Using Thermal Profiles of Cemented Paste Backfill to Predict Strength

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Civil Engineering
University of Toronto

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Abstract

Measurement of the strength development of Cemented Paste Backfill in laboratory cast cylinders does not replicate the in situ strengths of CPB in mine stopes. The mass of CPB in a filled stope is large and temperature rises due to the heat of hydration of the cementing materials, thus accelerating the gain in strength, relative to laboratory specimens stored at ambient temperature. The purpose of this study was to determine the impact on strength development when CPB test cylinders were subjected to a temperature profile mimicking that in a large mass, such as a mine stope. Also, maturity (the integral of time and temperature during hydration of the CPB) was compared to actual strengths, and the maturity – strength concept used in concrete technology was applied. It was found that the strength-maturity relationship was applicable to CPB once the base line or datum temperature was adjusted.
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Chapter 1
Introduction

1.1
During the hydration process of cement with water there is an increase in temperature due to the exothermic reactions. This rise in temperature becomes significant in cases of Cemented Paste Backfill (CPB) in mining where a massive amount of mix is deposited down a stope. Therefore the need for a better understanding of the effects of this parameter on physical characteristics of CPB led to research on this topic. Although the use of Cemented Paste Backfill has become more common in mining, the research on the thermal aspect of it is rather new.

1.2 Cemented Paste Backfill

Cemented Paste Backfilling (CPB) has become a popular method for management of solid waste (ground waste rock and tailings) generated by mining processes. It consists of water, 2% to 7% of binder (Cement with or without supplementary cementing materials), and dewatered tailings which when combined result in 70% to 85% of solids in CPB (Fall, Celestin, Pokharel, & Toure, 2010). In cases with insufficient amounts of mine tailings, “alternative sources, such as alluvial sands and quarried rocks are used to replace or supplement the mine waste as underground backfill” (Archibald, Hassani, Nantel, & DeGagne, 2000).

The main benefit of CPB is that it is an effective method for management and disposal of tailings. These finely ground tailings are left behind after the minerals have been extracted from ore which can add up massive amounts depending on the mining project. The mine waste produced in Canada alone was estimated around 500 million tonnes per year (Amaratunga & Yaschyshyn, 1997) and 45 million tonnes are produced annually in Sweden (SWRC, 1998). The underground voids due to mining have reached well beyond 10 million m$^3$ in Australia (Grice, 2001), and CPB provides a technique to fill these voids safely and reducing the tailings stored at the surface by 60% (Fall, Benzaazoua, & Saa, 2007).

This method gained some of its popularity due to the safety of the process when compared to other methods like Hydraulic Backfill which resulted in hazards such as failures of barricades
and subsequent mine fatalities (Fall, et al. 2010). CPB provides the ground support required to continue the mining process safely and economically.

The binder consumption is considered the major factor implicating the cost of a project. This constituent represents up to 75% of the cost in a Cementing Paste Backfill project (Grice T. 1998), which emphasized the importance of understanding the factors affecting the reactivity of this material, such as temperature. Until recently most of the research conducted on CPB were carried out at “laboratory” temperatures of about 20-25 °C which does not mimic the curing temperature at a mine level. For the purpose of this thesis, experiments were conducted on fill from three mines; Kidd mine and Williams mine in Canada, and Cayeli mine in Turkey. The Williams mine will be used for the most part to draw conclusions while the results for Cayeli and Kidd are provided in the appendices.

1.3 Objective

The objective of this research is to analyze the effect of temperature on physical characteristics of CPB, and further to provide a method for predicting the strength using the temperature developed by CPB in a mine.

1.4 Thesis Organization

First the literature is reviewed to illuminate the concepts such as hydration, CPB strength gain, and influencing factors. The materials used for the experimental aspect of research are then be mentioned and their impact on the overall characteristics of CPB is analyzed prior to explaining the experimental design itself. The results from Williams mine are presented and analyzed and used to draw conclusions and recommendations.
Chapter 2
Background

2

2.1 Hydration of Portland Cement

Hydration is a chemical process between the cement particles and water which ultimately leads to strength gain of the paste. The rate of reaction is dependent on the reaction of various cement phases with water. Portland cement has four major phases of Alite (impure $C_3S^*$), Belite (impure $C_2S$), Aluminate ($C_3A$), and Ferrite ($C_4AF$). The correct balance in quantity of these phases leads to the desired properties such as workability and early strength (Mamlouk & Zaniewski, 2006). Alite and Belite attribute to the strength gain at early and later age of the paste respectively, which makes them the most important phases. Aluminate reacts with water rapidly and evolves a lot of heat. This can lead to flash set, an irreversible hardening at less than 10 minutes into mixing, unless calcium sulfate is added to the cement (Mehta & Monteiro, 1993).

The main hydration product is Calcium Silicate Hydrate (C-S-H) which attributes to the ultimate strength of the paste. The byproduct of C-S-H is Calcium Hydroxide (CH) which accounts for 20% by mass of hydrated cement paste and adds no major strength gain. These two are the outcome of Alite and Belite undergoing the following reactions:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \quad \text{Equation 1}$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \quad \text{Equation 2}$$

It is seen from Equation 2 that Belite produces less CH than Alite, therefore it can be said that cement with more Belite can achieve higher ultimate strength. This is mainly due to the weak nature of CH and that the space occupied could be better filled with C-S-H that has a much higher strength (Hooton, 2009).

* Cement Chemical Notation: $C = CaO$, $S = SiO_2$, $A = Al_2O_3$, $F = Fe_2O_3$, $H = H_2O$
The degree of hydration is dependent on various variables such as ratio of water to cementitious material ratio, type of supplementary cementing material, curing conditions, and age. The water to cementitious material ratio in CPB is very high, around 15, relative to traditional concrete mixes which are preferably kept lower than 0.5. Therefore the volume of capillary voids (the space not filled by the solid components of the hydrated cement paste) in CPB are expected to be much higher.

Several methods are available to evaluate the progress of cement hydration in hardened concrete. These include measuring the following properties (Neville, 1995).

1. the heat of hydration
2. the amount of calcium hydroxide in the paste developed due to hydration
3. the specific gravity of the paste
4. the amount of chemically combined water
5. the amount of unhydrated cement paste using X-ray Quantitative analysis
6. the strength of the hydrated paste, an indirect measurement

In this paper, the heat of hydration of cement pastes was used as a quality check of the material.

2.1.1 Effect of Water Content on Cement Hydration

As shown in Equations 1 and 2, water is required to initiate and continue the hydration process. Researchers have evaluated the amount of water required for complete hydration of cement to be 0.23 to 0.25 grams of water for every gram of cement used (Mills, 1966; Powers, 1949). More water is added to account for other factors such as workability. The additional water would have an adverse impact on strength which will be discussed at later in this paper.

2.1.2 Effect of temperature on Cement Hydration

Temperature plays an important part in rate of hydration and subsequently on the strength of paste. The effect of temperature on cement hydration can happen at various phases from mixing to curing this is because these reactions are slow. Therefore “adequate temperature levels must be maintained for a sufficient time to provide the needed activation energy for the reactions to begin” (Mehta & Monteiro, 2006).
The heat generally assists in accelerating the hydration and therefore early strength development, which can lead to lower ultimate strength. These impacts on cement hydration and on strength change in either casting or curing temperature are demonstrated in Figure 2-1. As shown on the figure the cement hydration gets slower as the temperature is decreased and finally seems to be stalled when dropping close to -10 °C. This is an important observation that will be revisited later in this research in the maturity section.
Figure 2-1-Influence of casting and curing temperatures on cement hydration. (From Concrete Manual, U.S. Bureau of Reclamation, 1975)
2.2 Hardening Process of CPB

The hardening and hydration process of CPB has been determined to be much more complex than concrete due to the variety of tailings chemical compositions and various unknown variables such as organics. Various researchers have looked at this process by either monitoring the mechanical properties, such as Simon (2005), or looking at the microstructure of the sample likes of which has been done by Ramlochan et al.(2004).

Dragana Simon (2005) conducted various experiments on CPB and focused on the initial stages of cement hydration process. “Immediately after mixing all paste constituents, CPB behaves like a viscous non-Newtonian fluid. At early ages, the initial dissolution of PC grains occurs, resulting in an amorphous semi-permeable gel on the cement surface that prevents dissolved ions from entering the bulk pore fluid. During this period (known as the induction or dormant period), the paste is still plastic and workable, it is able to flow”, but aslo, “during the induction period of hydration (approximately two hours after mixing cement and water), Portland cement has little effect on the microstructure development, electromagnetic properties, shear wave velocity and apparent yield stress of cemented paste backfill” (Simon, 2005).

She also conducted tests on samples with different concentration of cement binder in order to grasp the effect of binder concentration in the hardening process. “As the Portland cement content (and cement to water ratio) in paste decreases, fewer hydration products form, the interconnectivity between the grains decreases (i.e. the porosity of the paste increases), and the hydration process is retarded as evidenced by delays in the conductivity peak and the sudden drop in the real relative permittivity”. This was only after the observation of hydration process at various ages. “With increasing hydration time, there is greater coverage of the large mine tailings particles by hydration products. However, the amount of hydration products is significantly less than for specimens with higher cement contents, and void spaces remain.” (Simon, 2005) This finding agrees with her observation on the impact of various water to cement ratios.

More detailed investigation using Energy Dispersive X-ray analysis (EDX) has revealed an effect of the host rock and the main composition of CPB. This was confirmed by Ramlochan, “the type of host mineral affects the packing and chemical composition of the particles that
adhere to large host grains after 3 hours of hydration. It appears that more small particles tend to adhere to the phyllosilicates, such as K-feldspar and plagioclase, as compared to quartz and pyrite grains. The EDX analyses of the small particles clusters reveal that the main component, regardless of the host mineral, is Si, followed by other elements” (Simon, 2005).

Ramlochan looked at the hydration products such as C-S-H using a Scanning Electron Microscope (SEM). He observed a small amount of C-S-H in samples of Williams mine using a relative high amount of cement, 15%. “Hydration products of the cementitious materials incorporated in the cemented paste backfill mixtures did not effectively fill the interstices separating the tailing particles” (Ramlochan, Grabinsky, & Hooton, 2004). This can be seen on Figure 2-2 as white cloudy halos formed on the surface of the tailings particles that barely fill the interstitial gap. The matrix of C-S-H and its impact can only be understood when compared with its matrix in concrete. Concrete’s strength is dependent on the development of this matrix as dense and interlocked as possible by filling in the voids and surrounding the aggregates, Figure 2-3. In this image the aggregate is located in the lower half and the C-S-H matrix appears light grey filling in the upper section of the figure. This structure of crystallization is responsible for giving concrete its impermeability and strength. D’Aux compared the images of CPB with concrete at the same resolution and the lack of C-S-H in the former was beyond doubt, “the presence of the black region between the aggregate grains in the CPB image indicates that the void space is largely void of C-S-H, except for a thin halo around the aggregate particles… in comparison to similar images of concrete, indicates that an interlocking matrix of C-S-H fibers is not developed in CPB, as the void space of cured CPB contains relatively little C-S-H matrix.” (D'Aux, 2008). This is an indication of the lack of tailing’s participation in the hydration process and infilling the void spaces with other hydration products in order to develop a microstructure such as of concrete to carry stronger loads.

Ramlochan observed a lack of Calcium Oxide, CaO, in the paste backfill mixture which was reflected by “depletion of calcium hydroxide and low Ca/Si ratios in the Calcium Silicate Hydrate” and suggested use of SCM such as slag or high lime fly ash as additive. The reactivity and effect of these admixtures on the microstructure of the paste became questionable due to low pH of fluid as was also mentioned in Simon’s work. “The pH of the fluid phase in the paste backfills investigated were fairly high, but they were somewhat lower than those typically found
in portland cement concrete. under these conditions, the reactivity of the SCM materials in the binder may be reduced. Increasing the pH of the fluid phase with additions of lime and/or alkali hydroxides to the mixing water would facilitate reaction of supplementary cementing materials.” (Ramlochan et al., )

Figure 2-2- C-S-H structures in Cemented Paste Backfill (Ramlochan, Grabinsky, & Hooton, 2004)
2.3 Strength and the Influencing Factors

“Strength is related to the stress required to cause failure and it is defined as the maximum stress the concrete samples can withstand” (Mehta & Monteiro, 2006). This property is generally used as a measure of quality control of concrete due to relatively easy testing procedure.

