STABILIZATION OF REACTIVE TAILINGS TO PREVENT ACID MINE DRAINAGE USING COLD-BOND AGGLOMERATION

BY

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ABSTRACT

This thesis describes an extensive study which was carried out to determine the effectiveness of environmental fixation of reactive pyrrhotite tailings in reducing or retarding acid formation through the use of selected chemicals, cementitious mixtures and natural organic materials. The main objective of the study was the investigation of the application of cold-bonding of reactive tailings by an agglomeration and encapsulation process to prevent acid mine drainage (AMD).

Humidity cell tests were conducted to observe the effect of weathering on agglomerated mill tailings and to retard the formation of acid from reactive pyrrhotite tailings in the environment. The humidity cells were designed and modified to suit the agglomerates. The agglomerates were tested with and without the addition of *Thiobacillus Ferrooxidans* bacterium to simulate the actual weathering process of agglomerated pyrrhotite tailings at an accelerated rate. The reactive tailings were agglomerated with selected binders to determine their potential for reducing acid production and evaluated according to representative parameters associated with this oxidation reaction. The parameters regularly measured over a period of 50 and 58 weeks were the pH, redox potential (Eh), conductivity, sulphate, acidity and dissolved metals in the leachate from the humidity cells.

The results showed that the control samples, as expected, produced significant amounts of AMD and that most of the encapsulated chemicals, cementitious mixtures and natural organic materials were effective in retarding AMD. Aqueous sealants, primarily such as ENVIROSEAL and secondly sodium silicate, showed promise as a suitable leachate retardant for reducing the acid generation reaction when the sulphidic tailings are exposed to oxygen and moisture under natural weathering conditions.

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CHAPTER ONE

1.0 INTRODUCTION

Mill tailings from copper, zinc, nickel, gold and uranium recovery operations contain various species of sulphide minerals. These sulphides, discharged from concentrators, become reactive upon exposure to air and/or water. Pyrrhotite (Fe_n S_{n-1}) and pyrite tailings in particular which are discharged from the beneficiation process in mining and mineral processing activities consist of very finely ground particles. The characterization and the long term behaviour of the tailings can have a significant impact on the environment. Upon exposure to oxygen and moisture, these tailings become reactive due to the instability of metal sulphide minerals present and undergo spontaneous decomposition, thereby producing a weak sulphuric acid. The weathering conditions can further exacerbate the oxidation process and consequently the acid run-off produces soluble metal compounds. Other heavy metals such as copper, nickel, zinc, iron, lead, and cobalt may be present as a metal leachate product and finally impact on the environment [1].

The sulphide oxidation process is exothermic and typically the production of acid depends on the sulphide minerals involved in the reaction. The majority of sulphide minerals produce various quantities of sulphate and acid when exposed to water and/or air. Several factors such as pH, temperature, redox potential, stoichiometry, bacterial effects and the environmental conditions affect the rate of oxidation process of sulphides that produce acid mine drainage (AMD).

Abandoned mine sites and metallurgical plants are major sources of AMD, consequently resulting in the presence of toxic elements in waste waters. Toxic lead is

presently leached out from over one hundred million tonnes of tailings and discharged to the surface at mine sites around the world [1]. The precipitated metals from waste materials along with residual sulphide when exposed to air and water allow the oxidation process to take place, producing sulphuric acid and subsequently impacting on the ecosystem.

1.1 The Purpose of the Proposed Research

In this work, the study concentrated on reactive mill tailings and the use of existing unit operations to investigate the feasibility of various treatment options for the agglomeration process. The cold-bond tailings agglomeration (CBTA) process has been developed mainly to be used as aggregate material for mine backfill purposes. This process has been successfully developed with mainly non reactive tailings and some sulphide tailings with low sulphur and iron content. Due to this low sulphur content, the chances of AMD generation underground from the backfill is extremely low. In addition, the chances of exposure of sulphide tailings pellets to oxygen and water are at a minimum as pellet exposure is impeded within the backfill. However, it is important to experimentally investigate the possibility of AMD generation from underground backfill.

Therefore, in order to find a solution for this problem, it was decided to use extreme reactive tailings as the agglomerate material. Furthermore, it was proposed to subject these reactive tailings pellets to extreme conditions of exposure to air and water by simulating the exposure to surface weathering. However, it is understood that

once the tailings pellets are placed underground as a backfill aggregate material, they will never be exposed to such extreme exposure conditions.

The hypothesis tested in this research project was that with extremely reactive pellets, the addition of chemical additives would show minimum AMD potential under extreme surface weathering conditions. Then chances of AMD generation from normal cold-bond aggregate backfill with regular low sulphur tailings would be virtually non existent.

An alternative, rapid and accelerated technique is by means of a "Humidity Cell". In this work the use of a humidity cell was examined more effectively. Various binders and chemical additives, which included sodium lauryl sulphate (SLS), sodium silicates, surfactants such as Enviroseal and some bactericidal and acid neutralizing additives, were examined throughout the test work. A humidity cell was constructed and tested to study the cold-bond agglomeration technology to retard AMD generation. The objectives of this thesis study may be summarized as follows:

1. Examine the feasibility of chemical treatment to minimize the generation of acid mine drainage from reactive tailings.
2. Utilization of the cold-bond agglomeration technique to mitigate AMD using selected chemicals, cementitious mixtures and natural organic material.
3. Development and evaluation of a humidity cell for AMD prediction for cold-bonded agglomerates.

1.2 THE PROBLEM OF ACID MINE DRAINAGE

A 1994 estimate of the amount of acid generating waste indicates that Canada contains about 12,000 hectares of tailings and 614 hectares of mine waste rock. The cost of stabilizing reactive waste is highly site specific. Under the most difficult conditions and applying existing technology, the cost of stabilizing some sites has been estimated to be as high as $410,000 per hectare [2]. Applying an average cost of $200,000 per hectare to the existing and future accumulation of acid generating tailings, the cost of reclamation at non-ferrous metal mine sites is in the order of $5.9 billion over the next twenty years [2]. The cost of stabilizing reactive waste will vary greatly from place to place.

Ontario accounts for 69 hectares of tailings and waste rock, respectively, that present an acid drainage problem. The Mine Environment Neutral Drainage Program (MEND) estimated costs for acid mine drainage liability as expressed in 1994 Canadian dollars are illustrated in Table 1.1. Canada's mining industry produces more than 500 million tonnes of waste rock and tailings each year, the largest portion of which originates from sulphide ore operations [3]. Upon weathering, these wastes produce acid mine drainage, which in turn leaches heavy metals and other toxic elements into solution. If left uncontrolled and untreated, the drainage could contaminate ground water and local water courses, affecting plants, wildlife, fish and human beings, for example, at a tailings area in North Eastern Quebec, the dam became damaged and allowed acid drainage to flow downstream. This acidic stream consequently destroyed aquatic and surface vegetation, marine life, and wildlife.

Table 1.1 Estimated Cost for AMD Liability in Canadian Dollars

TAILINGS	MINE WASTE ROCK
Collection and treatment 1.4 billion	Collection and treatment 0.33 billion
Provision of water covers 1.4 billion	Relocation to an open pit 1.7 billion
Application of dry covers 3.5 billion	Application of dry covers 0.54 billion

Acid mine drainage is a worldwide pollutant that has been affecting the environment for years and becomes increasingly dangerous to the environment as time passes by. This acidic effluent is a product of tailing and mine waste rock containing sulphide minerals that have oxidized in the presence of water and oxygen. The nature of mining, milling practices that ensure maximum metal recovery, also causes maximum surface area exposure of these tailings which make the tailings more susceptible to the oxidation process.

The acid mine drainage that has been produced because of mining and milling activities has detrimental effects on our aquatic and terrestrial ecosystem. One effect is that the acid produced from the tailings causes the soil to be acidic. The most deadly effect of the acid mine drainage on forests is that it leaches elements such as copper, nickel, zinc, iron, and cobalt. These elements have the tendency to damage stomatal wax plugs of leaves and needles [4].

1.3 THEORY OF ACID GENERATION

1.3.1 Chemistry of Acid Generation

Most base metal, precious metal, uranium, and coal mines contain sulphide minerals, either in the ore or the surrounding waste rock. When these sulphide minerals, particularly pyrite and pyrrhotite, are exposed to oxygen and water, they oxidize, and if sufficient acid-neutralizing materials are not present (such as calcite, as the major constituent of limestone) surface waters become acidic. Naturally occurring bacteria, *Thiobacillus ferrooxidans*, play an important role in the acidification process. The acidic water carries with it toxic concentrations of metals and elevated levels of dissolved salts. Rainfall and snow-melt flush the toxic solutions from the waste sites into the downstream environment.

As a result of SO_2 emissions into the atmosphere and acid mine run-off on land, the sulphur concentration in many surface waters has increased in recent times. The oxidation of pyrrhotite can be expressed by the following equations [5].

$$Fe_{1-x}S_{(s)} + 7/2\ O_2 + xH_2O \rightarrow (1-x)\ Fe^{2+} + SO_4^{2-} + 2xH^+ \qquad [1]$$

At low pH values (below 4.5), pyrrhotite may be oxidized by bacteria, particularly *Thiobacillus ferrooxidans* as shown in equations 2 and 3 [5].

Ferrous iron is oxidized to ferric iron at faster rates as follows:

$$Fe^{2+} + 1/4\ O_2 + 5/2\ H_2O \rightarrow Fe(OH)_3\ (s) + 2H+ \quad [2]$$

The oxidation of sulphide minerals with ferric iron as an oxidant is as follows:

$$Fe_{1-x}\ S_{(s)} + (8-2x)Fe^{3+} + 4H_2O \rightarrow (9-3x)\ Fe^{2+} + SO_4^{2-} + 8H^+ \quad [3]$$

When sulphide-containing minerals are exposed to the atmosphere, oxidation can result in the formation of large quantities of sulphuric acid (H_2SO_4) and the acidification of drainage streams. Pyrite and pyrrhotite are the major minerals involved in acidification in both acid sulphate soils and acid mine drainage. FeS in particular is readily oxidized by a chemical process to Fe_2O_3 and S°, and S° being readily oxidized to SO_4^{2-} by *Thiobacillus* bacterium; however, FeS_2 is much more resistant to oxidation. Once the reaction sequence is started, pyrite or pyrrhotite oxidation is determined by the amount of (Fe^{3+}) present. The ferric hydroxide precipitated in the mine serves as a source for soluble ferric iron (Fe^{+3}) as shown in equation 2 above.

As a result of the fine grinding in the milling circuit and reactions in subsequent flotation operations, a portion of sulphur from the pyrrhotite dissolves in water. The alkaline pH environment in the flotation circuits can accelerate this dissolution process as shown in equation 4 [6]. The pH of the oxidation products of pyrrhotite decreases to lower values as a result of sulphuric acid generation.

$$Fe_7\ S_8 + 2OH^- \rightarrow 7FeS + S^= + H_2O + 1/2\ O_2 \quad [4]$$

The dissolution of sulphur from pyrrhotite can be best described by the following equations: [5, 6, 7].

$$2\ S^{=} + 2O_2 + H_2O \rightarrow S_2O_3^{=} + OH^{-} \quad [5]$$

$$S_2O_3^{=} + H_2O + 4O \rightarrow 2SO_4^{=} + 2H^{+} \quad [6]$$

$$S_2O_3^{=} + (n-2)H_2O + 2(5-n)O \rightarrow 2S_nO_6^{=} + 2(n-2)OH^{-} \quad [7]$$

$$S_2O_3^{=} + (n-1)H_2O + (3n-5)O \rightarrow nSO_4^{=} + 2(n-1)H^{+} \quad [8]$$

Furthermore, the presence of sulphur-oxidizing bacteria can accelerate the oxidation process of pyrrhotite [7]. The polythionates such as $S_3O_6^{=}$, S_nO_6 (n = 4 to 8), which are the intermediate products of oxidation, oxidize to sulphuric acid as the process of oxidation progresses.

These reactions will eventually result in the production of sulphuric acid, which will lead to the generation of hydrogen ions and decrease in the pH level [8]. Thus, as the pyrrhotite is being disposed of in the tailings area and it makes contact with water and oxygen, sulphuric acid is produced which may run into the water system around the tailings area.

In previous studies, the bacterium *Thiobacillus* was identified in the tailings pond at Falconbridge's Strathcona milling operations, Onaping mines [9]. Furthermore, in studying Strathcona tailings sites and comparing the concentrations of polythionates in water before and after oxidation using lime treatment, the results showed considerable improvement in acid neutralization for pollution control and water quality [9].

1.3.2 Reaction Rates of Sulphides of Acid Generation

Mine drainage quality is related to the presence or absence of calcareous rocks. Surface mining in areas devoid of calcareous rocks due to non-deposition or weathering has resulted in AMD. Mines developed in areas of abundant limestone produce alkaline water [10].

The amount of acidity produced by a given sample of iron disulphide (FeS) over a period of time is a function, in part, of the rate at which oxidation takes place. Several factors have been shown to have an effect on the oxidation rate [11]. Mainly, these include the morphology and properties of iron disulphides and the ambient factors of the surrounding environment.

1.3.2.1 Factors Regarding Iron Disulphide

1) Surface area
2) Adsorbed impurities
3) Ferrous/ferric adsorption ratio and total iron concentration

1. Surface Area

Several studies have stated that the morphology of iron disulphide plays a significant role in acid production [11]. Non-acid drainage areas commonly contain iron disulphide having massive forms: most of them are greater than 400 μm (microns), the others being 5 to 10 μm. Framboidal pyrite is one of the classes which describes the morphologies of pyrite. In this type, each particle of pyrite comprising

the framboid is generally less than 0.5 μm diameter. Framboidal pyrite may occur as spheres or crystals affording a large surface area of reactivity [11]. In contrast, acid-producing areas often contain large percentages of framboidal pyrite, averaging 0.25 μm clustered into spheres approximately 25 μm in diameter [11]. Samples which exhibit the greatest surface area should also provide the greatest percentage of the total volume for surface reactions.

2. Adsorbed Impurities

Impurities adsorbed onto mineral surfaces may also affect the reaction rate. For example, chromium, copper, manganese, nickel, chloride, nitrate, and humic acid had no effect on oxidation rate, even when present in concentrations far in excess of those found in the natural environment. Fluoride and chlorate were found to increase oxidation rate; while thiocyanate, phenanthroline, bipyridine, hydroxylamine, calcium carbonate, and phosphate had an inhibitory effect on pyrite oxidation [11].

3. Ferrous/Ferric Adsorption Ratio and Total Iron Concentration

Pyrite selectively adsorbs ferrous iron over ferric iron. However, samples with the lowest oxidation rates had ferrous/ferric adsorption ratios that were 20 to 50 times greater than samples with the highest reaction rates. Furthermore, the rate of pyrite oxidation by ferric iron is a function of total iron concentration and controlled to a large extent by the ferrous/ferric ratio, but not redox potential. Pyrite oxidation rates are known to increase with increased redox potential (Eh) until all the soluble iron is

converted to the ferric state. At this point, the oxidation rate becomes constant, and further increases in Eh have no significant effect on the oxidation rate.

1.3.2.2 Ambient Factors

1) Temperature

2) Partial pressure of water

3) Oxygen concentration

4) pH

5) Bacteria

1. Temperature

The oxidation rate of pyrite is greatly affected by changes in temperature. At a constant relative saturation of water vapour, the oxidation rate nearly doubled with each 10° C incremental increase in the ambient temperature.

2. Oxygen Concentration

A significant correlation exists between the oxidation rate of iron disulphide samples and the oxygen concentration of the medium in which oxidation takes place. Oxidation rates for framboidal pyrite at 20% oxygen are more than 10 times greater than those at 0% oxygen, when inoculated with *Thiobacillus Ferrooxidans*. Uninoculated samples of framboidal pyrite are approximately 5 times more reactive at 20% oxygen than at 0%. Slight variation of the oxygen content of the earth's atmosphere should not significantly affect the oxidation rate. The uppermost metre of

the waste piles showed depletion of the oxygen, suggesting a relatively thin, near-surface zone in which most of the oxidation takes place.

3. Water Partial Pressure

The oxidation rate of pyrite increases with higher partial pressures of water vapour. The oxidation rate was also dependent upon the quantity of water adsorbed by the iron disulphide.

4. pH

The abiotic oxidation rate of pyrite increases with increasing pH. This is directly related to the conversion of ferrous iron to the ferric state with the subsequent oxidation of the disulphide by ferric iron. *Thiobacillus* acts as a catalyst for the oxidation of ferrous iron to ferric iron. The abiotic chemical oxidation of sulphides is enhanced by ferric iron [12].

The abiotic ferrous iron oxidation rate increases slowly up to a pH of 3 and rapidly as pH exceeds 6. However, the bacterial mediation is not a factor under the biotic conditions. Maximum oxidation of pyrite under biotic conditions occurs between a pH of 2.4 and 3.6 with a rapid decrease in oxidation above 3.6. In addition, changes in pH affect the occurrence of iron-oxidizing bacteria. Under natural conditions, ferrous iron oxidation by oxygen is slow, but is greatly catalyzed by the iron oxidizing bacteria such as *Thiobacillus ferrooxidans.* In turn, the increased concentrations of ferric ion oxidize the iron disulphide and accelerate the acid formation.

5. Bacterial Oxidation Reaction

Bacteria play a major role in the production of AMD. It is a difficult reaction to analyze because researchers are still unsure how the bacteria attacks the sulphide minerals. The bacterial species that is most dominant in sulphide oxidation are *Thiobacillus ferrooxidans*. These bacteria are naturally occurring and found almost everywhere sulphide minerals are found. Studies which have been conducted, show that the bacteria does not need to be physically attached to the sulphide in order to oxidize it [13]. It can oxidize the mineral while separated from it. However, if it were attached, it would reduce diffusion distances which would limit the rate of the reaction. The bacteria do not stay close to the mineral sulphide surface during oxidation and thus shifts the dissociation equilibrium in favour of further dissolution of the mineral. The oxidation rate can increase up to an order of five to six magnitudes due to the presence of this bacteria [14].

Iron oxidizing bacteria require aerobic conditions and the availability of oxygen affects the rate of ferrous iron oxidation. When the acid generation has progressed, the availability of oxygen becomes less important. The oxygen limitation on bacterial oxidation was studied by Erikson in 1985 [15]. The oxidation of sulphides occurs under anaerobic conditions, once the ferrous/ferric iron ratio established.

The pH influences the oxidation process and the characteristics of the gangue minerals govern the net acidity of oxidation process. The pH regime becomes significant when considering the growth requirements of the bacterium. The range for growth of *Thiobacillus ferrooxidans* is dependent on a highly acidic environment. The

rate of generation of the *Thiobacillus ferrooxidans* varies with different temperatures depending on the substrates present in the mine rock tailings.

1.4 AMD PREDICTION

Prediction of the potential for acid drainage formation is required as part of the mine decommissioning process in Canada and the USA. To reduce the potential for AMD drainage, mine plans for closure and post-closure care of mine wastes must be developed prior to mine development. Design of an effective pre-development mine waste management plan requires estimation of the quality and quantity of drainage generated by the various mine and mill wastes.

The objective of mine waste drainage quality prediction is to quantify the amount of waste. This can be done by applying static tests and kinetic tests. Static tests such as Acid-Base Accounting (ABA), Modified Acid-Base Accounting, B.C. Research Initial Test (BC RIT), and Alkaline Production Potential : Sulphur Ratio Test (APP:S Test) attempt to quantify the total capacities for a mine waste to produce and consume acid [16].

1.4.1 STATIC TESTS

1.4.1.1 Acid-Base Accounting (ABA)

Premining prediction of post-mining drainage is required by law in Canada and the USA but the method most often used, ABA, was never intended to predict mine drainage quality. ABA can be used to produce more accurate premining assessment of

post-mining drainage quality than other methods. Acid-base analysis was initially developed to assess the potential for waste materials of coal mines to generate acid drainage [17]. The procedure has become widely accepted as a tool in the assessment of waste rock and processing wastes from base metal and precious metal operations. The test determines the acid producing potential (APP) and acid neutralizing potential (NP) of a mine waste. Whether or not a waste will produce acid is determined by the Net Neutralization Potential (NNP) which is the difference between NP and APP (i.e. NNP = NP-APP). The APP is determined based on the total sulphur content, and NP is determined by titrating the waste sample to pH 7.0 with sodium hydroxide [18].

1.4.1.2 Modified Acid-Base Accounting

This method, developed by Coastech in 1989, bases the APP on the sulphide sulphur content and may employ a 24-hour digestion periods at ambient temperature to determine NP (titration to pH 8.3, rather than the value of 7.0 used in the ABA method) [19]. This technique correctly classified eight of nine samples which produced acidic drainage in the field.

1.4.1.3 B.C. Research Initial Test (BC- RIT)

Developed by Duncan and Bruynesteyn in 1979, the method was extensively used for gold and base metal mines in Canada [20]. It is similar to the ABA procedure in that it uses total sulphur to determine the maximum potential of a sample to produce acid. NP is determined by titrating the solid at room temperature to pH 3.5

using sulphuric acid. This technique correctly classified fifteen out of sixteen samples tested.

1.4.1.4 Alkaline Production Potential : Sulphur Ratio Test (APP:S)

This test was developed by Caruccio et al. in 1981 to evaluate the potential of coal mine wastes to produce acid [21]. It is similar to the ABA procedure in that it uses total sulphur content to reflect the potential for a sample to produce acid. The ability of a sample to consume acid is referred to as the Alkaline Production Potential (APP). This value is quantified by adding HCl to the sample and titrating to pH 5.0.

It is Lakefield Research's experience that the most frequently requested Acid Mine Drainage static tests are the B.C. Research Initial Test (BC-RIT) and the U.S. Environmental Protection Agency's Acid-Base-Accounting (ABA) procedure. AMD static tests are used to determine if mine waste rock and tailings should be considered potential acid generators and therefore be further evaluated using kinetic test methodologies. Both procedures are not absolute and should only be used as preliminary indicators [22].

1.4.2 KINETIC TESTS

The balance of acid-generating and acid neutralizing minerals in a sample of rock or tailings, as explained before, can be determined through static tests, such as acid-base accounting (ABA); whereas the reaction rates can be measured with

laboratory or field-based kinetic tests. Kinetic tests involve repetitive oxidation and leaching cycles on a sample, and are frequently used for the prediction of acid generation and neutralization. In general terms, a kinetic test involves continuous or repetitive oxidation and leaching of a sample with periodic rinses with water to remove the reaction products.

Although international standard methods do not exist for kinetic tests, the most popular laboratory-based kinetic test appears to be humidity cells. The second most popular test apparently is various types of columns, which are not always as well suited for determining reaction rates. Field kinetic tests are not as common, but have been recommended to calibrate laboratory tests [23].

CHAPTER TWO

2.0 CONTROL AND PREVENTION OF AMD

By limiting the necessary reactants required to produce AMD, controlling the conditions and varying the parameters that affect its rate of production, the formation of AMD can be eliminated at its source. A more complex method is to limit infiltration of reactants by either using covers and seals or specialized dump sites. Collection and treatment of acid mine drainage (AMD) is the most widely used control method because in most cases the tailings and waste materials have already been produced.

Presently a water cover is the most popular control method on a long-term basis. Its purpose is to reduce the rate of acid generation to levels that are harmless to the environment by excluding one of the vital ingredients, oxygen. It can be achieved by two methods, by either putting the waste under water at depth or by flooding the waste and maintaining flooding conditions.

This method is restricted to new mines since the cost of re-handling the waste by putting it under water is high as well as the time and energy needed to design new structures to accommodate flooding conditions. It should not be an option because there will always be some acid being generated and it will be too costly to remove the waste from water and, more importantly, the cost of damaging the aquatic ecosystem is too high a price to pay. If at least one of the factors that influence acid production from sulphide wastes are inhibited, the reactions take place slower or they are stopped. Therefore, prevention and control techniques are based on:

- Neutralization of acid drainage (using lime)
- Limiting gaseous oxygen infiltration (dry and wet covers)
- Coating of sulphide surfaces
- Control of bacterial activity

However, the best method to minimize or prevent AMD is to reduce the volume of reactive tailings.

2.1. Chemical Neutralization and Precipitation

The most commonly applied technology in the North American base metal mining industry for treatment of AMD is chemical neutralization and precipitation using lime. The lime not only neutralizes the acid but also precipitates metals as their oxides or hydroxides [24]. It is widely available, inexpensive, and easily handled. Chemical precipitation is controllable and predictable. Lime neutralization has been preferred for the following reasons:

- Capability of treating severe waste rock drainage
- A wide range of flows can be accommodated
- Capital and operating costs are moderate
- It is generally considered the best practical technology

The processes that have been widely used for lime neutralization include:

- Simple neutralization
- Neutralization with aeration to oxidize iron
- Neutralization with aeration and sludge recycle

The effective removal of base metals in a stable form in the high density sludge process is caused by the formation of a precipitate of calcium and coprecipitate with iron on the surface of a recycled particle. The process involves aeration to convert Fe^{2+} to Fe^{3+} in order to facilitate the precipitation of iron. Upon the addition of lime, calcium sulphate and metal hydroxides precipitate into bulky sludge, which is allowed to settle in settling ponds (lagoons).

The disadvantages associated with using lime include [25]:

- Increase in the hardness of the treated water
- Problems with scale (gypsum) formation on plant equipment
- Difficulties in dewatering or disposal of the large volumes of sludge that are produced
- Additional treatment with acid might be necessary to meet stricter limitations of effluent pH

The sludge resulting from lime neutralization is chemically unstable, and may be classified as a hazardous waste. As such, disposal options are both limited and expensive. Improvement of sludge stability may reduce disposal costs. A study completed in 1995 assesses the potential of a mixed lime - sodium silicate treatment to enhance sludge stability and, therefore, reduce the final cost of sludge disposal [26]. Initial results show that water quality objectives can be met at a lower treatment pH than with the use of lime alone and that certain components of the sludge are chemically stabilized by the presence of the soluble silicate.

2.2 TECHNIQUES BASED ON COVERS

Different types of covers are being used for limiting the oxygen infiltration and to prevent or reduce the acid drainage production in waste rocks or tailings. Some of the covers commonly used in industry today are as follows:

- Water cover
- Organic and Inorganic covers
- Soil covers
- Clay slurry seal
- Sand-bentonite mixture

2.2.1 Water Cover

Apart from lime neutralization, the only technique that has been applied to any extent on a long term basis is water covers. It is usually achieved by putting the waste under water at depth or by flooding the waste and maintaining flooding conditions. This method is restricted to new mines as the cost of re-handling the waste by putting it under water is high as well as the time and energy needed to design new structures to accommodate flooding conditions.

2.2.2 Organic and Inorganic Covers

An investigation into the potential for organic and inorganic covers to ameliorate acid mine drainage processes has been conducted and reported in various studies [27]. The investigation included a detailed characterization of several potential organic covers in an effort to understand the complex chemistry of the covers. Column and pilot scale research is being conducted to evaluate the interaction between tailings and the organic cover materials. The cover materials being investigated include peat, compost, alkaline stabilized sewage sludge and desulphurized slimes. The organic layers investigated are believed to have physical and chemical characteristics that will decrease the rate of acid generation process and precipitate sulphide.

2.3 CONTROL OF BACTERIAL ACTIVITY

2.3.1 Inhibition of *Thiobacillus* Species

One method of controlling AMD is to inhibit *the Thiobacillus* species which are responsible for metal sulphide oxidation. Two relatively non-toxic heterocyclic mercaptans were examined elsewhere, in pure culture to determine their ability to inhibit thiosulphate oxidation [28]. The results showed that the heterocyclic mercaptans can inhibit the oxidation of sulphur compounds in shake flask culture, with significant potential for optimizing their effectiveness.

2.3.2 Acid Reduction Using Microbiology

The Acid Reduction Using Microbiology (ARUM) technology provides a moderately low-cost, low maintenance, environmentally acceptable alternative for amelioration of AMD [29]. ARUM exploits the ability of anaerobic microbial processes to generate alkalinity and ameliorate AMD through acidity reduction and precipitation of heavy metals resulting from changes in pH and Eh. Anaerobic bacteria use a variety of electron donors and acceptors when molecular oxygen is depleted. For experimental purposes a test cell system was constructed near Sudbury, Ontario.

The system consisted of two cells for iron precipitation under oxidizing conditions, and two cells for acidity and metal removal under reducing conditions employing the ARUM technique. The test was done on an AMD seepage with high nickel concentration. The results reported indicate that the system was very effective in removal of heavy metals and acidity in 1992 and the system remained operating through 1994 with only the addition of potato waste to the ARUM cells [29].

2.3.3 Passive Microbial Process

Seeking an alternative treatment to liming, a field study was conducted regarding a passive microbial process development [30]. The treatment process is based on the activities of a complex microbial ecosystem which uses cellulosic material as its main carbon source and physical support.

The microbial populations, including sulphate-reducing bacteria and cellulose decomposers, multiply within the cellulosic material and interact to neutralize AMD

and reduce the sulphate to sulphide. Some metals co-precipitate with sulphide, while others precipitate as the pH increases.

2.4 SUDBURY AREA INITIATIVES

INCO Limited's Copper Cliff tailings area is one of North America's largest repositories of acid generating tailings (approximately 5,500 acres). Tailings have been deposited in the basin since the 1930's and future deposition capacity has been designed for more than 30 years. In 1993, a plant test at INCO's Clarabelle Mill demonstrated that a substantial quantity of residual sulphides in the rock tailings can be removed with increased flotation in a slightly acidic pulp [31]. This process leaves a large volume of potentially inactive low sulphur tailings which can be used for cover and dam construction material. An extensive environmental evaluation is being performed on the low sulphur tailings, main rock tailings, and total tailings. The evaluation involves static and kinetic column tests plus field tests. The results show that low sulphur tailings appear to be a relatively inert material.

At Falconbridge Limited, the battle against pollution has been fought on many fronts [32]. In the 1950s, for example, 83% of the sulphur contained in the ore was emitted by the smelter. In 1978, with the completion of the smelter redesign, the emission has been reduced to about 11% of the sulphur in the ore. From the remaining 89% sulphur, nearly 60% remains in the tailings by pyrrhotite rejection. The method used to reclaim high sulphide tailings is to prevent upward leaching and acidification by placing 8 to 10 cm diameter crushed material, possibly from the open pit at the

base of the pond. On top of this, a layer of sewage sludge will provide nutrients for plant growth. Pyrrhotite tailings are also covered with low sulphur tailings slimes to reduce the amount of nickel exposed to atmospheric leaching.

CHAPTER THREE

3.0 NEW TECHNOLOGY

3.1 Theory of Agglomeration

Agglomeration can be defined as the process of enlarging of solid particles by consolidation and binding in the presence of liquid to form larger agglomerated particles [33]. The main agglomeration methods are; agitation, pressure, thermal and liquid agglomeration. The agitation agglomeration method, which is the most common, is divided into two main types: pelletization and granulation.

3.1.1 Cold-Bond Tailings Agglomeration

Pelletization agglomeration was widely used since 1989 by the Agglomeration Research Group at Laurentian University led by L. M. Amaratunga. It involves subjecting fine tailings to a rolling action in a disc or drum pelletizer, in the presence of alkaline or non alkaline binders and water. Unlike in the iron ore pelletization industry, tailings are agglomerated using cementitious binders and for strength enhancement, no heat induction process such as in sintering is employed. Cold-bonding is due to curing, and a curing chamber is preferably used to develop the pellet strength. Hence, the process is called Cold-Bond Tailing Agglomeration process (CBTA). The mechanism of the nucleation stage and size change depends on several factors such as feed particle size, surface tension, viscosity and mode of operation [33].

The agglomerates, shape is affected by sprayed water, the fineness of the material fed into the mechanized system while the growth of the agglomerates is influenced by the positioning of the water spray. Irregular agglomerates are usually a result of adding too much water. In addition, the retention time on the disc or drum and the amount of added binder influence the porosity and agglomerate size. The angle of inclination of the disc or the drum also influences the height of fall agglomerates. A more compact agglomerate is a result of a steeper angle. Uniform operation of an inclined disc or drum would produce a consistent product.

Drum agglomeration has a longer residence time for hard materials and greater throughput capacity compared to disc agglomeration [33]. The disc requires less space and is less sensitive to operating controls. Furthermore, the gravitational force which tends to pull the rolling pellets down is greater in a drum than in a disc [34].

3.2 Mechanism of Balling

Pelletization or balling is the process involving the formation of agglomerates due to the tumbling of moist particles in a rotating disc or drum [35]. The layering process takes place as the new moist fines are added to a system of pellets. The interaction and collision of agglomerates in the system of material are the main factors responsible in the size enlargement of pellets [34]. The mechanisms of growth and decay in particulate processes are shown in Figure 3.1 [33].

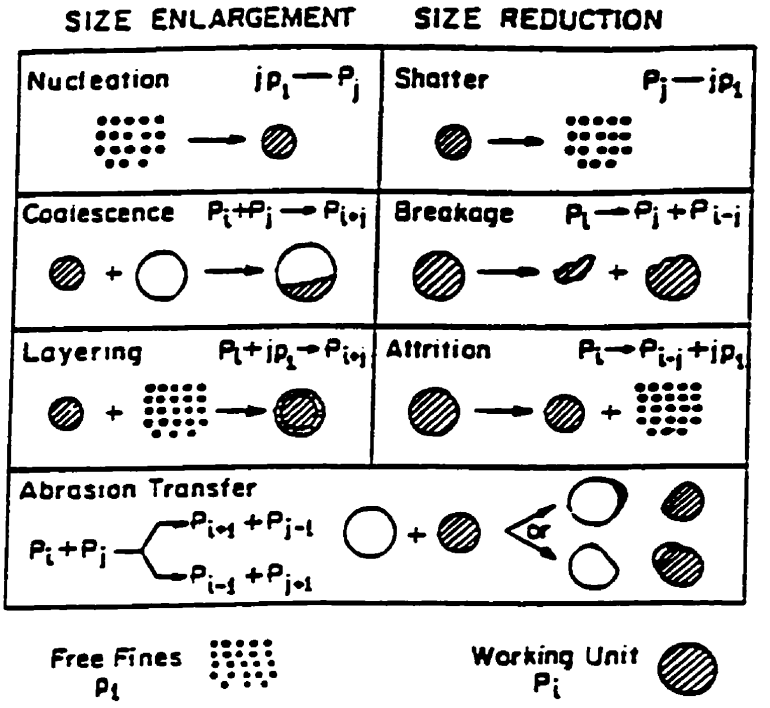


Figure 3.1 Growth and Decay Mechanisms in Particulate Processes [33]

The main bonding mechanism of size enlargement can be described by solid bridges between the particles in a granule [34]. The increased growth rate of pellets with moisture content is explained on the basis of capillary forces [35]. The major material properties that affect the pellet growth are the moisture content, feed material size distribution and the binder addition [35].

