EFFECTS OF TAILINGS AND BINDER GEOCHEMISTRY ON THE PHYSICAL STRENGTH OF PASTE BACKFILL

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Abstract: Before implementation of paste backfill at Brunswick Mining Division (BMD), Noranda Inc., laboratory tests showed decreases in cured paste strengths after 90 to 120 days of curing. This could imply a risk of premature underground failures of the backfilled paste. Such failures may lead to loss or dilution of ore in the secondary stopes nearby, and the failed material could oxidise, potentially leading to self-heating problems and even emission of sulphur dioxide gas. To find the causes for the strength reduction and to gather data for optimisation of the paste recipe, the relationship between tailings/binder geochemistry and cured paste strengths was investigated. Changes in geochemistry and mineralogy of wax-sealed paste cylinders were studied at different curing intervals ranging from 7 to 180 days. It was found that two paste mixtures attained the 1 MPa target strength and outperformed the control paste mixture. Maximum strength was generally achieved upon 120 to 180 days of curing and strength losses occurred after that. Intensified secondary ettringite formation does not seem to have occurred as a result of internal sulphate attack for curing times up to 180 days. A moderate pulse of secondary ettringite formation was observed after 120 days of curing and was considered a cause for strength deterioration. White clusters of gypsum and minor ettringite were visible in a one year old cured paste sample that used 5% Type 10 cement as binder. Addition of cement to tailings has the effect of immobilising metals which otherwise are easily dissolvable. Partial substitution of Type 10 cement with type F flyash in the binder appears to improve the sulphate resistance of the resulting paste. Selective Al dissolution seems to be an effective analytical technique for measuring low contents of ettringite in cemented paste.

Key words: paste backfill, sulphidic tailings, sulphate attack, UCS strength, geochemistry, environment.

Introduction

Brunswick Mining Division (BMD), Noranda Inc. is located 27 km south west of Bathurst, New Brunswick. Ore processed by BMD has come from two deposits: No. 6 and No. 12. No. 6 was a small ore body mined by open pit and underground methods until 1983. No. 12 is one of the world's largest Zn-Pb-Cu-Ag volcanogenic massive sulphide deposits, which is mined by underground methods. The host rock at No. 12 is comprised of metamorphic quartz-carbonate-chlorite-sericite-feldspar assemblages containing variable quantities of sulphides.[1,2,3] The ore is approximately composed of 20% valuable sulphides (sphalerite, chalcopyrite, galena, silver sulphide), 60% waste sulphides (pyrite, pyrrhotite), and 20% silicates and carbonates. As of the end of 1998, in excess of 100 million tonnes of ore have been mined, representing approximately two thirds of the known reserves.[4] About 80 million tonnes of tailings have been deposited in the tailings area.

Benefits of implementing the paste backfill technology at BMD are associated with improved mining operation and better environmental management. Paste backfill has the potential to stabilise the ground, increase ore recovery, reduce ore dilution, shorten the mining cycle, streamline the backfill operation (relative to the previous rock backfill), and lower the mining cost. Paste backfill reduces the amount of tailings destined for surface disposal, from 100% to about 35% of the total tailings production. This eliminates the need for new tailings areas to accommodate future tailings production, thereby saving the cost of construction. In addition, because of the high acid generation potential of the BMD tailings, underground backfill of this material is a better disposal option than surface deposition, as the tailings will be permanently flooded by ground water upon mine closure, essentially eliminating the possibility of acid mine drainage (AMD) generation.

The paste backfill operation was commissioned in the summer of 1998 at BMD. The history and technical issues related to the implementation have been discussed in two recent papers.[4,5] The implementation was accompanied by a research project, in which technical, environmental and economical aspects were considered. Earlier laboratory testing showed that test paste cylinders exhibited a decrease in UCS (unconfined compressive strength) over time after 90 to 120 days of curing. The causes concerns that such strength decreases may result in premature failures of backfilled stopes and subsequently give rise to potential for self-heating and even emission of sulphur dioxide gas due to oxidation of failed material. Such failures can also result in loss or dilution of ore. To ensure a safe and smooth commissioning of the paste backfill operation, a sulphate-resistant cement, Type 50, was adopted as the initial binder. It is anticipated that, in the future, less expensive binders will be substituted to cut binder cost. Testing of different binder recipes is ongoing.

The laboratory study reported in this paper was jointly conducted at Queen's University and Noranda Technology Centre (NTC). Several backfill paste mixes were made from different binders and BMD total tailings. Paste cylinders were cast, wax-sealed, and tested at pre-determined curing intervals for UCS (at Queen's) and geochemistry and mineralogy at NTC. The primary objectives of the study were to clarify the role of internal sulphate attack in the paste strength variation over time and to identify appropriate paste recipes that would meet the underground strength requirements and minimise the binder cost.[4] This paper describes the geochemical and mineralogical properties of the total tailings and the binders used, reports on the UCS and geochemical variation over curing time, and attempts to establish a relationship between the tailings/binder geochemistry and the cured paste UCS.