In general, strength is affected by porosity, water-cement ratio, compaction, curing condition, aggregate size and mineralogy, admixture types, specimen geometry, moisture condition, type of stress, and rate of loading. In this section, some of these variables will be examine further.

2.3.1 Water-Cement Ratio

In practice, many parameters are interdependent and therefore their influence cannot be separated. The two most important factors affecting strength are water-cement ratio and porosity. The effect that reduction of water-cement ratio has in increasing strength is demonstrated in
Figure 2-4. There is a decrease in strength with increase of water-cement ratio mainly due to increase in porosity.

Figure 2-4 – Influence of the water-cement ratio on concrete strength (Mehta & Monteiro, 2006).
2.3.2 Chemical Admixtures

Admixtures have been defined as ingredients other than cement or water that “may be added to concrete to impart a specific quality” (Mamlouk & Zaniewski, 2006). These admixtures have been classified by their chemical and functional characteristics as:

1. Air entrainers
2. Water reducers
3. Retarders
4. Hydration control admixtures
5. Accelerators
6. Thixotropic Admixtures
7. Specialty Admixtures (Hewlett, 1978)

These additives are added in a controlled and monitored matter to achieve four major advantages that has been identified by Portland Cement Association:

1. To reduce the cost of concrete construction
2. To achieve certain properties in concrete more effectively than by other means
3. To ensure quality of concrete during the stages of mixing, transporting, placing, and curing in adverse weather conditions
4. To overcome certain emergencies during concrete operations.

2.3.3 Supplementary Cementitous Materials (SCM)

Supplementary Cementitous Materials (SCM), such as slag and fly ash, are the major cement replacements used in the mines such as Kidd and Williams.

2.3.3.1 Effect of Fly Ash

Fly ash is a byproduct of the coal industry. “Combusting pulvernized coal in an electric power plant burns off the carbon and most volatile materials…The carbon content of common coals
ranges from 70 to 100 percent. The noncarbon percentages are impurities…which fuse as they pass through the combustion chamber…., fly ash” (Mamlouk & Zaniewski, 2006). Fly ash is primarily a glass composed of silica (SiO₂), alumina (Al₂O₃), iron oxide (Fe₂O₃), and lime (CaO), and has been classified as

- Class F – Fly ash with pozzolan properties (has CaO concentration of 5% to 10%)

- Class C- Fly ash with pozzolan and cementitious properties (has CaO concentration of 15% to 30%)

“The spherical shape of fly ash increases the workability” (Mamlouk & Zaniewski, 2006) and enters the hydration reaction at later stages by reacting with calcium hydroxide (CH) to form secondary calcium silicate hydrates (C-S-H) at areas with pH values of greater than 13 (Neville, 1995). This conversion of a weak CH to a much stronger C-S-H, which contributes to the strength of paste, benefits the overall strength in two regards. Initially it reduces the volume occupied by the weak, CH, and then by producing secondary C-S-H it influences the strength directly, making a stronger paste in long term (Monteiro et al., 1997). The secondary C-S-H layers have been found to have lower porosity than traditional C-S-H. It also affects durability of paste by reducing porosity due to smaller particle sizes compared to cement. This reduces the permeability of the paste and lowers the migration rate of alkali, sulphate and other undesirable ions through the paste. The smaller particles also serve as additional nucleation sites where hydration products can grow, which makes the hardened paste denser.

2.3.3.2 Effect of Slag

Iron blast-furnace slag is a white powder made from production of iron. “…if the liquid slag is rapidly quenched from a high temperature by either water or a combination of air and water, most of the lime, magnesia, silica, and alumina are held in a noncrystalline or glassy state” (Mehta & Monteiro, 2006). This SCM behaves and contributes to the hydration process; it goes into hydration at later ages, and forms secondary C-S-H bonds, which then contributes to the later age strength of paste.
2.3.4 Temperature

Temperature has an important effect on strength because “at normal and fixed temperatures concrete gains strength, rapidly at first and later more slowly, in accordance with a natural law” (Saul, 1951). This influence is so great that Saul goes on saying “we should thus only speak of the gain of strength of concrete with time when we know that the temperature is constant, but otherwise speak of its gain of strength with temperature multiplied by time” which is known as maturity as will be further discussed in this paper.

Temperature also has significant impact on quality of concrete, “In hot weather, unprotected concrete is subject to plastic shrinkage cracking. On the other hand, in cold weather the low temperature of concrete curing may be seriously impede the rate of strength development” (Mehta & Monteiro, 2006). In massive elements, like mining, where no measures for temperature control are taken, for a long time the temperature of the CPB will remain at a much higher level than the ambient temperature. Therefore, an understanding in influence of temperature on physical characteristics, such as strength, of the paste becomes necessary. In general it has been shown that “compared to the strength of the specimens cured at normal laboratory temperature, the in situ concrete strength” of such massive elements will be higher at early age and lower at later ages (Mehta & Monteiro, 2006). This is due to the effect of temperature on cement hydration and as shown in Figure 2-1, it appears the curing temperature is far more important to the strength development than placement temperature.

Many researchers have concluded that at a lower casting temperature, a relatively more uniform microstructure of the hydrated cement paste accounts for the higher strength at later ages (Mehta & Monteiro, 2006). As in Figure 2-1, the cement at moderately lower temperatures or a low heat cement gains strength slowly and significant strength gain occurs between 28 to 91 days (Hooton R., 2009). With moist-cured concrete, such as conditions in a mine, the influence of temperature on strength depends on the time-temperature history of casting and curing. The higher heat at the mine accelerates the early strength development. As shown in Figure 2-1, in the temperature range of 5 to 46°C, “when concrete is cast and cured at a specific constant temperature, it is generally observed that up to 28 days, the higher the temperature the more rapid the cement hydration”, and therefore the higher the strength gain (Mehta & Monteiro, 2006).
2.3.5 Porosity

The effect of porosity, volume of voids over total volume, on strength as previously mentioned is closely influenced by water to cement ratio. “In solids, there exists a fundamental inverse relationship between porosity (volume fraction of voids) and strength” (Mehta & Monteiro, 2006). The void space in concrete accounts for interlayer space in C-S-H, air voids, and capillary voids. The latter has the largest impact on strength, and its inverse relationship with on strength is represented in Figure 2-5. Initial porosity can be reduced mainly by reducing the water content. The initial porosity is then reduced by hydration reaction products.

![Figure 2-5 – Capillary Porosity-Strength relationship (Mehta & Monteiro, 2006)](image)

2.3.6 Testing Parameters

The conduction of a test has a large impact on the results obtained. This has been shown to be particularly important for strength tests that is influence by various errors in the procedure. These variables should be kept in mind when comparing strength results from various researchers with different testing procedures.

The size of the sample is an important parameter. In the US, the standard specimen size for a concrete sample is 150mm in diameter and 300 mm high (Mamlouk & Zaniewski, 2006), and
although other sizes are also used the height-diameter ratio of 2 should be kept. In Canada the standard size is $100 \times 200$ mm. This is important since the shorter, samples will withstand more load due to higher end friction with the test machine. The diameter of the sample should be kept three times greater than the maximum aggregate or sand size used in the mix. This is done to achieve a good packing and also avoid the wall effect. It has been shown that “the larger the diameter the lower will be the strength” (Mehta & Monteiro, 2006), even if the height to diameter ratio is kept at 2, this impact is shown on Figure 2-6.

![Graph showing the relationship between diameter and strength.](image)

**Figure 2-6- Influence of the specimen diameter on concrete strength when the height-diameter is equal to 2 (Concrete Manual, 1975).**

Other specimen conditions such as its condition after curing, and any entrapped voids on them can lead to, misleading lower strength. Furthermore, the sample needs to go though some preparation for the strength test, and the preparation can impact the results. The moisture condition of the sample affects the result, an unsaturated concrete wrongfully leads to a higher strength. “The lower strength of the saturated concrete is attributed to the disjoining pressure within the cement paste” (Mehta & Monteiro, 2006). There also needs to be smooth and parallel end surfaces in order to transfer the load uniformly. This is done either by capping the ends (with sulphur compounds), grinding the ends, or using un-bonded pad caps. After achieving parallel
ends, the sample needs to be placed on the centered in the machine, as an un-centered specimen leads to lower strength.

The machine used for conducting the test can also influence the result. The size of the machine affects the energy stored in the instrument as the specimen is loaded, a smaller instrument stores up a lot of energy which leads to lower strength. No matter the type of machine used, the rate of loading impacts the strength. If the rate is higher than it should be the results would show an unrealistic, stronger specimen. (Neville A. , 1995)

2.4 Maturity Method

The backfilling process of a stope is sometimes done in various stages and each stage is followed by a day or two of rest, In order for the cemented paste backfill to gain enough strength to support the next stage of backfill. In mines, once the CPB is poured, there is no way of measuring the strength of the material in the mine, however, the temperature in the stope can be measured. This is why a method like maturity could be very beneficial in predicting the strength of the material and therefore allow continuation of the filling.

The Maturity method was developed due to the need to relate the strength of concrete to its age, and since as explained previously one of the factors that affect strength is temperature, the relationship becomes:

\[ \text{Strength} \propto (\text{Time} \times \text{Temperature}) \]  (Plowman, 1956)

Maturity is the temperature history of the sample in °C-Hour, or the area contained below the time-temperature curve. A baseline datum temperature, which in Figure 2-7 is taken as -10°C, must be established.
At first, maturity was assumed to be the product of curing time in hours and temperature in degrees above the freezing point, “The “maturity” of concrete may thus be defined as its age multiplied by the average temperature above freezing which it has been maintained” (Saul, 1951). This value was found to be unsatisfactory when comparing samples cured at different temperatures. “From these it became apparent that a different zero was required, below the freezing point of water” (Plowman, 1956). Various temperatures by various researchers were tested which ended up agreeing on -10 °C (Bergstrom, 1953). This datum temperature for maturity is defined as “the curing temperature at which the strength of concrete remains constant irrespective of age” (Plowman, 1956). The datum temperature was later tested by Plowman and was determined as -11.7 °C (11 °F), as shown in Figure 2-8. In this figure as the curing temperature is reduced, so is the rate of growth of strength until it reaches zero at temperature of -11.7 °C (11 °F).
Plowman explained that the strength development of first 3 days was as to temperature gradient between the outside temperature and the centre of sample’s temperature. These variances are depicted in Figure 2-9 Error! Reference source not found. which indicates sample is above the datum temperature for initial hours.
Figure 2-9 - Temperature change in a Concrete Sample the sample with time (Plowman, 1956)

When the strength of a specific curing condition is plotted against the log$_{10}$ of maturity of respective samples, the relationship seems to be a straight line with the following formula:

**Strength** = $A + B \log_{10}(\text{Maturity})$ \hspace{1cm} **Equation 3**

Plowman conducted twenty-six sets of tests and in all cases the relationship as a straight line, some of these tests are depicted in Figure 2-10. He also expanded the research up to a year; the relationship between strength and log10 of maturity remained linear, indicating the reliability of the method up to the point which is of interest of most engineers (Plowman, 1956).
Figure 2-10 – Relationship between Strength and log Scale of Maturity (Plowman, 1956)

It has been shown that, “Concrete of the same mix at the same maturity has approximately the same strength whatever combination of temperature and time go to make up that maturity”, and the law of maturity is obeyed provided that the temperature remains in a specific range. “Concrete approximately obeys this law provided that its temperature has not reached 50°C until 1.5-2 hr nor 100°C until 5-6 hr after the time of mixing…When the concrete has been raised in temperature more rapidly than the above it fails to obey this law” (Saul, 1951).

Equation 3, The Strength-Maturity relationship, has proven to be independent of:

(1) Quality of the cement,

(2) The water/cement ratio,

(3) The aggregate/cement ratio, and
(4) The shape of the test specimen which can be comparable after the corrections for cube versus cylinder strengths (Plowman, 1956).

2.4.1 Assumptions of Maturity Method

The maturity method is based on some assumptions that need be kept in mind. First, this method assumes the samples are moist, to allow the cement to hydrate. This is due to effect of dryness of sample on strength, which has been previously discussed. Second, the starting time is from the time of set. And lastly, that temperature is measured above the datum temperature which is around -10°C has been used by the concrete industry (Hooton, 2009). The Datum temperature can also be determined for various mixes (ASTM C1074, 2004).