As moisture is sprayed on to an agitated mass of fine particles, the capillary and surface tension forces of water, and the force of agitation causes fine particles to consolidate into a firm body. During the early stages of agitation, the initial feed material begins to form into nuclei.

On tumbling the moist material in a balling drum and after a brief induction period, the flocs nucleate into porous, spherical, well-formed species [36].

When fine particles are subjected to the rolling and cascading action in a disc or drum, the force of gravity acting through larger spherical pellets can apply a tremendous pressure on a small particles [34]. As the balling process continues, balling or pelletizing, factors such as retention time, slope, feed rate and speed of rotation of the drum or disc pelletizer must be adjusted in order to achieve optimum pellets.

3.3 Cold-Bond Agglomeration Benefits

With increasing demand for fine grinding to achieve improved recoveries of metal values, the production of tailings and their safe disposal become an important issue to some Canadian and international mines and mills. The only way to dispose of these fine tailings is into the tailings pond. However, this becomes a major environmental concern to the mining industry.

The fine tailings can be agglomerated and recycled back to the mine operations for backfilling underground or used as gravel on the surface if oxidation of the fines is prevented. This can also result in less surface area for tailing disposal. Therefore, the agglomeration technique eliminates the constraints that are imposed on the fine grinding as an effective method of mineral value liberation. The selection of the binders also can prevent and control acid mine drainage since the binders and additives can act as acid neutralizers and bactericides. It also reduces the accumulation of sulphide tailings pond and may completely eliminate the tailings pond in the future.

In the milling of nickel sulphide ores, a large amount of pyrrhotite bearing tailings are produced. These tailings may contain up to 1% nickel, present either as pentlandite or as solid solution in the pyrrhotite. As an immediate concern, this material can lead to acid mine drainage, accompanied by heavy metal dissolution.

As a present and future concern, this material is a possible source of low grade feed to a nickel recovery plant. These two factors prompted an investigation into the cold-bond agglomeration as a new economic alternative in dealing with pyrrhotite tailings. Limited information is available in the literature with regards to previous agglomeration investigations on pyrrhotite as a source of iron ore for the iron-making blast furnace..

The concept of cold-bond agglomeration is an attractive and economic alternative to permanent disposal of tailings. The concept of agglomeration technology of fine tailings for use as a coarse aggregate for under-ground backfill or surface covering material was first reported by Amaratunga and Annor in 1989 [37]. Some researchers also investigated the agglomeration techniques for mill tailings [38, 39]. The agglomeration process of sulphide materials can provide a suitable resource of coarse material for various practical uses. The agglomeration process involves the utilization of alkaline and non-alkaline binders. Previous work conducted using alkaline and non-alkaline materials have shown positive and promising results [41-42].

The most important parameters investigated in the agglomeration process are the agglomerate's wet and cured strength after 1, 3, 7, 14, and 28 days. Wet strength is crucial in determining whether a raw pellet could survive material bending ,

transportation, and placement in the curing chambers. Cured strength becomes important either as an aggregate for backfill or gravel on surface usage.

The agglomerates must withstand forces applied during placement into a stope and the forces exerted when the agglomerate becomes a load bearing component of the fill composite. The proper size distribution of the agglomerates needed for a strong backfill is another important factor in the agglomeration process. Some of the other important factors besides the wet and cured strength characteristics are the pellet size, the curing period and the type and dosage of binder. The major objective of the agglomeration tests is the selection of an optimum pellet, that is, the one with adequate strength and of low unit cost compared to other binders.

3.4 Binding Agents and Cold-Bond Agglomeration

It is very important to ensure enough metal resources to the global economy without any impact on the ecosystem. In the development of the cold-bond tailings agglomerated (CBTA) technology at Laurentian University, various types of cementitious binders (portland cement, lime, blast furnace slag, gypsum beta hemihydrate, fly ash, etc) have been tested and proven effective for the cold-bonding process [42]. The majority of these binders are alkaline, however, in some applications non-alkaline and more economical binders are employed.

3.4.1 CBTA -Gypsum Beta-Hemihydrate as a Binder

In one particular study, various combinations and dosages of regular portland cement and gypsum beta-hemihydrate have been studied and proven to be effective for use as low-cost binders for the cold-bond agglomeration of mill tailings [42]. A recent investigation combining portland cement and gypsum beta-hemihydrate indicated that the combined binder provided adequate strength for fine gold mill tailings while keeping costs relatively low [43]. In previous studies, it was found that agglomeration of pyrrhotite tailings can be agglomerated by employing two binders, namely portland cement and gypsum. A number of various combinations were obtained to provide a useable aggregate product for usage either as mine backfill or as gravel for surface application [44,45].

The cold-bond tailings agglomeration (CBTA) process is a different concept for reactive fine tailings management. This concept utilizes the CBTA technology for backfill, thus placing the tailings underground or as gravel on the surface. Some industries are taking initiatives to reduce the quantities of surface impoundment of tailings by utilizing tailings underground as backfill in mine stopes [45].

In cold-bond agglomeration, portland cement is normally used to obtain the desired strength, however, it is expensive. In a separate investigation at Laurentian University, some of the other less expensive binders (such as fly ash, blast furnace slag cement and lime, used exclusively as binders) have demonstrated adequate strengths. The binder dosages are expressed in percentage of the total mass of material fed into the disc or drum.

The calculation is usually done on a dry weight basis as shown in the equation [9] which follows:

$$Binder\ dosage = \frac{mass\ of\ binder}{mass\ of\ binder + mass\ of\ dry\ tailings} \qquad [9]$$

The binder added is usually adjusted to Net NP of tailings by supplying acid consuming minerals to the tailings product, thereby reducing the potential of acid generation from tailings.

3.5 Criteria for Selection of Additives

The dominant oxidant in the formation of AMD is the ferric iron. Under acidic conditions, the oxidation of ferrous iron (Fe^{2+}) to ferric iron is the slow step in the process. However, the presence of *Thiobacillus ferrooxidans* bacteria can accelerate the oxidation process of ferrous iron.

Continuous addition of bactericides is necessary in treating tailings sites since a single treatment is not permanent [46]. Therefore, the new technology of utilizing of cold-bond agglomeration can take care of this problem. The cold-bond agglomeration process, through the addition of selected binders and bactericides, can provide a long-term solution. It appears that long-term stability of the cured pellets is highly dependent upon the initial dosage of the additives provided to the pellet. The additives serve a two fold purpose, firstly to inhibit AMD formation, secondly to enhance the green and cured strength of the pellet of suitable diameter.

The chemical additives are added to enhance the binding properties as a secondary issue. However, the primary purpose was to act as an inhibitor to reduce acid generation which is characteristic of AMD in the field. The chemical additives used in the laboratory study were selected according to their toxicity, environmental friendliness and cost. Most of these chemicals have been reported in the literature as effective chemical agents in retarding AMD. Detergents (sodium lauryl sulphate (SLS)), potassium sorbate, sodium benzoate and sodium chloride can be used at low dosages without any environmental problem. Previous studies have showed that (SLS) is more attractive in treating AMD from mine rock than potassium sorbate and sodium benzoate [47]. Sodium silicate was also studied according to previous research work done in treating pyrite tailings. The addition of sodium silicate to pyrite tailings during agglomeration increased the strength of agglomerates and showed a good resistance to weathering by forming a glassy coating within the agglomerates [48].

However, surfactants such as "ENVIROSEAL" and IMPC were also used in this study. The supplier actually provided a more superior formulation than Entac, which is used for dust control, called "Enviroseal". Enviroseal is the general trade name for a "family of coatings" which are employed in several industrial and commercial sectors. It is understood that the manufacturer can adjust the process to regulate the properties of the surfactant once applied and cured. IPMC (polyurethane) contains 20% solids, and a small amount of solvent. Although it strongly bonds to various materials and has a milky white colour, it is quite expensive. IPMC was obtained from IPMC. Inc., in Allentown, PA, USA and selected as another substance

to retard AMD from pyrrhotite tailings. "Enviroseal" is an organic emulsion which is produced from naturally occurring resins (treesap). It is produced in Hamilton, Ontario, Canada and one variation called "Entac" is generally used by INCO for dust control of its tailings. Both surfactants are environmentally safe, and in a previous study Enviroseal showed promising results when used as a retardant to prevent the incidence of acid drainage from waste mine rock [49].

3.6 HUMIDITY CELLS

The humidity cell test is a kinetic method designed to model the process of the geochemical weathering of mine waste materials. Also, it accelerates the real time weathering process under laboratory controlled conditions to a shorter duration. A humidity cell typically consists of a small apparatus which provides alternating dry and moist air flow across the top of the bed of waste materials such as sulphide bearing waste rock. It is similar to the common leaching column test protocol. The humidity cell test is usually conducted for a 3 to 4 month period by most researchers [50].

Humidity cell tests typically only use about 0.25 Kg of sample while column leaching tests employ larger quantities of material. The primary goal of employing a humidity cell is to simulate the actual weathering process of the charged materials (agglomerated mill tailings) at an accelerated rate. The rate of acid generation, the concentration of metals and other species in the leachate product, and their relationships to acid production as function of time were examined.

On a laboratory scale, humidity cell tests were employed to observe the effect of weathering on agglomerated mill tailings and to retard the formation of acid from tailings in the environment. It is generally accepted that leaching column tests tend to simulate actual field conditions more closely than humidity cells, however, the difficulty of achieving the desired observation takes months and maybe years [51]. This makes humidity cells more attractive in providing a range of experimental observations in a matter of weeks rather than months.

When a humidity cell is employed, the work conditions become more conducive to oxidation than normally experienced field conditions. Furthermore, easier control over air, temperature and moisture on a laboratory scale make humidity cells more suitable to the AMD phenomenon in the laboratory. Research studies were conducted at Laurentian University using the cold-bond tailings agglomeration (CBTA) to minimize the impact on the environment of mineral processing tailings from various metal sulphide operations [44]. The reactive tailings were agglomerated with selected binders to determine their potential of reducing acid production, and evaluated according to some of the parameters associated with the oxidation rate of these tailings.

In this study, humidity cells are designed and modified to suit the study of agglomerates. The performance of the cell tests and parameters that affect this performance were also studied closely. The parameters included cell design, air flow, leachate product volume, temperature, humidity and water addition.

The parameters were evaluated according to the previous studies done by MEND and Canadian Centre for Mineral and Energy Technology (CANMET) [51, 52].

A literature review showed that different types of humidity cells have been designed for testing of tailings and waste rock [50,51,52]. However, currently there is no standard cell that can be generally used.

This research study was conducted to determine how reactive tailings oxidize when exposed to the warm, and humid conditions of the cell environment. This will enable us to describe the true effect of weather on the charge.

The agglomerated reactive tailings pellets were tested immediately to determine the effectiveness of the oxidation process. The results will reflect the real time stability of the agglomerated pellets which may be utilized for either mine backfill or as gravel on the surface topography.

The amount of air flow introduced to the cell affects the amount of sulphate and acid reporting to effluent while varying effluent volume can increase acid generation [52]. The test procedures were conducted very precisely to minimize any variation in results.

4.1 MATERIALS

4.1.1 Characterization of Pyrrhotite Tailings

4.1.1.1 Physical and Size Characteristics

The pyrrhotite tailings, used in the laboratory testwork were obtained from the Sudbury, and Onaping, Ontario area mining operations. The material was obtained specifically from magnetic tailings flotation at Strathcona milling operations (Falconbridge Ltd.). These pyrrhotite tailings are discharged from the mill into the tailings area at 5 - 10 % solids by weight and 90 - 95 % liquid. The solid portion is dark in colour, and has a sandy texture with no odour. Its specific gravity is 4.4 and the pH of the slurry ranged between 8.9 and 9.3.

Two shipments of fresh pyrrhotite tailings, contained in several large covered steel drums, were delivered to Laurentian University Mineral Processing Laboratory. The samples were kept submerged in water in sealed steel drums to prevent oxidation. Particle size distribution studies using a laser particle analyzer (Brinkman) at CANMET indicated that the 80% passing size was 33 microns for the first shipment and 65 microns for the second shipment, respectively. The particle size distribution for both shipments is illustrated in Figure 4.1. The fine nature of the material was a result of the fine grinding in the milling circuit.

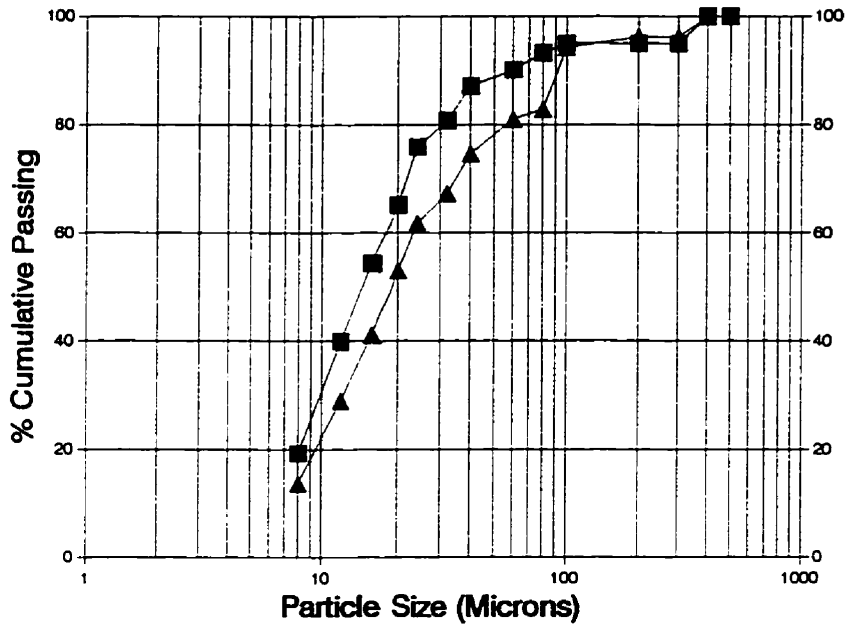


Figure 4.1 Particle Size Distribution of the Two Shipments of Pyrrhotite Tailings

4.1.1.2 Chemical and Mineralogical Characteristics

Three samples of pyrrhotite tailings from each shipment were formed into small pellets which were subsequently used in the X-ray analyses. The X - ray fluorescence analysis was carried out on a Philips PW 1404/10 X-ray spectrometer. The results from XRF analysis test provided a quantitative composition of samples to identify the major and minor elements and their concentrations. A chemical analysis on the pyrrhotite tailings represented in Tables 4.1 and 4.2 revealed that the nickel content was 0.87%.

The major elements of the samples analyzed for the first shipment were, 25.98% Fe, 18.75% S, 8.58% Si, 1.13% Na, and 0.87% Ni. The second shipment showed the same major elements, with 30.9% Fe, 26.9% S, 4.57% Si, 1.18% Na, and 0.72% Ni. Chemical analysis of the weighted average indicated that the samples analyzed have a strong potential for AMD generation. The tailings contained 18.75% and 25.98% total sulphur by weight for the first shipment and for second shipment, respectively, making the pyrrhotite tailings a potential AMD source. The chemical analyses of pyrrhotite tailings are represented in Tables 4.1 to 4.4.

Table 4.1 Chemical Analyses in (%) of the Major Elements for the First Shipment of Pyrrhotite Tailings

Sample	Fe	S	Si	Na	Al	Mg	Ca	Ti	K	Mn
1	25.87	18.51	8.53	1.09	0.86	0.55	0.43	0.13	0.03	0.02
2	26.01	18.98	8.56	1.10	0.67	0.66	0.47	0.13	0.03	0.02
3	26.07	18.76	8.64	1.21	0.75	0.59	0.46	0.13	0.03	0.02
Avg.	25.98	18.75	8.58	1.13	0.76	0.60	0.45	0.13	0.03	0.02

Table 4.2 Chemical Analyses in (ppm) of the Trace Elements for the First Shipment of Pyrrhotite Tailings

Sample	Ni	Zn	Cu	Cr	V	Co	Sr	Pb	Ba	Rb
1	8514	362.5	155.7	208.5	128.6	111	83.1	56.5	23.2	13
2	8658	386.9	199.3	193.1	135.1	111	91.9	72.1	20.2	29
3	8849	378.7	146.4	138.4	118.2	106	89.9	87.0	16.0	13
Avg.	8674	376.0	167.1	180	127.3	109	88.3	71.9	19.8	18

Table 4.3 Chemical Analyses of the Major Elements (%) for the Second Shipment of Pyrrhotite Tailings

Sample	Fe	S	Si	Na	Al	Mg	Ca	Ti	K	Mn
1	30.9	26.5	4.57	1.04	1.03	1.71	0.73	0.16	0.10	0.04
2	30.9	27.2	4.59	1.21	0.91	1.71	0.74	0.16	0.10	0.04
3	30.8	26.9	4.56	1.29	0.91	1.77	0.74	0.16	0.10	0.04
Avg.	30.9	26.9	4.57	1.18	0.95	1.73	0.74	0.16	0.10	0.04

Table 4.4 Chemical Analyses of the Trace Elements (ppm) for Pyrrhotite Tailings for the Second Shipment

Sample	Ni	Zn	Cu	Cr	V	Co	Sr	Pb	Ba	Rb
1	7204	188.4	542.8	114.9	38.31	172	65.4	1.43	32.3	4.3
2	7207	169	553.9	117.2	42.91	163	67.0	0.57	24.5	22.89
3	7134	179.5	539.6	124.4	31.74	153	59.1	0.09	45.2	9.88
Avg.	7181	178.8	545.5	118.8	37.65	163	63.8	0.70	34	12.4

4.1.1.3 Minerological Characteristics

A microscopic mineralogical analysis was also conducted on the tailings, revealing that there is less than 1% pentlandite present. The tailings are rich in sulphidic minerals, consisting predominately of 90% pyrrhotite, 5% gangue, <1% pentlandite, 2 % chalcopyrite and 3% magnetite. The several photomicrographs obtained from the petrographic analyses are accompanied by a full description. The photomicrographs labelled as Figures 4.2 to 4.11, illustrate the typical mineralogy of pyrrhotite tailings employed in the test work.

4.1.1.4 Mineral Descriptions

Pyrrhotite

Pyrrhotite comprises 95% of the sulphide assemblage and is observed as fractureless, inclusion-free, shard-like grains. Grains range in size from 0.1 mm to 0.01 mm in diameter with grain boundaries that are sharp, angular and highly irregular. Only rarely is pyrrhotite observed intergrown with chalcopyrite (refer to Figures 4.2 to 4.5). Grain boundaries between the two sulphide phases are sharp, but smooth and regular. Pyrrhotite grains appear to occur in sub-round to round clusters or agglomerations up to 1.5 mm in diameter (refer to Figures 4.2 to 4.5). Minor chalcopyrite and magnetite are also associated with these clusters.

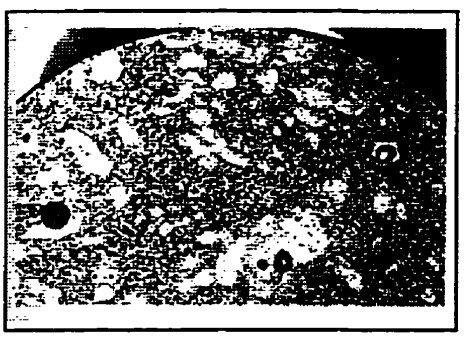


Figure 4.2 General micrograph of and field section., from low power. Note clusters of sulphide disseminated throughout a finer-grained sulphide-rich material.

Figure 4.3 Sulphide "Cluster". 5 x mag., field of view 2.6 mm.

Figure 4.4 Detailed photo of sulphide "cluster". Note angular shards of pyrrhotite gangue with the balsam mount.
20 x mag., field of view 0.62 mm.

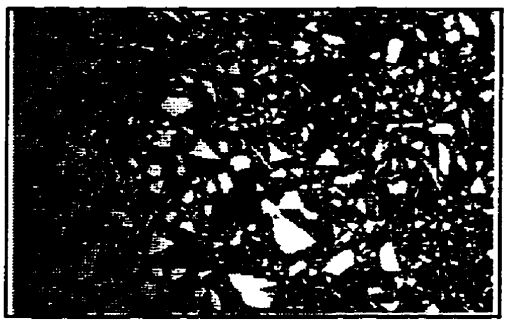


Figure 4.5 Typical habit pyrrhotite- jagged, angular shards. 20 x mag., and field of view 0.62 mm.

Chalcopyrite

Large homogenous grains of chalcopyrite are disseminated throughout the sample, comprising up to 2% of the sulphide assemblage. Grains are typically coarser than the pyrrhotite, up to 0.2 mm in diameter. Grain boundaries are sharp, angular and irregular, often having a shard-like habit similar to that of the pyrrhotite. Rarely, pyrrhotite occurs intergrown with the chalcopyrite. Minor inclusions of another sulphide (perhaps pentlandite) are also very rarely present. Chalcopyrite generally occurs within the clusters of pyrrhotite, but is also present in association with magnetite and gangue minerals. Mineral habit for each is identical, although grain size appears to decrease when associated with the gangue phases (refer to Figures 4.6 and 4.7).

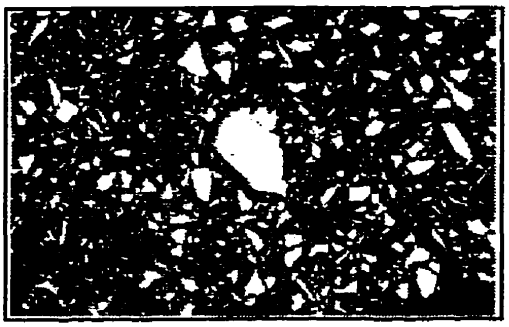


Figure 4.6 Large angular, irregular grain of chalcopyrite amid finer-grained pyrrhotite. 20 x mag., Field of view o.62.

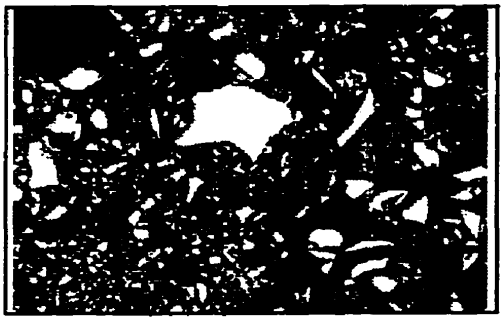


Figure 4.7 Large angular grain of chalcopyrite intergrown with pyrrhotite. Also fine inclusion of pentlandite (difficult to discern). 20 x mag., field of view 0.62 mm.

Magnetite

Magnetite occurs as small, light grains randomly distributed throughout the section. Grains range in size from 0.05 to 0.01 mm. Grain boundaries are sharp, angular and irregular, but in general, not as shard-like in habit as the pyrrhotite. Grains are generally homogenous, fractureless and inclusion-free minor magnetite has a "grungy" appearance, perhaps indicating the onset of alteration. Magnetite occurs within but is not restricted to the pyrrhotite cluster. Minor chalcopyrite is associated with the magnetite (refer to Figures 4.8 and 4.9).

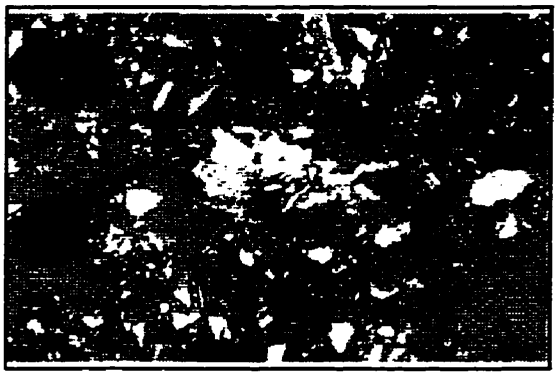


Figure 4.8 "Grungy" magnetic and associated chalcopyrite amid finer-grain with pyrrhotite. 20 x mag., field of view 0.62 mm.

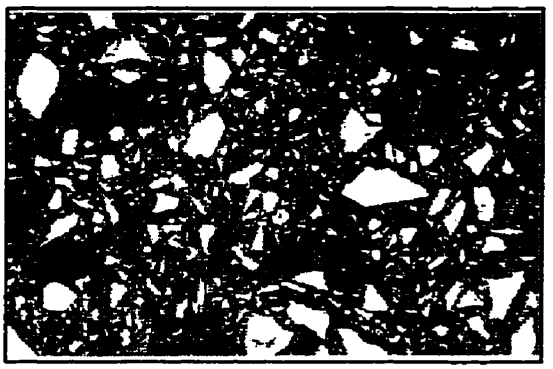


Figure 4.9 Irregular shaped magnetite grain with pyrrhotite. 20 x mag., field of view 0.62 mm.

Gangue Mineralogy

Precise determination of the gangue phases present is not possible due to the slide mount (puck as apposed to polished section). However, the crystal habit of several phases enable logical **assumptions** to be made. Long, subhedral, platy characteristics of one phase are highly suggestive of chlorite. This phase occurs randomly throughout, constituting only a minor proportion of the gangue assemblage. The most abundant gangue phase consists of sub-round grains that contain numerous internal reflections. These grains are assumed to be of carbonate mineralogy. This is the dominant gangue phase associated with chalcopyrite (refer to Figures 4.10 and 4.11).

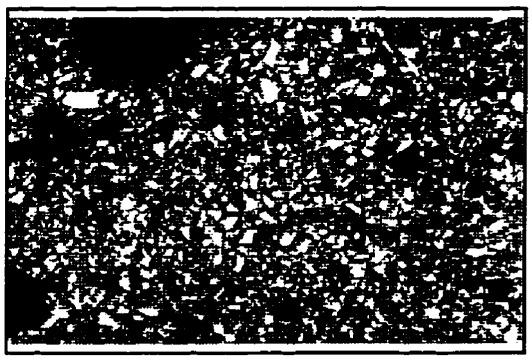


Figure 4.10 Platy gangue phase which may in fact be chlorite in mineralogy. of view 0.62 mm.

Figure 4.11 Large irregular grain with abundant internal reflections perhapsfield carbonate in mineralogy. 20 x mag., field of view 0.62 mm.

4.1.1.5 Evaluation of AMD Potential

Statistical prediction techniques to examine the chemical balance between the acid producing and acid consuming components in mine waste is usually conducted prior to the laboratory tests. There are various static tests with different approaches, in this study the samples of tailings were tested using the paste pH and standard acid-base accounting (ABA) methods. The pH paste method results showed that the pH is in the range of 8.9 to 9.3. The potential of a solid waste sample to produce acid effluent is based on percentage of sulphide contained in the waste sample. The acid potential (AP) was calculated for the pyrrhotite tailing sample by multiplying the percent sulphur in the tailings by 31.25 (stoichiometric factor). The laboratory test indicated that AP for the pyrrhotite tailings is 585 and 812 tonnes $CaCO_3$ equivalent per 1000 tonnes for the first and second shipment, respectively.

4.1.1.6 Neutralization Potential (NP)

The neutralizing potential (NP) is defined as the potential of a waste sample to neutralize acid effluents produced from oxidation of iron-sulphide mineral as based on the amount of carbonate present in the sample. The NP is determined by dividing the amount of the standard acid consumed by a known weight of the sample and calculating the amount on the basis of $CaCO_3$ equivalent.

The initial acid-base accounting tonnes of $CaCO_3$ equivalent/1000 tonnes of material test (ABA) characteristics for the pyrrhotite tailings, showed that on average the samples tested had an acid potential of 586; a neutralization potential of 1.3 and net neutralization deficiency of 585 for the first shipment. The initial acid-base accounting tonnes of $CaCO_3$ equivalent/1000 tonnes of material test (ABA) characteristics for the second shipment of pyrrhotite tailings, showed that on average the tailings had an acid potential of 812; a neutralization potential (NP) of 5 and net neutralization deficiency of 807. These results made the material a potential source of AMD.

4.1.2 BINDERS

4.1.2.1 Cementitious Materials

i) Normal portland cement type 10 (denoted as "PC")

ii) Class "C" fly ash from Lafarge Canada Inc. (denoted as "FA")

iii) Gypsum (beta-hemihydrate Form) from Wastroc Industries Ltd (denoted as "GY")

i) Normal Portland Cement Type 10

Portland cement type 10 was employed during the laboratory agglomeration process as a binder to retard AMD production. Cement is often used in combination with a less expensive binder, fly ash, to lower the binder cost. Cement and fly ash used in this study were obtained from Lafarge Canada Inc. Table 4.5 shows the average cement composition.

Table 4.5 Average Portland Cement Composition (%)[2]

Compound	Composition % by Weight
CaO	60-67
SiO_2	17-25
Al_2O_3	3.0-8.0
MgO	0.1-4.0
S (total)	n/a

ii) Fly Ash

Fly ash is produced as a result of combustion of coal in thermal power generating plants. It consists of fine particulates which are removed from the combustion gases by means of mechanical collectors or electrostatic precipitators (ESP's). There are two types of fly ash; namely type "F" and type "C". The type "F" ash contains a low lime content, however, this type forms a new cement compound when combined with portland cement due to the presence of calcium hydroxide released during the cement hydration process. The type "C" contains a higher lime content than type "F". Previous studies conducted at Laurentian University during the backfill operations had indicated that the type "C" fly ash was capable of replacing 33% and 60% of the portland cement, thereby providing cost savings [44]. Currently fly ash is extensively utilized in rockfill at various mines in Canada. Tables 4.6 and 4.7 show the average chemical composition of fly ash.

Table 4.6 Composition of Fly Ash(%)[2]

Compound	Composition % by Weight
SiO_2	43-45
Al_2O_3	19-23
CaO	11-14
Na_2O	5.5
Fe_2O_3	4.0-5.0
MgO	3.0
K_2O	0.9
SO_3	0.8
Carbon	<1.0

Table 4.7 Chemical Analysis of Bell River Type "C" Fly Ash (%)

Compound	Composition (%)	CAN3 -A23.5 Specification
Silicon Dioxide (SiO_2)	37.4	
Al_2O_3	20.0	
Fe_2O_3	6.7	
Total (SO_2+AL_2O_3)	64.8	Type C-50 minimum
CaO	16.3	
MgO	3.4	
SO_3	4.4	
Loss on Ignition	0.45	60 maximum

iii) **Gypsum (Beta-Hemihydrate Form)**

Gypsum has the potential to act as an inexpensive non-alkaline binder in the Cold-Bond Tailings Agglomeration (CBTA) process [42]. Furthermore, recently gypsum is available in the market as a flue gas desulphurization "FGD" gypsum, which is a waste by-product from sulphur dioxide gas scrubbing and emission control in several industries. The gypsum utilized in the laboratory study was obtained from Wastroc Industries Ltd. Previous studies conducted on gold tailings had showed that the addition of gypsum to portland cement actually increased the strength of agglomerates while reducing the consumption of cement. [43]. In addition, gypsum can also prevent further oxidation and percolation of precipitation such as snow and rain into the tailings pond. The chemical analysis of gypsum used in the laboratory test work is presented in Table 4.8.

Table 4.8 Chemical Analysis of the Major and Trace Elements of Gypsum

%										
Element	Fe	S	Si	Na	Al	Mg	Ca	Ti	K	Mn
	0.25	22.2	1.07	1.53	0.32	0.58	29.38	0.01	0.07	0.01
PPM										
Element	Ni	Zn	Cu	Cr	V	Co	Sr	Pb	Ba	Rb
	0.04	18.1	19.7	0.03	8.86	4.53	1022.7	9.10	1302.2	9.1

4.1.3 ADDITIVES

4.1.3.1 SURFACTANTS

i) Enviroseal- a water insoluble sealant or surfactant available in a liquid state prior to curing (non lignin) for dust control, tailings fixation and soil stabilization (denoted as "Enviroseal")

ii) IPMC polyurethane sealer from a U.S. supplier (Allentown, PA) (denoted as "IPMC")

i) **"Enviroseal"**

One variation of the "Enviroseal family" of products is presently being used by INCO for dust control of it's tailings. "Entac" is the trade name for an organic emulsion produced from naturally occurring resins (treesap) which has gained widespread usage for dust control. This liquid compound is manufactured in Hamilton, Ontario, Canada. The liquid Entac may be diluted with water in sufficient ratios prior to field applications.

However, the "Enviroseal" product is applied at full strength and dries to form a non-water soluble coating. The "Enviroseal" materials are environmentally friendly, unaffected by freeze-thaw, non-corrosive and simple to apply. The products are used to seal concentrate, coal and ash stockpiles by forming a waterproof skin, which prevents leaching and erosion. The formulation, once applied, provides better field results than petroleum-based emulsions and chlorides. Previous studies had showed promising results when Enviroseal was employed as an AMD retardant for mine waste rock [49]. It is also one of the lowest unit cost currently commercially available compared to other surfactants.

ii) IPMC

This standard grade surface sealer contains 20% solids and a small amount of solvent. IPMC sealer was supplied by IPMC Inc. located in Allentown, PA, USA and was selected as another potential retardant for AMD control. This compound which strongly bonds to various materials, has a milky white colour and an alkaline pH with a specific gravity of 1.05, However, it is more expensive than Enviroseal [50].

4.1.3.2 Neutralizers

i) Sodium Silicate

The physical characteristics of silicates are often described by the arrangement of SiO_4 tetrahedra. The sodium silicate is based on SiO_4 tetrahedra with metal ion of sodium occupying space between the tetrahedra. Sodium silicate is quite soluble in water and can

be produced when silicon dioxide reacts with NaOH on heating as follows:

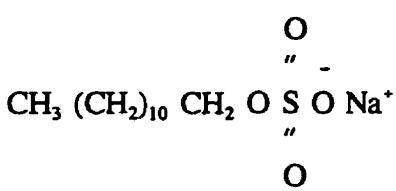
$$SiO_2\,(s) + 4\,NaOH \rightarrow Na_4\,SiO_4\,(s) + 2H_2O\,(g) \qquad [9]$$

Previous studies have shown that sodium silicate polymerization reactions with pyrite tailings and cement produced high strength and low porosity agglomerates.