Geochemistry and Mineralogy of Fresh Tailings and Binders

The BMD fresh total tailings contain 28 to 37% total sulphur (corresponding to about 52 to 69% pyrite), 1.0 to 2.5% soluble sulphate, 3.1 to 4.6% CO_2 (equivalent of about 7 to 11% $CaCO_3$), and 28 to 36% total Fe (owing to the high pyrite contents). The tailings also contain various amounts of unrecovered valuable minerals, i.e. the sulphides of Zn, Pb, Cu and Ag. The carbonates exist mainly as calcite and magnesian ankerite, with minor manganese siderite. The dominant silicate minerals are (in order of decreasing abundance) quartz, chlorite, feldspars and sericite. Minor amounts of diopside, actinolite and grunerite were also found. The dominant sulphide mineral is pyrite (40-64%). Other sulphides include (in decreasing order of abundance) pyrrhotite (5-14%), sphalerite, galena, and chalcopyrite. Arsenopyrite occurs as an accessory mineral. Magnetite is the main primary oxide mineral (0-7.2%), followed by rutile and cassiterite as accessory oxide minerals. Gypsum is the predominant secondary sulphate mineral (0-4.48%) and barite occurs as an accessory sulphate mineral.

The BMD tailings have high acid potentials (AP = 875 to 1156 kg $CaCO_3$ equivalent/t) and high sulphide acid potentials (SAP = 859 to 1159 kg $CaCO_3$ equivalent/t). In comparison their neutralisation potentials (NP = 17 to 77 kg $CaCO_3$ equivalent/t) and carbonate neutralisation potentials (CNP = 70 to 106 kg $CaCO_3$/t) are much lower, yielding highly negative net neutralisation potentials (NNP = NP - AP = -842 to -1131 kg $CaCO_3$ equivalent/t) and carbonate net neutralisation potential (CNNP = CNP - SAP = -758 to –1089 kg $CaCO_3$ equivalent/t). Therefore, the BMD tailings are highly potentially acid generating. Addition of cement, which is highly alkaline, even in small amounts, to fresh tailings should have the beneficial effects of buffering the paste pH at higher values, preventing the dissolution of easily mobilised metals. The effects of cement addition can be seen in the rinse chemistry of the total tailings compared with that of cemented tailings containing 5% binders (Figure 1).

Dry tailings or powders of cured paste were rinsed at a 1:1 mass ratio, using 30 g of solids in 30 mL distilled-deionised water. After the contact the solution was filtered and analysed by ICP-AES. Figure 1 shows that the metal concentrations in the rinse solution of the fresh total tailings were much higher than those in the rinse solution of the powdered pastes containing 95% total tailings and 5% binders. In fact, the metal concentrations in the rinse solution of the paste powders were generally at the detection limits. The potential for metal releases is diminished in the cemented tailings. Once the mine is permanently closed, flooding of the workings will occur which prevents oxidation of the backfilled stopes. The mobile metals originally present in the fresh tailings or the process water will be permanently locked in the backfilled paste. In the interim, oxidation of some filled paste does occur, especially in the edges of the filled stopes, leading to some release of metals into infiltrating water. This is however a short-term problem and can be adequately addressed by collection and treatment of the underground water, as is practised now.