2.4.1.1 Measuring Datum Temperature

Although -10°C has been used, as an approximate value, the American Society for Testing and Materials has included a procedure for determination of datum temperature in annex section of ASTM C1074. “The basic approach is to establish the compressive strength versus age relationship for mortar specimens cured in water baths maintained at three different temperatures”. The data from these tests can be used to find the rate constant for strength development, k-value, which then is used to determine the datum temperature. The k-value can be obtained by linear regression analysis or by plotting the strength-age data with “reciprocal of average cube strength as the y-axis and the reciprocal of the age beyond the time of final setting along the x-axis”, an example is shown in Figure 2-11. “For each straight-line, divide the value of the intercept by the value of the slope”, these values are k-values, the rate constants for strength development.
The three k-values then can be plotted against their respective curing temperature. A line of best-fit determines the intercept of the line with the temperature axis in Figure 2-12. The temperature obtained is the datum temperature used in the maturity calculations.
2.4.2 Benefits of Maturity Method

The maturity concept has been established for a long time in concrete industry, but and the main information and data from this method is based on concrete. Like mining, construction with concrete has various stages and “This practice can be used to estimate the in-place strength of concrete to allow the start of critical construction activities such as: (1) removal of formwork & reshoring; (2) post-tensioning of tendons; (3) termination of cold weather protection; (4) opening of the roadways to traffic” (ASTM C1074, 2004).

Furthermore, the tests conducted in the laboratory are usually performed at normal room temperature and this method can be used to estimate the strength of specimens cured under non-standard conditions (ASTM C1074, 2004).
2.4.3 Limitations of Maturity Method

With the assumptions made for this method, there comes some limitations that ASTM C1074 (2004) has recognized, as follows:

1. The concrete must be maintained in a condition that permits cement hydration.
2. The method needs to be supplemented by other indication of the potential strength of the concrete mixture.

The last point was explained in more detail by Mehta and Monteiro, "the maturity concept does not take into consideration the influences of humidity and temperature of curing at early age…Higher curing temperatures cause an acceleration of the hydration reactions, resulting in an increase in the early-strength development. At these early stages, concrete cured with higher temperature will have a higher strength than concrete cured with lower temperatures for the same maturity, computed according to maturity equations. At later ages, the reverse happens. Low-temperature curing produces a more uniform microstructure in the cement paste with low porosity, resulting in concrete with higher ultimate strength” (Mehta & Monteiro, 2006).

2.4.4 The Implementation of the Maturity Method

The maturity method can be implemented at a mine by calibrating the strength-maturity curve for various CPB mixes used in the mine. Each mix based on different amounts and types of cement, aggregate, water (and in cases of CPB, its type of tailings) has different characteristics and would have a unique formula based on strength-maturity relationship. During the pouring process, samples of the same mixed can be cured at room temperature in order to calculate the constants A and B of Equation 3 for the maturity method. This formula along with the temperature profile in the mine as it is filled with CPB can be used to estimate the strength of the mix in the stope and at various ages.

2.5 Main sources of heat

The importance of considering the influence of thermal effects on cemented paste backfill comes into perspective while illustrating the various sources of the heat in the mines. Although every
underground mine has a unique temperature profile, the sources of heat can be narrowed down to: the geographical location of the mine, the depth of excavation, geological conditions, transportation though pipes, self-heating mechanism, the binder hydration, and other human induced activities. Fall et al. (2010) have looked at these sources, and in this section the impacts of these various sources on the overall heat rise in the mine are described.

2.5.1 Geographical Location of the Mine

The geographical location of the mine has a large impact on the thermal profile of the mine when looking at extreme climate regions such as northern Canada where local rocks can be permanently frozen to depths as great as 1000m (Udd, 2006). This example although extreme, is not uncommon for some mines. The mixing water used at mines is usually from a natural source nearby, such as a lake, and therefore the geographical location and time of year also impacts the temperature of the mixing water. The mixing water temperature has an enormous impact on the rate of reactivity of the cement binder. This is very well established in the concrete industry where maintaining or monitoring the required temperature of the mixing water is a norm. This is not commonly considered in the design of CPB and can be due to the vast volume of mixing water used for a filling in massive stopes.

2.5.2 Depth of Excavation

Mining operations is move to greater depth as reserves available at shallow depths are getting used up, especially in Canada and South Africa (Fall et al., 2010). These deep excavations pass through various geothermal gradients that increase the heat influx. Rawling and Philips (2001) work at a deep gold mine in South Africa has revealed an average temperature of 35°C at 3000m, 50°C at 4000m and 70°C at 5000m. Similar rock temperatures were also reported by Fall et al. (2010), and in the near future one can anticipate depths of 5000m for underground mining.

2.5.3 Geological Conditions

Various rocks have different internal heat which can cause mine stopes located at the same depth to have different temperatures. “When mining operations take place near geothermal sources, the environment or the rocks can be subjected to high temperatures” (Fall et al., 2010). The Toyota mine in Japan introduced paste backfilling in mining in order to improve the underground
climate and to save energy, which can add up to 10 to 15% of the costs of mining (Rawlings & Philips, 2001, Yamatomia et al., 2005). In the Toyota mine, “It was found that CPB allows a substantial reduction of the heat load and thereby a significant reduction of the cost of refrigeration and ventilation systems to provide suitable environmental conditions underground” (Fall et al., 2010). This also agreed with Rawling and Philip’s (2001) finding that functionality of CPB goes well beyond the ground support and “can play an important role in terms of reduction of heat load and energy saving in the deep mines.

2.5.4 Transportation through Pipes

The paste is transported down to the stopes using pipes, and it can take up to 20 minutes from mixing of the paste to reach the stopes. “The increase of the temperature in the fresh backfill can occur during its transport in pipes from the surface to underground working areas of a production section” (Fall et al., 2010). This rise in temperature has been said to be governed by various factors such as fluid compression with depth, friction losses, non-use of energy recovery systems, selection of fluid flow rate in the conveying pipes, and fluid properties, such as thermal capacity (Rawlings & Philips, 2001).

2.5.5 Self-Heating Mechanisms

A high content of sulphide can lead to exothermic reactions of this element which leads to a very high temperature (400 °C) that was observed by Bernieir and Li (2003) in some Canadian mines. “The potential heat sources in these cases are the exothermic reactions of the sulphide minerals present in failed paste containing high pyrrhotite and other sulphides, in the rock mass with high amounts of sulphides (pyrrhotite and pyrite) surrounding the backfill structures, or in the cracked backfill structures containing high sulphides” (Fall et al., 2010). These extreme high temperatures are rarely reported in mining and are not the focus of this thesis.

2.5.6 Binder hydration

The heat produced by the binder hydration is the most important source of heat in Cemented Paste Backfill. This source becomes important since the cemented backfill structures are very large, several tens of meters in height and width, and therefore the “heat produced cannot dissipate quickly, thereby resulting in relatively high temperature increases (depending on binder
type and quantity) within the CPB structures” (Fall et al., 2010). This was seen in all three mines monitored by University of Toronto, (Williams, Kidd, And Cayeli), as illustrated in Figure 2-13. It has been demonstrated in the literature that after only approximately 4 days of curing, the backfill temperatures can increase up to 50°C, which agrees with the modeling studies done (Nasir and Fall 2008; Williams et al.,2001; Fall and Nasir 2009).

![Figure 2-13- Heat rise in the three mines monitored by University of Toronto](image)

This heat is due to exothermic reactions of all four major cement phases (Alite, Belite, Aluminate, Ferrite) with water which collectively is called the heat of hydration. “The compounds of Portland cement are nonequilibrium products of high temperature reactions and are therefore in a high-energy state. When a cement is hydrated, the compounds reacts with water to acquire stable, low-energy states and the process is accompanied by the release of energy in the form of heat” (Mehta & Monteiro, 2006). The amount of heat evolved in this process is directly related to the amount of the clinker phase that has reacted. This heat depends on the composition of cement (C₃A and C₃S generate the most heat), the fineness of cement, water to cement ratio, temperature, and relative humidity (Hooton, 2009).
The total amount of heat evolved is an indication of the reactivity of the cement and therefore the hydration reactions can be followed by monitoring the heat evolution and can be divided up into various stages of hydration. This can be seen in Figure 2-14 that gives a overall image of heat evolution during cement hydrations.

A quick rapid heat evolution happens, lasting only few minutes right after exposure of cement to water, shown as the ascending portion of A in Figure 2-14. This is due to dissolution of aluminates and formation of ettringite, there is also a contribution from the dissolution of C\textsubscript{3}S. Rehydration of hemihydrate to gypsum may also contribute to this spike of temperature. “This initial heat evolution ceases quickly (descending portion of peak A) when the solubility of aluminates is depressed in the presence of sulfate in the solution” (Mehta & Monteiro, 2006).

The next phase, the induction period, is better seen on Figure 2-15 and is indicated by “II”. In this phase the dissolution of C\textsubscript{3}S is continued, but the rate of reaction is low since nucleation is
the rate limiting mechanism. There is still ettringite being formed and there is also some formation of CH. The induction period has a very practical importance since it is the only phase that concrete remains plastic and has workability so it can be placed and workability.

![Figure 2-15 – Heat Evolution versus time for a portland cement (with gypsum) and a clinker (without any gypsum added). (Ramlochan, Personal Communication 2009)](image)

The next heat evolution cycle leading to the peak at point B on Figure 2-14, is known as the acceleratory period, this phase is marked as “III” on Figure 2-15. In this phase $\text{Ca}^{2+}$ and $\text{OH}^-$ concentrations have reached supersaturation and therefore CH begins to precipitate in quantity. There is a rapid dissolution of the $\text{C}_3\text{S}$ and nucleation and growth of C-S-H. This leads to stiffening and setting of concrete or paste in general. “The paste of properly retarded cement will remain much of its plasticity before the commencement of this heat cycle and will stiffen and show the initial set (beginning of solidification)” (Mehta & Monteiro, 2006), climax of point B which indicates the final set, complete solidification and beginning of hardening.

The deceleration period is the descending part of point B in Figure 2-14 and “IV” in Figure 2-15. At this stage, the rate of the reaction reduces since the C-S-H nuclei from adjacent particles begin to overlap. The small peak superimposed on the main peak at this stage is due the fact that $\text{C}_3\text{A}$ is reactive again. This is associated with depletion of sulphate in the pore fluid and therefore the $\text{C}_3\text{A}$ once again becomes active.
In the final period, “V” in Figure 2-15, reactions proceed much more slowly and only a small amount of heat is evolved. The hydration products continue to form and packing of the hydration products increases which yields to strength gain of paste and decrease in porosity.

The importance of data from heat of hydration studies should not be underestimated because, as discussed, these studies can be used for, “characterizing the setting and hardening behavior of cements, and for predicting temperature rise” (Mehta & Monteiro, 2006).

2.5.7 Human-Induced Activities

Any activity releases some of sort of thermal energy and these activities can add up in large project. “Temperature variations in an underground mining operation can also come from other variable sources, such as mine machinery, blasting operations, lighting, ventilation, fires, etc” (Fall et al., 2010). Although these temperature rises might not be significant alone the overall effect is significant in designing a stable, economical, and durable Cemented Paste Backfill and their effects cannot be underestimated.
3 Introduction

Gold-ore tailings from the Williams mine in Hemlo, Ontario were used in this detailed investigation of the thermal aspects of CPB. The materials from Cayeli mine in Turkey, and the Kidd mine in Ontario, Canada were also used and the results of these two mines are presented in Appendix A and B of this report respectively.