4.1.3.3 Bactericides

i) Detergents (Sodium Lauryl Sulphate (denoted as "SLS"))

Both synthetic and natural detergents contain surfactants. Surfactants are substances which have a long hydrocarbon chain attached to a polar "head group" which is frequently anionic. A detergent is a complex formulation of a surfactant and a builder which is a basic substance whose role is to provide a source of hydrogen ions. The chemical formula of sodium lauryl sulphate (SLS) is the following:



Sodium Lauryl Sulphate (SLS)

The surfactant usually dissolves in water at very low concentrations. As a result a solution of individual hydrate molecules is obtained. Dreft, $C_{12}H_{25}\,OSO_3^-\,Na^+$ which is chemically called "Sodium Lauryl Sulphate" or alternatively sodium dodecl sulphate "SDS" is commonly used in the laboratory. Previous studies have showed that SLS and other bactericides such as sodium benzoate and potassium sorbate inhibit AMD from waste rock and economically very cheap compared to the other bactericides [47].

CHAPTER FIVE

5.0 EXPERIMENTAL DETAILS

5.1 Agglomeration Process

Tailings were obtained from the mill as a slurry and concentrated by thickening. The tailings from the second shipment were filtered to 90 - 92% solids by weight using a laboratory pressure filter prior to the agglomeration process. The tailings were then mixed with the selected binders at dosages of 3%, 5%, and 7% binder by weight using portland cement (PC) and fly ash (FA) in the ratios of (0%PC:100%FA), (20%PC : 80%FA), (40%PC : 60%FA), (60%PC : 40%FA), (80%PC : 20%FA), and (100%PC : 0%FA) for each of the binder dosages employed for agglomeration purposes. Portland cement was previously used as an alkaline binder for cold-bond agglomeration with successful results [37,42,43,44]. Fly ash was the other alkaline binder selected for this investigation to study the behaviour of pyrrhotite tailings using the cold-bond agglomeration technique.

Batch pelletizing tests were carried out in a laboratory constructed steel drum (56 cm diameter x 74 cm long) with a 7 mm thick rubber lining and rotating at a speed of 33 rpm at a slope of 5° to the horizontal. Additional water was sprayed to the mixed feed during the pelletization process to control the desired size and shape of the pellets. The mechanism of the rotating drum, retention time and the sloped surface ensures the creation of pellets of all sizes. The flow sheet for agglomeration of pyrrhotite tailings is illustrated in Figure 5.1.

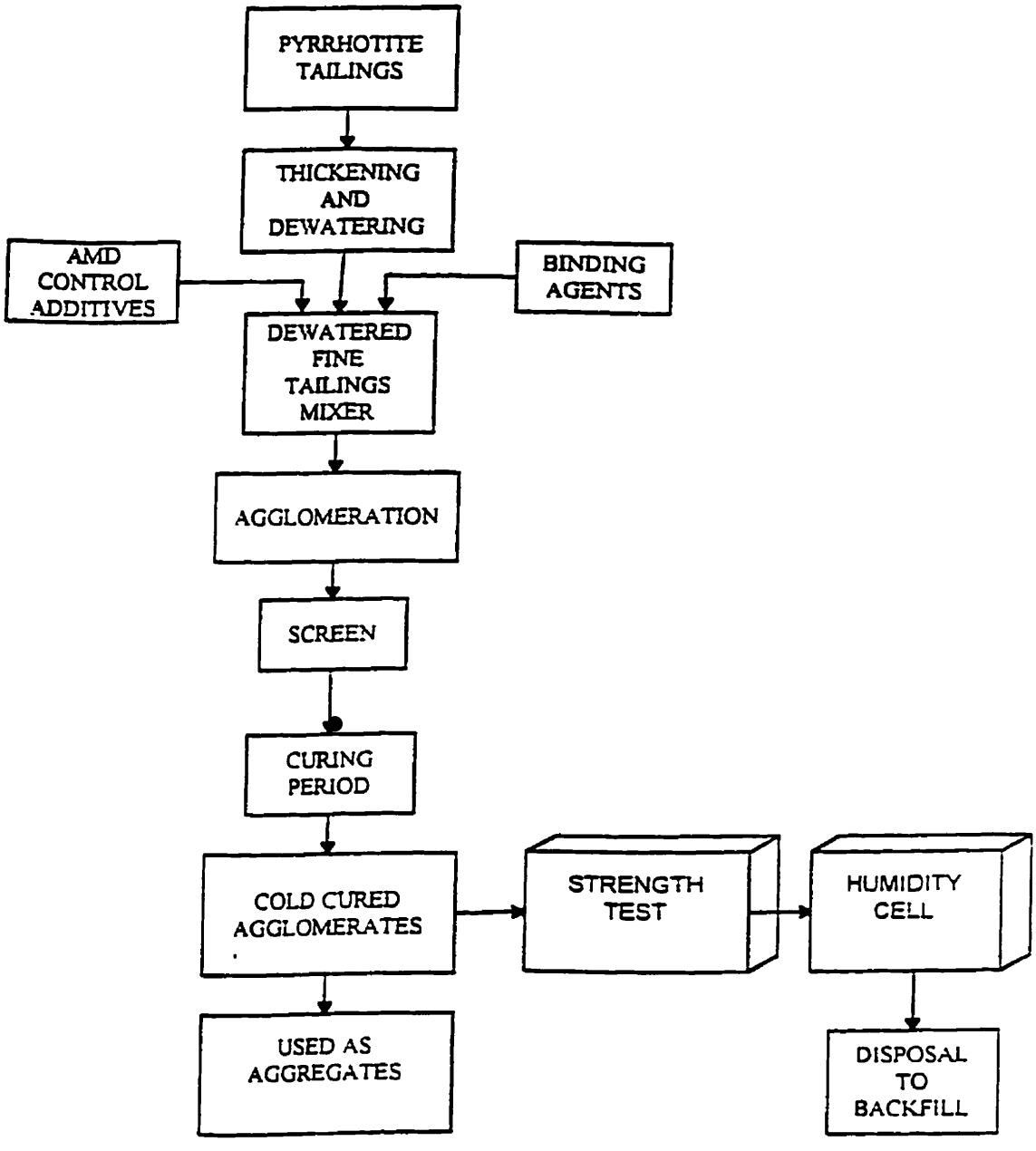


Figure 5.1. Schematic Flow Diagram for Laboratory Agglomeration Process of Mine Tailings.

There are many influencing factors that play a significant role in developing the pellet. Some of the more important factors are the wet and cured strength characteristics, the pellet size, the curing period and the type and dosage of binder. The most economical and optimum pellet was determined according to the green pellet strength, cured strength and amount of binder used.

5.2 Green Pellet Strength

A standard drop test (drop from a height of 46 cm on to a steel plate), was carried out for each batch of "green" pellets, with nominal diameters of 1/2" (12.7 mm) and 3/4" (19 mm), to determine their preliminary strength. The results of the pyrrhotite agglomeration project showed that on average the number of drops required to fracture the "raw" agglomerates during the drop test was in the range of 5 to 10 drops. This value is low compared with those reported for the gold mill tailings experiments [43]. Batches of pellets of size 1/2" (12.7 mm) & 3/4" (19 mm) diameter were allowed to cure for 1, 3, 7, 14, and 28 day periods in a curing chamber within a temperature range of 30^0 - 40^0 C and a humidity of 100 % in order to obtain the necessary strength through the formation of hydration bonds.

5.3 Pellet Fracture Load Test

A fully automated computer controlled pellet point-load tester (capacity of 2225 Newton per pellet (N/P)) constructed at the Tailings Agglomeration Research

Laboratory of Laurentian University, enabled a quantitative evaluation of the cured strength of the pellets. The results were saved in the computer and statistical mean values were calculated for the cold-bond agglomeration characteristics of pyrrhotite tailings.

The cured strength of a pellet is related to many factors, one of which is its size. All previous work regarding cold-bond agglomeration of fine tailings showed a trend of increased strength relative to increased pellet diameter. Therefore, to indicate the agglomerates fracture load capacity, the force at which it failed and its size must be reported together as Newton per pellet (N/P). For example, 400 N/P (12.7 mm) indicates a 12.7 mm pellet fractured at 400 N force. In this study, the pellet sizes used are those commonly accepted in the iron and steel industry, namely 12.7 mm (1/2 inch) and 19 mm (3/4 inch).

This standardization makes it easier to either compare pellet strengths reported in the literature or pellets consisting of similar materials. Upon analyzing the data produced from all the tests, conclusions based on the pellet size could be made. First, as the agglomerate size increased so did its strength, and secondly 12.7 mm (1/2 inch) and the 19 mm (3/4 inch) diameter pellets were generally consistent. That is to say that for a constant binder dosage the pellet strength increased with its physical size. However, previous publications have reported that a minimum 3-day curing period was required to ensure adequate strengths and handleability and also provide low storage capacity and operation cost [42].

The effect of curing on pellet strength was very similar to that due to size. As the curing period increases so does the strength, provided that a proper environment for curing is used. This has been found in all previous investigations and is fundamental to concrete processing technology. Figure 5.2 shows a typical plot of pellet strength versus curing period for 12.7 mm pellet at a total binder dosage of 5%. Results show that an adequate strength is achieved after 3 days of curing and the strength continues to increase until a maximum, usually after 14 days, when a slight decrease in strength is observed.

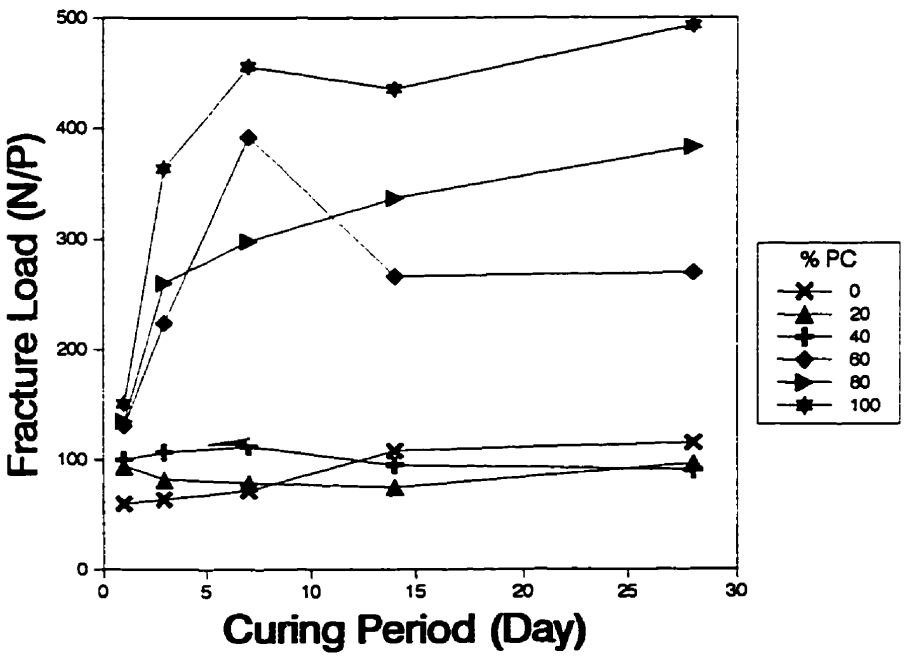


Figure 5.2 Effect of the Curing Period on the Fracture Load of (12.7 mm Pellet at Total Binder of 5%)

The results of the fracture load test for the 12.7 mm pellet of 5% total binder are illustrated in Table 5.1. The remainder of the data for the strength test is listed in Appendix A.

Table 5.1 Fracture Load (N/P) Results for 12.7 mm Pellet & Total Binder of 5%

Binder Composition (%)		Curing Period (Day)				
PC	FA	1	3	7	14	28
0	100	60	64	72	108	115
20	80	94	82	79	75	96
40	60	100	107	112	95	90
60	40	131	224	392	266	269
80	20	135	260	298	337	383
100	0	145	352	440	495	490

It should be noted that pellets attained a large percentage of their matured strengths by 3 days. Pellets that used portland cement as the only binder tended to have higher fracture load resistance strengths than those with fly ash or with no binder at all, while the pellets with fly ash also had higher strengths than the agglomerates with no binder, as shown in Figure 5.2. The results for the remaining fracture load resistance strength are illustrated in Appendix B.

5.4 Selection of the Optimum Pellet

The selection of the optimum pellet was based on the combined effects of binder dosage, binder composition (PC:FA), curing period, pellet size, low consumption of portland cement and, most off all, acceptable strength. The laboratory investigation indicated that very low binder dosage was economical but did not provide pellets with sufficient strength after 3 days of curing periods. This resulted on the rejection of the total binder dosage of 3%. The pellets showed rapid increase in strength in the early curing period and a slight decrease during the last days of the curing period.

As an important influence on the strength of backfill, the aggregate must withstand crushing and fracturing loads while the backfill is under load. Therefore, an acceptable strength of the agglomerates must be estimated. According to the previous standards observed from results established at the Tailings Agglomeration Research Laboratory at Laurentian University, the acceptable strength for 12.7 mm pellet was set at a 150- 200 N/P after three days of curing [42,43]. Based on this value a majority of the pellet compositions were eliminated as unacceptable in strength, and the most suitable combinations of ingredients for optimum pellet strength are shown in Table 5.2. The final variable investigated was the amount of cement in the pellet. The strength results were compared for 5% and 7% total binder dosage and their composition of (20%, 40%, 60%, 80% and 100%) portland cement. The pellets with the highest 3 day strength were selected as shown in Table 5.2.

Table 5.2 Pellet Comparison Satisfying an Acceptable Fracture Load Strength (3 Days of Curing , 150 N/P, and 12.7 mm pellet)

Total Binder (%)	Pellet Composition (PC:FA)	3 DaY Strength (N)
5	100:0	364
5	80:20	260
5	60:40	224
7	100:0	452
7	60:40	308
7	40:60	162
7	20:80	151

Further evaluation of these pellets was needed in order to select the optimum pellet. The most obvious candidate to be eliminated was pellet No. 4 (Table 5.3) because of its high portland cement consumption (7%). The other pellets Nos. 1, 2, and 5 were also eliminated because of their high portland cement consumption compared to the rest of the pellets. However, pellets Nos. 3, 6 and 7 contain lower portland consumption, The fracture loads of the three pellets at 1, 3, 7, 14 and 28 days were also examined, since only the 3-day pellet strength was examined earlier as shown in Table 5.4, a broader look at the maturing strength of the pellets A(3), B(6) and C(7) was necessary. Pellet "A" demonstrates a significant increase in fracture load capabilities for all curing periods while pellet "C" demonstrates the weakest of the three. The results showed an increase in strength for pellets "A" and "B" with

increasing curing periods at all stages. However, pellet "C", which just fell within the acceptable range for 3 day strength, showed a drastic decrease in mature strength after 28 days, hence it was eliminated and pellet A(3) was selected as the optimum pellet.

Table 5.3 Pellets Matching Both Criteria of Strength and Portland Cement Consumption (3 Day Strength, 12.7 mm Pellets

Pellet (No.)	Total Binder (%)	Binder Composition (PC : FA)	PC Consumption (%)	3 Day Strength (N)
1	5	100:0	5	364
2	5	80:20	4	260
3	5	60:40	3	224
4	7	100:0	7	452
5	7	60:40	4.2	308
6	7	40:60	2.8	162
7	7	20:80	1.4	151

Table 5.4 Final Selection of Agglomerates for the Optimum, Fracture Loads for Various Curing Periods

Curing Period (Days)	Pellet Strength (N)		
	Pellet A(3)* (3% PC)	Pellet B(6)* (2.8% PC)	Pellet C(7)* (1.4%PC)
1	131	109	152
3	224	162	151
7	392	210	205
14	266	216	228
28	269	252	184

* 3, 6 and 7 denotes pellet No.

5.5 Additives for Inhibiting AMD Production

Pyrrhotite tailings were dewatered using a pressure filter and then premixed with portland cement and fly ash and the chemical additives. The dosage of additives used in the tests were 1000 mg/kg, 3000 mg/kg and 5000 mg/kg. The type of dosages and compounds used in the encapsulation of agglomerates are outlined in Table 5.5.

The chemical additives were selected according to their toxicity, environmental friendliness and cost. A constant binder dosage of 5% (60PC:40FA) was selected to make pellets for all tests in order to compare the performance of the encapsulated pellets. Most of the chemicals have been reported in the literature as effective chemical agents utilized in preventing and controlling AMD from pyrite tailings [48].

5.6 Humidity Cell

5.6.1 Humidity Cell Design

A kinetic test, which is designed to monitor the oxidation process of typical mining waste materials, was set up in the laboratory. This special set-up is designed to provide control of various parameters such as air, temperature and moisture, thereby simulating actual field conditions occurring due to the weathering effect of nature. The customized test procedure, designed to accelerate the effects of natural atmospheric leaching was conducted using a humidity cell.

A preliminary study was conducted to determine which material oxidizes the most when exposed to warm humid conditions of the cell environment.

Table 5.5 Chemical Additives Used in Encapsulation of Agglomerates

Sample No.	Chemicals Additives	Dosages	Comments	Strength (N/P)				
				Curing Periods (Day)				
				1	3	7	14	28
1	Self aggl	Nil	Control	150	98	99	176	215
2	Enviroseal	1000 mg/kg	Surfactant	38	73	77	92	100
3	Enviroseal	3000 mg/kg	Surfactant	98	172	219	215	200
4	Enviroseal	5000 mg/kg	Surfactant	16	113	147	149	150
5	SLS*	1000 mg/kg	Bactericide	23	51	105	78	100
6	SLS*	3000 mg/kg	Bactericide	20	41	81	89	100
7	SLS*	5000 mg/kg	Bactericide	12	27	41	67	105
8	Tailings	Nil	Control	-	-	-	-	-
9	Sodium Silicate	1000 mg/kg	Neutralizer	129	215	235	250	273
10	Sodium Silicate	3000 mg/kg	Neutralizer	102	142	207	209	200
11	Sodium Silicate	5000 mg/kg	Neutralizer	105	126	203	195	199
12	60PC:40FA	Nil	Neutralizer	131	224	392	266	269
13	IPMC	1000 mg/kg	Surfactant	65	117	148	195	226
14	IPMC	3000 mg/kg	Surfactant	94	159	255	368	230
15	IPMC	5000 mg/kg	Surfactant	93	126	235	270	275
16	60GY:40PC	Nil	Neutralizer	76	106	162	183	211

* Denotes Sodium Lauryl Sulphate (SLS)
- All pellets have a constant binder dosage of 5% (60%PC:40%FA) except for Sample No.1, No.12 and No.16.
- For sample No.16, Pellets have a constant binder dosage of 5%(60%GY:40%PC)
- " Self Aggl" denotes no addition of binder or additive to the sample

The agglomerated tailings were tested to determine whether or not they oxidize easily using humidity cells. Therefore, two different humidity cells were designed and tested over a period of five weeks to determine the preferred cell for the study.

In the first humidity cell designed, which is referred to as Type "A", the agglomerates were held in a large (4L) container that had been perforated in the bottom and without a lid covering the top. This container was suspended inside a larger bucket by two rod supports so that no part of the inside chamber touched the outside chamber. The outer bucket had an inlet hole near the top and an outlet hole near the bottom into which spigots had been inserted so that air could be passed through the system. The outer bucket also had a sealing lid to prevent leakage from the top. When humid air was passed through the top spigot, it would humidify the pellets in the inner chamber. The second cell, which is referred to as Type "B", is rather different in design and aims to increase ease of operation and reduce condensation inside the cell. The cell consisted of two plastic containers that were made to fit inside each other tightly. The air inlet port was placed 30 mm from the bottom. The depth of the sample bed was 155 mm.

The leachate was added through the inlet port which was placed 160 mm from the sample surface to minimize erosion and produce turbulence in the air flow. The sample was supported by the perforated surface of the inside container. The perforated surface was covered with a filter media consisting of 12-ounce/square-yard polypropylene felt which characterized by 22 micron (0.009 inches) diameter filament. This media transmits dry air at a rate of 30 cfm according to ASTM standards (Method D 737).

This special filter media was used to prevent any contamination of the samples and the parameters measured such as pH, Eh, conductivity and concentration of dissolved metals in the solutions collected. The cell was sealed with a special lid. The lid of the cell was sealed to fit tightly and prevent any air loss from the system. The air was passed into the cell from the room into the system. The air flow to the cell was controlled by a needle valve-flowmeter-assembly. The air was dried by passing ambient air through columns of calcium sulphate anhydrate (Drierite). The relative humidity (RH) was decreased to less than 5%. Figure 5.3 represents the Type "B" cell.

The air was humidified by passing warmed ambient air through gas dispersion tube which was submerged in a bath tub in 35^0 C water. Relative humidity of the water was maintained above 95% and condensate was always present in the system. The RH of the air stream was monitored using a Therm-Hygro, which is made by Nortec, with measuring ranges of 0^0C - 50^0 C and 2% -98% RH. The RH was measured frequently to assure consistency.

One kilogram of agglomerated pyrrhotite tailings were placed in both cells. The samples size was selected to obtain a bed depth of 150 mm in each cell, this allowed the samples to be flooded during leaching without overflowing into the air lines. The cycle of leaching consisted of one day leaching and three days of humid air. All subsequent cycles were seven days in length comprising of a one day leaching period, three days of dry air and three days of wet air. Agglomerated tailings of 1.0 kg were placed in each cell and one litre of distilled water was added to moisten the samples. The cells were operated in a seven day cycle. For the first three days, dry air was passed into the cell.

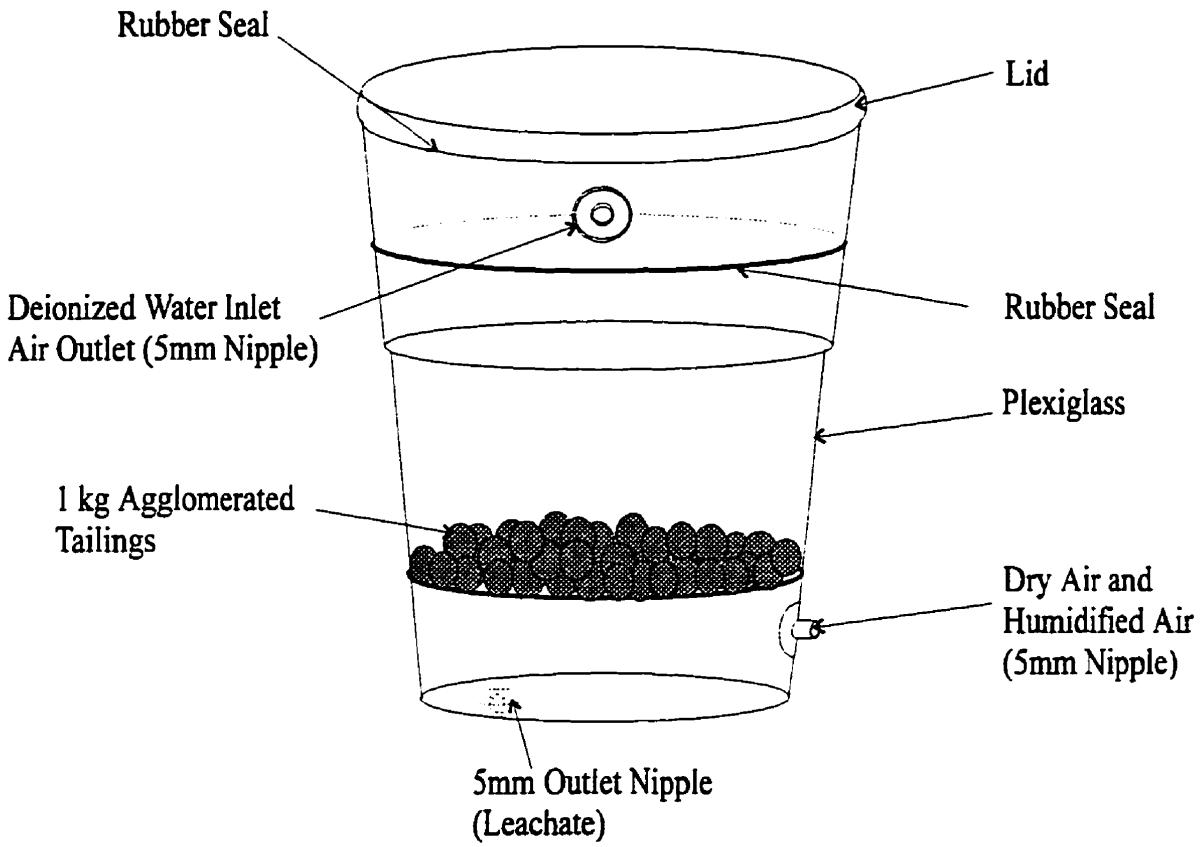


Figure 5.3 Humidity Cell Type "B"

For the next three days, air flow was switched to humid air from the humidifier. On the last day of the cycle, the humid air flow was disconnected and 1000 mL of distilled water was added and allowed to soak the sample for one hour. Then the cells were drained and the leachate collected from the double-chamber cell Type "A" was filtered to remove solids while the solution from the Type "B" cell did not require filtration. Both solutions, were then analyzed for dissolved metals using an ICP analytical technique.

The humidity cells outlined above were tested to determine their effectiveness under the most consistent conditions possible. The test duration of five weeks was conducted using both cells. The leachate collected from both cells was analyzed for various parameters such as pH and dissolved metals using ICP analysis at the INCO analytical services environmental laboratory at Copper Cliff, Ontario.

After both cells were properly tested, the Type "B" cell was chosen to be the most effective in the weathering tests of the agglomerated tailing samples. The pH and the analyses of dissolved metals after the 5th week of the test showed that the type "B" cell had much better results in weathering process of the agglomerates.

5.6.2 Type "B" Humidity Cell

A total of 16 cells of Type "B" were designed and made available for further testing and each group of eight cells were arranged in a circle to accommodate the simultaneous accelerated weathering of various agglomerated tailings samples shown in Table 5.5. An equal amount of sample (1.0 kg) was placed in each cell and each cell was labelled with a sequential number with the same number for the matching collection

container. All cells had the same weight and the same filter media. The filter media was cut to fit snugly and lie flat on the perforated support inside the cell. The air provided from the room was controlled by a special needle valve-flowmeter assembly which contained an oil/water trap, 0.01 micron, for inclusion in the feed air line. The assembly also operates as a bacteria filter tube, for inclusion of 0.1 micron particles.

The air flow then passed from the special air flow assembly through columns of anhydrate calcium sulphate (Drierite) to produce completely dry air before entering the manifold. The calcium sulphate was dried in a special oven at 200^0 - 250^0 C for complete dryness before being reused for each dry air cycle. The dried air was then distributed through the appropriate manifold to each cell. A flow meter was used to assure enough air was supplied during each cycle.

The feed air was routed to each cell through a plastic tubing. The feed air was metered to the manifold using a flowmeter and distributed at a selected normal rate of 3.2 to 3.6 L/min to each cell. The air-flow rate to each cell was checked each day and adjusted if necessary. The saturated air portion was routed by passing warm ambient air through a water-filled humidifier via a distilled gas dispersion fitted cylinder which was submerged in 35 ^{0}C water. The humidified air was introduced to the manifold and to each cell at normal rate of 3.2 to 3.6 L/min. Water displacement tests were conducted frequently to assure that the same amount of air was introduced to each humidity cell for each cycle. A water-bubbling vessel was attached to each humidity cell air exit port to prevent any short circuiting of air through cells containing the agglomerated samples. The water temperature in the humidifier was kept at 35^0 C to assure that the sparged air

maintained a relative humidity of 90-95% which was measured with a hygrometer frequently during the test period. The air flow rates of 3.2 to 3.6 L/min for the dry and wet portions of each cycle was measured every day at the same time.

5.6.3 Leaching Cycle

The characteristics of the leachate was initiated when the first leach was conducted. The first leach was designated as "week 0" leach which was started by flooding the samples with 1000 mL of distilled water. The cells were allowed to set for a period of one hour before draining the leachate into one litre containers which were placed under each cell. Then the leaching-draining process left to complete for the remainder of the leaching day. One litre of distilled water was introduced to each cell through the air outlet. The water was introduced slowly (dropwise) down the side of the cell until the sample was flooded to prevent any erosion to the sample. The weekly volume of water added was maintained constant throughout the test period. The first full-week cycle after the first leaching, this cycle was designated as "week 1"and subsequent weeks were designated as week 2, week 3, ...week n.

5.6.4 Leaching Analyses

The leachates were analyzed once per week for a number of parameters which included:

- pH
- redox potential (Eh)

- conductivity
- acidity
- sulphate (SO_4^{-2})
- frequent analyses on monthly basis for all the dissolved elements by inductively coupled plasma (ICP)
- secondary electron micrograph of pellets during the test period
- chemical analysis of pellets during the test period

The pH was measured using an Orion Research Digital Ionalyzer/501 pH meter. The redox potential (Eh) was measured using an Orion Research Digital Ionalyzer/501 and an Orion Model (96 - 78) platinum redox electrode calibrated to 260 using $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$, 0.1M solution. Conductivity was measured using the Chentrix Type 70 Conductivity Meter and sulphate was measured using the Spectronic 20 D Spectrophotometer. The solutions were analyzed for sulphur, iron, nickel, calcium and other metals by inductively coupled plasma (ICP) at the Ministry of Northern Development and Mines Laboratory, Sudbury, Ontario. Figure 5.4, shows the laboratory set-up for the experiment.

5.6.5 *Thiobacillus ferrooxidans* Bacteria for Cell Tests

The tests of the 16 samples shown in Table 5.5 were monitored for the above mentioned parameters. According to the results after 25 weeks of testing, six samples were selected for further studies using *Thiobacillus ferrooxidans* bacterium. These samples are shown in Table 5.6. One litre of the iron-based medium of Tuovinen and

Figure 5.4 The Laboratory Set-Up for the Experiment

Kelly (TK medium, 1973) was used to grow the bacterium *Thiobacillus ferrooxidans* [53]. The pH of the medium was adjusted to 2.1 using concentrated H_2SO_4. A 10% inoculum , which was obtained from a recently grown culture of strain D2 (Leduc et al. 1993) was used to inoculate the medium [54]. The culture was harvested by centrifugation using a Beckman JA-14 rotor at 25000 x g for 10 minutes at 4^0 C. The culture was placed on a gyratory shaker (150 rpm) and incubated at room temperature until a colour change in the medium from blue-green to rust-coloured was observed, at which time the cells were harvested. The cells were washed using sterile acidified water and resuspended in 100 ml of acidified water (pH 2.1). The resultant cell suspension was used to inoculate the humidity cells containing agglomerated tailings. Ten mL aliquots of the cell suspension were added to 990 ml volumes of deionized water and then added to the humidity cells.

Table 5.6 Selected Samples Tested in Presence of *Thiobacillus*

Sample No.	Chemical Additives	Dosages	Comments	Strength (N/P) Curing Periods (Day)				
				1	3	7	14	28
17	Self Aggl	nil	Control	150	98	99	167	215
18	Enviroseal	5000 mg/kg	Surfactant	16	113	147	149	150
19	SLS	1000 mg/kg	Bactericide	23	51	105	78	100
20	Sodium Silicate	1000 mg/kg	Neutralizer	129	215	235	250	273
21	60PC:40FA	nil	Neutralizer	131	224	392	266	269
22	60GY:40PC	nil	Neutralizer	76	106	162	183	211

•Sample Nos. 17, 18, 19, 20, 21, and 22 are Samples Nos. 1, 4, 5, 9, 12 and 16 from Table 5.5.

Prior to the addition of the bacterial suspension, the six samples were soaked for two weeks in a solution acidified to pH 2.0 using concentrated H_2SO_4. The cells then were drained and the leachate (acidic solution) was analyzed. The samples then were washed with distilled water and the leachate was also analyzed. The pellets showed high resistance to acidic conditions (at pH 2) for two weeks which indicated that the pellets are very resistant to acidic water prior to leaching.

CHAPTER SIX

6.0 RESULTS AND DISCUSSION

In this chapter, the characteristics of pyrrhotite agglomerates and the curing behaviour of agglomerates are discussed. The factors affecting the generation of AMD from reactive pyrrhotite tailings, such as pH level, redox potential (Eh), conductivity, sulphate, acidity, and the dissolved heavy metals, Fe, Ni, and Cu are presented and discussed. The treated and untreated agglomerates of pyrrhotite tailings were examined using a Scanning Electron Microscopic (SEM). The chemical composition of the leachate and the chemical composition of the agglomerates tested are also presented and discussed.

The effectiveness of the laboratory constructed humidity cell under the most consistent conditions possible are discussed. In this study, 22 samples were tested in the humidity cells. The samples tested included one tailings control sample No. 8, and two self-agglomerated samples No. 1 and No. 17. The agglomerated samples were pelletized with 5% binder (60% PC/40% FA) and then with and without additives as shown in Table 5.5. The self-agglomerated sample No. 1 was tested without the addition of bacterium *Thiobacillus,* while the self-agglomerated sample No. 17 was inoculated with *Thiobacillus*. The laboratory humidity cell test was conducted for a period of 58 weeks for samples No. 2 to No. 16 inclusive without the addition of *Thiobacillus*. Samples No. 18 to No. 22 inclusive, were tested for a period of 50 weeks with the addition of *Thiobacillus*.

6.1 Pyrrhotite Characteristics

The reactive pyrrhotite tailings were characterized with respect to size analysis, chemical composition, and SEM analysis. A typical scanning electron micrograph of pyrrhotite tailings revealed the presence of pyrrhotite, pyrite, and gangue minerals which comprised the major portion. The chemical analysis with respect to major and minor elements indicated that pyrrhotite tailings were high in iron and sulphur. The high concentration of sulphides and heavy metals concentration along with the fine nature of the material, due to the fine grinding in the milling circuit, made the pyrrhotite tailings very reactive.