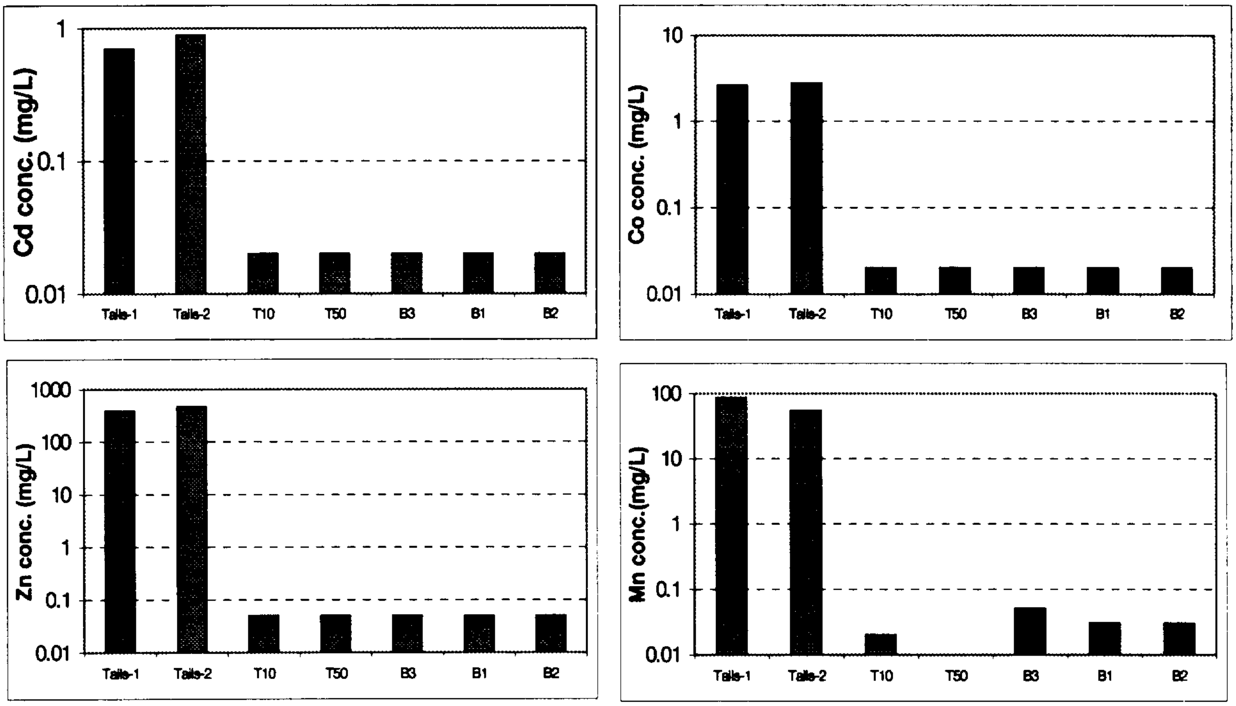

Figure 1. Dissolved elemental concentrations of Cd, Co, Zn and Mn in rinse solutions of total tailings (Tails-1, and -2) and powders of cured pastes containing 5% binders (T10, T50, B1, B2, B3, see text for meanings of the symbols) and 95% total tailings after 90 days of curing

The binders used in the present study were made from one, or a combination of two, of the following five materials: (1) normal Portland cement (Type 10 cement), (2) sulphate-resistant Portland cement (Type 50 cement), (3) a type F flyash (symbol FA), and (4) two slags (symbols S1, S2). The five kinds of pastes reported here were made of 95% total tailings and 5% of one of the following five binders (the percentages are expressed on a dry basis): (1) pure Type 10 cement, symbol T10, (2) pure Type 50 cement, symbol T50, (3) a 20:80 Type 10 cement: S1 mixture (symbol B1), (4) a 20:80 Type 10 cement: S2 mixture (symbol B2), and (5) a 60:40 Type 10 cement: FA mixture (symbol B3). The crystallinity and mineralogy of the flyash and the two slags were assessed by XRD. FA is crystalline and composed essentially of quartz, magnesian ferrite or chromite, hematite, and minor albite, graphite, muscovite and montmorillonite. S1 and S2 have contrasting crystallinity and mineralogy: S1 is amorphous and contains minor calcite, whereas S2 is crystalline and composed of wustite and metallic lead with minor siderite. The compositional characteristics of cements, tailings, flyash, slags, and binders can be best depicted with the aid of a ternary SiO_2-CaO+MgO-Al_2O_3+Fe_2O_3 diagram (Figure 2).

Ternary diagrams such as those in Figure 2 cannot be directly used for selecting binders, as cementing properties depend on many more factors than just chemical composition. One (and perhaps the most important) factor is the degree of glassiness of the material. Nevertheless, the ternary diagram is useful in screening materials for use as binders and for pointing out means of improving the cementing property of a specific material. For example, slag S1 is near the field of Portland cement and thus under favourable conditions it should be able to provide good cementing action. In addition, adding lime (CaO) to S1 would push the mixture towards the field of Portland cement, augmenting the cementing property of S1. For a second example, FA is near the field of "pozzolans", only somewhat deficient in silica (SiO_2). Because pozzolans need to be activated by lime to exhibit cementing action, it is clear that to use FA as a significant ingredient of a binder, there should be excess lime or portlandite ($Ca(OH)_2$) present in the binder to maintain the high pH required for pozzolanic activation.