3.1 Tailings

The mine tailings from the Williams gold mine were provided as filter cakes. The filter cake is the dewatered waste, produced during the flotation process of gold-bearing ore. Detailed analysis on the Williams tailings was done by Dragana Simon at University of Toronto. Her research revealed that the major components of the tailings are quartz (SiO$_2$), followed by albite (NaAlSi$_3$O$_8$) K-feldspar (KAlSi$_3$O$_8$), and pyrite (FeS$_2$) in descending order, conducted on dry mine tailings using XRay Diffraction-XRD (conducted by Dr. Petrov at Department of Chemistry, University of Toronto) and X-Ray Fluorescence-XRF, Figure 3-1, the full XRD diagram is provided in Appendix C. In another study, the specific gravity of mine tailings, using ASTM D 854, was determined as 2.73 g/cm$^3$. The particle size distribution analysis using a hydrometer (ASTM D422, 1985) classified these tailings as silt with an average particle size ($D_{50}$) of 19 µm, Figure 3-2 (d’Aux, 2008).
<table>
<thead>
<tr>
<th>PDF-2 Ref. No</th>
<th>Compound Name</th>
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<th>S-Q</th>
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<tr>
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(a)

<table>
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</tr>
<tr>
<td>Al₂O₃</td>
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</tr>
<tr>
<td>Fe eq</td>
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<tr>
<td>Ca eq</td>
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</tr>
<tr>
<td>MgO</td>
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<td>S eq</td>
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<tr>
<td>K eq</td>
<td>3.4</td>
</tr>
<tr>
<td>Others</td>
<td>9.5</td>
</tr>
</tbody>
</table>

(b)

Figure 3-1- A Dry 100% mine tailings (a) Scanning Electron Micrograph (b) XRD analysis of the mine tailing (Simon, 2005).
3.2 Binders

Since control over the water and the tailings in Cemented Paste Backfill can be complex, a further investigation of the cementing materials used becomes necessary. In order to illustrate the effectiveness of this component this material was tested using ASTM C1702, for heat of hydration, and ASTM C109, for strength. These will be described in detail in the experimental design section.

Heat of hydration of cement can be used as a measure of reactivity of the cementing material, as discussed in previous sections. Figure 3-3 demonstrates the heat of hydration of the cementing materials used for the purpose of this paper. A CSA A3001 GU (general use) Portland cement, from Holcim in Ontario was used as a control. Cayeli’s cement was tested twice: once with tap
water and the other with the processed water used at the mine. This was done because it was believed the process water contains organics that could impact hydration.

In Figure 3-3, the induction period that happens in the first hour after mixing, the induction period of the Kidd mine binder is much longer than normal and longer than the binders used at other mines. This difference was also noticeable during the casting of the samples, as they remained liquid for a longer time and could not withstand load after 24 hours. This prolonged induction period at room temperature is due to the 90% slag used in the preblended binder used at the Kidd mine. As mentioned previously slag, like fly ash, can have a retardation effect on the hydration process but both these supplementary cementing materials can lead to higher ultimate strengths. The duration of the induction period for the other cementing materials in the study were approximately same as the GU cement used as the control.

Figure 3-3 – Heat Evolution of Cementing Materials Used
In Figure 3-3, the acceleratory period of the hydrating cementing materials, other than Kidd, seem to be similar. One should be careful when comparing the cementing materials cured at the various mines, since performance in each mine is unique to its environment, and therefore Figure 3-4 shows the Williams mine only in comparison to the control at 25°C. The composition of cementitious materials, Alpena cement and fly ash used at Williams mine is available in Table 1.

In Figure 3-3, the second peak is much more noticeable for the Cayeli and Williams’ binders. This could be due to the higher quantity of C₃A in the material that is being active again. This phenomenon is not seen for the Kidd binder due to the low, 10% quantity of cement and therefore, much lower C₃A in the mix design.

![Figure 3-4 – The heat of hydration of Williams mine’s cement in comparison with Holcim GU cement.](image)
Table 1 – Composition of cementitious materials used at Williams mine (a) Fly ash (Ramlochan et al., 2004) (b) Williams Cement (Simon, 2005)

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<th>Fly ash (%)</th>
<th>Oxides/Elements</th>
<th>PC (%)</th>
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<tr>
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<td>Others</td>
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<tr>
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</tr>
<tr>
<td>BaO</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>LSO₃</td>
<td>1.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOi</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>99.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The other test that was conducted to understand the behaviour of the binders used in the experiments was the compressive strength of their respective mortar cubes which were cast and cured based on ASTM C109. Compressive strength is ultimately what is important, and provides a simpler means of comparison.

![Figure 3-5 - 28 day strength of cement mortars of binder at various mines](image)

The 90% slag binder used at Kidd resulted in the lowest strength cubes cured at 23°C, as seen in Figure 3-5. The samples tested at one day crumbled as soon as the load was applied. This should not be seen as an indication of weakness of the cementing material used at this mine, since as mentioned before every mine is unique and performs based on their respective conditions. In the Kidd mine, the higher temperature would accelerate the slag binder. The Cayeli mine cement required about 5% more water in order to get the required flowability required by the ASTM
C109 compared to the GU cement bench mark. The rate of reaction of the Cayeli binder slows down visibly after 7 days. This is less noticeable in the mortar mixed using the process water of the mine, nonetheless the rate of reaction of both are lower than the GU cement control.

In Figure 3-5, it is clear that the cement hydration is more rapid in the Williams mortars than for the GU control cement. This rate of hydration remained high up to 28 days. It should be mentioned that this performance is expected to change as fly ash is added; the rate will be lower in the CPB mix due to this addition. Fly ash contributes to later age rather than early age strength.

3.3 Water

The mixing water used with cementing materials can affect the characteristics of the paste. Impure water “may affect not only the concrete strength but also setting time, efflorescence, and corrosion of reinforcing and prestressing steel” (Mehta & Monteiro, 2006). Mehta and Monteiro suggested comparison of the 7 and 28 day strength data of samples using a reference drinking water and the water under analysis, “the strength should be the same or greater than 90% of reference samples”. The effect of organic substances, such as at Cayeli mine, “on the setting time of portland cement or the ultimate strength of concrete” is complex depending on the nature of various organics and environment of the surroundings (Kosmatka et al., 2002)

The water used in the casting of the samples used in this research was the same as the process water used at the mine. The process water chemistry was previously investigated by Ramlochan et al. in 2004, as shown in Figure 3-6 using a inductively couples plasma atomic emission spectroscopy (ICP-AES). This investigation indicated higher sulphate content when compared to the water used at other mines he studies which can influence the hydrated cement, and appreciable amounts of Ca\(^{2+}\), Na\(^{+}\). The additional alkalinity has shown to affect the hydration reaction.
<table>
<thead>
<tr>
<th>Species</th>
<th>Concentration, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al(OH)$_4^-$</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Ca$^{2+}$</td>
<td>18.7</td>
</tr>
<tr>
<td>Cl$^-$</td>
<td>2.01</td>
</tr>
<tr>
<td>Fe$^{2+}$</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>K$^+$</td>
<td>4.32</td>
</tr>
<tr>
<td>Mg$^{2+}$</td>
<td>0.32</td>
</tr>
<tr>
<td>Na$^+$</td>
<td>18.9</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>25.7</td>
</tr>
<tr>
<td>HSiO$_3^-$</td>
<td>0.20</td>
</tr>
<tr>
<td>pH</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Figure 3-6—Concentration of dissolved species in solution of process water from Williams mine (Ramlochan, Grabinsky, & Hooton, 2004)

The effect of mixing water can also be seen on strength of Cayeli in Figure 3-5. In this case, the process water seems to have a lubricating effect that caused a reduction of 10% in water-cement ratio for the same flowability that would lead to higher strength. This process water does not seem to have any effect on the rate of hydration of cement as shown in Figure 3-3.
Chapter 4
Experimental Design

4

4.1 Sample Proportion

The binder proportions used at the Williams mine varied in different stopes and, like any other realistic project, was dependent on availability of the material. In this report Williams tailings were investigated using three binder concentrations: 3% and 7% portland cement and also another set of samples with 1.5% cement and 1.5% fly ash which is the closest to the mix design used at the mine at the time this research was conducted. All the constituents of CPB (tailings, water, and cementitious material) were delivered from the mine.

4.2 Preparation for Casting

The tailings from mines are filtered and stored in buckets; this material settles and consolidates to become a relatively hard “cake”. In order to get a uniform mix of tailings and water content measurements of tailings, the filter cake needed to be vigorously mixed to homogenize a day prior to casting. The water content of the tailings was then used to adjust the required mixing water to the desired water content of the mine which in case of Williams was 38.9% , mass of liquid/ mass of solid  (Thompson, Grabinsky, & Bawden, 2008). The water content from the tailings was then used along with specific gravity of tailings and concentration of cement in order to get the quantities necessary, a sample of the spread sheet used for Williams (50:50FA) is presented in Appendix D.

The plastic moulds, 100 mm in diameter and 200 mm in height, were cut in half vertically and taped back together again. This was done since the CPB samples were not strong enough to undergo the air pressure demoulding technique used for concrete samples, especially at the first few days of age. This idea was inspired by the way the SureCure moulds were made for ease of demoulding without destruction of the sample. SureCure cylinders can be seen in Figure 4-1. The moulds were then oiled and left overnight.
4.3 Casting

Due to the large quantity of paste required for various tests, the specimens were mixed using an industrial mixer, a counter current pan mixer, with maximum capacity of 50L with mixing speed of 119 rpm. The wet tailings were initially mixed for one minute to achieve a uniform paste, the cement and water were added and hand mixed for 30 seconds to avoid any loss of material by dusting and then machine mixed for 2 minutes. After 2 minutes of rest, the cemented paste was mixed again for another 2 minutes for a total of about 8 minutes in mix cycle.

The plastic 100 x 200mm cylinders and the SureCure cylinders were filled in 3 layers, with each layer rodded 15 times. The reduction in roddings, from the common 25 times in concrete casting, was due to the liquid nature of the CPB mixes compared to concrete. The chamber for the CPB calorimeter was also filled and rodded in 3 layer. For correct measurement of temperature, it was ensured that cement paste covered the top of the sensors in the middle of the semi-adiabatic calorimeter chamber used for programming the SureCure cylinders for correct measurement of temperature.
4.4 Curing method

The filled plastic moulds were capped and sealed in individual plastic bags with addition of some water, around 50ml, in the bags to maintain 100% relative humidity. The samples were cured at 3 different curing conditions. A group of 18 cylinders were kept in a moist room provided maintained at high relative humidity by providing an almost continuous mist and a temperature of 23°C. The samples in this condition are referred to as “room temperature” samples and are indicated by a “RT” in the Figures. The samples from this group were scheduled to be tested on 1st, 3rd, 7th, 14th, 28th, and 90th day, there were moderate changes on these dates depending on the availably of the required instruments.

The Second group were also cast in the plastic moulds and were sealed in plastic bags with some water added. In addition, they were again sealed in a larger bucket with addition of some water in the bucket in order to maintain the high relative humidity. These buckets were then placed in a room with constant temperature of 38°C to accelerate curing. These samples were tested on days 7 and 14 and are labeled as “38C” in the Figures.

The last group were the SureCure cylinders which were cured by matching the temperature development of the CPB in the semi-adiabatic calorimeter. Initially these cylindrical samples were only covered with a plastic bag or shower caps as suggested by the manufacturer. This method was later determined to be insufficient in keeping the relative humidity high. Therefore, a second casting was done and this time wet towels were kept on top of the initial plastic bags which were then covered and sealed with another plastic bag to keep the humidity high. This group was tested on day 7 and is labeled as “SC” and “2nd-SC” referring to the first and second type of sealing, respectively.

4.5 Testing Programs

In order to follow the behaviour of CPB, various tests such as Uniaxial Compressive Strength (UCS), water content, and void ratio were conducted on specimens.
The term portland cement has been used very loosely, since there are a wide range of cements that are portland cements with various compositions. Three different cements used at the various the mines all were called portland cement. Therefore, in order to get a better understanding of the materials used, additional testing was done to examine cement reactivity using a more sensitive calorimeter and strength gain was tested using 50mm mortar cubes.

4.5.1 Uniaxial Compressive Strength

Strength is one of the properties of any solid material or mix that can characterize the quality of that material, whether concrete or CPB. In concrete it has been proven that the important relationship is between water to cement ratio and strength. The factors affecting strength can be generalized into three groups: characteristics and proportions of materials, curing conditions, and testing materials. Although these findings have been developed in the concrete industry they can still be implemented for cemented paste backfill. The literature on CPB also backs the importance of UCS in indicating the stability and structural integrity (Mitchell, Olsen, & Smith, 2002), and due to ease and nature of the test it can be used as a routine quality control at the mines (Fall, Belem, & Benzaazoua, 2005). Although the strength required at various mines is different depending on the nature of mining operations, strengths of 150 to 300 kPa have been suggested when the CPB is used for simply filling voids (Jewell, Fourie, & Lord, 2002). Less than 1MPa 28-day strength is needed for cut and fill usage of CPB (Hassani & Archibal, 1998).

