings (AT) used.	54
Table 3-2. Main chemical elements in the tailings (AT) used.	55
Table 3-3. Characteristics of the different types of binder used.	55
Table 3-4. Mix composition for the different samples.....	58
Table 4-1. Physical properties of the tailings	96
Table 4-2. Main chemical elements in the tailings	96
Table 4-3. Mixes prepared for UCS tests, split tensile tests and hydraulic conductivity tests.	98
Table 5-1 Chemical composition of material used in the liner preparation.....	163
Table 5-2 Atterberg limits and specific gravity for bentonite and artificial tailings	165

List of Figures

Figure 2-1. Stope configuration and backfilling process. (Adapted from Paynter and Dodd 1997).....	13
Figure 2-2. Schematic presentation of the different phases of the technology of cemented tailing backfill (CTB): preparation, transport and underground placing of the CTB, where it builds CTB structure (after Fall et al. 2008).....	14
Figure 2-3. Deformation of the backfill block under Vertical loading (adapted from Belem et al.).....	17
Figure 2-4. Effect of binder content, Water/Cement ratio, tailing fineness and tailings density on UCS (kPa) of Cemented Paste Backfill (CPB) after Fall et al. 2008.....	21
Figure 2-5. Mercury intrusion porosimetry showing large number of pores in the size of 0.05 to 1 micrometer in mixes made of tailings whose fines are more than 45%. It also shows large intrusion porosity for pores in the range of 1 to 10 microns in mixes made of tailings containing less than 45% fines (Fall et al. 2008).	24
Figure 2-6. Effect of curing temperature on strength development of CPB after Fall and Samb (2006).....	27
Figure 2-7. KD2 Thermal Analyser (Decagon devices inc).	32
Figure 2-8. Basic liner design (Adapted from Daniel 1993).	38
Figure 3-1. Grain size distribution of the artificial tailings and that of the average of 9 natural mine tailings.	54
Figure 3-2. Effect of binder type on thermal conductivity.	62

Figure 3-3. Effect of on binder proportion at constant slump on thermal conductivity.....	63
Figure 3-4. Effect of water/cement ratio (W/C) on the thermal conductivity	65
Figure 3-5. Effect of tailings grain size on thermal conductivity of CPB prepared at constant W/C ratio.	67
Figure 3-6. Effect of tailings fineness on void ratio (e) and porosity (n) on paste backfill cemented with 4.5% PCI/Slag	69
Figure 3-7. Effect of tailings grain size with constant slump on thermal conductivity.....	70
Figure 3-8. Influence of the mineralogical composition (quartz proportion) of the tailings on CPB's thermal conductivity.....	72
Figure 3-9. Effect of initial sulfate concentration on thermal conductivity of CPB	73
Figure 3-10. Effect of curing temperature on the thermal conductivity of CPB in relationship to curing time.....	75
Figure 3-11. Effect of time and curing temperature on thermal conductivity of CPB	76
Figure 3-12. Effect of the variation of water content with depth on the thermal conductivity of CPB aged of 90 days and cured at 50°C.....	78
Figure 4-1. Grain size distribution of the tailings used (SI) and the average grain size distribution of tailings from 9 eastern Canadian mines	97
Figure 4-2. Effect of curing temperature on the early age UCS development of paste backfill cemented with PCI (slump ~ 18 cm).....	102

Figure 4-3. Effect of curing temperature on the early age UCS development of paste backfill cemented with PCI/Slag (50/50) (slump ~ 18 cm).....	102
Figure 4-4. TG/DTA diagrams for 7-day-old cement pastes of CPB cured at different curing temperatures (20°C and 35°C; Fall 2008)	103
Figure 4-5. MIP pore size distribution of CPB with a) 4.5% PCI vs. curing temperature after 7 days of curing (W/C~7.5; slump~18 cm; Tailings: TA) and b) 7% PCI/Slag (20/80) vs. curing temperature after 14 days of curing (W/C~5.0; Tailings: TA) (Fall 2008).....	105
Figure 4-6. Effect of curing temperature on the development of the long term strength of PC-CPB and Slag-CPB (slump ~ 17 cm; %cement =4.5%).....	108
Figure 4-7. a) MIP pore size distribution and b) MIP cumulative porosity of CPB with 7% PCI/Slag (20/80; W/C=5;) vs. curing temperature after 160 days of curing (Fall, 2008)	111
Figure 4-8. Effect of curing temperature on the strength of CPBs made of various types of binders after a) 7 days and b) 28 days of curing (slump~18).	115
Figure 4-9. Combined effects of curing temperatures and binder content on UCS of PCI-CPB at a) 7 days b) 28 days c) 90 days curing (W/C~7.6; slump~18 cm; Tailings: TS-1).	117
Figure 4-10. Combined influence of tailings fineness and curing temperature on the strength of CPB after a) 7 days and b) 28 days of curing (W/C~7.6; slump~18 cm; Tailings: TS-1).	121
Figure 4-11. Influence of tailings fineness on the void ratio (e) and porosity (n) of paste backfill cemented with 4.5% PCI/Slag (slump = 18 cm) (Fall et al. 2004)	122

Figure 4-12. Combined effects of curing temperatures and W/C ratio on UCS of PCI-CPB at a) 7 days b) 28 days curing (slump~18 cm).....	125
Figure 4-13. Effect of curing temperature on the split tensile strength development of PCI-CPB.....	127
Figure 4-14. Effect of curing temperature on the 28 days split tensile strength of paste backfill containing 2%, 4.5% and 6% PC	127
Figure 4-15. Effect of curing temperature on the split tensile strength development of Slag-CPB.....	129
Figure 4-16. Combined effect of curing temperature and curing time on hydraulic conductivity of CPB.....	132
Figure 4-17. Coupled effect of temperature and binder type on hydraulic conductivity at various curing temperatures	134
Figure 5-1. Grain size distribution from sieve and hydrometer tests performed on artificial tailings compared to the average of 9 Canadian mines from east Ontario	157
Figure 5-2. Grain size distribution of bentonite from hydrometer test showing an average of 92% of clay proportion < 2microns.....	160
Figure 5-3. X-Ray diffractogram from Bentonite.....	161
Figure 5-4. Compaction curve for raw densified tailings.....	167
Figure 5-5. Phase change curve.	173
Figure 5-6. Sample under temperature monitoring.....	174
Figure 5-7. Effect of bentonite proportion on the characteristics of proctor compaction of densified tailings.....	176

Figure 5-8. Effect of super absorbent polymers proportion on the characteristics of the proctor compaction of densified tailings	178
Figure 5-9. Hydraulic conductivity scatter pattern of plain densified tailing compacted in the range of 10% to 24% water content	181
Figure 5-10. Effect of different bentonite proportions and water content on hydraulic conductivity of BDT.....	182
Figure 5-11. Variation of hydraulic conductivity within the compaction curve (4% Bentonite).	183
Figure 5-12. Effect of different SAP proportions and water content on hydraulic conductivity SAP densified tailings liner	187
Figure 5-13 Variation of hydraulic conductivity with compaction curve (0.2% SAP)	187
Figure 5-14. Expansion of the sample under swelling pressure developed by SAP.	190
Figure 5-15. Sample consistency prior adding SAP	191
Figure 5-16. Sample consistency after adding 0.1% of SAP.....	192
Figure 5-17. Variation of hydraulic conductivity with freeze-thaw cycles (8% bentonite, 23% water content)	193
Figure 5-18. Variation of hydraulic conductivity with freeze-thaw cycles (4% bentonite, 23% water content).	194
Figure 5-19. Evolution of hydraulic conductivity of BDT with freeze-thaw cycles (2% bentonite, 22% water content)	194

Figure 5-20. Evolution of hydraulic conductivity of SAP densified tailings tailings liner with freeze-thaw cycles (0.5% SAP, 41% water content)	198
Figure 5-21. Evolution of hydraulic conductivity of SAP densified tailings liner with freeze-thaw cycles (0.2% SAP 29% water content)	199
Figure 5-22. Evolution of hydraulic conductivity with freeze-thaw cycles and SAP content (0.1 SAP, 26% water content).	200
Figure 5-23. Evolution of hydraulic conductivity with freeze-thaw cycles and SAP content (0.05 SAP, 24% water content)	201
Figure 5-24. Relative benefit realization when using bentonite densified tailings liner as compared to a conventional 12% bentonite mixture.	203
Figure 5-25. Relative benefit realization when using SAP-densified tailings liner as compared to a conventional 12% bentonite mixture.	204

Acknowledgements

First of all, I would like to thanks my Professor Dr. Mamadou Fall who has been very encouraging toward me since the beginning of my graduate studies. His passion for research, his scientific curiosity and his technical approches have provided me with the taste of succes and achievement. I want to tell him special thanks for his unvaluable guidance throughout the thesis preparation process.

Thanks to my office colleagues Mukesh Pokharel and Othman Nasir for the various discussions held, we all togheter about our own laboratory experience, observations and discoveries in the field of mining materials .

I thank Faculty Scientist, Dr. Nimal de Silva of Faculty of Sciences, University of Ottawa and Technical Officer Gordon Chan from NRC (institute for Research in Construction) for providing me with ICP and XRD analysis, respectively.

I am very grateful toward my friends, my relatives and, especially my parents and my family for the long sacrifice period consented during my studies.

Abstract

Mining activities involve large tonnage of ore processing to extract valuable metal. After extraction of metals, considerable amount of waste is generated. They are technically identified as tailings. Their sulphur and heavy metal content make them prone to generate acid and to contaminate the environment; therefore they can be classified as hazardous materials. The possibility to transform these tailings into cemented paste tailings (CPT, mix of dewatered tailings, water and cement) for their disposal has also conducted to the necessity to study their properties and to characterize the final product into which they are going to be converted. In CPT (also called cemented paste backfill or cemented pastefill) the amount of tailings that is recycled can represent a fraction of up to 70% of the mass of the mix.

During the last fifteen years, considerable effort has been mobilized to characterize tailings and CPT. However even the variety of studies conducted on these materials, several information are not yet available on CPT and its derivates. For this reason, in this paper, some issues were addressed, particularly, the thermal conductivity, the mechanical and hydraulic properties under various thermal loadings and the eventuality to further reduce the amount of remaining tailings by using it as liner.

a) Quantitative evaluation of thermal conductivity of CPT was conducted on a comprehensive mix matrix prepared in order to include the various influencing

parameters considered. These parameters consisted specially of: the binder type, the curing time, the binder proportion, the water cement ratio, the tailings mineralogy, the sulphate concentration and the resulting coupling effect of curing temperature with water saturation degree. The tests were conducted using the KD2 Thermal Analyzer which allowed measuring the thermal conductivity without destruction of the sample and without provoking phase change in the material. Results showed that the tailings type, the tailings fineness and the curing temperature were the most affecting factors.

b) Unconfined compressive strength, split tensile strength and hydraulic properties tests were conducted under coupled effect of temperature and the influencing factors previously considered during the thermal conductivity tests. The mechanical tests showed that strength of the material was a result of the concurrent evolving rate of the affecting parameters in presence. It was verified that temperature was always the predominant factor that affected the mechanical and hydraulic properties during the coupling process. It was also noticed that addition of pozzolan improved the mechanical and hydraulic properties when coupled to temperature. It was finally observed that hydraulic conductivity generally decreases with temperatures.

c) At the end, the design feasibility of a barrier in the aim at further reducing and recycle more mine waste was investigated. To perform this investigation, raw tailings were mixed respectively with bentonite and superabsorbent polymers in

an effort to improve the hydraulic conductivity. Samples compacted at normal proctor energy with 4% bentonite and 0.5% SAP content exhibited hydraulic conductivity of 4.32×10^{-9} cm/s and 6.28×10^{-9} cm/s, respectively. These samples also completed successfully five cycles of freeze-thaw performance test under which they were submitted, and this, without appreciable change in their permeability. A undertaken cost analysis revealed that a net gain of 66.67% was realizable when using tailings-bentonite at 4% and a net gain of 90% when using tailings-SAP materials at 0.5%.

In each part of this study, results that are obtained have been as much as possible verified for availability in published papers. Up to the present time they appear to be unknown from the tailings field. In such circumstances, the results gained from this study may contribute to further promote the optimization of mixes and additionally reduce waste in mining industry. This study is also intended to open windows on new recycled materials and therefore reduce detrimental loads to environment.

1 Chapter 1: General Introduction

1.1 Introduction and problem statement

Precious metals are generally confined underground where they are trapped. Their relative location to earth surface varies depending if they were lifted up to a certain depth following geological activities like tectonic movement or weathering (Cole et al. 2000). The targeted resources are generally intimate parts of heterogeneous soils in the form of mineralogical rocks, identified as ores. Because the ores concentration in valuable metals is low, during extraction huge amount of waste material is generated. The size of the waste materials ranges from boulders (meters) to very fine particles in the order of micrometers (Sivakugan 2008, Lottermoser 2007).

The boulders are ordinarily produced at the beginning during the excavation phase when exposing the ores. Their content in metal, referred as grade, is generally so low, that it is not economical to process them and they go straight to waste deposit (Lottermoser 2007). Next, come the intermediate sizes particles from crushing, grinding and milling process during the minerals beneficiation. Finally, the wastes end in very fine particles, notably the tailings that result from the hydrometallurgical processing during mineral extraction/liberation process (Benzaazoua et al. 2004).

Tailings, which are the waste grain size category focused in this thesis, are in most of the cases reputed hazardous for environment, health and economy. Their sulphur components and heavy metals component become more apparent after they have been reduced to very fine particles which are more prone to chemical reaction under increased exposed specific surface and reactivity to oxygen and moisture.

The initial practices that existed to control these waste materials consisted but were not limited to: dam impoundments, lakes rededication/reattribution for water cover, underground fill, and in earlier ages of mining, it consisted in surface storage, river dumping, or simply abandonment. Nowadays, with environmental awareness, the regulations regarding the disposal of such waste are much stricter. Furthermore, the management and conditioning of mine waste represent substantial cost for short term and long term control based on their sulphur content and heavy metal remnants. Therefore, to reduce the adverse effects, the mining industry has come out with cemented paste tailings (CPT). CPT is a relatively new engineering material containing 60-70% of tailing, 2-7% of binder and 20-35% of water (Fall et al. 2008, 2004, Yilmaz et al. 2003, Landriault 1995). It appears that it represents one of the best alternatives to cope with uncertainties linked to the various methods of storage difficulties.

Since its first usage in Bad Grund Mine (Germany) (Yilmaz 2004, Fall et al. 2008) CPT has gained tremendous popularity among operators. Beside worriness

attached to environmental issues like dam failures, ground water contamination and fine particles transport under wind conditions, CPT offers advantage of increasing ore extraction capability by substituting pillars with CPT structures. Simultaneously it provides better stability than previous filling methods like: rock fill or slurry fill with capability of exposing the fill without significant dilution during ore recovery (Hassani and Archibal 1998, Fall and Samb 2006). CPT also allows for faster cycles in ore recovery cut and fill methods by providing required strength at early age, owing this performance from binder hydration.

The extensive use of CPT has led to several studies to understand various engineering properties, particularly, Uniaxial Compressive Strength (UCS), Split Tensile Strength, Modulus of Elasticity, and Hydraulic Conductivity. The effects of various influencing parameters have also been investigated, like the effect of temperature, tailings grain size, chemicals, water content, binder type and binder content. However, from best osculation of the literature, it appears that most of these studies were conducted in laboratory under isolated parameter effect. Furthermore, no previous study appeared to be available on the thermal conductivity of this relatively new material. While heat is one of the factors that can affect and can be affected by all the other parameters, similarly, it can be generated from various sources like the underground environment rock, the work equipment and the cement hydration in the CPT. Furthermore, temperatures varies with region location and mine depth. Therefore the coupling process results are of key interest for optimal CPT benefit.

In an effort to contribute to the filling of this lack of information, quantitative evaluation of the thermal conductivity of CPT under the effect of the previously enumerated parameters was conducted. In addition, the mechanical and hydraulic properties were investigated under coupled effect of temperature and mix components. Finally a beneficial recycle of excessive remaining tailings was investigated in possible usage as cover and liner for waste materials. The development of the enumerated studies are developed in various technical papers and presented in this thesis.

1.2 Objective of the thesis

In the field of experimental investigations, results obtained from the action of one or the interaction of several variables form generally the base of an engineering framework. Quantifying the results of mechanical, and chemical processes in a material can lead to formulations allowing the control if not the improvement of process by developing deterministic relationships between the parameters. However, many interactions are not yet investigated in CPT.

While in the mining industry, Cemented Paste Tailing is proficiently used, depending of the function targeted, for example, low strength is very acceptable for waste solidification purpose in order to protect environment. Higher strength up to 4 MPa (Fall and Benzaazoua 2005) or up to 5 MPa (Belem and Benzaazoua 2008) can be required for pillar substitution and ground support. In the latter option, the rate of strength gain, the ultimate strength developed and

the cost are the main parameters that control the mix optimization. To do so, it becomes necessary to know the appropriate choice of mix proportion, the temperature at the stope, the heat produced by the mix and the rate of interaction between the temperature at the interior of the paste and the environmental rocks temperature. Indeed, as the backfilling will not consume all the tailings deposited on surface, good alternative to minimize the remaining amount would be of great consideration. In an attempt to control the aforementioned parameters, the objective of this thesis is to:

- Study of the thermal conductivity of CPT and factors affecting it,
- Study of the effect of temperature on the mechanical properties and hydraulic conductivity or CPT
- Study the suitability of densified tailings for liner and the effect of freeze-thaw on its hydraulic conductivity.

1.3 Research Methodology

Tests are carried carefully in laboratory on controlled samples following prescribed standard recommendations to reflect as much as possible the engineering behaviour of the material. In this study, whenever available, tests where conducted under the Revision 2004 of the ASTM standards (American Society for Testing Materials). The methodology used is outlined in the followings paragraphs.

-In all circumstances, samples were prepared in duplicates and tests were repeated a least two times and the average of the results were considered as termination value.

-To determine the thermal conductivity the instrument used was the KD2 Thermal Analyser. Cemented paste tailings samples of sufficient mass were prepared to prevent rapid changes in temperature while the testing was in process. The mixed paste was poured in cylindrical plastic containers of 10 cm diameter by 20 cm height and kept with their lid in the appropriate environment chamber at the predefined temperature. For tests carried at temperatures different than room temperature, probe was inserted in samples while the latters were kept inside their environment chamber during the measurement period.

-The mechanical effect under coupled process was created by curing samples with different mix proportions at different temperatures. Unmolded samples were trimmed and installed in the compressive loading frame and submitted to stress at the temperature that they were curing when removed from the environment chamber without allowing them to reach the ambient temperature.

- For the cover and liner material development, raw tailings, alternatively designated as densified tailings, were simulated by the use of ground silica sands with grain size comparable to tailings. Materials having high swelling potential were chosen as admixtures in order to fill voids in the newly composite material during compaction. Freeze-thaw cycles were implemented by alternating samples to boundary temperatures of -20°C and $+20^{\circ}\text{C}$ during fixed intervals of

time sufficient to ensure all ice lenses disappeared. The evaluation of benefit that could be realized from the exploitation of such liner was calculated based on the average cost of soil mixtures containing 12% of bentonite.

1.4 Organization of the thesis

This study was realized essentially around mining materials from tailings to CPT. Some properties of the tailings were studied in cemented conditions (CPT) and one part of the study dealt with uncemented tailings incorporated in possible cover or liners design. These investigations were covered in separated studies and presented in form of individual papers. Prior introducing these papers, one chapter that provides general overview as background about physics of heat transfer is presented. The present chapter also deals with old mining practices in general and particularly the contemporary material, CPT, in regards to disposal and especially to mechanical and hydraulic response. The last chapter deals with raw densified tailings as possible recycling material.

Table 1-1 summarizes the thesis organization.

Table 1-1. General overview of the thesis organization.

Chapter	Tailings condition	Considerations, Investigations performed
1	General introduction	• Presentation of the problem of tailings as waste or engineering material and additional alternative measures

2	Technical background	• Physics of Heat • Relationships within thermal properties. • Mining operations • CPT technology • Environmental issues • Covers and liners function
3	Technical paper I	• Comprehensive study of thermal conductivity in CPT under selected and coupled influencing factors • Validation of thermal conductivity by verification of degree of saturation
4	Technical paper II	• UCS and Split tensile test of CPT under coupled process of selected influencing factors • Hydraulic conductivity under coupled loadings of selected influencing factors
5	Technical paper III	• Proposal of a cover/liner by exploiting the fineness of tailings and fillers • Criteria for suitability: hydraulic conductivity, freeze-thaw performance and cost

6	General conclusion	• Synthesis of the undertaken studies • Results of these studies • Recommendations
---	--------------------	--

1.5 References

Benzaazoua M., Fall, M., Belem T. A contribution to understanding the hardening process of cemented pastefill. Minerals Engineering, 17(2), (2004). 141-152.

Cole A., Wilkinson J. J., Halls C., Serenko, T. J. Geological characteristics, tectonic setting and preliminary interpretations of the jilau gold-quartz vein deposit, Tajikistan. Mineralium Deposita, 35(7), (2000) 600-618.

Fall M., Benzaazoua, M., Ouellet S. Effect of tailings properties on paste backfill performance. Proceedings of 8th International Symposia on Mining with Backfill. In Beijing, China 2004;193-202

Fall M., Benzaazoua M. Modeling the effect of sulphate on strength development of paste backfill and binder mixture optimization, Cement and Concrete Research, 35 (2005) 301-314.

Fall M., Benzaazoua M., Sae E. Mix proportioning of underground cemented paste backfill. International Journal of Tunnelling and Underground Construction 2007a; 23:80-90.

Landriault D. Paste backfill mix design for Canadian underground hard rock mining. Proceedings of the 97th Annual General Meeting of the CIM Rock Mechanics and Strata Control Session, Halifax, Nova Scotia, 1995:229-38

Lottermoser B. G. Mine wastes. Publisher Springer Berlin Heidelberg (2007) 1-32

Mitchell R. J. Earth structures engineering, Chapter 6. Allen & Unwin, London, (1983)

Sivakugan N. Geotechnical issues of mining with hydraulic backfills. School of Engineering, James Cook University, Australia 2008

Sivakugan N., Rankine, R. M., Rankine, K. J., Rankine, K. S. Geotechnical considerations in mine backfilling in australia. Journal of Cleaner Production, 14(12-13), (2006) 1168-1175.

Yilmaz E., Kesimal A., Ercjkdi B. The factors affecting strength and stability of paste backfill, Yerbilimleri. (2003) 155-169.

Yilmaz E., Kesimal, A., Ercidi, B. Strength development of paste backfill simples at Long term using different binders. Proceedings of 8th symposium MineFill04, China (2004) 281-285.

2 Chapter 2: Technical Background

2.1 Background on Cemented Paste Backfill

In the early ages of mining, wastes were generated at a slow rate by mining operations where the wastes were either stockpiled on surface or simply dumped into the excavated voids. There was no concern about detrimental environment damage. The aim was to take as much as benefit from the mine. The pillars concept was yet developed, but they were rather built with stones (Udd 1989). With advances in technology, the rate of mining has tremendously increased resulting in waste production at a faster rate. With new visions and legislation on environmental protection issues, operators have used the wastes to develop the cemented paste backfill (CPB) to prevent environmental damage and to render mines more beneficial and safer. For certain applications, operators understood that CPB must carry properties like sufficient strength to support hanging walls or adjacent stope in use for structural material to warrant workers security. Thereafter, studies (Fall and Samb 2008, Fall et al. 2008, Escalante-Garcia and Sharp 2001) determined that the strength gain is highly influenced by the temperature in the paste. They also determined that CPB must offer low hydraulic conductivity to prevent seepage of water through it as that might result in acid mine drainage that has the potential to contaminate ground and surface waters. With all these requirements in mind, CBP is prepared to fill principally the large underground cavities created by ores extraction. These cavities are known as stopes and they contribute to weaken the stability of the area where they are

located. To restore strength, to dispose of waste and ensure proper stability, it is desirable that stopes be backfilled (Sivakungan et al. 2006, Fall and Benzaazoua 2003). This operation requires at first, the construction of a barricade which is like a conventional retaining wall made of bricks or rocks with concrete having the task to obstruct the loading crosscut (service access of the stope) and prevent the CPT from flowing out of the stope (Figure 2-1). For economical reasons, the poured backfill bears two different strengths depending of its relative position. Thus, for the start pouring, the technique consists in adding relatively high binder content so this layer reaches rapid setting to minimize horizontal stress over the barricade. The second layer which is the one that occupy most of the stope volume needs to carry just the strength necessary for the final application of the stope. Thus, it corresponds to the layer with less binder content. Finally, a third mix having the same high binder content as the bottom one is used at the top to form the mucking floor and provide strength capable of supporting working equipments. Generally, the CPT is transported to the stope by mean of pipes from a pumping station. This configuration is found as an economic mean of transportation (Hassani and Archibal 1998). As recommended by Paynter and Dodd (1997), prior pumping, all pipelines and bore holes are wetted to prevent moisture from being eventually absorbed by the dry network that would result in the formation of a plug in the circuit. An alternative consists in preparing a high slump mix without cement from the plant and introduce it in the delivery system at startup. Its function is to coat the inner surface of the pipeline and borehole like a lubricant (Henderson et al. 2005)

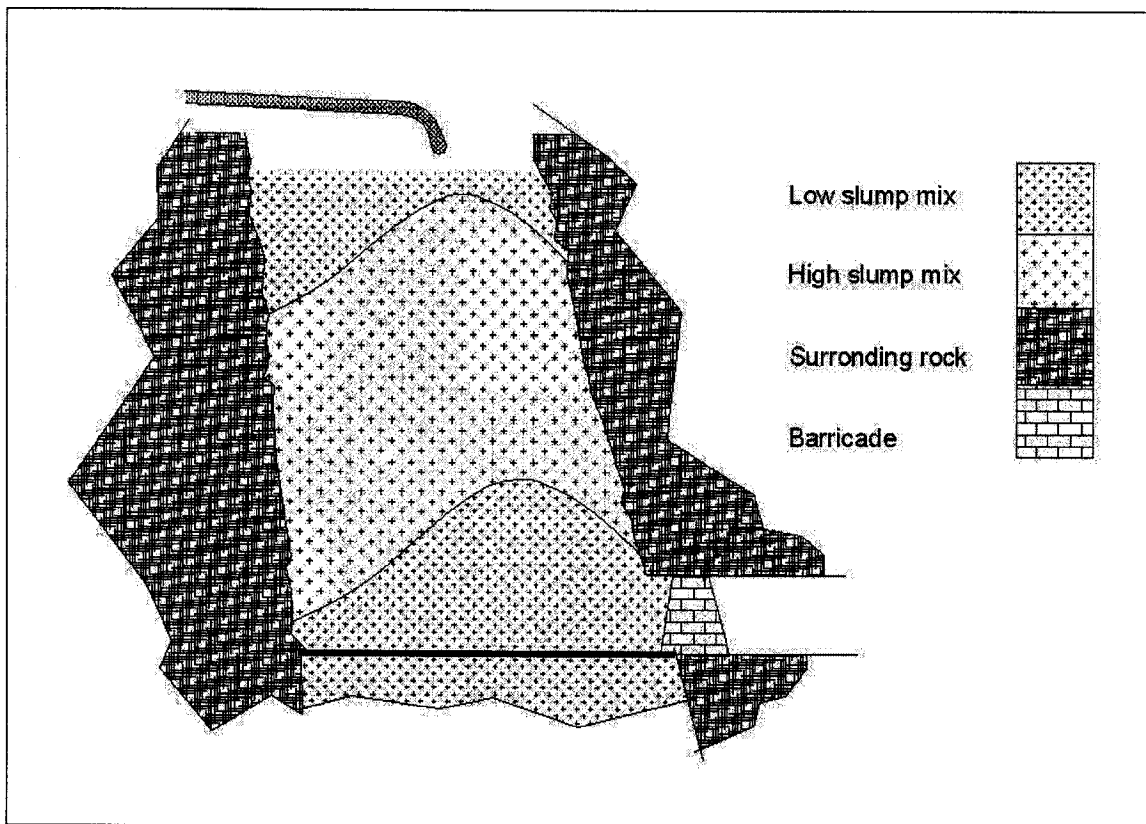


Figure 2-1. Stope configuration and backfilling process. (Adapted from Paynter and Dodd 1997)

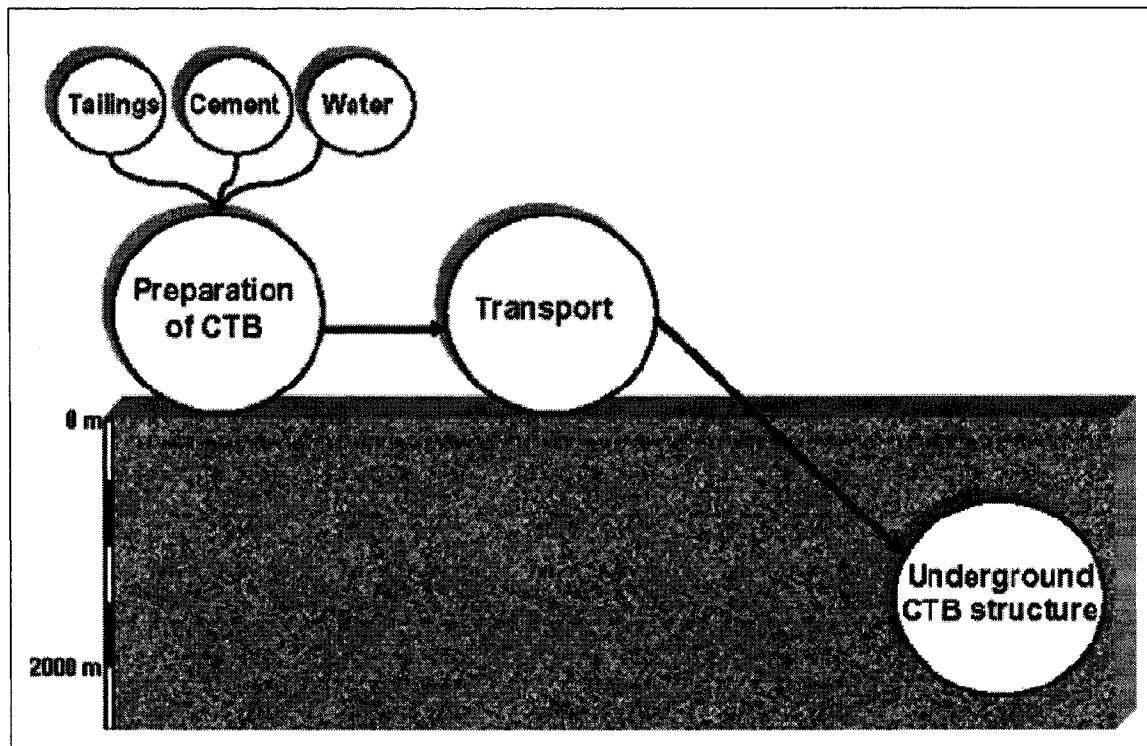


Figure 2-2. Schematic presentation of the different phases of the technology of cemented tailing backfill (CTB): preparation, transport and underground placing of the CTB, where it builds CTB structure (after Fall et al. 2008).

CPB technical design requirements may vary depending of intended function and depending of the mining plant. The design may even depend of particular stope filling sequence. According to Brakebush (1994) intended values of UCS are in the range of 0.7 to 2 Mpa. Other studies claim strength between 0.2 and 4 MPa (Fall and Benzaazoua 2005). A typical representation of backfilling operation is shown in (Figure 2-2). In order to reach any of theses strength, binder type and binder content are the most determinant parameters. In addition, binder is the component that mostly defines the economics of CPT as it accounts up to 75% of the cost (Grice 1998).

2.1.1 Geotechnical Design of Cemented Paste Backfill

As any engineering design, rational approaches are continuously developing to determine the mechanical properties of CPB for usage in underground hard rock mines as supporting structure or for its usage as waste solidifier. The main use consists in support for walls and pillars or even pillar substitution for improved production (Mitchell 1989). For design purposes, the geometry of the openings (height, wide, strike angle) and the intended use (waste tailings storage, ground support, roof support and working platform) are mostly controlled through the strength values. Strength is generally expressed in term of UCS (Unconfined Compression Strength) which offers in relatively simple tests mean to evaluate the stress that the bloc can withstand depending of parameters like: condition of the stope to which it is adjacent (intact ore blocks, or previously filled stope), its dimensions and the load it has to carry (Fall and Samb 2006). Cut and fill is the main method that makes use of the geotechnical engineering capacity of the CPB and this latter have to match to various geometries conditions of the stope. Although the production of CPB involves the added cost for acquisition of the binder material, the goal during its production is to design an optimal mix where cost is minimal and no compromising arises in strength.

Nevertheless, the traditional design in backfill is based on standing walls that require a uniaxial compressive strength (UCS) equal to the overburden stress at the bottom of the filled stope. In many cases however, the adjacent rock walls

actually help support the fill through boundary shear and arching effect. Therefore considering the entire overburden stress as the vertical stress at the base of the stope is somewhat conservative.

For example, a paste backfill wall adjacent to pillar (depending on the relative position of the backfill wall, and its usage) can have its design UCS determined by the relationship proposed by Donovan (1999) as follows:

$$UCS_{design} = (E_p \times \varepsilon_p)FS = Ep\left(\frac{\Delta H_p}{H_p}\right)FS \quad \text{Equation 2-1}$$

Where the UCS is assumed to be more related to the roof deformation (than the full overburden stress) as show in Figure 2-3. In this equation, the parameters are defined as follows:

E_p the pillar modulus of elasticity,

ε_p the pillar axial strain,

H_p the strata initial height,

ΔH_p the strata deformation.

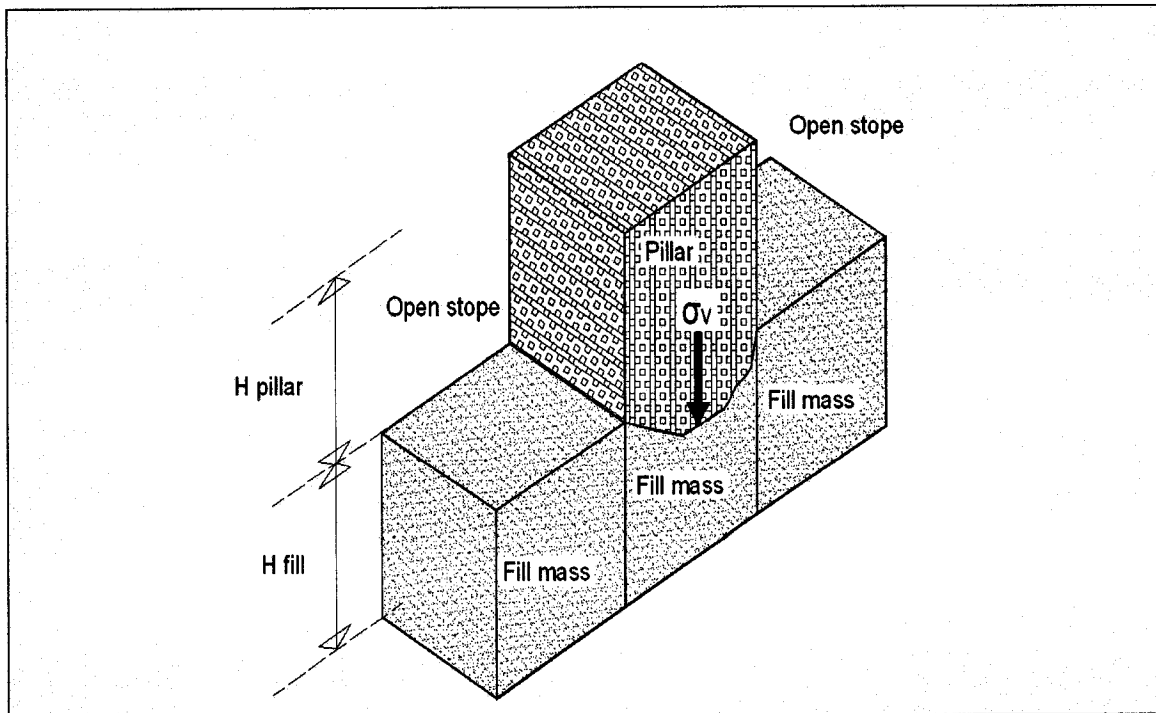


Figure 2-3. Deformation of the backfill block under Vertical loading (adapted from Belem et al.)

Depending on the mining cycle scheme, the design UCS must be adapted to the specific intended function. These intended uses can include:

- Pillars recovery that involves the exposure of previously filled stopes that have to be sufficiently stable to remain standing during operation. Furthermore, these free standing mass must be able to withstand the blasting shock inside the adjacent pillars. Therefore, Hassani and Archibald (1998) have estimated that strength close to 1 MPa can be considered as UCS design. When deformation already occurred in stope walls before backfilling, maximum loading by strata will probably never reached (Donovan 1999). UCS design can be expressed as

$$UCS_{design} = k(\gamma_p \times H_p) FS$$

Equation 2-2

Where

$0.25 < k < 0.5$, (scaling factor)

γ_p is the strata bulk weight,

H_p is the strata height,

FS is a factor of safety.

The pillar recovery can itself be presented in different situations where the number of exposed fill faces may vary. For example, when the backfill mass is subject to exposition at more than two faces after removal of confining pillar or fill during subsequent openings, the application of UCS design is expressed as:

$$UCS_{design} = (\gamma_f \times H_f) FS \quad \text{Equation 2-3}$$

Where

γ_f is the fill bulk weight,

H_f is the fill height,

FS is a factor safety.

- In the case of narrowly exposed face the method for determining the design UCS taking in account the arching is given by the relationship:

$$UCS_{design} = \frac{1.25B}{2K \times \tan \varphi} \left(\gamma - \frac{2C}{B} \right) \times \left[1 - \exp\left(-\frac{2H \times K \times \tan \varphi}{B}\right) \right] FS \quad \text{Equation 2-4}$$

Where C is the fill cohesion strength,

B the width of the stope,

φ the fill internal friction angle and

K the fill pressure coefficient determined by using the Terzaghi's earth pressure coefficient as follows;

$$K = \frac{1 + \sin^2 \varphi}{\cos^2 \varphi + 4 \tan^2 \varphi} = \frac{1}{1 + 2 \tan^2 \varphi} \quad \text{Equation 2-5}$$

In the case of a fill between two slope walls and considering that friction exist, the design UCS proposed by Mitchell (1983) is given by:

$$UCS_{design} = \left(\frac{\gamma \times L - 2C}{L} \right) \times \left[1 - \frac{B}{2} \tan\left(45^\circ + \frac{\varphi}{2}\right) \right] \times \sin\left(45^\circ + \frac{\varphi}{2}\right) FS \quad \text{Equation 2-6}$$

If one considers no friction is developed between the slope and the fill bloc, the UCS design is given by:

$$UCS_{design} = \left(\frac{\gamma \times L \times H}{L + H} \right) FS \quad \text{Equation 2-7}$$

Beside of UCS design for pillar recovery, other determination of UCS can include its usage as ground support or working platform. But, in the relationship of UCS for ground support, the contribution of the fill is more likely to provide increased lateral confining pressure to the pillars.

- For working platform, strength is determined by using calculations similar to shallow foundations bearing capacity method considering as footing a surface area resulting from the mobile equipment tire contact. Craig (1995) has proposed the following solution that corresponds to a modification of the Terzaghi bearing capacity:

$$Q_f = 0.4 \gamma \times B \times N_\gamma + 1.2 C \times N_c \quad \text{Equation 2-8}$$

Where

N_γ and N_c are bearing capacity factors,

B width of square footing at surface contact,

C is the fill cohesive strength.

Finally, the design UCS strength is function of the mix variables like binder type and proportioning, water content and chemistry, tailings grain size and mineralogy. Added to that, there are the effects of the curing temperature and the time. Furthermore, the mix has to remain economic; hence the search for an optimal mix proportioning receipt is desirable.

2.1.2 Effect of mix components and proportions on Cemented Paste

Backfill

The requirements for CPB mechanical and hydraulic properties generally vary with the final intended application. Thus, for simply disposal function, UCS in the range of 0.1 to 0.3 MPa is acceptable while for structural usage values higher than 5 MPa can be achieved (Grice 1998, Grice 2001, Le Roux et al. 2002, Hassani and Archibal 1998, Bloss 2002, Fall and Benzaazoua 2005, Fall et al. 2007). For instance, in a same stope, the initial and subsequent pouring may vary in order to optimize strength and cost simultaneously. Therefore to predict the maturity of such bloc fills, the knowledge of their rate of strength development and their ultimate UCS are necessary. However, these mechanical as well as hydraulic properties are largely dependent of the internal parameters like: the binder content, the binder type, the water/cement ratio, the sulphate content and external parameters like the temperature and the age. Several authors have studied the strength development in CPB, hence providing valuable information over the material (e.g Hassani et al. 2001, Fall et al. 2004, Kesimal et al. 2005, Fall et al. 2008). However, the experiments are mostly conducted at room

temperature. As example, a series of patterns obtained by Fall et al. (2008) during investigation undertaken on mix proportioning is presented in Figure 2-4. In the limits of their study, the authors deducted that the performance properties are mostly influenced by the tailings mineralogy, the water and cement for a given curing time.

- **Effect of binder content**

Binder is the only reactive material among the components that has the ability to transform into hardened material. This process occurs under chemical reactions that take place between the predominant chemicals (C_3S , C_2S , C_3A) present in the binder and the water. In the case of portland cement type I (PCI), new materials known as hydration products ($C-S-H$, CH , sulfo-aluminates) are formed

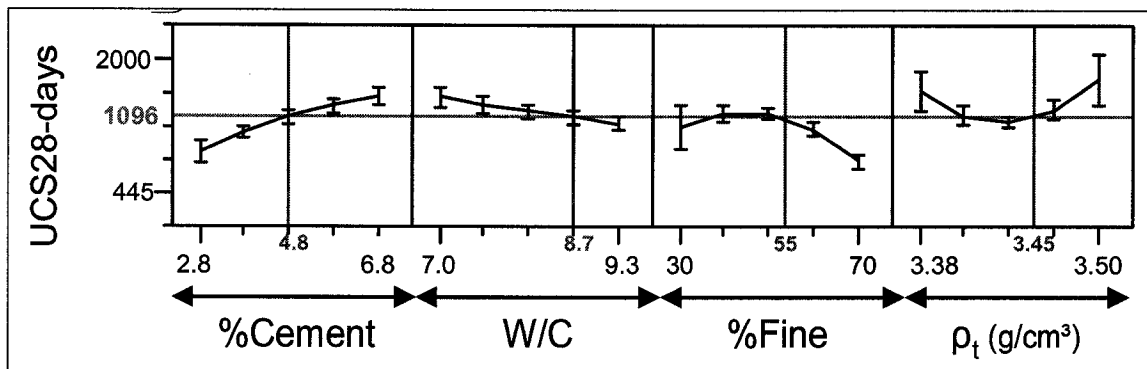


Figure 2-4. Effect of binder content, Water/Cement ratio, tailing fineness and tailings density on UCS (kPa) of Cemented Paste Backfill (CPB) after Fall et al. 2008.

in proportions of 70%, 25%, 7%, respectively and confers to the binder the bonding property. A residual 3% of secondary phases comprised of gypsum and ettringite also occurs. (Oner and Akyuz 2007). It become obvious that increased

amount of cement leads to higher CPB compression strength by the formation of increased cement hydration products in the cement matrix as show in Figure 2-4.

- **Effect of water cement ratio (W/C)**

Water cement ratio affects the slump through the amount of mixing water added when other parameters are fixed. W/C highly controls the porosity of the mix through the amount of voids left in the hardened matrix after consumption of the pore water. As the matrix is hardening, part of the water from the pore is consumed. It results in voids filled partially with water or eventually with air. These voids do not contribute to the strength of the solid material. The excessive availability of water corresponding to high W/C ratio will definitely increase the network of voids and hence, lead to a decreased strength (Amaratunga and Yaschyshyn 1997). It happens that UCS is inversely proportional with this parameter. This behaviour is seen in Figure 2-4 during test conducted by Fall et al. (2008).

- **Effect of tailings fineness**

Fineness determines the bounding affinity between cement paste and the grains of the tailings. Such affinity defines the overall porosity, the refinement of the hardened cement matrix pores and the capillary porosity of the interfacial transition zone (Monteiro et al. 1985, Fall et al. 2004, 2005). Figure 2-4 shows that the optimal strength is obtained for fines around 45% by weight with all other parameters fixed. This behaviour was the object of deeper investigations under

mercury intrusion porosimetry analysis (MIP). At this proportion of fines, bonding between cement paste and tailings grains is optimal. As this proportion increases, the compressive strength drops under increased specific surface in tailings. Higher specific surface means higher water demand, thus indirect W/C increase leading to higher porosity. Porosity study performed by Fall et al. 2008, shows an high Hg intrusion porosity in the pores measuring 0.05 to 1 micrometer. Such a drop is also noticed when the average grain size passing the 20 micron mesh is reduced below the 45% optimal. This drop is developed by conditions opposite to the high fines content, and is evidenced by the increase in capillarity porosity of the interfacial transition zone between the large tailings particles and the cement matrix. This behaviour is illustrated by the MIP showing an increased value for pores in the range of 1 to 10 micrometers as reported by Monteiro et al. (1985) (Figure 2-5). From MIP values results in this graph it appears that a balance occurs in the vicinity of 45% fines in the tailings.

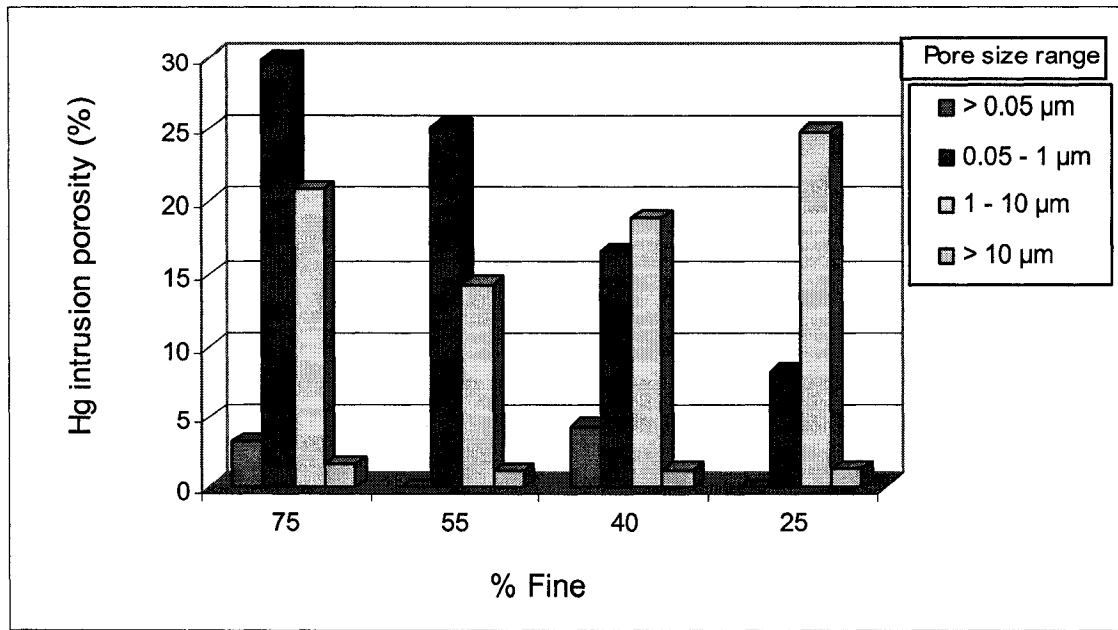


Figure 2-5. Mercury intrusion porosimetry showing large number of pores in the size of 0.05 to 1 micrometer in mixes made of tailings whose fines are more than 45%. It also shows large intrusion porosity for pores in the range of 1 to 10 microns in mixes made of tailings containing less than 45% fines (Fall et al. 2008).