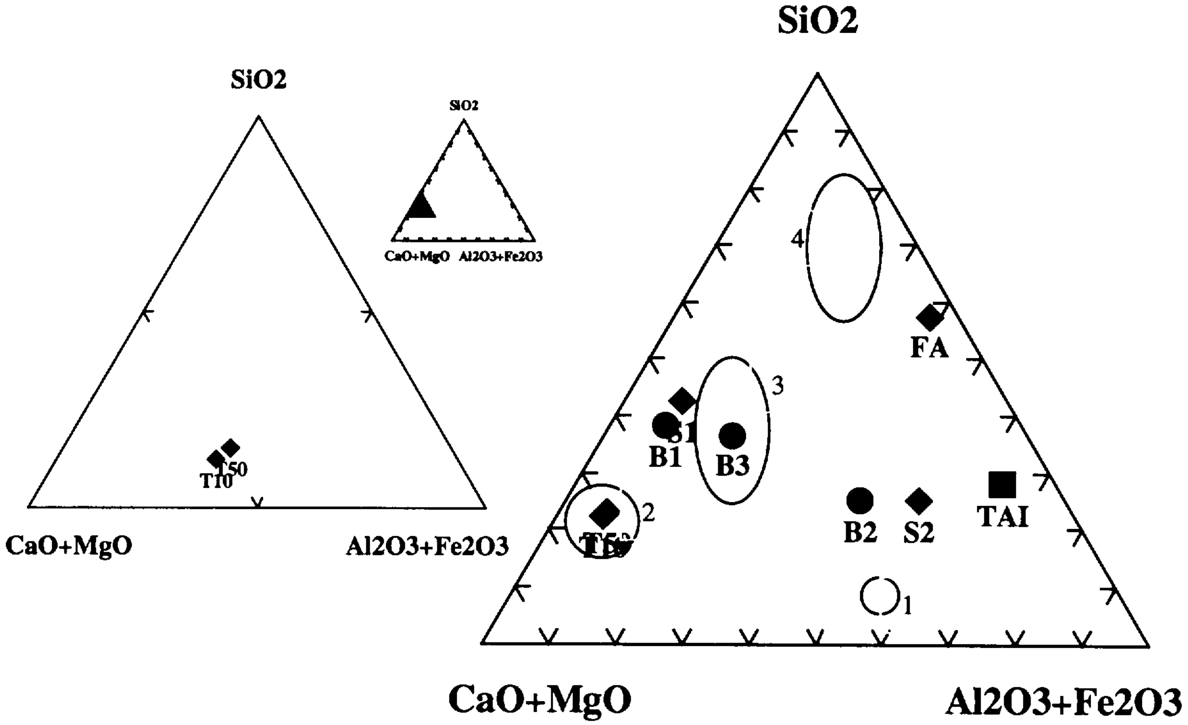

Figure 2. Ternary diagram SiO_2-CaO+MgO-Al_2O_3+Fe_2O_3 showing compositions of tailings and various binders. The numbered fields are 1-clay cements, 2-Portland cements, 3-granulated blast furnace slag and type C flyash, 4-pozzolans and type F flyash. TAI-fresh BMD total tailings. The ternary diagram on the left is an expanded view showing a portion of the diagram on the right - the expanded portion is shown as a shaded area in the smaller ternary diagram between the two large diagrams.

UCS of Paste Mixtures

Various pastes have been tested for UCS up to 360 days of curing time at Queen's University Rock Mechanics Group.[6] The paste ingredients (total tailings, binder, water) were mixed to obtain a target slump of 8 inches. This was usually achieved at a cast moisture of about 20%. The paste was loaded into cylinders measuring 2 inches internal diameter by 4 inches height and sealed at both ends by waxing. The cylinders were then cured in the laboratory and tested for UCS at pre-determined curing intervals.

The variation of UCS for five paste mixtures over time is shown in Figure 3. The target UCS for backfilling of primary stopes was 1 MPa. Two paste mixtures, B1 and T50, attained the target strength. The B1 mixtures, which used the glassy slag S1 and Type 10 cement as the binder, significantly outperformed all other paste mixtures and exceeded the control test (T10) strength by a factor of 4.5 after 180 days of curing. It is also the only mixture that did not record a decrease in UCS up to 180 days of curing. The control (T10), the sulphate resistant (T50), and the B3 paste mixtures all reached their maximum UCS at about 120 days of curing and exhibited UCS decreases of varying magnitude after that. The B2 mixture never gained an UCS greater than 0.3 MPa and its UCS testing was terminated at 120 days. Based on physical, chemical, and mineralogical data, the unusually high strength recorded for the B1 paste mixture can be attributed to four main factors: (1) the glassy nature of slag S1, (2) the higher CaO content (32%) of S1 compared with S2 (16%) and FA (2.5%), (3) the fine grain size of S1 (S1 is much finer than S2 and FA), and (4) the high reactivity of S1. The high reactivity of S1 is illustrated by an experiment where S1 was reacted with water in open atmosphere: S1 hydrated quickly and reacted with atmospheric CO_2 to form calcite, which is considered a cementing agent. Infrared spectrophotometry showed that S1 has an absorption peak between 1400-1550 cm^{-1}, indicating presence of CO_2 or HCO_3 in the slag. S1 possesses a highly disordered glassy structure, providing a high hydraulic effectiveness. In such glassy structures, the network of SiO_4^{4-} tetrahedrons is deformed by additional constituents such as Al and Mg (called network modifiers[7]).