4.5.1.1 Preparation and Instrumentation

Initially, trimming of cylinder ends was used to ensure parallel surfaces, but as samples aged the trimming stage got more difficult and time consuming. An unbonded capping system sometimes used for concrete samples, Appendix provides the specification and an image of the caps used.

Uniaxial compression tests were performed on the CPB specimens using a computer-controlled mechanical press. A loading rate of 0.5% of the sample’s length per minute (i.e. mm/min) was used. These tests were performed using an ELE Digital Tritest loading frame, with 1134 kg (2500 lb) capacity and 25 mm LDT displacement transducer in conjunction with a DaisyLab 8 acquisition system, shown in Figure 4-2. Just prior to testing, the mass and measurements of the samples were taken to be used in density and other calculations. During the test, load (kg) and displacement (mm) were monitored. Test results were grouped according to the maturity of the
paste and specimen type. The maximum load was then converted to stress for the purpose of this research.

Figure 4-2 – The Loading Instrument Used for UCS Test

4.5.2 Porosity/Void Ratio and Degree of Saturation

The presence of voids in a mix is unavoidable, and one can only control these by changing the mix design. Voids can be due to interlayer in C-S-H, capillary voids, interfacial transition zones, and entrapped air voids; “…air voids in the hydrated cement paste are much bigger than the capillary voids, and are capable of adversely affecting the strength” (Mehta & Monteiro, 2006).
The quantity of these air voids depends on water to cementing materials ratio and also the method of compaction. In mines, the water to cementing materials ratio is much higher than the traditional concrete range, and unlike in the lab procedure, there is no rodding or tamping to get rid of extra air bubbles. Therefore, the expected void ratio is high, and this high void ratio does adversely impact strength. In the concrete industry the common method to measure voids is porosity rather than void ratio, and the difference in calculation of each will be described in the next section. Since these two concepts essentially are similar and although both results are provided, only porosity will be used to draw conclusions. The degree of saturation is a method to examine the state of the sample at the time of testing since, as mentioned previously, the state of dryness of the sample can influence the results, and it can simply be calculated as a follow up to the void ratio calculations described next.

4.5.2.1 Procedure and Calculations

After the failure of a sample in UCS test, 6 pieces representing the sample from the tested sample were taken. Three of these pieces were used for water content measurements, explained later in the report, and the other three for void ratio measurement. A measured length of dental floss (string) was used to suspend each piece. The mass of sample plus string were measured before and after waxing. The paraffin wax, with specific gravity of 0.9, was melted and once the sample was immersed and taken out, the wax fully covered the sample and part of the string. The waxed sample was then suspended in water for apparent mass calculation. It was tried to minimize the amount of string used around the sample. The mass of extra string was measured after the test for an indication of the total mass used. It is recognized that the void ratio procedure is not included in ASTM C642, but it is the norm for Geomechanical tests to include the mentioned procedure for void ratio calculations. Therefore the following detailed calculation is provided to illuminate the calculations behind the procedure, and also the calculation of porosity and degree of saturation:

\[
\text{Mass of Wax} = \text{Mass of waxed specimen} - \text{Mass of Wet specimen}
\]

\[
\text{Volume of Wax} = \frac{\text{Mass of Wax}}{0.9}
\]
Volume of Specimen

\[ = (\text{Mass of Waxed Specimen} \times \text{Specific Gravity of water}) \]

\[ - (\text{Submerged Mass} \times \text{Specific Gravity of water}) - \text{volume of Wax} \]

Mass of Wet specimen = Mass of Specimen − Mass of String

Total Unit Weight = \( \frac{\text{Mass of Waxed Specimen} \times 9.81}{\text{Volume of Specimen}} \)

Mass of Water = \( \frac{\text{Mining Water Content}}{100} \) * Mass of Wet Specimen

Mass of Solid = Mass of Wet Specimen − Mass of Water

\[ \text{Volume of solids} = \frac{\text{Mass of Solid}}{\text{Specific Gravity of Tailings}} \]

Volume of Voids = Volume of Specimen − Volume of Voids

Dry Unit Weight = \( \frac{\text{Mass of Waxed Sample} \times 9.81}{\text{Volume of Solids} + \text{Volume of Voids}} \)

\[ \text{Void Ratio} = \frac{\text{Volume of Voids}}{\text{Volume of Solids}} \quad \text{Equation 4} \]

\[ \text{Porosity} = \frac{\text{Volume of Voids}}{\text{Volume of Solids} + \text{Volume of Solids}} \quad \text{Equation 5} \]

\[ \text{Degree of Saturation} = \frac{\text{Water Content} \times \text{Specific Gravity}}{\text{Void Ratio}} \quad \text{Equation 6} \]

Using the specific gravity of tailings, and not the CPB, could result in errors which have been estimated to be around 5% by conducting tests. In the case of Williams, the specific gravity of tailings was 2.73.
4.5.3 Water Content

Various mines require specific water contents in CPB, due to tailing characteristics, so a desired slump or ease of workability is needed the specific pump used. The water content has a direct impact on strength; the hydraulic materials mixed require enough water in order to initiate various chemical reactions, and also to carry on the other chemical reactions that develop strength at later ages. As mentioned in the background section, a water/cement ratio of 0.21-0.23 has been tested to be sufficient for complete hydration of cement, but in cases of mines other factors govern. The first reason is that the paste needs be fluid enough to be easily pumped down the pipes without a lot of pressure. The other factor in increasing water content is that the mines usually have vast volumes to fill in a tight schedule and a more workable mix assists in meeting deadlines.

In the mining industry, when there is mention of water content it almost always refers to the mining water content, which is the percentage of mass of water to the total mass. In the case of Williams, it is 38.9% (Thompson, Grabinsky, & Bawden, 2008). This is contrary to what is being used in the various formulas to get the characteristics of the mix such as void ratio which is the geotechnical water content, the percentage of mass of water to the mass of solids. Therefore, the reader should keep this in mind when looking at mix design requirements and actual outcome in water content calculations which later were used for void ratios. The values indicated in the result section and on the Figures refer to the geotechnical water content.

4.5.3.1 Procedure and Calculation

The moisture content of specimens was determined by taking the mass of a piece of the sample after completion of the UCS test. The mass was again measured after the sample was dried out in the oven at 105°C for 24 hours. Equation 7 was then used and the average of these samples was then taken as being representative of the water content of that specimen. To check the reproducibility, at least two other samples were measured each time in the lab to determine the moisture content of the paste. The values represented in the results section represent the average obtained from these samples. This average value was also used in void ratio calculations.

\[
\text{Water Content} = \frac{m_w}{m_s} \times 100, (\%) \quad \text{Equation 7}
\]
where: \( w \) – gravimetric water content, %

\[ m_w \] – mass of water, g

\[ m_s \] – mass of solids, g.

### 4.5.4 Hydration Chamber Semi-Adiabatic Calorimeter

The SureCure instrument purchased for the purpose of this research included a semi-adiabatic calorimeter. This calorimeter (or hydration chamber) unlike conventional calorimeters had the capacity to hold large quantities of paste of up to 7 Litres. This chamber was able to monitor the temperature due to the hydration of the mix inside for a long period of time, at least 35 days. The insulated chamber was able to keep the increase in temperature inside so that the paste essentially neither gained nor lost heat to the surrounding environment. This was done by having two sensors, one in the middle and one at the outside. In this case if the surrounding temperature is less than the middle, there will be heat added to balance out the two temperatures. The SureCure cylinders worked in the same way; they had both a sensor and input energy plug which made sure the cylinder temperatures followed that of the center of the hydration chamber, as shown in Figure 4-3.

![Hydration Chamber assembly](image)

*Figure 4-3* - Hydration Chamber assembly used for monitoring temperature rise due to hydration of CPB
4.5.5 Isothermal Conduction Calorimeter

The heat of hydration, as explained in the background section, can represent the reactivity of the cementing material. In this work, an isothermal conduction calorimeter was used to get the total heat of hydration of hydraulic cementitious material up to 7 days old at 25°C. This calorimeter is much more sensitive than the one in hydration chamber which was used for large volumes of samples. “The output from the calorimeters is the difference in heat flow (thermal power) between the sample cell and the reference cell” (ASTM C1702, 2009). The sensors are highly sensitive and can capture a small temperature gradient that develops across the device, but “the heat is removed from the hydrating sample fast enough that, for practical purposes, the sample remains at a constant temperature” (ASTM C1702, 2009).

4.5.5.1 Procedure

In the standard, two methods have been suggested, the direct way of mixing inside the calorimeter and indirect way of mixing outside calorimeter which can result in small errors due to the initial period of hydration being missed (ASTM C1702, 2009). The indirect method was chosen for the purpose of this research as the detailed hydration in the initial few minutes did not seem to be necessary. For the purpose of this research, the Isothermal Calorimetry was carried out using a TAM AIR machine from TA instruments.

Materials were placed in the mixing room for at least an hour to bring them to a constant temperature. A water to cement ratio of 0.5 was used by mixing 100 g of cementitious material with 50 g of water inside a Pyrex container using a hand held eggbeater, using only one fork. The following mixing technique was used:

15 s combine materials
45 s mixing at slowest speed
30 s scrape surfaces of pyrex container
30 s mix at slowest speed

The paste was transferred into calorimetry jars, using a syringe. Extra paste was then added or removed to achieve 6.00 gram ± 1% of paste. They were then placed in the calorimeter (see
Figure 4-4) within 4-7 minutes of the cementitious material touching the water. Therefore, it is thought that the outside mixing method was sufficient for the purpose of this research.

4.5.6 Compressive Strength of Hydraulic Cement Mortars

This test enables the analysis of cementing materials both by comparison of strength and also by comparison of water required to achieve a specific consistency. This was important in this research because it was believed that the water used at one of the mines (Cayeli mine in Turkey) had some additive that stalled hydration. This test gave a benchmark to test the difference in strength from using tap water and process water used at this specific mine.

4.5.6.1 Procedure

The water content used for the mine cements was adjusted to obtain a flow of 110±5 in 25 drops of the flow table. This was made ensured by conducting various tests commencing with a w/c of 0.485 as suggested in the standard (ASTM C109, 2008), and adjusting each trial according to the
result of the flow. The mortars made had one part cement for 2.75 parts sand proportioned by mass. As suggested in ASTM C109, the mixing was done according to ASTM C305 (2006) and the flow determination was done according to ASTM C1437 (2007). The samples were moved to a moist closet for curing at 23°C as suggested in the standard. The compressive strengths were done all in the permissible time tolerance range, shown in Table 2, and 3 mortar cubes were tested at each particular age (ASTM C109, 2008).

Table 2-Permissible Time Tolerances in completing the compressive strength of mortar cubes

<table>
<thead>
<tr>
<th>Test Age</th>
<th>Permissible Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 h</td>
<td>±1/2 h</td>
</tr>
<tr>
<td>3 days</td>
<td>± 1 h</td>
</tr>
<tr>
<td>7 days</td>
<td>± 3 h</td>
</tr>
<tr>
<td>28 days</td>
<td>± 12 h</td>
</tr>
</tbody>
</table>
Chapter 5 Results and Discussion

5

5.1 Result-Williams

5.1.1 Introduction:

The cemented paste backfill used at Williams mine consisted of 3% cementitious materials with 50% substitution of portland cement by fly ash. The desired water content, mass of liquid/mass of solid, of the mix at the mine was 38.9% with a slump of 200mm (8 inches) (Thompson, Grabinsky, & Bawden, 2008). These mix qualifications were followed in the lab to achieve the same mix as in the mine. Another attribute which is of great importance in the concrete industry is the water/cementitious materials ratio, which as mentioned in the background can have a great impact on the porosity and the ultimate strength of the material. In case of Williams mine the water-cement ratio was calculated as 13.61, taking into account the water content of tailings plus the added water, and dividing by the cementing material. The high value of water-cement ratio is due to the nature of CPB in general; the mix needs to have enough fluidity to be pumped down to the stope and still meet the necessary physical characteristics. The ultimate constrained strength, void ratio/porosity, water content, density, and maturity impact the CPB characteristics individually and they also have an effect on each other.