- **Effect of sulphate content**

Sulphate manifests in the mix by acting over the binder during the hydration process in the early stage and, at advanced age by attacking the precipitated hydration products. One can observe an inhibition of hydration product formation at the early age, or the formation of secondary precipitation products (gypsum, ettringite) at advanced age. Both manifestations have as effect to decrease the strength of the CPB. However, as expansion takes place in the CPB, it happens that the CBP becomes denser. At this point, the sulphate may appear to be beneficial. However, past a certain concentration, the expansion leads to cracks

that lead the effect to become detrimental (Fall and Benzaazoua 2005, Czemin 1962)

2.1.3 Effects of Temperature on Cemented Paste Backfill

- **Effect of temperature**

From studies conducted on cement paste, it is observed that increased temperature contributes actively to the acceleration of chemical reactions in the clinker phases predominantly the tricalcium silicate (C_3S), dicalcium silicate (C_2S) and tricalcium aluminate (C_3A). Precipitation of hydration products like calcium hydroxide (CH) and calcium silicate hydrate (C-S-H) occur at a faster rate that results in the development of high early compression strength (Lothenbach et al. 2007, Escalante-Garcia et al. 2007). These studies also report that at advanced age that the ultimate strength at increased temperature is lower than the one produced at room temperature. Qualitative analysis undertaken on the samples showed that the porosity increased in pastes hydrated at higher temperatures and this was attributed to the fact that a non-uniform distribution of the hydration product within the microstructure with high concentration of hydration product building up around hydrating grains and hindering further subsequent hydration. However, at room temperature ($\sim 20^\circ\text{C}$), hydration products have sufficient time to diffuse and precipitate relatively more uniformly throughout the cement matrix.

However this mechanism of hydration is owed from cement paste and concrete, where the cement content is high. Meanwhile CPB is a relatively new complex

cemented material which is far different from concrete (Fall and Benzaazoua 2005, Benzaazoua et al. 2003). Among the few studies available, although the one published in 2006 by Fall and Samb was conducted at variable temperatures, however, the samples were prepared with same mix proportioning and only the early age (up to 28 days) behaviour was studied. Yet, for edification purpose, the results recorded up to 28 days curing on the samples considered (Figure 2-6) are useful, as they constitute a benchmark in the domain of CPB. From Figure 2-6, it is noticeable under various thermal loading conditions that the strength increases progressively with temperature. By evaluating the work of the previously quoted authors, where the study didn't take into account the variables like W/C, fineness, mineralogy and cement content in the tailings mixes, it becomes necessary to implement a comprehensive investigation of the CPB under thermal loading. The thesis incorporates a collection of tests to overcome such lack of information through a framework capable of reflecting and informing on the behaviour of CPB as a function of its mix proportioning with temperature.

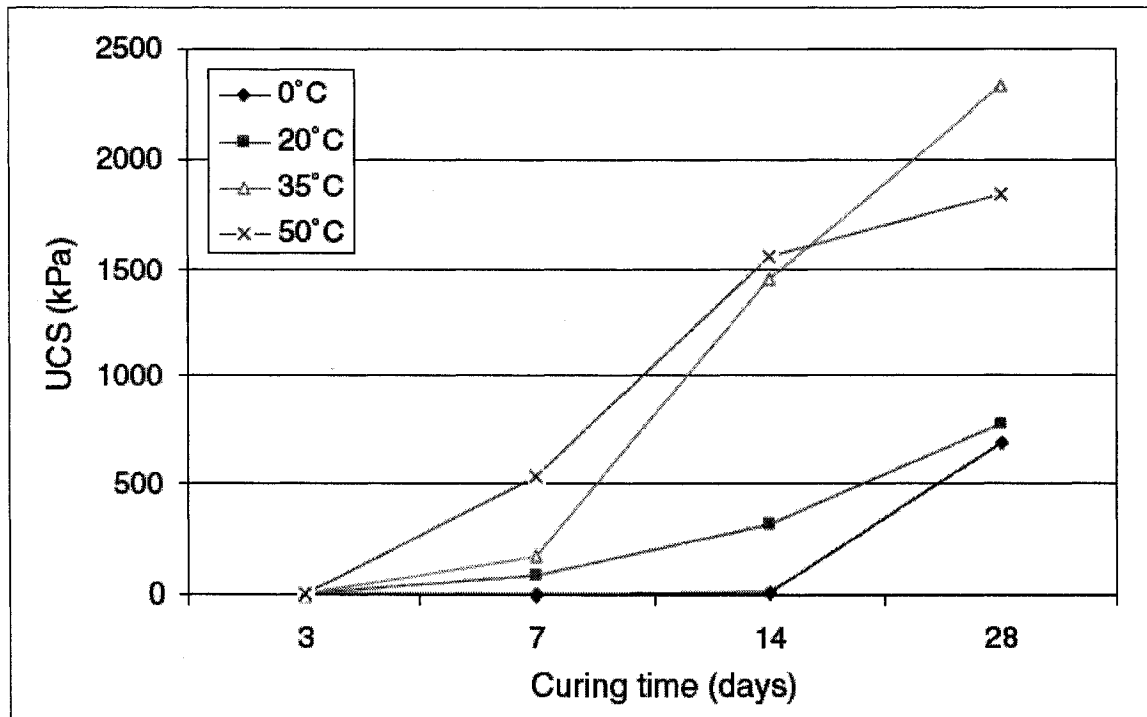


Figure 2-6. Effect of curing temperature on strength development of CPB after Fall and Samb (2006)

2.1.4 Sources of Temperature in Mines and Backfill Operations

The amount of time that a certain heat is held in CPT is function of the thermal conductivity of the paste. The thermal conductivity is of prime importance as it dictates the rate at which temperature exchange takes place between the paste mass and the surrounding temperature in the stope.

Temperature in backfill operation is function of several parameters that can be classified as internal and external.

By internal one, the reader can refer to the temperature generated from inside of the backfill itself. The backfill being a cementitious material, it contains a hydraulic binder which, when it enters in contact with moisture, its components C_3S , C_2S , C_3A react chemically to form new products like CH , $C-S-H$, $C_6\bar{A}S_3H_{32}$ while exhibiting heat.

By external source of temperature, one can consider the environment rocks which inherit from the geothermal gradient that varies with the depth of the operations. The external source of temperature can also depend of the region and it can be positive or negative (below zero). Added to this principal source, there are the heat generated by the blasting operations and machinery. The interaction between these different sources can produce effects that are advantageous or detrimental for the mechanical evolution of strength or hydraulic conductivity in CPT.

2.2 Determination of Thermal Conductivity by using KD2

Thermal properties of a material are of crucial importance. The thermal conductivity, the thermal diffusivity and the specific heat are such properties that inform about the material heat exchange interaction with its surroundings. For instance, the thermal conductivity informs how fast heat is traveling in the CPT mass, the thermal diffusivity relates how easy or difficult the heat can be transferred by absorption or removal and the specific heat indicates the capacity of the material to store an amount of heat.

2.2.1 Thermal conductivity

Joseph Fourier (1768-1830) postulated that the rate of heat transfer is proportional to the temperature gradient through the thermal conductivity (Tae S. 2005). It is the ratio of heat flux density to temperature gradient in a material given by

$$\lambda = dQ/dT \quad \text{Equation 2-9}$$

where

Q is the heat in joules, and

T is the temperature in °C.

It informs on the ability of the material to conduct heat. Various methods can be used to determine the thermal conductivity of materials, notably steady state and transient state. The latter one includes the two linear parallel probes by Carslaw, the plane heat source, the hot guarded plate (Kim et al. 2003) and other indirect methods like the laser flash. Most of the transient methods can measure all the thermal properties simultaneously and may be used even for materials whose thermal conductivity is dependent from temperature.

2.2.2 Thermal diffusivity

It is the ratio of the thermal conductivity to the thermal capacity as expressed by

$$D = \lambda / \rho \times C_p \quad \text{Equation 2-10}$$

Where

λ is the thermal conductivity in W/m °C

D is the thermal diffusivity in m²/s

ρ is the bulk density of the material kg/m³

C_p is the specific heat in J/kg °C

The thermal diffusivity determines the ability of the material to transmit thermal changes. This property is important to be able to predict the behaviour of a material. When diffusivity is low, it can give rise to heat diffusion in transient state. "Methods based on transient state for the determination of diffusivity offer the advantage of being rather fast, but require a more complex experimental data processing and entail relatively advanced means of measurements" (Krishnaiah and Singh 2006). The initial method which was developed to measure thermal diffusivity was making use of steady state condition. The drawback of the latter method is that it requires a relatively long time to reach equilibrium for the stationary conditions, in particular for materials with great thermal inertia (Bairi et al. 2007).

The steady state can be inconvenient from the fact that moisture and chemicals inside the sample may vary during the waiting time. This is the case in the differential scanning calorimeter (DSC) (Kodur and Sultan 2003, Merzhyakov 2001). Though DSC is found to be quite helpful in evaluating the endothermic and exothermic behavior of the material, melting phase present in it, and determining its specific heat, C_p , it is a very costly and cumbersome technique

(Krishnaiah and Singh. 2006). The transient technology is more convenient for the task of determining the diffusivity values at the activity temperature. On the other hand, transient heating methods consist in applying heat flux to the sample and to measure the resulting rise in the sample. Thermal conductivity and diffusion can be calculated using the mathematical relation which is in the form of a non-linear series

$$\frac{\partial T}{\partial t} = K \left(\frac{\partial^2 T}{\partial r^2} + r^{-1} \frac{\partial T}{\partial r} \right) \quad \text{Equation 2-11}$$

where T is temperature in °C,

t is time in second,

K is the thermal diffusivity expressed in m²/s and

r is radial distance in meter.

When this equation is developed and when removing the negligible terms, the solution is given by:

$$T - T_o = \frac{q}{4\pi\lambda_h} \left(\ln(t) - y - \ln\left(\frac{r^2}{4K}\right) \right) \quad \text{Equation 2-12}$$

where q is the heat produced per unit length per unit time (W/m),

T_o is the initial temperature in °C,

λ_h is the thermal conductivity of the medium (W/m°C) (Baïri et al 2007),

K is the thermal diffusivity expressed in m²/s.

This is the principle under which the KD2 Thermal properties analyzer presented in Figure 2-7 (used in this study) works (Decagon).

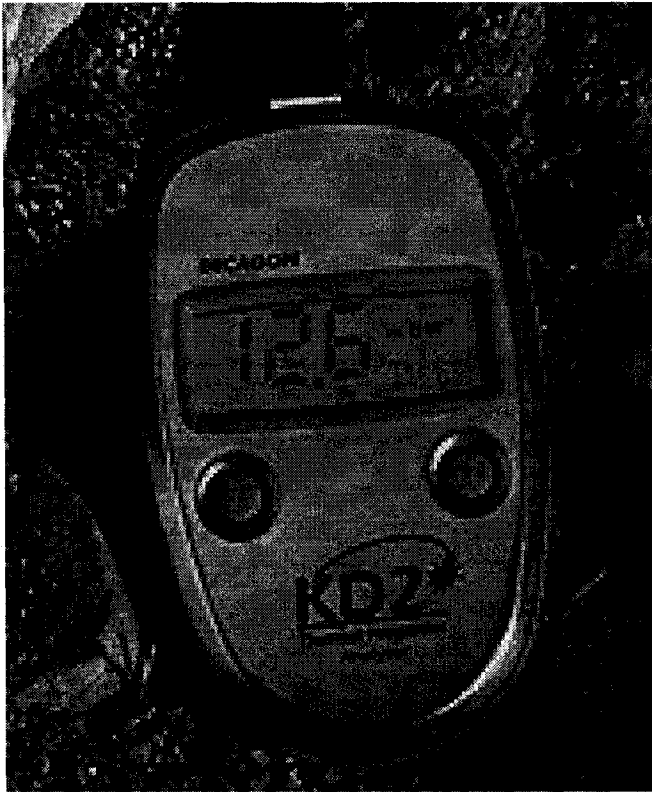


Figure 2-7. KD2 Thermal Analyser (Decagon devices inc).

2.2.3 Specific heat capacity

After Dickerson (1965), the specific heat is related to the thermal diffusivity and thermal conductivity through the equation

$$D = \lambda / \rho \times C_p \quad \text{Equation 2-13}$$

where

D is the diffusivity in m^2/s ,

λ is the conductivity in $\text{W}/\text{m}^\circ\text{C}$,

ρ is the density of the material kg/m^3 and

C_p the specific heat in $\text{J}/\text{kg } ^\circ\text{C}$.

The specific heat capacity is strongly dependent on porosity, water-cement ratio, water content and temperature. It is often expressed in term of thermal or volumetric heat capacity which is equal to the product of specific heat by density and expressed in $\text{Joule/m}^3 \text{ } ^\circ\text{C}$. It defines the heat needed to raise the temperature of a material of one degree (Kodur and Sultan 2003, Sidney and Young 1981).

2.3 Background on mine geotechnical barriers (Liners and Covers)

2.3.1 Mining application

Mining operations are often associated with acid mine drainage and heavy metal release resulting from sulphide rich ore exposed to oxygen and washed by moisture.

The mining management units rely on protective material layers (soil or synthetic) capable of playing the role of buffer to prevent acid mine drainage or hazardous leachates to seep into underground water or surface water. To do so, wastes are protected from oxygen contact and water infiltration through them. These measures are necessary in order to meet environmental protection agency recommendations. Besides of seepage, the oxygen consumption by the chemical reactions that take place in these masses represents threat to the environment. To prevent such undesirable conditions to build up, geotechnical barriers known

as liners and covers are generally installed at the waste containment or processing facility.

In mine waste management the main function of covers is to limit, if not to impede complete access of oxygen to the mass. Another function consist in offering low hydraulic conductivity that can limit access of water which is the essential solute for the production of leachates or acid mine drainage in the mining waste mass. As oxygen is the element necessary for reaction to take place in these waste and oxygen diffusion is very slow in water, it becomes profitable to keep the cover layer at a high saturation degree. This measure has for effect to keep the oxygen away from the reacting wastes.

Among the several researches that have been related to soil covers, one can enumerate, Nicholson et al. (1989), Chapuis (2002), Yanful et al. (2003) where the authors recall that water storage have to be kept during all the drought period by minimizing its evaporation and preventing its ingress into the waste mass. Yanful (1993) observed that the fine grain material sandwiched between two coarse grain soil materials in a multilayer cover served as a moisture retaining medium. In the acid tailings considered by the author, he reported that the oxygen flux was reduced 85% to 95% due to saturation. The coarse grain materials in the other hand played the role of protective layers in the resulting capillary barrier by helping to preserve the saturation degree as indicated by Benson et al. (1994). The coarse grain sand lead to identify these covers as

capillary break type, while another type of cover defined as, store and release cover, makes essentially use of maximum moisture stored from rainfall in the cover material. In the store and release cover, while maximum rainfall is stored, no percolation is allowed from the cover material to the waste; instead moisture is slowly released to the environment during drought periods by evapotranspiration. It is determined that each cover type carries its own advantages and finds appropriate usage depending of the climate. For instance, the capillary break cover is more suitable for humid regions while the store and release one finds its best application in arid climates (O'Kane and Waters 2003, O'Kane et al. 2000).

Covers and liners must satisfy to various criterions where one can be stricter than another. Such criterions lead to consider the shape and geometry design, the nature of the waste to contain and the available material used for design. It is also desirable for the barrier to be able to keep its performance and integrity during its design period by being able to withstand earthquakes, mobile maintenance equipment loads, extreme temperature variations and mineralogical stability.

2.3.2 Municipal waste disposal application

Open dump wastes disposal practices has evolved with time and has been replaced by landfills that represent an (a refinement) improvement of the previous method. In these repositories, wastes are isolated at the top by a

geotechnical work designated as covers. By the 1970's (Daniel 1993) bottom isolation was found to be adequate measure to further protect from leachates. At this moment liners installation started their popularity. The objective in a landfill design is to protect human health and environment by attenuating if not preventing chemical seepage and gases to escape from the waste degradation. This objective should be compatible for short term as for the predicted design period. It becomes therefore interesting to address the design of such liners with modified paste backfill materials.

For hazardous waste landfills EPA (environmental protection agency) requires that the compacted soil liner be at least 0.9 m with maximum hydraulic conductivity of 1×10^{-7} cm/s and a leak detection system generally made of geotextile with a response of 24 hours. A double liner system is required with a leachate collection between the two liners. Nevertheless, for non-hazardous waste, less strict prescriptions are required where a minimum liner consists of a single composite liner with a leachate collection system. Typical containments present in hazardous landfill waste are listed in Table 2-1 (Ehrig 1988) and a typical landfill liner system is presented in Figure 2-8 (Adapted from Daniel 1993).

Table 2-1. Typical containments present in hazardous landfill waste after Ehrig (1988)

Parameter	Unit	Average
Cl	mg/l	2100
Na	mg/l	1350
K	mg/l	1100
alkalinity	mg CaCO ₃ /l	6700
NH ₄	mg N/l	750
orgN	mg n/l	600
total N	mg N/l	1250
NO ₃	mg N/l	3
NO ₂	mg N/l	0.5
total P	mg P/l	6

AOX adsorbable organic halogen.

Continue.		
Parameter	Unit	Average
AOX	µg Cl/l	2000
As	µg/l	160
Cd	µg/l	6
CO	µg/l	55
Ni	µg/l	200
Pb	µg/l	90
Cr	µg/l	300
Cu	µg/l	80
Hg	µg/l	10

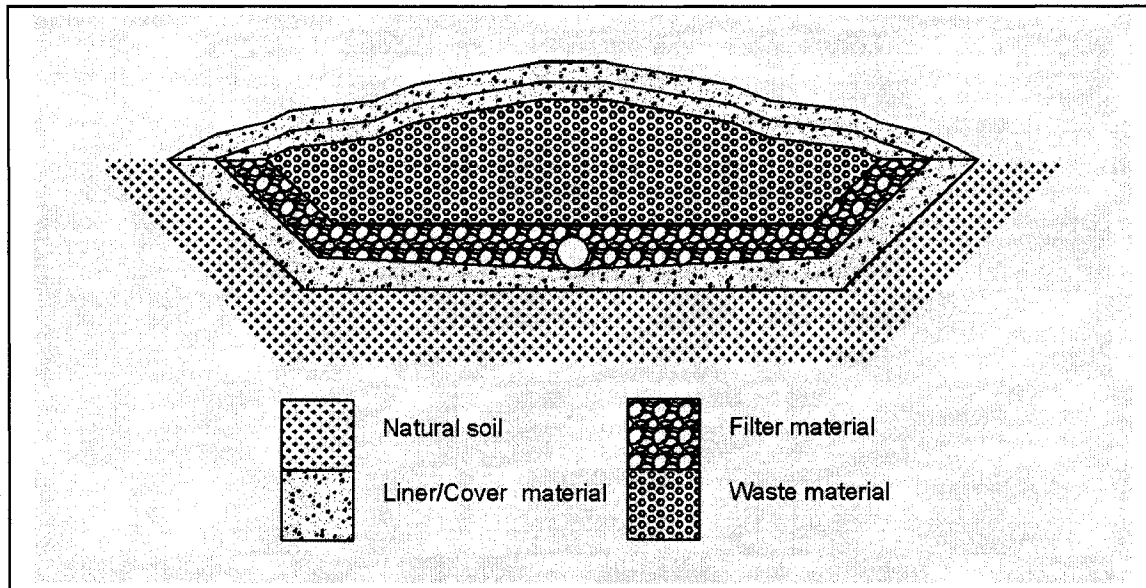


Figure 2-8. Basic liner design (Adapted from Daniel 1993).

2.3.3 References

Amaratunga L. M., Yaschyshyn D. N. Development of a high modulus paste fill using fine gold mill tailings. *Journal of Geotechnical and Geological Engineering* 15, (1997) 205–209.

Archibald J. F., DeGagne D. O., Lausch P., De Souza E. M. Ground waste glass as a pozzolanic consolidation agent for mine backfill. *Journal of CIM* 88 (1995), 80–87.

Aubertin M., Li L., Arnoldi S., Belem T., Bussi re B, Benzaazoua M., Simon R. Interaction between backfill and rock mass in narrow stopes. In: *Proceedings of 12th Panamerican conference on soil mechanics and geotechnical engineering and 39th U.S. rock mechanics symposium*, 22–26 June, Boston,

Massachusetts, USA, vol 1, Verlag Gu"ckauf GmbH, Essen, (2003) 1157–1164

Baïri, A., García de María, J. M., Laraqi, N. Thermal diffusivity measurements of building materials based on 2D models. *Computational Materials Science*, 38 (2007), 838-846.

Belem T., Benzaazoua M. Design and application of underground mine paste backfill technology, *Geotechnical and Geological Engineering*. 26 (2008) 147-174.

Benson C., Bosscher P., Lane D., Pliska R. Monitoring system for hydrologic evaluation of landfill final covers. *Geotechnical Testing Journal* 17 (2), (1994) 138–149.

Benzaazoua M., Fall M., Belem T. A contribution to understanding the hardening process of cemented paste backfill, *J. Miner. Eng.* 17 (2) (2003) 141–152.

Bloss M. Below ground disposal (mine backfill), *Paste and Thichened Tailings: A Guide*, in: R.J. Jewell, A.B. Fourie, E.R. Lord (Eds.), University of Western Australia, Nedlands, Western Australia, (2002), 103– 126.

Brackebusch F. W. Basics of Paste Backfill Systems. Minerals. Engineering. New York, 46(10), October, (1994).1175-1178.

Chapuis R. P. The 2000 R.M. Hardy Lecture: full-scale hydraulic performance of soil-bentonite and compacted clay liners. Canadian Geotechnical Journal 39, (2002) 417–439.

Craig R. F. Soil mechanics, 5th edition. Chapman and Hill Publishing, London (1995) 427 pp.

Czernin Wolfgang. Cement chemistry and physics for civil engineers, New York Chemical Publishing Co. Inc., 1962.

Daniel D. E. Geotechnical practice for waste disposal. Chapman and Hall (1993) 683 pp.

Donovan J. G. The effects of backfilling on ground control and recovery in thin-seam coal mining, M.Sc. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, (1999)

Ehrig H. J. Water and element balances of landfills. Lecture notes in Earth Science. Springer-Verlag Berlin (1988) (From Daniel D.E. 1993)

Escalante-García J. I., Sharp J. H. Effect of temperature on the hydration of the main clinker phases in Portland cements: Part I, neat cements, Cement and Concrete Research. 28 (1998) 1245-1257.

Escalante-García J. I., Sharp J. H. The microstructure and mechanical properties of blended cements hydrated at various temperatures, Cement and Concrete Research. 31 (2001) 695-702.

Fall M., Benzaazoua M., Saa E.G. Mix proportioning of underground cemented tailings backfill, Tunnelling and Underground Space Technology. 23 (2008) 80-90.

Fall M., Nasir, O., Célestin J. C. Paste backfill response in deep mine temperature conditions. 9th Symposium on MineFill, Montreal 2007b.

Fall M., Samb S.S. Influence of curing temperature on strength, deformation behaviour and pore structure of cemented paste backfill at early ages, Construction and Building Materials, (2006) In Press, Corrected Proof.

Fall M., Benzaazoua M. Modeling the effect of sulphate on strength development of paste backfill and binder mixture optimization, Cement and Concrete Research. 35 (2005) 301-314.

Fall M., Benzaazoua M., Ouellet S. Experimental characterization of the influence of tailings fineness and density on the quality of cemented paste backfill. Mineral engineering 18 (2005) 41-44.

Fall, M., Benzaazoua M., Ouellet, S. Effect of tailings properties on paste backfill performance. In: Proceedings of the 8th International Symposia on Mining with Backfill, Beijing, China, (2004) 193–202.

Fall M., Benzaazoua, M.. Advances in Predicting Performance Properties and Cost of Paste Backfill. Int. Conf. Tailings & Mine Waste '03, Colorado, USA; A.A. Balkema, Swets & Zeitlinger, Lisse, ISBN 90 5809 593 2 (2003).73-86.

Grice, T. Underground mining with backfill. In: Proceedings of 2nd Annual Summit, Mine Tailings Disposal Systems. Brisbane, Australian, Australasian Institute of Mining and Metallurgy, Carlton South, Australia (1998) p. 14.

Grim R. E. Clay mineralogy. 2nd edition, Mc Graw Hill, New York (1968) 596 pp.

Hassani F. P., Ouellet J., Hossein M. Strength development in underground high sulphate paste backfill operation, CIM Bulletin. 94 (1050) (2001) 57– 62.

Hassani F., Archibal J. Mine Backfill, CD-Rom, Canadian Institute of Mine, Metallurgy and Petroleum, Montreal, Quebec, (1998) 262 pp.

Henderson A., Revell M. B., Landriault D., Coxon J. Paste Fill, Handbook of Mine Fill. Australian Centre for Geomechanics (2005) 83-95

Kesimal A., Yilmaz E., Ercikdi B., Alp I., Deveci H. Effect of properties of tailings and binder on the short-and long-term strength and stability of cemented paste backfill. Materials Letters, 59(28), (2005) 3703-3709.

Kim K. H., Jeon S. E., Kimb J. K., Yang S. An experimental study on thermal conductivity of concrete. Cement and Concrete research 33 (2003) 363-371.

Kodur V. K. R., Sultan M. Effect of temperature on thermal properties of high strength concrete. Journal of materials in civil engineering, ASCE, 15 (2003) 101-107

Krishnaiah S., Singh D. N. Determination of thermal properties of some supplementary cementing materials used in cement and concrete. Construction and Building Materials. 20, (2006) 193-198

Landriault D., Welch, D., Morrison D. Mine Tailings Disposal as a Paste Backfill for Underground Mine Backfill and Surface Waste Deposition. Society for Mining, Metallurgy, and Exploration, Inc. Short Course – March 9 & 10, (1996)

Le Roux K. A., Bawden W. F., Grabinsky M. W. F. Assessing the interaction between hydration rate and fill rate for a cemented paste backfill. In: Proceedings of the 55th Canadian geotechnical and 3rd joint IAH-CNC groundwater specialty conferences. Niagara Falls, Ontario, 20–23 October (2002) 427–432

Lothenbach B., Winnefeld F., Alder C., Wieland E., Lunk P. Effect of temperature on the pore solution, microstructure and hydration products of Portland cement pastes, *Cement and Concrete Research*. 37 (2007) 483-491.

Marston A. The theory of external loads on closed conduits in the light of latest experiments. Bulletin No. 96, Iowa Engineering Experiment Station, Ames, Iowa (1930)

Merzhyakov M. Thermal conductivity from dynamic response of DSC. *Thermochimica Acta*. 377 (2001) 183-191

Mesri G., Olson R. E. Mechanisms controlling the permeability of clays. *Clays and clay minerals* 19 (1971) 151-158

Mindess S., Young F. *Concrete*, Englewood N. J, Prentice-Hall (1981). 671p.

Mitchell R. J. Earth structures engineering, Chapter 6. Allen & Unwin, London, (1983) pp 265.

Mitchell R. J. Stability of cemented tailings backfill. Computer and physical modelling in geotechnical engineering. Balkema, Rotterdam, (1989) 501–507

Monteiro P. J. M., Maso J. C., Ollivier J. P. The Aggregate–Mortar Interface. Cement Concrete Research 15 (1985) 953–958.

Nicholson R. V., Gillham R. W., Cherry, J. A., Reardon, E. J. Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Canadian Geotechnical Journal 26 (1989) 1–8.

O’Kane M., Porterfield D. P., Weir, A., Watkins, A. L. Cover System Performance in a semi-arid climate on horizontal and sloped waste rock surfaces. Proceedings of the Fifth International Conference on Acid Rock Drainage, Denver, Colorado, USA (2000)

O’Kane, M., Waters P. Dry cover trials at Mt. Whaleback—a summary of overburden storage area cover system performance. Proceedings of Sixth International Conference for Acid Rock Drainage, Cairns, Qld., Australia, CD (2003).

Oner A., Akyuz S. An experimental study on optimum usage of GGBS for the compressive strength of concrete, *Cement and Concrete Composites*. 29 (2007) 505-514.

Paynter, J. T., Dodd, J. C. The Design, Commissioning and Operation of the Golden Giant Paste Backfill Plant. Proceedings of the 29th annual meeting of the Canadian Mineral Processors (Division of the CIM), Ottawa, Ontario, 21-23 January 1997, pp. 382-403.

Potvin Y., Thomas E. G., Fourie A. B. Handbook on mine fill (2005) 179 pp.

Sivakugan N., Rankine, R. M., Rankine, K. J., Rankine, K. S. Geotechnical considerations in mine backfilling in australia. *Journal of Cleaner Production*, 14(12-13), (2006) 1168-1175.

Skalny J., Marchand J., Odler I. Sulfate Attack on Concrete, (2002) 240 pp.

Terzaghi K., Theoretical soil mechanic, John Wiley & Sons, New York, (1943) 729 pp.

The KD2 thermal properties analyzer vs. published standards. Decagon devices Inc.

Udd J. E. Backfill research in Canadian Mines. Fourth international symposium.

Innovations in ;backfill mining technology. Editors Hassani E.P., Scoble M. J.,

Yu T.R Balkema, Rotterdam (1989)

Van Horn A. D. A study of loads on underground structures, part III. Iowa

Engineering Experiment Station (1963)

Yanful E. K., Morteza Mousavi S., De Souza L. P. A numerical study of soil cover

performance, Journal of Environmental Management. 81 (2006) 72-92.

Yanful E. K, Morteza S. M., Yang M. Modeling and measurement of evaporation

in moisture-retaining soil covers, Advances in Environmental Research. 7

(2003) 783-801.

Yanful E. K. Oxygen diffusion through soil covers on sulphidic mine tailings.

Journal of geotechnical engineering. ASCE 119 (1993) 1207-1228.

Yun T. S. Mechanical and thermal study of hydrate bearing sediments; Thesis

(2005) 77 pp.

3 Chapter 3

3.1 Technical Paper I

Thermal conductivity of cemented paste backfill material and factors affecting it

3.2 Abstract

Cemented Paste Backfill (CPB) is extensively used in underground mine operations. Several studies have been conducted to investigate the mechanical properties of CPB. However, little attention has been devoted to the thermal conductivity of CPB. The knowledge of this thermal property is vital for the design of cost-effective and durable CPB materials. This paper presents the results of a comprehensive laboratory study on the thermal conductivity of CPB. Influencing factors on the thermal conductivity of CPB were quantitatively investigated. The measurements of thermal conductivity were performed by using the KD2 Thermal Properties Analyzer. Valuable results with regards to the effects of CPB's mix components, curing time and temperature, water saturation degree on the thermal conductivity of CPB were gained. It is felt that the present study would contribute to the better optimization of CPB mixtures and the design of more cost-effective and durable CPB underground structures.

Keywords: Cemented Paste Backfill; Thermal Conductivity; Hydration; Temperature; Sulphate; Tailings.

3.3 Introduction.

In the mining industry where selective production is replaced by mass production, tailings volume produced by milling is important (Udd 1989). To maximize ore recovery, pillars that provide support to the ore structure are also extracted while cemented paste backfill (CPB) substitutes them (Chugh et al. 2002). CPB is an engineering material composed of hydraulic binder, tailings and water (Fall and Benzaazoua 2005). The binder used is mostly Portland cement type I (PCI) in a proportion of 2% to 7% by weight (Yilmaz et al. 2003). A proportion up to 10% is sometimes used to increase early strength (Williams et al. 2001). PCI is sometimes blended with mineral admixtures, such as Slag or Fly Ash. CPB often contains between 70% and 85% solids by weight, depending on the desired consistency (Landriault 1995). The concentration of CPB's components depends on its final destination.

The key functions of CPB are the mechanical stabilization of underground mine openings and the maximization of safe and economic ore recovery. To assure the aforementioned function, the CPB must show acceptable mechanical properties. These properties must be secure and allow the CPB to withstand each particular environment. They must prevent it from collapsing during adjacent mining operations. Indeed, mine backfill failures have considerable financial ramifications and also often result in fatalities or injuries as reported around the world. The CPB also provides a means to dispose tailings that are waste from the ore process back into the stopes or on the surface. As waste

disposal, the mechanical properties of the CPB must prevent it from degradation, such as cracking (Yilmaz et al. 2003). The latter alteration can be responsible for acid formation due to exposition to oxygen and water and by this, lead to groundwater pollution. In the case of stope fill, its mechanical properties at an early age must prevent it from liquefying during adjacent operations (Fall and Benzaazoua 2005).

As a result of the increased and intensive usage of CPB materials in underground mining operations, several studies (Landriault 1995, Amaratunga and Yaschyshyn 1997, Yilmaz et al. 2003, Fall and Benzaazoua 2005, Annor et al. 2006, Fall et al. 2007a) have been conducted to better understand its mechanical (e.g. strength, stress-strain behaviour) and microstructural (vital for the durability of the CPB structures) properties and determine the different factors that can affect these properties. However, as of the present, almost all of these studies have ignored the investigation of the thermal conductivity of CPB and the main factors affecting it. Additionally, most of the available results that were derived from studies on the thermal properties of cemented material were implemented for normal or classical concrete (e.g. Kodur and Sultan 2003, Krishnaiah and Singh 2006). However, since CPB is different from normal concrete, the above results are not suitable. This means that there is a lack of knowledge on the thermal conductivity of CPB. The knowledge of these properties is vital for engineering designs of cost-effective and durable CPB materials as explained below.

Previous studies (e.g. Fall and Samb 2006, Fall et al. 2007b) have revealed that the curing temperature significantly affects the mechanical and durability properties of CPB as well as its cost. The main sources of temperature variation in backfill operations include the temperature of the rock surrounding the CPB structures (hot rock temperature in deep mines and cold rock temperature in permafrost mines), the heat produced by the binder hydration and a potential addition of heat to the CPB (technology of hot CPB) (Fall et al. 2007b). To be able to predict the impacts of these various thermal loads on CPB's performance, the temperatures in the structure must be determined. Furthermore, the heat transfer between the CPB structures and the surrounding media (rock, air) must be known. For such calculations, knowledge of the thermal conductivity of the CPB materials is required.

Furthermore, the determination of the thermal properties of CPB is also required for both the reduction of energy consumption in deep mining (mining is an energy intensive industry with energy use accounting for 15% to 30% of production costs (CIM 2004), with the majority of greenhouse gas emissions directly related to energy consumption (CIM 2004), and economical reasons. According to (Rawlins and Phillips 2001), cemented backfill offered significant advantages beyond the obvious rock support and stability roles in terms of ventilation condition control. Indeed, backfill also results in reduced heat induction (up to 53%) through the exposed rock into the stoping areas of a deep mine (as observed in various South African deep mines and Japanese mines in hot rocks). Taking a near futuristic view where production would take place at a vertical rock breaking

depth of above 4000 m (Rawlins and Phillips 2001), the choice of environmental control systems and cost of their operation could well determine the very existence of such a mine. The contribution of a mine environmental control system is currently 10% to 15% of the cost of mining (Rawlins and Phillips 2001). Therefore, the significance of cemented backfill in improving the climate of deep to very deep underground mine cannot be underestimated (Rawlins and Phillips 2001). However, the evaluation of the performance of CPB in terms of ventilation condition control needs a deeper understanding of thermal conductivity and heat transfer in CPB. Unfortunately, the level of knowledge on these mechanisms is still limited.

In contrast to deep mine high temperature conditions, in colder mines, CPB structures can contribute to the heat load on the air climate of the mine, as reported by (De Souza and Hewitt 2005). Indeed, since CPB structures are often very large (several tens of meters in height and width), binder hydration can release (depending on the cement content and type) a significant quantity of heat inside the cemented backfill structure, as shown in studies conducted by Williams *et al.* 2001). In turn, this heat can be released into the colder mine climate, thus contributing to heat load. Knowing the thermal conductivity of CPB is necessary to evaluate and predict the contribution of hydrating CPB structures to heat load in shallow depth mines.

Considering the aforementioned facts, experimental studies were conducted to investigate the thermal conductivity of CPB materials and the main factors affecting it.

The main objectives of this paper are:

- to present the results of the experimental evaluation of thermal conductivity of CPB;
- to develop an understanding of the key factors affecting the thermal conductivity of CPB.

3.4 Experimental techniques and materials used

3.4.1 Materials used

The materials that were used included tailings, binders and water.

Tailings

Artificial tailings (AT, ground silica) and natural tailings (NT) sampled from an East African mine were used as basic tailings materials. The usage of AT provided an accurate control of the mineralogical and chemical composition of the tailings materials. In addition, NT often contain sulphide minerals whose oxidation before or during the preparation of CPB samples can produce additional sulphate in the CPB and thus, significantly affect the results of the tests. The used AT present a grain size curve close to that of nine Canadian mines as shown in Figure 3-1. From this figure, it can be noted that the AT has 45% of fine particles (particles with diameters lower than 20 μm) and can be classified as medium tailings. The AT contained 99.8% SiO_2 (quartz). Further physical and chemical properties of the AT are given in Table 3-1 and Table 3-2.

The NT were used in order to evaluate the changes in the mineralogical composition of the tailings on the thermal conductivity of CPB. The NT contained about 45% fine particles and can thus, also be classified as medium tailings. Their mineralogical composition is mainly characterized by quartz (45%) and pyrite (25%).

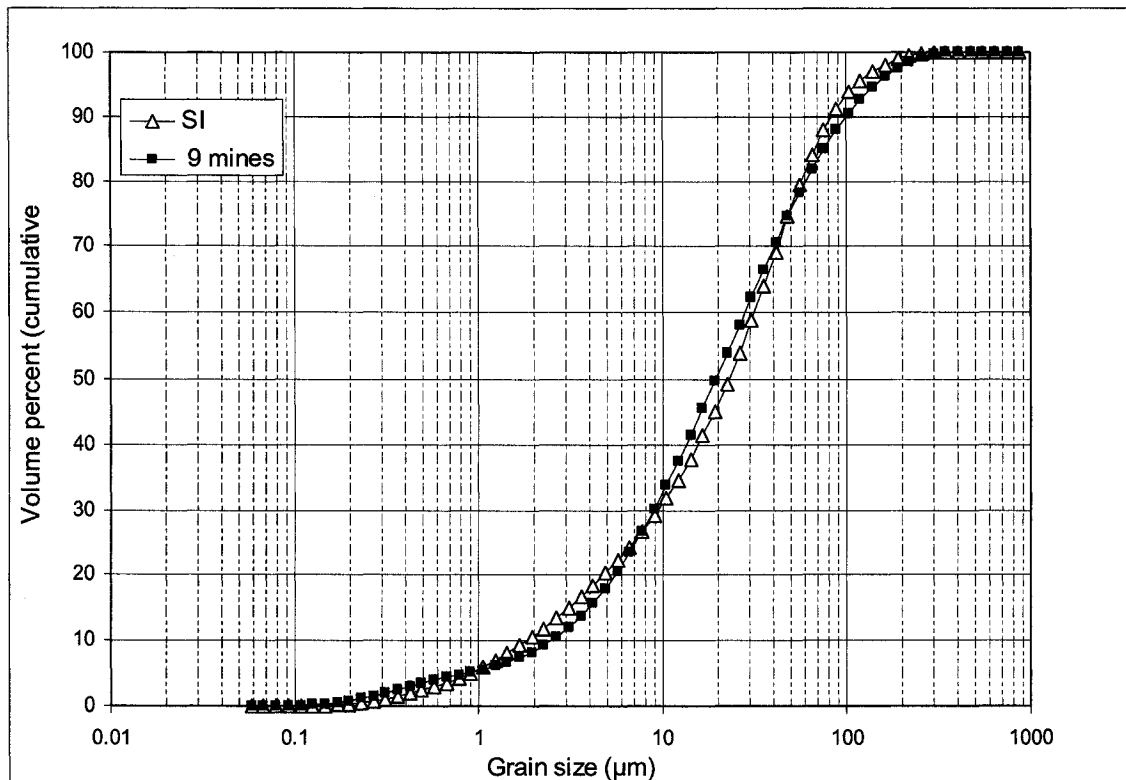


Figure 3-1. Grain size distribution of the artificial tailings and that of the average of 9 natural mine tailings.

Table 3-1. Physical properties of the tailings (AT) used.

Element	G_s	D_{10}	D_{30}	D_{50}	D_{60}	D_{90}	C_u	C_c
unit	-	μm	μm	μm	μm	μm	-	-
AT	2.7	1.9	9.0	22.5	31.5	88.9	16.2	1.3

Table 3-2. Main chemical elements in the tailings (AT) used.

Element	Al	Ca	Si	Fe	Na	Pb	S	K
unit	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %
AT	0.1	<0.01	99.8	<0.01	<0.01	0.0	0.0	0.0

Binder

The most popular cement used in backfill operations is Ordinary Portland Cement (PCI). Hence, PCI was used as a reference binder alone or blended with blast furnace Slag (Slag). The blending ratios of PCI and Slag were 50/50 and 20/80 in weight proportion. The usage of Slag allowed us to analyze the effect of mineral admixtures on the thermal conductivity of CPB. The physical and chemical properties of the binders that were used are outlined in Table 3-3.

Table 3-3. Characteristics of the different types of binder used.

	MgO	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	Relative Density	Specific Surface (m ² /g)
PC I	2.65	62.82	18.03	4.53	2.70	3.82	3.1	1.3
Slag	10.98	41.14	34.23	9.54	-	3.87	2.84	2.2

Mixing water

Tap water was used to mix the binders and tailings. However, to prepare the mixing water with specific amounts of sulphate, distilled water was used. The addition of specific amounts of sulphate concentrate (granular ferrous sulfate

FeSO₄ 7H₂O) to the distilled water allowed us to prepare mixing water with well known sulphate concentrations (0, 5000, 10000 ppm).

3.4.2 Measurement device

The thermal conductivity tests were conducted by using the KD2 Thermal Properties Analyzer manufactured by Decagon. It is a commercial thermal property analyzer that uses an indirect method by creating a heat disturbance in the sample. The KD2 calculates values for thermal conductivity (K) and resistivity by monitoring the dissipation of heat from a line heat source given a known voltage (KD2 2006). The methodology is based on the transient line heat conduction in homogeneous, isotropic medium. The thermal conductivity is measured with a relative error of 5%. The KD2 analyzer allows a quick determination of the thermal conductivity in comparison to the DSC (Differential Scanning Calorimeter) which requires a relatively long equilibrium time and consequently, can result in changes in CPB properties.

3.4.3 Mix preparation and procedures

The tailings material, binders and water were mixed and homogenized by hand in a container for about 7 minutes to produce the desired CPB mixtures. For samples with a constant slump of 18 cm, trial slump tests were conducted previously by using the slump test cone as prescribed in the ASTM C-143. Water cement ratio (W/C) ratio was back calculated by utilizing the weight of water

used. The produced CPB mixes were poured into curing cylinders, 10 cm in diameter and 20 cm in height. The prepared moulds were then sealed and cured in environmental chambers at specific curing temperatures (2°C, 20°C, 35°C and 50°C) for periods of 1, 3, 7, 14, 28, 90 and 120 days. Various mixes with different material proportions were prepared to determine the influence of various factors on thermal properties of the CPB. Thus, the effect of binder type, binder proportion, W/C ratio, slump, grain size distribution, concentration of sulfate and temperature were considered. The prepared mixes are summarized in Table 3-4. After specific curing times and temperatures, tests for determination of the thermal conductivity were performed by using the measurement devices described above.

Table 3-4. Mix composition for the different samples

Sample Identification	%PCI in the binder	%Slag in the Binder	% of Binder	% of Quartz	% Fine (<20 μ m)	Mixing Water	Sulfate content (ppm)	W/C ratio
-----------------------	--------------------	---------------------	-------------	-------------	----------------------	--------------	-----------------------	-----------

Effect of binder type

S-PCI	100	0	4.5	100	45	Tap	0	7.7
S-PC/SL 50/50	50	50	4.5	100	45	Tap	0	7.7
S-PC/SL 80/20	80	20	4.5	100	45	Tap	0	7.7

Effect of binder proportion at constant slump

S-2%PCI	100	0	2	100	45	Tap	0	15.2
S-4.5%PCI	100	0	4.5	100	45	Tap	0	7.7
S-6%PCI	100	0	6	100	45	Tap	0	5.9

Effect of curing temperature

S-Temp	100	0	4.5	100	45	Tap	0	7.7
--------	-----	---	-----	-----	----	-----	---	-----

Effect of W/C ratio

S-W/C5	100	0	4.5	100	45	Tap	0	5
S-W/C7.7	100	0	4.5	100	45	Tap	0	7.7
S-W/C10	100	0	4.5	100	45	Tap	0	10

Effect of grain size and mineralogical composition

S-0% Fine	100	0	4.5	100	0	Tap	0	7.7
S-20% Fine	100	0	4.5	100	20	Tap	0	7.7
S-45% Fine	100	0	4.5	100	45	Tap	0	7.7
S-NAT	100	0	4.5	50	45	Tap	0	7.7
S-AT/NAT	100	0	4.5	75	45	Tap	0	7.7

Effect of grain size at constant slump

S-45%Fine-Cst	100	0	4.5	100	45	Tap	0	7.7
S-35%Fine-Cst	100	0	4.5	100	35	Tap	0	6.1
S-20%Fine-Cst	100	0	4.5	100	20	Tap	0	5.9

Effect of sulphate								
S-0ppm	100	0	4.5	100	45	Tap	0	7.7
S-5000ppm	100	0	4.5	100	45	Dist	5000	7.7
S-10000ppm	100	0	4.5	100	45	Dist	10000	7.7

Legend: PCI = Portland cement type I; SLAG = Blast furnace slag; Tap = Tap water; Dist = Distilled water; W/C ratio = mass of water divided by the mass of binder

3.4.4 Experimental techniques

The initial thermal conductivity of the fresh paste prepared at 20°C was measured immediately after casting as zero day reading by inserting the thermal probe into the fresh paste. Moreover, to carry out the measurement of thermal conductivity on the hardening CPB, holes of 1.28 mm in diameter were first drilled in the center of the CPB sample after approximately 24 hours of curing. At specific curing times, the thermal probe was then inserted into the hole to determine the thermal conductivity of the CPB specimen. Measures of thermal conductivity were taken every day up to 7 days, every 7 days up to 28 days and every 10 days up to 90 days, to evaluate the time-dependent development of the thermal conductivity. Each test was repeated at least three times and the average value was considered as the thermal conductivity of the sample tested.

3.5 Results and discussion

3.5.1 Effect of binder types and curing time on the thermal conductivity

CPB samples were prepared with plain PCI and blended PCI and Slag. The total binder content was fixed at 4.5% and W/C ratio fixed at 7.7 for all mixes (Table 3-4). The samples obtained were cured at 20°C in an environment chamber with controlled humidity. The thermal conductivity readings were recorded at different periods and plotted in Figure 3-2. Figure 3-2 shows the variation of the thermal conductivity of CPB with binder type in relationship to the curing time. It is apparent in Figure 3-2 that the type of binder or the mineral admixture had an influence on the thermal conductivity of CPB. However, the magnitude of this influence depends on the curing time. Just after mixing, i.e. at zero day curing, the maximum thermal conductivity of 2.15 W/m°C was observed with the samples containing plain PCI. It decreased with the usage of Slag as a replacement for cement. The reductions in thermal conductivity, due to Slag, were about 10%. This can be mainly attributed to the fact that, the density of CPB decreased with the increase of Slag content (Fall 2005) and the Slag has a lower specific gravity (Table 3-3). Similar observations were made on normal concrete (Demirboga 2007). Another factor that can be considered as a contributor to the decrease of the thermal conductivity with Slag replacement is the amorphous structure of Slag. Indeed, the thermal conductivity of crystalline silica is about 15 times as that of amorphous (Loudon 1979, Onaran 1993, Fu

and Chung 1999). An observation of Figure 3-2 shows that up to 40 curing days, the thermal conductivity of the samples cemented with PCI is higher than that of the samples containing Slag. This is related to the aforementioned mechanisms (lower density and amorphous structure of Slag). However, an analysis of Figure 3-2 indicates that the thermal conductivity of the CPB containing Slag shows an increasing trend from 4 to 40 days, while those of CPB made with PCI is almost constant and then decreases slightly. This is because the hydration process is slower and delayed in Slag compared to the one in PCI (Khan 2002, Demirboga 2007). For this reason, the binder hydration induced porosity reduction in CPB made with only PCI was faster than that in CPB containing Slag. Lower porosity leads to denser cemented materials, thereby to higher thermal conductivity. Figure 3-2 also shows that for a curing time longer than 40 days, within the experimental error of the measurement, all of the samples tended to have a single value of thermal conductivity as $2.1 \text{ W/m}^\circ\text{C}$, i.e. the effect of curing time and mineral admixtures on CPB's thermal conductivity was negligible. This indicates a slowing down of the binder hydration. The relative similar thermal conductivities of PCI-CPB and Slag-CPB can be attributed to the filler effect of the mineral admixture Slag. Indeed, it is well known, that the addition of mineral admixture such as Slag, because of its filler effect and its reaction with CH produced by the cement hydration, improves the microstructure of CPBs (finer porosity, denser microstructure, Fall and Samb 2008) at advanced curing times. Thus, this improvement in the microstructure made the hardened CPB more homogeneous and denser and consequently, increased its thermal conductivity

at an advanced age. The obtained values of thermal conductivity of CPB at an advanced age were relatively close to those of classical quartzite-concretes whose thermal conductivity is around 2.1 W/m°C W (Khan 2002).