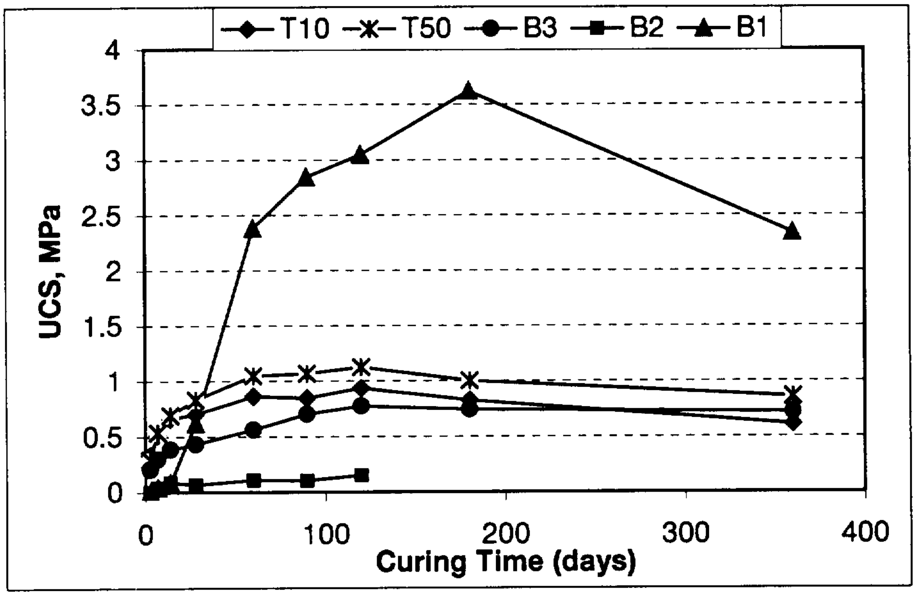

Figure 3. Variation of unconfined compressive strength (UCS) with curing time for five paste mixtures

Figure 3 shows strength losses occurring after 120 days of curing for paste mixtures T10, T50 and B3 and after 180 days for B1. The strength losses at 360 days of curing as a percentage of maximum UCS are B1 (-35%), T10 (-35%), T50 (-24%), and B3 (-7%). The relatively small UCS loss for the paste mixture using 5% B3 binder (which is comprised of 60% Type 10 and 40% FA) likely indicates that the addition of FA to cement increased the sulphate resistance of the paste mixtures. This is in agreement with concrete research findings reported in the literature. The most likely cause for the strength losses is internal sulphate attack[8,9], as discussed below.

Internal Sulphate Attack and Strength Loss

Primary and Secondary Ettringite Formation

Primary ettringite formation (PEF) occurs during early hydration of Portland cement in a reaction involving tri-calcium aluminate ($Ca_3Al_2O_6$), water and gypsum:

$$Ca_3Al_2O_6 + 3\ CaSO_4{\cdot}2H_2O + 26\ H_2O \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O \qquad (1)$$

Reaction (1) continues until either gypsum or tri-calcium aluminate is consumed. In hydrated Portland cement, the primary ettringite concentration is maximal after one day of curing and starts to decrease when it begins to transform into monosulphate ($Ca_4Al_2SO_4(OH)_{12}{\cdot}8H_2O$).[13] The formation of primary ettringite is what prevents the so-called "flash setting" in concrete and is also why a small quantity of gypsum is added in Portland cement. Without gypsum, tri-calcium aluminate would react violently with water to form calcium aluminate hydrate ($Ca_4Al_2O_7{\cdot}19H_2O$), causing irreversible flash setting of concrete.

Secondary ettringite formation (SEF) usually accompanies sulphate attack on partially or completely hydrated cement. Sulphate attack is well documented in concrete research.[10,11,12] Sulphate attack is produced when concrete is put in contact with sulphate-containing solutions (external attack) or when sulphate is present in the interior of the concrete (internal attack). Internal sulphate sources can be the product of oxidation of sulphides such as pyrite contained in the aggregate material or the mineral gypsum already present in the aggregate (e.g. the fresh BMD total tailings). In an internal sulphate attack process, sulphate combines with unreacted tri-calcium aluminate or the ferrite phase ($Ca_4Al_2Fe_2O_{10}$) in the cement and water to cause SEF.[13] Soluble sulphate can react with portlandite in partially set cement to precipitate gypsum. The expansion pressure of secondary ettringite or gypsum causes internal stress and may result in such detrimental effects as strength loss, cracking, and even disintegration.

Analytical Detection of Ettringite

To test whether internal sulphate attack was an important factor in causing strength loss in the BMD paste, four analytical methods were evaluated for quantifying ettringite (chemical formula $Ca_6Al_2(SO_4)_3\,(OH)_{12}\cdot 26H_2O$) in cured pastes: (1) X-ray diffraction (XRD), (2) differential thermal analysis (DTA) coupled with differential scanning calorimetry (DSC) and thermogravimetric analysis (TG), (3) scanning electrons microscopy (SEM) and back scattered electron (BSE) imaging, and (4) selective dissolution of ettringite. A major problem in attempting to quantify ettringite in paste samples is the small amount of cement used (~5%) in forming pastes compared with the amount of cement used in forming concrete (~30%).

To define the detection limit for ettringite by XRD, pure Portland cement and various mixtures of Portland cement and tailings were hydrated and analysed. It was found that for paste mixtures with less than 10% cement, the peaks of primary ettringite were undetectable by XRD. Therefore, XRD is not an appropriate analytical technique for quantification of cured pastes, which normally contain ~5% cement as binder.