5.1.2 Unconfined Compressive Strength

The unconfined compressive strength of the Williams Cemented Paste Backfill (CPB) was measured at various ages and curing conditions as shown in Figure 5-1. As previously mentioned, a second trial had to be done for the SureCure samples which were found to have dried out the first time around, and another set of room temperature samples were also tested to act as the benchmark. The first trial, as shown, indicated a “false” higher strength than other curing conditions, this is thought to be due to the dryness of the sample.
Figure 5-1 - Strength behaviour of Williams CPB Using 3% (50:50FA) Cement at Various Ages and Curing Conditions

Although the hardening process of cemented paste backfill as previously mentioned is complex and is dependent on various elements, it still behaves as in concrete. That is, there is an increase in strength with age and also, as seen in Figure 5-2, there is an expected decrease in the rate of strength as the hydration reaction progresses.
The strength gain of CPB is influenced by the curing condition in the same manner as in concrete. That is, a higher curing temperature has a positive impact on the hydration process. In Figure 5-3, it is demonstrated that with an increase of curing temperature from 23°C (the “RT” condition) to 38°C there is a noticeable increase in strength. This effect can also be illustrated by comparing the strength of specimens in three curing conditions of 38°C, the SureCure condition, and at 23°C on (day 7) in Figure 5-1.
Figure 5-3 – Effect of Curing Conditions on Strength Gain of Williams 3% (50:50), showing relationships for both 23°C and 38°C

It is shown in Figure 5-1 that the average strength of samples cured at 38°C is higher than both the samples at room temperature (constant 23°C), and the SureCure samples in the second trial. Figure 5-4 shows the temperature development in the hydration chamber which was used to program the SureCure samples. It is only after day 6 that it reached 38°C and therefore the samples in the SureCure cylinders were cured at a lower temperature than the samples cured at constant 38°C and hence the lower strength. The first trial was able to emphasize the effect of temperature when SureCure and room temperature samples were compared while it was not able to prove the same finding when SureCure and samples at 38°C were compared. This is believed to be due to loss of relative humidity and therefore drier samples in the SureCure that lead to higher strength than samples kept sealed in high relative humidity at 38°C. It has been proven in concrete or cement paste specimens that drier samples result in higher strength, and the same reasoning can be used to explain the apparent higher strength of dry CPB samples in the first trial.
The simple act of increasing the curing temperature from $23^\circ$C to SureCure condition, presented on Figure 5-1, increased the average strength of specimens on day 7 by about 50%. The impact of temperature was further emphasized by an increase of 84%, increasing strength from 64kPa to 118kPa on day 7 when the samples of cured at $38^\circ$C compared to samples cured at $23^\circ$C. The impact of temperature reduces with time due to decreasing rate of hydration which shows in an increase of 43% in samples at day 14 cured at $38^\circ$C when compared to samples of the same age cured at $23^\circ$C. Therefore, it is important to consider the actual mine temperature when predicting the strength since as shown, temperature has a positive impact on strength, and by ignoring it the performance of the mix design is underestimated by about 50%.

Figure 5-4 - Temperature Development of Williams 3%(50:50Fa) as developed in the semi-adiabatic hydration chamber mimiced in the SureCure cylinders
The other issue that can affect the strength development of a mix is the use of a Supplementary Cementing Material (SCM). In the case of Williams, this was fly ash. In order to show the contribution of this SCM material, another set of samples was tested with no fly ash, cured and conditioned consistent with the previous samples. The detailed results on the various conditions of this mixes are available in Appendix F. The room temperature data for both mix designs are compared in Figure 5-5. As in concrete, fly ash contributes to the long term strength by mainly converting CH to C-S-H that are the main contributors to strength. In general, fly ash delays set and lowers the early strength development, but at later ages it contributes greatly to the strength by the secondary production of C-S-H from CH hydration products, described previously.

![Figure 5-5 – Impact of fly ash on strength at early and later ages](image)

5.1.3 Porosity / Void Ratio

Porosity, volume of voids/ volume of total and void ratio, and volume of voids/volume of solids, as previously described, are factors that can impact the strength and the overall quality of the
mix, such as durability. In order to satisfy readers from both the concrete materials and mining industry, the results of both are provided but porosity is simply referred to illustrate points.

The conventional perception on porosity is that there should be a reduction in voids with time as hydration takes place. This point was challenging to prove in cases of CPB where higher water contents used caused a higher initial porosity. Figure 5-6 shows a small increase in porosity with age. This indicates that the hydration products are not contributing to filling in voids. In this figure the lower porosity in the SureCure and 38°C conditions seem to skew down the initial porosity and therefore, Figure 5-7 demonstrates porosity of specimens cured in the same condition at 23°C. This reduces the R² value in Figure 5-7 compare to R² value in Figure 5-6 which is more comforting. It is thought that due to small amount of cementing material involved, the hydration products do not have much impact on the overall porosity, this is similar to the findings from tests conducted on field samples (Grabinsky, Bawden, Simon, & Thompson, 2008), where there is little to no change in porosity with time.
Figure 5-6 – Response of Void Ratio and Porosity with Age

R² = 0.066

R² = 0.065
Figure 5-7 – Response of Void ratio and Porosity of the same curing condition with Age
The degree of saturation of specimens used for porosity, as seen on Figure 5-8, is on average 99.3% with a standard deviation of 0.85% in the room temperature cured samples. The effect of porosity on strength as mentioned in the “background” section is an inverse relationship. Therefore, it is expected that lower porosity would lead to higher strength, but this is not what the results demonstrate in Figure 5-9. There seems to be no relationship between the two parameters. Other than the mix design, porosity can also be influenced by casting procedures. No matter how careful the casting procedure, there would be differences between one casting to another. This can be due to differences in casting temperatures, rodding, or placing of the mix. Therefore the data from the second casting was eliminated in Figure 5-10. This time a more reasonable trend is illustrated; there is a slight decrease in porosity with strength gain. The smaller effect is believed to be due to the small amount of cementitious material used in CPB. The same reasoning can be used to explain the lack of relationship between density and porosity in Figure 5-11, and density-strength relationship in Figure 5-12.
Figure 5-8 – Degree of Saturation in the Williams 3% (50:50) Specimens at Various Ages
Figure 5-9 – Response of Void Ratio and Porosity with Strength
Figure 5-10 – Response of Void Ratio and Porosity of the same mix to Strength
Figure 5-11 – Relationship of Density with Porosity/Void Ratio in William CPB using (50:50FA) Cement
5.1.4 Water Content

The mining water content (mass of liquid/mass of total), of CPB at Williams mine was 29% which was used in void ratio calculations and determined considering various factors such as tailing characteristics and ease of workability at the mine. Figure 5-13 demonstrates the geotechnical water content (mass of liquid/ mass of solid) at various ages and conditions, and it should be remembered that this is the geotechnical water content. The initial Geotechnical water content of Williams was around 39%.
Due to the high content of water in the mix there is a lot of bleed water that evaporates soon after which explains the reduction in the initial water content from 39%. This reduction is much more noticeable at higher temperature curing conditions, i.e. the SureCure cylinders both in the first and second trials. This reduction was not as noticeable in the samples in the 38°C curing condition, because the samples were doubled sealed in plastic bags and sealed again in a bucket to reduce evaporation, as was explained in the “experimental design” section. The added evaporation protection in the second trial of SureCure seems to be somewhat effective in reducing water loss.

The reduction in the water content in the SureCure samples has skewed results in a manner that there seems to be an increase in water content with age in Figure 5-13. Therefore the same analysis was done with the samples of the same condition as presented in Figure 5-14. As mentioned in the “background” section, only 0.23 to 0.25 w/c is required for complete hydration of cement, and the small reduction in the water content in this figure can be related to this
hydration phenomena combined with evaporation of the bleed water. The same observation, “no significant change in water content”, was also reported in the field samples (Grabinsky, Bawden, Simon, & Thompson, 2008).

Figure 5-14 – Water Content of Williams 3% (50:50) at Curing Condition of 23°C

The relationship between water content and strength is complicated. Water is necessary for initialization of cement hydration and to be able to continue the reactions, but excess water has adverse impact on strength since it leads to larger porosities. In mining there is not a set value for water content that can optimize this relationship, and as mentioned, the ease of workability governs mining operations.
Figure 5-15 – Water Content Relationship with Respect to Strength in Williams 3%(50:50)

The relationship between water content and strength is depicted on Figure 5-15; the relationship although not very strong, $R^2 = 0.168$, but it does prove the point. There is definitely enough water to carry out the hydration and other reactions in Cemented Paste backfill. Therefore, a reduction in the amount of water leading to a higher strength, Figure 5-15.

5.1.5 Maturity

The point of the maturity concept is to be able to predict the in-situ strength at times where testing is not possible, like the conditions in the mine. As was explained in the “experimental design” section, the samples cured at 23 °C were tested up to 90 or 100 days and therefore provided a maturity data of up to that point. The maturity of samples cured at 23 °C with their respective strengths up to ages of 100 days is shown in Figure 5-16.
The $R^2$ value of 0.962 indicates a very good correlation between maturity and strength of samples in room temperatures, and the line of best fit’s formula can be written in the maturity formula format, the maturity formula for Figure 5-16 is:

$$fc = A(\log M) + B$$

$$fc = 110.6 \ (\log M) - 344.8 \quad \text{Equation 8}$$

The constants in Equation 8 can be obtained by either taking to points from the best fit line on maturity versus strength, such as Figure 5-16, and solving for A and B by having two equations and two unknowns. Or one can achieve the same results by graphing the strength versus log of maturity and simply drawing the line of best fit’s equation. Figure 5-17 shows the same data point only presented as strength versus log value of maturity.
Figure 5-17 – Strength-log Maturity relationship of Williams 3% (50:50FA) based on results up to 100 days

The maturity value of interest can then be plugged into the formula to calculate the predicted strength for the specific maturity. The maturity values for other curing conditions in this research experiment, SureCure and 38°C, were calculated separately and the strength for a given maturity was calculated based on Equation 8.

The calculation for the maturity value for the 38°C curing condition was straightforward, multiplying 48 by the age of interest in hours and using -10°C as datum temperature, resulting in 8,064 °C-Hr and 16,128 °C-Hr for ages of 7 and 14 days respectively. The SureCure maturity value can be a bit more complicated. The temperature profile of the calorimeter needed to be known in order to indicate a relationship between temperature and time for integration to be
possible, as shown in Figure 5-18. The -0.008 on the polynomial equation indicated that the $x^4$ has very little effect on the final temperature and therefore it is suggested that the equation is sufficient for integration to indicate the maturity value, which is the area underneath the curve, based on $-10^\circ$C.

Figure 5-18 – 7 day Temperature profile of Williams 3%(50:50FA)

The detailed calculation for obtaining the maturity value is as follows:

Trend line equation from hydration chamber calorimeter:

$$y = -0.008x^4 + 0.129x^3 - 0.806x^2 + 4.335x + 22.88$$

Integrated Formula:
\[ \int_0^7 y = -\frac{0.008}{5} x^5 + \frac{0.129}{4} x^4 - \frac{0.806}{3} x^3 + \frac{4.335}{2} x^2 + 22.88 x \]

\[ = 224.76 \, ^{\circ}\text{C-Day} = 5394 \, ^{\circ}\text{C-hr} \]

For maturity, the datum starts at \(-10^\circ\text{C}:\)

\[ -10 \, ^{\circ}\text{C} \times 7 \text{ Day} \times 24 \frac{\text{Hour}}{\text{Day}} = 1680 \, ^{\circ}\text{C} - \text{hr} \]

Total maturity value for Williams 3% (50:50FA) at age 7 cured in the SureCure Cylinder is:

\[ 1680 \, ^{\circ}\text{C} - \text{hr} + 5394 \, ^{\circ}\text{C} - \text{hr} = 7074 \, ^{\circ}\text{C} - \text{hr} \]

Table 3 indicates a summary of the strength found from maturity concept based on Equation 8, the actual strength tested in the lab, along with the error between the two values. As mentioned before, this mix was tested twice in the SureCure cylinders and at room temperature and therefore the second time was marked as 2\(^{nd}\) trial.