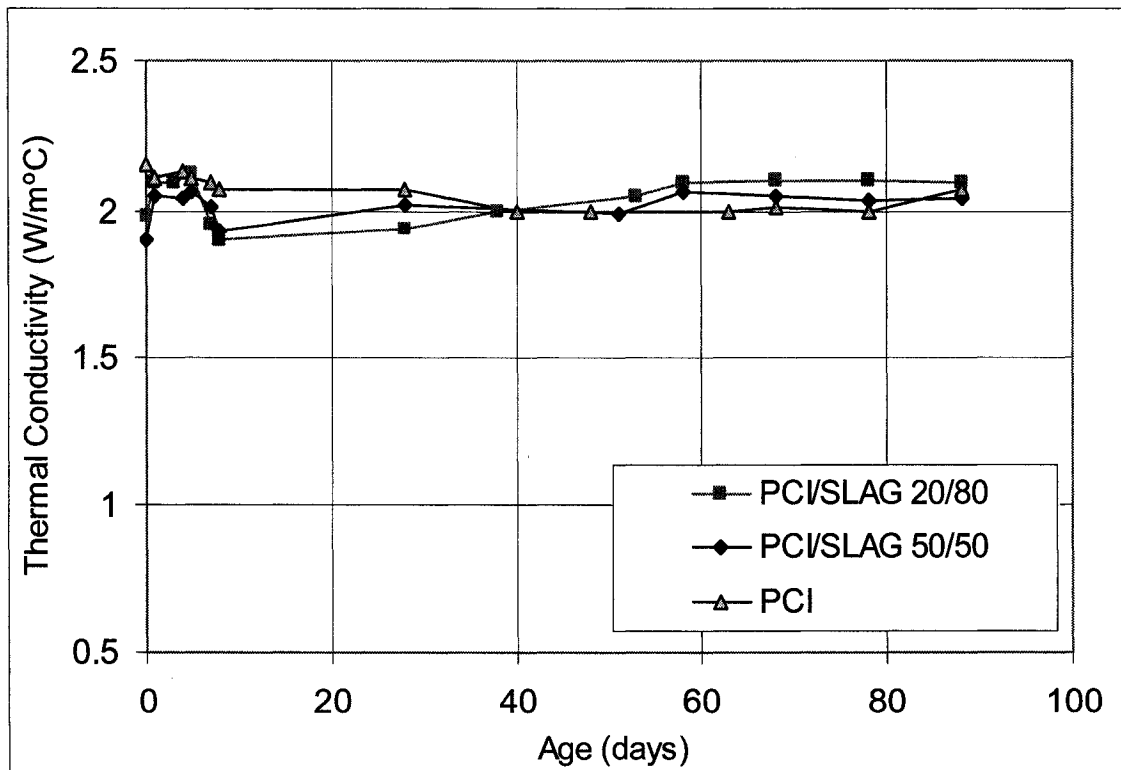


Figure 3-2. Effect of binder type on thermal conductivity.

3.5.2 Effect of binder proportion on the thermal conductivity

Since CPBs are usually prepared with binder proportions varying from 2% to 7%, CPB samples containing 2%, 4.5% and 6% PCI were tested with regards to thermal conductivity (Table 3-4). A series of CPB samples was tested. This series included CPB samples prepared with various binder contents at a constant slump (Table 3-4). To keep the slump constant at different binder contents, the water content and W/C ratio in the samples were varied accordingly. Figure 3-3

shows the effect of binder proportion on the thermal conductivity of CPB prepared at constant slump in relationship to the curing time. It can be noted that at a constant slump, the binder content only slightly impacted the CPB's thermal conductivity. The thermal conductivities that were measured appear generally to fall in a narrow range 2.0 to 2.15 W/m°C. This can be explained by the fact that at a slump of 18 cm, all CPB samples remained almost fully saturated (post-test water saturation degree, S_r , measurements indicated values of S_r between 95 to 97%) and the volume fractions of tailings were unchanged for all CPB samples. The influence produced by the mass of cement is less relevant compared to that induced by the volume of tailings and the water saturation degree.

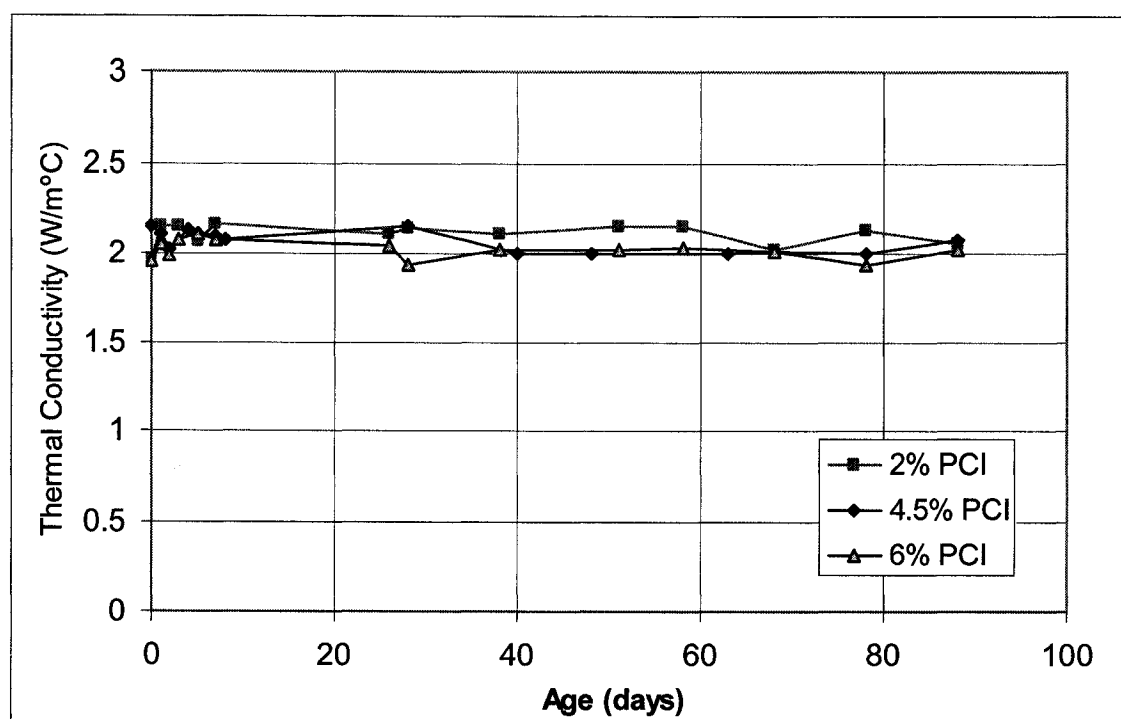


Figure 3-3. Effect of on binder proportion at constant slump on thermal conductivity.

3.5.3 Effect of water/cement ratio on the thermal conductivity

CPB materials prepared in the mine plants can have different water/cement ratios, W/C (usually 6 to 12) to reach optimal consistency. The proportion of water in CPB will certainly influence the thermal behavior of the mix as in classical concrete materials (Kim et al. 2002). Hence, thermal conductivity tests were conducted on CPB samples made with 4.5% PCI with a change of W/C ratio. The W/C ratio was varied in steps of 5, 7.7 and 10. The workability of the sample with W/C = 5 was poor. This W/C ratio was only selected from a research point of view. The results of these tests are presented in Figure 3-4. This figure shows that the W/C ratio influences the thermal conductivity of CPB in a slightly manner only at the early ages (≤ 3 days). At these ages, the sample with W/C = 5 exhibited higher thermal conductivity. Its conductivity was about 5 to 7% higher than that of CPB with W/C = 7.7 or 10. This can be attributed to the fact that a lower W/C ratio leads to faster binder hydration and thereby, increasing the density of CPB with lower W/C ratio quicker. This increase in density is associated with higher thermal conductivity as discussed previously. However, as the samples aged, all of the thermal conductivities tended to approximate the same mean value of $2.10 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$. This means that contrary to classical concrete, the effect of W/C on CPB's thermal conductivity becomes insignificant at an advanced curing time. This insignificant impact of W/C ratio on CPB's thermal conductivity at an advanced age can be attributed to high W/C ratios used in the preparation of CPB. Indeed, despite lower W/C ratios, the CPB with W/C = 5 was still almost fully saturated (water saturation degrees close to 95%

were obtained from post-test evaluation). This eliminated any possibility of an absorption of a significant amount of air inside the CPB matrix that would have led to the decrease of the thermal conductivity due to the low thermal conductivity of air (0.0243 W/mK, Clark 1966)) in comparison to the thermal conductivity of the other constituents of CPB that were studied (8.8 W/mK for silica tailings, 0.6 W/mK for water).

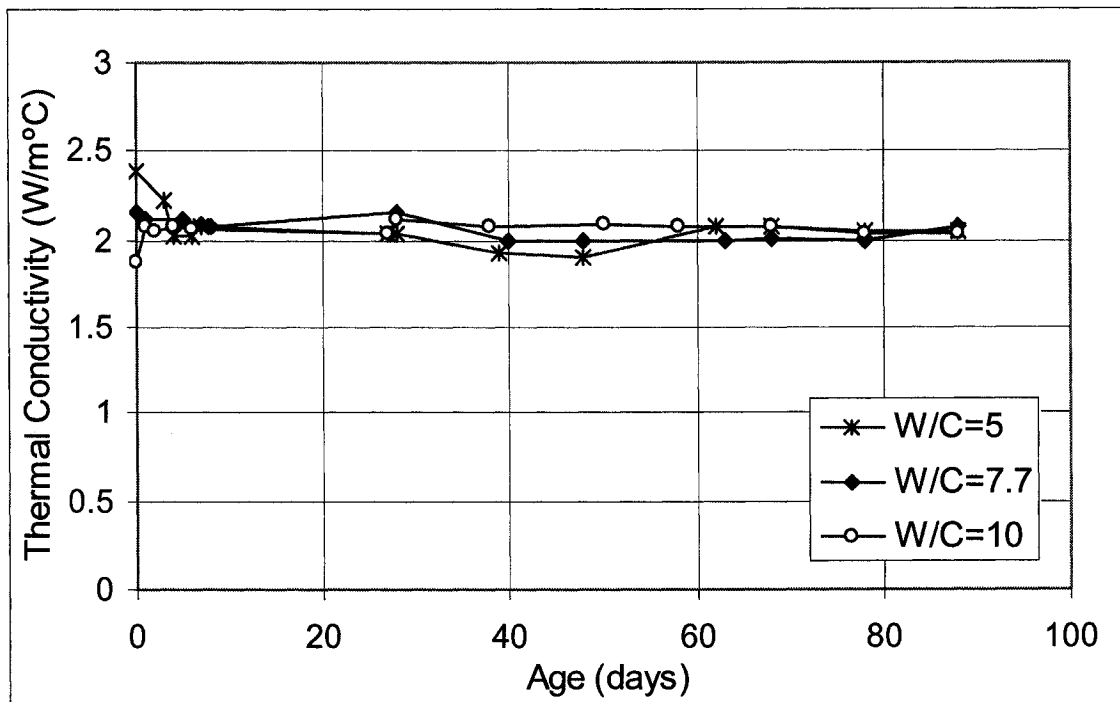


Figure 3-4. Effect of water/cement ratio (W/C) on the thermal conductivity

3.5.4 Effect of tailings characteristics on the thermal conductivity

Tailings used in preparation of CPB materials can be very different with regards to their mineralogical composition and grain size distribution. The mineralogical

composition of the tailings is mainly controlled by that of the initial rock that contained the ore. Depending on the processed ore, different tailings grain size distribution may be obtained. It may also be possible to combine the tailings with other sands of different sizes to affect the coefficient of uniformity C_u and the coefficient of curvature C_c to improve compressive and tensile strength (Fall and Benzaazoua 2005) for cemented backfill. Hence, the influence of tailings grain size (tailings fineness) and mineralogical composition (tailings types) were investigated.

To evaluate the impact of tailings fineness on CPB's thermal conductivity, four tailings materials having a percentage of passing 20 μm of 45%, 35%, 20%, 0% by weight respectively were prepared. The prepared tailings had the same chemical and physical (except grain size distribution) as those in Table 3-2 and Table 3-3. This allowed us to isolate the grain size factor and evaluate its impact on CPB's thermal conductivity. Two series of CPB samples were prepared. The first series included CPB samples prepared at a constant W/C ratio ($W/C = 7.7$) and with tailings materials having of proportion of fine of 45%, 20%, 0% (Table 3-4). The second series represented CPBs that were prepared at a constant slump (18 cm, see Table 3-4). In this series, the tailings with the proportion of fine of 45%, 35%, 20% were used (Table 3-4). The main results of the effect of tailings fineness on the thermal conductivity of CPB prepared at constant W/C ratio are presented in Figure 3-5.

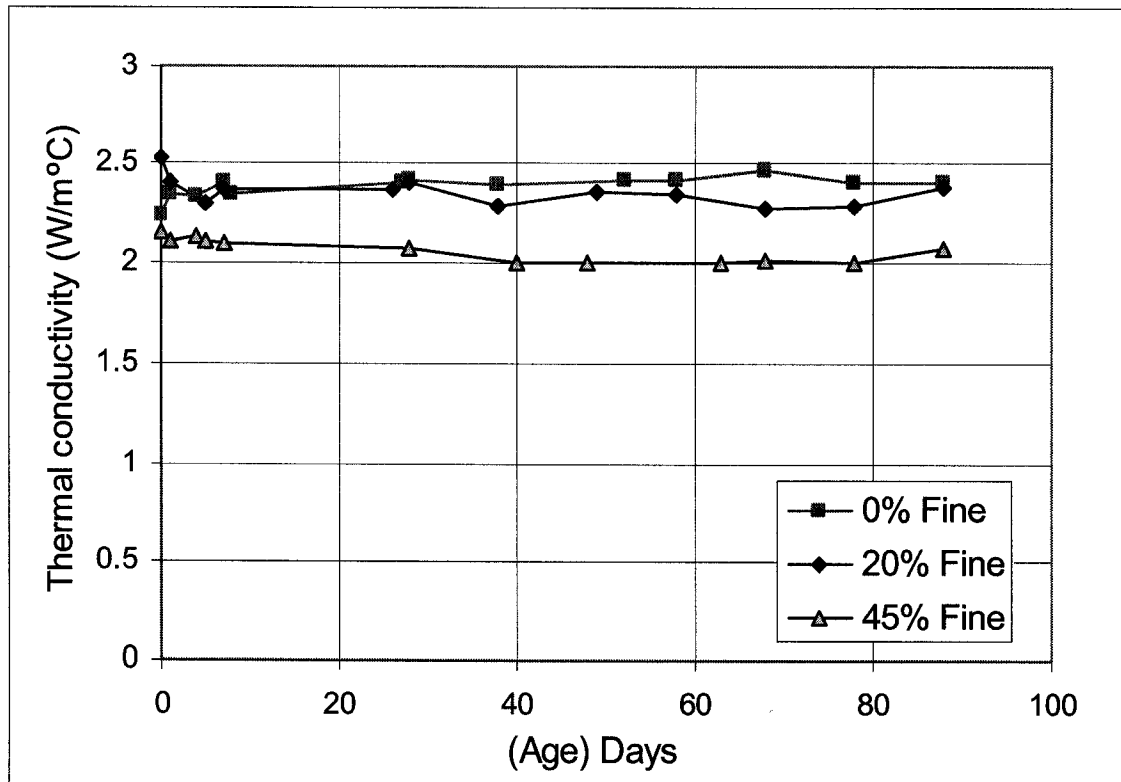


Figure 3-5. Effect of tailings grain size on thermal conductivity of CPB prepared at constant W/C ratio.

It can be noted that the thermal conductivity decreases as the grain size decreases. This decrease can be mainly explained by the fact that increasing the tailings fineness reduces the well-gradation of the tailings and leads to a lower packing density of the tailings materials, and consequently, to a higher volume of void spaces between the tailings particles available for cement hydration products. This contributes to increasing the overall porosity of the hardened cement matrix and thereby, decreasing the thermal conductivity. This assumption is supported by the experimental results presented in Figure 3-6 obtained by (Fall et al. 2004). This figure presents the results from studies on the influence of

tailings fineness on the overall porosity and void ratio of CPB. It can be observed, that the finer the tailings material used, i.e., the greater the proportion of fine tailings particles, the greater the overall porosity and void ratio of the CPB becomes. Another mechanism, i.e., the increasing of particle to particle contact surface by larger grain, could have contributed to the increase of thermal conductivity with tailings coarseness. However, from Figure 3-5, it can be observed that the increase of CPB's thermal conductivity with tailings coarseness does not follow a linear trend. This increase is higher from CPB with 45% to 20% fine particles (average increase of 12%) than from CPB with 20% to 0% fine particles (average increase of 5%). This can be explained with experimental demonstrations by (Fall et al. 2004), that as the proportion of fine particles reached a critical level (25-20% in this study), a further increase of the tailings coarseness would lead to a reduction of the well-graduation of the tailings and then to lower packing density. This in turn, would lead to an increase of the proportion of macropores (1–10 μm) within the CPB (Fall et al. 2004). This higher proportion of macropores (1–10 μm) may be the cause of the small decrease in the rate of thermal conductivity increase with the tailings coarseness for CPB having 20% to 0% fine particles.

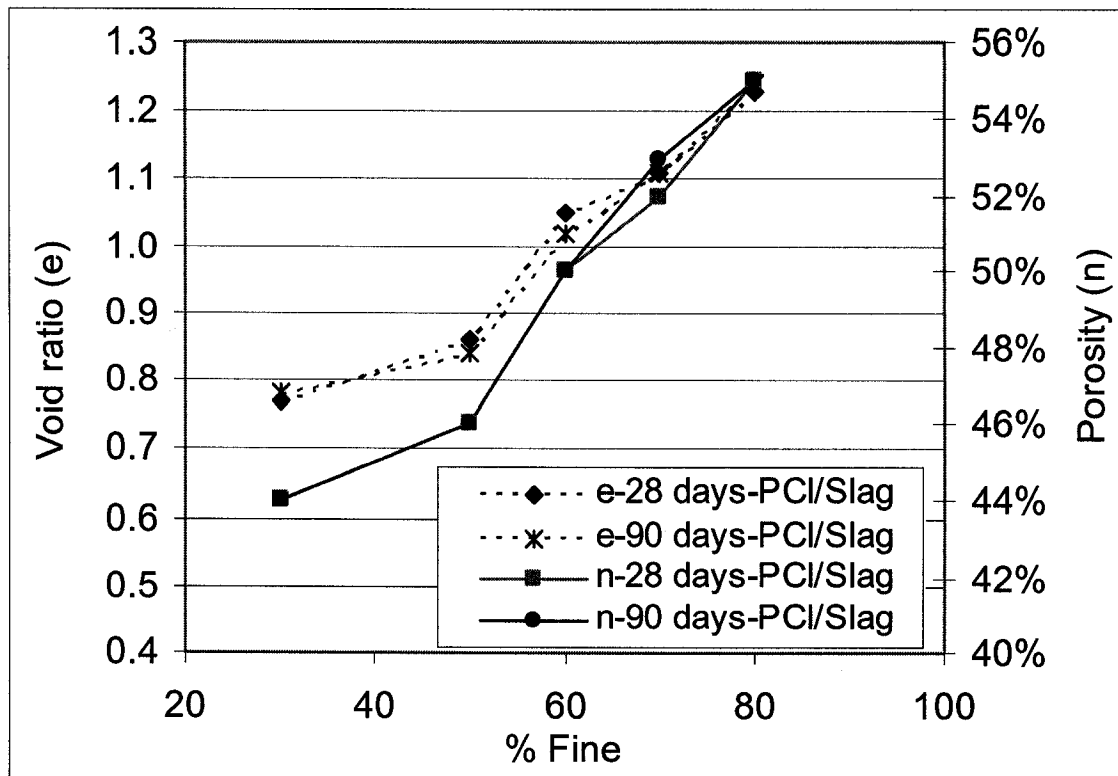


Figure 3-6. Effect of tailings fineness on void ratio (e) and porosity (n) on paste backfill cemented with 4.5% PCI/Slag

Figure 3-7 shows the effect of the tailings fineness on the thermal conductivity of CPB prepared at a constant slump. The pattern obtained in this group of mixes has shown once again, the predominant effect of the grain size on the thermal conductivity response. At the time of mixing, all samples showed a conductivity level lower than the one developed after one day. Past this first day, all samples (the 45%, 35% and 0% passing 20 μm) experienced an increase of thermal conductivity. The increase of thermal conductivity with tailings coarseness resulted from the modification of the porosity and pore structure of the CPB associated with this tailings grain size change and also from the increasing of

particle to particle surface contact as explained above. However, another additional mechanism should be suggested as an explanation for this decrease of the thermal conductivity with tailings fineness at a constant slump. This mechanism is the fact that for a given consistency, the water demand (or W/C ratio) of CPB made with finer tailings is higher than that of CPB made with coarser tailings as demonstrated in previous studies (Fall et al. 2004). Higher W/C ratio leads to a slight decrease of CPB's thermal conductivity as discussed in the previous section.

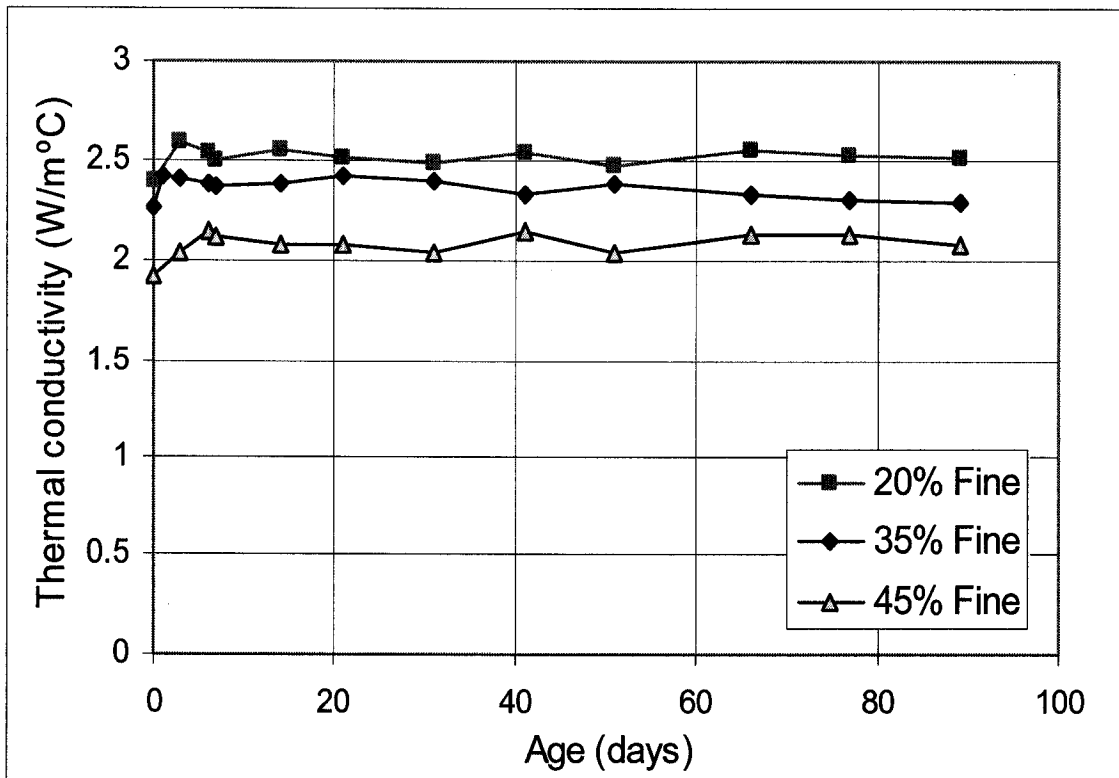


Figure 3-7. Effect of tailings grain size with constant slump on thermal conductivity

Aside from the influence of tailings grain size on CPB's thermal conductivity, the effect of the mineralogical composition of tailings (tailings types) on the thermal

conductivity was also studied. NT containing 50% quartz minerals was mixed in different proportions with AT containing 100 % quartz (99.8% precisely) to produce tailings materials with the following proportion of quartz: 50%, 75% and 100% by weight. The prepared tailings showed relatively similar grain size distribution curves. These tailings were used to prepare CPB samples at a constant W/C ratio (7.7) and binder content (4.5% PCI) (see Table 3-4). The results of the thermal conductivity tests performed on these samples are plotted in Figure 3-8. This figure reveals that the mineralogical composition of tailings or the proportion of quartz present in the tailings materials had a significant impact on the thermal properties of CPB. The thermal conductivity of CPB increased with an increase in quartz content. This is because the thermal conductivity of quartz was much higher than that of other minerals (e.g. $K=7.7\text{W/m}^{\circ}\text{C}$ for quartz, $2.25\text{ W/m}^{\circ}\text{C}$ for Feldspar, $2.03\text{ W/m}^{\circ}\text{C}$ for Mica, $3.46\text{ W/m}^{\circ}\text{C}$ for amphibole according to Horai (1971)) and also other components of CPB (water and cement paste). It can be concluded from these results that for a given CPB mix, the tailings materials with less thermal conductivity will produce the less conductive CPB, whereas more conductive tailings will produce more conductive CPB.

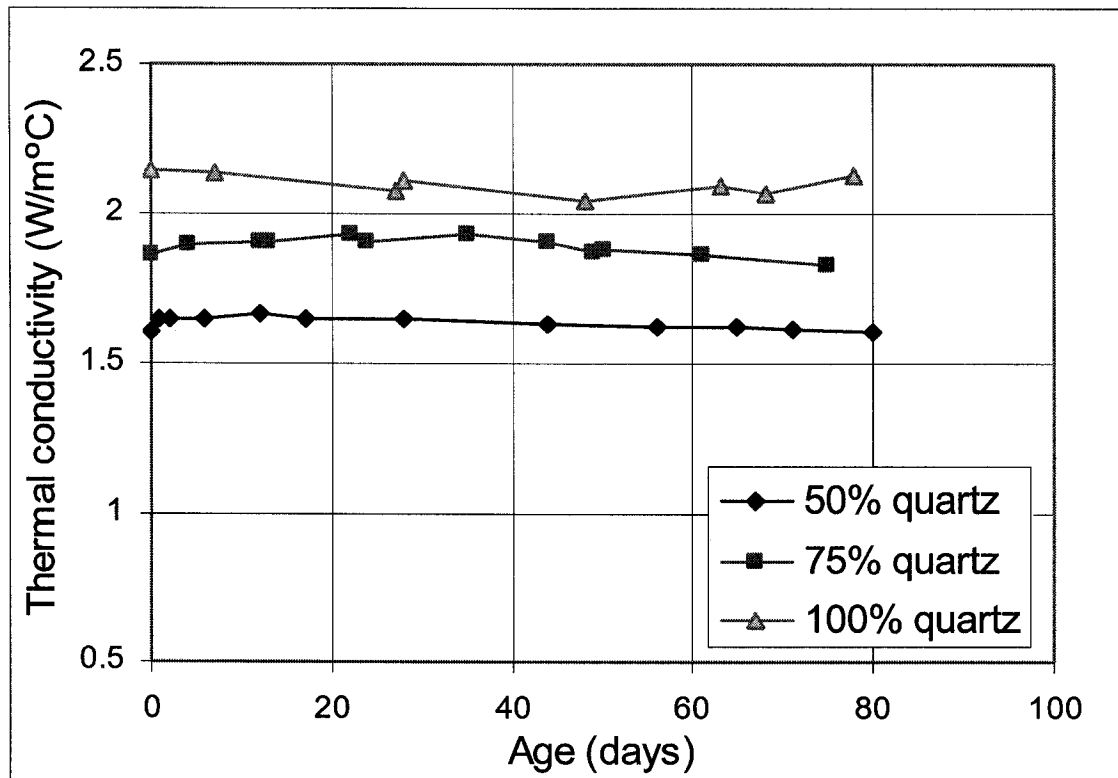


Figure 3-8. Influence of the mineralogical composition (quartz proportion) of the tailings on CPB's thermal conductivity.

3.5.5 Effect of sulphate concentration on the thermal conductivity

Tailings that come from milling in the mining industry and/or the mixing water of CPB often contain chemicals, such as sulfate. These chemicals influence the mechanical properties (Fall and Benzaazoua 2005), the curing process and could also affect the thermal properties of CPB. However, our understanding of the impact of sulphate on CPB's thermal properties is limited. For this reason, CPB mixes were prepared with sulfate concentrations equivalent to 0, 5000 and 10000

ppm. The thermal conductivities obtained from such samples are represented in Figure 3-9.

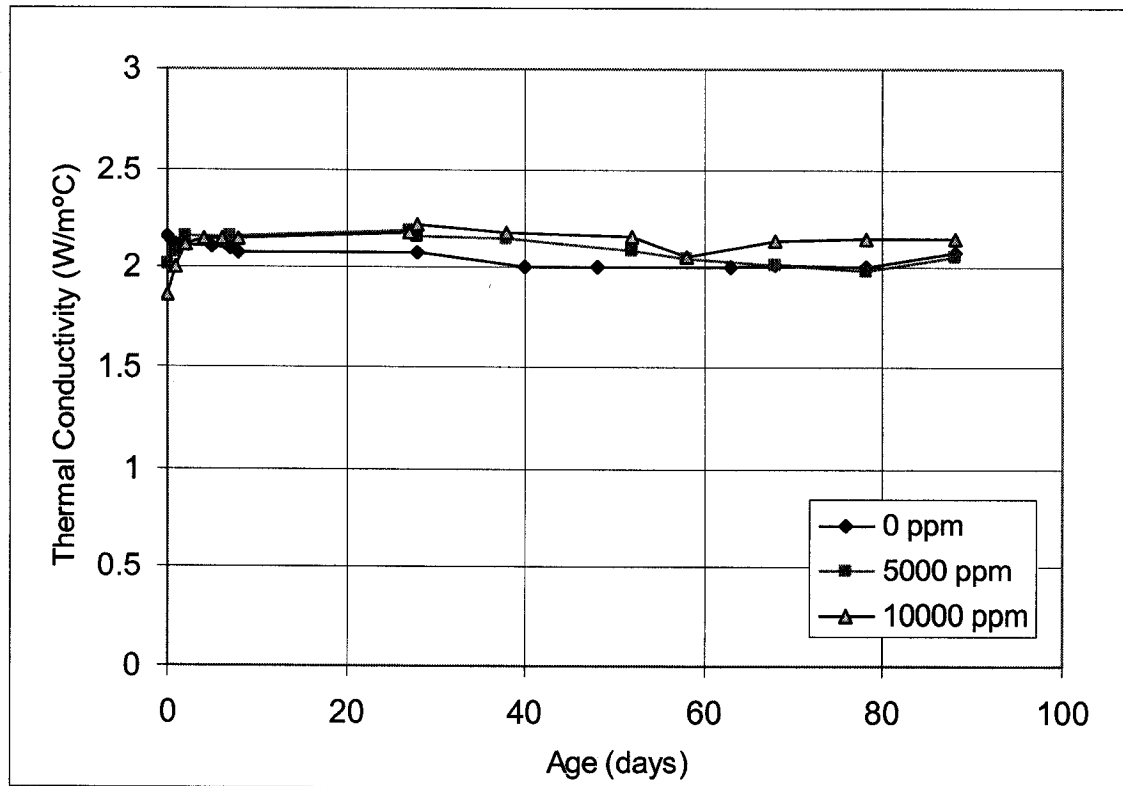


Figure 3-9. Effect of initial sulfate concentration on thermal conductivity of CPB

The samples 5000 and 10000 ppm showed globally higher thermal conductivity during all of the hydration processing, from the early days up to 90 days. This higher thermal conductivity associated with sulphate concentration can be explained by the fact that, as mentioned in Fall and Benzaazoua (2005), relatively low sulphate concentrations (as used in this study) contributed to the decrease of CPB's porosity. The reason is attributed to the precipitation of secondary hydrated minerals (such as gypsum, ettringite and brucite) in the empty capillary pores that are present in the CPB. This is graphically

demonstrated by the results of SEM observations presented in Fall and Benzaazoua (2005). From this study, it can be seen that secondary hydrated minerals precipitated in the pores that were inside the cement matrix and thus, reducing its porosity. However, it should be mentioned, as shown in Figure 3-9, that the magnitude of the impact of sulphate on CPB's thermal conductivity is relatively low. Indeed, the maximal difference in thermal conductivities values between CPBs containing sulfate and those without sulfate is only 9%.

3.5.6 Coupled effect of curing temperature and water saturation degree on the thermal conductivity

It is well known that chemical reactions are sensitive to temperature. The rate of reaction increases with temperature. The temperature has a considerable influence on CPB's binder reactions (Fall and Samb 2008). Consequently, it can be assumed that the temperature should significantly affect the thermal conductivity of CPB. Hence, to verify this assumption, thermal conductivity tests were conducted on one type of paste mix (4.5% PCI, W/C=7.7) distributed into 4 samples that were cured at different temperatures; namely 2°C, 20°C, 35°C and 50°C. The results of these tests are presented in Figure 3-10 and Figure 3-11.

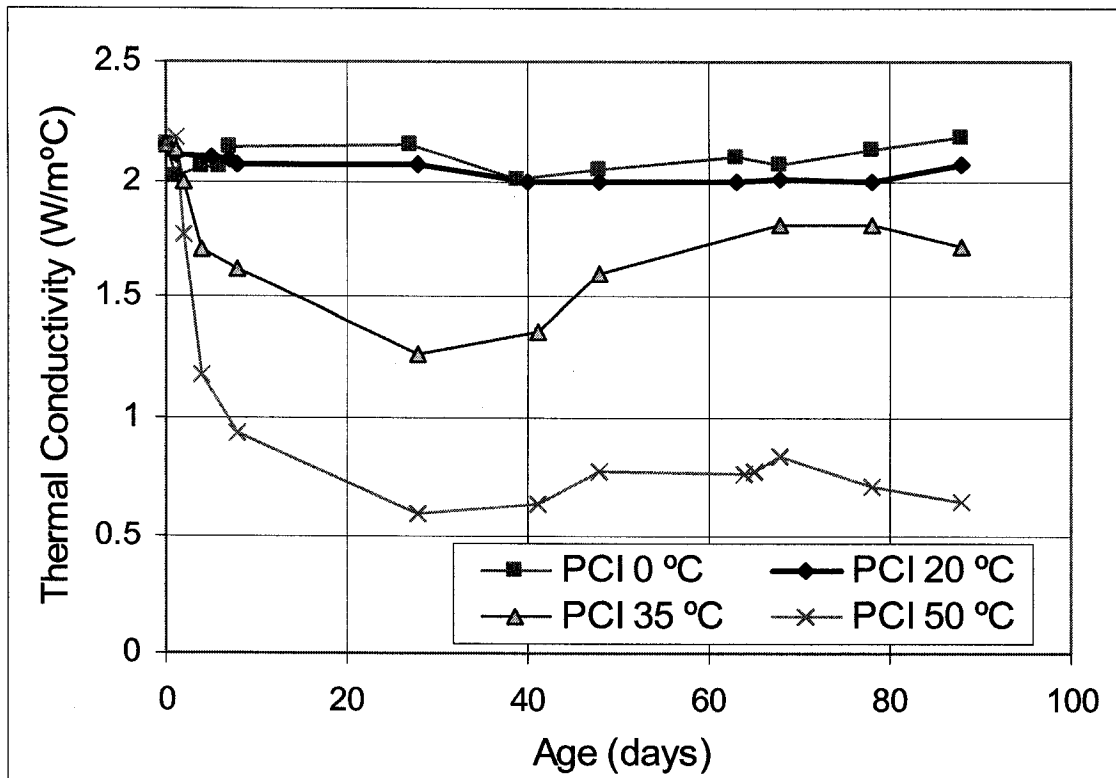


Figure 3-10. Effect of curing temperature on the thermal conductivity of CPB in relationship to curing time

These figures show that globally, the thermal conductivities decrease as the specimen temperature increases. These findings are in agreement with earlier results on the effect of temperature on thermal conductivity of classical concrete reported by Kim et al. (2002). This study has shown that thermal conductivity decreased linearly with temperature. This observed decrease of the thermal conductivity of CPB with increasing curing temperature can be mainly attributed to the impact of a higher curing temperature on the cement hydrations process and thus, to the variation of thermal conductivity affected by pastes (Kim et al. 2002).

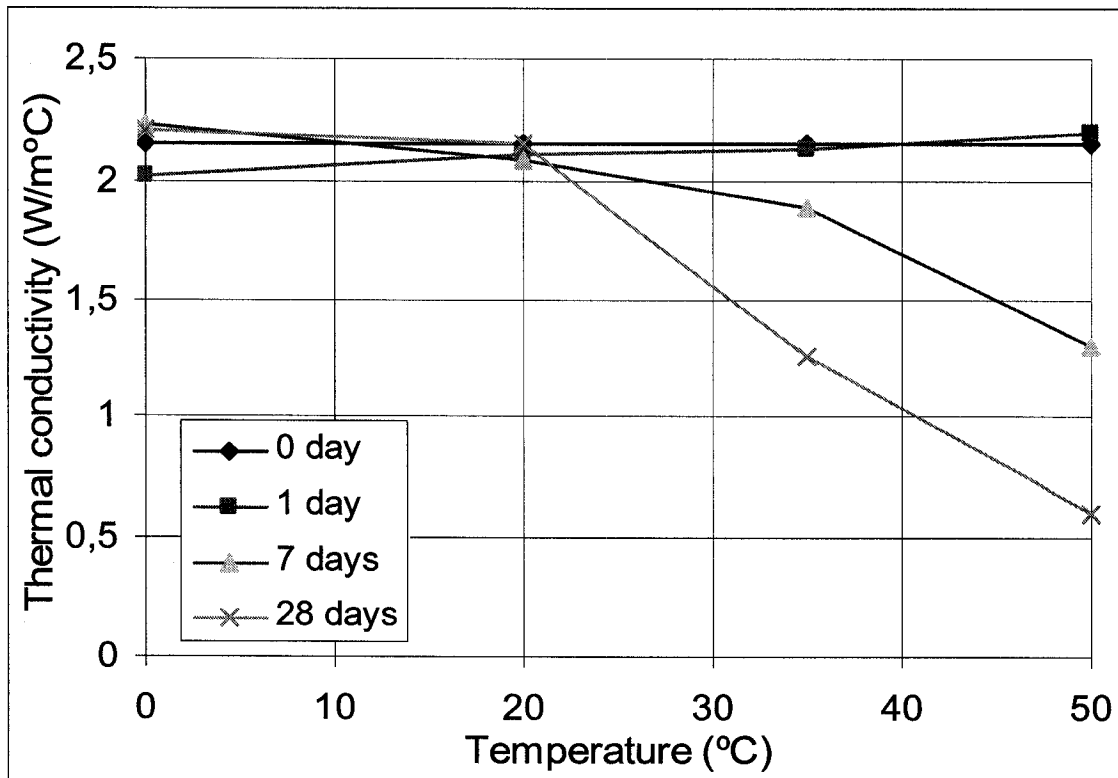


Figure 3-11. Effect of time and curing temperature on thermal conductivity of CPB

However, due to the large drop in the thermal conductivity noted at temperatures of 35°C and 50°C, it was believed that the measured decrease in thermal conductivity could be additionally explained by higher desaturation of the CPB with higher curing temperature and particularly, at the top of the cylinders. Indeed, post-testing evaluation showed a decrease of the water content and saturation degree of the CPB from the bottom to the top of CPB samples cured at 35°C and 50°C. For CPB cured at 2°C and 20°C, the water content and saturation degree remained unchanged. For example, an analysis of the saturation degree of the top layer revealed saturation degree values of 88%, 93%, 94% and 94% for the temperatures of 50°C, 35°C, 20°C and 2°C degrees,

respectively at 28 days. Furthermore, additional thermal conductivity tests were conducted on CPB samples cured at 2°C, 20°C, 35°C and 50°C from the top to the bottom of the CPB cylinder following a 2.5 cm measurement interval. The results showed that the thermal conductivity of CPB cured at 35°C and 50°C increased from the top (lower water saturation degree) to the bottom (higher water saturation degree) of the CPB cylinder. The thermal conductivity remained almost constant for CPB cured at 20°C and 2°C due to the relative constant water saturation degree. Figure 3-12 illustrates an example of the effect of water content on the thermal conductivity of CPB cured at 50°C. It can be observed that as the water content decreases, the thermal conductivity decreases. This is because as the water content decreased, the water saturation decreased and the water or moisture in CPB was partially replaced by air. Since water has a thermal conductivity about 25 times that of air, it is obvious that when the air content increased, the CPB's thermal conductivity will also decrease. Similar observations were made on classical concrete (Short and Kinniburgh 1978, Schnider 1982, Morabito 1989, Ashworth 1991).

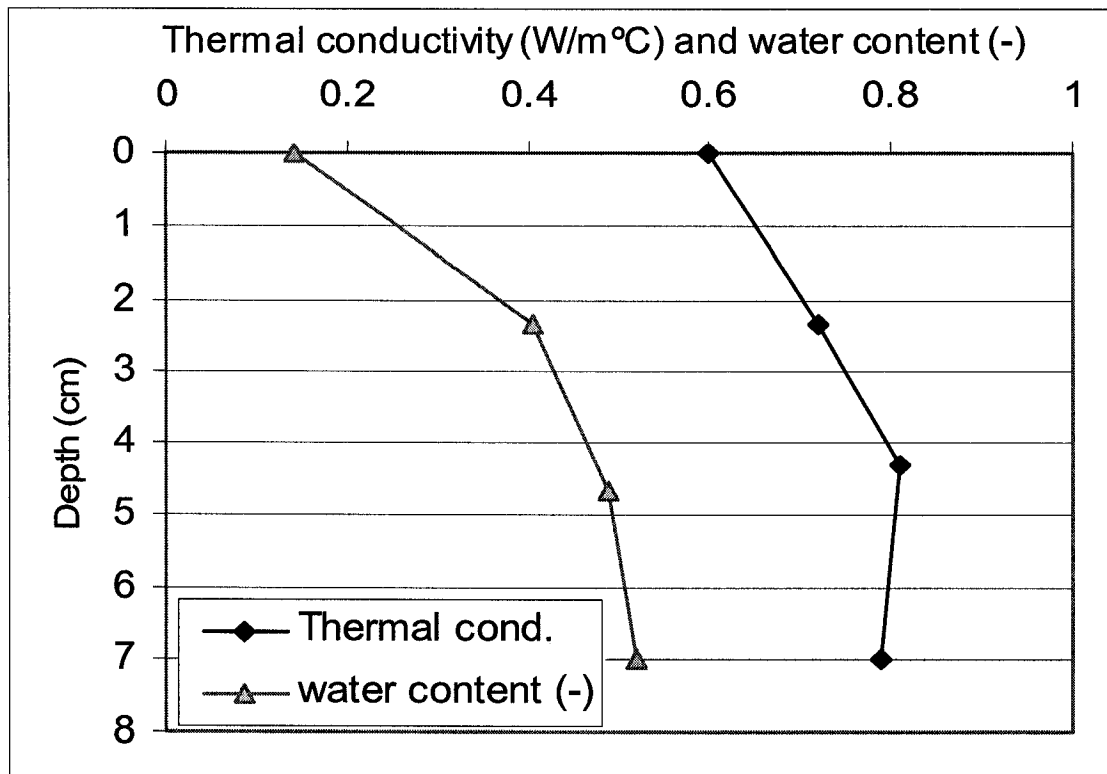


Figure 3-12. Effect of the variation of water content with depth on the thermal conductivity of CPB aged of 90 days and cured at 50°C.

3.6 Summary and conclusions

Due to limited knowledge on the thermal properties of CPB and their relevance in the design of CPB structures, the aim of this study was to investigate the thermal conductivity of CPB, a relatively new cementitious mine backfill material. Various mixtures having different components (e.g. cement type and proportions, water content, sulphate concentration) and cured at various temperatures and times were used in the investigation. The measurements of thermal conductivity were performed by using the KD2 Thermal Properties Analyzer. Valuable results with

regards to the effects of CPB's mix components, curing time and temperature, water saturation degree on the thermal conductivity of CPB were gained.

Based on the studies presented in this paper, the following conclusions can be drawn:

1. The CPB's mix components, such as tailings type and tailings fineness have a very noticeable influence on the thermal conductivity of CPB. Tailings with higher quartz content produce CPBs with higher conductivity, while CPBs made of coarse tailings have a higher thermal conductivity than those made of fine tailings.
2. The mix parameters, such as the W/C ratio, cement type, binder content (at constant slump) and sulphate content, have a minor effect on the thermal conductivity of CPB.
3. For a given CPB mix, at an advanced curing time (≥ 28 days), the thermal conductivity tends to stabilize to a steady value as observed in classical concrete materials. The curing time influences the thermal conductivity of CPB only at an early age.
4. Higher curing temperatures lead to lower thermal conductivity, while lower water saturation degrees cause a decrease of the CPB's thermal conductivity.

This work brings new knowledge to the thermal properties of CPB that can contribute to the better optimization of CPB mixtures and design of more cost-effective and durable CPB underground structures.

Acknowledgments

The authors would like to extend their thanks to NSERC, Dr. P. Simms, IRND and Cement Lafarge Canada.

3.7 References

- Amaratunga L. M., Yaschyshyn D. N. Development of a high modulus paste Fill using fine gold mill tailings. *Geotechnical and Geological Engineering* ,15 (1997) 205-219.
- Annor A., Tarr K. Fynn D. Mechanical properties of a composite backfill material- Project 602510: Proceedings of the Core Project on Deep Mining Version: June 2006.
- Ashworth T., Ashworth E. Insulation materials: testing and applications, in: R.S. Graves, D.C. Wysocki (Eds.), *ASTM STP 1116*, Philadelphia 1991;415–29.
- ASTM C143/C143M-05a, Standard test method for slump of hydraulic cement concrete. *Annual Book of American Standard of Testing Materials Standards* 2005.
- Chugh Y. P., Biswas D., Deb D. Underground placement of coal processing waste and coal combustion by-products based paste backfill for enhanced mining economics. Final report; 2002.
- CIM Building on our Strength - A World Leader in Mining. A Brief to the 61st Annual Mines Ministers' Conference, Iqaluit, Nunavut. July 20, 2004.

Clark S. P. Thermal conductivity, Handbook of Physical Constants, Geological Society of America. Memoir, 97 (1966) 461-482

De Souza E., Hewitt A. The Contribution of Cemented Backfill to Heat Loads. In Mines, 8th International Mine Ventilation Congress – Brisbane, (2005) 87-93.

Demirboga R. Thermal conductivity and compressive strength of concrete incorporation with mineral admixtures. Building Environment, 42 (2007) 2467–2471

Fall M., Samb S. Pore structure of cemented tailings materials under natural or accidental thermal loads. Material Characterization, 59 (2008) 598-605.

Fall M., Samb S. Influence of curing temperature on strength, deformation behaviour and pore structure of cemented paste backfill at early ages. Construction Building Material 2006 (in press).

Fall M., Nasir O., Celestin J. C. Paste backfill response in deep mine temperature conditions. 9th Symposium on MineFill, Montreal 2007b.

Fall M., Benzaazoua M., Sae E. Mix proportioning of underground cemented paste backfill. *International Journal of Tunnelling and Underground Construction*, 23 (2007a) 80-90.

Fall M., Benzaazoua M. Modeling the effect of sulphate on strength development of paste backfill and binder mixtures optimization. *Cement and Concrete Research*, 35 (2005) 301-14.

Fall M. Geotechnical and geo-environmental research results with potential applications in Senegal; Research contribution, Dakar 2005.

Fall M., Benzaazoua M. Ouellet S. Effect of tailings properties on paste backfill performance. *Proceedings of 8th International Symposia on Mining with Backfill*. In Beijing, China 2004;193-202

Fu X., Chung D. D. L. Effect of admixtures on the thermal and thermomechanical behavior of cement paste. *ACI Materials Journal*, 96 (1999) 455–461

Horai K. I. Thermal conductivity of rock-forming minerals. *Journal of Geophysical Research*, 76 (1971) 1278–308.

Khan M. I. Factors affecting the thermal properties of concrete and applicability of its prediction models. *Building Environment*, 37 (2002) 607–614

KD2, The KD2 thermal properties analyzer vs. published standards. Decagon devices Inc.

<http://www.decagon.com/appnotes/TheKD2ThermalPropertiesAnalyzevsPublish.pdf>; 2006

Kim K. H., Jeon S. E., Kim J. K. Yang S. An experimental study on thermal conductivity of concrete. Cement and Concrete Research, 33 (2003) 363-371.