Several photomicrographs obtained from the petrographic analysis were accompanied by a full mineralogical description of a representative pyrrhotite tailings sample. The microscopic examination of the test sample, to provide approximate mineralogical composition and description of mineral occurrences and relationship, was performed at the Geology Department Laboratories, Laurentian University. The photomicrographs prior to weathering tests illustrated the typical mineralogy of pyrrhotite tailings. The microphotographs indicated that the tailings were rich in sulphide minerals consisting predominantly of pyrrhotite, silicate, pentlandite, and chalcopyrite.

Although the pH of pyrrhotite tailings is basic and lies between 8.9 - 9.3, its net neutralization deficiency of 807 tonnes of $CaCO_3$ equivalent per 1000 tonnes of material were strong indicators that this tailings material would definitely generate acid if exposed to air and water. The material had respective NP and AP values of 5 and

812 , for a NNP deficiency of 807 tonnes of $CaCO_3$ equivalent per 1000 tonnes indicating a potential AMD source. This can be confirmed once it is exposed to air and/or water, where it will be naturally inoculated with the airborne bacteria called *Thiobacillus ferrooxidans.*

6.2 Pyrrhotite Agglomerates Characteristics

A series of investigations regarding the study of acid mine generation from pyrrhotite tailings using the method of cold-bond agglomeration was conducted and was found to effectively decrease AMD when subjected to environmental simulations. Using this cold-bond approach, pyrrhotite tailings were agglomerated with the addition of low cost binders, bactericides, surfactants and neutralizing agents.

The fly ash and type 10 portland cement were used as a binder to agglomerate pyrrhotite tailings. The agglomerates were compared according to their performance throughout the weathering tests. The results indicated that all pellets investigated had adequate strength to withstand forces encountered during transportation to a curing chamber.

The performance of encapsulated agglomerates with various additives was compared at a constant binder dosage of 5% (60% PC and 40% FA). The chemical additives were selected according to their ability to inhibit or neutralize AMD generation. Their toxicity, environmental friendliness and cost were also significant factors in selecting these additives. With the number of physical and chemical parameters established, the potential of the weathering tests was evaluated.

6.3 Curing Behaviour of Pyrrhotite Agglomerates

The wet strength was a qualitative test to determine the ability of "green" pyrrhotite pellets to achieve a sufficient strength to withstand falls during transportation without breaking. The fly ash and portland cement provided strong cold-bond agglomerates at moderate dosage of 5% (60 % portland cement and 40% fly ash). The optimum pellet was selected on the basis of the effect of binder dosage, binder consumption, curing period, pellet size, low portland cement consumption and acceptable strength which was the key parameter used as criteria.

It was observed that the moisture content is critical in the production of spherical pellets during agglomeration. The critical moisture content and binder addition were studied very closely to ensure the required pellet size and shape for effective agglomeration of pyrrhotite tailings. The strength of the encapsulated agglomerates increased with increasing curing period (refer to Appendix A and B).

All pellets demonstrated a significant increase in fracture load strength after 3 days of curing. The increase may be due to the acidic nature of tailings and the fine size of the tailings. The addition of fly ash and portland cement may have enhanced the strength of pellet as previously stated [40,44]. Strong and stable agglomerates were produced from reactive tailings with appropriate addition of fly ash and portland cement, moisture content and adequate curing period. The pyrrhotite pellets exhibited a higher fracture load strength than previously experienced with mill gold tailings pellets [43]. Furthermore, the fly ash and portland cement pellets (Sample No. 12) showed a higher fracture load compared to gypsum pellets (sample No. 16) using

pyrrhotite tailings (refer to Table 5.5). The results indicated that the majority of the pellets achieved 60% of their 28 day strength after 3 days of curing. It was demonstrated that the pyrrhotite tailings agglomerated pellets resulted in higher fracture load strength and stronger bonding with a combination of portland cement and fly ash than portland cement and gypsum. This can be explained by the strong bonds created in the portland cement hydration during the curing period. The gypsum and portland cement pellets showed lower strength than portland cement and fly ash pellets after 28 days of curing. Furthermore, this may be due to the precipitation occurring from an acid neutralization reaction between the tailings and the cement as previously explained [41].

The characteristics of cold-bonded pyrrhotite tailings agglomerated with portland cement and fly ash can be summarized as follows. The pellet strength increased with its size and the large pellets demonstrated a higher strength than small pellets. Portland cement and fly ash were successful binders for agglomeration of pyrrhotite tailings. The test work commenced with the initial investigation of the agglomerated tailings being conducted in humidity cells.

6.4 Humidity Cell

Humidity cells designed and constructed were tested to determine their effectiveness under the most consistent conditions possible. Test duration of five weeks was conducted using both cells Type "A" and Type "B". The leachate collected from both cells was analysed for various parameters such as pH and dissolved metals

using ICP analysis at the INCO Analytical Services Environmental Laboratory at Copper Cliff, Ontario. During the five weeks duration of the test, a few advantages and disadvantages in the design of both cells were discovered. There were a few advantages in using the "B" cell than the double-chambered humidity cell "A". First of all Type "B" is easier to construct and putting the cell together was simple. Furthermore, the construction materials were cheap and readily available. Washing the agglomerates after the humidification cycle was completed was also quite easy. However, the bottom outlet spigot was found to be poorly placed, which was later placed in the side of the bottom of the cell.

One of the main disadvantages of the double-chambered cell "A", was that the inner chamber has to be moved for a short period of time for washing after each leaching cycle. Time was also needed for the liquid inside the chamber to drain through the perforation and put the container bucket back together. The primary disadvantages with this cell were the lack of sufficient air flow in the inner chamber to allow proper humidification since air is not actually being forced in into the chamber. Another drawback was that the leachate had to be filtered after it was collected, since there was no filter built-in like in the Type "B" humidity cell.

There were a few flaws and problems other than those outlined above such as the difficulty of placing several of the double chamber cells Type "A" in parallel or in series because no two cells have exactly the same resistance to air flow. After both cells were properly tested, the Type "B" cell was chosen to be the most effective in the weathering tests of the agglomerated tailing samples.

6.5 pH of the Leachate

Potential for generation of AMD is indicated by various parameters such as low pH, high sulphate content, high acidity, and the amount of dissolved metals such as iron in the leachate. The results for these parameters for the self-agglomerated control sample (No. 1) are presented in Table 6.1. The results of the majority of these parameters are presented in Tables 6.2 through 6.22 as listed in Appendix C. The variables such as redox potential, pH, acidity, conductivity, dissolved metals and sulphate content were monitored throughout a continuous period of 58 weeks for sample Nos. 1 to 16, and 50 weeks for sample Nos. 17 to 22. The *Thiobacillus* bacteria have been maintained and growing on pyrrhotite tailings material. To maintain a favourable environmental conditions for *Thiobacillus ferrooxidans*, the optimal pH was kept between 1 to 5 for a week before starting the first leaching cycle. Therefore, acid adjustment to a pH less than 3 was necessary with H_2SO_4 to allow the chemical control and ensure the ideal conditions for bacteria to grow in the cells.

The pH values for the first week of testing indicated the high values for some samples. These levels of pH during the first week ranged from 9.46 to 3.41. The variation of leachate pH for each monitored cell for a period of 50 and 58 weeks are illustrated in Appendix C. The highest values of pH were always exhibited from cells No. 4 (0.5% Enviroseal), No. 5 (0.1% SLS), No. 6 (0.3% SLS), No. 7 (0.5% SLS), No. 10 (0.3% sodium silicate), and No. 16 (60%GY:40%FA).

Table 6.1 Control Sample Self-Agglomerated (self aggl)
Sample No.1
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.41	406	500	32	32	0.1	0.1	_	0.01	38.55	0.47	0.37	82.68
1	7.1	378	300	101	133	0.1	0.2						
2	7.14	325	600	45	178	0.1	0.3						
3	7.16	313	750	56	234	0.1	0.4						
4	7.18	195	250	36	270	0.1	0.5	0.05	0.02	14.61	0.43	0.06	24.28
5	7.17	220	720	33	303	0.1	0.6						
6	7.2	221	720	57	360	0.1	0.7						
7	7.1	221	200	40	400	1.2	1.9						
8	7.5	191	195	37	437	1.2	3.1	0.06	0.02	19.65	1.07	0.05	44.64
9	7.29	244	250	77	514	2.1	5.2						
10	7.25	205	250	78	592	2.1	7.3						
11	7.27	165	550	105	697	1.8	9.1						
12	6.52	164	200	45	742	1.1	10.2	0.005	0.005	19.6	1.93	0.083	58.4
13	5.78	207	220	48	790	1.6	11.8						
14	5.75	185	225	52	842	1.6	13.4						
15	6.85	271	250	32	874	1.7	15.1						
16	6.72	275	200	35	909	1.0	16.1	0.315	0.07	22.7	1.4	0.074	55.4
17	6.74	270	300	48	957	0.9	17.0						
18	6.68	261	225	46	1003	0.4	17.4						
19	6.72	255	250	58	1061	1.6	19.0						
20	6.6	260	300	71	1132	1.6	20.6	0.157	0.03	35.9	2.31	0.091	76.6
21	6.58	252	300	88	1220	1.6	22.2						
22	6.7	230	375	157	1377	1.5	23.7						
23	6.74	224	375	77	1454	1.5	25.2						
24	6.69	226	350	89	1543	0.8	26.0						
25	6.69	210	350	90	1633	1.1	27.1	0.339	0.07	27	1.87	0.041	47.05
26	6.55	230	225	104	1737	0.7	27.8						
27	6.69	248	450	162	1899	1.3	29.1						
28	6.71	242	600	175	2074	0.1	29.2						
29	6.71	243	500	153	2227	0.2	29.4						
30	6.81	242	300	89	2316	1.3	30.7	0.141	0.048	42.6	3.61	0.037	71.1
31	6.67	223	300	67	2383	1.3	32.0						
32	6.83	243	450	194	2577	1.3	33.3						
33	6.8	240	400	120	2697	1.1	34.4						
34	6.77	232	350	184	2881	1.1	35.5	0.133	0.001	38.9	5.71	0.068	80
35	6.7	268	350	48	2929	1.7	37.2						
36	6.71	248	550	147	3076	2.2	39.4						
37	6.77	231	250	303	3379	0.1	39.5						
38	6.78	229	750	334	3713	0.1	39.6	0.06	0.06	41.53	2.62	0.012	52.8
39	6.56	228	250	75	3788	1.1	40.7						
40	6.66	270	350	390	4178	1.2	41.9						
41	6.82	266	400	415	4593	1.3	43.2						
42	6.83	233	350	153	4746	1.4	44.6	0.123	0.205	64.36	4.15	0.03	72.2
43	6.76	230	400	283	5029	1.0	45.6						
44	6.84	245	450	65	5094	1.0	46.6						
45	6.83	237	650	215	5309	1.0	47.6						
46	6.51	228	300	63	5372	1.0	48.6	0.22	0.528	61.95	4.44	0.064	78.8
47	6.48	235	400	52	5424	1.0	49.6						
48	6.52	232	750	326	5750	0.1	49.7						
49	6.63	235	400	75	5825	0.1	49.8						
50	6.25	240	400	62	5887	1.4	51.2	0.767	1.51	107.8	7.99	0.118	148
51	6.51	275	600	334	6221	1.2	52.4						
52	5.75	281	300	105	6326	1.0	53.4						
53	5.12	292	700	286	6612	2.6	56.0						
54	5.2	276	700	584	7196	3.3	59.3	235	27.9	5.878	3.35	0.016	174
55	5.02	282	600	201	7397	0.2	59.5						
56	5.21	248	900	63	7460	0.5	60.0						
57	5.89	251	750	92	7552	0.7	60.7						
58	5.31	291	750	81	7633	0.8	61.5	0.074	7.75	132.4	13.1	0.094	203

The lowest pH values were produced from cells No. 1 (self-agglomerated pyrrhotite control sample), No. 8 (tailing control sample), No. 3 (0.3% Enviroseal) and No. 17 (self-agglomerated control sample with addition of *Thiobacillus*). A common result for the control samples was the sign of a gradual decline in pH values over time as can be seen clearly in Figure No. 6.1. The results of the remaining pH values for all samples are presented in Appendix D.

It appears that chemical reducing conditions tend to decrease the alkalinity which in turn causes the leachate pH to drop. The pH measurements for samples Nos. 4 to 7, 9 to 11, 13 to 15 and 18 to 20, showed fluctuations as a function of leaching time. Despite these fluctuations, a general trend can be discerned. All of these samples showed a neutral pH level during the test period as illustrated in Figure D1 to D6 (Appendix D). The tailings control sample No. 8 and self-agglomerated with addition of *Thiobacillus* sample No. 17 underwent a change in the pH values from 3.41 to 3.18 and from 4.09 to 3.05 over a period of 58 weeks and 50 weeks, respectively. This indicated that the acidity of the leachate had increased for both control samples. It was clearly observed that both control samples had the lowest pH values relative to that of other samples. The behaviour of the leachate for treated agglomerated samples (with addition of additives) had a higher pH, reflecting the alkaline chemical composition of the tailings and the binding agents. Samples No. 18 (0.5% Enviroseal), No. 19 (0.1% SLS), and No. 20 (0.1% sodium silicate) with addition of *Thiobacillus* showed a similar profile. The samples agglomerated and bonded with fly ash and portland cement showed relatively stable pH values within a

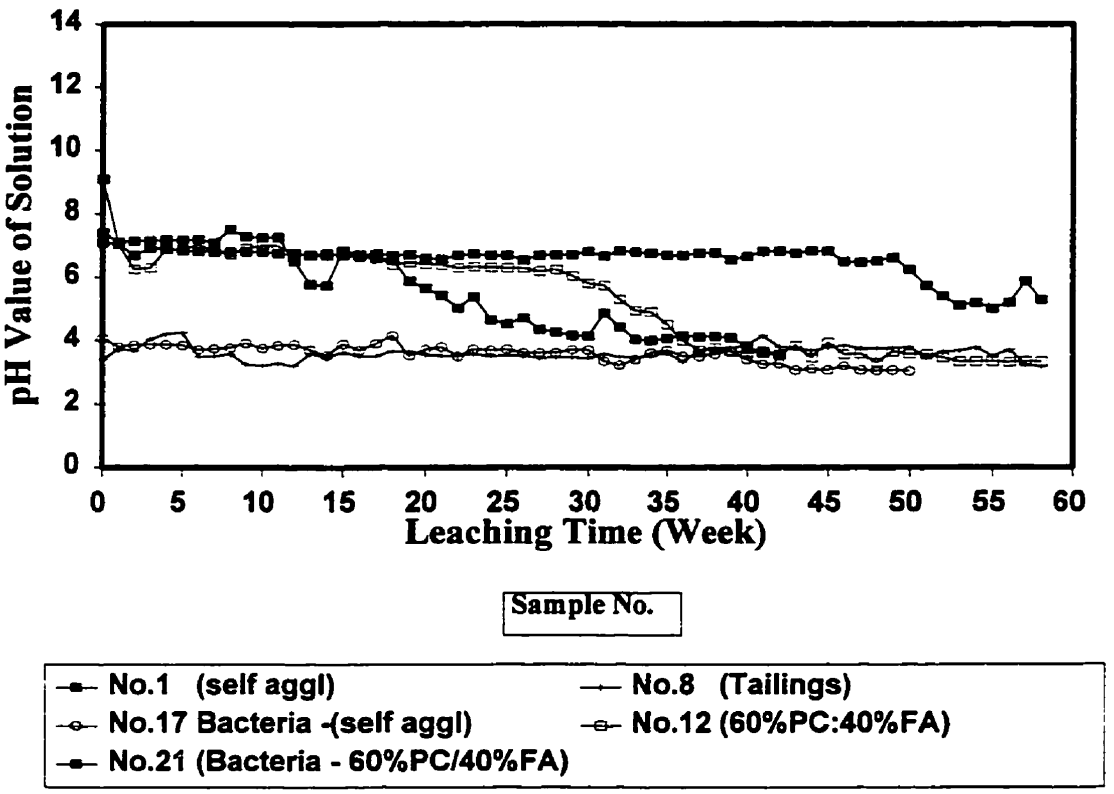


Figure 6.1 pH vs Leaching Time

This behaviour was consistent during the duration of the test period with the observation from the weathering tests. The pH values for the SLS additives at dosages of 0.1%, 0.3% and 0.5% exhibited a stable profile. The addition of *Thiobacillus* to the 0.1% SLS sample No. 19 showed a slight initial decrease in pH values but a steady rate of increase during the testing period. The sodium silicate additives at dosages of 0.1%, 0.3% and 0.5% showed a steady pH profile. However, the addition of *Thiobacillus* to the 0.1% (sodium silicate) sample No. 20 showed a slight decrease in pH values. The Enviroseal addition at dosages of 0.1, and 0.5% exhibited a similar pH profile, where a slow but steady rate of increase of pH was demonstrated with time.

The addition of *Thiobacillus* to the 0.5% (Enviroseal) sample No. 18 showed a slight decrease in the early stage but became stable in week 14 and fluctuated afterwards. The addition of Enviroseal at a dosage of 0.3% showed a consistent downward trend due to the breakage of pellets in the early stage of the weathering test. It was observed that the pellets were broken in the second week of testing due to the weak bonding that was developed during the agglomeration process. The pH values for the IPMC at dosages of 0.1, 0.3 and 0.5% showed the lowest values of pH among all the surfactants added during the agglomeration process. The IPMC agglomerates showed the weakest bonding and lowest fracture load strength. The pH profile for the IPMC showed reasonably stable trend and declined very slightly during the late stage of testing compared to the 0.5% Enviroseal and sodium silicate encapsulated pellets. The 60% PC/40% FA sample No. 12 showed stable pH values in the early stage of the weathering test; however, after 25 weeks, a sharp decline

continued reaching a low value of 4 in week 36. The 60% GY:40% PC sample No. 16 showed a continuous fluctuation in pH values reaching lowest value (6.48) in week 54. The addition of *Thiobacillus* to the 60%GY and 40%PC sample showed sharp decline in week 26 and continued until reaching its lowest value (3.41) in week 49.

Although the pH was continually changing, the values were consistently grater than 6.5 for all samples except for the control samples and the tailings sample. The tailings samples results showed that the surface area was a significant factor in the fast oxidation of the samples. The control samples Nos. 8 and 17 showed higher initial pH values and a gradual decline, indicating the onset of true AMD at pH values of 3.18 and 3.05, respectively.

The agglomerates control samples had a higher initial value than the tailings control sample (cell No. 8). This was due to the reduction of surface area of the fine grains of tailings resulting from the agglomeration process. The self-agglomerated control samples showed a decrease in the pH value and dropped to 5.31 at the end of the test period indicating evidence of the undergoing oxidation and subsequent acid generation. The control samples decreased steadily as expected and reached the lowest values of 5.31 in week 58 for self-agglomerated control sample (cell No. 1), and 3.18 for control tailings sample (cell No. 8).

The pH profile for the control samples had changed from 7.41 to 6.25 for the self- agglomerated control sample (cell No. 1), from 3.41 to 3.18 for the tailings sample (cell No. 8), whereas the control sample with addition of *Thiobacillus* decreased from 4.09 to 3.05 in the same period (50 weeks). The graphs and tabulated

data illustrate the effect of pH measurements as predicted in which untreated pyrrhotite tailings sample containing sulphides tends to generate AMD as soon as it exposed to water and air. However, the agglomeration of pyrrhotite tailings slowed the generation of AMD. The alkaline binders and the chemical additives used in the agglomeration process inhibited the generation of AMD during the test period. According to the pH profile results, the addition of *Thiobacillus* to the encapsulated pellets had insignificant effect on the behaviour of the encapsulated pellets. However, the pH profile for sample No. 21 (60%PC:40%FA) and No.22 (60%GY:40%PC) showed that pH values decreased in earlier stage of testing than previously experienced due to the breakage of more pellets in presence of *Thiobacillus*.

6.6 Redox Potential

Trace metals are released as a result of change in Eh values. The extent of this release depends on the type of tailings used. Thus, monthly analysis of leachate samples from humidity cells were conducted for major and trace elements such as Fe, Ni and Cu using the ICP technique. The Eh values for the sodium silicate pellets at dosages of 0.1%, Enviroseal pellets at dosage of 0.5%, and SLS pellets at dosages of 0.3% and 0.5% were within a very narrow range, 150 <Eh<260 mV. This indicates that no acid or very insignificant amounts of acid were generated.

The control sample No. 17 and the tailings control sample No. 8 showed a steady increase to higher values of Eh than the initial values while a steady decrease in pH was observed. However, the self-agglomerated control sample No.1 showed a

high Eh value of 400 mV in the first week and dropped to 200 mV in week 4 and remained in the range of 150 and 260 mV for the remaining weeks. This indicated that no acid or very insignificant amount of acid was generated during the first 50 weeks. The significant increase in the Eh for the remaining control samples indicated that acid drainage was clearly observed as can be seen in Figure 6.2. The control sample No.17 and tailings sample No.8 showed a drop in pH and significant increase in Eh value during the test periods. The remainder of the results for the redox potential for all samples are presented in Appendix E.

It is clear that the actual additives composition had an effect on the waste tailings samples examined. The heavy metals were detected during the time of experiments for all samples. The graphs (Figure E1, E2 and E3) in Appendix E and the tabulated data in Appendix C illustrate the effect of the Eh values in which sodium silicate, Enviroseal and SLS samples do in fact limit AMD and control the amount of heavy and trace metals released.

The Eh is defined as the negative logarithm of the relative electron activity Eh = - Log [e] which is a parallel to the pH, where pH = - Log [H^+] [55]. Satisfactory results were achieved for most of the humidity cells. This was indicated by the limit of the range of redox potential and also by the apparent correlation between pH and Eh values.

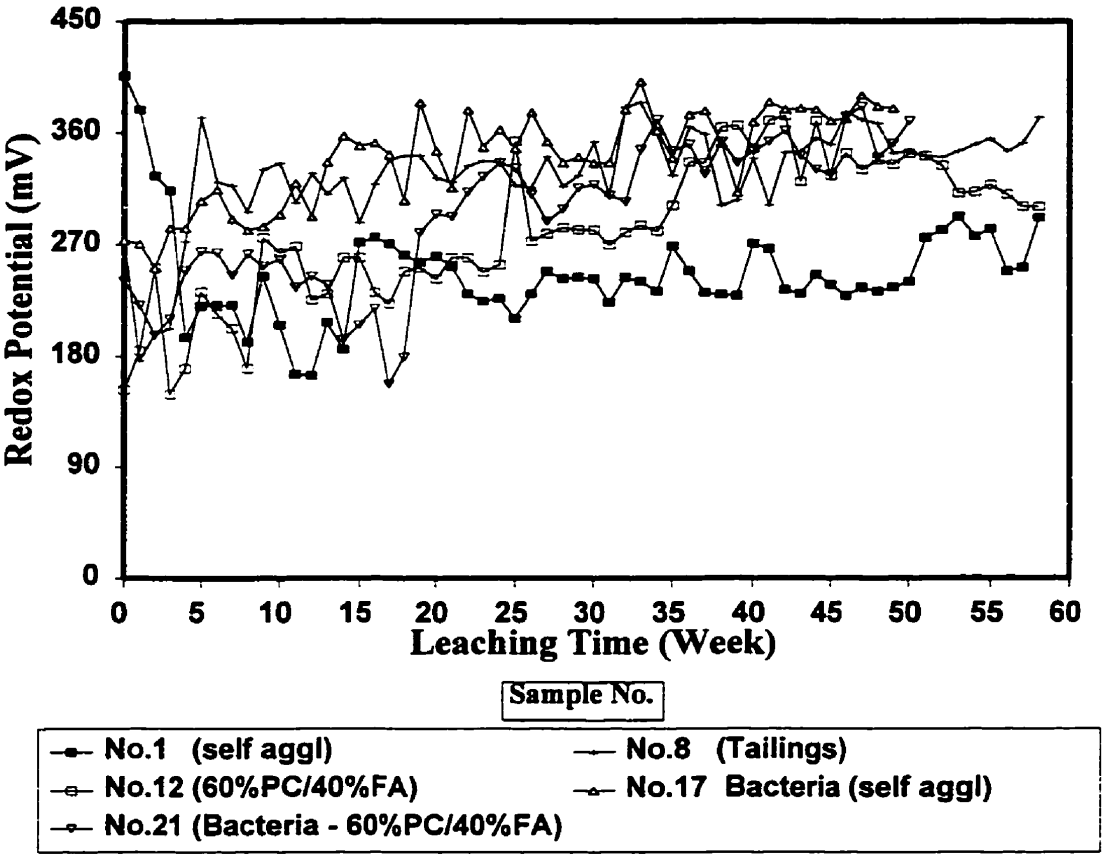


Figure 6.2 Redox Potential vs Leaching Time

The actual results from ICP analysis determination for control samples Nos. 1, 8 and 17 showed the presence of major and trace metals dissolved in the leachate solutions. This provided a clear evidence of the effect of acidity of leachates with pH less than 3.06 and on high Eh values as illustrated in Figure D7 (Appendix D).

The tendency of a mineral to oxidize depends on the voltage (Eh) of its environment, and oxidizing and reducing environments are characterized by the Eh [51]. Thus, with increasing the oxidation conditions the redox potential will also increase.

The oxidation of tailings was enhanced in the presence of *Thiobacillus ferrooxidans*. The acid tolerance of bacteria is usually pH 1.5 to 5.2 [11]. Under the acidic conditions and the in presence of *Thiobacillus*, the oxidation process of sulphide tailings increased and as a result a significant increase in Eh values was observed. This can clearly be seen for control sample No. 17 which was tested with addition of *Thiobacillus*.

The bacteria oxidize the ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) since it obtains its energy from the oxidation process of iron. The other treated samples showed very insignificant increase in Eh values. However, these values were higher than those experienced for samples which were not inoculated with *Thiobacillus*. Production of *Thiobacillus ferrooxidans* increases with a decrease in pH and the bacterial oxidation causes further pH decrease below pH 3.0.

6.7 Conductivity

Conductivity can be defined as the ability of a solution to pass electrical current. It can provide an indication of the amount of sulphate and heavy metals in the leachate. The inorganic ions such as nitrates, chlorides and sulphates along with some cations such as copper, sodium and calcium are the main species responsible for the conductivity levels in the leachate. As it can be seen from the graphs presented in Appendix F, the conductivity level shows an increasing trend for all samples during the early stage of the test period. The conductivity levels were highest for the tailings control samples No. 8 and self-agglomerated control sample with addition of *Thiobacillus* (sample No. 17) throughout the test period. The trend for the tailings sample No. 8 was increasing steadily until week nine but was followed by a rapid decrease reaching a value of 1400 micromhoms/cm in week 15. This was followed by a steady decrease to the end of the test period. However, the self-agglomerated control sample No. 1 had an increasing trend until week six, followed by a levelling off at 400 - 600 micromhoms/cm. This was followed by a slight increase in week 53 and reaching it's highest value of 900 micromhoms/cm in week 56. The significant fluctuations in the conductivity levels for the control samples are presented in Figure 6.3.

The increase in conductivity levels for the control samples was accompanied by a decrease in pH level, indicating a containing increase in acidity. The presence of the sulphate in the leachate can be related to the conductivity levels. Therefore, conductivity may be a good measure of sulphate production.

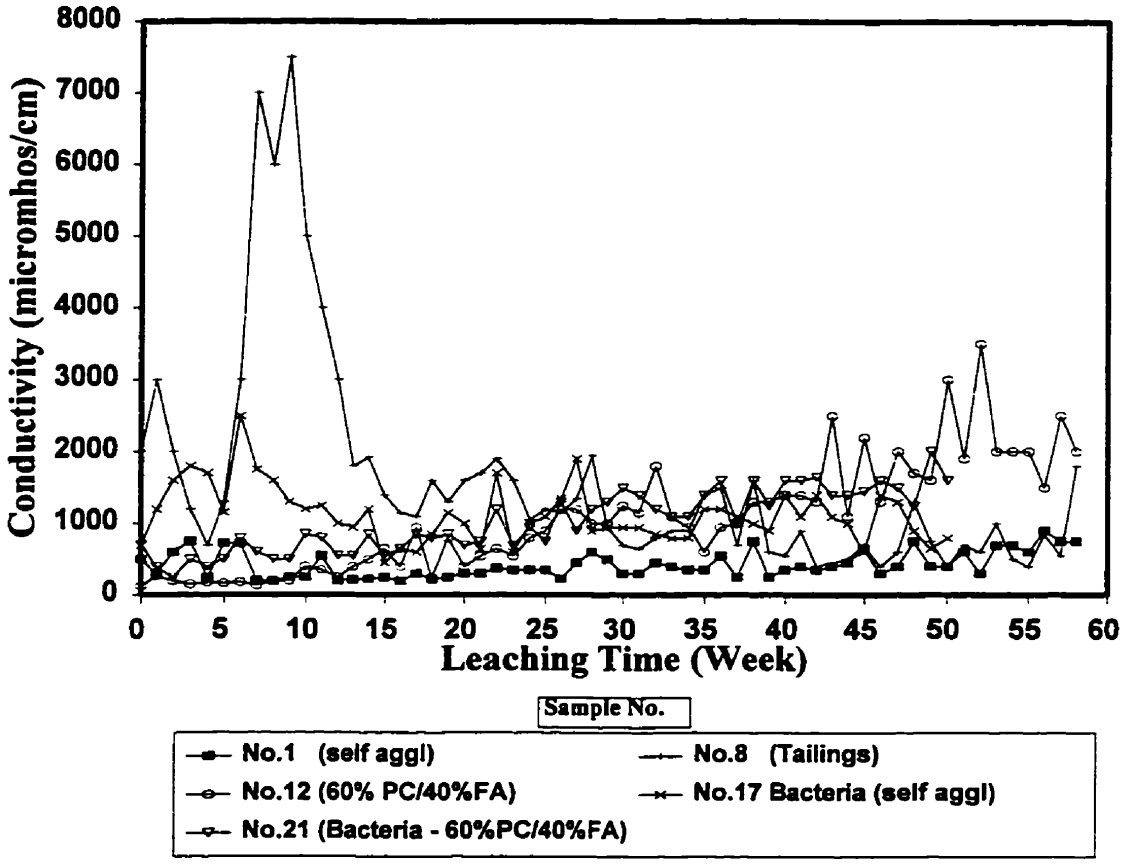


Figure 6.3 Conductivity vs Leaching Time

However, the presence of alkaline binders such as fly ash and cement, which are high in Ca^{2+}, Mg^{++}, $Al^{3+}$and the soluble Ca^{++}, can limit the (SO_4^{-2}) and (SO_4^{-2}) may reach a steady state. In this case, conductivity may still increase due to other ions such as Ca^{++}.

The graphs (Figure F1 and F5) showed periodic peaks which may be indication of the time pellets may have broken up, thereby releasing more metals in the leachate than usual. The conductivity level for all treated samples fluctuated and were in the range of 200 and 3000 micromhoms/cm for most of the test period. Sample Nos. 4, 5, 9, 10, 11, 13, 15, 18, and 20 showed a similar trend in which the level of conductivity was as high as 2000 and decreased to 150-200 micromhoms/cm by week 45. The conductivity level was the highest for sample No. 8 (tailings control sample) and lowest for sample No. 19 (SLS with addition of *Thiobacillus*) and sample No. 18 (0.5% Enviroseal with addition of *Thiobacillus*). The control sample No. 17 (self-agglomerated sample with addition of *Thiobacillus*) showed the second highest values of conductivity during the 50 - weeks period. The conductivity values kept decreasing and a levelling off for a short duration for samples Nos. 4, 5, 9, 10, 11, 14, 15, 18, 19 and 20.

6.8 Sulphate

The sulphate content in the leachate is another indicator of AMD production. The level of the sulphate leached during the test period of 50 weeks and 58 weeks showed an increasing trend for all samples (refer to Appendix G). The highest level of

sulphate was shown for sample No. 8 (tailings control sample) and the lowest values for sample No. 18 (0.5% Enviroseal with addition of *Thiobacillus*) and sample No. 19 (0.1% SLS with addition of *Thiobacillus*). The increase in the sulphate values for the control sample No. 8 and No. 17 was accompanied by a decrease in a pH level as shown in the graphs and tabulated data, (refer to Appendix D&G), indicating a continuous increase in the acidity. The sulphate level had a similar trend to the conductivity tests as discussed earlier. The results indicated the wide difference in the amount of sulphate leached from sample No. 8 (tailings control sample) and sample No. 17 (self-agglomerated sample with addition of *Thiobacillus*) as illustrated in Figures 6.4 and 6.5. The amount of sulphate produced as a result of the oxidation product of sulphides indicated similar trend to the conductivity levels during the duration of the test work. A large fluctuation during the start of the test was evident for most of the samples while it maintained a constant rate of production of sulphate for the rest of the time. The results from the graphs (Figures 6.4, and G1 to G6) and tabulated data indicated that considerably more sulphate and metals can be produced. The majority of samples showed increased release of sulphate from pellets while keeping a neutral pH level. The increase in the sulphate level was accompanied by fluctuation in the amount of metals released. Sample No. 3 (0.3% Enviroseal sample) and sample No. 12 (60%PC/40%FA) produced a high amount of sulphate on a cumulative basis due to the breakage of some of the pellets in the early stage of the test period (refer to Appendix G).