**Table 3 – Summary of Estimated Strength Based on Maturity Graph of 100 Days and datum of \(-10^\circ\text{C}**

<table>
<thead>
<tr>
<th></th>
<th>Maturity ((^{\circ}\text{C-Hr}))</th>
<th>Strength Based Equation 8 (kPa)</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38(^\circ\text{C})-Day 7*</td>
<td>8064</td>
<td>87.62</td>
<td>118</td>
<td>26</td>
</tr>
<tr>
<td>38(^\circ\text{C})-Day 14</td>
<td>16128</td>
<td>122.3</td>
<td>151</td>
<td>19</td>
</tr>
<tr>
<td>SC- Day 7**</td>
<td>7074</td>
<td>80.1</td>
<td>132</td>
<td>39</td>
</tr>
<tr>
<td>SC-Day 7-2(^{nd}) trial</td>
<td>6480</td>
<td>76.7</td>
<td>96</td>
<td>20</td>
</tr>
</tbody>
</table>

* 38\(^\circ\text{C}\)-day 7 indicates the samples were cured at 38\(^\circ\text{C}\) and tested at day 7

** SC indicated the mix was in the SureCure cylinders and followed the hydration chamber calorimeter for temperature development

The prediction Error was calculated based on the following formula, using results for “38\(^\circ\text{C}\)-Day 7” as an example:

\[ \text{Error (\%)} = \frac{[\text{Actual Strength} - \text{Estimated Strength}]}{\text{Actual Strength}} \times 100 \]

\[ \text{Error (\%)} = \frac{[118 - 87.62]}{118} \times 100 \]

\[ \text{Error (\%)} = 25.7 \]
As was mentioned in the “experimental design” section, the SureCure samples initially were protected against drying using simple shower caps as was suggested by the manufacturer. After the analysis of the data it was concluded that the shower caps were not sufficient enough to keep the relative humidity constant, and therefore the high strength in the lab results was due to a dry sample and was not the true strength. Therefore, the results from the initial SureCure samples will not be used further for analysis. Even if the first trial of SureCure samples is eliminated, the average in the errors is about 22%. It is worth pointing out that in all cases the maturity equation has underestimated the actual strength and therefore it is on the conservative side. The datum temperature, as explained in the previous sections, can be measured by conducting the suggested tests in ASTM 1074, but has been commonly taken as -10°C. In the case of CPB, due to the small concentration of cementing material used, it is therefore reasonable to believe that the reactivity temperature might be different and higher than -10°C. Therefore, various potential datum temperatures of 0°C, 5°C, 15°C, and finally 13°C, were examined in order to estimate the optimal datum temperature by the method of trial and error, since the actual strength was available for comparison.

Using a datum temperature of 0°C decreased the average error to about 17%. This was obtained from the new maturity formula in Equation 9, it should be pointed out that in this equation as in Equation 8 the slope of the line remains the same, 110.6, and the line is only being shifted down. Equation 9 was then used to predicted strength indicated in Table 4:

\[
fc = 110.6 \log M - 327.4 \quad \text{Equation 9}
\]

<table>
<thead>
<tr>
<th>Maturity (°C-Hr)</th>
<th>Strength Based on Equation 9 (kPa)</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°C-Day 7</td>
<td>6384</td>
<td>94</td>
<td>118</td>
</tr>
<tr>
<td>38°C-Day 14</td>
<td>12768</td>
<td>128.6</td>
<td>151</td>
</tr>
<tr>
<td>SC-Day 7-2nd trial</td>
<td>4800</td>
<td>79.7</td>
<td>96</td>
</tr>
</tbody>
</table>

The calculations and results for datum temperatures of 5°C and 15°C are provided Table G-1 and Table G-2 in the Appendix section respectively. In case of 15°C the estimated strength was
overestimated by about 3%, therefore it was decided to reduce the datum temperature to 13°C. The estimated strength based on 13°C was then calculated from Equation 10 as summarized on Table 5, which indicates an underestimation in strength of about 3%.

\[ f_c = 110.6 \, \log M - 287.4 \]  \hspace{1cm} \text{Equation 10}

**Table 5 – Summary of Estimated Strengths Based on Maturity Graph of 100 days and using a Datum Temperature of 13°C**

<table>
<thead>
<tr>
<th>Maturity (°C-Hr)</th>
<th>Strength Based Equation 10 (kPa)</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°C-Day 7</td>
<td>4200</td>
<td>114.7</td>
<td>118</td>
</tr>
<tr>
<td>38°C-Day 14</td>
<td>8400</td>
<td>149.3</td>
<td>151</td>
</tr>
<tr>
<td>SC-Day 7-2nd trial</td>
<td>2616</td>
<td>91</td>
<td>96</td>
</tr>
</tbody>
</table>

Figure 5-19 shows these predicted strengths based on up to 100 days of data relative to the actual strength obtained in the lab. As previously mentioned, the predicted strength obtained from the strength-maturity relationship, when based on datum temperature of 13°C, results in strengths in the same range as the actual strength. Therefore the maturity concept is able to estimate the strength of CPB if the datum temperature is calibrated. This calibration can be done using the method described in the “background” section.
One argument that can be made about the above procedure for estimating strength is that it has used all the data up to age of 100 days. This undermines the advantage of the maturity method in predicting strength since if there was time to get the room temperature strengths up to 100 days then surely there is time to wait until the required CPB strength is met. The counter argument on the point is that the calibration can be done ahead of time to be used at various stopes with similar characteristics and therefore a low error can be obtained. The use of limited data is also studied in this report in order to see the impact of smaller range of data points. Use of 7 day strengths is both reliable and short enough to be considered a better cutting point for maturity versus strength relationship, as seen in Figure 5-20. The error of the estimated strength obtained by limiting data to 7 days is expected to increase, and the reduction in $R^2$ value to 0.84 is a clear indication of it.
In order to prove the reason for changing the datum temperature, both -10°C and 13°C will be used to calculate the estimated strength. Equation 11 and Table 6 present the formula and summary of results obtained using -10°C as datum temperature. The maturity value and formula were obtained as previously described.

\[ f_c = 70.92 \log M - 203.4 \quad \text{Equation 11} \]
Table 6 - Summary of Estimated Strength Based on Maturity Graph of 7 days and Datum Temperature of -10°C

<table>
<thead>
<tr>
<th>Maturity (°C-Hr)</th>
<th>Strength Based on ( f_c = 70.92 (\log M) - 203.4 ) (Equation 11(kPa))</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°C-Day 7</td>
<td>8064</td>
<td>78.5</td>
<td>118</td>
</tr>
<tr>
<td>38°C-Day 14</td>
<td>16128</td>
<td>104.2</td>
<td>151</td>
</tr>
<tr>
<td>SC-Day 7-2\textsuperscript{nd} trial</td>
<td>6480</td>
<td>70.4</td>
<td>96</td>
</tr>
</tbody>
</table>

As expected, when the conventional datum temperature of -10°C was used the error is high, it is around 30% which is higher than the error of 20% from using all the data. Increasing the datum temperature to 13°C and using only the initial 7 days data, resulted in maturity Equation 12 and maturity values and predicted strengths presented in Table 7. The graph of maturity-strength relationship is available in Figure G-1 in the Appendix section.

\[ f_c = 70.92 (\log M) - 166.6 \]  \hspace{2cm} \text{Equation 12}

Table 7 - Summary of Estimated Strength Based on Maturity Graph of 7 days and Datum Temperature of 13°C

<table>
<thead>
<tr>
<th>Maturity (°C-Hr)</th>
<th>Strength Based Equation 12 (kPa)</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°C-Day 7</td>
<td>4200</td>
<td>90.4</td>
<td>118</td>
</tr>
<tr>
<td>38°C-Day 14</td>
<td>8400</td>
<td>111.7</td>
<td>151</td>
</tr>
<tr>
<td>SC-Day 7-2\textsuperscript{nd} trial</td>
<td>2616</td>
<td>75.8</td>
<td>96</td>
</tr>
</tbody>
</table>

The error in predicting the strength of Williams 3% (50:50FA) CPB using the initial 7 days data is around 23%, which is as high as the error in predicting the same mix using 100 days of data. This error might seem high but it is still on the conservative side.

As was mentioned in the “experimental design” section, two other mix designs using Williams materials were also tested, Williams with 3% and 7% cement without any fly ash. The maturity method was also used for these two mix designs to further prove the reliability of this method, and then depict the effect of higher binder content on this method. In these two mix designs,
SureCure samples are not used for comparison, since the samples for this condition dried up and depicted a “false” high strength. Therefore only samples cured at 38°C will be used and this set was tested at an age of 14 days. Williams with 3% cement was tested up to 100 days at room temperature (23°C) to obtain the maturity-strength relationship demonstrated on Figure 5-21 based on datum temperature of -10°C and Figure 5-22 based on datum temperature of 13°C.

![Figure 5-21 - Maturity-Strength Relationship of Williams 3% based on 100 days of Data and Datum Temperature of -10°C](image)

The maturity equations for this mix with datum temperature of -10°C and 13°C are Equation 13 and Equation 14 respectively. The summary of estimated strengths obtained from these equations is depicted on Table 8.

\[ fc = 79.46 \log M - 216.4 \]  
**Equation 13**

\[ fc = 79.46 \log M - 175.2 \]  
\(80\)  
**Equation 14**
Figure 5-22- Maturity-Strength Relationship of Williams 3% based on 100 days of Data and Datum Temperature of 13°C

Table 8- Summary of Estimated Strength of Williams 3% Cured at 38°C for 14 Days

<table>
<thead>
<tr>
<th>Datum Temperature</th>
<th>Maturity (°C-hr)</th>
<th>Strength based on Maturity Formula (kPa)</th>
<th>Actual Strength (kPa)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10°C</td>
<td>16128</td>
<td>122</td>
<td>152</td>
<td>20</td>
</tr>
<tr>
<td>13°C</td>
<td>8400</td>
<td>143</td>
<td>152</td>
<td>6</td>
</tr>
</tbody>
</table>

In this mix design the error from using a datum temperature of -10°C is around 20% as with the mix design with fly ash and reduced by increasing datum temperature to 13°C. Reducing the data
points to 7 days as discussed will increase the error, decrease in $R^2$ value in Figure 5-23, and for Williams with 3% cement as shown in Table 9 the error has increased to 18% although 13°C was set as the datum temperature. Equation 15 was used to calculate the predicted strength.

![Figure 5-23 – Maturity-Strength Relationship for Williams with 3% cement based on 7 days of data and Datum Temperature of 13°C](image)

**Figure 5-23** – Maturity-Strength Relationship for Williams with 3% cement based on 7 days of data and Datum Temperature of 13°C

$$fc = 44.92 \log M - 98.85$$  \hspace{1cm}  \text{Equation 15}

**Table 9 – Summary of Estimated Strength of Williams Using 3% Cement Cured at 38°C for 14 days**

<table>
<thead>
<tr>
<th>Datum Temperature</th>
<th>Maturity (°C-hr)</th>
<th>Strength based on Maturity Formula (kPa)</th>
<th>Actual Strength (kPa)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13°C</td>
<td>8400</td>
<td>124</td>
<td>152</td>
<td>18</td>
</tr>
</tbody>
</table>
As mentioned, the other mix design used for analysis of Williams mine had 7% cement. For this mix design the samples at 38°C were cured for 7 days, and the samples cured at 23°C were tested up to 90 days. The maturity relationship for this mix design using datum temperature of -10°C is presented in Figure G-2 in the Appendix section and the equation obtained is presented in Equation 16. Figure 5-24 and Figure 5-25 show the maturity relationship with strength with datum temperature of 13°C considering 90 days and 7 days of data respectively and the maturity formula obtained from these figures are presented as Equation 17 and Equation 18.

$$f_c = 181.0 \cdot \log M - 357.8 \quad \text{Equation 16}$$

![Figure 5-24 - Maturity-Strength Relationship of Williams with 7% cement based on 90 days and Datum Temperature of 13°C](image)
\[ f_c = 181.0 \log M - 263.9 \quad \text{Equation 17} \]

\[ f_c = 217.3 \log M - 364.6 \quad \text{Equation 18} \]

Table 10 summarizes the results from these figures, using the actual strengths of samples cured at 38°C for 7 days. As in previous mix designs there is a decrease in error with changing the
datum temperature from -10°C to 13°C. Limiting the data to 7 days, however, did not result in an increase in error, the calculated strength is close to that of obtained using 90 days of data. There seems to be a trend of decreasing the error with an increase in the amount of cement used in the mix design as presented in Table 11.