Krishnaiah S., Singh D. N. Determination of thermal properties of some supplementary cementing materials used in cement and concrete. Construction and Building Material, 20 (2006) 193-198.

Kodur V. K. R., Sultan M. Effect of temperature on thermal properties of high strength concrete. Journal of Materials in Civil Engineering, ASCE, 15 (2003) 101-107.

Landriault D. Paste backfill mix design for Canadian underground hard rock mining. Proceedings of the 97th Annual General Meeting of the CIM Rock Mechanics and Strata Control Session, Halifax, Nova Scotia (1995) 229-38

Loudon A. G. The thermal properties of lightweight concretes. International Journal of Cement Composites and Lightweight Concrete 1 (1979) 71–85.

Morabito P. Measurement of thermal properties of different concretes. High Temperatures–High Pressures, 21 (1989) 51-59.

Onaran K., Materials science (Malzeme Bilimi), Science Technical Press, İstanbul, Turkey (1993) (p. 174).

Rawlins C. A., Phillips H. R. Reduction of mine heat loads. Proceedings of the 7th International Mine Ventilation Congress (2001) 381-389.

Short A., Kinniburgh W. Lightweight Concrete, Galliard Printers Ltd., Great Yarmouth, Great Britain 1978.

Schnider U. Behavior of Concrete at High Temperatures, Deutscher Ausschuss für Stahlbeton, Heft 337, Berlin 1982.

Udd J. E. Backfill research in Canadian Mines Fourth international symposium. Innovations in Mining Backfill Technology. Hassani et al. (eds) 1989 Balkema, Rotterdam ISBN 90 6191 985 1

Williams T. J., Denton D. K., Larson M. K., Rains R. L., Seymour J. B., Tesarik D. R., Geomechanics of Reinforced Cemented Backfill in an Underground Stope at the Lucky Friday Mine, Mullan, Idaho. Report of Investigations 9655. 2001; p.24.

Yilmaz E., Kesimal A., Deveci H., Ercikdi B. The Factors Affecting the Performance of Paste Backfill; Physical, Chemical and Mineralogical Characterization. First Engineering Sciences Congress for Young Researcher (MBGAK'03), Istanbul (2003).

4 Chapter 4

4.1 Technical Paper II

Effects of curing temperature and mix components on the mechanical properties and hydraulic conductivity of cemented paste backfill

4.2 Abstract

Increasing usage of cemented paste backfill in underground mines combined with the fact that every single mine or backfill structure is unique with regards to their temperature conditions require a need to clarify and quantify the effect of curing temperature on the performance properties (mechanical properties, hydraulic conductivity) of CPB. Hence, the main objective of this study is to use an experimental approach to study the influence of curing temperature and combined effect of curing temperature and CPB components on: (i) the main mechanical properties (compressive and split tensile strength,), and (ii) the saturated hydraulic conductivity of CPB. Thus, different types of CPB specimens are tested at different curing times and temperatures (2°C, 20°C, 35°C, and 50°C). The compressive and split tensile strength are evaluated by laboratory tests. The results show that the curing temperature has a significant influence on the mechanical properties and hydraulic conductivity of CPB. Moreover, the

effect of temperature on these properties depends on the binder type, W/C ratio, tailings type and curing time. The study demonstrates that the mine and backfill temperatures is an important parameter that should be considered in mine backfill operations.

Keywords: cemented paste backfill; tailings; temperature; strength; mechanical properties; hydraulic conductivity; mine; deep mine

4.3 Introduction

The financial revenues generated by the mining industry are vital for the economy and the well being of several countries and populations in the world. However, the mining industry produces a huge amount of solid waste (waste rock, tailings) as well as generates a large volume of underground and/or surface voids. For example, the quantity of mine solid waste produced yearly in Canada is estimated at around 500 million tonnes (Amaratunga and Yaschyshyn, 1997), while in Sweden, 25 million tonnes of waste rock and 20 million tonnes of tailings are produced and deposited annually (SWRC, 1998). In Australia, 10 million cubic metres of underground voids are generated annually as a result of mining (Grice 2001). The management of the aforementioned mine waste on the earth surface is not only expensive, but can represent serious geotechnical (e.g. tailings dam failures) and environmental (e.g. acid mine drainage, groundwater pollution) hazards (Fall and Merkel 2001). Hence, since the last century, in minimizing the geotechnical and environmental hazards associated with the surface management of mine solid waste and the creation of large voids in the underground (which can cause subsidence, stope and regional instability), a large amount of the solid waste produced has been returned to the previously mined underground voids (called stopes) by a process commonly referred as cemented backfill (CB). CB is one of the key components of the underground mining operations. It plays three important roles. First, it can be used as a construction material to create a floor, wall or roof/ head cover for mining

activities. Secondly, it is a major means of ground-support, thereby providing a safe work environment. Finally, CB provides an effective means of mine waste disposal (Landriault 1995, Archibald et al. 2000, Fall et al. 2004). The materials used for backfill at most underground mines generally consist of mill tailings or waste rock from underground or open-pit mining (Archibald et al. 2000). At sites where these materials are not available in sufficient quantities to meet the mining method requirements, alternative sources, such as alluvial sands and quarried rocks are used to replace or supplement the mine waste as underground backfill (Archibald et al. 2000).

There are three main types of mine cemented backfill: cemented hydraulic, rock and paste backfills. Each has certain advantages and disadvantages and usage is dependent on certain aspects of the present mining methods and surrounding ground conditions (Amaratunga and Yaschyshyn 1997). Hydraulic backfill (HB) is a mixture of alluvial sand and/or mill tailings and a relatively small percentage of cement. The mixture is generally about 60-75% solids by weight. Rockfill is usually a mixture of waste rock, tailings/or sand, water and cement. The CPB, a relatively recent development, is an engineered mixture of tailings from the processing operations of the mine, water and binders (2% to 7% by weight usually). It contains typically between 70 % and 85 % solids.

In response to the high hazards posed by HBs (failures of backfill barricades and subsequent mine fatalities), nowadays, the use of the HB is restricted and used increasingly less. On the other hand, CPB is extensively used in underground mine operations and increasingly used. This is because of the technical and

economic advantages as it is more profitable and safe than HB. Cement consumption using CPB is generally about 40–70% of what would be used in alternative backfills with comparable mechanical properties (Landriault 2001). However, although CPB has been successfully applied in underground mining, it remains a relatively new technology. The industry is still on a learning curve with respect to the performance properties or criteria of CPB.

Mechanical stability, economical performance and durability represent important performance criteria for CPB. Once placed, CPB has to satisfy certain mechanical stability requirements to ensure a safe underground working environment for all mining personnel. This is because mine backfill failure not only has considerable financial ramifications, but can also result in several injuries and/or fatalities. Hence, the mechanical stability of CPB is a major safety concern in underground mining operations. The most important parameters used in practice to judge the mechanical stability of CPB structure include UCS (Fall et al. 2008). This is because the UCS test is relatively inexpensive and quick, and can be easily incorporated into routine quality control programs at the mine (Vergne 2000). The required UCS for the CPB in a typical underground mining operation is 0.7-2 MPa (Brackebusch and Shillabeer 1998). This UCS largely varies, depending on the dimensions of the CPB structure, application or function of the CPB and mine characteristics.

Binder consumption is the factor that has the most significant influence on the cost or economical performance of CPB. The binder can represent up to 75% of the cost of CPB (Grice, 1998).

Finally, the most important parameters affecting the environmental performance and durability of CPB are the fluid transport ability (e.g. permeability), cracking sensitivity and its microstructure (pore structure, porosity, pore size distribution, tortuosity and interconnectivity of the pore system). Susceptibility to AMD and ability to release contaminants into the mine areas and/or groundwater (after mine flooding) are relevant environmental design criteria for CPB structures. The sensitivity of CPB to AMD is strongly dependant on the reactivity (oxidation potential) of the tailings contained in the CPB. In turn, this reactivity is not only dependant on the types and quantity of sulphide minerals present in the CPB system, but also on the ease with which fluids (oxygen, water) enter and move through the CPB matrix, i.e. on the permeation properties of CPB. These permeation properties can be assessed from the knowledge of the hydraulic conductivity of the CPB. Furthermore, the hydraulic conductivity is one of the main parameters controlling the groundwater flow rate through the CPB structure, once it is flooded. In other words, it significantly affects the leaching potential and the transport of contaminants through the CPB to groundwater (Levens et al. 1996). Furthermore, it is widely accepted that the service life and durability of cemented materials are strongly influenced by their microstructure and/or the cracks present in the cemented materials. Since these parameters strongly influence the fluid transport properties (permeability, sorptivity, diffusivity) (ACI Committee 201 1977, Bentz et al. 2002) of any cemented materials. Aside from the microstructure, cracking of CPB material is a significant factor that needs to be considered in service life and durability evaluation of CPB

structures. It can allow and accelerate fluid transfer (oxygen, water) between the CPB and the surrounding media, thereby resulting in increased potential oxidation of the sulphide minerals contained in the tailings and reducing service-life (through sulphate attack). Cracks in the CPB are mostly caused by traction force (Orejarena and Fall, 2008). This means that the tensile strength gives a good indication of the ability of the CPB to resist cracking.

During the past fifteen years, main research efforts have been mostly spent on understanding the factors that affect the compressive strength development (e.g. Landriault 1995, Hassani and Archibald 1998, Archibald et al. 1998, Rankine et al. 2001, Kesimal et al. 2003, Fall et al. 2005a, Fall et al. 2008) of CPB. Despite the tremendous progress that has been made by the aforementioned studies in understanding the mechanical properties of CPB under compressive loads, a fundamental understanding of the effect of all influencing factors on the main performance (mechanical, hydraulic) properties of CPB is still far from complete. Most of the previous research were centered on the factors influencing UCS. Technical data on the tensile properties hydraulic conductivity and binder consumption of CPB is quite limited. Furthermore, until recently, most of the studies were carried out on CPBs cured at "laboratory" curing temperatures (20-25°C). This means that the impact of colder or warmer temperatures on the performance properties (mechanical, hydraulic, binder consumption, microstructural) of CPB is still not well understood.

Recent studies (Fall et al., 2005, Fall and Samb, 2006) revealed that the curing temperature significantly affects the strength and pore structure of CPB at the early ages (≤ 28 days). However, these studies only focus on the short-term properties of CPB, and only limited CPB mixtures are tested. This means that no information about the UCS and deformation behaviour at advanced ages as well as about the tensile properties of CPB at any ages is gained. The coupled effects of curing temperature and CPB mix components on CPB properties are also not addressed in the aforementioned studies. Thus, there is an urgent need to substantially increase our knowledge about the impact of curing temperatures on the performance properties of CPB, since every single underground mine and backfill structure is unique regarding temperature conditions. Hence, a research program is conducted at the University of Ottawa to study the effect of curing temperature on the mechanical and durability properties of CPB.

The main objectives of this paper are:

- to present and discuss the results of the experimental evaluation of the impact of curing temperature on the mechanical properties (uniaxial compressive strength, split tensile strength) properties of CPB,
- to present and discuss the results of the experimental evaluation of the impact of curing temperature on saturated hydraulic conductivity of CPB,
- to develop a basic understanding of the mechanical and hydraulic properties when exposed to different curing temperature conditions.

This paper is organized as follows: The materials used and experimental tests conducted are first presented. After that, the results of the effect of curing temperature on the mechanical properties of CPB are presented and discussed. This is followed by the presentation of the effect of temperature on the hydraulic conductivity of CPB. Finally, we will present our conclusions.

4.4 Materials and experimental program

4.4.1 Materials used

The materials used included binders, tailings, and water.

Binders

The most common binder used in the preparation of CPB is Portland cement (PC). However, due to the relatively high costs of PC, other by-products commonly designated as mineral admixtures (e.g. blast furnace slag (Slag), fly ash (FA)) are often substituted for PC in various amounts to produce blends of lower costs. Hence, PCI and Slag, were used as binders. PC I was used alone or blended with Slag. The blending ratio of PC I and Slag was 50/50. These binders are often used for CPB mixtures in mines located in eastern Canada.

Tailings

Artificial tailings were used in this study. Industrial silica sands, SI with 45% per weight passing the 20 micron diameter were used as basic tailings materials. The silica tailings, SI, show a grain size distribution (Figure 4-1) close to the average of 9 mine tailings (coming from eastern Canada). The use of silica tailings allows controlling with accuracy, the mineralogical and chemical compositions of the tailings. Indeed, natural tailings contain several chemical elements and often sulphide minerals (they oxide and produce sulphate during contact with oxygen) that can interact with the cement and thus affect the interpretation of the results as well as the outcome of this study. Table 4-1 and Table 4-2 give the main physical and chemical characteristics of the tailings. SI can be classified as medium tailings.

Table 4-1. Physical properties of the tailings

Element	G_s	D_{10}	D_{30}	D_{50}	D_{60}	D_{90}	C_u	C_c
unit	-	μm	μm	μm	μm	μm	-	-
SI	2.7	1.9	9.0	22.5	31.5	88.9	16.2	1.3

Ss: specific surface; G_s : Specific gravity; C_u : Coefficient of uniformity; C_c : Coefficient of curvature.

Table 4-2. Main chemical elements in the tailings

Element	Al	Ca	Si	Fe	Na	Pb	S	Zn
unit	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %
SI	0.1	<0.01	99.8	<0.01	<0.01	0.0	0.0	0.0

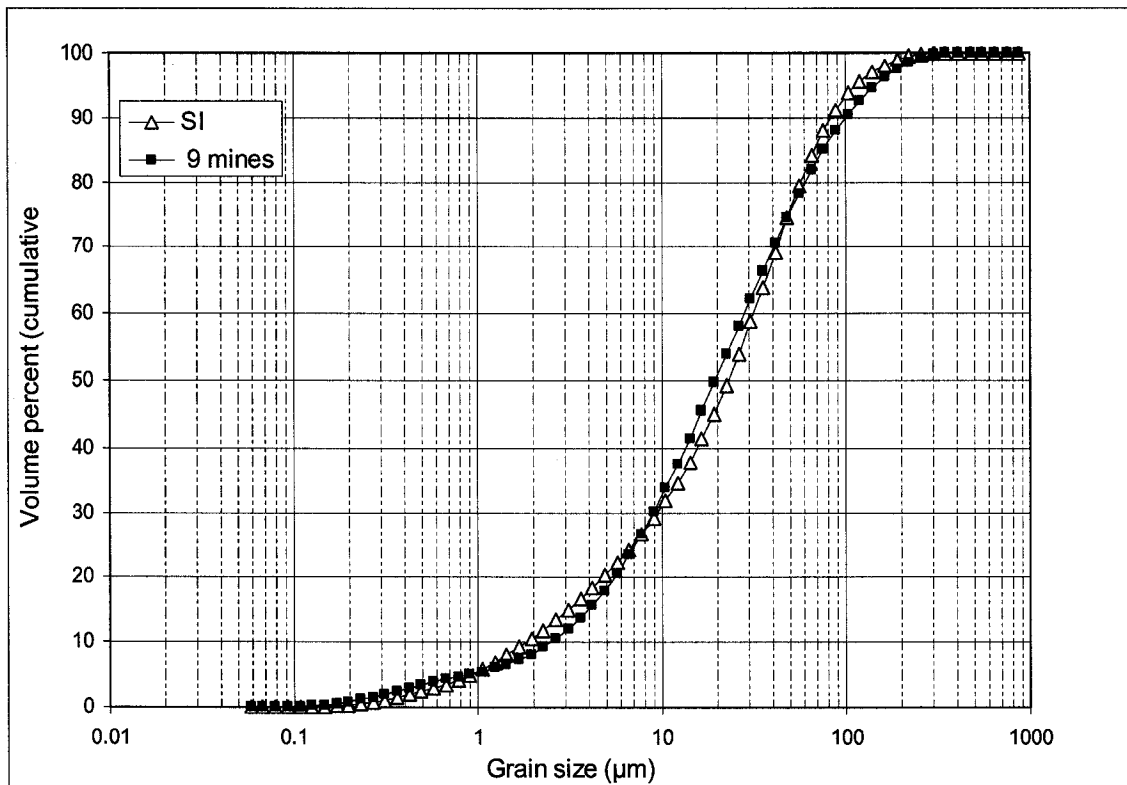


Figure 4-1. Grain size distribution of the tailings used (SI) and the average grain size distribution of tailings from 9 eastern Canadian mines

Water

Tap water was used to mix the binders and tailings.

4.4.2 Specimen preparation and mix proportions

CPB specimens with different binder contents, binder types, W/C and tailings with different particle sizes (by mixing SI with an artificial tailings containing 20% particle with size lower than 20 μm) were prepared. The tailings materials, binders and water were mixed and homogenized until obtaining a homogeneous paste. Then, the consistency of the paste mixtures was measured by the slump test in accordance to ASTM C 143-90. The produced CPB mixes were poured

into curing cylinders, 5 cm in diameter and 10 cm in height. The specimens were then sealed (this avoids the evaporation of water) and cured in environmental chambers at specific curing temperatures of 2°C, 20°C, 35°C and 50°C for periods of 1, 3, 7, 14, 28, 90 and 150 days. After the specific curing times, the CPB samples were subjected to various tests (mechanical, microstructural tests). Table 4-3 shows the CPB mixtures prepared for studying the effect of curing temperatures on the performance properties of CPB. More details about the mixes prepared will be given in Section 4.5.

Table 4-3. Mixes prepared for UCS tests, split tensile tests and hydraulic conductivity tests.

UCS

	Temperature (°C)	Curing time (days)
Binder content % 2, 4.5, 6	2, 20, 35, 50	7, 28, 90
Binder type PCI, PCI/slag		
Grain size 25, 35, 45 (<20µm)		
W/C 5, 7.6, 10		

Split tensile

	Temperature (°C)	Curing time (days)
Binder content % 2, 4.5, 6	2, 20, 35, 50	3, 7, 28, 90
Binder type PCI, PCI/slag		
Grain size 25, 35, 45 (<20µm)		
W/C 5, 7.6, 10		

Hydraulic conductivity

	Temperature (°C)	Curing time (days)
Binder content % 2, 4.5, 6	2, 20, 35, 50	1, 3, 7, 28, 90
Binder type PCI, PCI/slag		
Grain size 45 (<20µm)		
W/C 7.6		

4.4.3 Testing of specimens

4.4.3.1 Mechanical tests

Uniaxial compression (ASTM C39) and split tensile tests (ASTM C496) were performed on the CPB specimens. The specimens were tested using a computer-controlled mechanical press. The press has a normal loading capacity of 50 kN. The compressions tests were carried out at a constant deformation rate of 1 mm/min. All data regarding the test were collected by using a computerized data logging system. The results were monitored and saved by using the computer software LabView.

4.4.3.2 Hydraulic conductivity tests

Saturated hydraulic conductivity tests were conducted at all time periods of 0, 1, 7, 28 to 90 days at curing temperatures of 2 °C, 20 °C, 35 °C and 50 °C. Even in the early ages (0, 1, 3 and 7 days), a rigid wall permeameter in falling head mode following ASTM D 5856-00 was used. This method proved impractical for advanced age (28, 90 days) sample testing. During these periods, the hardened

samples required a higher hydraulic gradient to become infiltrated by the permeant. Another difficulty arose with the requirement of destructing the cell after testing as the hardened paste was almost impossible to be removed from the permeameter cell. As at least 36 tests had to be conducted in these conditions, therefore, the choice of a flexible wall technique was addressed. The procedure for this method is described in ASTM D5084-00 and was conducted in the constant head mode.

4.5 Results and discussions

4.5.1 Relationship of curing temperature to compressive strength development of CPB

The influence of curing temperature on the strength development of CPB at early ages is illustrated by Figure 4-2 and Figure 4-3. In Figure 4-2, the early age strength of CPB made of PC is plotted against the curing temperature (7 and 28 days), while Figure 4-3 illustrates the impact of curing temperature on the early age strength of CPB containing Slag. From these figures, it is obvious that the curing temperature has a significant impact on the rate of gain in strength and the early age strength of CPB. The results show that the UCS increases as the curing temperature increases. The reason for this is that a higher temperature accelerates the binder hydration. Indeed, the amount of hydration products (e.g. calcium-silicate-hydrate or C-S-H, portlandite or CH, calcite) increases with the temperature. This is beneficial for CPB strength gain, since C-S-H is considered to be the major binding phase in hardened cement (Taylor 1964, Gani 1997). This higher amount of hydration product, such as C-S-H, and CH associated with higher curing temperatures, is demonstrated by the results of different thermal analyses performed by Fall (2008) on 7 day old cement pastes of CPB cured at 20°C and 35°C, respectively (Figure 4-4). Figure 4-4 presents the DTG/DTA diagram of cement pastes of CPB made of PC. The DTA locates the ranges corresponding to thermal decompositions of different phases in paste, while DTG simultaneously gives the weight loss due to these decompositions. This figure

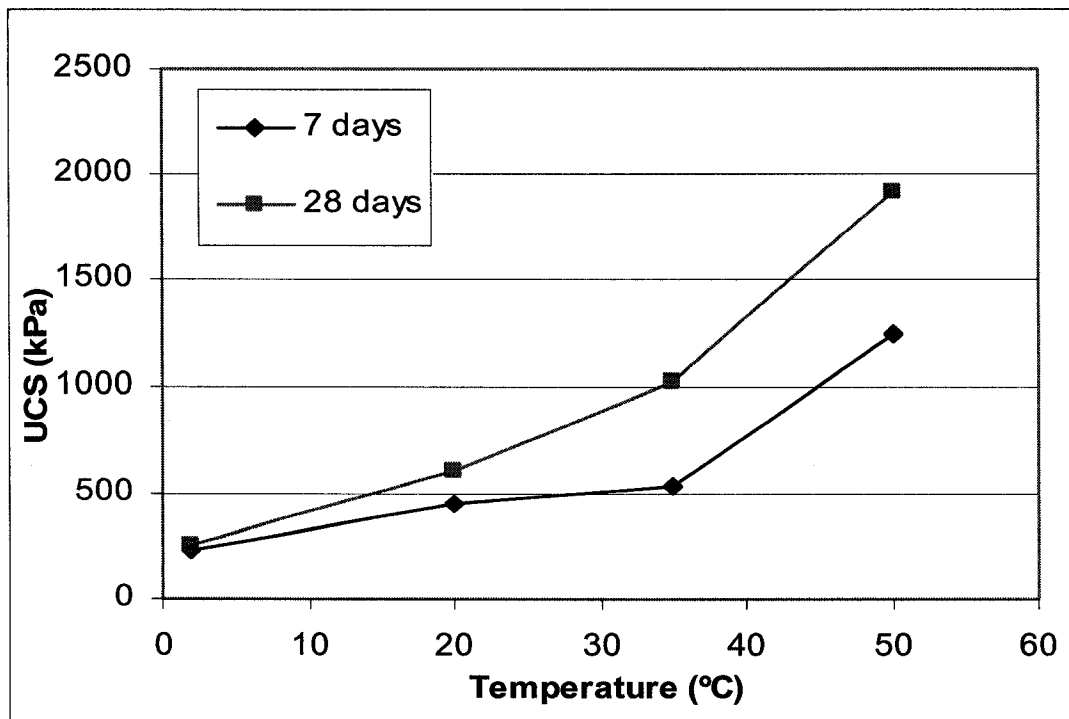


Figure 4-2. Effect of curing temperature on the early age UCS development of paste backfill cemented with PCI (slump ~ 18 cm)

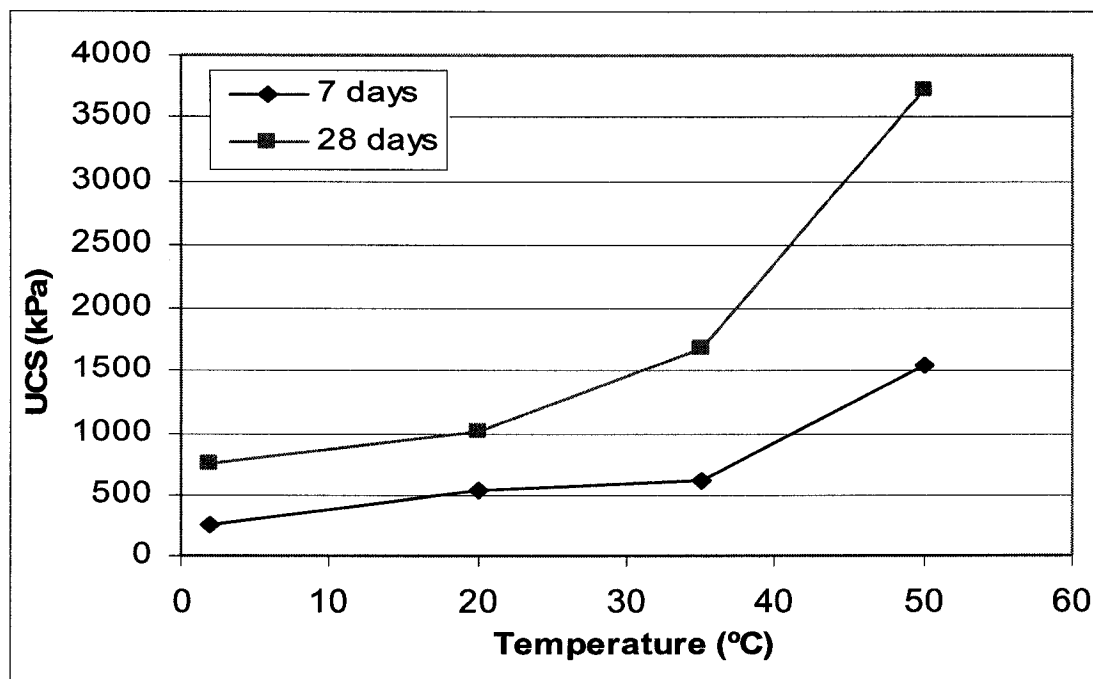


Figure 4-3. Effect of curing temperature on the early age UCS development of paste backfill cemented with PCI/Slag (50/50) (slump ~ 18 cm)

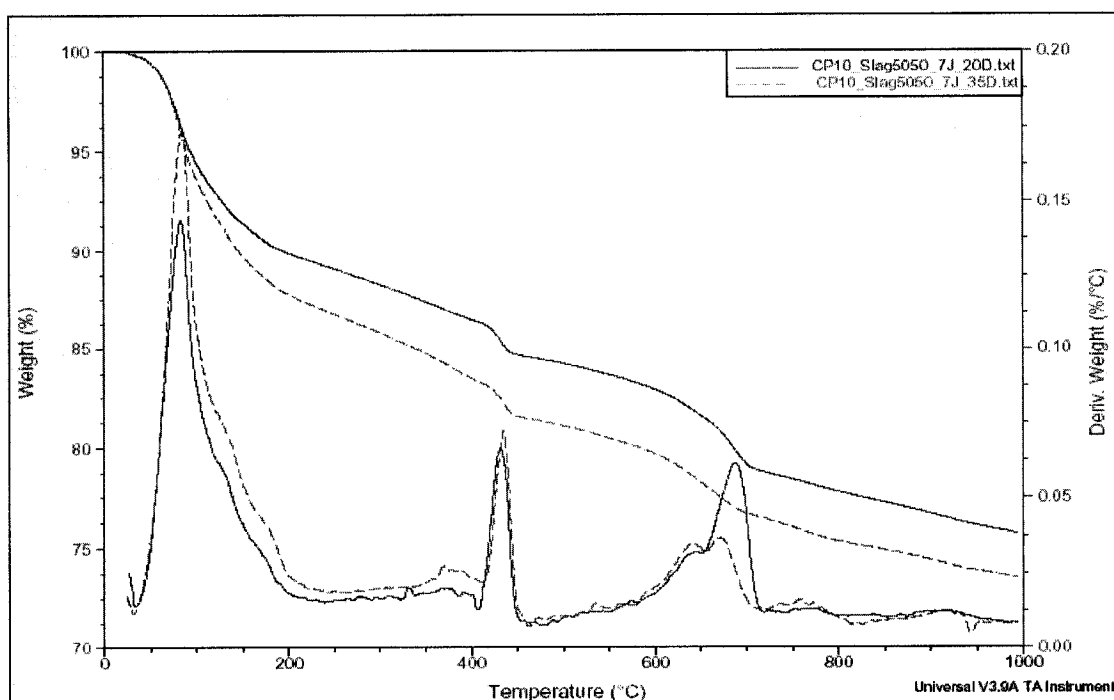
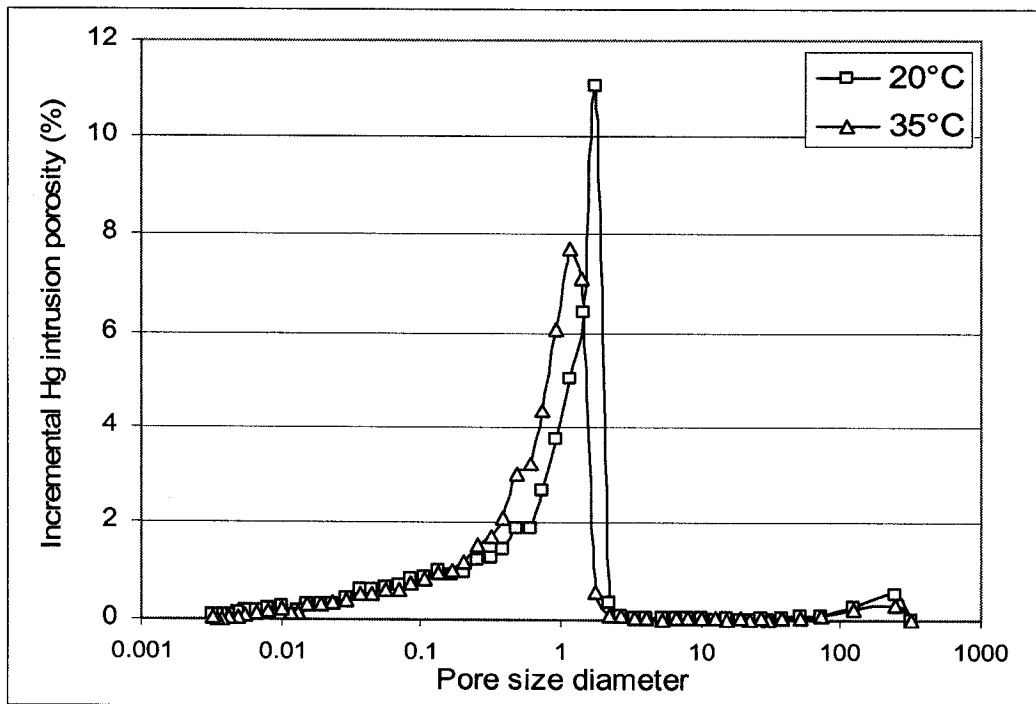


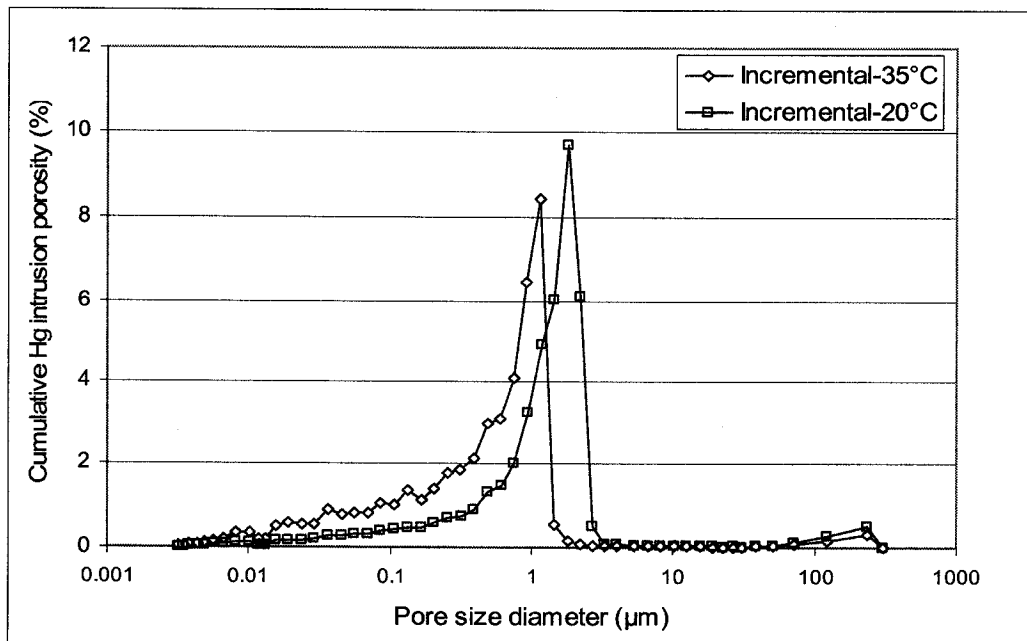
Figure 4-4. TG/DTA diagrams for 7-day-old cement pastes of CPB cured at different curing temperatures (20°C and 35°C; Fall 2008)

shows globally, three main endothermic peaks associated with rapid weight loss and major phase transformations. The first peak or weight loss, located between 100 °C and 200°C, results from the dehydration reactions of the hydrates, such as C-S-H, carboaluminates, ettringite, and gypsum. Indeed, according to Anderberg (1997), Zhou and Glasser (2001), the decomposition of gypsum (with a double endothermal reaction) Anderberg (1997), Nounowé (1995), decomposition of ettringite and loss of water from part of the carboaluminate hydrates (Zhou and Glasser 2001), take place in the temperature range of 110–170°C while previous studies (Khoury 1992, Anderberg (1997), Nounowé (1995), Zhou and Glasser 2001) showed that at 180–300°C, the weight loss is mainly due to the loss of bound water from the decomposition of the C-S-H. The second

main peak or major weight loss, observed at 400–500°C, is the result of the dehydroxylation of CH. Finally, the third weight loss occurs at a temperature range between 650 °C and 750°C. This loss is attributed to the decomposition of calcite (CaCO_3) Anderberg (1997), Nounowé (1995). The comparison of the DTG/DTA diagrams of the cement pastes cured at 20°C and 35°C shows that the endothermic peaks or weight losses are higher for cement paste cured at 35°C. This suggests that the amount of hydration products formed increases with the curing temperature. An additional factor should be suggested as a contributor to the temperature induced strength increase of CPB at early ages. This factor is the refinement of the pore structure of CPB with higher curing temperature because of the larger precipitation of hydration products. This is graphically demonstrated by the results of MIP tests performed by Fall (2008) on 7 and 14 day old CPB samples made of PCI (Figure 4-5a) and PCI/Slag (20/80) (Figure 4-5b), respectively, and cured at 20°C and 35°C, respectively. From Figure 4-5, it can be clearly observed that the CPB cured at hotter temperature (35°C) has a denser microstructure with a finer distribution of the pores than the CPB cured at room temperature (20°C).



a)



b)

Figure 4-5. MIP pore size distribution of CPB with a) 4.5% PCI vs. curing temperature after 7 days of curing (W/C~7.5; slump~18 cm; Tailings: TA) and b) 7% PCI/Slag (20/80) vs. curing temperature after 14 days of curing (W/C~5.0; Tailings: TA) (Fall 2008)

From Figure 4-2 and Figure 4-3, it can be also noticed that the lowest values of UCS are observed for CPB cured at cold temperatures (2°C) regardless of the binder used. This is because a low temperature inhibits cement hydration, thereby resulting in lower amounts of C-S-H, CH, and ettringite in the CPB sample. Similar observations were made on conventional concrete by McIntosh (1956). A comparative analysis of Figure 4-2 and Figure 4-3 reveals that the effect of curing temperature on the UCS of CPB at early ages is strongly affected by the type of binder used. From these Figure 4-2 and Figure 4-3, it is obvious that the rate of gain in strength and increases in strength of CPB mixtures containing Slag and PC mix (in the weight ratio 50/50) exceed those observed for CPB mixtures made using only Ordinary Portland cement (OPC). These results suggest that curing at elevated temperature gives a more significant contribution to (Slag) pozzolanic reaction than that to OPC hydration. This is because hydration of Slag is much more sensitive to temperature than PC. Indeed, higher temperatures lead to the increase of the hydration reaction of PC, and thus the formation of C-S-H and CH. The Slag admixture reacts with the CH in varying degrees. Consequently, extra C-S-H is produced. This is positive for the CPB strength development. These results then imply that in the case of hot curing temperatures ($>20^{\circ}\text{C}$), the partial replacement of OPC by Slag increases the compressive strength of CPB (up to 28 days).

The results presented above with respect to the effect of hot temperatures on the early age strength of CPB may have significant practical applications. Indeed, a

high rate of early backfill strength gain achieved in an economical manner is a target for all in the mining industry. Early strength gain is of special importance for opening of the barricades, scheduling the extraction of adjacent stopes and thus, reduction of the mining cycle time, hence increasing mining efficiency and production. This is obviously associated with economical benefit for mines. Furthermore, this high early age strength gain may play a significant role in reducing the potential for CPB liquefaction at early age of cure and thus decreasing barricade failure risk. This is because the binder hydration product is able to create bonds between individual tailings particles of the CPB and provides strength.

However, not only is the early age mechanical stability (i.e. early age strength) of CPB structure a key design factor, but also in several cases, the long term mechanical stability (i.e. the strength for long term) of the CPB structure must be satisfied to ensure the safety of the mine workers. For example, the strength of CPB in the primary stopes must be sufficient enough to ensure the stability of the backfill mass as the remnant pillars are mined as secondary stopes. For this reason, the effect of curing temperature on the strength of CPB at advanced ages is evaluated. About 150 CPB samples with different compositions were prepared and cured at different temperatures (2°C to 50°C) and at 90 days. To illustrate the influence of curing temperature on the development of CPB strength at advanced curing times, the CPB strength is plotted against curing time (90 days) for different curing temperatures (Figure 4-6). Figure 4-6 shows the effect of curing temperatures on the strength of PC-CPB and Slag-CPB at advanced

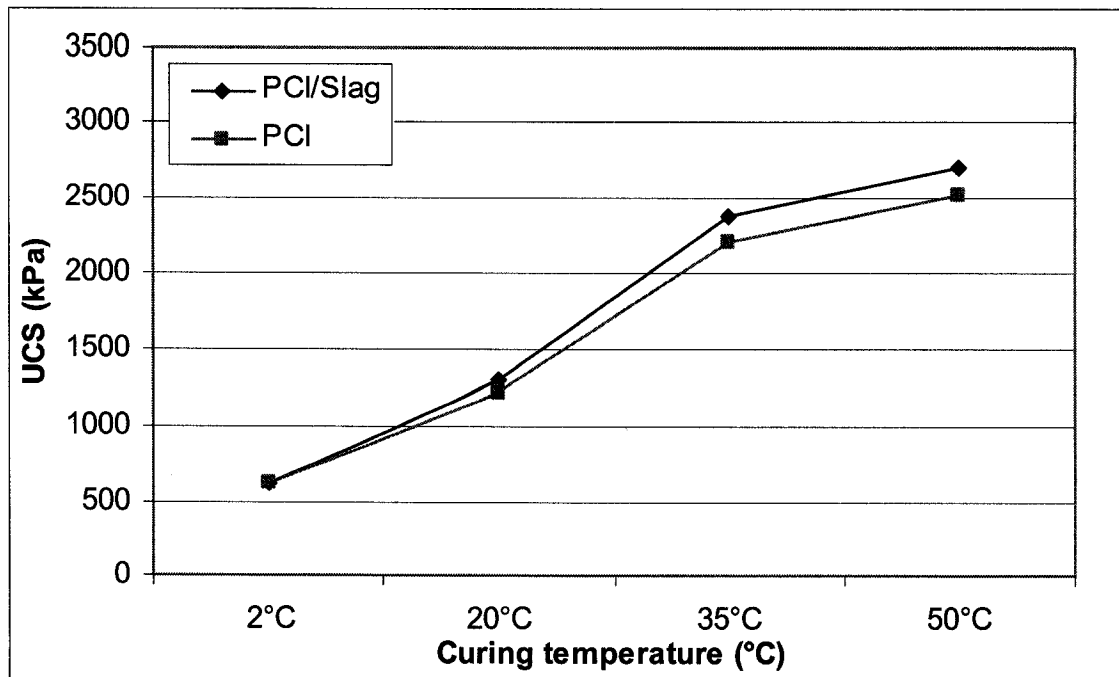


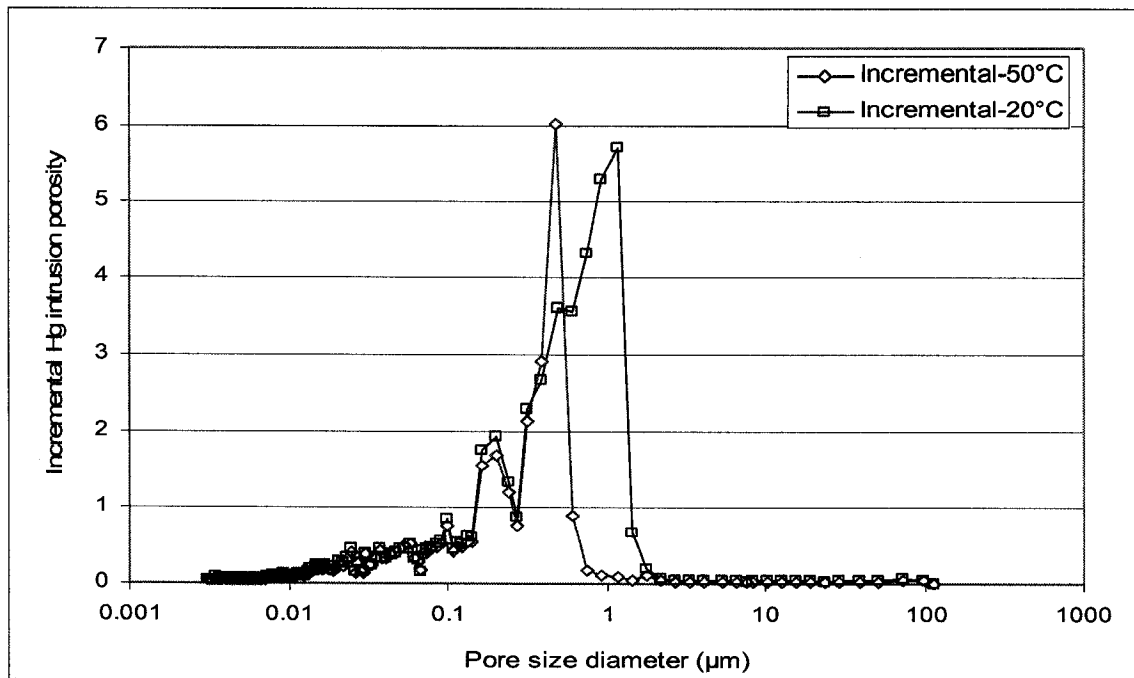
Figure 4-6. Effect of curing temperature on the development of the long term strength of PC-CPB and Slag-CPB (slump ~ 17 cm; %cement =4.5%)

curing times (90 days). From this figures, it can be seen that regardless of the type of binder (PC or PCI/Slag in ratio 50/50), the strength of CPB increases with the curing time (90 days) and curing temperature. This increase in strength can be attributed to the continuous hydration of unhydrated cement components with time and the formation of secondary C-S-H from pozzolanic reaction (for Slag-CPB). The CPB specimens cured at 2°C show lower strength than those cured at higher temperatures. The lowest strength values were given by the Slag-CPB cured at 2°C. This can be explained by the fact that this temperature is too low to favour the hydration of the Slag, which makes only a small contribution to the overall compressive strength at this age (Escalante-Garcia and Sharp, 2001).

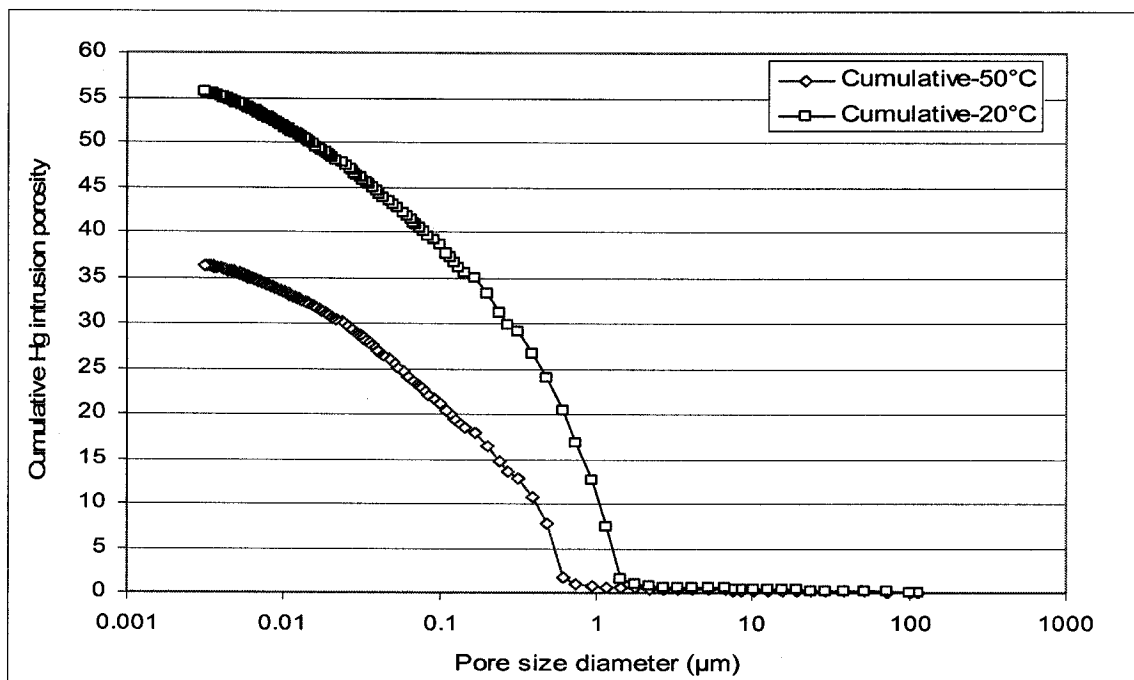
This is consistent with the well known fact that at low temperatures, the Slag has a reduced reactivity.