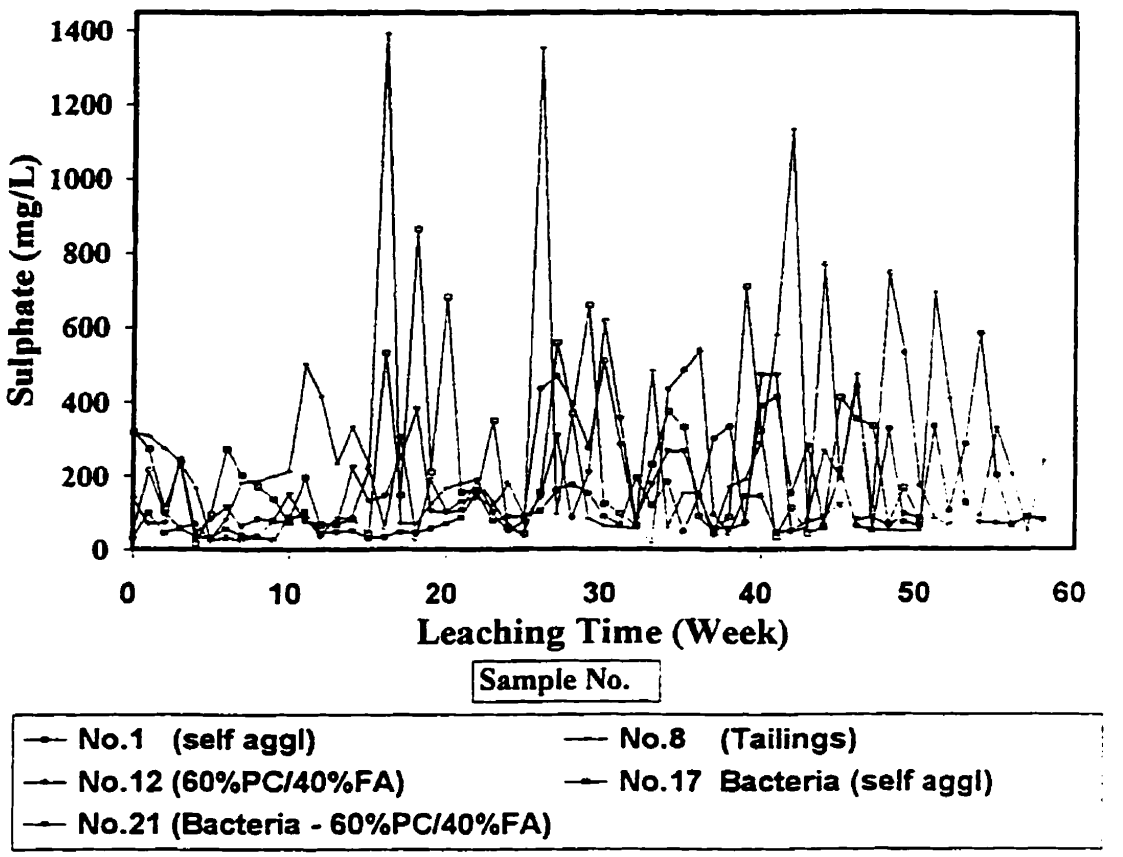


Figure 6.4 Sulphate (mg/L) vs Leaching Time (week)

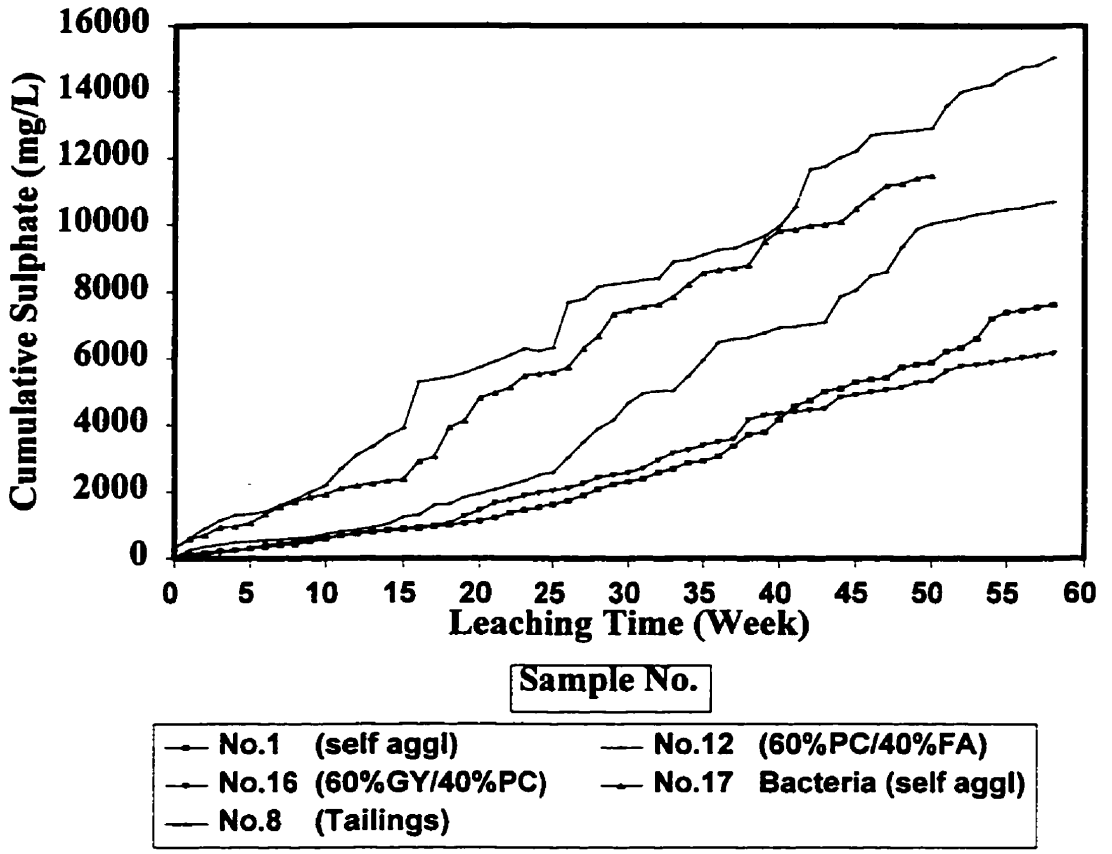


Figure 6.5. Cumulative Sulphate vs Leaching Time

As it can be seen from the tabulated data (refer to Appendix C), the increase in magnesium (Mg^{2+}) and calcium ions (Ca^{2+}) in the leachate resulted in an increase in the solubility of sulphate. As expected, the high concentration of calcium and magnesium released in the leachate for the treated samples were very likely due to their presence in fly ash and cement. Sample No. 8 (tailings control sample) showed high initial values of sulphate during the first 16 weeks due to the release of the oxidation product prior to test period. The sulphate concentration fluctuated significantly for all samples until the end of the test period. The amount of sulphate leached throughout the duration of the test work proceeded slowly and then increased rapidly with respect to time for most of the treated samples (refer to Appendix G).

6.9 ACIDITY

The increased acidity as measured in mg/L is an indication of acid generation. The acidity results showed some fluctuation periodically during the test for most of the samples. An increase in acidity was indicated as a result of increase in the sulphate level for the control tailings sample No. 8. This increase in the sulphate value was accompanied by a decrease in the pH level as shown in the tabulated data and graphs presented in Appendix D and G. This trend can be clearly seen for the control sample No. 1 in week 53 and 54, respectively. An increase in the redox potential and the level of conductivity was observed in the same period. Sample No. 2 (0.1% Enviroseal) showed higher values of acidity than the control sample No. 1 due to the breakage of some pellets during the early stage of the test period. Sample No. 3 (0.3% Enviroseal)

indicated higher values of acidity based on the cumulative basis than the remaining samples including the control samples. This can be best explained by the breakage of some pellets during the first six weeks of testing. The high acidity was accompanied by high sulphate concentration, redox potential and conductivity level. Sample No. 4 (0.5% Enviroseal) showed the lowest values of acidity (<1) among the Enviroseal samples. A similar trend was observed for sample No. 18 (0.5% Enviroseal with addition of *Thiobacillus*). Sample No. 5 (0.1% SLS), No. 6 (0.3% SLS) and No. 7 (0.5% SLS) underwent a change in pH value in the first 8 weeks and as a result the acidity values increased as expected. By comparison, the results for untreated samples No. 1 (self-agglomerated sample), No. 8 (tailings control sample) and No. 17, self-agglomerated with addition of *Thiobacillus*), indicated that significant oxidation had occurred by the end of the test period. The tailings control sample No. 8 showed an increasing trend in the first 9 weeks followed by a fluctuation to the end of the test period. The acidity values were the highest for sample No. 3 (0.3% Enviroseal) and lowest for sample No. 19 (0.1% SLS with addition of *Thiobacillus*) and sample No. 18 (0.5% Enviroseal with addition of *Thiobacillus).* The tailings control sample No. 8 showed the second highest values of acidity during the test period. The control sample No. 17 with the addition of *Thiobacillus* also showed high values of acidity during the duration of the experiment.

The acidity results for the control samples are illustrated in Figures No. 6.6 and 6.7. On the weekly observations, pellet breakage for sample No. 3 (0.3% Enviroseal) was observed during the early stage of the test period.

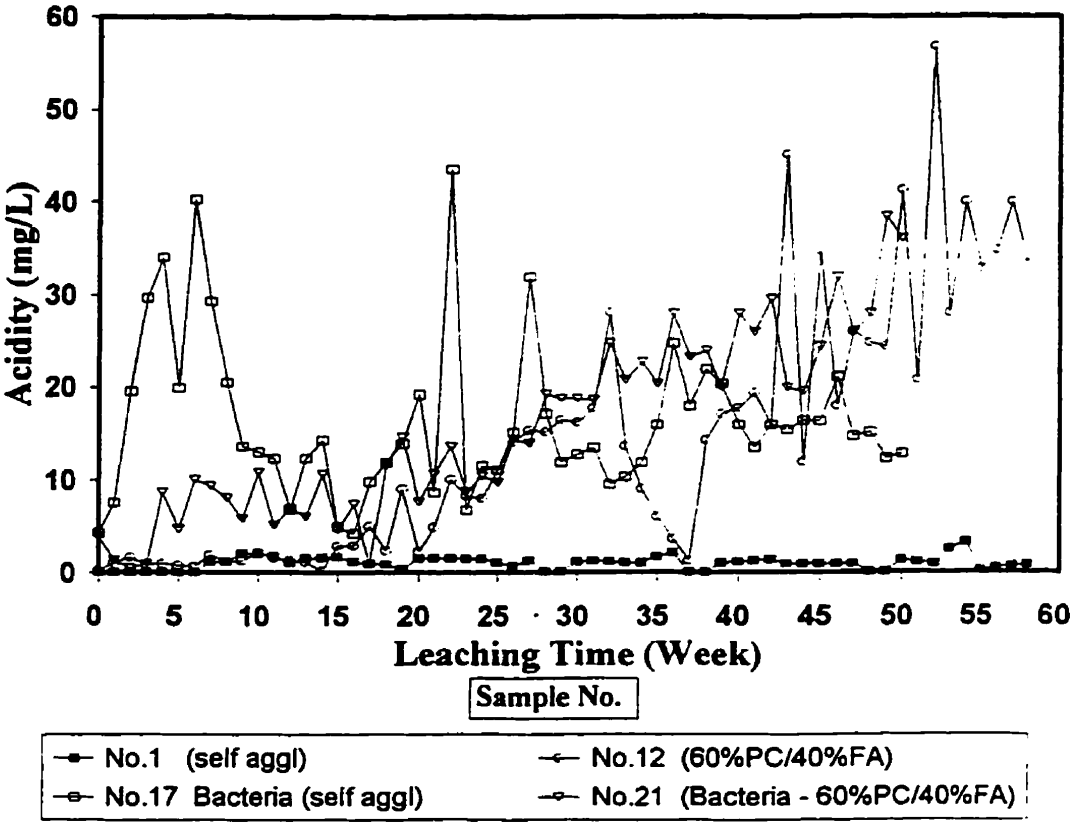


Figure 6.6 Acidity (mg/L) vs Leaching Time (week)

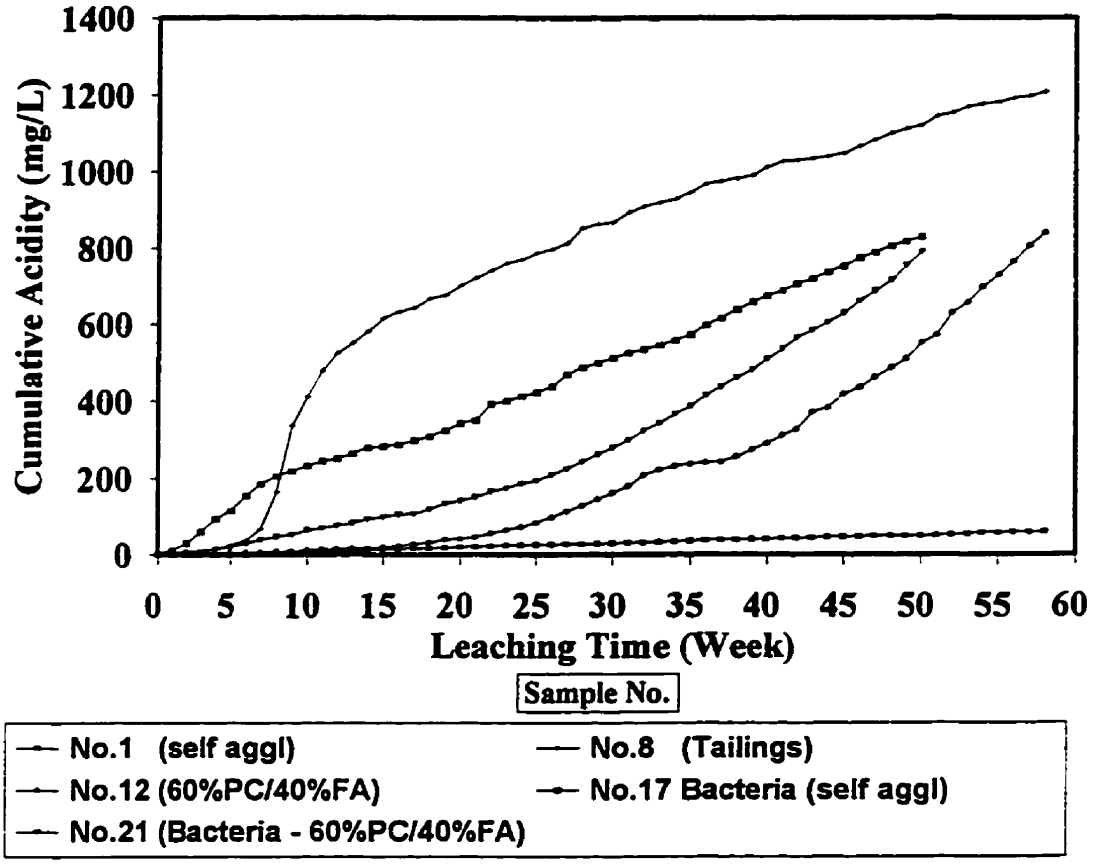


Figure 6.7 Cumulative Acidity (mg/L) vs Leaching Time (Week)

A similar observation was evident for sample No. 12 and sample No. 22, where 90% of pellets had disintegrated in the first 40 weeks. However, the pH values of these samples dropped shortly after the breakage had occurred and then maintained close to neural pH. The remainder of the acidity results are presented in Appendix H.

6.10 Metals Production in the Leachate

As expected, untreated samples would release metals in the leachate when exposed to air and water. The amount of metals released from sample No. 8 (tailings control sample) was the highest among all samples. The amount of iron released for sample No. 8 increased in the initial period and started to decrease. A maximum value of 3481 mg/L was reached in week 8 and then started to fluctuate until the end of the experiment. The nickel concentration of the leachate for sample No. 8 fluctuated and peaked at 462 mg/L. Similar trends were observed for the amount of calcium, magnesium, copper and sulphur released for the control sample No. 8. The self-agglomerated control sample No. 1 showed insignificant concentration of metals in the first 50 weeks of the test period. However, an increase took place for iron concentration in week 54 reaching a peak value of 235 mg/L. The amount of iron, nickel, copper, calcium and sulphur leached for samples No. 1 varied significantly, showing higher values at the end of the test work. This can be seen for the control samples in Figures No. 6.8, and 6.9 which show the amount of iron and nickel released during the test period.

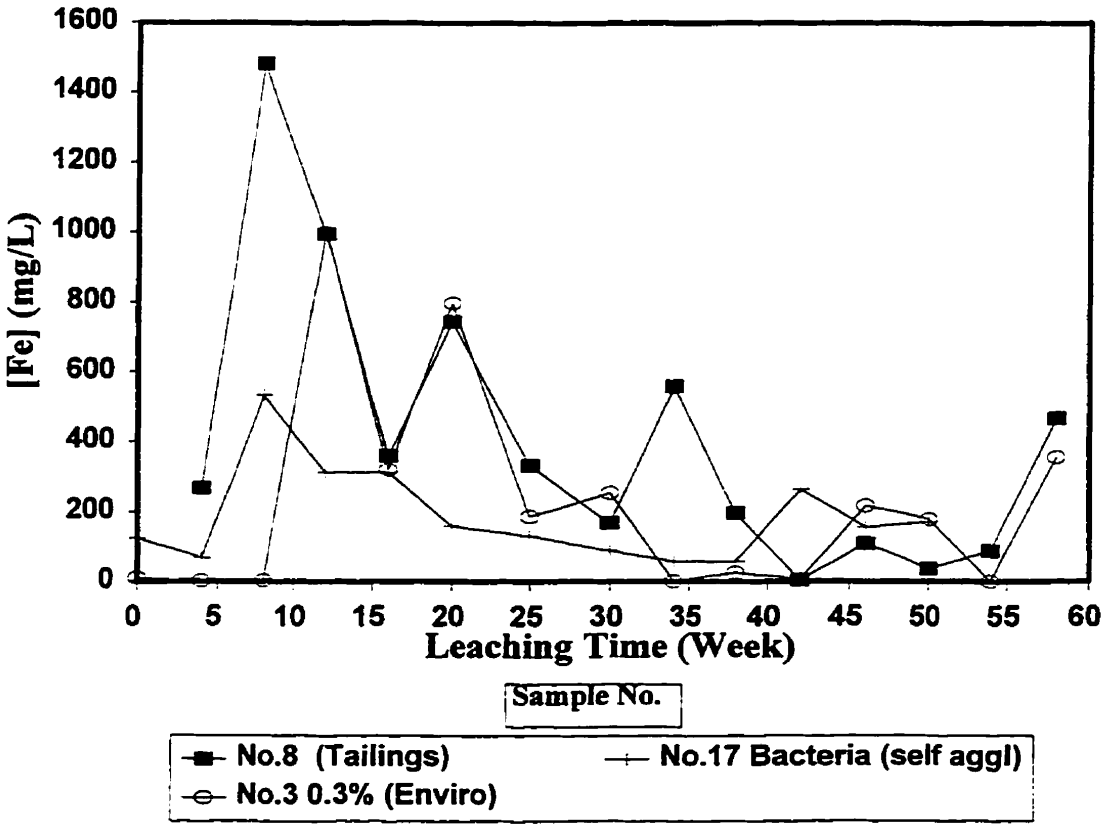


Figure 6.8 Leachate [Fe] (mg/L) vs Leaching Time (week)

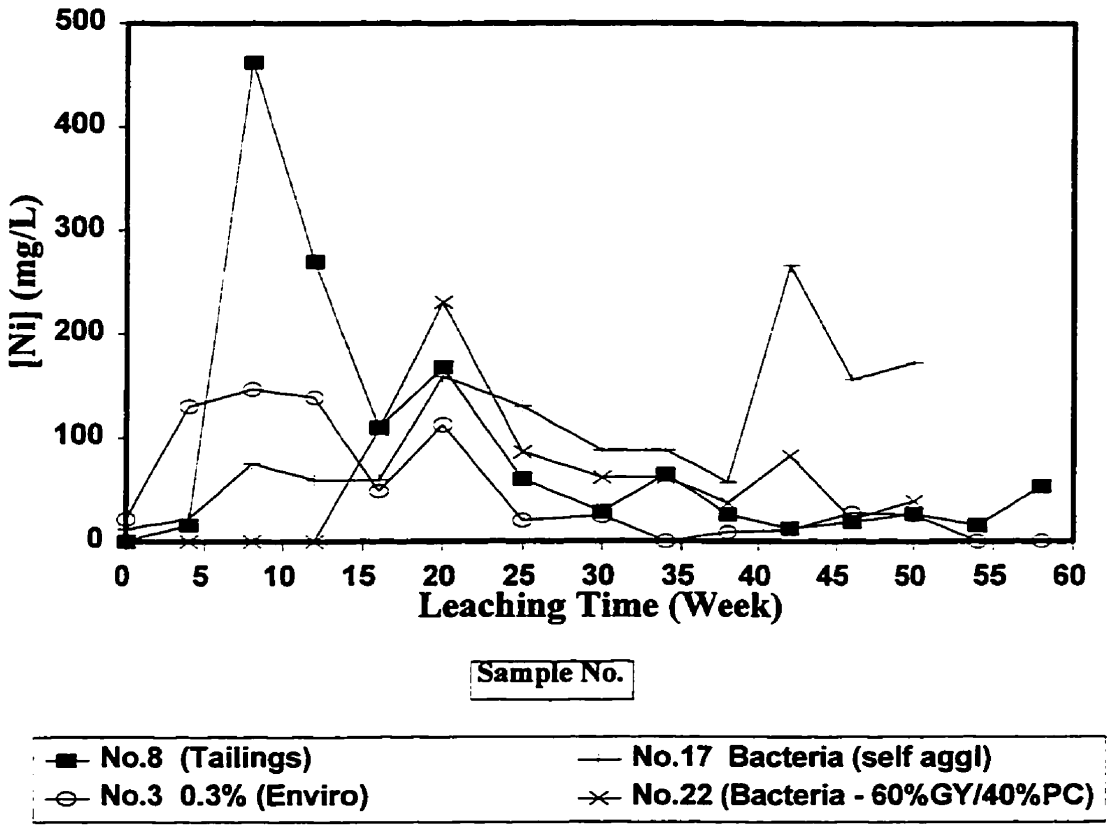


Figure 6.9 Leachate [Ni] (mg/L) vs Leaching Time (week)

With the exception of the leachate from the control samples Nos. 8, No. 17, and the Enviroseal 0.3% which had various amounts of iron and nickel in the first 55 weeks, all remaining samples showed insignificant concentration of trace metals due to the effect of binders and additives of these samples. This can be clearly seen in Figure 6.6 and from graphs presented Appendix I. The amount of calcium leached for all treated samples varied significantly due to the presence of calcium in the binder.

6.10 SEM EXAMINATION

An examination by the Scanning Electron Microscopic (SEM) of the agglomerated pyrrhotite compared to the unagglomerated (tailings) revealed more oxidation on the surface of the tailings sample (No. 8) than other pelletized samples. SEM analysis revealed major physical change in the pyrrhotite grains which tended to associate with shreds of the gangue minerals.

The nickel concentrations generated by humidity cell, control sample (No. 17) with addition of *Thiobacillus*, increased near the end of the test period. This increase was accompanied by increased total sulphur and iron relative to other samples. A trend of higher nickel concentration (>20 ppm) accompanied by higher sulphur and iron level was apparent for all control samples, sample No. 1, sample No. 8 and sample No. 17. A limited nickel quantity for the remaining samples may be due to the presence of an impermeable oxide layer on the surface of the agglomerated samples. Nickel appeared as the highest concentration during the first few months. The SEM images for the control samples Nos. 1 and 8 are presented in Figure 6.10 and 6.11.

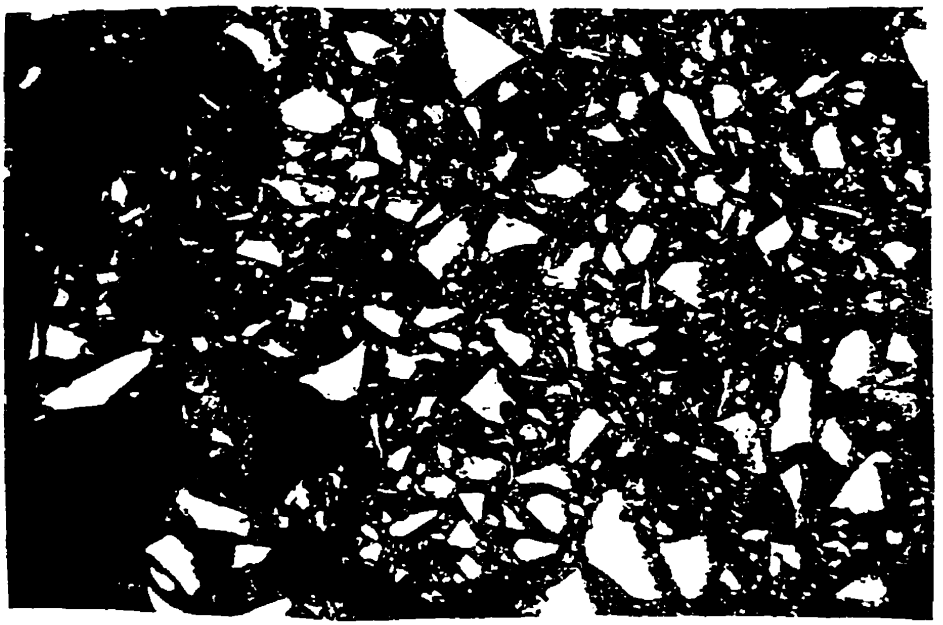


Figure 6.10 Detailed micrograph of sample No. 1 (self-agglomerated) before leaching, showing angular shards of pyrrhotite, 20 X mag., field view of 0.62 mm.

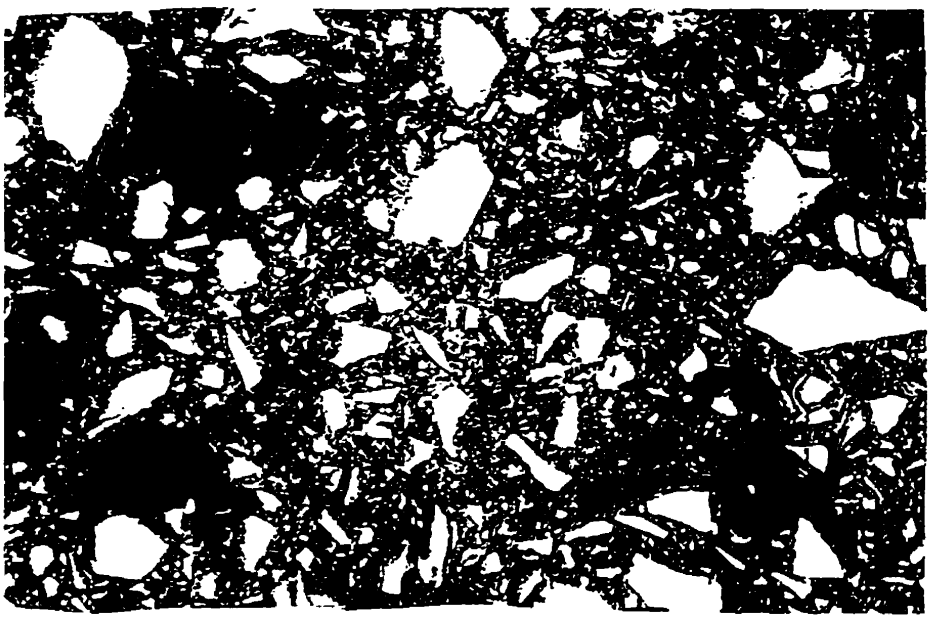


Figure 6.11 Micrograph of sample No. 8 (tailings) showing irregular shaped magnetite grain with pyrrhotite, before leaching, 20 X mag., field of view 0.62 mm.

From the image analysis of the leached agglomerate, the presence of iron oxide layer was evident for all control samples. Using SEM analysis, the stability characteristics , the physical morphological changes of the agglomerates were compared (i) before the accelerated weathering, (ii) during the leaching tests, and (iii) at the end of the test period. The image analyses of cured agglomerates and surface morphology as revealed by both Back Scattered Electrons (BSE) and Secondary Electron images for all samples are presented in Appendix J.

The secondary electron microphotograph of the samples were accompanied by quantitative analysis and chemical compositions (i) before leaching, (ii) after 20 weeks of testing, and (iii) at the end of the test period. The secondary electron image of the interior oxidation of the outside layer of oxidized pellet of control sample No. 17 showed clear oxidation layers of the agglomerates. This was clearly evident through the analysis of the chemical composition of the pellets in week 50 of the test. The chemical analysis showed higher iron concentration with high total sulphur and nickel (refer to Appendix K). This trend was also observed for the oxidation of the first layer of a broken pellet of the same sample using BSE. However, less oxidation was observed on the surface of the pellets for sample Nos. 18, 19, 20, and 21, which can be attributed to by the presence of binders and additives. The scanning electron micrograph of sample No. 1 before leaching showed long-thread shaped grains which become longer after 20 weeks of testing. The image analysis of sample No. 4 revealed dark material (fly ash) with some gangue minerals (Silica) due to the presence of fly ash and cement binders. It showed more silica, sodium and aluminum than the control

sample No. 1 (self-agglomerated). Sample No. 5 (0.1% SLS), showed pyrrhotite was not as clear as on the control samples. It also revealed that fly ash and cement were not as clear and in lesser amounts. The structure showed mostly dark material (fly ash and cement) and some pyrrhotite. This was confirmed by the chemical composition results in which the presence of high calcium and silica were evident. Sample No. 10 (sodium silicate) did not show any physical changes to pellets before leaching and after 20 weeks of weathering. Sample No. 12 revealed only fly ash, cement and some pyrrhotite around the edges. Sample No. 15 and Sample No. 16 showed less physical change than other samples after 20 weeks of testing. Furthermore, these samples showed less iron and silica according to the chemical analysis. However, sample No. 16 showed higher nickel concentration than sample No. 15 during the first 20 weeks of testing. The image analyses of the self-agglomerated sample (No.17) with addition of *Thiobacillus* showed pyrrhotite (light smooth areas) at various stages of alteration to sulphur bearing hydroxides (dark with rough surface). As can be seen from the images, (Appendix J), pyrrhotite grains after extensive weathering and leaching were still intact. A protective crust was formed under the external leaching zones of the agglomerates for all the Enviroseal samples (No. 4 and sample No. 18). However, sample No. 3 (0.3% Enviroseal) pellets broke before the 20 weeks of testing and this may be due to the weak bonding developed during the agglomeration process. The chemical analysis for the final weeks of the test for all samples support the results of the oxidation process that was revealed by SEM analysis.

CHAPTER SEVEN

7.0 CONCLUSIONS

The conclusions of this laboratory program work can be summarized as follows:

(1). An optimum pellet, is based upon meeting the combined criteria of binder dosage and composition, curing period, pellet diameter, low consumption of cement, and primarily acceptable strength. The optimum pellet was designated as a 12.7 mm diameter pellet formed by a total binder dosage of 5% comprising a 60:40 ratio of portland cement and fly ash.

(2). In general, "green" pellets showed sufficient strength while high strength was achieved economically using portland cement and fly ash as binders instead of cement only.

(3). The specially constructed humidity for agglomerates cell was proven to be very effective in studying the cold-bond agglomeration process and the weathering process of the encapsulated pellets.

(4). Considering both the economical and technical properties of the sealants tested, "Enviroseal" appears to be the most effective surfactant in preventing the AMD process. Enviroseal also produced a stable pH level in neutral range.

(5). Although not as effective as Enviroseal, sodium silicate shows some promise as an alternative leachate retardant to reduce acid generation. Unfortunately, one adverse effect of the sodium silicate was that higher quantities of calcium, magnesium and sulphur reported to the leachate.

(6). The addition of sodium lauryl sulphate (SLS) was effective in preventing AMD process, however it reduced the strength of pellets and eventually led to the breakage of some pellets after 30 weeks of testing.

(7). The addition of *Thiobacillus ferrooxidans* bacterium to the pellets prior the weathering test resulted in a decrease of the cured strength of pellets. The bacterium affected the sulphidic grain structure and impacted upon the resistance of the pellet to leaching.

(8). The production of acidity is accompanied by high positively correlated relationship between conductivity and sulphate concentration of the leachate indicating the oxidation process of agglomerates and consequently the leachate has become more acidic.

(9). The samples with the lowest rate of sulphate yielded leachate with consistently neutral pH and samples with highest rates yielded the lowest acidic pH.

(10). The SEM analysis showed that agglomerates are highly resistant to weathering due to the presence of binders and chemical additives.

(11). The effect of pH measurement as an indicator of AMD generation was very effective as predicted, in which the tailings sample and agglomerated sample in presence of *Thiobacillus ferrooxidans* tend to produce AMD at low pH.

(12). The redox potential (Eh) graphical correlation indicated an inverse relationship with respect to pH levels, ($Eh \propto 1/pH$).

(13). The increase in acidity (mg/L) showed a good correlation with the continuous increase in soluble metals such as (Fe, Ni, and Cu) concentration of the leachate.

14). It is possible to use reactive tailings pellets stabilized with Enviroseal and sodium silicate as aggregate component of a backfill to prevent AMD generation. The research project may have found the answer for the most important question for Laurentian University Tailings Agglomeration Research Group. In comparison with the findings for reactive tailings pellets exposed to surface weathering, the chances of AMD generation from normal low sulphur tailings backfill are extremely remote in underground backfill environment.

CHAPTER EIGHT

RECOMMENDATIONS

The results of the laboratory work indicated that the following areas should be investigated in further research:

(1). It is strongly believed that Enviroseal may have initially been used as a binder in lieu of the cement/fly ash mixture. However, time constraints prevented examination of this alternative. Enviroseal, at modest addition rates, likely would have provided both "green" and cured pellet strength either at par or superior to that experienced during the test work described herein.

(2). Examine other binders and additives using the present method of CBTA which would retain a positive characteristics attributed to the study of AMD generation.

(3). Further study the structure of weathered pellets and the impermeability of the pyrrhotite surface developed in particular of the control sample due to the precipitation of iron oxide as a result of oxidation of iron sulphide minerals (particularly pyrrhotite).

(4). Study and develop a numerical model such as the shrinking-core oxidation mode to simulate the diffusion of oxygen into the encapsulated pellets.

(5). Examine the pellet strength and resistance to acid generation in relation to particle size of the tailings material which is agglomerated and determine the net neutralizing potential of agglomerates produced.