TG, DTA and DSC were tested at CANMET. Hydrated Portland cement (Type 10) and a paste mixture containing 5% Type 10 cement and 95% tailings were compared. It was found that the DSC technique was the most sensitive. For the hydrated Portland cement, a broad endothermic band was recorded between 75-200°C (dehydration of CSH) with a small endotherm at 123°C attributable to dehydration of ettringite. However, none of these endotherms were detected in the paste mixture. Thus these methods were also judged to be inadequate for characterisation of pastes.

Several paste mixtures were also studied using SEM and BSE. It was found that ettringite could not be quantified by image analysis of SEM or BSE photos. Ettringite becomes unstable when hit by the electron beam under high vacuum. The rims of hydrated cement surrounding tailings particles were too thin (generally < 1 μm). SEM was thus only used in a qualitative manner to look at cured paste textures and to generate elemental compositions using EDS.

The most promising method for quantifying ettringite in cured pastes was a selective dissolution technique.[14] Of all the different Al_2O_3 bearing phases, only ettringite dissolves appreciably and preferentially in a 1:3 ethylene glycol-methanol solvent. The Al concentration in the extract is determined by ICP analysis and converted to ettringite concentration stoichiometrically. To test this method, a sample of hydrated Portland cement (Type 10) was analysed after 3 days of curing and was found to contain 1160 μg/g extractable Al in one test and 1149μg/g extractable Al in another test. This translates to about 2.7% ettringite. In contrast, when the sulphate resistant cement (Type 50) was hydrated, it contained 937 μg/g extractable Al (or 2.2% ettringite) after 3 days of curing. These results are consistent with expectations: Type 50 cement contains less tri-calcium aluminate ($Ca_3Al_2O_6$) than Type 10, therefore less primary ettringite should be formed upon hydration.

Internal Sulphate Attack and Ettringite Formation in BMD Pastes

The selective dissolution method was applied to cured paste samples to monitor ettringite formation throughout the testing period. The results obtained are shown in Table 1.

Table 1. Ettringite content (%) in cured pastes (5% binder) calculated from extractable Al in selective dissolution

Test Binder	Paste Curing Time (days)					
	3	28	60	90	120	180
T10	0.32	0.30	0.14	0.06	0.23	0.10
T50	0.61	0.29	0.29	0.07	0.28	0.04
B3	0.47	0.15	0.10	0.07	0.45	0.07
B1	0.20	0.07	0.08	0.05	0.12	0.06
B2	0.33	0.05	0.09	0.09	0.12	0.04

Table 1 shows that ettringite contents either continuously decreased with curing time or first decreased then stabilised until day 120, when an abrupt increase occurred in all paste mixtures. The continuous decreases in ettringite content with curing age are interpreted as a result of the gradual transformation of primary ettringite to monosulphate. The sudden increase at day 120 may reflect a pulse of secondary ettringite formation (SEF). This would be consistent and corroborate with the observation that T10, T50, and B3, which showed the highest ettringite content increases, also exhibited UCS decrease after 120 days of curing. In addition, B1, which did not show a significant increase in ettringite content, continued gaining strength after day 120. The ettringite contents were not able to reach the day 3 values, indicating that SEF was less intense that PEF.

Figure 4 suggests that there is a dilution effect in the pattern of extractable Al concentration: the higher the Type 10 cement in a given binder (B1-B3 and T10, Type 10 content in the binder ranges from 20 to 100%), the higher the extractable Al concentration for that binder at a given curing age. This suggests that S1, S2 and FA (the non-cement ingredient in binders B1, B2, B3, respectively) did not contribute significantly to the formation of primary ettringite during curing time tested.