From Figure 4-6, it is interesting to notice that up to 90 days of curing time, the studied PCI-CPB and Slag-CPB samples do not show any high temperature inversion in the compressive strengths as commonly observed in conventional concrete and mortar materials. This phenomenon of temperature inversion in the compressive strength of conventional concrete and mortar materials has been the subject of much attention in the last decades. It is called the “crossover effect” (Alexander and Taplin, 1962). Several researchers reported that the “crossover effect” is mainly attributable to the fact that high initial curing temperature generates coarser pore structure of the concrete material (Kjellsen et al. 1991, Escalante-Garcia and Sharp, 2001) at advanced ages and reduces the ultimate degree of hydration of the anhydrous cement phases (Brooks and Kaisi 1990, Ma W 1994, Verbeck and Helmuth 1969). This coarser pore structure with higher curing temperature observed on conventional concrete and mortar is explained by many researchers (e.g. Alexander and Taplin 1962, Kjellsen and Carino 1981) as resulting from the physical effect of the temperature and the non uniform distribution of cement hydration products. Indeed, as the curing temperatures increase, water and void inside the concrete increase. When the initial stress resulting from this phenomenon is higher than the tensile strength, microcracks form and/or coalesce, voids increase, and the strength of concrete or mortar decreases (Alexander and Taplin 1962, Carino 1981). The reduced ultimate degree of hydration of the anhydrous cement phases is caused by the

retarding effect of the shell on the diffusion of the hydrate in the secondary reaction of cement hydration (Alexander and Taplin 1962, Carino 1981). Due to their low solubility and diffusivity, cement hydration products will not be able to diffuse to a significant distance from the cement grain in the time allowed by rapid hydration. Thus, elevated hydration temperatures will result in a highly non-uniform distribution of the solid phases (Kjellsen et al. 1990). The dense hydration products around the cement grains serve as diffusion barriers, slowing or even effectively preventing further hydration (Kjellsen et al. 1990). In order to verify the applicability of the aforementioned mechanism of coarsening of the pore structure in concrete or mortar with higher curing temperatures for CPB, MIP tests results obtained by Fall (2008) on 160 day old CPB samples cured at 20°C and 50°C were analyzed. Figure 4-7 shows the influence of hot temperatures on pore size distribution (Figure 4-7a) and porosity (Figure 4-7b) of CPBs at advanced cure ages (160 days). These figures underline that hot curing temperatures have a significant impact on the pore structure (pore size distribution and porosity) of CPB at advanced ages. However, contrary to conventional concrete and mortar materials, higher curing temperatures (20°C to 50°C) lead to refinement of the pore structure of studied CPB at advanced ages (up to 160 days). From these figures, it can be observed that the porosity and coarseness of the pore structure and proportion of macropores in the CPBs decrease with higher curing temperatures. This refinement of the pore structure of the CPB with higher curing temperature can be considered as an additional cause of the increase in strength of the CPB with the curing time and curing



a)



b)

Figure 4-7. a) MIP pore size distribution and b) MIP cumulative porosity of CPB with 7% PCI/Slag (20/80; W/C=5;) vs. curing temperature after 160 days of curing (Fall, 2008)

temperature observed in Figure 4-6. The absence of a crossover effect on PCI-CPB samples cured up to 90 days is an important finding. This finding suggests that the effect of a high initial curing temperature on the strength development of PCI-CPB or Slag-CPB is not fully similar to that on conventional PC concrete and mortar materials. Most of the PC concretes cured at high temperatures show a drop in their strength or strength inversion after 28 days of curing time. Lack of drop in strength of PCI-CPBs and Slag-CPB cured at high temperatures ($\geq 35^{\circ}\text{C}$) up to 90 days may be due to the high W/C (7.6 in Figure 4-6) used in the preparation of CPB. This high W/C ratio results in a "dilution effect" with respect to the cement in CPB system, since there is more water to react in the cement of CPB than in the cements of conventional concrete. In turn, this dilution effect in CPB system will allow the cement particles to be surrounded by more water, thereby favouring the diffusion of the cement hydration products to a significant distance from the cement grains. This will result in more homogeneous distribution of the binder hydration products than in conventional concrete (where the W/C ratios are usually 0.4-0.6). This can lead to a delay or even preventing the drop of the long term strength of PCI-CPB and Slag-CPB. An additional mechanism can be suggested to explain this non drop or inversion of strength of the CPB cured at high temperatures ($\geq 35^{\circ}\text{C}$) up to 90 days. This mechanism is contrary to concrete or mortar, the hardening processes within the CPB system is not only caused by the cement hydration, but also by the precipitation of hydrated

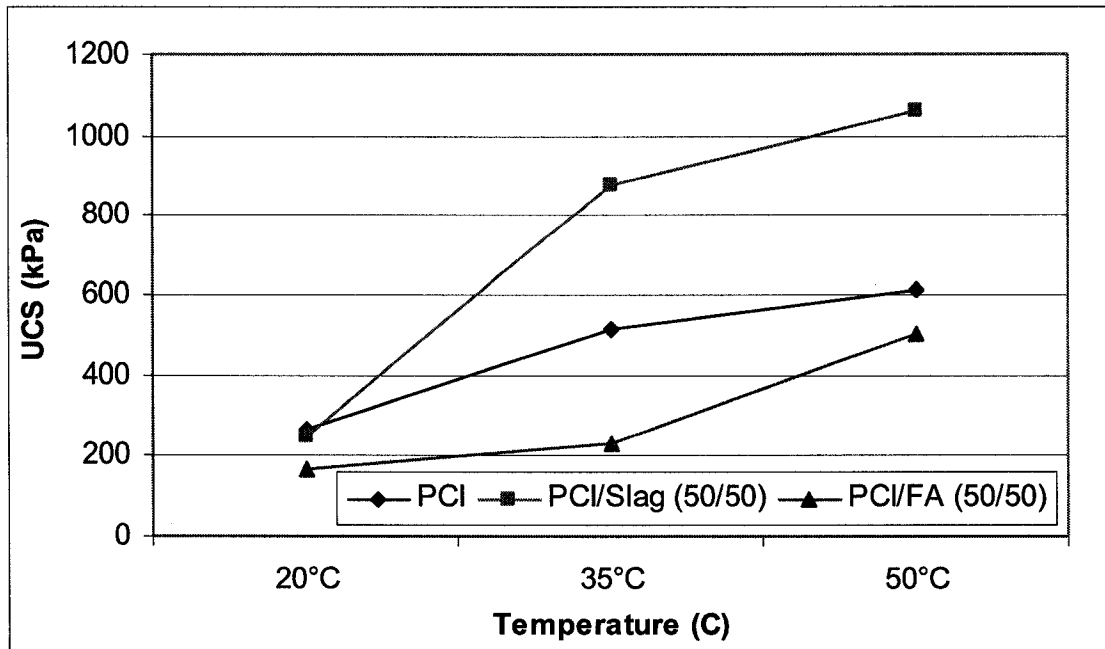
phases from the pore water of the paste as reported by Benzaazoua et al. (2003).

The findings regarding the effect of curing temperature on the long term strength (up to 90 days) of CPB presented above suggest, for curing times less than 90 days, high curing temperatures ($\leq 50^{\circ}\text{C}$) lead to higher CPB strength. This can result in a more economical design of CPB structures. However, it should be mentioned that the CPB strength may decrease for curing times higher than 90 days. Furthermore, it should be noticed that the mix components of CPB vary from one mine to another, and one CPB to another. These components can significantly affect the UCS of CPB (e.g. Hassani and Archibald 1998. Yilmaz et al. 2005, Fall et al. 2008). This gives rise to the following question: what are the combined effects of curing temperature and mix components on the UCS of CPB? These questions are answered in the following section.

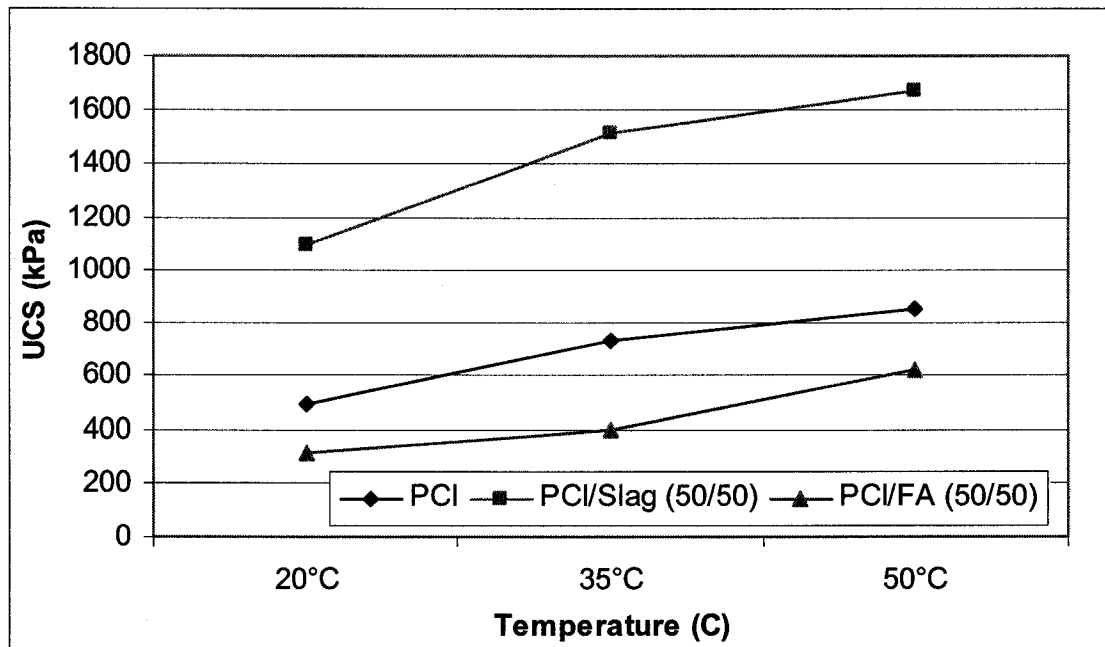
4.5.1.1 Combined effects of curing temperature and mix components on UCS development of CPB

In recent years, blended cements (PCI blended with mineral admixtures such as Slag and FA) have been increasingly used as a binder in CPB. Advantages that accompany the use of blended cement include savings in PC consumption (cost reduction of CPB) and improvement in durability of the CPB. Hence, additional laboratory tests were performed to study the mechanical response (UCS) of CPB samples made of PCI, PCI and Slag as well as PCI and FA in a proportion of

50/50. The main results are presented in Figure 4-8 (Figure 4-8a, Figure 4-8b). Figure 4-8a and Figure 4-8b highlight the effect of curing temperature on the strength of paste backfill cemented with PCI, PCI/Slag (50/50), and PCI/FA after 7 days and 28 days of curing respectively. From these figures, it can be observed that the strength of PCI-CPB and Slag-CPB increases with the curing temperature. The Slag-CPB shows the highest rate of gain in strength. The mechanisms responsible for the aforementioned increase in strength of CPB and highest rate in gain of strength for Slag-CPB with curing temperature are explained in the previous section. The strength of FA-CPB increases with the curing temperature. However, test results show that the FA significantly contributes to reducing the compressive strength of CPB at all curing temperatures (20°C, 35°C and 50°C). The reason for this disappointing compressive strength development of FA-CPB is that the FA blended cement CPB requires an extended curing time in order to take advantage of the beneficial effects of the pozzolanic activity and pore refinement. This observation is consistent with the previous conclusions of several researchers (e.g., Diamond et al. 1989, Xu 1992, Taylor 1992, Xu et al. 1993) who also observed that the hydration of most types of FA only starts after a substantial curing period. However, it should be emphasized that as underlined by many authors (e.g., Maltais and Marchand 1997), the FA/cement reaction processes significantly depend on the chemical and physical properties of FA. These properties tend to differ markedly from one source to another. Even within one source, individual grains are highly variable in nature (Maltais and Marchand 1997).



a)

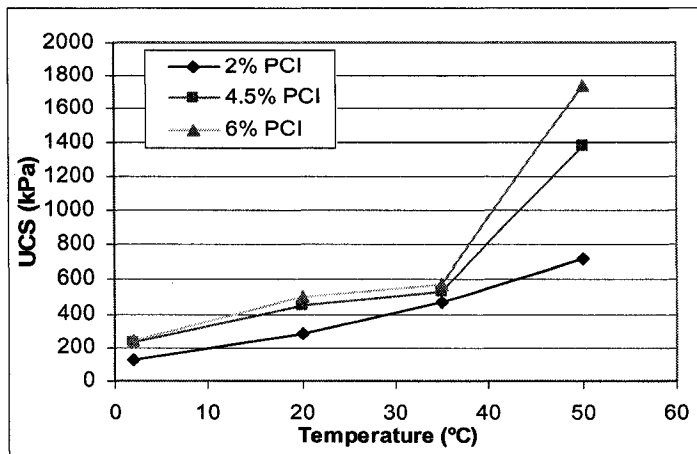


b)

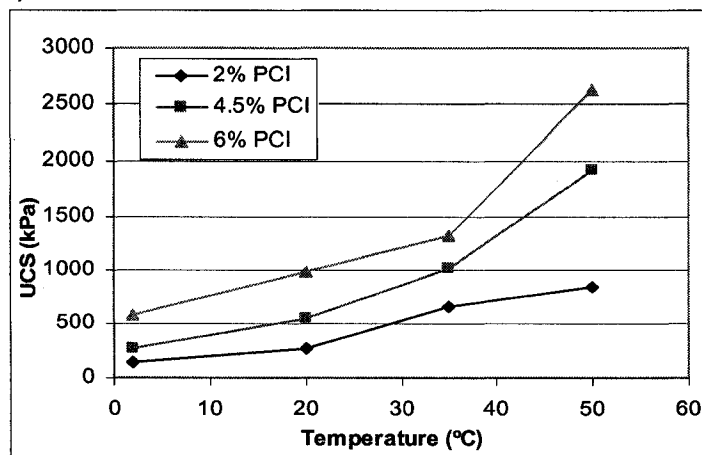
Figure 4-8. Effect of curing temperature on the strength of CPBs made of various types of binders after a) 7 days and b) 28 days of curing (slump~18).

4.5.1.2 Combined effects of curing temperature and binder proportions on UCS development of CPB

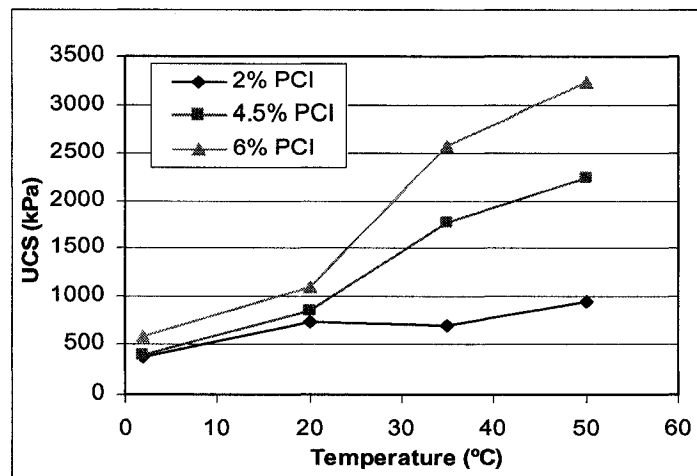
Since CPBs are usually prepared with binder proportions varying from 2% to 7%, about 75 CPB samples containing 2%, 4.5% and 6% of PCI (Table 4-3) are prepared at constant slump (18 cm), cured at various temperatures (2°C, 20°C, 35°C, 50°C), and tested with regards to UCS. The results of these tests are presented in Figure 4-9. As expected, it can be seen from these figures that regardless of the curing time, the trends of strength development show clearly that samples prepared with a higher binder proportion develop higher UCS. This is because higher binder content is associated with the presence of more cement reagents (C_3S , C_2S , C_3A) in the mix and thus, with precipitation of more cement hydration products (e.g. C-S-H, CH). It is interesting to notice that the CPB with 2% cement and cured at 35°C shows almost the same compressive strength as the CPB with 4.5% cement and cured at 20°C, and a higher compressive strength than CPB containing 4.5% or 6% cement and cured at 2°C for all curing times. This is an important finding with regards to reducing the cost of CPB.



a)



b)



c)

Figure 4-9. Combined effects of curing temperatures and binder content on UCS of PCI-CPB at a) 7 days b) 28 days c) 90 days curing (W/C~7.6; slump~18 cm; Tailings: TS-1).

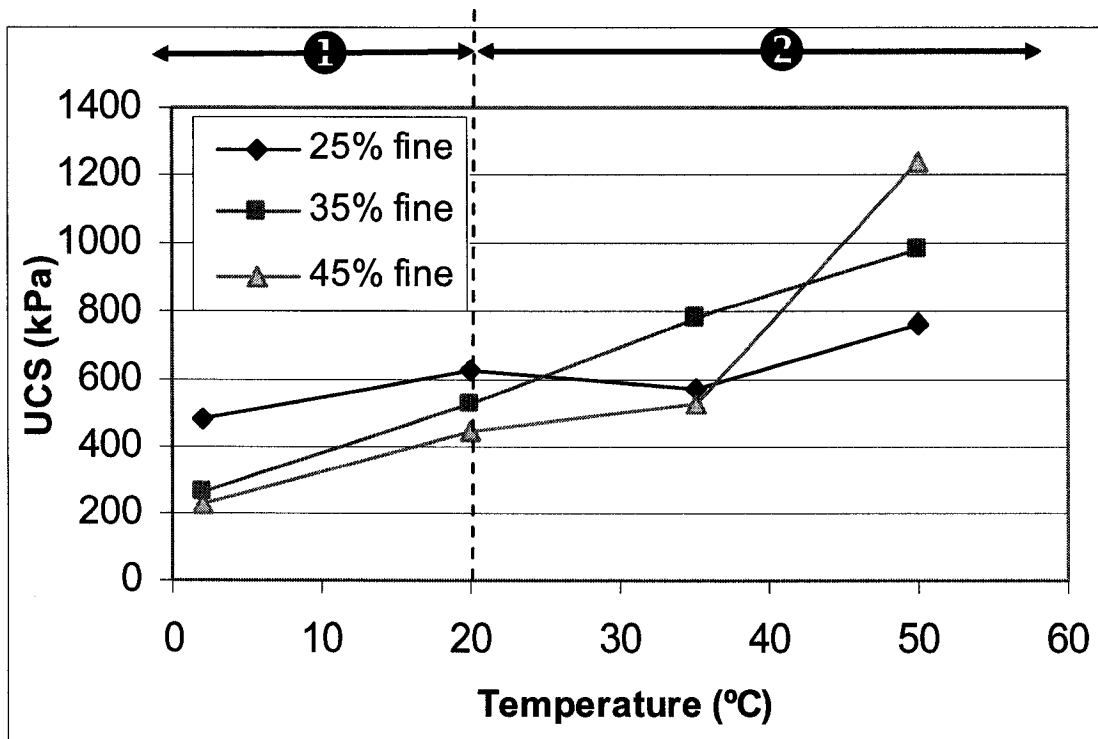
4.5.1.3 Combined effects of curing temperature and tailings fineness on UCS development of CPB

Tailings are one of the most important components of CPB. Tailings particle grain size plays an important role in CPB strength development as it controls the void space within the CPB and therefore, the porosity (Fall et al. 2005a). However, the grain size distribution of the tailings used in preparation of CPB materials can vary from one mine to another or CPB to another. Depending on the processed ore, different tailings grain size distribution may be obtained. It may also be possible to combine the tailings with other sands of different sizes to affect the coefficient of uniformity C_u and the coefficient of curvature C_c to improve compressive and tensile strength (Fall and Benzaazoua 2005) for cemented backfill. According to Landriault (1995), most mine tailings in the world will fall into three approximate tailings size distributions (coarse, medium and fine) for CPB mix design. Coarse tailings contain between 15 % and 35 % (by weight) of 20 μm particles, medium tailings have between 35 % and 60 % (by weight) of 20 μm particles and fine tailings contain 60 % to 90 % finer than 20 μm . Fine tailings are not very suitable for CPB mix design because they confer to the CPB, a lower strength than CPB made of coarse and medium tailings (Fall et al. 2005). Additionally, a CPB mixture requires 15 % to 20 % proportion of tailings particles finer than 20 μm to achieve sufficient colloidal water retention to create paste flow properties (Landriault, 1995; Brakebusch, 1994). Hence, the coupled effects of curing temperature and tailings grain size (tailings fineness) on the UCS

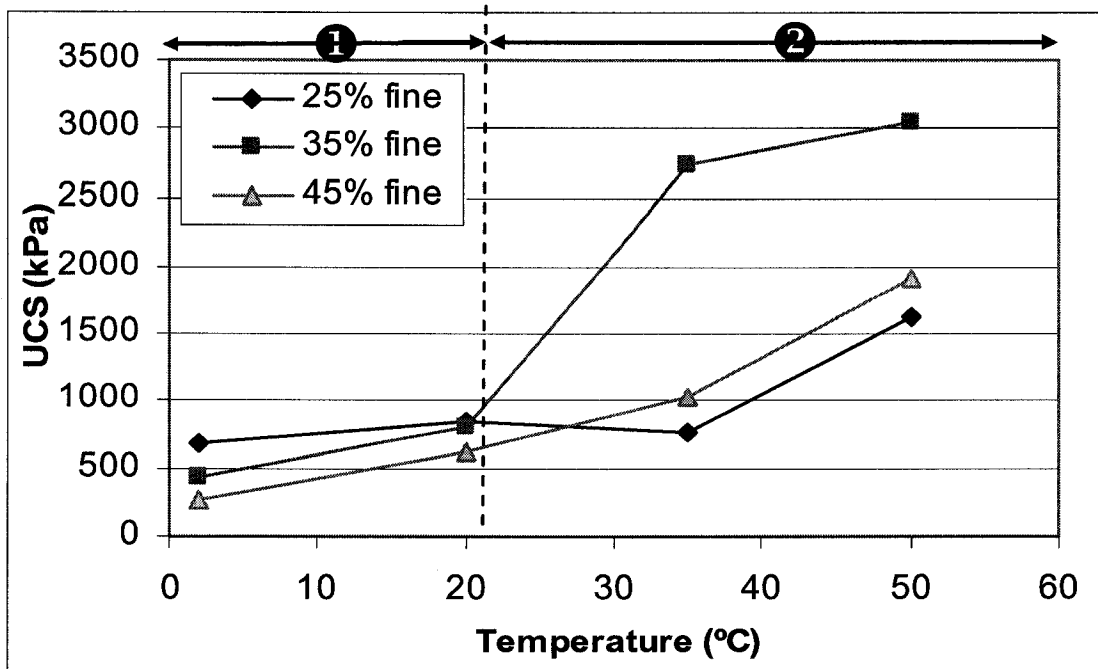
development of CPB were investigated. To obtain tailings particle size distributions belonging to the above coarse and medium tailings size distribution categories as well as to create a tailings material containing at least 15 % to 20 % particles finer than 20 μm , the tailings TS-1 (45%>20 μm) and TS-2 (20%>20 μm) were mixed in various proportions. This allows the fabrication of tailings with 25%, 35% and 45% of particles finer than 20 μm . Then, around 50 CPB samples were prepared with the fabricated tailings at constant slump (18 cm) and subjected to four environmental temperatures (2°C, 20°C, 35°C and 50°C). Their strength development at 7 and 28 days is presented in Figure 4-10a and Figure 4-10b, respectively. From these figures, it is obvious that not only the isolated effect of tailings fineness and curing temperature on the strength development of CPB is significant, but also the interaction between tailings fineness and curing temperature significantly affects the strength development of CPB. Since the mechanisms responsible for the isolated effect of tailings fineness and curing temperature on the UCS development of CPB are already explained in Fall et al.(2004, 2005b), and in the previous section, respectively, in the interest of brevity, only the coupled effects of tailings fineness and curing temperature will be discussed below. The results presented in Figure 4-10 clearly indicate that the coupled effects of tailings fineness and curing temperature can be globally classified into two domains for the given tailings fineness. For low curing temperature ($\leq 20^\circ\text{C}$), i.e. in the first domain (❶), the CPB strength decreases with the fineness of the tailings material. The reason is the fact that increasing the tailings fineness leads to a higher volume of void spaces between the tailings

particles available for cement hydration products. This contributes to increasing the overall porosity of the hardening cement matrix and thereby, decreasing the strength. This assumption is supported by the experimental results presented in Figure 4-11 obtained by Fall et al. (2004). This figure presents the results from studies on the influence of tailings fineness on the overall porosity and void ratio of CPB cured at room temperature ($\sim 20^{\circ}\text{C}$). It can be observed that finer tailings material used, i.e., a greater proportion of fine tailings particles, results in a greater overall porosity and void ratio of the CPB. Another additional mechanism, i.e. the increase of the W/C ratio of the CPBs with the tailings grain fineness for a given consistency (slump) of the CPBs, contributes to the increase of the porosity of CPB made of finer tailings as reported in Fall et al. (2004).

From Figure 4-10, it can be also observed that in domain 1 (●), as the curing time increases, the gap between the strength developed by CPB samples made of coarse tailings (25% of 20 μm particles) and those made of finer tailings (35% and 45% of 20 μm particles) becomes smaller. This is because as the curing time increases, more cement hydration products will be generated. These products will reduce the porosity of the CPB, thereby increasing its strength.



a)



b)

Figure 4-10. Combined influence of tailings fineness and curing temperature on the strength of CPB after a) 7 days and b) 28 days of curing (W/C~7.6; slump~18 cm; Tailings: TS-1).

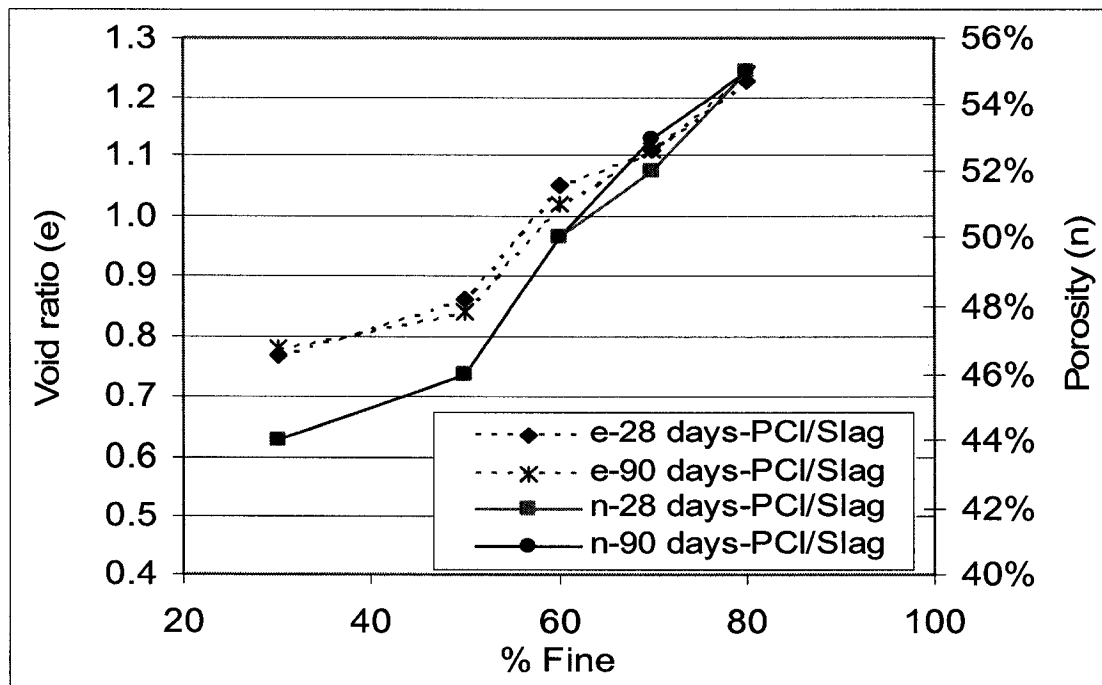


Figure 4-11. Influence of tailings fineness on the void ratio (e) and porosity (n) of paste backfill cemented with 4.5% PCI/Slag (slump = 18 cm) (Fall et al. 2004)

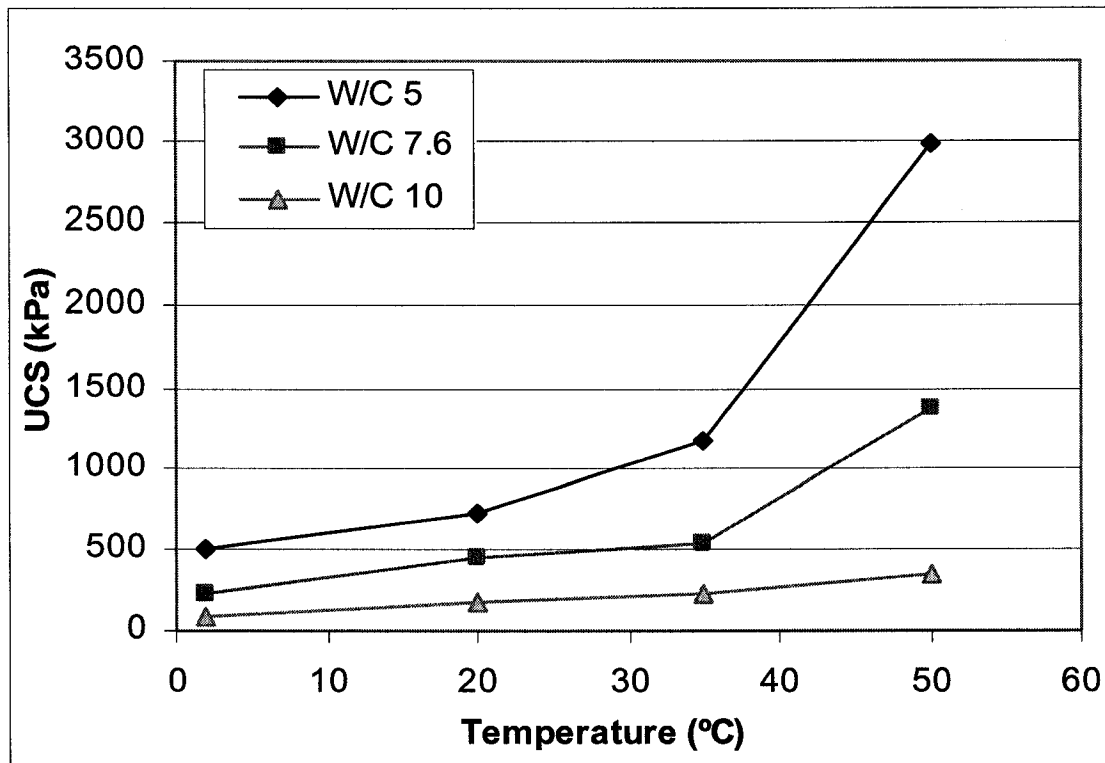
Figure 4-10 also reveals that the mechanical response (UCS) of CPB to the coupled effect of tailings fineness and curing temperatures in domain 2 (②), hot curing temperatures, temperature $\geq 35^{\circ}\text{C}$) is different from that of the CPB in domain 1 (①) (temperature $\leq 20^{\circ}\text{C}$). The CPB samples made of medium tailings (35% and 45% of 20 μm particles) generally show higher strength than those made of coarse tailings (25% of 20 μm particles) regardless of the hot curing temperature. At first, this may seem contradictory to the common conception that CPB made of coarser tailings have higher porosity, thereby lower strength. This seemingly conflicting result can be explained by the combined effect of the following mechanisms: (i) the CPB made of coarse tailings has a lower content of aggregate per unit volume of materials than those with medium tailings. In other

words, they have a higher hydration product/aggregate ratio. As the curing temperature increases, this ratio also increases because of the acceleration of the cement reaction. This can lead to the fact that in CPB with high hydration product/aggregate ratio (i.e. CPB made of coarse tailings), the tailings do not form a rigid skeleton, but a set of inclusions trapped in a continuous cemented paste matrix. This cemented matrix, due to its rigidity, is more susceptible to crack. Hence, a minimum amount of tailings (aggregate) must be contained in the cemented matrix to assure an adequate joint mechanical work by binder and tailings, (ii) the lower porosity, i.e. amount of pores observed in CPBs made of coarse tailings, will result in a formation of denser cement gel with higher curing temperature, which in turn is increasingly detrimental to further hydration at later ages and higher curing temperatures. Figure 4-10b shows that after 28 days of curing at hot temperatures ($\geq 35^{\circ}\text{C}$), CPB made of tailings with 35% fine have the optimal amount of pores to accommodate the hydration products formed. The CPB made of 45% fine present an excess of pores with respect to the amount of hydration products formed; this can have led to a lower strength. It can be expected that at long term and hot curing temperatures, CPB made of 45% fine will have a higher strength.

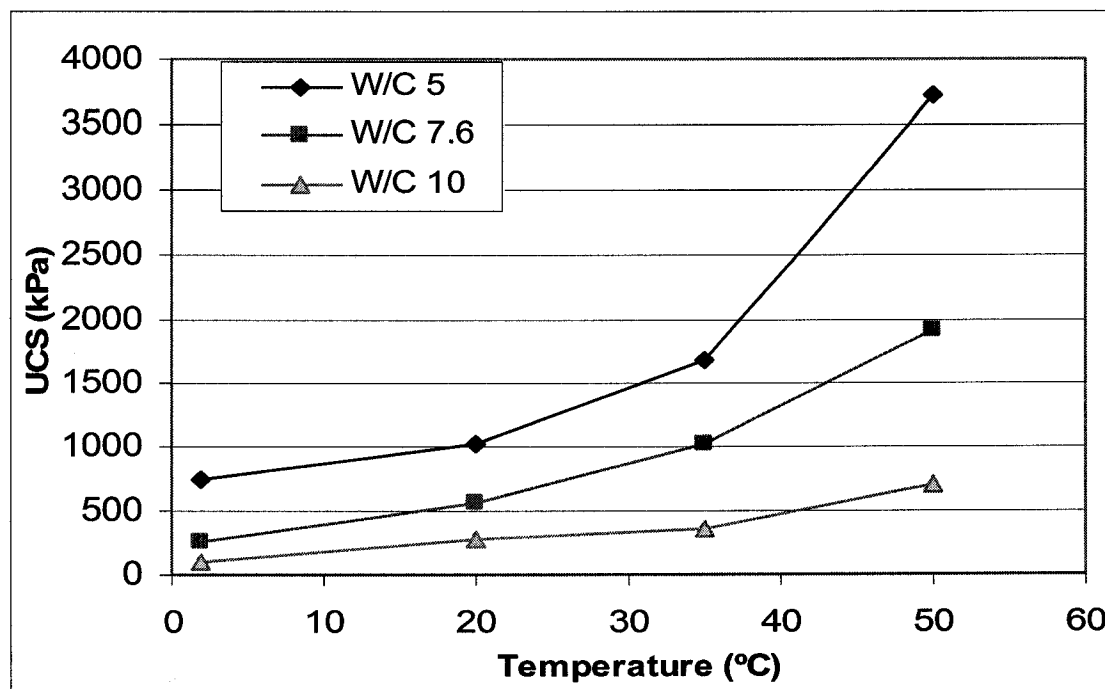
4.5.1.4 Combined effects of curing temperature and W/C ratio on UCS development of CPB

CPB is always prepared with an excess of water (in terms of W/C) to enable its transport by pipeline flow. The optimal amount of water or the W/C used to

prepare CPB varies very much (W/C 5 to 12) and strongly depends on many factors, such as the pumping and distribution system in the mine, tailings types, and CPB mix components. However, our understanding of the combined effect of curing temperature and W/C ratio on the strength of CPB is limited. Hence, around 50 CPB samples were prepared with different W/C ratios (5, 7.6, 10) and cured at various temperatures (2°C, 20°C, 35°C and 50°C). Figure 4-12 shows a set of typical results of the coupled effect of temperature and W/C ratios on the strength development of CPB. The analysis of the results presented in Figure 4-12 (4-12a, 4-12b) reveals that the effect of curing temperature on the development of CPB strength is also a function of the W/C ratio, i.e. the water content of the CPB. CPB with lower W/C ratios show higher strength and higher rate of gain in strength. The reason is that a lower W/C ratio means a smaller initial capillary pore content in the cemented matrix of CPB. This will result in faster and more complete filling of the pores with hydration products, thereby resulting in higher rate of gain in strength and strength due to lower porosity. These observations are in concordance with the MIP results or microstructural observations presented in Fall et al. (2006), which indicate that CPBs with a lower W/C ratio have a lower overall porosity.



a)



b)

Figure 4-12. Combined effects of curing temperatures and W/C ratio on UCS of PCI-CPB at a) 7 days b) 28 days curing (slump~18 cm).

4.5.2 Effect of curing temperature on the split tensile strength development of CPB

To investigate the effect of curing temperature on the split tensile strength development around 100 CPB samples made of PCI or PCI/Slag (50/50) were prepared. The slump of all samples (except those containing 2% or 6% cement) was kept at 18 cm (i.e. $W/C=7.6$). The samples were cured at various temperatures (2°C, 20°C, 35°C and 50°C) and different curing times (3, 7, 28, 90 days). Typical results of the split tensile tests performed on PCI-CPB samples are presented in Figure 4-13 and Figure 4-14. Figure 4-13 shows the effect of curing temperature on the split tensile strength development of PCI-CPB with 4.5% binder at different curing periods. Figure 4-14 illustrates the effect of curing temperature on the split tensile strength of PCI-CPB containing various amounts of PC (2%, 4.5% and 6%). From these figures, it can be observed that like for the compressive strength, regardless of the curing time and binder content, higher curing temperatures lead to higher split tensile strength of the PCI-CPB. As explained previously, this is because the increase in temperature corresponds to increased chemical reactions and faster production of hydration products (i.e. more C-S-H) (Wang et al. 2004) and lower porosity.

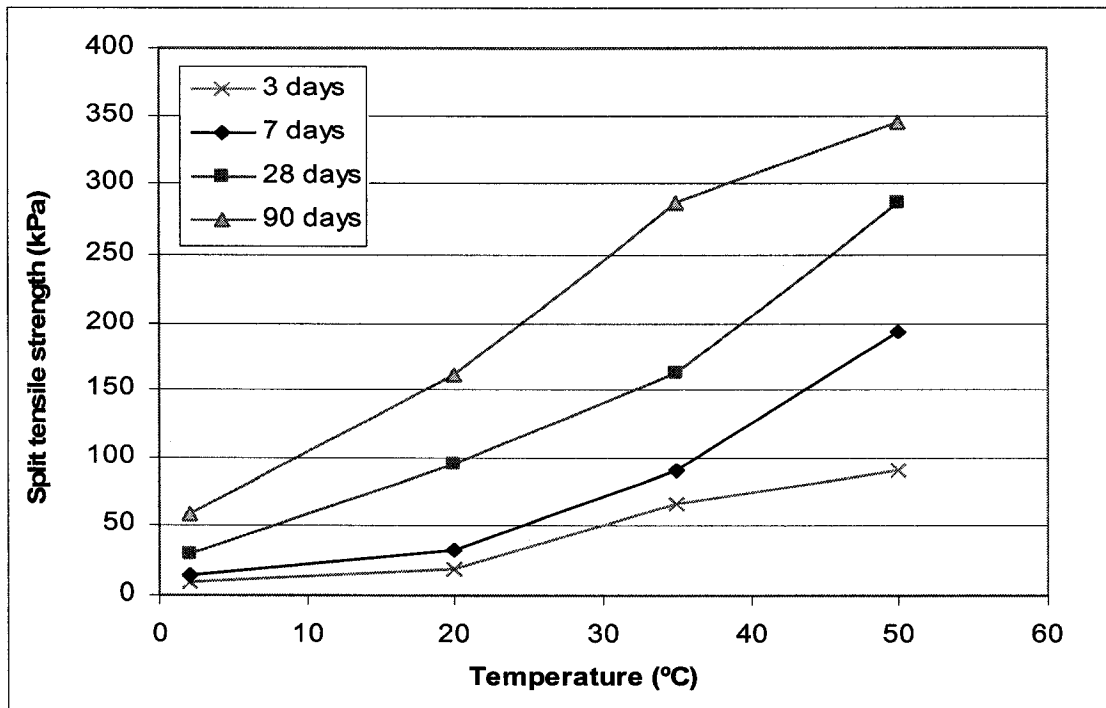


Figure 4-13. Effect of curing temperature on the split tensile strength development of PCI-CPB

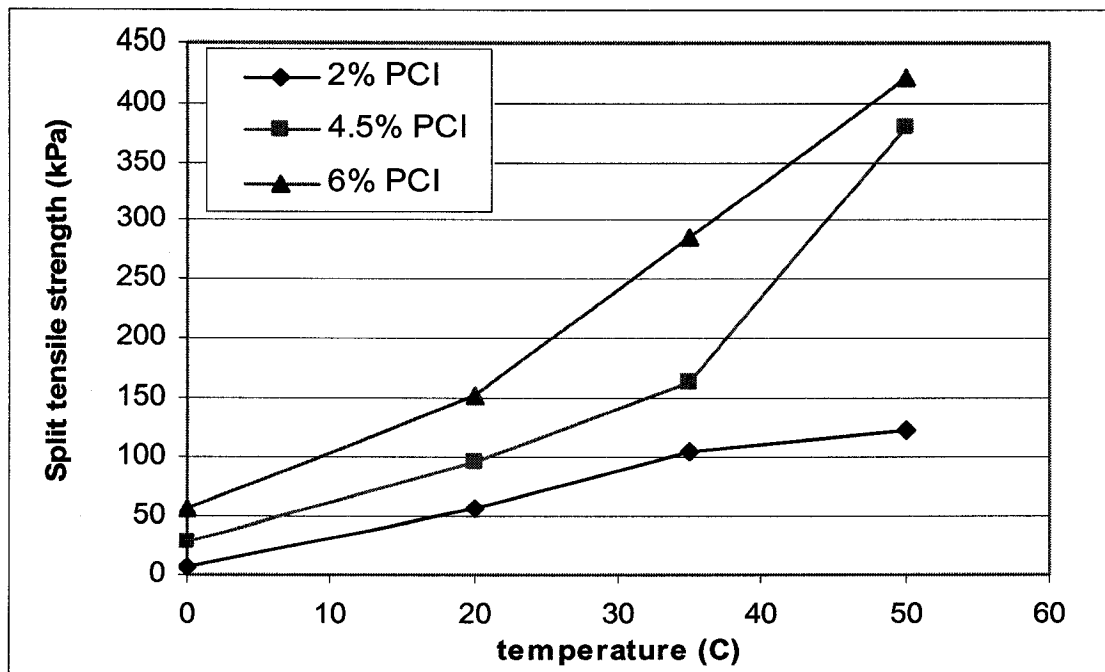


Figure 4-14. Effect of curing temperature on the 28 days split tensile strength of paste backfill containing 2%, 4.5% and 6% PC

As for compressive strength development, the obtained results revealed that the effect of curing temperature on the split tensile strength of CPB is a function of the binder type. Figure 4-15 shows typical results of the effect of curing temperature on the split tensile strength of CPB containing Slag (PCI/Slag 50/50) as mineral admixtures. From the comparison of Figure 4-13 and Figure 4-15, it can be noticed that the split tensile strength for the two types of binders increases with temperature. This behaviour is expected because increase in temperature corresponds to increased chemical reactions and faster production of hydration products (Wang et al. 2004). However, it can also be observed that the split tensile strength of CPB made of blended cements is superior over the samples made of PCI alone. The significant gain in strength is the result of the consumption of CH (produced by the hydration of PCI) by available silica in Slag to form additional C-S-H which further contributes to strength gain (Skalny et al. 2002). Furthermore, in terms of grain size dimensions in Slag, its finer grains confer it with the ability to fill the voids encountered in the crystalline CH matrix and amorphous C-S-H gel (Oner et al. 2005, Fall and Samb 2008), thereby leading to finer pore structure of the CPB. From Figure 4-13 and Figure 4-15, it is also clearly noticeable that the CPB containing Slag is more sensitive to the high temperature induced strength inversion than the CPB without Slag.

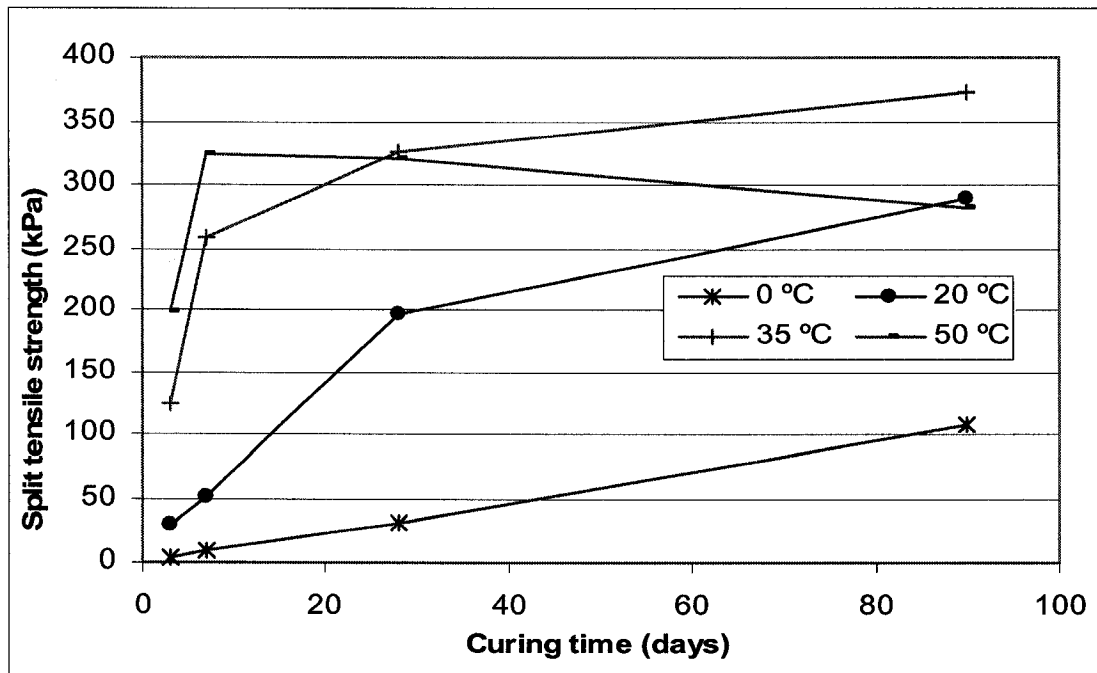


Figure 4-15. Effect of curing temperature on the split tensile strength development of Slag-CPB

4.5.3 Relationship of curing temperature to hydraulic conductivity of CPB

To investigate the effect of curing temperature on the saturated hydraulic conductivity of CPB, around 50 CPB samples made of PCI or PCI/Slag (50/50) were prepared. The slump of all samples was kept at 18 cm (i.e. W/C = 7.6). The samples were cured at various temperatures (2°C, 20°C, 35°C and 50°C) and different curing times (1, 7, 90 days). Figure 4-16 presents the hydraulic conductivity of PCI-CPB samples cured at 2 °C, 20 °C, 35 °C and 50 °C for various curing times. From this figure, it is noticed that the hydraulic conductivity decreases with curing time and temperature. At one day of curing time, the hydraulic conductivity is always higher than all the other advanced curing times.

The hydraulic conductivity appears to be affected in almost the same extent by temperature and curing time. For example, on one hand, the difference in hydraulic conductivity drops from 6.97×10^{-5} to 1.40×10^{-5} cm/s (5.57×10^{-5}) for 1 day samples, 6.02×10^{-5} to 154×10^{-6} cm/s (5.86×10^{-5}) for 7 day samples and from 4.72×10^{-6} to 1.54×10^{-6} cm/s (3.18×10^{-6}) for 90 day samples in terms of difference when the temperature changes from 2 °C to 50 °C. These variations expressed in terms of percentage represent a decrease in hydraulic conductivity of 79 %, 74 % and 67 %, respectively. These results show that the changes in hydraulic conductivity with temperature are more significant in early age samples (up to 7 days). On the other hand, the changes recorded with varying curing times from 1 to 90 days at 2 °C, 20 °C, 35 °C and 50 °C were 6.50×10^{-5} cm/s, 2.08×10^{-5} cm/s, 2.21×10^{-5} cm/s, and 1.25×10^{-5} cm/s in terms of difference or 93%, 90%, 97%, and 89% in terms of decrease percentage, respectively. Changes are slightly more significant at low curing temperatures than at higher temperatures. By examining samples cured at 2 °C, they all bear the highest hydraulic conductivity. Their higher values can be explained from the fact that hydration products are formed slowly under low reactivity conditions caused by the low temperature leading to a slow chemical reaction in binder (slow hydration). A considerable amount of time (90 days) was required for the formation of sufficient hydration products which produces a relatively dense cementitious system that fill the voids. Thus, at 1 day, the presence of non absorbed water is very high (Jensen and Hansen 2002), liquid phase is continuous, and thereby, voids are possibly sufficiently well interconnected to provide an easy path for liquid flow. As the

temperature increases up to 50 °C, a significant drop is observed in hydraulic conductivity and this decrease continues with longer curing time. This means that the hardening process has evolved following minimum binder stoichiometry (Mindess and Young 1981). The rate of formation of hydration products has a direct incidence on the short and long-term refinement structure of the solid matrix (Fall and Benzaazoua 2005, Fall et al. 2005, Fall and Samb 2006 in press) and is therefore, responsible for the drop in hydraulic conductivity encountered at these temperatures. This is because of the increase of curing temperature which significantly accelerates the hydration rate of the cement paste (Lothenbach et al. 2007). Fall and Samb (2007) also observed the increase in the formation of CH, C-S-H and calcite with increase of curing temperature by performing a thermal analysis on hardened cemented paste of CPT (see Figure 4-4). This is also confirmed by the results of XRD tests performed on cemented paste of CPB cured at various temperatures by Mukesh (2008). These results show that the high curing temperature allows CPB samples to form high amounts of hydration products. These products fill the voids and reduce the porosity so that the sample has low hydraulic conductivity at higher curing temperatures.