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APPENDIX (A)

Effect of Curing Period on 12.7 mm and 19 mm Pellets at Total Binder of 3%, 5% and 7 % (Tabular Form)

Table A1. Fracture Load (N/P) Results for 12.7 mm Pellets & Total Binder of 3%

Binder Composition PC (%)	Curing Period (Day)				
	1	3	7	14	28
0	40	44	62	96	116
20	52	80	53	42	114
40	98	93	94	96	103
60	81	105	99	123	137
80	98	100	129	136	189
100	80	84	123	141	189

Table A2. Fracture Load (N/P) Results for 19 mm Pellet & Total Binder of 3%

Binder Composition PC (%)	Curing Period (Day)				
	1	3	7	14	28
0	52	58	84	85	129
20	97	124	48	44	72
40	107	114	98	70	80
60	85	106	116	70	95
80	95	96	98	79	98
100	105	120	108	200	189

Table A3. Fracture Load (N/P) Results for 12.7 mm Pellet & Total Binder of 5%

Binder Composition PC (%)	Curing Period (Day)				
	1	3	7	14	28
0	60	64	72	108	115
20	94	82	79	75	96
40	100	107	112	95	90
60	131	224	392	266	269
80	135	260	298	337	383
100	145	352	440	495	490

Table A4. Fracture Load (N/P) Results for 19 mm Pellet & Total Binder of 5%

Binder Composition PC (%)	Curing Period (Day)				
	1	3	7	14	28
0	65	80	93	123	130
20	82	91	88	81	84
40	98	118	154	86	77
60	134	234	293	283	245
80	145	352	440	495	490
100	139	351	582	-	-

Table A5. Fracture Load (N/P) Results for 12.7 mm Pellet & Total Binder of 7%

Binder Composition PC (%)	Curing Period (Day)				
	1	3	7	14	28
0	81	115	98	135	181
20	152	151	205	228	184
40	109	162	210	216	252
60	218	308	392	457	511
80	100	104	107	258	293
100	122	452	606	483	544

Table A6. Fracture Load (N/P) Results for 19 mm Pellet & Total Binder of 7%

Binder Composition PC (%)	Curing Period (Day)				
	1	3	7	14	28
0	235	472	742	-	-
20	120	157	219	334	-
40	114	177	201	220	182
60	279	501	692	676	854
80	160	250	466	708	853
100	136	472	742	874	1301

APPENDIX (B)

Effect of Curing Period on 12.7 mm and 19 mm Pellets at Total Binder of 3%, 5% and 7% (Graphic Form)

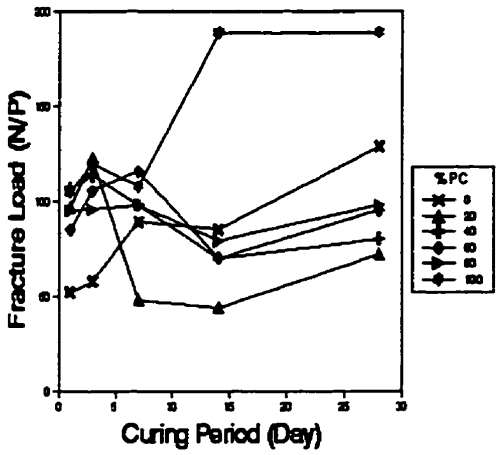


Figure B1. Effect of Curing Period on 19 mm Pellet at Total Binder of 3%

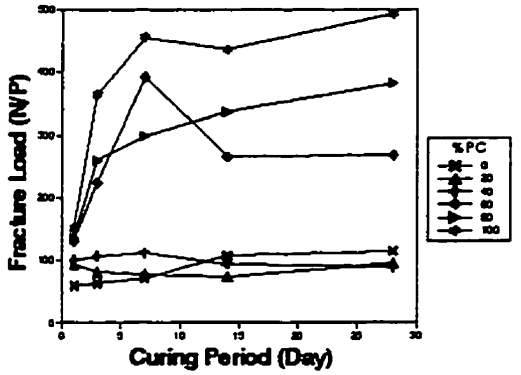


Figure B2. Effect of Curing Period on 12.7 mm Pellet at Total Binder of 5%

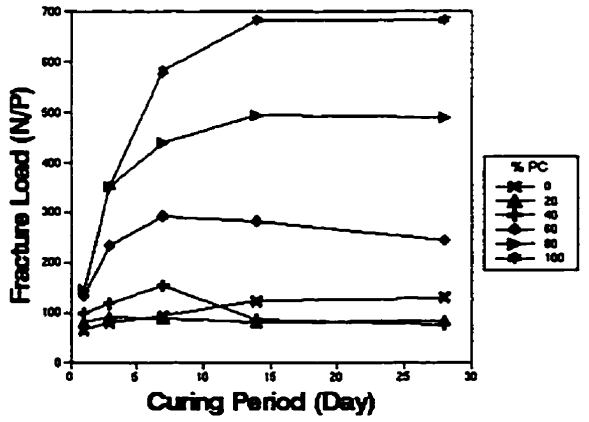


Figure B3. Effect of Curing Period on 19 mm Pellet at Total Binder of 5%

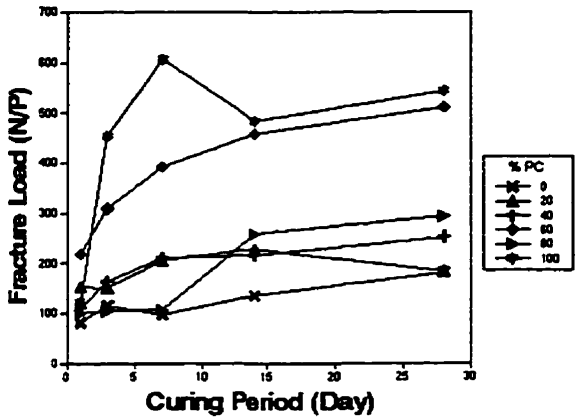


Figure B4. Effect of Curing period on 12.7 mm pellet at Total Binder 7%

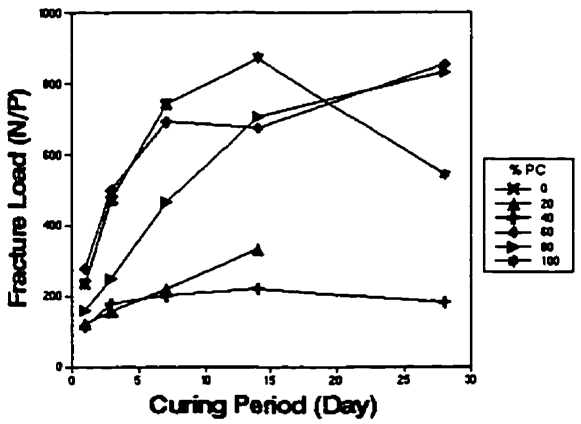


Figure B5. Effect of Curing Period on 19 mm Pellet at Total Binder 7%

APPENDIX (C)

Results of the Factors Effecting the Generation of AMD

Table 6.2 0.1% ENVIROSEAL (ENVIRO)
Sample No.2
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidit mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.69	330	200	114	114	0.1	0.1	_	0.01	33.76	0.42	0.02	_
1	7.13	318	100	304	418	0.1	0.2						
2	7.1	312	800	249	667	0.1	0.3						
3	7.05	320	900	268	935	0.1	0.4						
4	6.65	220	225	242	1177	0.2	0.6	0.02	0.01	16.63	0.79	0.09	31.62
5	7.19	154	140	22	1199	0.3	0.9						
6	7.15	224	150	42	1241	0.6	1.5						
7	7.11	229	160	24	1265	1.2	2.7						
8	7.15	170	200	25	1290	1.2	3.9	0.03	0.01	21.15	1.48	0.05	49.4
9	7.25	238	200	68	1358	2.6	6.5						
10	7.2	240	250	77	1435	2.4	8.9						
11	7.37	166	350	81	1516	2.4	11.3						
12	7.15	164	250	36	1552	1.2	12.5	0.334	0.05	23.5	2.9	0.102	81.2
13	6.8	198	225	78	1630	2.3	14.8						
14	6.4	166	350	79	1709	2.3	17.1						
15	7.24	228	400	124	1833	2.8	19.9						
16	7.37	312	425	123	1956	2.7	22.6	0.315	0.064	22.7	1.4	0.301	138
17	6.97	240	500	136	2092	2.5	25.1						
18	7.07	248	450	74	2166	1.5	26.6						
19	7.09	244	600	157	2323	2.0	28.6						
20	6.93	248	900	71	2394	4.1	32.7	0.091	0.086	132	15.7	0.301	334
21	6.96	244	700	244	2638	3.9	36.6						
22	7.02	230	600	123	2761	3.8	40.4						
23	7.01	211	625	220	2981	3.5	43.9						
24	6.89	210	550	153	3134	1.6	45.5						
25	7.17	201	625	215	3349	2.0	47.5	0.242	0.124	67.5	7.18	0.136	121.9
26	6.96	220	450	126	3475	1.8	49.3						
27	7.04	241	650	238	3713	2.9	52.2						
28	7.02	227	750	231	3944	5.5	57.7						
29	7.06	233	650	210	4154	3.2	60.9						
30	7.05	232	500	160	4314	2.7	63.6	0.123	0.179	85.39	8.45	0.11	133.9
31	6.97	215	500	177	4491	2.9	66.5						
32	6.91	243	600	255	4746	3.1	69.6						
33	6.9	235	350	242	4988	1.3	70.9						
34	6.88	225	550	172	5160	2.0	72.9	0.457	0.151	67.4	9.21	0.235	245.6
35	6.85	230	450	82	5242	3.6	76.5						
36	6.83	254	800	276	5518	4.7	81.2						
37	6.81	218	400	119	5637	1.6	82.8						
38	6.86	240	800	291	5928	4.9	87.7	0.421	1.36	78.79	6.26	0.044	121
39	6.82	246	450	142	6070	1.2	88.9						
40	6.82	248	400	505	6575	1.5	90.4						
41	6.84	247	550	206	6781	1.7	92.1						
42	6.86	192	460	149	6930	2.3	94.4	0.697	1.84	71.81	5.48	0.054	104
43	6.53	230	450	581	7511	3.1	97.5						
44	6.56	228	850	233	7744	3.5	101.0						
45	6.51	235	1050	230	7974	4.0	105.0						
46	6.18	240	600	207	8181	4.9	109.9	0.401	5.01	113.4	8.52	0.068	181
47	6.21	199	600	71	8252	6.7	116.6						
48	6.38	269	1050	114	8366	10.2	126.8						
49	6.34	253	500	45	8411	3.7	130.5						
50	6.28	253	750	61	8472	4.9	135.4	13.2	14.2	194.1	15.9	0.073	376
51	5.98	260	1050	723	9195	4.2	139.6						
52	5.97	272	900	327	9522	3.4	143.0						
53	5.92	271	400	116	9638	3.2	146.2						
54	5.72	269	950	250	9888	7.3	153.5	0.019	0.083	77.91	5.44	0.011	70.7
55	5.66	273	650	307	10195	5.3	158.8						
56	5.66	229	1300	599	10794	14.4	173.2						
57	4.45	281	1200	351	11145	4.3	177.5						
58	3.7	292	1300	346	11491	3.9	181.4	67.7	45.8	157.6	39.6	0.243	436

Table 6.3 0.3% ENVIROSEAL (Enviro)
Sample No.3
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	4.14	560	650	307	307	0.3	0.3	10.96	21.71	61.85	5.52	0.03	155.6
1	3.69	350	2000	69	376	2.3	2.6						
2	3.78	325	3000	66	442	4.3	6.9						
3	3.66	365	6500	66	508	8.3	15.2						
4	3.46	347	4500	60	568	16.3	31.5	1.64	129.9	26.53	19.91	0.37	864.1
5	3.52	345	3250	69	637	32.4	63.9						
6	3.64	305	2500	111	748	64.4	128.3						
7	3.54	315	2275	69	817	142.8	271.1						
8	3.77	266	3500	85	902	152.0	423.1	2.51	146.6	26.71	29.18		1123
9	3.85	278	3250	1442	2344	112.0	535.1						
10	3.71	293	2500	929	3273	40.0	575.1						
11	3.67	262	2250	212	3485	44.0	619.1						
12	3.67	272	2500	358	3843	18.3	637.4	1000	139	20.1	13.3	0.172	771
13	3.7	273	2250	361	4204	36.0	673.4						
14	3.64	267	2000	247	4451	34.5	707.9						
15	3.67	315	1800	171	4622	30.0	737.9						
16	3.59	315	1100	171	4793	20.0	757.9	322	49.3	23.3	3.75	0.125	311
17	3.66	333	900	429	5222	9.2	767.1						
18	3.75	325	1650	176	5398	31.4	798.5						
19	3.68	295	900	74	5472	8.9	807.4						
20	3.72	295	1600	249	5721	31.2	838.6	797	113	9.21	35.1	0.071	604
21	3.68	290	700	74	5795	23.6	862.2						
22	3.69	292	725	46	5841	19.1	881.3						
23	3.62	350	1450	44	5885	11.2	892.5						
24	3.69	312	800	38	5923	8.5	901.0						
25	3.8	287	1600	205	6128	70.8	971.8	186.4	20.7	24.87	2.52	0.068	146.3
26	3.63	290	800	63	6191	6.3	978.1						
27	3.75	290	1600	162	6353	24.8	1002.9						
28	3.92	275	1550	251	6604	24.0	1026.9						
29	3.49	306	800	72	6676	7.9	1034.8						
30	3.72	272	800	53	6729	9.5	1044.3	254	24.6	14.9	2.8	0.037	175
31	3.62	336	750	59	6788	6.3	1050.6						
32	3.66	359	550	46	6834	4.6	1055.2						
33	3.47	326	1400	226	7060	25.5	1080.7						
34	3.51	330	900	94	7154	11.3	1092.0	0.137	0.062	169.3	3.75	0.036	166.2
35	3.5	329	1600	164	7318	23.5	1115.5						
36	3.98	344	1250	56	7374	18.9	1134.4						
37	3.92	366	400	166	7540	9.0	1143.4						
38	3.8	360	1800	258	7798	30.1	1173.5	24.8	9.09	12.86	1.26	0.032	85.8
39	4.16	317	800	201	7999	12.3	1185.8						
40	4.16	324	900	133	8132	10.6	1196.4						
41	4.17	321	1200	665	8797	10.1	1206.5						
42	3.78	345	500	190	8987	9.0	1215.5	7.3	11.1	22.13	1.52	0.032	88.1
43	3.77	336	550	662	9649	10.0	1225.5						
44	3.75	340	850	340	9989	8.0	1233.5						
45	4.06	350	400	112	10101	11.3	1244.8						
46	3.69	367	800	150	10251	23.5	1268.3	217	27.6	16.28	3.35	0.038	256
47	3.67	313	1100	45	10296	27.5	1295.8						
48	3.68	338	2000	134	10430	10.2	1306.0						
49	3.8	325	600	78	10508	6.4	1312.4						
50	3.77	322	700	332	10840	3.4	1315.8	179	25.9	16.94	3.27	0.043	228
51	3.79	320	1100	264	11104	6.9	1322.7						
52	3.58	325	550	77	11181	10.8	1333.5						
53	4.12	305	1200	316	11497	24.0	1357.5						
54	3.72	312	900	535	12032	10.4	1367.9	0.058	0.064	135.4	6.58	0.018	114
55	3.41	327	350	302	12334	4.8	1372.7						
56	4.17	330	700	48	12382	8.8	1381.5						
57	3.57	331	1000	201	12583	8.8	1390.3						
58	4.13	319	1400	366	12949	10.4	1400.7	357	0.649	11.09	3.02	0.085	245

Table 6.4 0.5% ENVIROSEAL (Enviro)
Sample No.4
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.35	196	115	249	249	0.1	0.1	_	0.04	18.07	0.31	0.05	13.32
1	6.9	200	250	101	350	0.4	0.5						
2	6.85	360	600	91	441	0.8	1.3						
3	6.79	362	650	81	522	0.6	1.9						
4	6.67	262	300	61	583	0.4	2.3	0.41	0.06	13.35	0.18	0.14	16.42
5	6.96	245	110	21	604	0.3	2.6						
6	6.96	272	150	36	640	0.6	3.2						
7	6.85	221	120	23	663	1.0	4.2						
8	6.91	167	100	22	685	0.8	5.0	0.74	0.08	11.71	0.56	0.05	24.5
9	7.29	134	130	21	706	0.9	5.9						
10	7.2	203	250	52	758	1.4	7.3						
11	6.76	144	200	33	791	0.7	8.0						
12	6.77	158	160	24	815	0.7	8.7	0.557	0.096	14.3	1.15	0.079	38.9
13	6.21	218	165	27	842	0.7	9.4						
14	6.3	214	185	34	876	0.1	9.5						
15	6.68	224	200	33	909	1.4	10.9						
16	6.75	281	175	48	957	1.1	12.0	0.257	0.062	19.9	0.995	0.077	41.7
17	6.94	246	300	61	1018	1.0	13.0						
18	7.05	267	350	75	1093	0.7	13.7						
19	6.75	243	250	51	1144	0.7	14.4						
20	6.95	240	300	78	1222	1.2	15.6	0.195	0.042	126	6.18	0.099	69.5
21	7.15	235	400	184	1406	1.1	16.7						
22	7.27	245	800	298	1704	1.0	17.7						
23	6.52	297	350	78	1782	0.7	18.4						
24	6.99	212	825	232	2014	5.2	23.6						
25	7.15	231	600	197	2211	1.0	24.6	0.781	0.131	61.47	4.31	0.217	85.23
26	6.95	220	400	122	2333	0.8	25.4						
27	7.03	249	450	163	2496	0.8	26.2						
28	7.08	236	625	200	2696	3.6	29.8						
29	7.03	252	550	180	2876	2.0	31.8						
30	7.04	236	400	148	3024	1.2	33.0	0.109	0.024	56.6	4.46	0.092	75.7
31	7.03	276	400	119	3143	1.0	34.0						
32	6.98	305	400	195	3338	0.7	34.7						
33	6.95	373	400	183	3521	0.5	35.2						
34	6.92	280	450	153	3674	1.0	36.2	0.286	0.086	60.1	6.26	0.063	82.9
35	6.9	274	400	126	3800	1.0	37.2						
36	6.98	290	400	107	3907	0.7	37.9						
37	7.01	309	300	98	4005	0.6	38.5						
38	6.97	289	300	122	4127	0.8	39.3	0.002	0.035	55.58	3.07	0.033	60.6
39	6.92	281	300	135	4262	0.4	39.7						
40	7.14	276	300	504	4766	0.5	40.2						
41	7.17	242	250	123	4889	0.6	40.8						
42	7.19	246	500	298	5187	0.9	41.7	0.056	0.022	62.7	5.4	0.014	85.8
43	6.84	263	450	218	5405	0.5	42.2						
44	6.87	253	450	162	5567	0.5	42.7						
45	7.1	250	650	83	5650	0.5	43.2						
46	6.95	308	400	86	5736	0.6	43.8	0.198	0.057	68.68	3.71	0.043	68
47	7	281	400	74	5810	0.7	44.5						
48	7.05	273	450	101	5911	0.9	45.4						
49	7.06	263	400	49	5960	0.7	46.1						
50	6.82	254	400	72	6032	0.4	46.5	0.173	0.064	89.66	4.67	0.046	91
51	6.8	261	500	455	6487	1.8	48.3						
52	6.75	253	350	78	6565	3.2	51.5						
53	6.65	251	250	238	6803	1.0	52.5						
54	6.68	253	400	494	7297	0.4	52.9	0.185	0.425	170.9	9.02	0.116	219
55	6.51	286	400	109	7406	0.5	53.4						
56	6.78	280	500	460	7866	0.6	54.0						
57	6.85	272	400	70	7936	0.5	54.5						
58	6.79	262	300	81	8017	0.4	54.9	0.1	0.097	69.26	2.34	0.059	66

Table 6.5 0.1% Sodium Lauryl Sulphate (SLS)
Sample No.5
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.37	310	150	246	246	1.2	1.2	0.04	0.08	19.63	0.28	0.04	24.45
1	6.74	295	350	80	326	3.3	4.5						
2	6.79	225	1000	101	427	4.3	8.8						
3	6.9	251	2000	122	549	4.8	13.6						
4	6.5	245	1250	167	716	5.1	18.7	0.26	0.06	13.26	0.41	0.06	20.39
5	6.12	250	800	260	976	5.3	24.0						
6	6.95	235	925	242	1218	5.2	29.2						
7	6.65	225	575	96	1314	5.3	34.5						
8	7.05	177	650	151	1465	5.6	40.1	0.26	0.03	75.64	5.53	0.21	246.1
9	6.91	262	1300	742	2207	19.7	59.8						
10	7.02	249	1100	723	2930	9.3	69.1						
11	7.77	150	1100	232	3162	4.2	73.3						
12	7.66	161	850	242	3404	4.5	77.8	0.221	0.046	100	8.81	0.277	287
13	6.89	201	650	175	3579	1.4	79.2						
14	6.85	184	700	236	3815	1.8	81.0						
15	7.45	216	550	180	3995	2.7	83.7						
16	8.01	270	600	223	4218	1.6	85.3	0.166	0.054	127	7.94	0.193	199
17	7.55	206	700	230	4448	1.4	86.7						
18	7.57	257	600	311	4759	1.4	88.1						
19	7.91	240	850	447	5206	0.5	88.6						
20	7.66	250	600	208	5414	1.0	89.6	0.08	0.034	126	6.18	0.081	163
21	7.58	260	600	227	5641	1.0	90.5						
22	7.5	265	700	246	5887	1.0	91.5						
23	7.52	270	750	247	6134	1.0	92.5						
24	7.71	184	575	191	6325	0.9	93.4						
25	7.81	215	750	324	6649	1.0	94.4	0.062	0.086	139.9	5.66	0.058	144.7
26	7.55	220	650	238	6887	0.2	94.6						
27	7.65	236	750	315	7202	1.3	95.9						
28	7.72	224	700	213	7415	1.3	97.2						
29	7.73	245	800	316	7731	4.1	101.3						
30	7.81	233	700	302	8033	0.8	102.1	0.1	0.038	170.4	4.95	0.06	161.2
31	7.77	272	600	261	8294	0.8	102.9						
32	7.78	315	650	323	8617	0.7	103.6						
33	7.8	270	600	250	8867	0.7	104.3						
34	7.5	268	650	327	9194	1.0	105.3	788.7	62.4	26.7	7.88	0.102	5.06
35	7.81	251	400	99	9293	0.3	105.6						
36	7.65	258	700	261	9554	0.4	106.0						
37	7.89	265	400	156	9710	0.2	106.2						
38	7.66	254	700	281	9991	0.7	106.9	-	-	-	-	-	-
39	7.59	225	600	231	10222	0.3	107.2						
40	7.63	251	650	602	10824	1.0	108.2						
41	7.82	221	550	322	11146	0.7	108.9						
42	7.86	265	550	115	11261	0.4	109.3	0.026	0.032	133.6	2.3	0.01	114
43	7.67	253	400	104	11365	0.5	109.8						
44	7.68	253	700	511	11876	0.5	110.3						
45	7.69	251	800	1476	13352	0.4	110.7						
46	7.85	270	625	146	13498	0.4	111.1	0.083	0.046	1.97	131.1	0.024	113
47	7.9	286	600	153	13651	0.4	111.5						
48	7.81	252	650	47	13698	0.3	111.8						
49	7.67	264	600	48	13746	0.3	112.1						
50	7.57	248	650	296	14042	0.2	112.3	0.059	0.048	2.21	170.5	0.028	131
51	7.4	253	700	703	14745	1.1	113.4						
52	7.47	254	750	739	15484	2.1	115.5						
53	7.41	248	600	78	15562	0.2	115.7						
54	7.38	268	800	146	15708	0.4	116.1	79.5	51.5	32.7	187.9	0.051	673
55	7.3	275	700	48	15756	0.3	116.4						
56	7.25	270	800	70	15826	0.4	116.8						
57	7.22	265	800	72	15898	0.5	117.2						
58	7.15	245	700	90	15988	0.8	118.0	0.166	0.07	217.5	2.69	0.046	160

Table 6.6 0.3% Sodium Lauryl Sulphate (SLS)
Sample No.6
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.18	325	145	246	246	0.1	0.1	0.02	0.06	20.01	0.26	0.08	25.77
1	6.79	315	450	92	338	0.3	0.4						
2	6.68	305	2000	86	424	0.5	0.9						
3	6.75	226	2500	79	503	1.0	1.9						
4	6.4	228	2000	65	568	1.9	3.8	0.04	0.05	20.05	0.22	0.1	24.65
5	6.15	215	1750	38	606	3.7	7.5						
6	6.96	224	2500	90	696	3.6	11.1						
7	6.92	186	1200	10	706	7.2	18.3						
8	7.25	158	1200	40	746	8.0	26.3	0.07	0.04	179.6	11.76	0.76	487
9	6.81	162	1250	41	787	18.7	45.0						
10	7.75	160	1200	86	873	3.6	48.6						
11	6.75	87	1200	105	978	3.8	52.4						
12	7.98	146	1100	314	1292	3.5	55.9	0.285	0.068	198	10.6	0.252	325
13	7.22	186	1125	352	1644	3.1	59.0						
14	7.45	180	1000	437	2081	3.1	62.1						
15	7.62	211	850	488	2569	3.3	65.4						
16	8.06	240	900	435	3004	2.2	67.6	0.137	0.061	237	8.33	0.2	302
17	7.97	197	900	387	3391	1.2	68.8						
18	7.79	244	850	311	3702	1.8	70.6						
19	7.96	226	700	285	3987	2.5	73.1						
20	7.64	230	725	336	4323	1.4	74.5	0.825	0.067	181	6.4	0.17	228
21	7.52	240	700	319	4642	1.6	76.1						
22	7.65	250	800	300	4942	1.7	77.8						
23	7.75	239	725	286	5228	2.0	79.8						
24	7.47	188	775	319	5547	1.2	81.0	1.37	0.101	180.7	4.67	0.101	203.4
25	7.65	210	700	236	5783	0.9	81.9						
26	7.5	230	750	274	6057	2.0	83.9						
27	7.51	226	1050	256	6313	2.4	86.3						
28	7.49	223	900	395	6708	0.4	86.7						
29	7.39	242	700	287	6995	1.2	87.9	0.097	0.044	142.8	2.78	0.065	144.1
30	7.62	225	600	251	7246	1.1	89.0						
31	7.46	267	650	258	7504	0.9	89.9						
32	7.25	303	600	285	7789	1.6	91.5						
33	7.25	287	650	302	8091	0.9	92.4						
34	7.28	312	700	311	8402	1.0	93.4	0.113	0.032	80.18	1.67	0.02	68.8
35	7.3	270	700	250	8652	1.0	94.4						
36	7.23	246	750	278	8930	1.4	95.8						
37	7.21	239	850	405	9335	0.6	96.4						
38	7.45	221	600	397	9732	1.0	97.4	0.101	0.074	205.5	3.47	0.053	203
39	7.46	241	500	445	10177	0.8	98.2						
40	7.42	216	700	351	10528	0.5	98.7						
41	7.53	272	650	196	10724	0.1	98.8						
42	7.54	251	650	195	10919	0.6	99.4	0.353	0.096	161	2.09	0.035	138
43	7.82	251	650	113	11032	0.5	99.9						
44	7.73	262	700	84	11116	0.4	100.3						
45	7.67	270	700	312	11428	0.3	100.6						
46	7.66	283	1000	96	11524	0.1	100.7	0.083	0.044	162.4	1.76	0.02	151
47	7.62	252	700	88	11612	0.2	100.9						
48	7.76	260	850	115	11727	0.3	101.2						
49	7.62	251	800	74	11801	0.7	101.9						
50	7.48	248	650	62	11863	0.4	102.3	0.017	0.042	171.4	1.37	0.017	130
51	7.2	251	650	149	12012	0.3	102.6						
52	7.35	247	600	247	12259	0.3	102.9						
53	7.15	251	550	69	12328	0.1	103.0						
54	7.2	268	550	71	12399	0.3	103.3	615	138	82.33	23.1	0.025	633
55	7.16	270	500	77	12476	0.3	103.6						
56	7.21	222	850	65	12541	0.9	104.5						
57	7.16	245	650	65	12606	0.4	104.9						
58	7.05	241	850	78	12684	0.3	105.2	0.133	0.168	227.3	1.89	0.073	193

Table 6.7 0.5% Sodium Lauryl Sulphate (SLS)
Sample No.7
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
	pH	EMF	Conductivity	Sulphate	Cum.	Acidity	Cum.	Fe	Ni	CA	Mg	Cu	S
Week		mV	micromhos/cm	mg/L	Sulphate	mg/L	Acidity	0.04	0.09	117.4	0.95	0.43	231.2
0	7.05	349	750	252	252	0.3	0.3						
1	7.02	196	2250	316	568	0.4	0.7						
2	6.96	225	2000	274	842	0.5	1.2						
3	6.4	215	3000	467	1309	0.7	1.9	0.83	0.04	126.9	2.88	0.33	331.3
4	6.25	223	1400	308	1617	1.1	3.0						
5	6.35	394	1100	17	1634	1.9	4.9						
6	6.92	241	1500	111	1745	3.6	8.5						
7	6.9	260	1100	36	1781	6.9	15.4	0.07	0.06	231.9	8.41	0.6	497.1
8	6.95	295	1225	25	1806	8.7	24.1						
9	6.43	252	1225	247	2053	31.6	55.7						
10	7.05	144	1350	142	2195	9.8	65.5						
11	7.83	122	1400	590	2785	5.8	71.3	0.737	0.105	181	7.61	0.349	305
12	7.83	151	1000	366	3151	7.1	78.4						
13	7.22	262	1125	508	3659	2.5	80.9						
14	7.33	180	900	385	4044	3.4	84.3						
15	7.5	198	750	363	4407	3.1	87.4	0.294	0.094	170	6.89	0.12	228
16	7.74	263	750	265	4672	1.8	89.2						
17	8.02	205	800	362	5034	1.3	90.5						
18	7.98	224	1000	479	5513	1.8	92.3						
19	7.97	225	860	263	5776	2.2	94.5	1.31	0.106	260	9.67	0.314	300
20	7.78	230	950	55	5831	1.4	95.9						
21	7.07	245	900	334	6165	1.6	97.5						
22	7.93	240	900	265	6430	1.7	99.2						
23	7.9	231	825	651	7081	1.9	101.1	0.688	0.152	207.4	6.49	0.057	216.7
24	7.58	162	900	409	7490	1.2	102.3						
25	7.57	230	950	388	7878	2.0	104.3						
26	7.41	240	800	332	8210	1.1	105.4						
27	7.84	223	650	221	8431	1.6	107.0						
28	7.41	220	900	489	8920	2.5	109.5	0.093	0.049	184	4.25	0.036	181.6
29	7.38	242	650	201	9121	1.9	111.4						
30	7.71	226	700	290	9411	1.5	112.9						
31	7.44	263	650	274	9685	1.7	114.6						
32	7.3	290	600	227	9912	1.9	116.5						
33	7.25	289	600	217	10129	1.3	117.8	0.165	0.087	111.98	3.44	0.021	119.5
34	7.08	262	500	201	10330	2.0	119.8						
35	7.28	270	550	160	10490	1 1	120.9						
36	7.11	285	450	157	10647	0.7	121.6						
37	7.09	227	500	190	10837	0.8	122.4						
38	7.31	249	750	339	11176	0.3	122.7	0.091	0.042	120.7	2.48	0.026	125
39	7.34	239	450	122	11298	0.6	123.3						
40	7.35	238	500	614	11912	0.6	123.9						
41	7.35	252	500	84	11996	0.7	124.6						
42	7.37	267	400	135	12131	0.7	125.3	0.394	0.01	81.83	1.25	0.084	95.5
43	7.57	250	400	419	12550	0.9	126.2						
44	6.98	268	700	547	13097	0.9	127.1						
45	7.39	270	400	175	13272	0.9	128.0						
46	7.41	272	400	177	13449	0.9	128.9	0.217	0.104	113.4	2.21	0.127	106
47	7.36	268	650	177	13626	1.0	129.9						
48	7.47	270	550	78	13704	1.1	131.0						
49	5.91	246	450	213	13917	0.8	131.8						
50	7.21	264	300	46	13963	0.6	132.4	0.152	0.081	120	1.72	0.191	95.5
51	6.85	260	500	114	14077	1.3	133.7						
52	6.91	261	400	88	14165	2.0	135.7						
53	7.27	258	600	122	14287	0.5	136.2						
54	7.05	256	900	154	14441	0.1	136.3	0.505	0.21	119.6	1.67	0.231	106
55	7.06	268	650	122	14563	0.5	136.8						
56	7.31	230	1100	74	14637	0.6	137.4						
57	7.12	253	950	75	14712	0.2	137.6						
58	7.15	242	850	73	14785	0.3	137.9	0.11	0.067	244.4	1.78	0.036	179