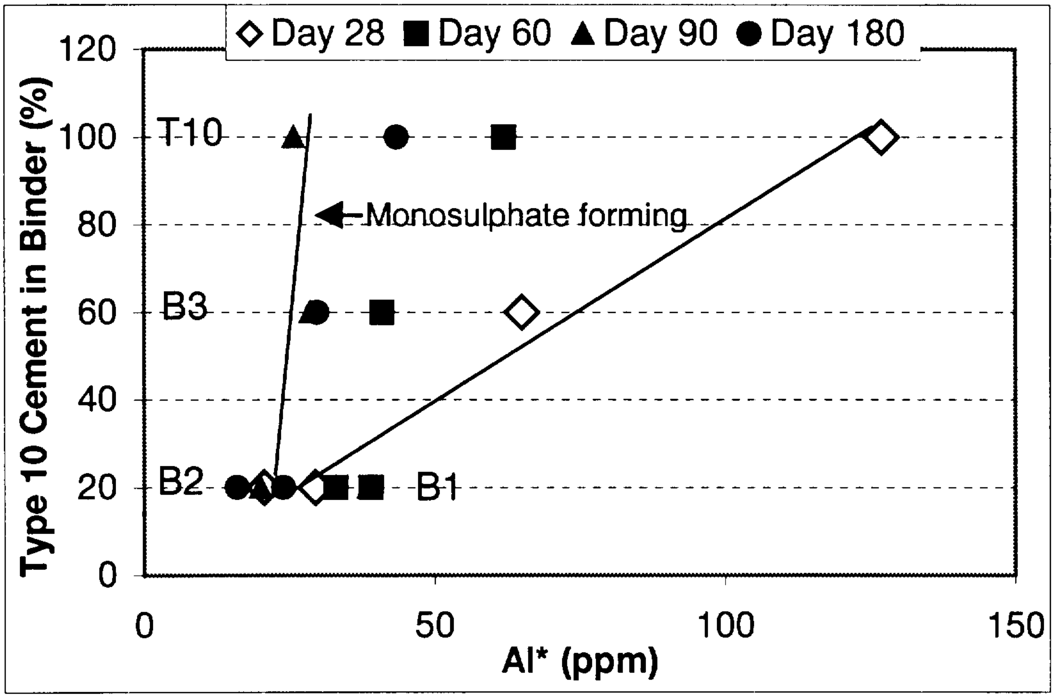

Figure 4. Variation of extractable Al (symbol Al*) concentration with the percentage of Type 10 cement in the binder

Mortar bar expansion tests were also undertaken to investigate the deterioration of various paste mixtures due to internal sulphate attack. The paste mixtures were made with about 30% binders (six times the amount normally used for making paste backfill) and about 70% tailings. 2300 mg/L of SO_3 added as Na_2SO_4 to the make-up water was used as the sulphate source. Results show that none of the mixtures exhibited more than 0.04% expansion. Excessive expansion (defined here as >0.1%) did not occur. It was therefore concluded that internal sulphate attack did not contribute significantly to expansion in these tests. It is possible that due to the large amounts of cement binder used, majority of the soluble sulphate added was consumed in PEF, leaving little sulphate in the remaining pore water to initiate SEF. It should be cautioned that, also because of the high binder contents (30%), the results of these tests should not be directly extrapolated to backfill pastes where 5% binders are the norm.

On the other hand, examination of a large test cylinder made of 5% Type 10 cement (as binder) and 95% tailings revealed signs of secondary phase growth, as indicated by the white clusters in the sample (Figure 5A). The cylinder was about one year old (counting from the day of casting the cylinder) and was kept humid in a sample bag after UCS testing. Signs of oxidation were also apparent in the form of iron oxide stains along cracks. XRD analysis indicated that the white clusters were composed of gypsum, opal, and ettringite. The white clusters were also studied under SEM and the EDS spectra showed peaks of Ca, S, Al and Si, consistent with the XRD identification (Figure 5B and 5C).

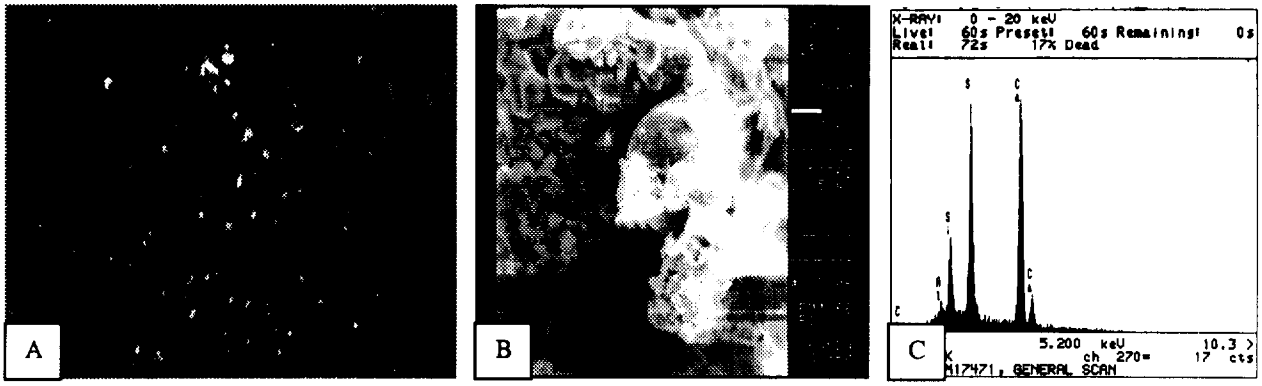

Figure 5 (A) White clusters of secondary phases and iron oxide stains in an old broken paste cylinder. (B) SEM image of a white cluster at 1000X magnification. Notice the abundant gypsum platelets in the background and the ettringite needles sitting on top of a round opal particle. (C) EDS spectra of the area in B indicating the presence of Ca, S, Si and Al.

The secondary sulphate phase growth shown in Figure 5 probably represents an extreme case where internal sulphate attack did occur to a large extent. The sample was kept humid and partially in contact with the atmosphere for several months. The results of internal sulphate attack in this sample manifested as new secondary phases (including SEF), fine cracks, and oxidation veins. Such textures were not observed in any of the cylinders studied throughout the 180 days of curing.