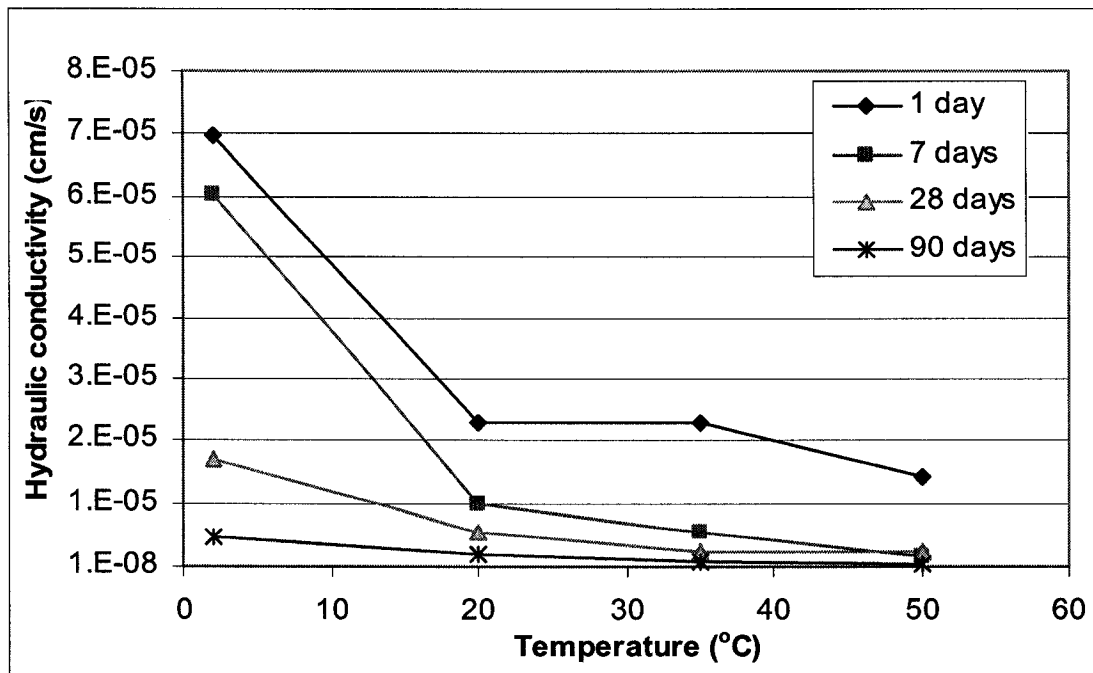


Figure 4-16. Combined effect of curing temperature and curing time on hydraulic conductivity of CPB.

The hydraulic conductivity recorded on four groups of samples (1, 7 28 and 90 days) made of PCI and PCI/Slag-50/50 cured during same period of time and temperature conditions were selected to observe the coupling effect of temperature and binder type. Figure 4-17 reveals clearly, the distinct behaviour of the two different binders. One can notice that at 1 day of curing time and temperature of 2 °C, the hydraulic conductivity of samples containing Slag is higher than the ones made of neat PCI. However, at higher temperatures of 20 °C, 35 °C and 50 °C, the hydraulic conductivity of samples containing Slag is lower than the one made of neat PCI. This cross behaviour at different temperatures leads to invoking the cemented and pozzolanic properties of the two binders in presence. First, PCI as a hydraulic binder possesses low activation energy and can initiate formation of hydration products rapidly due to

the glassy phase and C_3A in its minerals (Mindess and Young 1981). By its side, Slag as pozzolan contains crystalline particles that generally require either the presence of an alkaline environment or CaO and water to develop binding qualities (Palmer et al. 2000, Wang et al. 2004). Furthermore, these pozzolans bear higher activation energy to start the chemical reaction. Therefore, it can be inferred from this graph that at $2^\circ C$ while hydration has started in PCI, it is necessary for the mixes containing Slag to wait until the pore water becomes sufficiently alkaline prior starting the pozzolanic reaction in order for the Slag to contribute to the formation of hydration products. This delay in the apparition of hydration products leaves the voids in the samples containing Slag partially free of precipitates and therefore, the CPT is less dense. Such a material is more porous at the beginning, allowing an easier flow of permeant fluid than in the case of samples made of neat PCI. However, at temperatures ranging from $20^\circ C$ to $50^\circ C$ and for all studied curing times ≥ 7 days, the hydraulic conductivity is lower in samples containing Slag. This suggests that pores in Slag samples are extensively filled by precipitation products. This filling has even surpassed void size of samples made of neat PCI. This is due to the fact that aside from the binding effect, additional C-S-H has been formed from the poor crystalline CH produced by PCI, leading to decrease in pore volume and hence, an increase in the length of the interconnected pore path (Doven and Pekrioglu 2005). Also, due to its finer grain structure, the Slag contributes to filling voids of smaller sizes (Belem et al. 2002); a behaviour that PCI grains are not able to achieve.

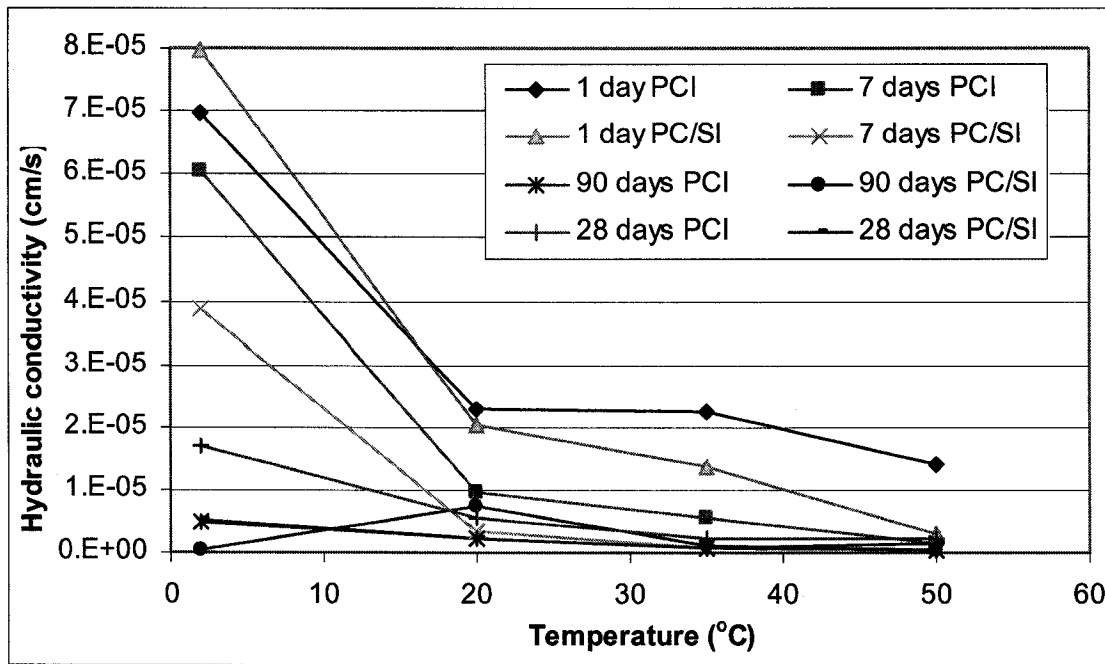


Figure 4-17. Coupled effect of temperature and binder type on hydraulic conductivity at various curing temperatures

4.6 Summary and conclusions

Various CPT mixes with different binder contents, binder types, grain size distribution and W/C are investigated at four temperature levels during different curing times. These parameters represent conditions that are likely to be encountered at mine facilities depending on the hosting rock mineral, metal being extracted, temperature of the region, and maturity period targeted for operations in the vicinity of adjacent filled stopes. The laboratory results are representative of the behaviour of CPT under coupling process similar to actual occurrences in the field.

Consideration is given to the possible use of Slag depending on its availability and lower cost as a recycled material. Using this laboratory program, the

following findings on UCS, split tensile and hydraulic conductivity tests are gained.

- The curing temperature has a significant effect on the mechanical properties and saturated hydraulic conductivity of CPB. However, this effect depends on the CPB mix components and curing time.
- It is found that the addition of pozzolan results in better mechanical and hydraulic performance of samples at advanced ages compared to that made of PCI alone.
- It is observed that the gain in strength with decreasing W/C in mixes is accelerated with increase of temperature.
- It is observed that the effect of the temperature generally benefits UCS and split tensile strength development in CPT when coupled to other parameters in the range of this study. Particularly, the increase in strength is more apparent and the effect of temperature is more prevalent than the other parameters in coupled contexts where cement content, binder type and grain size represent the other parameters.
- For hydraulic conductivity, it is verified that this value changes more significantly in samples cured at low temperatures than higher temperatures. This property decreases in all instances with an increase in temperature, and overall, when cement content or type is involved in the coupling process.
- A remarkable correspondence behaviour is noticed between mechanical performance and hydraulic conductivity under the coupled process. This is, in all samples, when the UCS or split tensile strength increased, the hydraulic

conductivity varies in an opposite manner. This suggests that the formation of hydration products increases the density of CPT, while this process limits the pore sizes, reduces porosity and therefore, hinders the ability of liquid transport into the porous media, resulting in a decrease in the hydraulic conductivity property of CPT.

4.7 Acknowledgement

The writers would like to acknowledge the National Sciences and Engineering Research Council of Canada (NSERC), the University of Ottawa, Cement Lafarge Inc, and the National Research Council (NRC) of Canada.

4.8 References

ACI Committee 201 (1997) Guide to Durable Concrete, ACI 201.2R-92 (Reapproved 1997). Manual of Concrete Practice 1, ACI (Ed.), Michigan, 1997. 41 pp.

Alexander K. M., Taplin J. H. Concrete strength, cement hydration and the maturity rule, Australian Journal of Applied Science. 13 (1962) 277–284.

Amaratunga L. M., Yaschyshyn D. N. Development of a high modulus paste Fill using fine gold mill tailings. Geotechnical and Geological Engineering 15 (1997) 205–219.

American Society for Testing and Materials Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using Rigid Wall Compaction Mold Permeameter ASTM D 5856-95, Annual Book of ASTM Standards, Pennsylvania, 2004.

American Society for Testing and Materials Standard Test Methods for Slump of Hydraulic Cement Concrete: ASTM C 143/C 143-03, Annual Book of ASTM Standards, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Method for Split Tensile Strength of Cylindrical Concrete Specimens: C496/C496M-04, Annual Book of ASTM Standards, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter : D 5084-00, Annual Book of ASTM Standards, Pennsylvania, 2004.

American Society for Testing and Materials, Test Method for Compressive Strength of Cylindrical Concrete Specimens: C39/C39M-03 Annual Book of ASTM Standards, Pennsylvania, 2004.

Anderberg Y. Spalling phenomena of HPC and OC. In: Proceedings of the International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg 1997.

Archibald J. F., Chew J. L., Lausch P., Use of Ground Waste Glass and Normal Portland Cement Mixtures for Improving Slurry and Paste Backfill Support Performance. 100th Annual General Meeting of the Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, Quebec, Canada (CD-ROM publication), 1998.

Archibald J. F., Hassani F., Nantel J., DeGagné D. O. (2000) Mine Backfill, An Operator's Guide. An interactive CD-ROM for mine operators and engineers.

Belem T., Bussière B., Benzaazoua M. The Effect of Microstructural Evolution on the Physical Properties of Paste Backfill. Tailings and Mine Waste'01, January 16-19, Fort Collins. (2002).

Benz D. P., Ehlen M. A, Ferraris C. F, Winpigler J. A. Service life prediction based on sorptivity for highway concrete exposed to sulfate attack and freeze-thaw conditions. Report N°. FHWA-RD-01-162, US Department of Transportation, (2002). 62 pp.

Brackebusch F., Shillabeer J. Use of paste for tailings disposal, in: Proceedings of the 6th International Symposium on Mining with Backfill (Minefill 98). AusIMM, Publication no.1/98, (1998), pp 53-58.

Brackebusch F. W. Basics of paste backfill systems, Mining Engineering, 46 (1994) 1175-1778

Brooks J. J., Kaisi A. F. Early strength development of Portland and slag cement concretes cured at elevated temperature. ACI Material Journal ;87 (1990) 503-507.

Carino N. J. Temperature Effects on the Strength–Maturity Relation of Mortar, Report No. NBSIR 81-2244, National Bureau of Standards, Washington, D.C., (1981) 90 pp.

Diamond S., Sheng Q., Olek J. Materials Research Society Symposium Proceedings (1989) 137, 437.

Doven A. G., Pekrioglu A. Material properties of high volume fly ash cement paste structural fill, Journal of Materials in Civil Engineering. 17 (2005) 686-693.

Escalante-Garcia J. I., Sharp J. H. The microstructure and mechanical properties of blended cements hydrated at various temperatures. Cement and Concrete Research (2001); 31:695–702.

Fall M., Benzaazoua M., Sae E. Mix proportioning of underground cemented paste backfill. International Journal of Tunnelling and Underground Construction 23 (2008) 80-90.

Fall M. 2008. Fundamentals of the effects on temperature on cemented paste backfill. Journal of Rock Mechanics mining sciences (submitted).

Fall M., Samb. S. Pore structure of cemented tailings materials under natural or accidental thermal loads. *Materials Characterization* 59(2008):598-605.

Fall M. Geotechnical and geo-environmental research results with potential applications in Senegal; Research contribution, Dakar 2005.

Fall M., Benzaazoua M. Modeling the effect of sulphate on strength development of paste backfill and binder mixture optimization. *Cement Concrete Research* 35 (2005) 301-314

Fall M., Benzaazoua M., Ouellet S. Effect of tailings properties on paste backfill performance. *Proceedings of 8th International Symposia on Mining with Backfill*. In Beijing, China (2004)193-202

Fall M., Benzaazoua M., Ouellet S. Experimental characterization of the effect of tailings fineness and density on the quality of cemented paste backfill. *Journal Minerals Engineering*, 18 (2005a) 41-44.

Fall M., Bussière B., Belem T., Benzaazoua M., Samb S. Effect of curing temperature on paste backfill properties. In: CGS, editor. *Proceedings of 58th Canadian Geotechnical Conference*, Saskatoon, Saskatawan, Canada, (2005b) 1-8.

Fall M., Merkel B. (eds.) Kontamination aus der Nutzung von Ressourcen – Probleme und Lösungen. Proceedings of the 1st conference of Geo-Environment of the Graduatenskolleg (272): Geowissenschaftliche und Geotechnische Umweltforschung” – TU Freiberg – Germany, Wissen. Mitt. Institut für Geologie, 2001; Heft 18. 20 Beiträge, 200 p.

Fall M., Nasir, O., Célestin J. C. Paste backfill response in deep mine temperature conditions. 9th Symposium on MineFill, Montreal 2007b.

Fall M., Samb S. Influence of curing temperature on strength, deformation behaviour and pore structure of cemented paste backfill at early ages. Construction and Building Material 2006 (in press).

Fall M., Samb S. 2006, Touré M. Some factors affect the performances properties of cemented tailings. Internal report. uOttawa. 10p.

Gani M. S. J. Cement and concrete. 1st edition. London: Chapman and Hall; (1997) 212p.

Grice T. Recent mine developments in Australia. Proceeding of the 7th international symposium on mining with backfill (MINEFILL). (2001) 351-7.

Hassani F., Archibal J. 1998. Mine Backfill, CD-Rom, Canadian Institute of Mine, Metallurgy and Petroleum, 1998.

Jensen O. M., Hansen P. F. Water-entrained cement-based materials: II. Experimental observations, Cement and Concrete Research. 32 (2002) 973-978.

Kesimal A., Ercikdi B., Yilmaz E. The effect of desliming by sedimentation on paste backfill performance. Journal Minerals Engineering 16 (2003) 1009 – 1011.

Khoury G. A. Compressive strength of concrete at high temperatures: A reassessment. Magazine of Concrete Research 44 (1992) 291–309.

Kjellsen K. O., Detwiler R. J. Later ages strength prediction by a modified maturity model, ACI Material Journal. 90 (3) (1993) 220–227.

Kjellsen K. O., Detwiler R. J., Gjorv O. E. Pore structure of plain cement pastes hydrated at different temperatures. Cement and Concrete Research. 20 (1990) 927–933.

Kjellsen K. O., Detwiler R. J., Gjorv O. E. Development of microstructures in plain cement pastes hydrated at different temperatures. Cement and Concrete Research. 21 (1991) 179–189.

Landriault D. Backfill in underground mining. In: W.A. Hustrulid, Editor, Underground Mining Methods Engineering Fundamentals and International Case Studies, SME, USA (2001), pp. 608–609.

Landriault D. Paste backfill Mix design for Canadian Underground Hard Rock Mining. 97th Annual General Meeting of CIM. Rock Mechanics and Strata Control Session. Halifax, Nova Scotia, (1995). 229-238.

Levens R. L., Marcy A. D., Boldt C. M. K. Environmental impacts of cemented mine waste backfill. RI 9599, United States Bureau of Mines, (1996) 23 p.

Lothenbach B., Winnefeld F., Alder C., Wieland E., Lunk P. Effect of temperature on the pore solution, microstructure and hydration products of Portland cement pastes, Cement and Concrete Research. 37 (2007) 483-491.

Ma W., Sample D., Martin R., Brown P. W. Calorimetric study of cement blends containing fly ash, silica fume and slag at elevated temperatures, cement and concrete and aggregates. CCAGPD, 16 (2) (1994) 93–99

Maltais Y., Marchand J. Influence of curing temperature on cement hydration and mechanical strength development of fly ash mortars. *Cement and Concrete Research*, 27 (1997) 1009-1020.

McIntosh J. D. The effects of low-temperature curing on the compressive strength of concrete, Gen. Report of session BII, Proceedings of RILEM symposium Winter Concreting, Danish Institute for Building Research Copenhagen, 1956.

Meredith P., Donald A. M. Water anomaly in capillary liquid absorption by cement-based materials. *Journal Material Sciences Letters*, 14 (1995) 1178–1181.

Mindess S., Young F. Concrete. N. M. Newmark and W. J. Hall, editors. Prentice-Hall Inc. Englewood Cliffs, New Jersey 07632, (1981) 671p

Noumowé A. Effet des hautes températures (20 °C–600 °C) sur le béton, PhD thesis, Institut National des Sciences Appliquées, 1995.

Oner. A., Akyuz S., Yildiz R. An experimental study on strength development of concrete containing fly ash and optimum usage of fly ash in concrete, *Cement and Concrete Research*. 35 (2005) 1165-1171.

Orejarena L., Fall M. Mechanical response of a mine composite material to extreme heat load. Bulletin of Engineering Geology and Environment (2007) in press.

Palmer B. G., Edil T. B., Benson C. H. Liners for waste containment constructed with class F and C fly ashes, Journal of Hazardous Materials. 76 (2000) 193-216.

Platret G. Suivi de l'hydratation du ciment et de l'évolution des phases solides dans les bétons par analyse thermique. Caractéristiques microstructurales et propriétés relatives à la durabilité des bétons. Méthodes de mesure et d'essai de laboratoire. Méthodes d'essai No. 58, Laboratoire Central des Ponts et Chaussées, Février (2002).

Pokharel M.. Geotechnical and environmental response of cemented paste tailings systems to coupled thermo-chemical loadings. Master (M.A.Sc.) Thesis, University of Ottawa (2008)

Rankine R. M, Rankine K. J., Sivakugan N., Karunasena W., Bloss M. L. Geotechnical characterisation and stability analysis of BHP Cannington paste. II. Proc. of the 15th intern. Conf. on soil mechanics and geotechnical engineering, (2001) pp. 1241-1244.

Rawlins C. A., Phillips H. R. Reduction of mine heat loads. Proceedings of the 7th International Mine Ventilation Congress, (2001) 381-389.

Taylor H. F. W. Cement Chemistry, Academic Press, London, UK, (1992) 475 pp

Taylor H. F. W. The chemistry of cements, 1st edition, volume 1. London: Academic Press; 1964.

Verbeck G. J., Helmuth R. H. Structures and physical properties of cement paste. Proceedings of the 5th International Symposium on the Chemistry of Tokyo (1969), 1-32

Verburg, R. B. M. Use of paste technology for tailings disposal: potential environmental benefits and requirements for geochemical characterization. IMWA Symposium 2001. p. 1-13.

Vergne J (2000) Rules of thumb for the hard rock mining industry. In Hard Rock Miner's Handbook, third edition, ed. McIntosh Engineering Inc. USA, 42 pp. NIST, 1996.

Wang K., Shah S. P., Mishulovich A. Effects of curing temperature and NaOH addition on hydration and strength development of clinker-free CKD-fly ash binders. Journal Cement and Concrete Research, 34 (2004) 299-309.

Xu A. PhD Thesis, Chalmers University of Technology, Goeteborg, Sweden (1992).

Xu A., Sarkar S. L., Nilsson L. O. Materials and Structures, 26, (1993). 414 pp

Zhou Q., Glasser F. P. Thermal stability and decomposition mechanisms of ettringite at $<120^{\circ}$. Cement Concrete Research 2001; 31 (9): 1333–1339.

5 Chapter 5: Technical Paper III

Recycling of densified tailings as geotechnical barrier material

5.1 Abstract

The mining industry produces annually huge amount of tailings which necessitates storage and maintenance in large repository areas. These very fine materials (mean grain size around 20 microns) can exhibit alone a hydraulic conductivity of 10^{-6} cm/s which is around one order of magnitude higher than the EPA (environment protection agency) required limit of less than 10^{-7} cm/s for liner construction for hazardous waste facility. This inherent property of these materials suggested the modification of their fabric for exploitation in geotechnical barriers. In this paper, improvements of the hydraulic properties were realized by using in a first time compaction to densify the tailings and in a second time, additives like natural bentonite, and synthetic polymers were mixed to paste tailings to further reduce the voids that control the hydraulic conductivity. Significant decrease in hydraulic conductivity was observed with these transformations. During the program, hydraulic conductivity was measured all along the compaction curve and more frequent measures were conducted overall around the wet of optimum where minimum hydraulic conductivity could be expected to be very low because of minimum of voids. Values as low as

1×10^{-9} and 6×10^{-9} cm/s were obtained in 8% bentonite and 0.5% polymer mixes, respectively. Basing on these satisfactory values, additional investigations were conducted to evaluate the freeze-thaw performance up to five cycles. The results showed that negligible to acceptable change in hydraulic conductivity occurred. None of the changes reached one order of magnitude. It was realized that samples containing as low as 4% bentonite and samples containing as low as 0.5% polymer additive presented good properties for liners design. As a final step, a cost analysis was undertaken to evaluate the economical benefits that could be withdrawn from such new material. When compared to conventional compacted clay-bentonite barrier or sand-bentonite with 12% bentonite concentration, it was found that the 4% bentonite- densified tailings and the 0.5% polymer-densified tailings were less expensive of 66% and 89%, respectively. The results can place this recycled material as a promising candidate for liners design while reducing the amount of waste to be managed.

5.2 Introduction

Tailings occurring from ore processing facility must be disposed of as they represent waste material, either they contain sulphides or they are non reactive. By their fine content of approximately 45% passing the 20 microns, raw tailings bears rheological properties allowing them to be deposited as paste tailings. Paste tailings is simply slurries which have been thickened (removal of excess water) in order that they reach a consistency that prevent them to segregate (Grabinsky et al. 2002). They present ordinarily low hydraulic conductivity after

consolidation (Yunxin et al., 2001). In fact, one of the most desirable properties in liners design is low hydraulic conductivity that prevents migration of hazardous fluids to underlain area where wastes are deposited. In the case of compacted clay, EPA (environment protection agency) requires a minimum thickness of 0.9 m of compacted clay and a hydraulic conductivity less than 10^{-7} cm/s (Daniel, 1993). In regions where preferred materials like clay are not available for the design, small percentage of bentonite whose hydraulic permeability is 2×10^{-9} cm/s (Kashir and Yanful 2001) is mixed to sands to achieve low permeability property. Alternatively, as soil permeability is governed by the proportion and the nature of the finer fraction (Shafiee 2008), tailings mixed with other fine or swelling materials like bentonite, or polyacrylates could play the role of replacement for clay as the practice has use to do for other fine grain sands (Palmer et al. 2000, Shafiee 2008). It is known that the study of hydraulic conductivity for fine grain material is extensive (Aubertin et al. 1995, Dixon et al 1999). However, the recycling of non sulphuric densified tailings with high specific surface and low hydraulic conductivity ($10^{-5} - 10^{-7}$ cm/s) has not yet been proposed as hydraulic barrier. In this study, taking advantage of the inherent low hydraulic conductivity of densified tailings, small amount of bentonite was added to the latter prior moisturizing or small amount of polymer was added after moisturizing the tailings. The purpose of the additives (bentonite, polymer) being to further increase specific surface, increase the cation exchange capacity (Andrejkovičová et al. 2008) and to glue the pores openings. The resulting modified densified tailings materials were compacted and submitted to

permeability tests at room temperature and to performance tests under freeze-thaw conditions to evaluate their suitability as liner. Based on the quantity and cost of mixed additive required to meet the EPA specifications an economical evaluation of the modified tailings liner was undertaken. The objective of this study is to determine through rational approach how mine waste material (densified tailings) can be converted into beneficial material with high savings in cost and minimized environmental impact. The findings of the investigations are presented in this paper.

5.3 Background, Transformations in natural liners

5.3.1 Natural compacted clay liners

Natural compacted clay liners have been for long time the engineering barrier used in dams impervious core, lagoons, ponds and more recently in landfill disposal sites (Elsbury et al. 1990). Its definite fine grains size and its relatively high swelling capacity allow it to present low permeability. Improved property is generally achieved by compaction at wet of optimum (Simon and Müller 2004) to confer to the clay a hydraulic conductivity as low as 10^{-8} cm/s to prevent migration of potential containment to underlying ground water.

5.3.2 Geosynthetic clay liners

Geosynthetic clay liners (GCL) are industrially made barriers containing a thickness of 6 to 10 mm of bentonite encased between 2 geotextile layers (Katsumi et al. 2008, Southen 2007). The GCL are available in two textures: the woven needle punch one and the non-woven one. In the latter texture the bentonite is generally glued to the geotextile. The intrinsic low hydraulic conductivity of bentonite (principally sodium mineral one) has allowed construction of these thin mats with hydraulic conductivity in the range of 10^{-8} cm/s. The GCL offers the advantage that it is ready to use and its lightweight presentation does not require heavy equipment for installation.

5.3.3 Composite liners

Various composite liners models have been developed by combining compacted clay with Geosynthetic clay liners and geomembranes. When used as composite, the different layers are superposed, and one layer can be encountered twice. The geomembrane is also a synthetic material particularly a poly-vinyl-chloride (PVC) or a high density poly ethylene (HDPE). Ordinarily they are an intimate contact of hydrophobic and hydrophilic system where they protect each other mutually against possible defect or disturbance (Simon and Müller 2004). Sometimes a layer can be repeated.

5.3.4 Low permeability material research

In many facilities, the engineered liner is designed from a mix of clay or sand with bentonite. Bentonite is ordinarily added to a certain percentage 5-15% (Datta 2003) as it is often the most expensive material used in the composition of such barriers. Cutoff wall can incorporate bentonite and cement as additives (Datta 2003). Further studies have reported the positive effect of silica fume on the hydraulic conductivity (Kalkan and Akbulut 2004) and the design of liners made of fly ash (Palmer et al. 2000). Dense prehydrated geosynthetic clay liner is another approach that was developed in the various liner models (Shan and Daniel 1991, Katsumi et al. 2008). It consists in compacting and prehydrating bentonite enclosed between 2 geotextile sheets. Values of hydraulic conductivity as low as 1×10^{-10} cm/s were reported in such models. Modified bentonite materials have also been developed to alleviate chemical incompatibility and improve performance of natural bentonite (Katsumi et al. 2008, Onikata et al. 1999a). Synthetic polymer additive is reported to amend sand-bentonite mixture (Simon and Müller 2004, Katsumi et al. 2008). The addition of synthetics increases the hydrophilic property of the mix and also renders the mix less susceptible to desiccation. A group in Germany who has evaluated these products believe that it can be used as replacement for compacted clay liner (CCL) and thereby, decrease up to 10 times the thickness of the barrier layer (Simon and Müller 2004).

5.4 Experimental program

5.4.1 Materials

5.4.1.1 Densified Tailings

In this study artificial tailings prepared industrially from ground silica and available commercially were used (U. S. Silica). They have the same physical property as natural tailings coming from the milling process. The selection of artificial presents the advantage to be exempt of chemicals that could interfere with the test results. For comparative task, the grain size distributions from 9 eastern Canadian mines are presented in Figure 5-1 with artificial tailings (Fall and Samb 2006). Additional characteristics are studied in section 5.4.3.

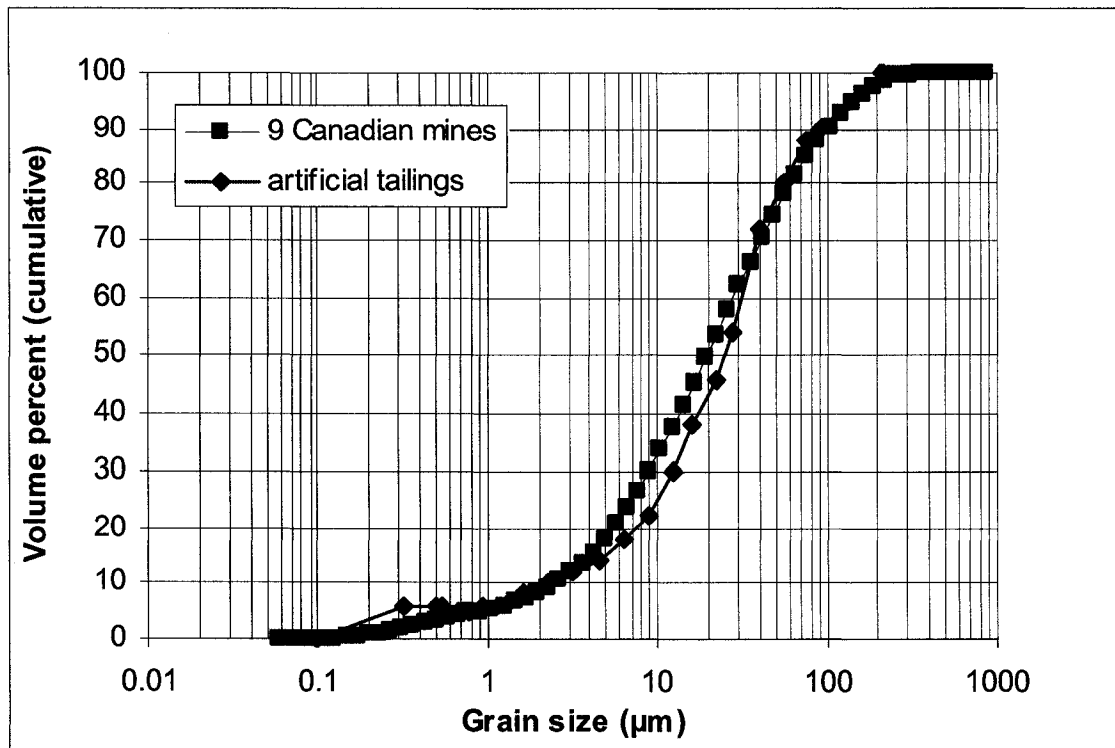


Figure 5-1. Grain size distribution from sieve and hydrometer tests performed on artificial tailings compared to the average of 9 Canadian mines from east Ontario

5.4.1.2 Bentonite

Bentonite is formed by the weathering of volcanic ash. The weathering process, by which the clay minerals are formed from the parent minerals are complex but the main factors are climate, topography, vegetation, and time of exposure (Jackson 1957). Bentonite was obtained from a commercial distributor. The choice aimed toward sodium mineral type as it presents good swelling potential, absorbing almost 5 times its weight and occupying a volume up to 15 times its bulk dry volume at full saturation (Kashir and Yanful 2001). The swelling property confers it the ability to plug voids in a mix and therefore improve hydraulic

conductivity (Kashir and Yanful 2001). Some tests were conducted in section 5.4.3 for characterization of the bentonite.

5.4.1.3 Polyacrylates (SAP)

The presence of reactive material can improve the efficiency of liners by either further dropping the hydraulic conductivity, by inducing chemical conversion or retarding the movement of containments (Palmer et al. 2000, Karickhoff et al 1979). Commercially available cross-linked insoluble sodium polyacrylates with a free swell capacity of 250 g/g in deionized water was mixed with densified tailings. The ion exchange capacity in the polymer confers it the hydrophobic nature and good retention properties. As polymer is solvated, chains unfold and ionic repulsive forces expand its molecules, creating large absorption capacities. Gellation occurs from multiple hydrations of the lattice structure of the molecule (Arkent 2003). Therefore beside of blocking the pores, fluid absorption may delay significantly transport.

5.4.1.4 Water

Deionised water was used for the mixing of the tailings. This choice was made to ensure no chemical parameter was involved during this series of tests.

5.4.2 Method

5.4.2.1 Preparation of specimens

Depending of the pure tailings or densified tailings-mix to be tested, different mixing schemes were used. For plain tailings and bentonite-densified tailings mixes, the anhydrous material was first homogenized in dry state. Once mixing completed, the amount of deionized water was gradually added until uniform hydration of blend. In the case of polymer-densified tailings blends, densified tailings were hydrated alone first. Once hydration completed, SAP was added and mixing continued until uniform distribution. After compaction in proctor mould, cutting cylinder of 5 cm diameter was used for sampling undisturbed cores for hydraulic conductivity. Thereafter, specimens were removed from the cylindrical sampling tube using mechanical press and stored in polyethylene package for 24 hours prior conducting hydraulic conductivity test. Hydrated samples were trimmed and installed in triaxial cell where the hydraulic conductivity measurement took place.

5.4.3 Tests conducted and characteristics of the materials

5.4.3.1 Sieve and Hydrometer tests

Based on the fine appearance of the tailings and bentonite, the grain size distribution was determined using the lower mesh sieves #80, 100 and 200 followed by hydrometer tests according to ASTM C 136 and ASTM D 422-63

respectively. The grain size distributions are drawn in Figure 5-1 and Figure 5-2, from these tests. When observing these graphs, a percentage of 0% and 92% of clay can be noticed in the tailings and in the bentonite, respectively, and the values are reported in Table 5-2.

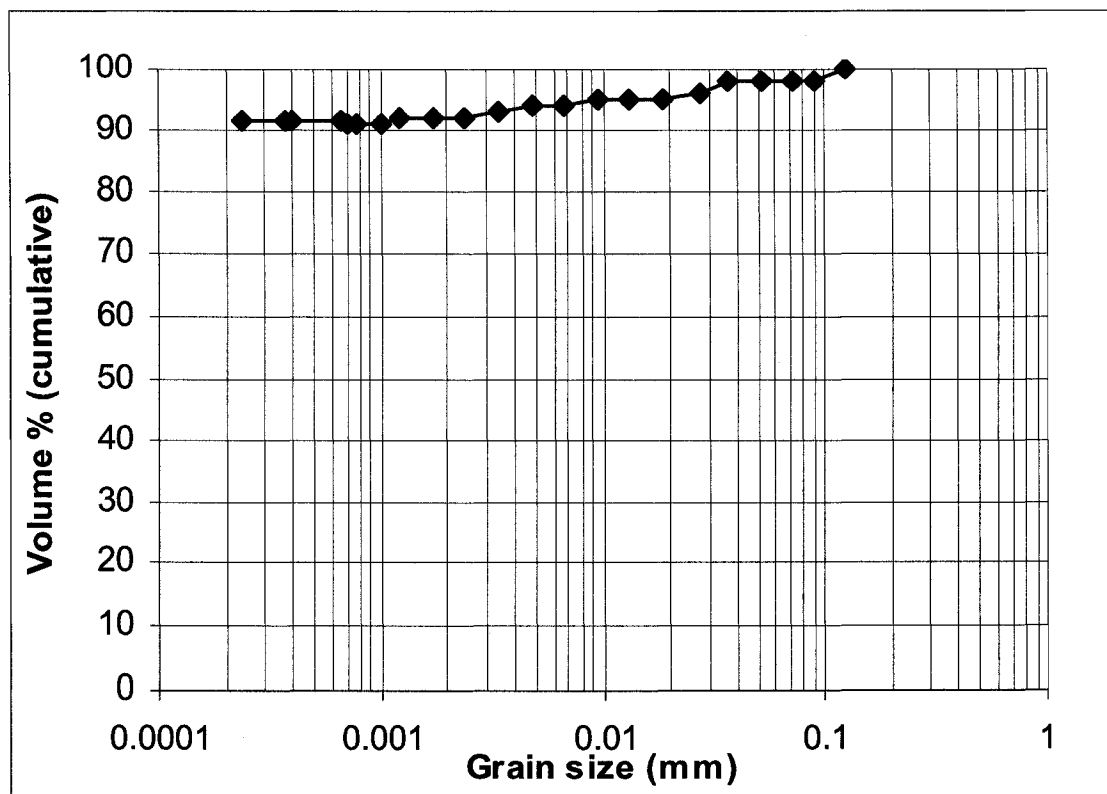


Figure 5-2. Grain size distribution of bentonite from hydrometer test showing an average of 92% of clay proportion < 2microns

5.4.3.2 X-ray diffraction

In order to verify the minerals present in the bentonite, X-ray diffraction of the powder material was performed at NRC (Institute for Research in Construction)

using Scintag XDS 2000 XRD. The results of the diffractogram displayed in Figure 5-3 show that the dominant clay mineral present is smectite (sodium montmorillonite) based on the intensity at $5.9^{\circ} 2\theta$. Other important minerals present but in less intensities are kaolinite, clinoptilolite, quartz and calcite. The sodium bentonite type has single water layer particles containing Na^+ as the exchangeable ion. When Na^+ is exchanged by Mg^{++} or Fe^{++} , it confers to the clay the swelling potential by the absorption of water (Kashir and Yanful 2001).

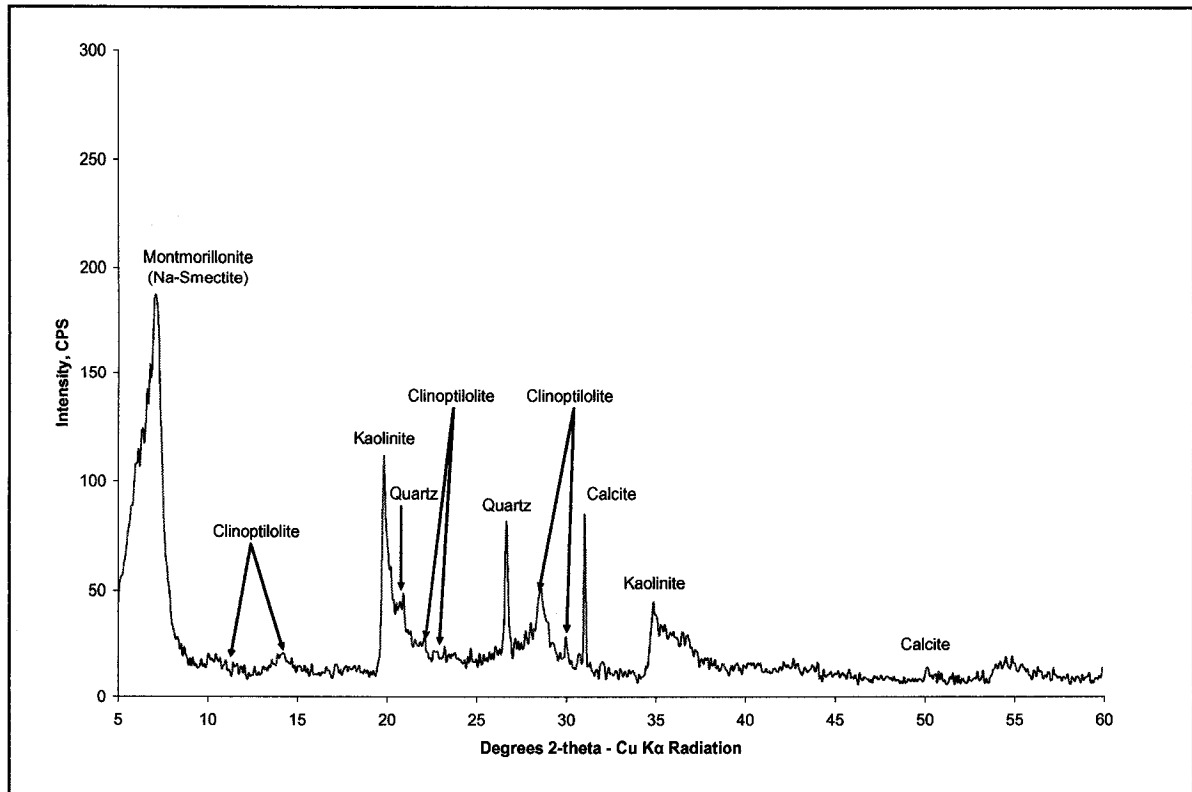


Figure 5-3. X-Ray diffractogram from Bentonite.

The minerals list of artificial tailing was provided by the distributor and is also included in Table 5-1 Chemical composition of material used in the liner preparation

The principal component of this material is quartz whose percentage is listed as 99%.

5.4.3.3 Inductively coupled plasma – emission spectroscopy (ICS-ES)

ICP-ES was performed using Varion Vista ICP-ES instrument located at laboratory for plasma spectroscopy at Earth Sciences, University of Ottawa. The results indicated in quantitative form the chemicals present in the bentonite. The detected minerals are listed in Table 5-1. The fraction of sodium present in the samples is the important criteria in selecting the type of bentonite as it determines its cation exchange capacity and hence its water absorption and swelling potential. Quantitative and qualitative chemical composition of the artificial tailings were supplied by the manufacturer and are also listed in the table.

Table 5-1 Chemical composition of material used in the liner preparation

Chemical	Chemical	Artificial tailings	Bentonite
Silicon Dioxide	SiO ₂	99.8	62.4
Iron Oxide	Fe ₂ O ₃	0.035	2.82
Aluminum Oxide	Al ₂ O ₃	0.05	13.5
Titanium Dioxide	TiO ₂	0.02	0.088
Calcium Oxide	CaO	0.01	1.183
Magnesium Oxide	MgO	<0.01	1.68
Sodium Oxide	Na ₂ O	<0.01	1.59
Potassium Oxide	K ₂ O	0.02	0.125
Boron Oxide	B ₂ O ₃	-	0.015
Barrium Oxide	BaO	-	0.009
Copper Oxide	CuO	-	0.0003
Manganese Oxide	MnO	-	0.017
Phosphorous Pentoxide	P ₂ O ₅	-	0.038
Sulphur	S	-	0.194
Strontum Oxide	SrO	-	0.026
Zinc Oxide	ZnO	-	0.017
	LOI	0.1	

5.4.3.4 Plasticity tests

Tailings and bentonite were tested for some index properties (liquid and plastic limits) following ASTM D 4318. The tailings were unworkable in order to determine any of these parameters at the laboratory. However Aubertin et al. (1996) reported from extrapolation a plastic limit of 17.5% but, no liquid limit. From the experimental work, the used tailings can be classified as sandy silts of low plasticity, ML in the Unified Soil Classification System. At the opposite of tailings, the Atterberg limits of bentonite were well defined. A liquid limit of 657 and a plastic limit 52 were determined, conducting to a plasticity index of 605. Therefore bentonite can be classified in the CH group (inorganic, fat clays, highly plastic clay)

5.4.3.5 Specific gravity

Specific gravity was conducted following the prescriptions of ASTM D854-02. The values determined were 2.66 and 2.58 for artificial tailings and bentonite, respectively.

The values obtained from the previous tests are summarized in Table 5-2. Atterberg limits and specific gravity for bentonite and artificial tailings. Atterberg limits and specific gravity for bentonite and artificial tailings are presented in order to reveal the contrast between sand and clay like materials.

Table 5-2 Atterberg limits and specific gravity for bentonite and artificial tailings

Property	Artificial tailings	Bentonite
Specific Gravity	2.66	2.58
Specific surface	8.5 m ² /g	550 m ² /g
Liquid limit (%)	N/A	657
Plastic limit (%)	N/A	52
Plasticity index (%)	N/A	605
Clay content (%)	0	92
Activity, A	N/A	6.72

5.4.3.6 Compaction (Standard proctor tests)

Compaction was performed following ASTM D 698-00a for Standard Proctor. The rational of compaction was to increase the dry density and thereby to reduce the void in the material. To come up with the optimum moisture content (OMC), initially, several specimens of raw densified tailings were prepared and tested at water contents from the range of 4% to 24% in gradual increments of 2% of water. The compaction curve drawn from these tests showed that the wet of optimum lied around the 20% moisture content and a maximum density of 1580 kg/m³ was determined.

For proper characterization of compaction behaviour, tests were conducted as least on two points at the wet side, two points at the dry side and at the optimal

water content. The water content from the optimum was considered to ensure that all tests have taken place in a range susceptible to lead to maximum dry density (i.e. minimum void ratio) for all other tests. Thus, the indication of maximum density from the raw densified tailings was used as a reference for all tests with modified densified tailings prepared with bentonite or SAP. It was also used to correlate the hydraulic conductivity in regard to water content. When referring to reports from studies undertaken by Aubertin et al. (1996), Qiu et al. (2001) and Dixon et al. (1999), mercury intrusion porosimetry (MIP) performed at different dry densities showed that, macropores that are the most important vectors in fluids transport, always decrease with increased dry density and water content while the micropores, the less participating ones, almost remain unchanged. Proctor curve is presented in Figure 5-4 for the raw densified tailings and shows a shape similar to sand materials.

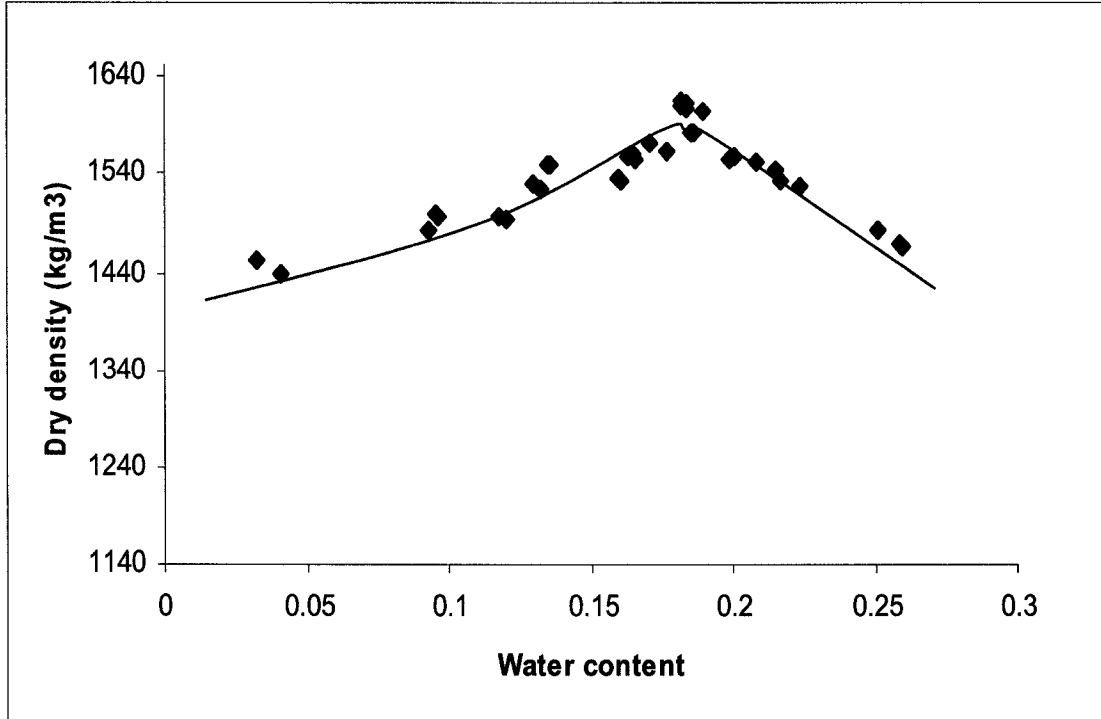


Figure 5-4. Compaction curve for raw densified tailings

5.4.3.7 Hydraulic conductivity tests

Flexible wall permeameter principle was used following ASTM D 5084-00 to perform hydraulic conductivity tests. Effluent head was kept constant at 10 kPa, while influent head was calculated from desired gradient to be applied as a function of the sample thickness. Saturation was achieved by bridging the influent and effluent line and applying backpressure. Saturation was considered complete by verifying influent intake against effluent water volume supply until they became equal.