Table 6.8 Tailings Control Sample (TAILINGS)
Sample No.8
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	3.41	272	2000	316	316	2.4	2.4	_	0.02	10	0.12	0.43	15.7
1	3.74	176	3000	308	624	2.8	5.2						
2	3.68	198	1700	274	898	2.8	8.0						
3	4.05	202	1200	236	1134	3.6	11.6						
4	4.21	272	700	167	1301	5.1	16.7	269	16.17	85.02	10.51	0.01	379.5
5	4.27	372	1300	28	1329	8.2	24.9						
6	3.49	320	3000	85	1414	14.4	39.3						
7	3.52	317	7000	183	1597	29.8	69.1						
8	3.57	296	6000	186	1783	96.2	165.3	3481	462.3	25.86	19.71	0.26	2072
9	3.27	330	7500	200	1983	172.0	337.3						
10	3.22	335	5000	213	2196	76.0	413.3						
11	3.28	303	4000	502	2698	68.5	481.8						
12	3.21	327	3000	417	3115	44.2	526.0	995	270	15.6	51.4	1.71	683
13	3.58	310	1800	233	3348	27.2	553.2						
14	3.49	323	1925	334	3682	30.2	583.4						
15	3.63	287	1400	230	3912	33.9	617.3						
16	3.5	318	1150	1393	5305	17.6	634.9	360	110	7.59	54.8	0.383	390
17	3.51	338	1100	70	5375	9.8	644.7						
18	3.67	341	1600	70	5445	25.4	670.1						
19	3.65	341	1300	124	5569	8.3	678.4						
20	3.55	323	1600	169	5738	24.5	702.9	743	168	12.3	53.9	0.212	678
21	3.52	320	1700	180	5918	21.0	723.9						
22	3.52	333	1900	191	6109	19.8	743.7						
23	3.57	337	1600	129	6238	17.8	761.5						
24	3.51	336	1050	68	6306	9.2	770.7						
25	3.53	317	1200	36	6342	17.2	787.9	333.6	60.3	27.1	5.36	0.096	274.5
26	3.54	315	1150	1355	7697	10.4	798.3						
27	3.45	340	1350	96	7793	15.5	813.8						
28	3.46	316	1950	361	8154	39.1	852.9						
29	3.47	325	950	85	8239	10.3	863.2						
30	3.44	352	700	63	8302	5.5	868.7	168.4	28.76	12.95	2.93	0.122	139.2
31	3.57	309	650	59	8361	24.5	893.2						
32	3.48	380	800	57	8418	15.9	909.1						
33	3.47	384	900	483	8901	10.1	919.2						
34	3.51	358	900	59	8960	9.8	929.0	558.6	65.1	11.01	6.73	0.031	392.7
35	3.62	325	1400	153	9113	17.7	946.7						
36	3.33	364	1500	153	9266	21.8	968.5						
37	3.66	358	700	38	9304	7.0	975.5						
38	3.77	301	1600	171	9475	6.7	982.2	197	26.1	10.16	3.13	0.019	180
39	3.76	305	600	191	9666	6.7	988.9						
40	3.86	339	550	291	9957	24.5	1013.4						
41	4.16	301	900	582	10539	12.9	1026.3						
42	3.79	343	400	1134	11673	4.1	1030.4	4.24	12.7	7.104	2.05	0.02	73.3
43	3.79	344	450	86	11759	4.5	1034.9						
44	3.68	355	500	269	12028	4.8	1039.7						
45	3.78	350	700	194	12222	9.8	1049.5						
46	3.85	376	400	473	12695	17.7	1067.2	109	18.9	5.49	2.46	0.033	125
47	3.76	370	600	52	12747	15.5	1082.7						
48	3.77	367	1300	51	12798	18.6	1101.2						
49	3.75	343	750	49	12847	11.3	1112.5						
50	3.81	345	400	51	12898	8.8	1121.3	36.7	26.6	9.015	4.02	0.021	136
51	3.49	341	700	693	13591	24.5	1145.8						
52	3.65	340	600	409	14000	8.0	1153.8						
53	3.68	345	1000	135	14135	16.0	1169.8						
54	3.78	350	500	92	14227	7.2	1177.0	88.2	15.6	6	2.551	0.031	81.8
55	3.51	355	400	331	14558	4.4	1181.5						
56	3.71	345	850	205	14763	10.8	1192.2						
57	3.56	351	550	50	14813	6.0	1198.2						
58	3.18	372	1800	240	15053	10.0	1208.2	467	53.6	12.83	5.65	<.005	391

Table 6.9 0.5% Sodium Silicate (Sod Sil)
Sample No.9
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	3.01	243	600	88	88	3.1	3.1	3.65	0.09	3.44	0.29	0.23	7.16
1	3.86	196	225	73	161	1.2	4.3						
2	6.75	218	200	79	240	1.9	6.2						
3	6.57	181	150	71	311	0.9	7.1						
4	6.76	252	200	72	383	0.9	8.0	0.13	0.04	28.41	1.12	0.11	89.28
5	6.71	206	300	73	456	2.7	10.7						
6	6.94	174	450	123	579	2.2	12.9						
7	6.77	206	350	109	688	1.6	14.5						
8	6.82	174	300	69	757	1.1	15.6	1.24	0.2	28.93	1.5	0.09	74.32
9	6.7	286	200	48	805	3.8	19.4						
10	7.08	254	500	130	935	1.3	20.7						
11	6.83	234	200	47	982	0.6	21.3						
12	7.05	209	450	175	1157	1.8	23.1	0.82	0.263	58.8	2.25	0.123	117
13	7.13	282	500	157	1314	0.9	24.0						
14	7.11	262	450	124	1438	1.0	25.0						
15	7.07	223	450	136	1574	1.1	26.1						
16	6.89	235	300	61	1635	1.1	27.2	0.138	0.061	33.6	0.697	0.042	46.7
17	7.03	300	1100	269	1904	1.1	28.3						
18	7.05	276	400	93	1997	0.4	28.7						
19	7.2	219	1300	366	2363	3.8	32.5						
20	7.14	237	400	104	2467	0.6	33.1	0.601	0.119	39.09	1.88	0.059	72.94
21	7.03	246	600	199	2666	0.1	33.2						
22	7.05	241	500	111	2777	0.8	34.0						
23	7.06	240	400	100	2877	1.1	35.1						
24	7.09	234	350	97	2974	0.1	35.2						
25	6.98	233	300	84	3058	0.2	35.4	2.41	11.36	111.2	32.5	0.143	312.55
26	6.92	226	400	87	3145	0.4	35.8						
27	6.95	243	500	88	3233	0.6	36.4						
28	6.98	259	450	237	3470	0.5	36.9						
29	6.9	225	450	166	3636	0.5	37.4						
30	6.94	307	400	109	3745	0.8	38.2						
31	7.29	251	400	127	3872	0.9	39.1						
32	7.22	249	900	327	4199	2.0	41.1						
33	7.01	255	400	124	4323	0.6	41.7						
34	6.96	228	500	463	4786	0.9	42.6	0.105	0.7	32.64	1.91	0.021	65.5
35	7.15	274	350	93	4879	0.8	43.4						
36	6.91	281	400	599	5478	0.5	43.9						
37	7.04	232	300	408	5886	0.7	44.6						
38	7.24	237	300	58	5944	1.0	45.6	0.04	0.033	45.87	1.46	0.024	48.6
39	6.93	238	250	270	6214	0.3	45.9						
40	7.09	231	300	146	6360	0.1	46.0						
41	7.01	272	250	91	6451	0.2	46.2						
42	6.98	342	300	42	6493	0.8	47.0	0.232	0.19	58.19	2.46	0.05	64.4
43	6.97	246	400	47	6540	0.5	47.5						
44	6.86	257	200	208	6748	1.0	48.5						
45	6.98	251	400	476	7224	1.1	49.6						
46	6.35	244	200	99	7323	4.8	54.4	0.019	0.038	102.2	4.12	0.056	124
47	6.84	249	450	83	7406	0.6	55.0						
48	6.58	245	600	72	7478	0.8	55.8						
49	6.85	244	350	106	7584	0.9	56.7						
50	6.95	287	400	62	7646	0.5	57.2	0.093	0.032	78.62	1.63	0.026	77.9
51	6.78	268	500	80	7726	0.5	57.7						
52	6.61	265	300	54	7780	0.1	57.8						
53	6.6	261	250	71	7851	0.2	58.0						
54	6.66	292	250	64	7915	0.2	58.3	0.198	0.055	50.5	1.17	0.022	51
55	6.68	285	250	67	7982	0.2	58.5						
56	6.7	261	200	134	8116	0.2	58.7						
57	6.67	271	300	77	8192	0.3	59.1						
58	6.69	260	300	88	8280	0.4	59.5	0.049	0.013	64.39	1.76	0.032	62.7

Table 6.10 0.3% Sodium Silicate (Sod Sil)
Sample No.10
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidit mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	9.25	141	75	16	16	0.2	0.2	_	0.02	9.71	0.17	0.02	7.57
1	7.15	166	150	84	100	0.7	0.9						
2	7.6	244	100	156	256	1.8	2.7						
3	7.1	156	200	99	355	1.0	3.7						
4	7.16	167	200	108	463	1.6	5.3	0.14	0.01	24.09	1.35	0.25	68.97
5	7.31	197	300	45	508	0.8	6.1						
6	7.26	180	175	32	540	0.9	7.0						
7	6.7	202	200	42	582	1.3	8.3						
8	7.02	173	300	67	649	1.1	9.4	0.22	0.06	28.44	1.62	0.15	67.61
9	7.34	277	250	83	732	1.2	10.6						
10	7.18	259	250	53	785	1.1	11.7						
11	7.1	240	170	44	829	0.1	11.8						
12	7.4	226	700	312	1141	1.6	13.4	0.344	0.058	102	4.91	0.23	200
13	7.7	283	700	260	1401	1.3	14.7						
14	7.58	232	800	287	1688	0.1	14.8						
15	7.6	226	800	287	1975	1.7	16.5						
16	7.1	224	400	78	2053	1.6	18.1	0.008	0.014	39.9	1.56	0.076	61.9
17	7.21	250	425	101	2154	0.9	19.0						
18	7.31	254	425	90	2244	1.0	20.0						
19	7.58	210	900	263	2507	3.6	23.6						
20	7.41	241	500	168	2675	1.4	25.0	0.61	0.154	49.25	3.31	0.184	109.9
21	7.44	244	800	304	2979	1.7	26.7						
22	7.61	238	550	73	3052	0.9	27.6						
23	7.45	235	450	140	3192	3.5	31.1						
24	7.38	235	450	136	3328	0.9	32.0						
25	7.35	237	500	166	3494	1.7	33.7	3.13	0.132	111.2	1.91	0.198	47.42
26	7.32	237	350	111	3605	0.4	34.1						
27	7.24	222	500	206	3811	0.6	34.7						
28	7.31	238	550	231	4042	0.9	35.6						
29	7.38	222	450	150	4192	0.6	36.2						
30	7.35	234	500	179	4371	1.7	37.9	_	_	_	_	_	_
31	7.17	231	150	41	4412	0.4	38.3						
32	7.45	232	1200	520	4932	3.1	41.4						
33	7.3	243	450	328	5260	0.6	42.0						
34	7.1	241	450	525	5785	0.9	42.9	0.105	0.065	32.64	1.91	0.024	52.3
35	7.32	261	250	78	5863	0.7	43.6						
36	7.48	252	400	632	6495	0.5	44.1						
37	7.25	228	350	452	6947	0.3	44.4						
38	7.4	246	350	54	7001	0.4	44.8	0.093	0.05	51.94	2.07	0.053	57.1
39	7.21	222	300	374	7375	0.3	45.1						
40	7.22	229	350	44	7419	0.2	45.3						
41	7.12	261	300	48	7467	0.2	45.5						
42	7.15	282	300	50	7517	0.3	45.8	0.047	0.03	71.65	3.34	0.031	74.2
43	7.04	243	400	171	7688	0.5	46.3						
44	7.05	254	200	106	7794	0.2	46.5						
45	7.02	253	400	90	7884	0.4	46.9						
46	6.57	267	200	311	8195	0.2	47.1	0.025	0.045	120.4	5.44	0.045	124
47	6.95	243	550	75	8270	0.6	47.7						
48	6.78	240	650	144	8414	0.5	48.2						
49	6.89	239	400	358	8772	0.4	48.6						
50	6.91	287	400	122	8894	0.2	48.8	0.065	0.015	86.32	2.15	0.05	77
51	6.72	258	400	479	9373	0.2	49.1						
52	6.65	257	400	51	9424	0.2	49.3						
53	6.61	222	350	56	9480	0.2	49.5						
54	6.67	238	250	75	9555	0.3	49.8	0.063	0.04	54.09	1.57	0.011	51.6
55	6.69	242	250	88	9643	0.2	50.0						
56	6.71	249	200	215	9858	0.3	50.4						
57	6.68	250	300	80	9938	0.2	50.6						
58	6.71	262	250	73	10011	0.2	50.8	<.005	0.007	87.56	3.27	0.056	83

Table 6.11 0.1% Sodium Silicate (Sod Sil)
Sample No.11
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	9.46	157	70	17	17	0.2	0.2	_	0.02	9.69	0.18	0.02	6.37
1	7.2	179	175	57	74	0.6	0.8						
2	7.15	234	125	16	90	1.0	1.8						
3	6.95	159	175	80	170	0.7	2.5						
4	7.32	161	190	81	251	1.1	3.6	_	0.01	11.54	0.45	0.07	18.39
5	7.03	221	115	63	314	0.5	4.1						
6	7.31	208	175	21	335	1.1	5.2						
7	6.55	199	165	28	363	1.0	6.2						
8	6.78	167	180	36	399	1.0	7.2	0.12	0.04	17.61	1	0.15	40.62
9	7.21	272	150	30	429	1.5	8.7						
10	7.11	262	250	71	500	1.0	9.7						
11	7.15	251	250	83	583	1.3	11.0						
12	7.19	250	400	107	690	0.8	11.8	0.192	0.057	51.4	2.09	0.186	87.6
13	7.04	289	250	73	763	0.7	12.5						
14	7.03	251	400	78	841	0.3	12.8						
15	7.38	235	650	240	1081	1.1	13.9						
16	7.28	222	400	97	1178	1.1	15.0	0.025	0.029	51.8	1.46	0.048	70.4
17	7.39	228	800	217	1395	1.9	16.9						
18	6.95	244	200	48	1443	0.6	17.5						
19	7.25	209	750	160	1603	3.0	20.5						
20	7.07	241	180	40	1643	0.9	21.4	1.32	0.14	18.01	0.913	0.175	30.93
21	7.33	239	225	49	1692	0.5	21.9						
22	7.36	230	500	150	1842	1.0	22.9						
23	7.67	223	200	24	1866	0.9	23.8						
24	7.78	219	250	60	1926	0.3	24.1						
25	7.18	242	200	208	2134	0.6	24.7	0.965	0.232	33.69	1.56	0.12	52.7
26	7.25	220	600	218	2352	0.9	25.6						
27	7.19	240	550	186	2538	1.0	26.6						
28	7.26	240	500	47	2585	0.5	27.1						
29	7.15	282	250	49	2634	0.5	27.6						
30	7.25	225	450	100	2734	0.5	28.1	_	_	_	_	_	_
31	7.27	223	200	48	2782	0.4	28.5						
32	7.46	221	1100	103	2885	3.0	31.5						
33	7.2	223	400	269	3154	0.8	32.3						
34	7.1	221	550	459	3613	0.9	33.2	0.036	0.046	14.5	1.6	0.044	26.2
35	7.15	259	200	80	3693	0.3	33.5						
36	7.32	242	350	299	3992	0.3	33.8						
37	7.2	243	350	470	4462	1.9	35.7						
38	7.45	238	400	58	4520	0.2	35.9	0.097	0.028	24.72	1.35	0.017	25.5
39	7.31	226	300	336	4856	0.6	36.5						
40	7.13	227	200	140	4996	0.4	36.9						
41	6.96	272	200	96	5092	0.1	37.0						
42	6.94	281	150	51	5143	0.1	37.1	<.005	0.019	39.9	1.77	0.004	38.1
43	6.86	244	250	36	5179	0.2	37.3						
44	6.98	249	200	185	5364	0.3	37.6						
45	6.78	250	400	446	5810	0.2	37.8						
46	6.92	275	550	412	6222	0.2	38.0	<.005	0.045	157.8	6.92	0.045	124
47	7.15	242	600	171	6393	0.1	38.1						
48	6.86	250	800	101	6494	0.2	38.3						
49	6.93	244	450	252	6746	0.3	38.6						
50	6.86	286	450	59	6805	0.1	38.7	0.086	0.035	0.025	58.09	0.011	49.1
51	6.78	241	350	254	7059	0.1	38.8						
52	6.75	263	250	149	7208	0.6	39.4						
53	6.6	236	300	47	7255	0.2	39.7						
54	6.66	281	250	69	7324	0.2	39.8	0.052	0.035	50.3	3.85	0.017	62.6
55	6.69	242	250	65	7389	0.6	40.5						
56	6.71	241	350	88	7477	0.2	40.7						
57	6.68	251	350	197	7674	0.2	40.9						
58	6.71	260	350	54	7728	0.2	41.1	0.063	0.012	54.22	2.12	0.035	54.7

Table 6.12 60% Portland cement/40% Fly ash (60%PC/40%FA)
Sample No.12
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	9.1	153	120	45	45	0.3	0.3	—	0.05	17.99	0.17	0.03	14.82
1	7.05	184	275	216	261	1.1	1.4						
2	6.26	251	200	99	360	1.7	3.1						
3	6.3	149	150	59	419	0.9	4.0						
4	6.9	170	175	70	489	1.0	5.0	0.05	0.03	27.46	1.01	0.14	40.23
5	6.87	232	165	25	514	0.8	5.8						
6	7.04	214	180	33	547	0.7	6.5						
7	6.82	202	135	26	573	1.9	8.4						
8	6.73	170	200	37	610	1.2	9.6	0.12	0.11	26.86	2.15	0.11	51.2
9	6.92	275	200	26	636	1.3	10.9						
10	7	263	400	88	724	2.2	13.1						
11	6.98	268	350	89	813	1.6	14.7						
12	6.77	225	250	38	851	1.4	16.1	0.521	0.314	39.1	2.67	0.119	70.9
13	6.7	230	400	82	933	1.2	17.3						
14	6.69	259	500	88	1021	0.2	17.5						
15	6.75	259	650	221	1242	2.9	20.4						
16	6.72	231	400	60	1302	3.0	23.4	0.144	0.501	54.5	3.55	0.045	70.4
17	6.65	222	950	304	1606	5.1	28.5						
18	6.4	248	250	32	1638	2.4	30.9						
19	6.48	251	800	190	1828	9.1	40.0						
20	6.42	242	400	104	1932	2.3	42.3	12.2	3.04	67.17	10.76	0.156	140.6
21	6.4	259	550	131	2063	4.9	47.2						
22	6.3	259	650	143	2206	10.1	57.3						
23	6.35	247	550	115	2321	8.3	65.6						
24	6.32	253	800	179	2500	8.0	73.6						
25	6.3	353	900	92	2592	11.1	84.7	—	—	—	—	—	—
26	6.31	272	1200	436	3028	14.2	98.9						
27	6.2	278	1200	470	3498	15.4	114.3						
28	6.25	283	1000	394	3892	15.2	129.5						
29	6.05	286	1000	276	4168	16.6	146.1						
30	5.8	281	1250	510	4678	16.3	162.4	—	—	—	—	—	—
31	5.75	269	1150	285	4963	17.8	180.2						
32	5.3	279	1800	62	5025	28.1	208.3						
33	4.95	285	1100	13	5038	13.7	222.0						
34	4.91	280	950	433	5471	9.1	231.1	1.78	18.6	63.66	22.3	0.028	198
35	4.5	301	600	485	5956	6.1	237.2						
36	4	336	950	538	6494	3.7	240.9						
37	3.7	335	1000	96	6590	1.3	242.2						
38	3.78	364	1300	45	6635	14.4	256.6	51.3	97.3	54.9	33.4	0.31	380
39	3.67	365	1300	146	6781	17.2	273.8						
40	3.6	347	1400	147	6928	17.8	291.6						
41	3.67	369	1400	48	6976	19.4	311.0						
42	3.57	373	1300	51	7027	16.0	327.0	634	267	110	3.4	0.063	1040
43	3.84	320	2500	56	7083	45.2	372.2						
44	3.46	369	1100	769	7852	12.0	384.2						
45	3.94	325	2200	194	8046	34.8	419.0						
46	3.58	343	1300	442	8488	18.0	437.0	404	163	122	25.7	0.682	513
47	3.59	330	2000	108	8596	26.0	463.0						
48	3.31	338	1700	745	9341	24.8	487.8						
49	3.65	334	1600	532	9873	24.4	512.2						
50	3.59	343	3000	174	10047	41.3	553.5	652	117	42.95	16	0.149	515
51	3.58	341	1900	88	10135	20.8	574.3						
52	3.47	333	3500	65	10200	56.8	631.1						
53	3.34	311	2000	126	10326	28.0	659.1						
54	3.35	312	2000	73	10399	40.0	699.1	890	149	39.8	16.9	0.12	749
55	3.344	318	2000	72	10471	32.8	731.9						
56	3.33	310	1500	67	10538	34.8	766.7						
57	3.34	300	2500	88	10626	40.0	806.7						
58	3.35	300	2000	78	10703	33.2	839.9	1130	162	195	13.8	0.157	1140

Table 6.13 0.5% IPMC
Sample No.13
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	9.3	142	90	13	13	0.3	0.3	_	0.02	12.23	0.21	0.02	12.05
1	7.05	192	95	30	43	0.5	0.8						
2	6.15	262	125	78	121	1.2	2.0						
3	6.62	182	140	41	162	0.2	2.2						
4	7.1	185	145	40	202	0.7	2.9	_	0.01	14.1	0.79	0.36	29.35
5	6.9	243	175	22	224	2.0	4.9						
6	6.88	222	130	40	264	0.9	5.8						
7	6.6	243	145	23	287	1.5	7.3						
8	6.92	170	175	24	311	1.1	8.4	_	0.02	20.04	1.48	0.39	48.55
9	7.03	272	175	28	339	1.1	9.5						
10	7.05	270	275	30	369	2.0	11.5						
11	6.96	248	250	28	397	0.9	12.4						
12	7.06	240	250	58	455	1.0	13.4	0.163	0.046	33	1.2	0.123	58.2
13	7.54	245	275	95	550	0.8	14.2						
14	7.38	241	300	89	639	0.3	14.5						
15	7.47	258	300	96	735	0.7	15.2						
16	7.3	228	500	81	816	0.6	15.8	0.093	0.049	45.6	4.39	0.094	160
17	7.09	226	825	99	915	6.0	21.8						
18	6.9	245	400	42	957	2.0	23.8						
19	7.1	246	1000	207	1164	8.5	32.3						
20	6.96	247	550	87	1251	11.0	43.3	1.17	0.261	47.2	9.75	0.173	203.96
21	6.98	237	425	109	1360	3.3	46.6						
22	6.91	232	225	41	1401	0.6	47.2						
23	6.9	229	300	57	1458	1.6	48.8						
24	6.88	224	250	60	1518	0.3	49.1						
25	6.89	241	350	75	1593	0.4	49.5	_	_	_	_	_	_
26	6.87	245	200	46	1639	0.6	50.1						
27	6.89	233	550	181	1820	1.6	51.7						
28	6.87	251	500	167	1987	1.4	53.1						
29	6.85	248	300	69	2056	0.9	54.0						
30	6.84	241	300	73	2129	0.6	54.6	_	_	_	_	_	_
31	6.83	239	200	54	2183	0.3	54.9						
32	6.95	242	750	282	2465	1.1	56.0						
33	6.91	238	400	522	2987	0.9	56.9						
34	6.77	258	350	106	3093	0.8	57.7	0.056	0.104	32.27	4.63	0.024	48.5
35	6.87	250	250	553	3646	0.7	58.4						
36	6.71	242	400	250	3896	0.6	59.0						
37	6.72	265	250	119	4015	0.5	59.5						
38	6.65	273	300	488	4503	0.4	59.9	0.076	0.083	51.74	2.6	0.036	52.46
39	6.66	247	300	203	4706	0.3	60.2						
40	6.67	251	300	117	4823	0.3	60.5						
41	6.3	286	350	49	4872	0.4	60.9						
42	6.68	315	350	50	4922	0.3	61.2	0.212	0.213	85.21	4.86	0.022	87.2
43	6.31	283	450	222	5144	0.6	61.8						
44	6.25	355	250	491	5635	0.6	62.4						
45	6.1	266	500	120	5755	0.9	63.3						
46	6.55	306	450	385	6140	0.8	64.1	0.019	0.237	157.8	8.27	0.138	163
47	6.75	273	600	468	6608	2.1	66.2						
48	6.52	260	750	199	6807	1.1	67.3						
49	6.34	280	450	203	7010	1.0	68.3						
50	6.51	304	400	282	7292	1.5	69.8	1.06	0.535	107.7	4.76	0.176	126
51	6.32	235	500	468	7760	0.1	69.9						
52	6.21	237	400	59	7819	0.2	70.1						
53	6.3	231	450	60	7879	2.6	72.7						
54	6.25	256	500	70	7949	2.5	75.2	0.451	0.492	85.92	7.27	0.158	150
55	6.31	261	500	77	8026	2.1	77.3						
56	6.45	260	450	64	8090	2.2	79.5						
57	6.41	250	600	90	8180	2.3	81.8						
58	6.39	261	500	77	8257	2.4	84.2	0.434	0.816	156.8	10.8	0.168	216

Table 6.14 0.3% IPMC
Sample No.14
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.98	204	40	3	3	0.1	0.1	0.06	0.03	4.69	0.17	0.04	5.28
1	7.2	190	85	35	38	1.0	1.1						
2	7.15	253	200	98	136	2.9	4.0						
3	6.21	143	145	8	144	0.9	4.9						
4	6.94	181	185	63	207	1.2	6.1	_	0.01	20.37	0.83	0.25	45.5
5	6.94	236	195	48	255	1.8	7.9						
6	7.01	176	140	46	301	0.6	8.5						
7	6.52	220	160	45	346	1.0	9.5						
8	6.9	174	180	44	390	1.4	10.9	_	0.02	19.56	1.12	0.18	47.56
9	7.09	270	175	16	406	0.9	11.8						
10	6.95	270	325	70	476	1.6	13.4						
11	6.97	253	250	72	548	1.1	14.5						
12	6.83	242	225	58	606	0.3	14.8	0.18	0.054	29.6	0.964	0.097	50.3
13	6.83	238	200	56	662	0.7	15.5						
14	6.89	248	300	65	727	0.2	15.7						
15	6.93	248	250	61	788	0.6	16.3						
16	6.64	224	750	127	915	0.7	17.0	0.491	0.054	68.8	5.71	0.575	220
17	6.92	206	500	37	952	3.5	20.5						
18	6.93	240	600	221	1173	3.8	24.3						
19	7.17	244	900	61	1234	6.8	31.1						
20	7.12	237	250	61	1295	0.6	31.7	1.03	0.138	37.3	1.81	0.394	42.2
21	6.93	252	300	74	1369	0.4	32.1						
22	6.96	228	250	54	1423	0.6	32.7						
23	6.92	222	200	43	1466	0.5	33.2						
24	6.95	223	250	50	1516	0.9	34.1						
25	6.93	239	250	57	1573	0.6	34.7	_	_	_	_	_	_
26	6.92	244	200	288	1861	0.3	35.0						
27	7.01	269	600	214	2075	1.9	36.9						
28	7.02	262	500	172	2247	1.7	38.6						
29	6.99	250	400	100	2347	1.5	40.1						
30	6.98	251	350	82	2429	1.3	41.4	_	_	_	_	_	_
31	7.09	256	400	104	2533	1.2	42.6						
32	7.08	254	700	223	2756	1.2	43.8						
33	7.05	256	250	486	3242	0.6	44.4						
34	6.91	252	220	319	3561	0.5	44.9	0.171	0.078	37.78	4.21	0.037	60.9
35	6.9	251	250	469	4030	0.8	45.7						
36	6.95	258	400	261	4291	1.1	46.8						
37	6.92	259	200	105	4396	0.3	47.1						
38	6.96	263	250	45	4441	0.1	47.2	<.005	0.037	41.5	1.17	0.011	35.1
39	6.87	262	200	155	4596	0.2	47.4						
40	6.83	264	200	208	4804	0.2	47.6						
41	6.81	276	200	132	4936	0.2	47.8						
42	6.78	281	225	45	4981	0.2	48.0	0.013	0.037	55.73	1.76	0.01	50.6
43	6.75	263	300	48	5029	0.2	48.2						
44	6.62	330	175	644	5673	0.1	48.3						
45	6.63	274	400	82	5755	0.1	48.4						
46	6.88	301	200	501	6256	0.3	48.7	0.019	.03	79.49	3.13	0.015	76.6
47	6.66	276	300	204	6460	0.2	48.9						
48	6.68	279	450	125	6585	0.2	49.1						
49	6.69	277	450	489	7074	0.2	49.3						
50	6.46	238	450	614	7688	0.1	49.4	0.072	0.036	81.27	1.55	0.013	66.9
51	6.42	235	350	148	7836	0.1	49.5						
52	6.31	234	200	59	7895	0.2	49.7						
53	6.2	268	250	587	8482	0.2	49.9						
54	6.46	253	200	64	8546	0.2	50.1	0.056	0.029	37.88	0.99	0.016	34.7
55	6.51	261	200	56	8602	0.2	50.4						
56	6.62	250	200	89	8691	0.2	50.6						
57	6.61	260	250	81	8771	0.1	50.7						
58	6.69	258	250	86	8858	0.2	50.9	0.083	0.032	61.5	1.84	0.017	51.4

Table 6.15 0.1% IPMC
Sample No.15
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	9.08	153	85	17	17	0.5	0.1	-	-	11.39	0.29	0.02	5.28
1	7.15	188	125	59	76	0.9	1.0						
2	6.95	252	200	30	106	0.7	1.7						
3	6.35	157	110	35	141	0.7	2.4						
4	6.95	180	80	38	179	0.4	2.8	0.1	0.03	11.92	0.6	0.26	28.99
5	6.7	240	120	23	202	0.8	3.6						
6	7.02	219	160	42	244	0.6	4.2						
7	6.96	209	135	42	286	0.7	4.9						
8	6.78	173	145	19	305	0.7	5.6	-	-	15.75	0.93	0.2	34.8
9	7.02	269	190	36	341	0.9	6.5						
10	6.77	276	225	61	402	0.8	7.3						
11	6.85	260	225	40	442	0.6	7.9						
12	6.83	287	200	37	479	0.4	8.3	0.145	0.0446	22.4	0.642	0.07	32.2
13	6.89	265	200	48	527	0.5	8.8						
14	6.91	262	200	48	575	0.5	9.3						
15	6.92	253	200	49	624	0.5	9.8						
16	6.91	235	300	51	675	0.6	10.4	0.037	0.032	38.9	0.918	0.037	48.9
17	6.95	216	625	89	764	3.3	13.7						
18	6.91	231	225	42	806	0.9	14.6						
19	7.15	225	950	289	1095	6.3	20.9						
20	6.98	250	600	68	1163	2.4	23.3	2.35	0.157	49.6	8.06	0.337	188.46
21	7.05	259	450	111	1274	0.7	24.0						
22	7.01	229	250	54	1328	0.5	24.5						
23	7.03	234	500	109	1437	1.5	26.0						
24	7.01	231	350	91	1528	0.6	26.6						
25	7.01	242	300	90	1618	0.4	27.0	0.899	0.171	39.85	4.05	0.127	68.8
26	6.99	243	200	50	1668	0.2	27.2						
27	7.02	262	400	157	1825	0.5	27.7						
28	7.1	257	350	104	1929	0.4	28.1						
29	7.08	251	250	71	2000	0.3	28.4						
30	7.03	256	200	41	2041	0.3	28.7	-	-	-	-	-	-
31	7.01	251	250	70	2111	0.2	28.9						
32	7.15	249	800	302	2413	5.7	34.6						
33	7.09	257	250	63	2476	0.6	35.2						
34	7.02	253	400	318	2794	1.1	36.3	0.211	0.087	40.6	5.84	0.056	89.8
35	6.95	257	350	460	3254	0.9	37.2						
36	6.96	254	350	408	3662	0.8	38.0						
37	6.98	251	200	95	3757	0.1	38.1						
38	6.85	276	200	45	3802	0.3	38.4	0.073	0.059	43	1.87	0.03	40
39	6.82	250	150	200	4002	0.3	38.7						
40	6.78	272	250	116	4118	0.3	39.0						
41	6.65	291	200	49	4167	0.2	39.2						
42	6.62	325	200	62	4229	0.5	39.7	0.135	0.057	56.199	2.79	0.026	61.3
43	6.72	264	250	57	4286	5.4	45.1						
44	6.58	335	200	593	4879	0.9	46.0						
45	6.58	293	350	385	5264	0.4	46.4						
46	6.54	336	200	218	5482	2.0	48.4	0.123	0.065	89.42	4.6	0.07	105
47	6.61	278	550	430	5912	0.2	48.6						
48	6.35	268	500	134	6046	0.4	49.0						
49	6.57	275	300	565	6611	0.4	49.4						
50	6.54	228	700	1099	7710	0.0	49.4	0.307	0.436	79.99	2.45	0.069	85.6
51	6.61	238	400	247	7957	0.1	49.5						
52	6.23	232	300	88	8045	0.4	49.9						
53	6.62	225	200	56	8101	0.4	50.3						
54	6.64	220	200	65	8166	0.4	50.6	0.185	0.056	36.43	1.39	0.25	37.6
55	6.68	243	200	78	8244	0.6	51.2						
56	6.72	247	175	69	8313	0.4	51.6						
57	6.78	250	175	111	8424	0.4	52.0						
58	6.75	248	200	88	8512	0.2	52.2	0.053	0.206	34.77	1.25	0.024	33.5