Finally, washing tests have been conducted using sulphate-free tap water and sulphate-free soda ash solution in an attempt to remove sulphates from fresh BMD tailings samples. It was found that, although the washings were successful in removal of dissolved sulphates originally present in the tailings water, little success was achieved in removing the solid-phase sulphates existing as gypsum in the tailings, even after several repeated washings.

Synopsis on Internal Sulphate Attack and Ettringite Formation

Summarising the foregoing discussion, the experimental evidences for (points 1 to 4 below) and against (point 5 below) internal sulphate attack and SEF occurring in the pastes during curing are as follows:

1. All cured pastes showed a moderate to large decrease in UCS after 120 or 180 days of curing.
2. The cured paste which used the sulphate-resistant cement (Type 50) as binder acquired higher UCS than the paste that used the normal (Type 10) cement as binder for the duration of the test.
3. A spike in ettringite contents, as calculated from extractable Al concentrations, coincided with the beginning of UCS decline for tests T10, T50, and B3.
4. An aged broken paste cylinder sample showed SEF.
5. High extractable Al representing high SEF was not detected after day 3 up to day 180 of curing. Moderate spikes were detected only for day 120 of curing time.

In reconciliation of the above experimental evidences, the following statements can be made. For pastes made of the fresh BMD tailings (which contain 2 to 3% gypsum) and various binders studied, no intensified SEF occurred as a result of internal sulphate attack for curing times up to 180 days. A moderate pulse of SEF had probably occurred near 120 days of curing time and was probably the cause for the UCS drop in tests T10, T50, and B3 from day 120 to day 180. The reason for this pulse of SEF occurring specifically after 120 days of curing and not earlier is unclear. In any event, the rate of SEF was less than that of PEF.

After a longer curing time such as one year, the likelihood for secondary ettringite formation as well as secondary gypsum formation to occur becomes greater and, when they do occur, the newly grown phases can be visible to the naked eye. This is supported by further UCS losses shown in Figure 3 and the examination of the old broken paste sample shown in Figure 5. Unfortunately, the selective Al dissolution results (360 days) are not yet available at the time of writing this paper.

The present study raises more questions than it provides answers in terms of the relationship between tailings/binder chemistry and paste UCS. To what degree is the gypsum in the fresh BMD tailings involved in PEF and what are the effects of this on strength development? Has sulphide oxidation contributed to the observed loss of strength? Do other mechanisms such as alkali aggregate reactions (AAR) and alkali carbonate reactions (ACR) play a role in modifying the UCS one way or another? Has the quartz in the tailings become reactive after grinding to induce alkali silica reactions (ASR)? Do the small amounts of swelling clay minerals present in the tailings affect the strength of the paste? To answer these and other questions, more research is needed. In particular, better and quicker analytical techniques of quantifying small amounts of ettringite in cured pastes will be a definite asset in further quests into the relationship between tailings/binder chemistry and strength development.

Conclusions

This study attempted to establish some relationship between the geochemistry and mineralogy of tailings/binders and the development of strength over time in cured pastes. Several backfill paste mixes were prepared from different binders and fresh BMD tailings. Paste cylinders were cast, wax-sealed, and tested at pre-determined curing intervals for UCS as well as geochemistry and mineralogy. Conclusions drawn from this study are given below.

- Two paste mixtures reached the 1 MPa target strength and outperformed the control paste mixture that used 5% Type 10 cement as binder: the paste using 5% sulphate resistant Type 50 cement as binder, and the paste using a glassy slag and type 10 cement as binder.

- The strength losses at 360 days of curing as a percentage of maximum UCS are -35% for test B1, -35% for test T10, -24% for test T50, and -7% for test B3.

- Intensified secondary ettringite formation does not seem to have occurred as a result of internal sulphate attack for curing times up to 180 days. A moderate pulse of secondary ettringite formation had probably occurred near 120 days of curing time and was probably the cause for the UCS drop in tests T10, T50, and B3 from day 120 to day 180. The reason for this pulse of SEF occurring specifically after 120 days of curing and not earlier is unclear. In any event, the rate of SEF was less than that of PEF.

- At longer curing times, the likelihood for secondary ettringite formation as well as secondary gypsum formation to occur becomes greater. White clusters of gypsum and minor ettringite and opal were visible in a one year old cured paste sample using 5% Type 10 cement as binder.

- Addition of cement to tailings has the beneficial effect of immobilising metals contained in the tailings which otherwise are easily dissolvable.

- Partial substitution of Type 10 cement with type F flyash in the binder appears to improve the resistance of the paste mixture to internal sulphate attack.

- Selective Al dissolution seems to be an effective analytical technique for quantifying low contents of ettringite in cemented paste. Other analytical techniques evaluated including XRD, SEM, TDA and TG failed to detect low amounts of ettringite in cured pastes.

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