During preliminary hydraulic conductivity tests conducted at room temperature, compacted plain densified tailings samples were prepared at various water contents with a thickness of 7.5 cm. The recorded values were in the order of 10^{-6} to 10^{-5} cm/s under a hydraulic gradient of 30 as recommended by ASTM D 5084. Investigations carried out by Aubertin et al. (1996) and Yunxin and Sego (2001) reported hydraulic conductivity of compacted and consolidated tailings to be almost in the same range, this: 10^{-7} to 10^{-5} cm/s. When it came the turn to test bentonite-densified tailings samples, it was observed during the recording operation that even after periods of 36 hours, these samples remained unsaturated and no flow took place. This led to infer that the value of hydraulic conductivity has significantly decreased. For this reason, in a first period, the thickness of the samples was reduced to an average of 3.5 cm. As this modification didn't appear to stimulate flow, an additional measure consisting in increasing gradually the hydraulic gradient up to a final value of 600 was adopted to provoke flow. That was the value at which acceptable flow took place in reasonable period of time. It was first verified that the compacted material was sufficiently consistent (Shafiee 2008) to accept this gradient without perturbation of the results. Also, this gradient can be considered acceptable as literatures report values up to 1800 (Kashir and Yanful 2001) used during permeability tests in low hydraulic conductivity materials. The effective stress maintained in the cell was an average of 130 kPa, which is a value that can be produced by overlying waste (Kashir and Yanful 2001) or that can be found in the majority of tailings management facilities (Yunxin and Sego 2001). The constant hydraulic gradient

of 600 was applied during tests using controlled air pressure from the control panel that was translated into head following the relationship:

$$h = u / (\rho \times g) \quad (1)$$

$$i = h / L \quad (2)$$

$$h = i \times L \quad (3)$$

$$i \times L = u / (\rho \times g) \quad (4)$$

$$u = \rho \times g \times i \times L \quad (5)$$

$$u = 1000 \times 9.81 \times 600 \times L \quad (6)$$

$$u = 5886000 \times L \text{ (Pa)} \quad (7)$$

where

h is the hydraulic head in meter

i , the hydraulic gradient

L , the length of the sample in meter

u , the pressure applied in Pascal

g , the gravity m/s^2

ρ , the density of water in kg/m^3

This relationship is calculated prior application of head for each sample as it would be difficult to trim them at the same thickness, L . The gradient in this routine allowed to achieve steady state condition and to obtain representative amount of flow for calculations. Additional care was also taken to collect specimens as much as possible at the middle of the compaction mould so they

can be considered all under the same compactive condition. Finally the hydraulic conductivity was calculated using the constant head principle given by the equation:

$$k = (\Delta Q \times L) / (A \times h \times \Delta t) \quad (8)$$

where

ΔQ is the quantity of flow in m^3

A , the area of the sample in m^2 and

Δt , the interval of time in seconds and

h , is the pressure head defined by the Bernouilli relationship expressed as:

$$h = y + \frac{u}{\rho \times g} + \frac{v^2}{2g} \quad (9).$$

However in equation (9) the elevation head (y) was neglected as the pore water gauges for influent and effluent lines are located at the same elevation inside the TRI-FLEX control panel. Further consideration of equation (9) allows to verify that the contribution of velocity head ($v^2/2g$) can also be considered insignificant, thus can be neglected. In summary, the only part of the equation that was taken into account from the total head was the pressure head defined previously by

$$h = u/\rho \times g \quad (1)$$

which is a translation of the control panel pressure (u) into water head (h) in the relationship

$$k = (\Delta Q \times L) / (A \times h \times \Delta t) \quad (8)$$

Finally, temperature correction factor

$$k_{20} = k_T \times \eta_T / \eta_{20} \quad (10)$$

was applied to calculated values for uniformity in results with,

k_{20} , the permeability at 20°C

k_T , the permeability at the lab temperature, and

η_T/η_{20} , the viscosity correction.

At least hydraulic conductivity was conducted over a range of water content plus or minus 4% optimum moisture content (OMC) at different water contents.

5.4.3.8 Freeze-thaw tests

To evaluate the performance of the proposed liners to freeze-thaw conditions, compacted bentonite-densified tailings and polymer-densified tailings samples were submitted to cyclic freeze-thaw. In general freeze-thaw develops in fine grained soils following the principle where "ice lenses first form in the largest pores where the water potential and freezing point are highest. As the temperature decreases, the pore water freezes in progressively smaller pores, and films of water coating the soil particles gradually freeze. Water flows from unfrozen regions of higher potential through the unfrozen water films to the growing ice lenses. As water films thin, particles of soil are drawn closer together, which causes a rearrangement of particles and shrinkage of the soil." (Kim and Daniel 1992, Hohmann 2002). Samples were first prepared at water content corresponding to the minimum hydraulic conductivity which was determined during previous compaction accompanied with hydraulic conductivity tests at 20 °C temperature. Investigations were carried out over samples submitted to 1 up to 5 cycles of freeze-thaw. ASTM D 6035-96 was followed during freeze-thaw stress application by ascertaining that all ice lenses melted and moisture in

samples became at equilibrium. The time necessary for the samples to freeze or thaw to the extreme temperatures at fixed rate of change in temperature was measured by preparing a control sample having the same physical size, water content and compaction level as the ones to be tested by protruding a thermal probe to the middle of the sample. The average time required for samples to freeze from 20 to -20 °C was 140 minutes and the time required for samples to thaw and reach back the room temperature was 180 minutes. However during the study, samples were allowed to stay at rest for 12 hours for each alternation in the cycle for the purpose of uniformity. It was arranged that all samples be submitted to the freeze-thaw influence at their moulded water content. This detail necessitated the preparation of as many samples as cycles tested by sample type, because, each sample was discarded after testing as it was saturated during the process. The thermal loading was applied tridimensionally under hermetic condition to prevent modification in initial water content during the process of temperature change by enclosing specimens in sealed plastic bags. One graphs of the temperature evolution with time was selected and presented in Figure 5-5 and the instrumentation setup to determine the inner temperature is presented in Figure 5-6.

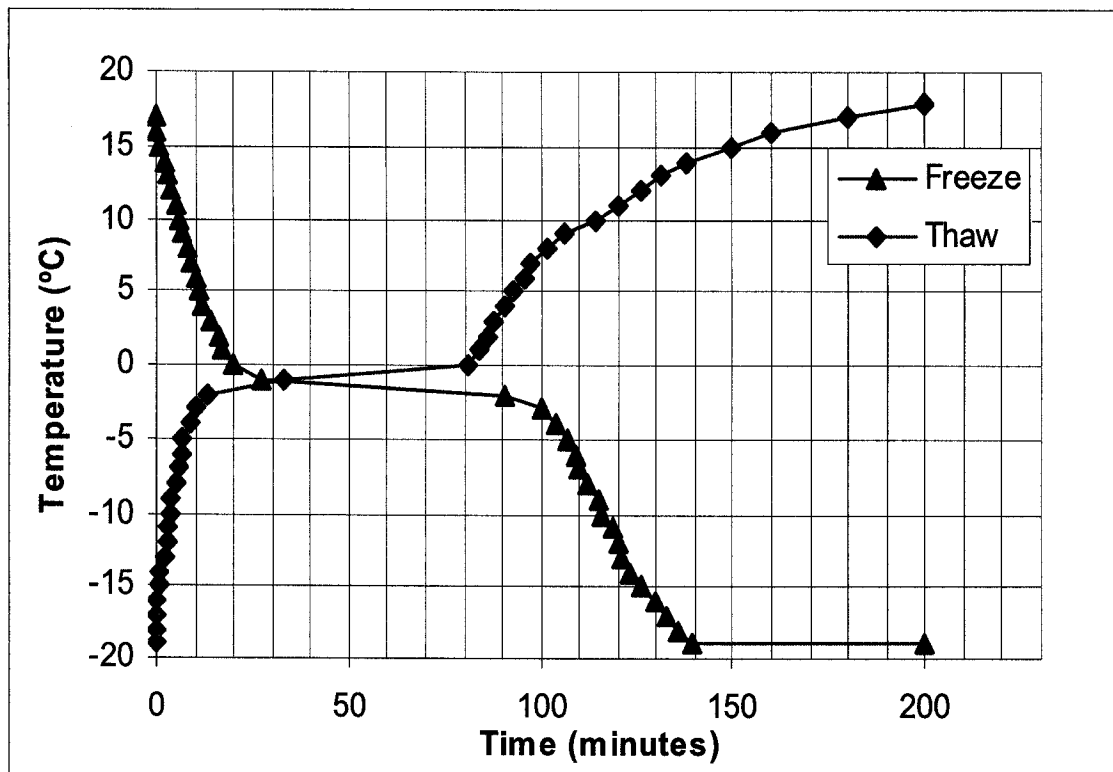


Figure 5-5. Phase change curve.

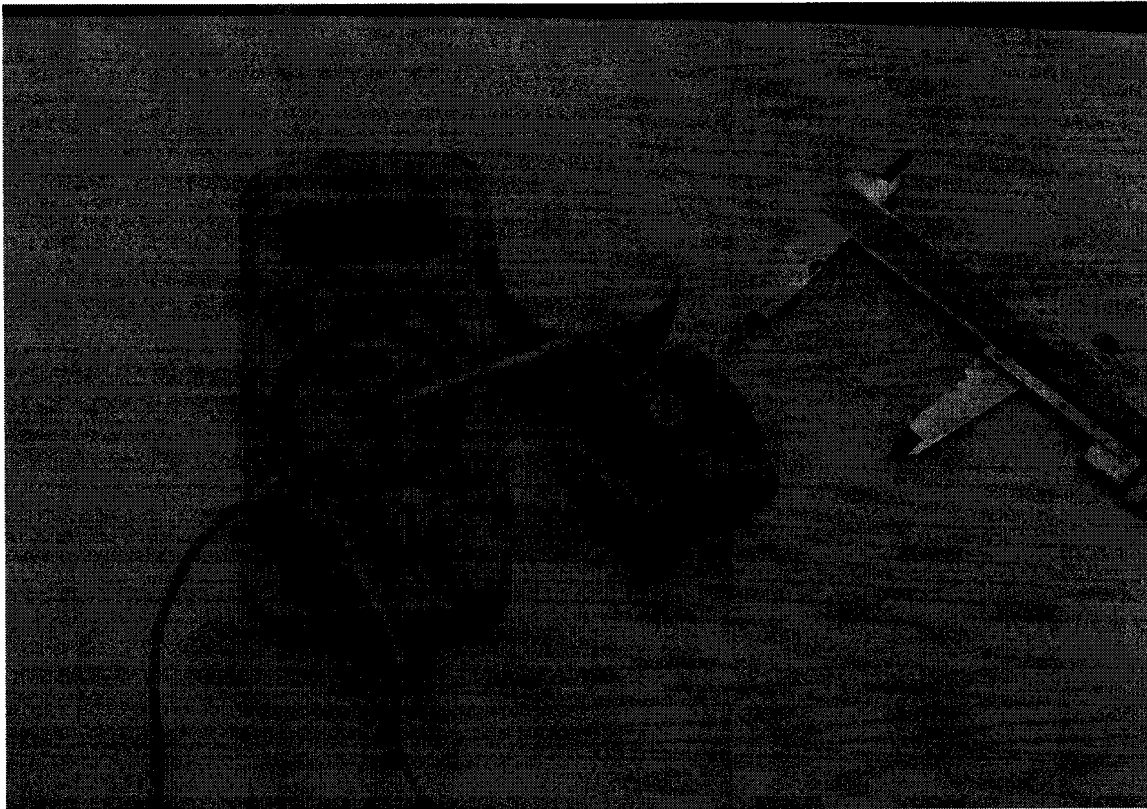


Figure 5-6. Sample under temperature monitoring

5.4.3.9 Cost analysis

For the proposed material to be of interest, it should be capable to provide value addition compared to existing alternatives available in the construction practices beside of the recycling capacity. Based on the EPA minimum requirement for hydraulic conductivity and good behaviour under freeze-thaw conditions, cost analysis was conducted on the bentonite densified tailings and the polymers densified tailings mixes. It is obvious to understand that the additive materials are essentially the part that controls the prices in such mixtures. The investigation was conducted over both proposed liners categories (bentonite densified tailings and the polymers densified tailings) taking into account variable additive

proportion. A balance can be established between saving cost and an acceptable level of permeability. For appreciation at a glance, costs were compared to reference barriers made of sand and clay mixed with 12% bentonite.

5.5 Results and discussions

5.5.1 Compaction

5.5.1.1 Compaction of the reference raw densified tailings

Figure 5-4 presents the compaction curve for plain densified tailings using an effort of 592.7 kJ/m^3 as prescribed by ASTM D 698-00a. The maximum dry density of 1580 kg/m^3 was obtained for a water content of around 19%. This point corresponds to the one where minimum voids are achieved. The information gathered from this curve will be used as guidance for the approximate location of the optimum water content for subsequent mixes of densified tailings with bentonite or polymers as additives.

5.5.1.2 Compaction of modified bentonite densified tailings (BDT)

Results of the aforementioned raw densified tailings compaction were used to determine the range of water content that could correspond to dry/wet of optimum in BDT mixes. This point found for the raw tailings eventually informs about the range of best hydraulic conductivity for the material itself and mixes to be enhanced or improved with additive.

As the optimal water content was determined to lie in the 19% range, further tests were conducted on densified tailings bentonite mixees containing bentonite in proportion of 2, 4 and 8% by weight to determine the effect of the bentonite on the dry density. Proctor tests were conducted at the dry side up to 16% and at the wet side and up to 24% of the optimum water content initially determined in plain tailings. The results of the standard proctor curves obtained by varying the water content with the compaction tests were plotted and presented in Figure 5-7.

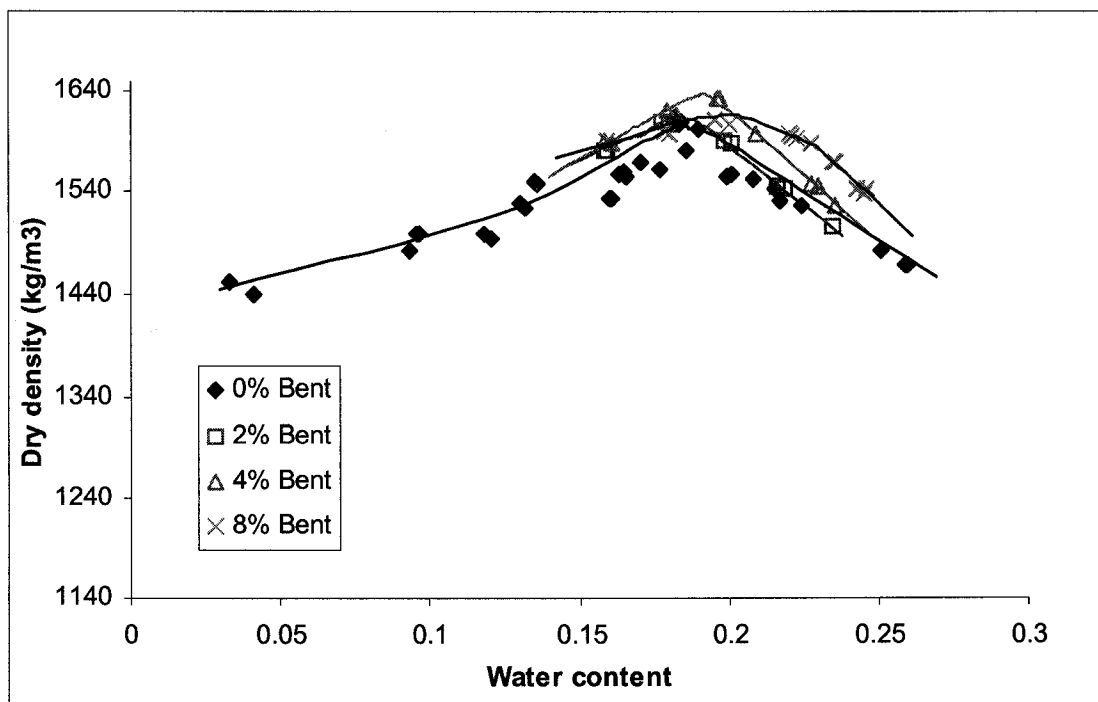


Figure 5-7. Effect of bentonite proportion on the characteristics of proctor compaction of densified tailings.

In this graph it appears that the material with lower maximal dry density (1580 kg/m^3) corresponds to the plain densified tailings. This may result from the fact that, even the coefficient of curvature of 1.36 lies in the range of 1 to 3, and the coefficient of uniformity of 2.86 is lower than 6 (that allows to consider this tailings as well graded) it happens that specimens containing bentonite develop better packing density.

In such conditions the voids left after compaction in the plain tailings are more significant than the voids left in samples mixed with bentonite. When observing the samples mixed with 2% of bentonite, one can notice that the compaction quality has improved, giving rise to an maximum dry density of 1610 kg/m^3 . This result of better packing density is realized with the presence of the proportion of bentonite which has finer grains compared to the tailings. The fines grains have the ability to fill part of the voids that could be left during the compaction of the mixture. Best improvement is realized with the addition of 4% of bentonite which gives a dry density of 1640 kg/m^3 . Up to this proportion, however, further increasing the bentonite content doesn't lead to proportional increase of the dry density. Instead, one can notice a drop in the dry density value of the sample made with 8% of bentonite. The value fell to about 1610 kg/m^3 , value which is almost similar to the mix with 2% of bentonite.

Furthermore, in the sample with 8% of bentonite, the peak corresponding to the dry of optimum appears to be less defined (flat). The curve presents a flat summit which is often noticed in compacted clays. This behaviour and shape in the curve

is merely due to the fact that, after the presence of bentonite have contributed to densify the tailings by supplying appropriate fines to fill the voids and build the best packing density, the relatively high proportion of fines supplied by the bentonite has detrimental effect in mix. It tends to have the mix behaves like a clay where the tailings grains are prevented to have good contact each other, leading them to slide in the plastic bentonite densified tailings. Otherwise, the bentonite film has played the role of lubricant for the tailings. This property of bentonite is sometimes used in wells drilling (Falode 2008).

5.5.1.3 Compaction of polymers densified tailings (PDT)

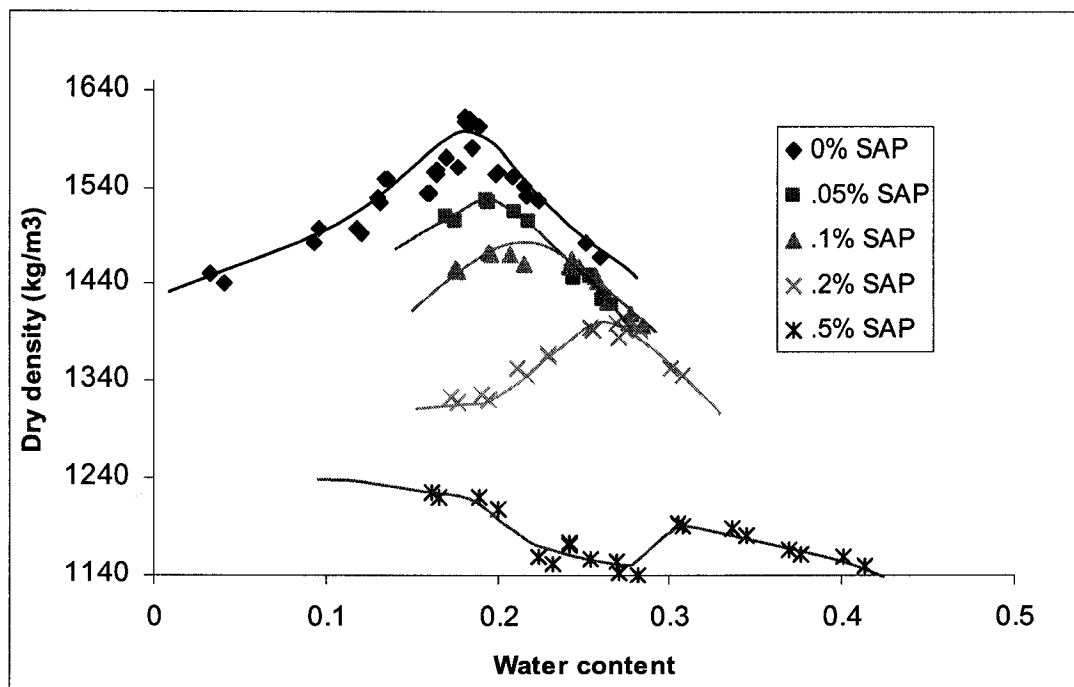


Figure 5-8. Effect of super absorbent polymers proportion on the characteristics of the proctor compaction of densified tailings

The compaction curves obtained with different SAP proportions mixed to tailings is presented in Figure 5-8. The plain tailings exhibited the highest dry density of 1580 kg/m^3 . As a content of 0.05% of SAP is added, the dry density recorded becomes 1530 kg/m^3 . Further increasing the SAP proportion to 0.1% led to a detrimental decrease to 1490 kg/m^3 of the dry density. It was noticed that, as the SAP proportion was increased, a continuous decrease was recorded in the maximal dry density. This behaviour appeared to be somewhat opposite to the compaction tests previously conducted on the bentonite densified tailings samples. The explanation which can be attributed to this behaviour is the fact that the replacement of tailing with swollen SAP (density of dry SAP is already low, when filled with water, the density becomes comparable to that of water), in a first period, contribute significantly to a decrease of specific gravity of the material to be compacted. In a second time, the SAP gel, beside of filling voids, decreases the proximity which existed between tailings grains. In fact, by absorbing the water film which could play the role of bond between the grains, the SAP swells and develops pressure that pushes the grains apart. More SAP are present, more this influence is relevant. Furthermore, during compaction, the SAP grains filled with water transformed into gel that also absorb the energy supplied by the hammer by encompassing deformation and reinstating their former shape after the impact. These mechanisms can be the main phenomenon that may conduct to a significant decrease of dry density with increasing the proportion of SAP. Finally, as the amount of SAP is increased to 0.2% and up to 0.5% the pattern drawn by the compaction curve tends to recall the one exhibited by loose sands

with exaggerations. Eventually the dry density of the tailings-SAP mix (at 0.5% SAP proportion or more) would bear the highest density at completely dry condition (0% water content). This assumption appears to be rational, because of the swelling pressure that any small amount of SAP is capable, any presence of moisture can cause the sample to increase in volume, thereby, decreasing the density of the material.

5.5.2 Hydraulic conductivity

5.5.2.1 Hydraulic conductivity of raw tailings

In a first stage, permeability tests were conducted along the compaction process in a range of 10% to 24% water content (Figure 5-9) compared to the range of 2 to 24% water content for the compaction results of raw tailings. Tests for hydraulic conductivity at water content less than 9% were impractical to be conducted in the triaxial cell, because sampling and manipulating the compacted cohesiveless core from the cylindrical cutter was failing. Similarly, tests at water content higher than 24% were not possible because the paste-like consistency of the plain tailings. A continuous narrow pattern of hydraulic conductivity values was difficult to draw at once, however a certain decreasing trend was recognized in the scatter of permeabilities ranging from 1.3×10^{-5} to 4.1×10^{-6} cm/s in the testing interval of water contents considered. As reported by tests conducted on clays and sands (Abichou et al. 2004), a minimum hydraulic conductivity was

expected at certain point past the maximum dry density due to minimum voids in this interval.

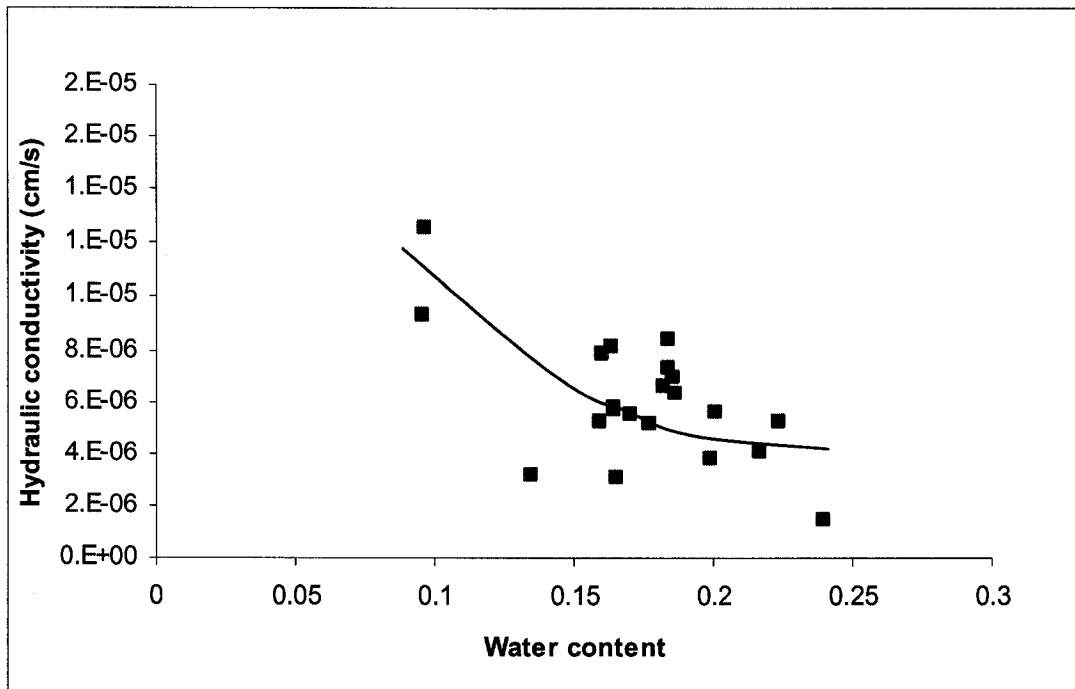


Figure 5-9. Hydraulic conductivity scatter pattern of plain densified tailing compacted in the range of 10% to 24% water content

5.5.2.2 Hydraulic conductivity of bentonite densified tailings (BDT)

Based on hydraulic conductivity values determined from raw compacted tailings samples at various water contents, further improvement was investigated by mixing bentonite in proportions of 2%, 4% and 8% to tailings by total weight. Referring to results presented in Figure 5-10, it can be noticed that the hydraulic conductivity decreased in all samples as the water content is increased. For

illustration purpose, one example of superposition is presented for the tailings-bentonite mix containing 4% of bentonite in Figure 5-11.

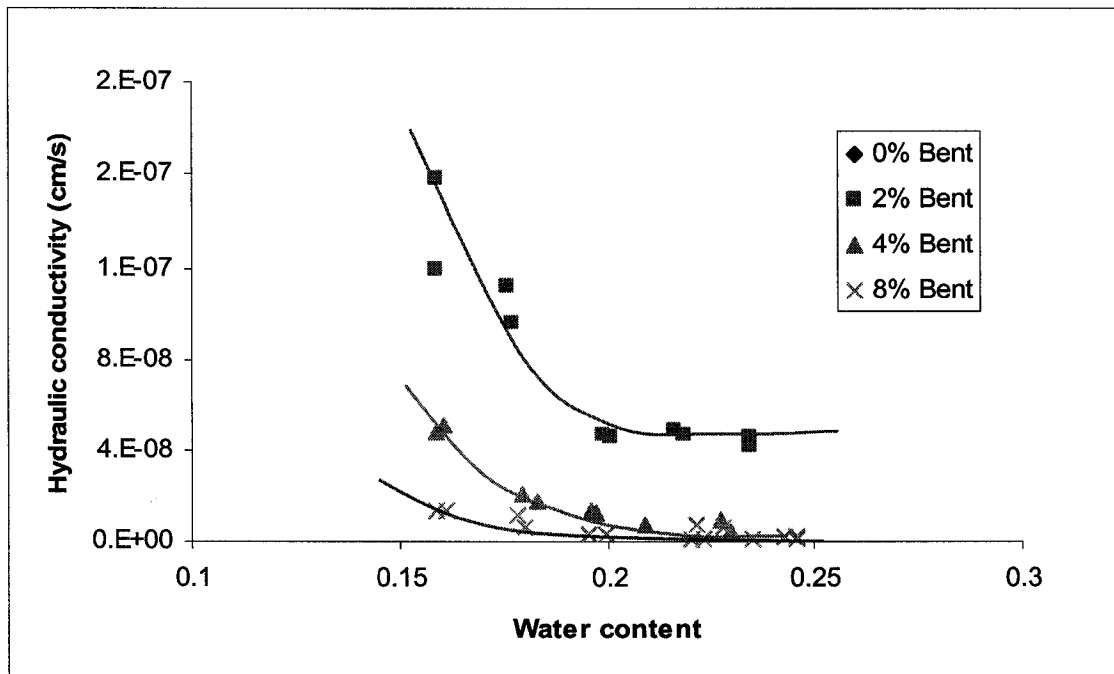


Figure 5-10. Effect of different bentonite proportions and water content on hydraulic conductivity of BDT.

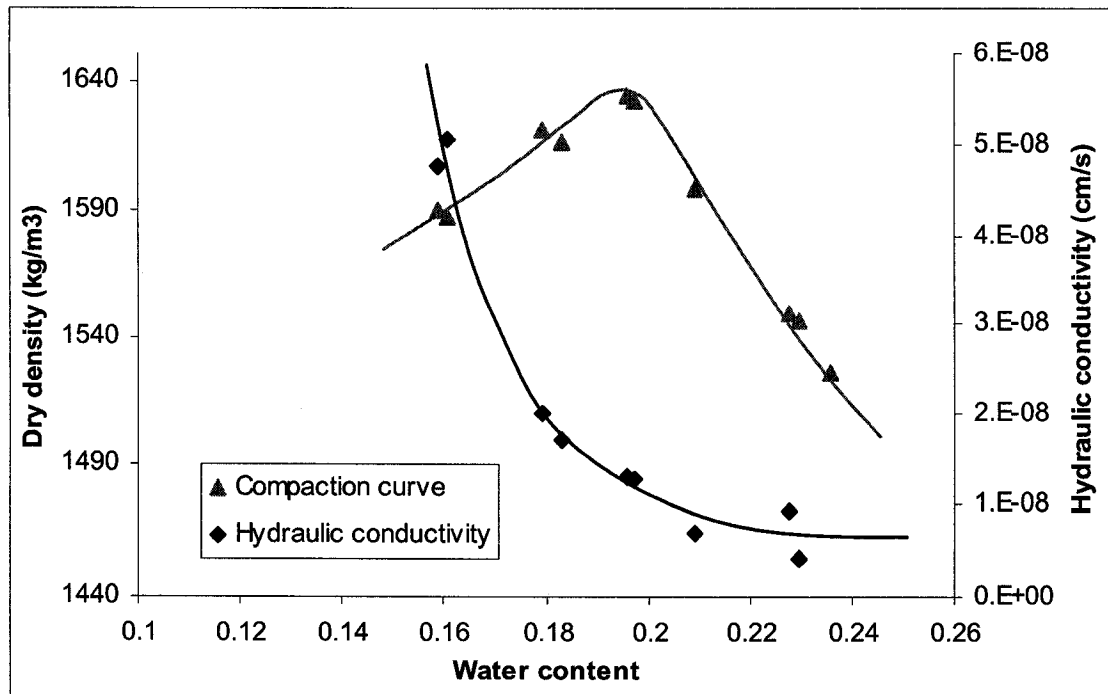


Figure 5-11. Variation of hydraulic conductivity within the compaction curve (4% Bentonite).

In this figure, it was noticed that the slope of the decrease in hydraulic conductivity was steeper at the dry of optimum up to an early point at the wet optimum where it tended to remain constant. It is also important to recall that no more hydraulic conductivity test was conducted up to the point where the consistency of the material was no longer suitable for sampling nor handling for hydraulic measurements. In a global view of the hydraulic conductivity behaviour versus water content and bentonite proportion, the main observation from Figure 5-10 is that hydraulic conductivity evolution is inversely proportional to the bentonite content. Contrarily to the compaction curves where the maximum dry density decreased after optimal bentonite content (i.e. 4% bentonite content), in

the case of hydraulic conductivity, the decreasing trend was continuous with the increase in bentonite content. This is illustrated by the values where samples with higher bentonite content (8%) showed an hydraulic conductivity of 6.27×10^{-10} cm/s at wet of optimum. This low value was followed by samples with 4% bentonite which showed a value of 9.58×10^{-9} cm/s and finally the highest values were recorded in samples with 2% bentonite where the value was 4.35×10^{-8} cm/s. The explanation to this behaviour may entail two reasons. First, flow in porous media relies on voids spaces and interconnectivity for fluids movement. When proceeding with compaction, the higher dry density is an indication of minimum void achieved during the process. This point would theoretically correspond to the minimum hydraulic conductivity under minimum void ratio. On the other hand, the fact that higher bentonite content occupies more efficiently the reduced pore left during compaction and contributes to their further blockage, it thereby hinders the movement of fluids. Furthermore, the presence of bentonite involves the effect of cation exchange capacity which is a process by which water molecules are attracted by its double layer diffuse, retarding significantly the flow (Dixon et al. 1999). Finally, the sample being restrained in the triaxial cell, swelling pressure developed by bentonite plays a significant role in obstructing pores when hydrated by the permeant. It is important to recall that the hydraulic conductivities were conducted at the nearest same effective stress and hydraulic gradient for all the specimens. This choice was selected to have a uniform reference and to prevent any interpretation ambiguity with respect to variable deformation intensities which could arise in

different loading conditions for each specimen. This would have for effect to shrink or dilate the voids in different proportions as reported by Shafiee (2008).

5.5.2.3 Hydraulic conductivity of polymer densified tailings (PDT)

Samples prepared with polymers in proportions of 0.05, 0.1, 0.2 and 0.5% SAP are presented in Figure 5-12. It can be observed that in each particular sample, the hydraulic conductivity decreases as the water content was increased during compaction. For illustration purpose, one hydraulic conductivity curve was superposed to the corresponding compaction curve during the entire range of the two processes and presented in Figure 5-13.

The trend of the hydraulic conductivity and the position where minimum occurred for each mix appeared to be a function of the polymer content and compaction water content. Another observation is that, samples containing more SAP tend to develop their lower conductivity at higher water contents. This may be due to the fact that more polymers in the mix leads to more water absorption causing the need for additional quantity to wet the grains of tailings. Like BDT mixes, the same trend in hydraulic conductivity, particularly, steep decreasing slope up to optimum moisture content followed by a near constant value at wet of optimum or near paste consistency-like is noticed. The slowness (slow down) in the decreasing rate of the hydraulic conductivity is probably due to the fact that maximum clogging of the pores already took place and no further swelling pressure is developed as the SAP has reached this value (taking into account the

space it is confined to). Another way to say that would be: past a certain amount of water absorbed, the swelling pressure developed in SAP is less important. Other probability is that, at the optimum moisture content where voids are minimum and at the wet of optimum the swelling SAP particles were in deformable gel phase, therefore were able to fit the pores during the compaction process. Then, during hydration under permeant, they are already at the appropriate location to fulfil the blockage. The effectiveness of their swelling is more acute than when the SAP grains (in dry of optimum) remained as a whole solid at a specific location where the swelling took place. Therefore, as the water content was increased, the hydraulic conductivity continued to decrease but, at a slower rate. This is probably because the clogging of the pores, as such as the swelling cannot further develop.

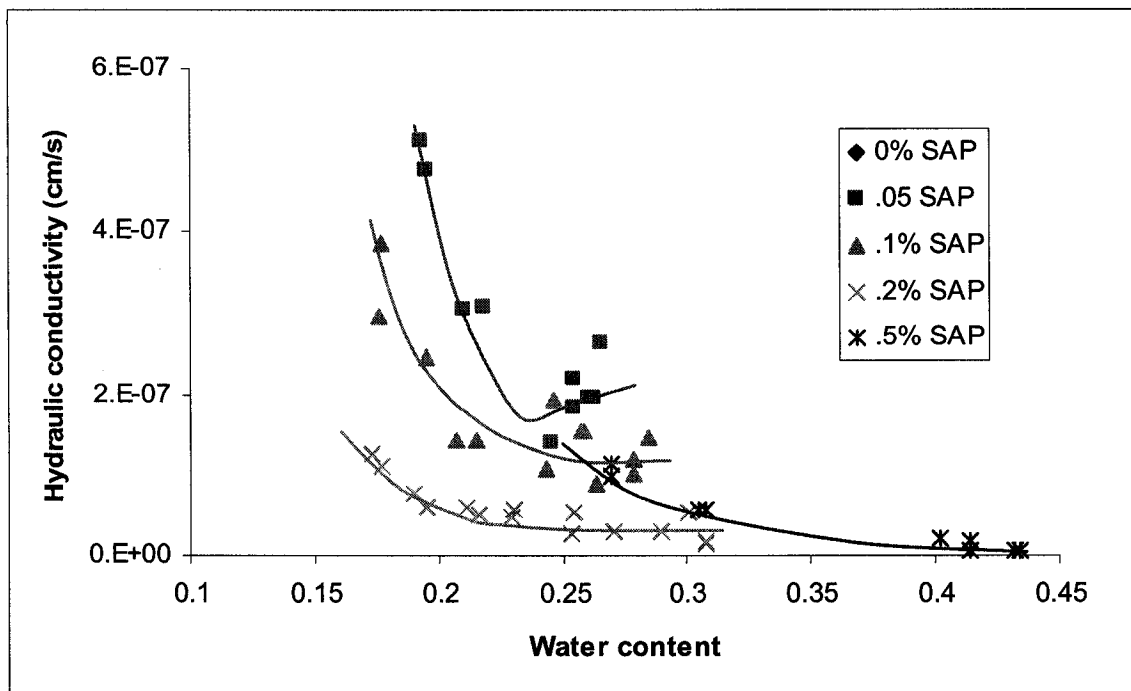


Figure 5-12. Effect of different SAP proportions and water content on hydraulic conductivity SAP densified tailings liner

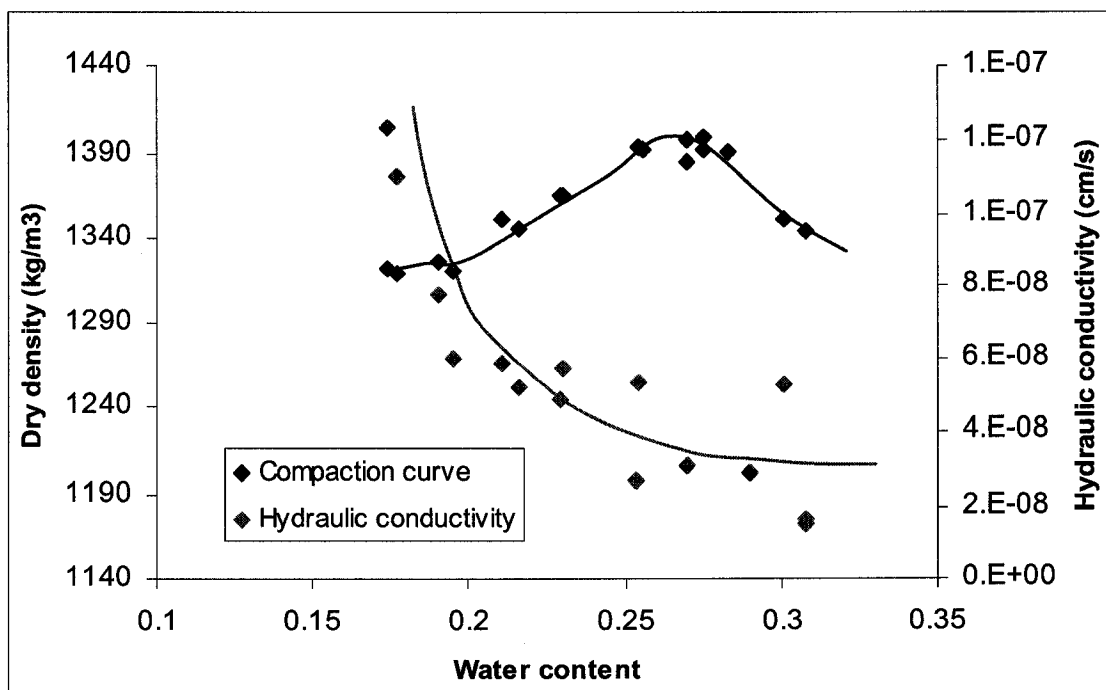


Figure 5-13 Variation of hydraulic conductivity with compaction curve (0.2% SAP)

When comparing the different mix proportions, one can realize that, as the percentage of SAP was increased, the hydraulic conductivity was decreased. For instance, the values recorded for 0.05, 0.1, 0.2 and 0.5% SAP were respectively 2.00×10^{-7} , 1.04×10^{-7} , 4.00×10^{-8} and 8.00×10^{-9} cm/s. Therefore, one can deduct that increasing the polymer content has a positive effect on the hydraulic conductivity of the densified tailings.

This positive effect can be explained by 2 processes which has taken place in the tested samples. First, the polymers are highly hydrophilic with a very high absorption capacity. They posses this feature from their cross linked structure where internal ions provoke osmosis, leading to water attraction that drives to a considerable increase in volume. In the case of the polymers used in this study, the absorption capacity in deionized water is 250 times their own weight (Arkent 2003). Therefore, the polymer as a solute attracts and associates itself with the molecules of the solvent water. This association of the water molecules with the ions in the polymer develops repulsive forces internally in the polymer that expand its molecules, creating large absorption capacities. These ionic forces have also for effect to act over the flow of water causing it to slow down in the specimen. Added to the charged ions effect, the expansion of the polymer contributes to a large extent to the filling of the pores in the previously compacted tailings. This ability to increase in volume is remarkable by the swelling tendency of the samples after they were removed from the sampling cylinder. The swelling

is manifested by cracks development when sample is not restrained (Figure 5-14). This process takes place even in the absence of supplying water because polymers continue to suck interstitial water which existed in the pores of the mix. It is important to recall that during hydraulic tests in the triaxial cell, once the sample is installed, it is restrained by a lateral confining pressure, the base and the loading cap preventing it from expanding (in one direction). Therefore as the polymers grains or gel tend to expand, instead they contribute to fill the pores and also develop swelling pressures which inhibit water flow in pores. For further illustration Figure 5-15 shows the mix of tailings and water having paste-like consistency which was converted into apparent non cohesive clumps after polymer addition in Figure 5-16.

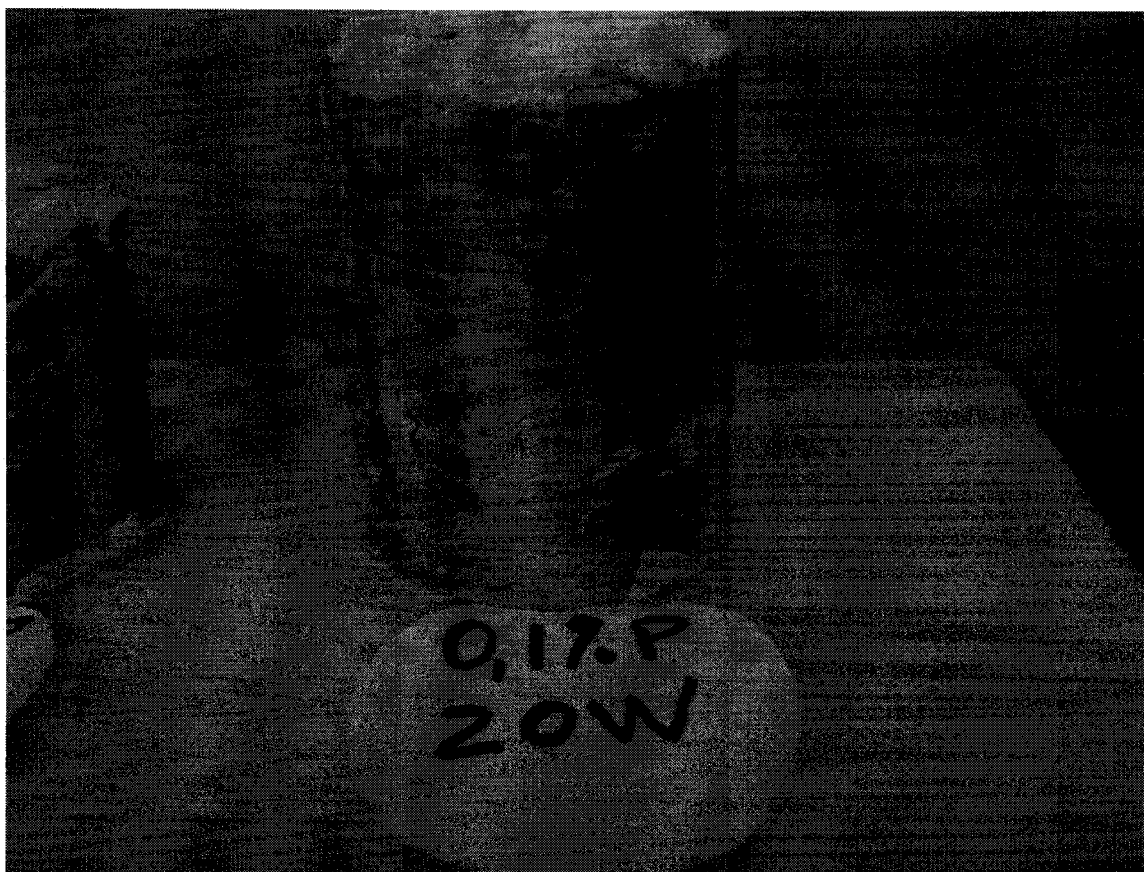


Figure 5-14. Expansion of the sample under swelling pressure developed by SAP.



Figure 5-15. Sample consistency prior adding SAP

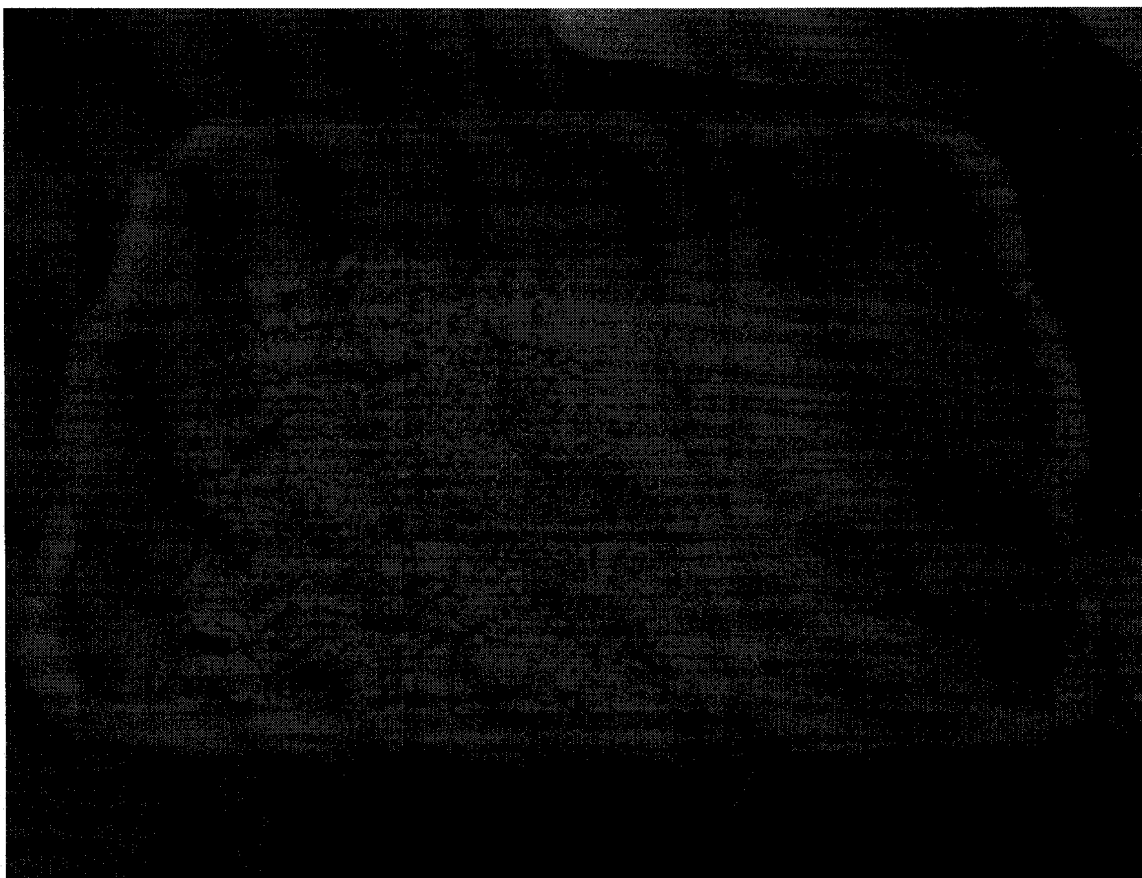


Figure 5-16. Sample consistency after adding 0.1% of SAP.

5.5.2.4 Effect of freeze-thaw on hydraulic conductivity

5.5.2.4.1 Hydraulic conductivity of bentonite densified tailings (BDT) liner under freeze thaw conditions.

The effect of cyclic freeze-thaw on hydraulic conductivity of tailings amended with bentonite for the proportions analyzed are presented in Figure 5-17 to Figure 5-19. From Figure 5-17, it can be observed that for 8% bentonite that the values fluctuated between 4.77×10^{-10} and 1.21×10^{-9} cm/s which represents a 153%

increase of the hydraulic conductivity, or an increase factor of 2.54. In another way, the increase is less than one order of magnitude.