**Table 10 – Summary of Estimated Strength of Williams Using 7% cement cured at 38°C for 7 days**

<table>
<thead>
<tr>
<th>Datum Temperature</th>
<th>Maturity (°C-hr)</th>
<th>Strength based on Maturity Formula (kPa)</th>
<th>Actual Strength (kPa)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10°C</td>
<td>8064</td>
<td>378</td>
<td>490</td>
<td>23</td>
</tr>
<tr>
<td>13°C</td>
<td>4200</td>
<td>427</td>
<td>490</td>
<td>13</td>
</tr>
<tr>
<td>13°C-7DD*</td>
<td>4200</td>
<td>433</td>
<td>490</td>
<td>11.5</td>
</tr>
</tbody>
</table>

* Using the initial 7 days of data to develop

$$r = 217.3 \log(M) - 364.6$$

Equation 18 to calculate strength.

**Table 11 – Summary of Estimated Strength of Various Mixed design for Williams cured at 38°C for either 7 or 14 days**

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Maturity (°C-hr)</th>
<th>Strength based on Maturity Formula (kPa)</th>
<th>Actual Strength (kPa)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% (50:50 FA)</td>
<td>4200</td>
<td>90.4</td>
<td>118</td>
<td>23</td>
</tr>
<tr>
<td>3% (50:50 FA)</td>
<td>8400</td>
<td>112</td>
<td>151</td>
<td>26</td>
</tr>
<tr>
<td>3%</td>
<td>8400</td>
<td>124</td>
<td>152</td>
<td>18</td>
</tr>
<tr>
<td>7%</td>
<td>4200</td>
<td>433</td>
<td>490</td>
<td>11.5</td>
</tr>
</tbody>
</table>
6

6.1 Conclusions

In general, there is an increase in strength of CPB with age. This strength gain due to the cement hydration process and is influenced by temperature. There is an increase in strength, with an increase in curing temperature. In these experiments, there was 84% increase in strength with an increase of 15°C in the curing temperature. Fly ash does influence the later age strength of paste and contributed to strength gain after 14 days of age in the case of Williams mine.

The impact of influencing factors such as porosity, density, and water content of CPB were found to be more challenging to relate to strengths developments. There was no significant change in porosity with age which can be due to low amount of cementing material used in this experiment. The small reduction in porosity did show a small relation with increasing strength. The density of specimen, however, did not have any relationship with porosity and no significant relationship with strength.

The initial water content of Cemented Paste Backfill is determined by the required workability and therefore the added water is much more than required for cement hydration. The small reduction in water content due to the amount required for hydration of the small amount of cementing material combined with some water loss due to evaporation and bleeding is very small relation to the initial water content of the CPB. The reduction in water content does show a relationship with increasing temperature.

The maturity method was shown to work for Cemented Paste Backfill specimens. This was shown by a strong correlation between maturity and strength which can then be used to develop coefficients for the maturity formula. This method required some revision and calibration of the base temperature of -10°C typically used in the concrete industry. Due to the small concentration of cementing material used, increasing the datum temperature to 13°C proved to be
sufficient for estimating strength with reasonable errors. The estimated strengths were on the conservative side when compared to the actual strength obtained from lab experiments.

6.2 Recommendation for Future Work

The datum temperature obtained in this research can be further investigated by conducting the test for determining datum temperature in the annex of ASTM C1074. This analysis needs to be done for various tailings with different concentrations of cementing material in order to establish specific datum temperatures CPB. This will then allow the mines to use the established datum temperature based on the concentration of cementing material used.

Until then, it is recommended that the mines invest in temperature matching system for CPB samples, such as SureCure, to follow the temperature development already being monitored in the stopes and obtain CPB test strengths more representative of in-situ values.
References


Fall, M., Celestin, J., Pokharel, M., & Toure, M. (2010). A contribution to understanding the effects of curing temperature on teh mechanical proprpoerties of mine cemented tailings backfill. Engineering Geology (114), 397-413.


Appendices

Appendix A – Results with Cayeli Mine CPB

The Cayeli mine located in east north of Turkey mining for Nickel, uses two types of tailings in their backfilling process, each have a different chemical composition mainly the sulphide content. In this section the results of experiments conducted on both type of tailings is provided. The water content used at the mine is 23%, mass of water to mass of total. And the specific gravity of tailings was determined to be 4.52.

Appendix A.1 – Cayeli Mine, Non-Spec tailing with 6.5% cementing Material.

Figure A1- 1 – Strength behavior of Cayeli Non-spec CPB using 6.5% cement at various ages and curing conditions
Figure A1-2 – Temperature Development of Cayeli Non-spec CPB using 6.5% cement as developed in the semi-adiabatic hydration chamber mimiced in the SureCure Cylinders.
Figure A1-3 – Response of void ration and porosity with age
Figure A1-4 – Degree of Saturation in Cayeli Non-spec CPB using 6.5% cement at various ages
Figure A1-5 – Relationship of Density with Porosity/Void Ratio in Cayeli Non-spec CPB using 6.5% cement
Figure A1-6: Relationship of Density with strength in Cayeli Non-spec CPB using 6.5% cement
Figure A1- 7– Water Content of Cayeli Non-spec CPB using 6.5% cement at various ages and conditions

Figure A1- 8 – Water content relationship with respect to strength in Cayeli Non-spec CPB using 6.5% cement
Appendix A2 – Cayeli Mine, Spec tailing with 8.5% cement

Figure A2-1 – Strength Behaviour of Cayeli spec CPB using 8.5% cement at various ages and curing conditions
Figure A2- 2 – Temperature Development of Cayeli spec CPB using 8.5% cement as developed in the semi-adiabatic hydration chamber mimiced in the SureCure cylinders
Figure A2-3 - Response of Void Ratio and Porosity with age
Figure A2-4 – Degree of Saturation in the Cayeli spec CPB using 8.5% cement specimens at various ages
Figure A2-5 – Response of Void Ratio and Porosity with Strength
Figure A2- 6 – Relationship of Density with Porosity/Void Ratio in Cayeli spec CPB using 8.5% cement
Figure A2-7 – Relationship of Density with Strength in Cayeli spec CPB using 8.5% cement
Figure A2-8 – Water content of Cayeli spec CPB using 8.5% cement at Various ages and conditions

Figure A2-9 – Water content relationship with respect to strength in Cayeli spec CPB using 8.5% cement
Appendix B – Results of testing on Kidd mine

The Kidd mine located in Ontario, Canada mining for Nickel, uses 55% sand, 45% tailings in their mix design for backfilling. In this section the results of experiments conducted on the material obtained from this mine, using 2.5% binder, is provided. The binder used at the mined is a premix binder containing 90% slag and 10% cement. The water content used at the mine is 22%, mass of water to mass of total. And the specific gravity of the tailings used was determined to be 2.77.

Figure B-1 – Strength behaviour of Kidd CPB using 2.5% binder at various ages and curing conditions
Figure B-2 – Temperature development of Kidd CPB using 2.5% binder as developed in the semi-adiabatic hydration chamber mimiced in the SureCure cylinders
Figure B-3 – Response of Void Ratio and Porosity with Age
Figure B- 4 – Degree of Saturation in the Kidd CPB using 2.5% binder specimens at various ages
Figure B-5 – Response of Void Ratio and Porosity with Strength
Figure B- 6 – Relationship of Density with Porosity/Void Ratio in Kidd CPB using 2.5% binder
Figure B-7 – Relationship of density with strength in Kidd CPB using 2.5% binder
Figure B-8 – Water content of Kidd CPB using 2.5% binder at various ages and conditions

Figure B-9 – Water content relationship with respect to strength with Kidd CPB using 2.5% binder
Appendix C – XRD Analysis on the Tailings of Williams mine
Appendix D – Spread Sheet Used for Williams’ Material Preparation

Note: Industrial Water Content being $M_{\text{Water}}/M_{\text{Total}}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Enter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement (% of solids):</td>
<td></td>
<td>enter 3</td>
</tr>
<tr>
<td>Mass of dry PC (g):</td>
<td></td>
<td>590.90</td>
</tr>
<tr>
<td>Mass of dry Mt (g):</td>
<td></td>
<td>19105.8</td>
</tr>
<tr>
<td>Mass of Additive (g):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density of Paste (g/mL):</td>
<td></td>
<td>1.86</td>
</tr>
<tr>
<td>Density of Mine Tailings (g/mL):</td>
<td></td>
<td>2.77</td>
</tr>
<tr>
<td>Density of Portland Cement (g/mL):</td>
<td></td>
<td>3.13</td>
</tr>
</tbody>
</table>

Additive:

<table>
<thead>
<tr>
<th>By Concentration</th>
<th>By Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration (mol/L):</td>
<td>Wt.% of PC:</td>
</tr>
<tr>
<td>Molecular Weight (g/mol):</td>
<td>Mass of Additive (g): 0.000</td>
</tr>
<tr>
<td>Mass of Additive (g):</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Water Content: measured

<table>
<thead>
<tr>
<th>Water Content:</th>
<th>wet tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dish No.</td>
<td></td>
</tr>
<tr>
<td>Mass of Dish</td>
<td>27.67 25.76 27.12</td>
</tr>
<tr>
<td>$M_{\text{wet}} + M_{\text{dish}}$</td>
<td>116.2 100.57 82.06</td>
</tr>
<tr>
<td>$M_{\text{dry}} + M_{\text{dish}}$</td>
<td>92.87 80.84 67.32</td>
</tr>
<tr>
<td>W (%)</td>
<td>35.80 35.82 36.67</td>
</tr>
</tbody>
</table>
Appendix E - Compression Pads Specification

The Retaining Cup retains the compression pad and fits over the ends of the concrete cylinder. ECON-O-CAP Retaining Cup is machined from high alloy steel to the same tolerances as your plasters. The steel has minimal temperature variation and no deflection under load. The high alloy steel resists scratches, eliminating the need for additional machining.

The Compression Pad, made of tough elastomeric material, flows into irregularities and distributes the test load uniformly without creating air pockets to assure consistent breaks.

Compression pads are available in several hardnesses. ECON-O-CAP System is available in 2", 3", 4" and 6" diameters. Meets AASHTO Standard T22. Meets ASTM Standard C1231

New "Stay-In-Place" Pads

New "Stay-In-Place" pads have patented nubs which secure pad into retaining cup during use
Appendix F – Strength Behavior of Williams 3% at various age and curing condition

[Graph depicting the relationship between age (in days) and strength (in kPa) for different curing conditions.]
Appendix G– Maturity Calculations

Table G-1 – Estimation of Estimation of Strength based on 100 days of results and Datum temperature of 5°C

Maturity equation:

\[ f_c = 110.6 \ (\log M) - 315.6 \]

Summary of Estimated Strength Based on Maturity Graph of 100 days and Datum of 5°C:

<table>
<thead>
<tr>
<th>Maturity</th>
<th>Strength Based Equation (kPa)</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°C-Day 7</td>
<td>5544</td>
<td>99.16</td>
<td>118</td>
</tr>
<tr>
<td>38°C-Day 14</td>
<td>11088</td>
<td>133.82</td>
<td>151</td>
</tr>
<tr>
<td>SC-Day 7-2nd trial</td>
<td>3960</td>
<td>82.34</td>
<td>96</td>
</tr>
</tbody>
</table>
Table G-2: Estimation of Strength based on 100 days of results and Datum temperature of 15°C

Maturity equation:

$$fc = 110.6 \log M - 276.7$$

Summary of Estimated Strength Based on Maturity Graph of 100 days and Datum of 15°C:

<table>
<thead>
<tr>
<th>Maturity (°C-Hr)</th>
<th>Strength Based Equation (kPa)</th>
<th>Strength as tested in the lab (kPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38°C-Day 7</td>
<td>3864</td>
<td>121.66</td>
<td>118</td>
</tr>
<tr>
<td>38°C-Day 14</td>
<td>7728</td>
<td>156.3</td>
<td>151</td>
</tr>
<tr>
<td>SC-Day 7-2nd trial</td>
<td>2280</td>
<td>95.3</td>
<td>96</td>
</tr>
</tbody>
</table>
Figure G-1 - Maturity vs. Strength relationship based on datum temperature of 13°C

\[ y = 258.7e^{0.03x} \]

\[ R^2 = 0.878 \]
Figure G-2 - Maturity-Strength relationship of Williams using 7% cement based on 90 days of data and Datum Temperature of -10°C

\[ y = 126.6e^{0.011x} \]

\[ R^2 = 0.933 \]