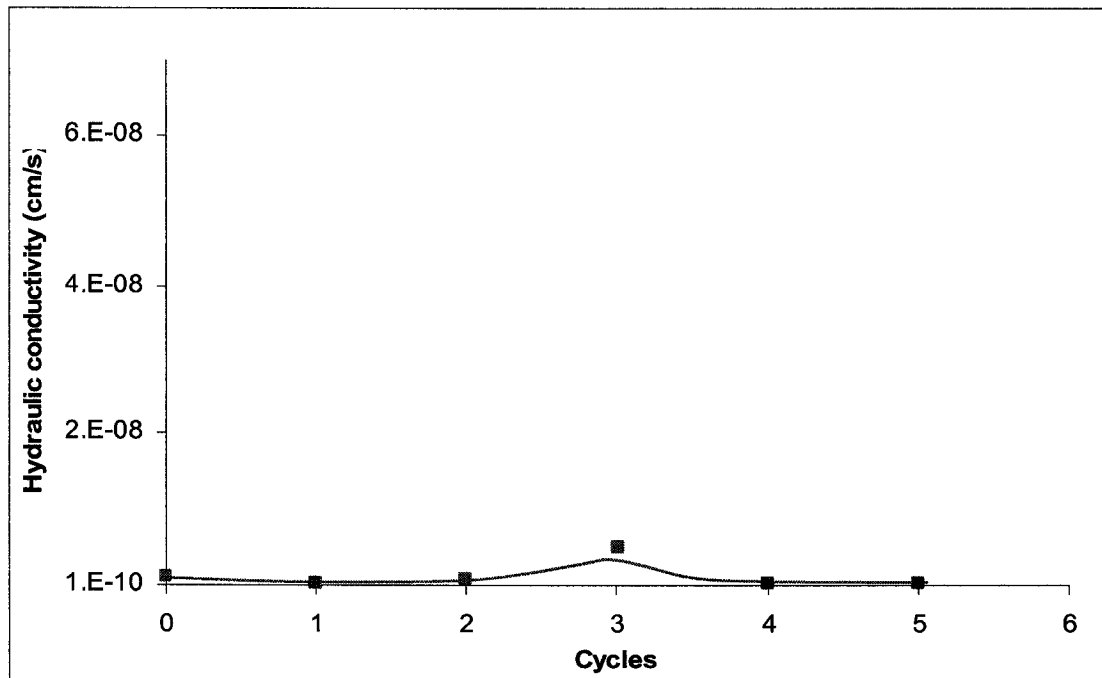


Figure 5-17. Variation of hydraulic conductivity with freeze-thaw cycles (8% bentonite, 23% water content)

For 4% bentonite mixes presented in Figure 5-18, minor fluctuations in hydraulic conductivity occurred in the range of 2.83×10^{-9} to 1.29×10^{-8} cm/s within the 5 freeze-thaw cycles which represents an increase of 355% or a factor of 4.56 times increase. This increase is also less than one order of magnitude.

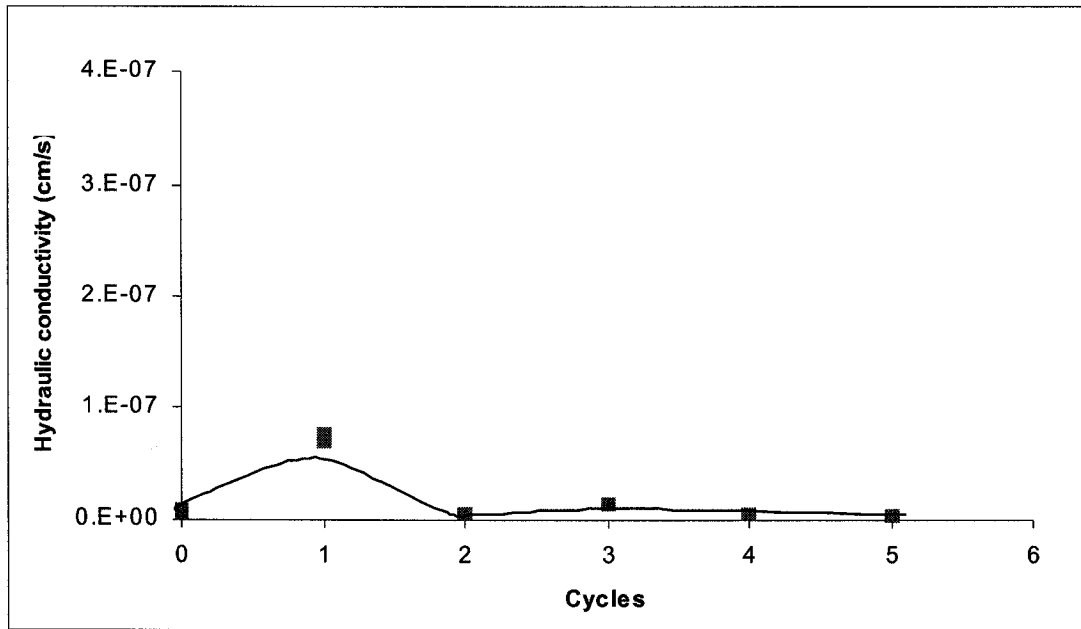


Figure 5-18. Variation of hydraulic conductivity with freeze-thaw cycles (4% bentonite, 23% water content).

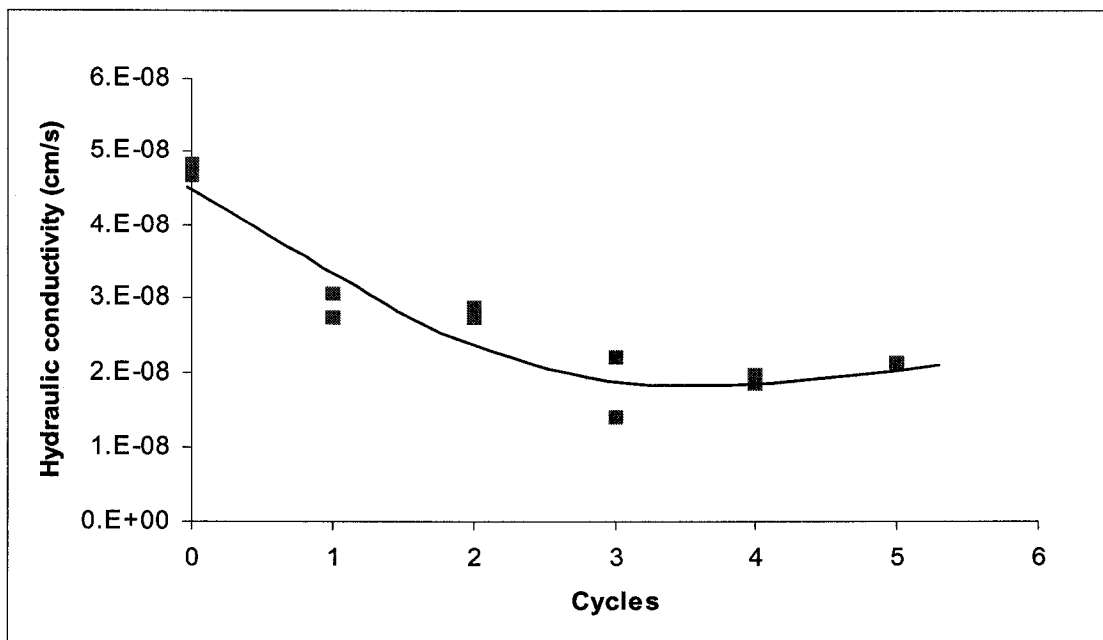


Figure 5-19. Evolution of hydraulic conductivity of BDT with freeze-thaw cycles (2% bentonite, 22% water content)

The values for the 2% bentonite (Figure 5-19) appeared to decrease slightly from 4.69×10^{-8} to 2.14×10^{-8} cm/s with the number of cycles. It represents a decrease factor of only 0.46. In terms of percentage, it represents a decrease of 54% in the hydraulic conductivity. In the tests, one could expect the hydraulic conductivity would increase significantly under these conditions in compacted clays like reported by several authors like Kim and Daniel (1992), Othman and Benson (1993) or, one can accept (be satisfied or be contented) by the results of small increase like reported by Viklander (1997), Hohmann-Porebska (2002). In the former stream of studies, researchers attributed increase in hydraulic conductivity to likely changes due to ice lenses formation and shrinkage due to water migration under temperature gradient. After Othman and Benson (1993, 1993a) Andersland and Anderson (1978), temperature gradient is reported as to be one of the most influencing parameter. However Hohmann-Porebska (2002) splitted the process into regions; the unfrozen and the freezing one. Aggregation took place due to water migration from the former to the latter. While particles are drawn closer in the unfrozen region giving rise to increased porosity, the opposite process occurs in the ice formation zone where microaggregates are destroyed. In the present study, the small effect, less than one order of magnitude in hydraulic conductivity, produced by these thermal loadings may be due to the fact that the heat removal rate brought moisture in the sample to the solid state in a very fast period of time. Figure 5-5 shows that it requires only 2 hours for the temperature to drop from 0 °C to -19 °C. In this small interval of phase change,

the formation of ice lenses and advancement of the front (Hewitt and Daniel 1977) were so fast that no migration of water that could form large ice lenses and affect the fabric of the material took place. Based on the definition used by Othman (1993a) the freezing rate applied to the samples in the present study would be considered as being 1.04×10^{-4} m/s while Othman and Benson (1993a) considered a rate of 10^{-6} m/s as being fast.

Therefore freezing would take place globally as a whole in the sample. This way, all ice lenses would develop simultaneously, preventing suction effect and cancelling fluid movement to large individual ice lenses which would exercise stresses by their higher volume inside the material. The stresses would generally be translated into cracks which would have for effect to damage the material fabric (Hohmann-Porebska 2002, Othman and Benson 1993). In the case of the 2% bentonite mix, the appearance of the slight decrease with cycles count may be attributed to experimental error due to the sensitivity of the readings corresponding to only 1/10 ml graduation. All samples were inspected for visual cracking on their surfaces or for other damage which could happen to them. No visual sign was detected, only some apparent film of ice would cover parts of the samples. One explanation could be that each individual ice lens built up at its original pore position and stayed immobile as gradient terminated early. Any expansion or shrinkage would take place locally without extending the pores network connexion. This inhibition of flow may become more pronounced by the low hydraulic conductivity of the material, where more time would be required for

the fluid to advance within the cold front. For the cycle completion, during the thawing, the fabric would only restore to the samples original fabric without noticeable damage.

5.5.2.4.2 Hydraulic conductivity of polymer densified tailings (PDT) liner under freeze thaw conditions.

The different SAP tailings mixes containing additive in proportions of 0.05, 0.1, 0.2 and 0.5% were submitted to freeze-thaw conditions up to a concurrence of 5 cycles. The results of the hydraulic conductivities were recorded after each cycle and reported on the graphs presented in Figure 5-20 to Figure 5-23. Compared to the bentonite samples, it was easier to discover, with the unaided eyes, after each freezing or thawing, that the initial small cracks appeared to be more visible in the SAP densified tailings samples. The appearance of horizontal cracks in the same direction as the deposited compacting layer (lifts) was already common to this type of material and manifested once it was removed from the sampling cylinder and put to rest as previously noticed in Figure 5-14. As the material was not plastic at all and behaves more likely as an elastic material, it was determined that these cracks were reclosable under application of very small vertical stress. The cracks were more visible in samples with higher SAP content. This can be understood from the fact that, more SAP is capable of more water absorption from the mixtures. Water absorption converted the SAP into grains or gel of higher volume that pushed the desiccated tailings grains apart, up to the appearance of the cracks.

In the 0.5% SAP tailing densified samples, a continuous increase in hydraulic conductivity is developed with the number of cycles as shown in Figure 5-20. This increasing appeared to become more important at the third cycle. The computed increase in hydraulic conductivity is found to be 715% and the factor affecting this increase is evaluated to 8.15 therefore less than one order of magnitude.

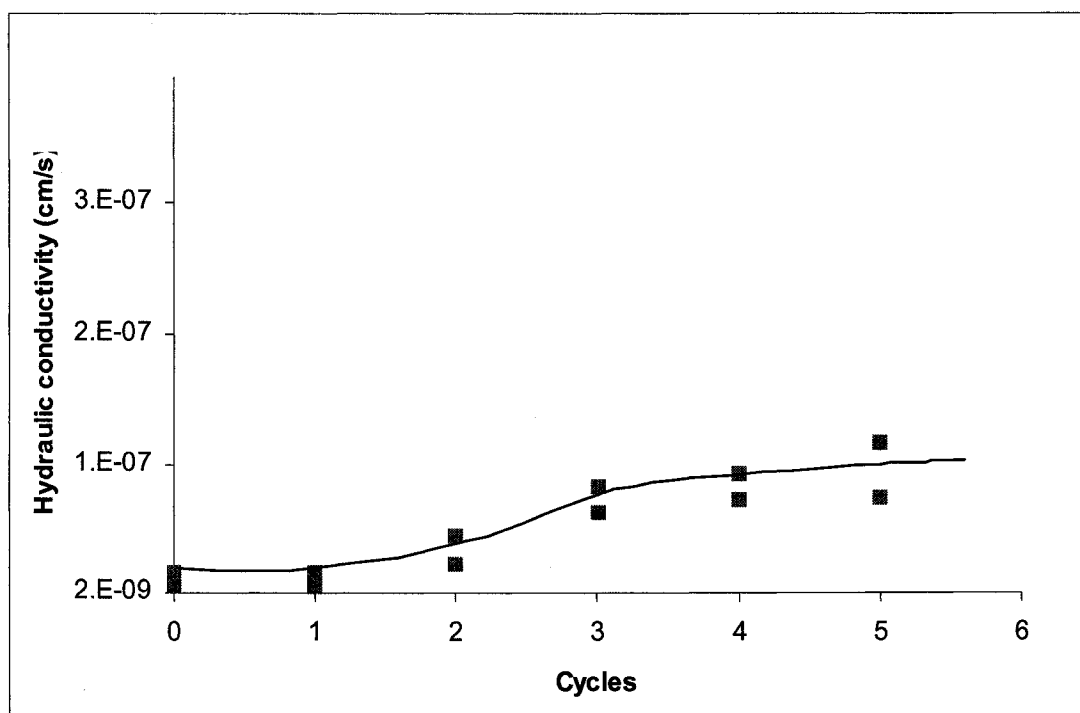


Figure 5-20. Evolution of hydraulic conductivity of SAP densified tailings tailings liner with freeze-thaw cycles (0.5% SAP, 41% water content)

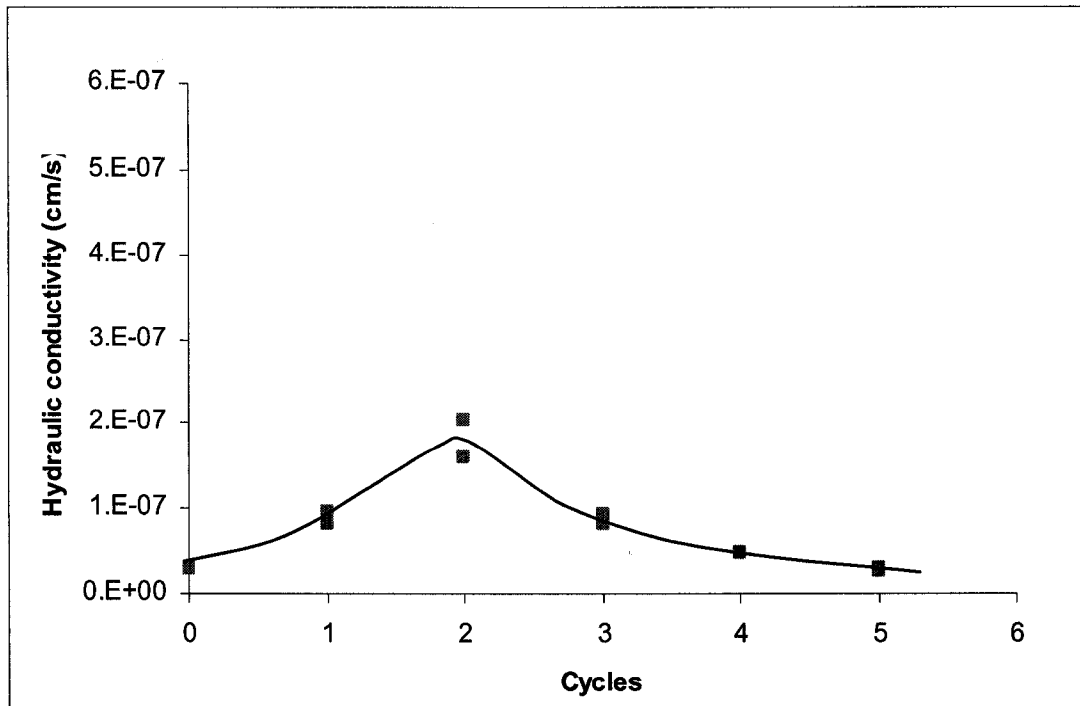


Figure 5-21. Evolution of hydraulic conductivity of SAP densified tailings liner with freeze-thaw cycles (0.2% SAP 29% water content)

SAP densified tailings samples incorporating 0.1% of SAP also demonstrated an increase in their hydraulic conductivity as the number of cycles increased. The evolution presented in Figure 5-22 shows clearly this trend. The low spike that was recorded at the third cycle may be attributed to experimental error or to a sample having some perturbations. Evaluation of the increase in hydraulic conductivity showed that relative change of 105 % change took place in the positive direction with corresponds to a factor of 2.05. The variation remained under the magnitude order.

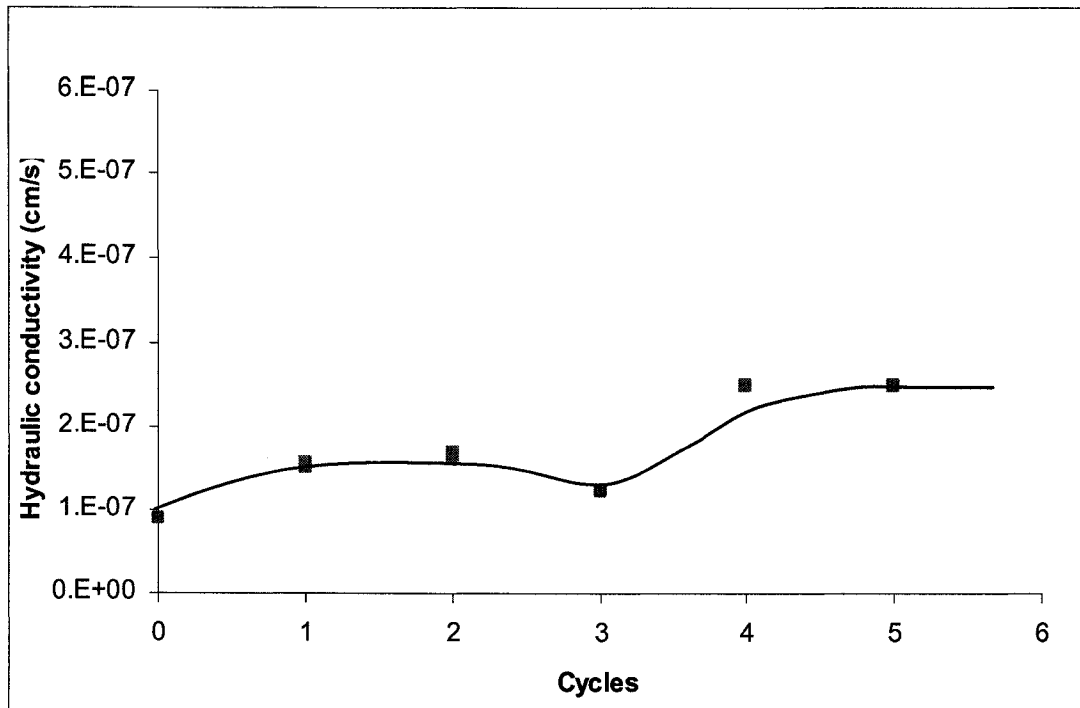


Figure 5-22. Evolution of hydraulic conductivity with freeze-thaw cycles and SAP content (0.1 SAP, 26% water content).

In the SAP- tailings mixes series, the 0.05% SAP represented the category with the lowest additive. The evolution of freeze-thaw on the effect of hydraulic conductivity up to 5 cycles is drawn in Figure 5-23. This graph shows a definite difference as compared to mixes containing 0.5%, 0.2% and 0.1% SAP. When discarding the value presented in the third cycle which can be easily attributed to some dysfunction, the trend would end to a decrease in the hydraulic conductivity with the freeze-thaw conditions. That is the initial value of hydraulic conductivity did a relative drop of 86% which corresponds to a decrease factor of 0.14. Therefore, when taking a closer look of the change in factor this can be

considered almost negligible if one takes into account, the factor of error that such laboratory test can entail.

This very low change in hydraulic conductivity may be attributed to the low water content present in the sample (24%) and the presence of small amount of SAP (0.05%) which would infer that, increasing the SAP proportion which leads to an increase in water content would position the material in an increased sensitivity to freeze-thaw cycles.

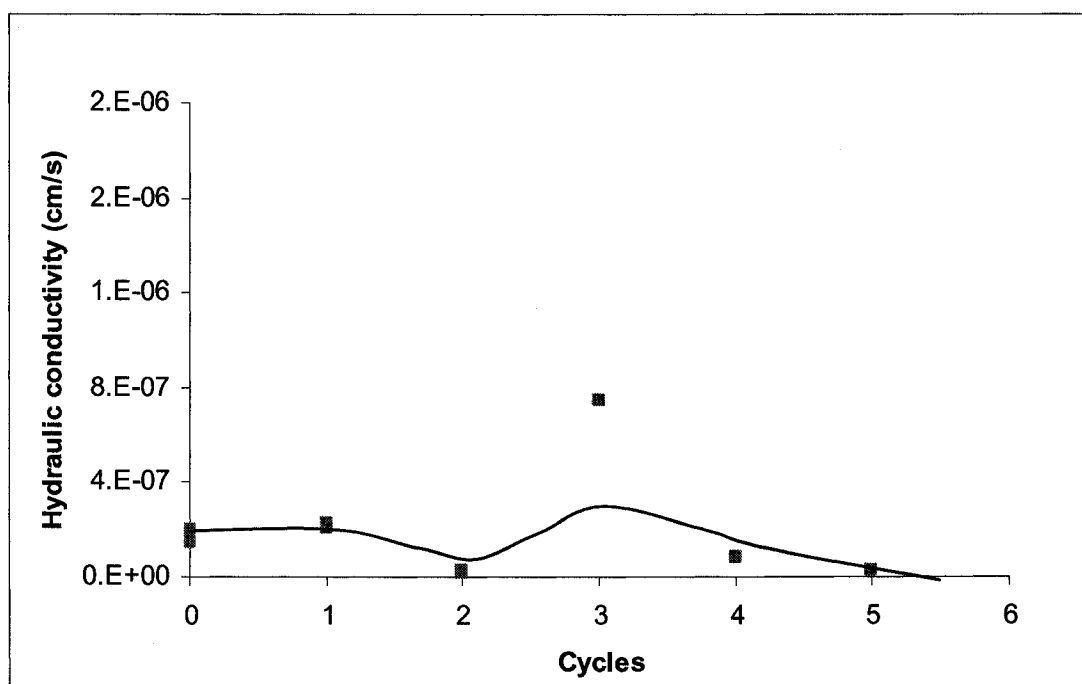


Figure 5-23. Evolution of hydraulic conductivity with freeze-thaw cycles and SAP content (0.05 SAP, 24% water content)

However, here also, like in bentonite mixes, no significant change in hydraulic conductivity was detected. One important observation is that, as the proportion of SAP was increased, the changes in hydraulic conductivity were more apparent, even though before any application of freeze-thaw that the sample containing higher SAP content presented lower hydraulic conductivity. Finally the slight fluctuations encountered during the various cycles for particular SAP content could be more attributed to slight difference in samples compaction or experimental error overall when placing the top cap and fixing the ram in the triaxial cell as the SAP samples were lightweight and difference in ram pressure could be of importance.

5.5.3 Cost effectiveness

Based on the fact that bentonite is extensively used in hydraulic barriers mixed with sand or clay (Datta 2003), during this study, either bentonite or superabsorbent polymers was introduced in the densified tailings in various concentrations to improve the hydraulic properties of the tailings. Amounts of 2%, 4% and 8% of bentonite from one hand and, 0.05%, 0.1% 0.2% and 0.5% of polymers were considered as acceptable concentrations which conferred to the tailings a significant decrease in hydraulic conductivity, till the minimum requirement for the usage as liner. Therefore in such conditions, it arose the question to know if it is beneficial to use such amended tailings materials. To have an idea of the cost positioning, the price per unit of mass was compared to the one of a barrier made of sand or clay mixed with 12% of bentonite in total

mass (Chapuis 1990). At a unit Kilogram price of 3.96 \$ for bentonite and a unit Kilogram price of 9.79 \$ for polymer, for any determined mass M of liner, the cost for 12% bentonite is estimated to 0.47 \$ while the costs for 8%, 4% and 2% of bentonite are estimated to 0.32 \$, 0.16 \$, and 0.08 \$, respectively.

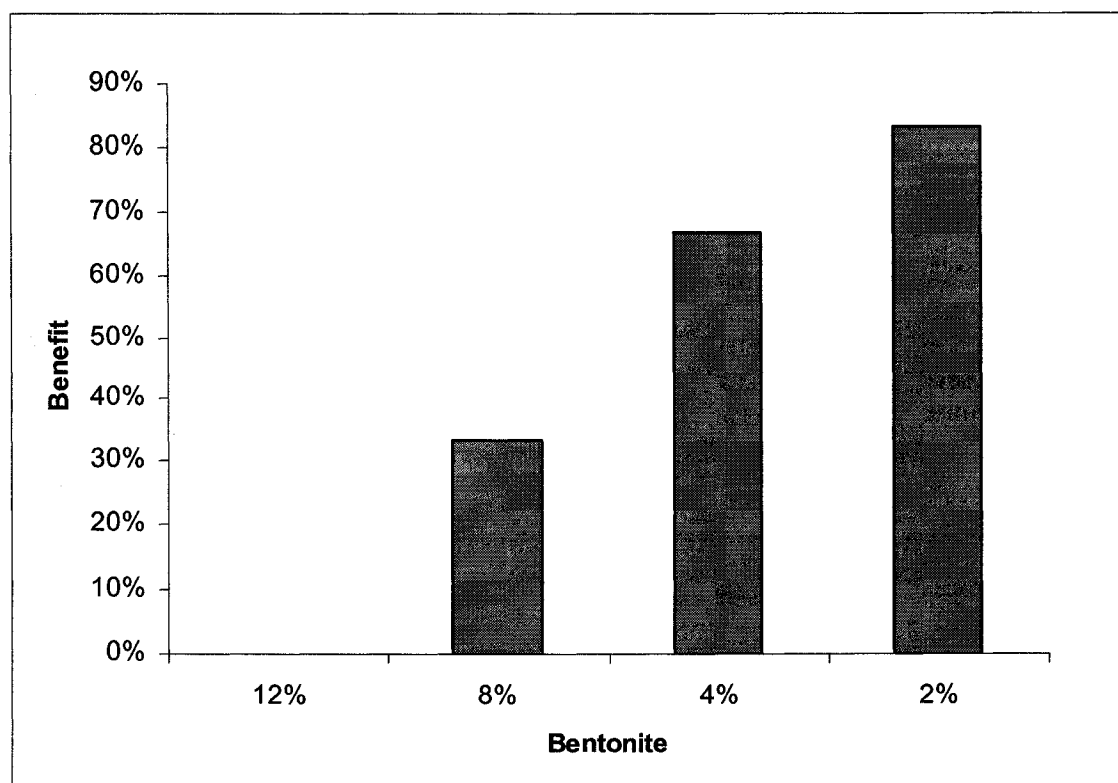


Figure 5-24. Relative benefit realization when using bentonite densified tailings liner as compared to a conventional 12% bentonite mixture.

On the other hand, for the same considered mass M of liner, the costs for 0.05%, 0.1%, 0.2% and 0.5% of polymer densified tailing liner are 0.0048 \$, 0.0097 \$, 0.019 \$ and 0.049 \$, respectively. Still taking as reference the 12% bentonite cost, the benefit realized could be estimated to 33%, 66% and 83% when using

bentonite densified tailings liners containing 8%, 4% and 2% of bentonite. For the SAP densified tailings liner category the benefit can be evaluated to 99%, 98%, 96%, 90%, for mixes made with 0.05%, 0.10%, 0.20%, 0.50% of polymers, respectively during the production. The benefit is presented graphically for ease of comparison in Figure 5-24 and Figure 5-25

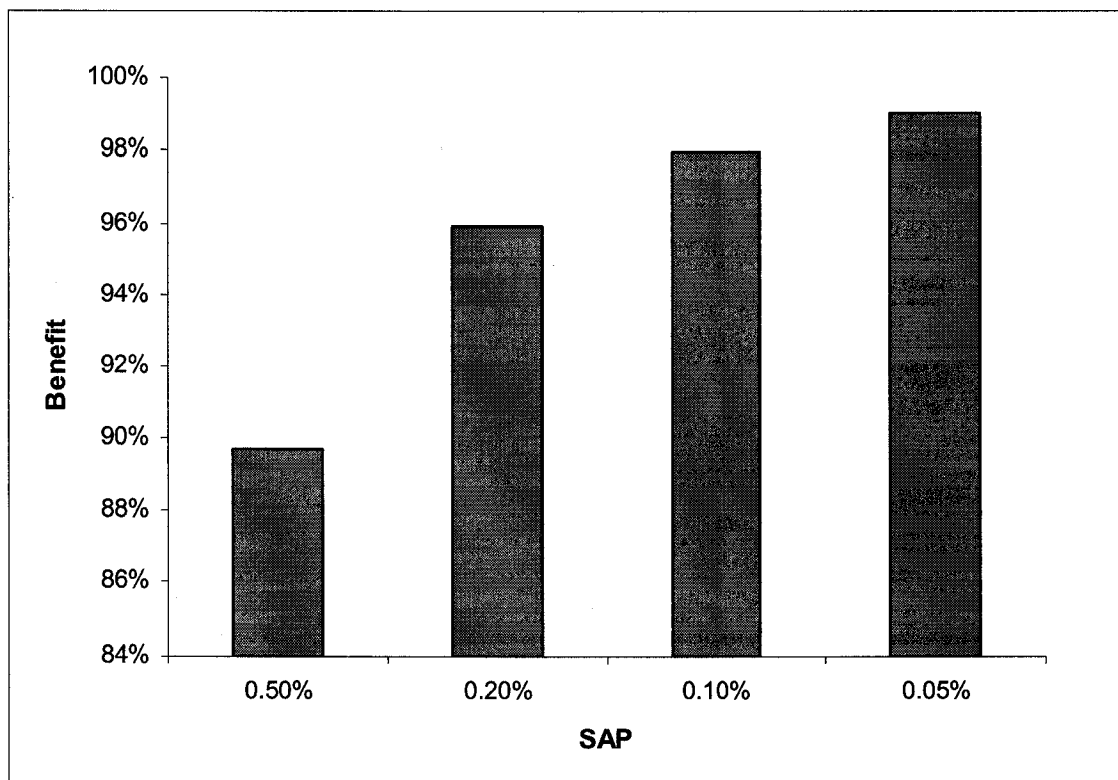


Figure 5-25. Relative benefit realization when using SAP-densified tailings liner as compared to a conventional 12% bentonite mixture.

It becomes obvious that 12% of bentonite is more significant than any of the amount (8, 4, 2%) of bentonite required to be mixed in the tailings to achieve the recommended low conductivity. More cost benefit is realized when making usage

of SAP with the tailings even though the cost per unit mass of SAP is 2.5 higher than the one of bentonite. This is due once more to the fact that further less SAP is used during the mix. Another way to explain this is that the percentage of additive is the determinant factor in the final cost. This is essentially due to its very low concentration in the mixes.

5.6 Summary and conclusions

In this paper, investigation on waste mine densified tailings was conducted which aims at the beneficial recycling of these materials. Based on the low hydraulic conductivity of compacted tailings, 10^{-5} - 10^{-6} cm/s, at wet of optimum, bentonite and superabsorbent polymers were added to improve this property. These additives were chosen for their high swelling pressure and absorption capacity. The tests comprised of two categories of mixes: one composed of tailings and bentonite in 8%, 4% and 2% proportion and another one comprised of tailings and polymers in proportion of 0.05%, 0.1%, 0.2% and 0.5%. The composite tailings mixes exhibited hydraulic conductivity as low as 1.38×10^{-9} cm/s with 8% bentonite. The SAP densified tailings mixes series of 0.2%, 0.1% and 0.05% were discarded after investigation because of their fluctuation when submitted to freeze-thaw beyond the 1×10^{-7} cm/s limit recommended for hazardous waste. It was found that after fast decrease of hydraulic conductivity at the wet of optimum, that one reached an almost steady value when it crossed the 2% (higher than the OMC) wet of optimum in bentonite samples. This behavior corroborates various studies that reported a minimum hydraulic conductivity near

4% water content higher than the optimum (Palmer et al. 2000, Abichou et al. 2004). It is also supported by the theory which let knows that the "hydraulic conductivity of compacted fine-grained soils depends strongly on the moisture content, and that lower permeability values can be obtained for water contents wet of optimum" (Mitchell et al. 1983). The concept of high permeability in dry of optimum and low permeability in wet of optimum is supported by the flocculated and disperse structure at the dry and wet optimum after Lambe (1958). Mitchell et al. (1965) and Barden and Slides (1970) evoked the preferential flow through clusters and clods and macropeds. Beyond a certain percentage of additives, searching for further drop in hydraulic conductivity with further increasing the proportion of these latter may not be justifiable. Therefore, it can be inferred that it existed an optimum percentage of additive at which the hydraulic conductivity is acceptable (Shackelford 1994). It was discovered that low hydraulic conductivity took place far from the optimum moisture content in 0.5% SAP contrarily to the close positioning in samples with lower SAP content.

The long term performance consisting in the application of freeze-thaw cycles at moulding water content demonstrated that this factor had light adverse effect. That could be attributed to imperceptible cracks development or no intense change in the fabric of the materials. It appeared that the small increases in hydraulic conductivity occurred only in composite made of SAP and it would be a little more significant in sample with higher proportions. It was even observed a progressive decrease in this property with samples containing 0.05% SAP with

the number of cycles. None of the sample developed change in the order of magnitude. The good response of the composite material may be due to possible resealing of micro-cracks with self healing property entailed by the high swelling additives.

Cost assessment of the material in reference to 12% bentonite (usually used in sand mixtures) was also investigated. Feasibility showed economical gains as high as 90% and 67% could be earned when using 0.5% of SAP and 4% of bentonite, respectively. The use of 8% of bentonite (hydraulic conductivity 6.27×10^{-10} cm/s) would drop savings to 33%, but one has to evaluate the ratio hydraulic conductivity versus economy prior taking decision.

However, this study has unexplored phases essentially:

- Mechanical parts; shear stress, bearing capacity, tensile stress, modulus of elasticity.
- Leachates; it is known that, type and concentration of chemical can affect hydraulic conductivity (Katsumi et al. 2008, Shackelford et al. 2000 and Kashir and Yanful 2001) by leading to collapse of the bounding, and double layer effect existing in the additives. It is also susceptible to reduce absorption capacity in polymers as specified by manufacturer data sheet (ARK 2008). Thus this part of the study may have under-estimated the hydraulic conductivity by using deionized water.

- Vertical stress; vertical stress was considered equal to zero. Assigning it a value comparable to overburden pressure would definitely decrease the recorded values of hydraulic conductivity (Kashir and Yanful 2001, Kim and Daniel 1992). Omitting this effect led this study to overestimate the hydraulic conductivity in the densified tailings materials.
- Hydraulic gradient; In field gradient of 600 is unlikely to happen. However, it was inescapable because of the excessive time that would be required to conduct the tests with values comparable in waste repositories. Literatures published about accelerated tests by subjecting samples to high hydraulic gradients are variables and inconclusives about the effect on hydraulic conductivity results (Dixon et al. 1999).

Authors are unanimous to recognize that high gradient provides valuable information about the range of hydraulic conductivity. They all support the fact that confining pressure, effective stress and overburden have positive effect on the hydraulic conductivity of liners (Shafiee 2008, Smith et al 1999).

5.7 References

Abichou T., Edil T.B., Benson C. H., Tawfiq K. Hydraulic conductivity of foundry sands and their use as hydraulic barriers, Geotechnical Special Publication. (2004) 186-200.

American Society for Testing and Materials, Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³)) D 698-00a, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, C 136, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Method for Particle-Size Analysis of Soils D 422-63, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Method for measurement of hydraulic Conductivity of Saturated porous Materials Using Flexible Wall Permeameter D 5084-00, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Method for Determining the Effect of Freeze-Thaw on Hydraulic Conductivity of Compacted or Undisturbed Soil Specimens Using a Flexible Wall Permeameter D6035-96, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils D 4318-00, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

American Society for Testing and Materials, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer D 854-02, Annual Book of ASTM Standards, vol. 04.02, Pennsylvania, 2004.

Andersland, O. B., Anderson, D. M. Geotechnical Engineering for Cold Regions. McGraw-Hill Book Co., Inc., New York, N.Y. (1978)

Andrejkovicova S., Janotka I., Komadel P. Evaluation of geotechnical properties of bentonite from Lieskovec deposit, Slovakia, Applied Clay Science. 38 (2008) 297-303.

ARK. The ARK Entreprises, Inc. PO box 725, Peculiar, Missouri 64078. (2003), http://www.arkent.com/products/aqua_sorb.html

Aubertin M., Bussière B., Chapuis R. P. Hydraulic conductivity of homogenized tailings from hard rock mines, Canadian Geotechnical Journal. 33 (1996) 470-482.

Barden, L., Sides, G. R. Engineering behavior and structure of compacted clay." J. Soil Mech. and Found. Div., ASCE, 96 . (1970). 1171-1200.

Chapuis R. P. Sand-bentonite liners: predicting permeability from laboratory tests, Canadian Geotechnical Journal. 27 (1990) 47-57.

Daniel D. E. Geotechnical practice for waste disposal. Chapman and Hall, London, (1993) 683p

Datta M., Geotechnical study for hydraulic barrier systems at tailings pond, Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management. 7 (2003) 163-169.

Dixon D. A., Graham J., Gray M. N. Hydraulic conductivity of clays in confined tests under low hydraulic gradients, Canadian Geotechnical Journal. 36 (1999) 815-825.

Elsbury B. R., Daniel D. E., Sradars G. A., Anderson D. C. Lessons learned from compacted clay liner, *Journal of geotechnical engineering*. 116 (1990) 1641-1660.

Fall M., Samb S. S. Impact of high temperature on the performance properties of underground cemented paste backfill (2006) *Sea to Sky Geotechnique*.

Falode O. A., Ehinola O. A., Nebeife P. C. Evaluation of local bentonitic clay as oil well drilling fluids in Nigeria, *Applied Clay Science*. 39 (2008) 19-27.

Grabinsky M. W., Therieult J., Welch D. An overview of paste thickened tailings disposal on surface. In: *Proceedings of the Symposium 2002 sur l'environnement et les mines: Défis et perspectives*. Rouyn-Noranda, CIM, Papier 533.

Hewitt R. D., Daniel D. E. Hydraulic conductivity of geosynthetic clay liners after freeze-thaw, *Journal of Geotechnical and Geoenvironmental Engineering*. 123 (1997) 305-313.

Hohmann-Porebska M. Microfabric effects in frozen clays in relation to geotechnical parameters, *Applied Clay Science*. 21 (2002) 77-87.

Jackson N. L. Frequency distribution of clay minerals in major great soil groups as related to factors of soil formation. *Clay Mineral* 5 (1957) 279–288

Kalkan E., Akbulut S. The positive effects of silica fume on the permeability, swelling pressure and compressive strength of natural clay liners, *Engineering Geology*. 73 (2004) 145-156.

Karickhoff S. W., Brown D. S., Scott T. A. Sorption of hydrophobic pollutants on natural sediments, *Water Research*, 13 (1979) 241-248.

Kashir M., Yanful E. K. Hydraulic conductivity of bentonite permeated with acid mine drainage, *Canadian Geotechnical Journal*. 38 (2001) 1034-1048.

Katsumi T., Ishimori H., Onikata M., Fukagawa R. Long-term barrier performance of modified bentonite materials against sodium and calcium permeant solutions, *Geotextiles and Geomembranes*. 26 (2008) 14-30.

Kim W., Daniel D. E. Effects of freezing on hydraulic conductivity of compacted clay, *Journal of geotechnical engineering*. 118 (1992) 1083-1097.

Lambe T. W. The structure of compacted clay. *Journal of the Soil Mechanics and Foundation Division, ASCE*, 84 (1958). 1-34.

Mitchell R. J., Olsen R. S, Smith J. D. Model studies on cemented tailings used in mine backfill. Can geotech J, V19, N1, Feb 1982, P14–28, International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, 20 (1983) A12-A12.

Mitchell J. K., Hooper, D. R., Campanella, R. G. Permeability of compacted clay. Journal of the Soil Mechanics and Foundation Division, ASCE, 91 (1965). 41-65.

Onikata M., Kondo M., Hayashi N., Yamanaka S. Complex formation of cation-exchanged montmorillonites with propylene carbonate: osmotic swelling in aqueous electrolyte solutions. Clays and Clay Minerals 47 (5), (1999a) 672–677.

Othman M. A., Benson C. H. Effect of freeze-thaw on the hydraulic conductivity and morphology of compacted clay, Canadian Geotechnical Journal. 30 (1993) 236-246.

Othman M. A., Benson C. H. Effect of Freeze-Thaw on the Hydraulic Conductivity of Three Compacted Clays from Wisconsin, Transportation Research Record, 1369. (1993a) 118-125.

- Othman M. A.; Benson C. H. Effect of freeze-thaw on the hydraulic conductivity and morphology of compacted clay, *Can Geotech J* (30), (1993) 236–246
- Palmer B. G., Edil T. B., Benson C. H. Liners for waste containment constructed with class F and C fly ashes, *Journal of Hazardous Materials*. 76 (2000) 193-216.
- Qiu Y. J., Sego D. C. Laboratory properties of mine tailings, *Canadian Geotechnical Journal*, 38 (2001) 183 190
- Shackelford C. D., Benson C. H., Katsumi T., Edil T. B., Lin L. Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids, *Geotextiles and Geomembranes*. 18 (2000) 133-161.
- Shackelford C. D., Glade M. J. Constant-flow and constant-gradient permeability tests on sand-bentonite-fly ash mixtures, *ASTM Special Technical Publication*. (1994) 521-545.
- Shafiee A. Permeability of compacted granule-clay mixtures, *Engineering Geology*. 97 (2008) 199-208.
- Simon F., Müller W. W. Standard and alternative landfill capping design in Germany, *Environmental Science & Policy*. 7 (2004) 277-290.

Smith C. C., Cripps J. C., Wymer M. J. Permeability of compacted colliery spoil - a parametric study, *Engineering Geology*. 53 (1999) 187-193.

Southen J. M., Kerry Rowe R . Evaluation of the water retention curve for geosynthetic clay liners, *Geotextiles and Geomembranes*. 25 (2007) 2-9.

U.S. Silica Company Material Safety Data Sheet. U.S. Silica Company. P.O. Box 187, Berkeley Springs, WV 25411-0187

Viklander P., Knutsson S. Permeability changes in a fine-grained till due to freezing and thawing. In: *Proc. 8th Int. Symp. Ground Freezing*, A.A. Balkema, Rotterdam, Netherlands (1997). 193–202.

6 Chapter 6

6.1 Conclusions and recommendations

Mining waste materials (tailings), converted into cemented paste tailings (CPT) were evaluated for thermal conductivity property, mechanical and hydraulic response under coupled loading of temperature and mix components. Densified tailings were also investigated in non cementitious state condition for their suitability for liner design material while admixture materials were added to them to improve their hydraulic conductivity.

From the laboratory tests conducted, information not yet available has been withdrawn from tailings materials in the two investigated states and can be reported as follows.

During quantitative evaluation of the thermal conductivity with the KD2 Thermal Analyzer, the extent of variation of this property was found to be more or less affected depending of the external factors (curing time and temperature) and internal parameters (binder content, binder type, water cement ratio, tailings fineness, tailings mineralogy and sulphur content). Part of these influencing factors can be classified as negligible or significant.

It was found that the binder type, the binder content, and the slump were of minor importance while the mineralogy, the fineness and the curing time were of significant importance. Furthermore, the significant ones can be classified as

two groups. One causing proportional variation in thermal conductivity as it is the case of the mineralogy through the quartz content and, another one causing the thermal conductivity to vary inversely with it, as it is the case of the fineness and saturation degree.

Though CPT is a material that differs from concrete by far, however, it owes its properties from the materials that compose it. From this perspective, the thermal conductivity can therefore be predicted from the minerals ponderance that form CPT as this was reflected in the paste compounds measurements during experiments. From the recall that light aggregates lead to decrease in thermal conductivity and quartz ones lead to increase in this property in concrete, it was noticed that quartz content produced the same effect in CPT.

On the other hand, the effect of chemical reactions that took place with time in hardening CPT showed intense fluctuations in the thermal conductivity at the early ages while for any chosen paste mix, at advanced age these fluctuations gradually stabilized to a constant value.

It is suggested to link this behavior to the chemical activity entailing the hydration process as reported by various authors who studied the hydration process in binder portland cement (Mindess and Young 1979, Zhang et al. 2002) where their studies showed that hydration starts within the first hours of contact of binder with moisture. In the case of paste tailings, it was noticed that this process was delayed over a longer period of time. Determination of the cause brought the attention of the author to possible hydration effect superposed to

evaporation effect thus led to study variations of parameters within CPT mass.

For such investigation of probable causes, a series of tests involving vertical and horizontal measurements of thermal conductivity with depth revealed that, this behavior was more related to the changes in saturation degree of CPT. It was found that the profile of saturation corresponded to low value at the top while it was increasing with depth. The explanation was, after that fluctuations in thermal conductivity reduced at the end of hydration process, evaporation process took control. Another valuable insight is the fact that after 28 days of curing at 35 °C that the degree of saturation in the experimental sample remained 93%. This observation offered complementary knowledge about retention capacity of backfill under low cement content and high specific surface (Henderson et al. 2005).

On another hand, the effect of coupling the mix proportioning to the temperature, showed how sensitive the CPT is to the combined interaction principally due to evaporation at exposed surfaces.

Under coupled effect of temperature and mix proportioning, while in all instances temperature had positive effect on the strength development and split tensile stress, hydraulic conductivity at the opposite varied inversely with this parameter.

At low temperature (2 °C) the coarser grain size always developed higher strength than their counterpart finer grains.

During all the test processes, it was always appearing that split tensile and UCS go by pair, following the same trend. However, hydraulic conductivity on the other side, appeared to always be inversely related to the mechanical parts. Therefore, it appears possible that a modeling investigation could determine the relationship between these three properties.

Such observations could not be noticed out of a range of coupled temperatures that matches site specific materials and proportioning. These laboratory tests were in measure to reflect probable field conditions at the opposite of previous studies focusing on a single mix proportion.

Possibilities of using densified tailings as liner materials appeared very promising owing their good hydraulic performance from inheriting fine grain size and the reduced cost from the low admixture amount necessary to further improve this performance. In the compacted material mixes, hydraulic conductivity was always found to be less and decreasing after the OMC. This behavior of the material always led to the same final result independently of the theory considered. Based on hydraulic conductivity results, both, the theory preconized by Lambe (1958) invoking flocculation at the dry of optimum and disperse arrangement at wet of optimum or the clods theory stipulated by Olsen (1962), where flow would take place in the interclod pores are satisfactory adapted to the laboratory tests conducted on the densified tailings.

As the thesis could not include the full characterization range of the material, these final recommendations are proposed:

- The investigation of strength development and hydraulic conductivity gradient as a function of depth in CBP mass under conditions of coupled temperature and mix proportioning to verify how these properties could be affected as it was the case for the degree of saturation and thermal conductivity profiles with depth.
- Application of vertical stress to simulate overburden stress as condition exists on field. This is also necessary to evaluate the liner response and would allow to quantify the extent of overestimation recorded in the current study in the absence of this parameter.
- The good liner response to deionized water needs to be verified against acids and leachates permeants under variable compaction energies for a full assessment of this new proposed material.
- This same suggestion applies to its performance to harsh temperatures as in opposite to freeze thaw conditions.

6.2 References

Fall M., Benzaazoua M. Modeling the effect of sulphate on strength development of paste backfill and binder mixtures optimization. Cement Concrete Research (2005); 35: 301-14.

Henderson A., Revell M. B., Landriault D., Coxon J. Paste Fill. Handbook on mine fill. Australian Centre for Geomechanics, PO Box 3296 Broadway, Nedlands, Western Australia, Australia 6009 (2005) 83-97

Olsen H. W. Hydraulic flow through saturated clays. Proceedings ninth national conference on clays and clays minerals, West Lafayette Indiana 9 (1962) 131-161

Zhang Y., Sun W., Liu, S. Study on the hydration heat of binder paste in high-performance concrete. Cement and Concrete Research, 32, (2002). 1483-1488.