Table 6.16 60% Gypsum / 40% Portland cement (60%GY/40%PC)
Sample No.16
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	9.2	148	80	13	13	0.2	0.2		0.01	10.92	0.23	0.03	24.28
1	7.1	206	150	50	63	0.7	0.9						
2	7.09	229	90	50	113	1.1	2.0						
3	7.08	157	145	60	173	0.5	2.5						
4	7.05	185	190	71	244	1.5	4.0	0.05	0.03	35.77	1.6	0.3	88.19
5	7.03	215	275	64	308	2.1	6.1						
6	7.02	245	350	104	412	2.9	9.0						
7	6.98	224	200	32	444	1.5	10.5						
8	6.9	182	300	65	509	0.8	11.3	0.06	.04	42.02	2.13	0.17	99.66
9	6.95	275	250	48	557	1.7	13.0						
10	7.05	266	400	83	640	1.6	14.6						
11	6.98	264	250	57	697	1.1	15.7						
12	6.92	260	250	68	765	1.1	16.8	0.145	0.056	42.3	1.2	0.084	68.7
13	6.79	260	300	56	821	0.8	17.6						
14	7.3	248	300	48	869	1.6	19.2						
15	7.3	248	210	32	901	1.7	20.9						
16	6.86	237	225	39	940	0.6	21.5	0.037	0.029	30.7	0.68	0.069	43
17	6.94	198	250	48	988	1.0	22.5						
18	6.89	234	950	68	1056	1.5	24.0						
19	7.22	225	800	216	1272	6.9	30.9						
20	7.2	241	800	175	1447	5.8	36.7						
21	7.18	253	500	222	1669	4.7	41.4						
22	7.24	245	450	91	1760	2.2	43.6						
23	7.21	241	300	126	1886	2.4	46.0						
24	7.19	238	300	88	1974	0.7	46.7						
25	7.16	241	200	73	2047	1.7	48.4	0.56	0.058	43.8	2.15	0.039	54.25
26	7.15	242	400	73	2120	0.3	48.7						
27	7.15	246	400	142	2262	0.5	49.2						
28	7.15	247	500	167	2429	1.1	50.3						
29	7.16	251	300	92	2521	0.6	50.9						
30	7.05	260	300	59	2580	4.7	55.6						
31	7.02	259	450	129	2709	2.2	57.8						
32	7.08	251	900	259	2968	0.9	58.7						
33	7.06	250	350	206	3174	0.6	59.3						
34	7.03	249	300	84	3258	0.4	59.7	0.032	0.064	50.85	4.94	0.008	61.6
35	7.1	252	400	147	3405	0.3	60.0						
36	7.17	251	350	98	3503	0.2	60.2						
37	7.09	248	250	84	3587	0.1	60.3						
38	6.96	263	350	596	4183	0.1	60.4	0.026	0.046	44.81	4.32	0.01	51.3
39	6.96	248	200	129	4312	0.2	60.6						
40	6.94	242	350	46	4358	0.2	60.8						
41	7.16	255	300	47	4404	0.1	60.9						
42	7.21	315	3300	52	4457	0.1	61.0	0.06	0.08	61.53	5.05	0.012	107
43	6.98	272	400	56	4513	0.2	61.2						
44	6.86	327	200	336	4849	0.2	61.4						
45	6.94	287	400	72	4921	0.2	61.6						
46	6.82	307	200	74	4995	0.1	61.7	0.089	0.055	120.4	4.39	0.022	69.8
47	6.98	267	400	68	5063	0.2	61.9						
48	6.91	271	450	84	5147	0.1	62.0						
49	7	276	450	142	5289	0.5	62.5						
50	6.82	230	550	52	5341	0.3	62.8	0.113	0.148	112.6	2.77	0.046	103
51	6.81	239	400	295	5636	0.1	62.9						
52	6.61	231	425	134	5770	0.5	63.4						
53	6.58	251	450	54	5824	0.6	64.0						
54	6.48	228	300	59	5883	0.4	64.4						
55	6.51	241	300	77	5960	0.6	65.0	0.185	0.05	106.7	3.43	0.121	105
56	6.67	237	350	78	6038	0.8	65.8						
57	6.69	241	400	62	6100	0.7	66.5						
58	6.75	243	350	67	6167	0.4	66.9	0.133	0.043	102.3	3.11	0.178	103

Table 6.17 Control Sample Self-agglomerated With Addition of Theobacillus
Sample No.17
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micmhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	4.09	273	700	320	320	4.3	4.3	124	11.8	31.7	2.4	0.048	204
1	3.81	270	1200	275	595	7.6	11.9						
2	3.87	251	1600	111	706	19.6	31.5						
3	3.89	283	1800	237	943	29.7	61.2						
4	3.89	283	1700	17	960	34.0	95.2	68.2	22.6	22.1	1.46	0.021	154
5	3.86	305	1150	96	1056	20.0	115.2						
6	3.71	314	2500	275	1331	40.3	155.5						
7	3.75	290	1750	203	1534	29.3	184.8						
8	3.78	281	1600	173	1707	20.6	205.4						
9	3.92	284	1300	138	1845	13.7	219.1	534	75.2	9.05	3.53	0.041	534
10	3.77	294	1200	74	1919	13.1	232.2						
11	3.85	319	1250	196	2115	12.4	244.6						
12	3.89	292	1000	66	2181	6.9	251.5						
13	3.71	336	950	68	2249	12.4	263.9						
14	3.54	357	1200	85	2334	14.4	278.3	313	59.7	6.365	6.66	0.025	263
15	3.9	349	450	44	2378	5.0	283.3						
16	3.69	351	650	534	2912	4.3	287.6						
17	4.15	342	600	149	3061	9.9	297.5						
18	3.53	305	850	866	3927	12.0	309.5						
19	3.53	384	1150	212	4139	14.0	323.5						
20	3.72	345	1000	683	4822	19.3	342.8	159	63.20	9.463	8.93	0.03	311
21	3.81	315	650	158	4980	8.7	351.5						
22	3.5	378	1700	162	5142	43.6	395.1						
23	3.74	348	600	351	5493	6.8	401.9						
24	3.7	362	1000	58	5551	11.6	413.5						
25	3.72	347	1100	45	5596	11.2	424.7	130	20.5	6.154	2.8	0.006	121
26	3.62	376	1350	157	5753	15.2	439.9						
27	3.61	352	1900	559	6312	32.0	471.9						
28	3.62	335	1100	368	6680	17.2	489.1						
29	3.71	340	900	660	7340	12.0	501.1						
30	3.69	335	950	124	7464	12.8	513.9	88.1	15.6	6	2.51	0.081	81.8
31	3.36	335	950	98	7562	13.6	527.5						
32	3.22	378	850	65	7627	9.6	537.1						
33	3.41	401	800	231	7858	10.4	547.5						
34	3.61	361	800	374	8232	12.0	559.5	–	–	–	–	–	–
35	3.69	339	1200	332	8564	16.0	575.5						
36	3.52	374	1200	92	8656	24.8	600.3						
37	3.51	377	1100	47	8703	18.0	618.3						
38	3.58	351	1000	89	8792	22.0	640.3	57.2	27.9	5.69	2.3	0.023	327
39	3.67	311	900	710	9502	20.4	660.7						
40	3.4	368	1400	324	9826	16.0	676.7						
41	3.26	384	1100	36	9862	13.6	690.3						
42	3.28	378	1400	114	9976	16.0	706.3	266	50.2	6.32	4.61	0.013	327
43	3.08	381	1100	44	10020	15.5	721.8						
44	3.12	379	1000	60	10080	16.4	738.1						
45	3.07	378	600	412	10492	16.4	754.5						
46	3.21	369	1400	354	10846	21.2	775.7	156	17.1	4.29	1.59	0.009	121
47	3.08	371	1300	335	11181	14.8	790.5						
48	3.06	390	900	67	11248	15.2	805.7						
49	3.07	381	650	167	11415	12.4	818.1						
50	3.05	379	800	77	11492	12.9	831.0	172	16.5	2.87	1.34	0.007	130

Table 6.18 0.5% Enviroseal with Addition of Thiobacillus (Bacteria - 0.5% Enviro)
Sample No.18
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	6.49	336	750	80	80	2.9	2.9	0.14	0.029	91.6	0.935	0.065	301
1	6.5	216	300	54	134	0.9	3.8						
2	6.4	199	150	22	156	1.3	5.1						
3	6.61	217	175	13	169	2.0	7.1						
4	6.51	238	150	23	192	0.6	7.7	0.14	0.034	34.4	0.709	0.035	52.8
5	6.47	241	150	21	213	1.1	8.8						
6	6.85	193	250	46	259	0.6	9.4						
7	6.75	235	200	36	295	0.2	9.6						
8	6.78	231	200	40	335	1.0	10.6						
9	7.01	241	200	73	408	0.6	11.2	0.33	0.041	18.7	0.877	0.083	32.5
10	6.85	264	350	74	482	1.6	12.8						
11	6.75	283	150	72	554	0.2	13.0						
12	6.82	255	200	47	601	0.3	13.3						
13	6.83	274	200	52	653	0.3	13.6						
14	6.94	220	350	74	727	1.3	14.9	0.08	0.047	56.13	5.1	0.037	55.5
15	6.92	225	200	51	778	0.2	15.1						
16	6.89	230	150	41	819	0.2	15.3						
17	6.81	254	200	105	924	4.9	20.2						
18	6.78	287	300	127	1051	0.9	21.1						
19	6.9	291	300	90	1141	1.3	22.4						
20	6.86	239	150	66	1207	0.2	22.6	0.015	0.037	43.45	3.17	0.015	43.2
21	6.88	245	300	474	1681	0.1	22.7						
22	6.75	258	250	50	1731	0.2	22.9						
23	6.81	286	200	338	2069	0.3	23.2						
24	6.74	290	225	47	2116	0.2	23.4						
25	6.17	330	200	51	2167	0.2	23.6	0.019	0.026	37.74	1.66	0.007	34.7
26	7.14	230	300	50	2217	0.2	23.8						
27	6.69	272	200	310	2527	0.1	23.9						
28	6.89	262	100	6	2533	0.2	24.1						
29	6.61	276	600	299	2832	1.0	25.1						
30	6.66	270	200	115	2947	1.0	26.1	0.284	3.49	134.4	10.9	0.023	181
31	6.59	340	400	241	3188	0.7	26.8						
32	6.61	320	400	572	3760	0.4	27.2						
33	6.3	321	150	290	4050	0.7	27.9						
34	6.56	304	200	222	4272	0.4	28.3						
35	6.51	268	200	73	4345	0.9	29.2						
36	6.41	314	300	272	4617	0.9	30.1						
37	6.46	302	300	71	4688	0.5	30.6						
38	6.76	337	200	80	4768	0.5	31.1	0.182	0.114	36.3	1.57	0.011	35
39	6.38	263	200	50	4818	0.6	31.7						
40	6.33	296	400	509	5327	0.5	32.2						
41	6.35	342	200	316	5643	0.6	32.8						
42	6.35	314	200	293	5936	0.2	33.0	2.63	0.634	84.1	3.94	0.024	80.1
43	6.45	298	200	135	6071	1.0	34.0						
44	6.66	291	200	99	6170	0.9	34.9						
45	6.45	277	200	78	6248	0.3	35.2						
46	6.51	278	200	335	6583	0.5	35.6	0.929	0.392	41.65	1.48	0.015	44.1
47	6.61	281	200	349	6932	0.5	36.1						
48	6.68	291	200	88	7020	0.4	36.5						
49	6.76	262	300	70	7090	0.1	36.6						
50	6.75	259	200	99	7189	0.5	37.1	0.102	0.267	66.9	2.21	0.011	58.8

Table 6.19 0.1% SLS with Addition of Thiobacillus (Bacteria - 0.1% SLS)
Sample No.19
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.25	326	400	35	35	1.4	1.4	0.074	0.035	63.7	0.351	0.012	134
1	6	230	300	61	96	0.6	2.0						
2	6.45	201	125	35	131	0.7	2.7						
3	6.78	212	200	91	222	0.6	3.3						
4	6.75	237	200	57	279	0.6	3.9	0.071	0.612	30.4	0.552	0.069	43
5	6.7	247	150	38	317	0.6	4.5						
6	6.74	194	200	42	359	1.2	5.7						
7	6.75	233	200	37	396	0.7	6.4						
8	6.8	216	175	32	428	0.1	6.5						
9	6.89	232	150	33	461	0.3	6.8	0.043	0.035	19.7	0.526	0.018	27.7
10	6.84	239	150	37	498	0.5	7.3						
11	6.85	265	150	36	534	0.4	7.7						
12	6.82	255	150	16	550	0.3	8.0						
13	6.8	271	150	21	571	0.2	8.2						
14	6.98	218	400	114	685	0.6	8.8	0.316	0.043	76.43	6	0.088	82.1
15	6.89	225	150	31	716	0.3	9.1						
16	7.1	239	250	56	772	0.4	9.5						
17	6.89	237	250	63	835	0.4	9.9						
18	6.91	260	250	355	1190	0.7	10.6						
19	6.88	273	450	488	1678	0.4	11.0	<.005	0.098	49.71	4.18	0.002	34.7
20	6.89	356	250	98	1776	0.2	11.2						
21	6.85	311	150	103	1879	0.2	11.4						
22	6.88	265	150	126	2005	0.2	11.6						
23	6.86	284	400	81	2086	0.2	11.8						
24	6.35	276	200	42	2128	0.1	11.9						
25	6.31	319	200	86	2214	0.2	12.1	23.6	23.1	154.5	16.8	0.083	282
26	7.19	249	100	191	2405	0.1	12.2						
27	6.63	300	100	191	2596	0.2	12.4						
28	6.74	243	150	82	2678	0.2	12.6						
29	6.68	271	150	273	2951	0.4	13.0						
30	6.76	270	150	69	3020	0.2	13.2	_	_	_	_	_	_
31	6.78	252	650	59	3079	0.2	13.4						
32	6.75	265	500	189	3268	0.4	13.8						
33	6.45	309	650	163	3431	0.7	14.5						
34	6.56	310	300	93	3524	0.2	14.7						
35	6.52	266	200	80	3604	0.1	14.8	0.038	0.032	23.57	0.98	0.011	20.4
36	6.55	302	350	343	3947	0.4	15.2						
37	6.56	284	250	50	3997	0.4	15.6						
38	6.61	302	600	100	4097	0.5	16.1						
39	6.65	254	150	56	4153	0.5	16.6						
40	6.68	261	700	611	4764	3.5	20.1	2.59	0.649	193.3	7.37	0.085	265
41	6.66	271	175	220	4984	0.3	20.4						
42	6.68	281	200	119	5103	0.3	20.7						
43	6.65	262	200	54	5157	0.3	21.0						
44	6.64	280	200	60	5217	0.2	21.3						
45	6.64	284	200	70	5287	0.2	21.5	_	_	_	_	_	_
46	6.68	340	200	74	5361	5.2	26.7						
47	6.72	330	175	77	5438	0.2	26.9						
48	6.73	282	200	63	5501	0.3	27.2						
49	6.74	272	300	71	5572	0.3	27.6						
50	6.69	269	200	67	5639	0.3	27.8	0.19	0.156	76.13	2.53	0.009	69.5

Table 6.20 0.1% Sodium Silicate with Addition of Thiobacillus (0.1% Sod Sil)
Sample No.20
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micmhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.59	233	400	22	22	3.5	3.5	0.155	0.049	134	0.172	0.021	273
1	7.35	218	300	30	52	1.2	4.7						
2	7.05	209	250	53	105	0.5	5.2						
3	7.19	222	250	74	179	3.9	9.1						
4	6.65	244	400	57	236	3.1	12.2	0.08	0.035	65.1	0.923	0.041	108
5	6.7	258	500	62	298	6.1	18.3						
6	6.95	272	1100	115	413	4.1	22.4						
7	6.85	259	500	70	483	5.5	27.9						
8	6.85	251	700	90	573	8.6	36.5	0.049	0.037	45.8	1.78	0.039	83.1
9	6.89	254	800	80	653	9.7	46.2						
10	6.85	266	700	70	723	5.3	51.5						
11	6.74	261	650	77	800	6.7	58.2						
12	6.8	260	550	64	864	5.4	63.6						
13	6.89	267	500	80	944	43.7	107.3						
14	6.85	285	250	206	1150	6.1	113.4	0.891	0.165	170.3	17.7	0.299	303
15	6.89	205	350	69	1219	1.5	114.9						
16	7.03	265	400	73	1292	0.4	115.3						
17	6.91	288	600	138	1430	3.3	118.6						
18	6.86	251	600	425	1855	4.1	122.7						
19	6.84	273	600	97	1952	7.5	130.2	0.218	0.226	119.3	12.3	0.129	261
20	6.96	275	400	90	2042	3.7	133.9						
21	6.86	278	350	232	2274	1.5	135.4						
22	6.89	268	300	611	2885	4.9	140.3						
23	6.82	291	300	137	3022	1.5	141.8						
24	6.72	277	600	47	3069	4.1	145.9						
25	6.81	297	550	51	3120	4.3	150.2	0.217	0.158	59.71	4.18	0.075	91.1
26	6.9	255	750	60	3180	1.6	151.8						
27	6.74	294	600	260	3440	1.9	153.7						
28	6.64	253	500	69	3509	3.2	156.9						
29	6.65	274	450	208	3717	4.9	161.8						
30	6.93	269	500	120	3837	3.5	165.3	0.031	0.06	100.3	4.84	0.011	84
31	6.81	278	700	114	3951	3.9	169.2						
32	6.82	281	700	74	4025	0.1	169.3						
33	6.62	271	600	571	4596	3.7	173.0						
34	6.67	310	600	534	5130	3.1	176.1						
35	6.68	260	600	108	5238	3.7	179.8						
36	6.69	263	800	639	5877	2.5	182.3						
37	6.7	272	600	185	6062	2.4	184.7						
38	6.73	306	200	54	6116	2.2	186.9	1.06	0.431	143.5	5.39	0.071	204
39	6.62	265	600	547	6663	2.5	189.4						
40	6.72	302	400	143	6806	0.2	189.6						
41	6.71	281	600	56	6862	3.7	193.3						
42	6.65	290	650	184	7046	3.2	196.5	0.066	0.08	100	4.03	0.015	88.1
43	6.85	270	650	48	7094	3.6	200.1						
44	6.72	261	500	67	7161	3.1	203.2						
45	6.81	262	450	264	7425	0.3	203.5						
46	6.83	291	700	64	7489	0.1	203.6						
47	6.91	292	650	78	7567	0.1	203.7						
48	6.67	286	650	60	7627	5.3	209.0						
49	6.72	272	650	93	7720	2.6	211.6						
50	6.81	278	650	65	7785	2.4	214.0	0.428	0.731	164	5.92	0.053	207

Table 6.21 60% Portland cement/40% Fly ash with Addition of Thiobacillus (Bacteria - 60%PC/40%FA)
Sample No.21
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.1	241	710	138	138	4.0	4.0	0.11	0.035	142	2.65	0.039	305
1	7.05	221	400	71	209	1.4	5.4						
2	6.7	197	250	70	279	0.5	5.9						
3	6.92	210	500	246	525	1.0	6.9						
4	6.91	249	400	47	572	8.8	15.7	0.062	0.08	55.5	1.6	0.045	104
5	6.85	264	500	83	655	4.8	20.5						
6	6.82	263	800	116	771	10.1	30.6						
7	6.85	245	600	64	835	9.4	40.0						
8	6.8	262	500	83	918	8.1	48.1	0.061	0.146	47.5	2.59	0.064	99.4
9	6.82	252	500	81	999	5.9	54.0						
10	6.81	258	850	150	1149	10.9	64.9						
11	6.75	235	800	75	1224	5.2	70.1						
12	6.72	244	550	71	1295	7.1	77.2						
13	6.71	237	550	68	1363	6.1	83.3						
14	6.75	193	850	223	1586	10.7	94.0	8.93	6.19	146.3	26.3	0.182	375
15	6.7	205	550	131	1717	4.7	98.7						
16	6.65	218	650	148	1865	7.5	106.2						
17	6.6	157	850	250	2115	1.0	107.2						
18	6.55	179	800	381	2496	11.7	118.9						
19	5.88	279	850	106	2602	14.7	133.6	3.82	14.4	160.4	20.3	0.105	466
20	5.65	294	700	100	2702	7.7	141.3						
21	5.43	292	750	107	2809	10.7	152.0						
22	5.04	312	1200	188	2997	13.7	165.7						
23	5.4	324	700	101	3098	8.8	174.5						
24	4.65	335	950	48	3146	10.5	185.0	8.19	15	119	16.4	0.078	298
25	4.52	331	750	77	3223	9.8	194.8						
26	4.72	310	1320	142	3365	14.5	209.3						
27	4.36	288	900	306	3671	14.0	223.3						
28	4.27	298	1200	83	3754	19.3	242.6						
29	4.16	315	1300	208	3962	18.8	261.4	0.132	0.422	155	7.11	0.118	191.7
30	4.14	318	1500	614	4576	18.8	280.2						
31	4.87	309	1400	353	4929	18.7	298.9						
32	4.42	304	1200	81	5010	24.8	323.7						
33	4.05	346	1100	175	5185	20.8	344.5						
34	4	370	1100	267	5452	22.8	367.3	_	_	_	_	_	_
35	4.08	345	1400	267	5719	20.4	387.7						
36	4.15	350	1600	143	5862	28.0	415.7						
37	4.12	326	1000	56	5918	23.2	438.9						
38	4.13	352	1600	56	5974	24.0	462.9	1.3	68.9	159.9	25.6	0.073	627
39	4.09	335	1250	69	6043	20.0	482.9						
40	3.82	345	1600	473	6516	28.0	510.9						
41	3.6	352	1600	473	6989	26.0	536.9						
42	3.55	361	1650	52	7041	29.6	566.5	48.2	110	199.1	39.8	0.1	926
43	3.61	341	1400	75	7116	20.0	586.5						
44	3.51	330	1400	88	7204	19.6	606.1						
45	3.62	326	1450	121	7325	24.4	630.5						
46	3.58	372	1600	80	7405	32.0	662.5	178	0.1	160.9	25.2	0.047	692
47	3.6	381	1500	88	7493	26.0	688.5						
48	3.59	340	1250	60	7553	28.0	716.5						
49	3.58	351	2000	96	7649	38.4	754.9						
50	3.61	369	1600	84	7733	36.0	790.9	418	198	49.5	189.1	0.075	1080

Table 6.22 60% Gypsum/40% Portland Cement with Addition of Thiobacillus (Bacteria - 60%GY/40%PC)
Sample No.22
Sample Weight 1000 grams

Cycle No.	Leachate Analyses							ICP ANALYSIS (mg/L)					
Week	pH	EMF mV	Conductivity micromhos/cm	Sulphate mg/L	Cum. Sulphate	Acidity mg/L	Cum. Acidity	Fe	Ni	Ca	Mg	Cu	S
0	7.02	241	750	48	48	1.5	1.5	0.129	0.091	140	3.35	0.074	200
1	6.96	227	550	129	177	0.8	2.3						
2	6.6	193	300	50	227	1.2	3.5						
3	6.76	203	450	101	328	3.0	6.5						
4	6.78	280	600	97	425	4.1	10.6	0.099	0.2	53.6	1.52	0.034	76.4
5	6.6	233	500	81	506	7.2	17.8						
6	6.71	258	850	174	680	14.2	32.0						
7	6.7	238	550	70	750	7.9	39.9						
8	6.65	251	550	99	849	8.6	48.5						
9	6.6	251	550	141	990	8.0	56.5	0.08	0.394	49.5	2.75	0.053	78.7
10	6.58	274	600	114	1104	8.4	64.9						
11	6.2	237	650	146	1250	12.0	76.9						
12	6.05	272	750	227	1477	14.2	91.1						
13	5.8	289	550	283	1760	9.9	101.0						
14	5.5	244	1600	115	1875	30.1	131.1	68.7	108	120.8	113	0.049	799
15	5.25	241	800	31	1906	11.7	142.8						
16	4.95	291	1300	44	1950	4.0	146.8						
17	4.5	303	1400	105	2055	12.4	159.2						
18	4.15	292	1300	1073	3128	28.7	187.9						
19	4.5	255	1600	457	3585	24.8	212.7						
20	3.85	344	1800	872	4457	16.9	229.6	389	231	44.1	119	0.771	821
21	3.81	335	1700	485	4942	33.8	263.4						
22	3.58	356	3000	211	5153	16.1	279.5						
23	3.83	350	1200	122	5275	16.0	295.5						
24	3.73	372	2000	34	5309	34.0	329.5						
25	3.59	365	2000	42	5351	34.0	363.5	282	86.7	26.24	32.1	0.047	354
26	3.4	370	2500	84	5435	31.6	395.1						
27	3.44	345	2500	703	6138	26.0	421.1						
28	3.52	332	1800	57	6195	28.0	449.1						
29	3.64	325	950	947	7142	20.0	469.1						
30	3.51	344	1700	762	7904	24.8	493.9						
31	3.93	304	2000	741	8645	29.2	523.1						
32	3.61	329	1700	81	8726	27.2	550.3						
33	3.54	368	1200	249	8975	21.6	571.9						
34	3.55	368	1800	79	9054	29.2	601.1	63.8	61.9	241	28.12	0.075	346.4
35	3.79	370	2200	53	9107	28.4	629.5						
36	3.77	345	2200	56	9163	24.8	654.3						
37	3.67	349	1800	335	9498	20.4	674.7						
38	3.73	355	1750	54	9552	21.2	695.9	113	37.2	30.2	3.74	0.065	262
39	3.98	367	1100	700	10252	22.4	718.3						
40	3.38	335	1800	40	10292	24.8	743.1						
41	3.42	361	1550	49	10341	25.3	768.4						
42	3.43	368	1400	48	10389	18.8	787.2	445	82.8	41.14	8.51	0.033	537
43	3.46	339	1400	70	10459	17.2	804.4						
44	3.43	330	1200	77	10536	20.0	824.4						
45	3.41	324	700	87	10623	19.2	843.6						
46	3.53	356	1800	226	10849	22.8	866.4	148	21.5	31.41	1.63	0.034	164
47	3.43	361	1900	230	11079	28.4	894.8						
48	3.39	334	700	80	11159	24.4	919.2						
49	3.41	361	1000	84	11243	12.8	932.0						
50	3.51	342	1600	67	11310	13.2	945.2	315	39.3	2.93	42.8	<.002	274

APPENDIX (D)

The Results of pH as an Indicator of AMD Generation

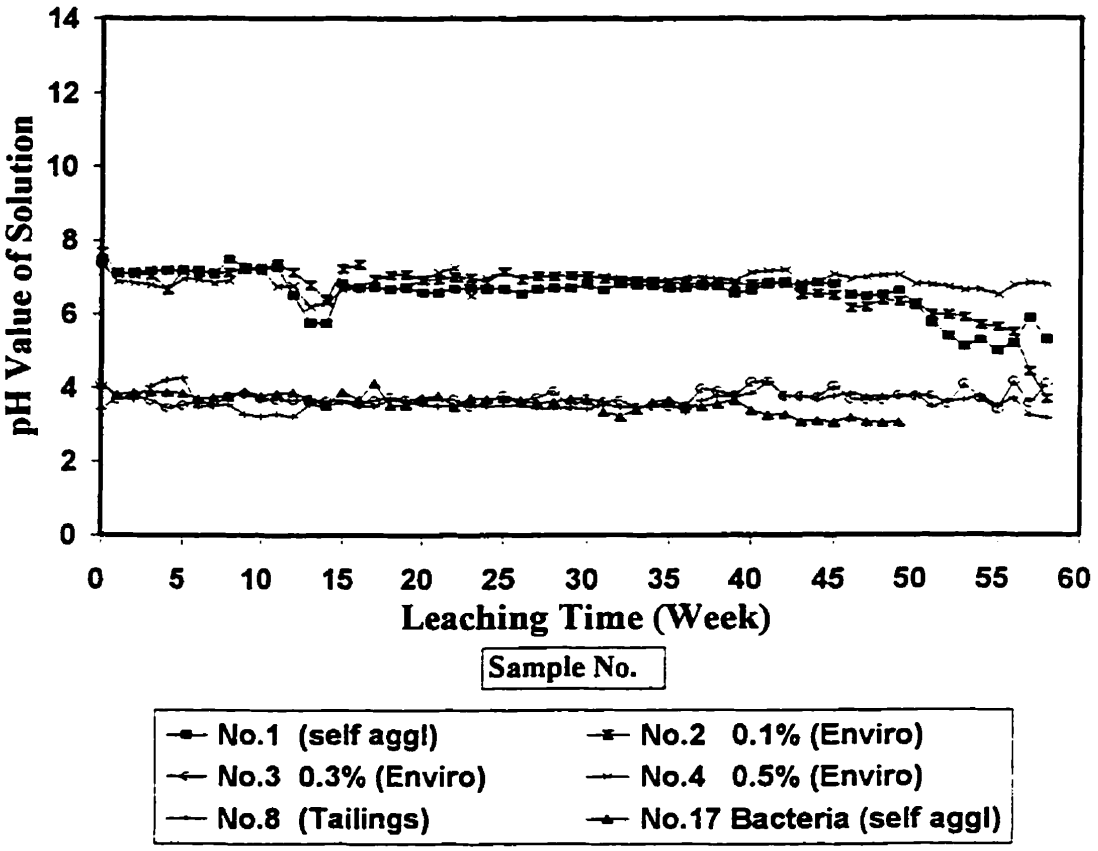


Figure D1. pH vs Leaching Time

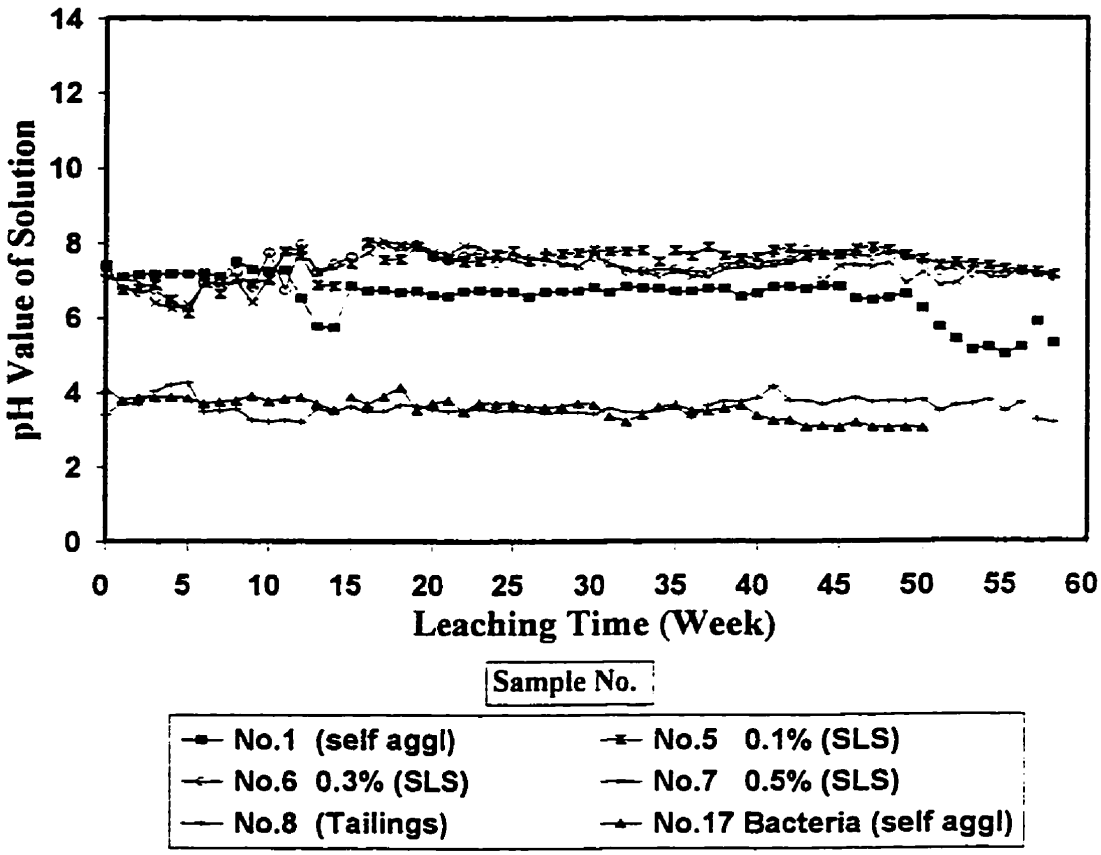


Figure D2. pH vs Leaching Time

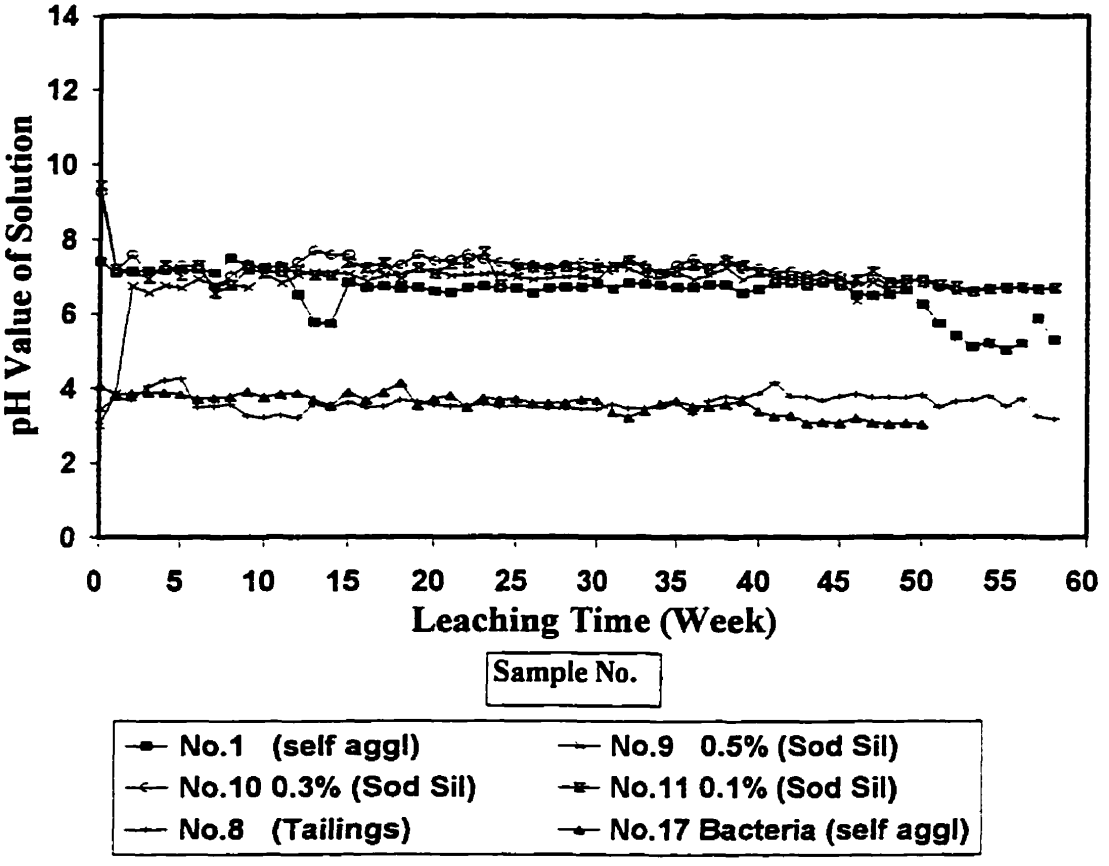


Figure D3. pH vs Leaching Time

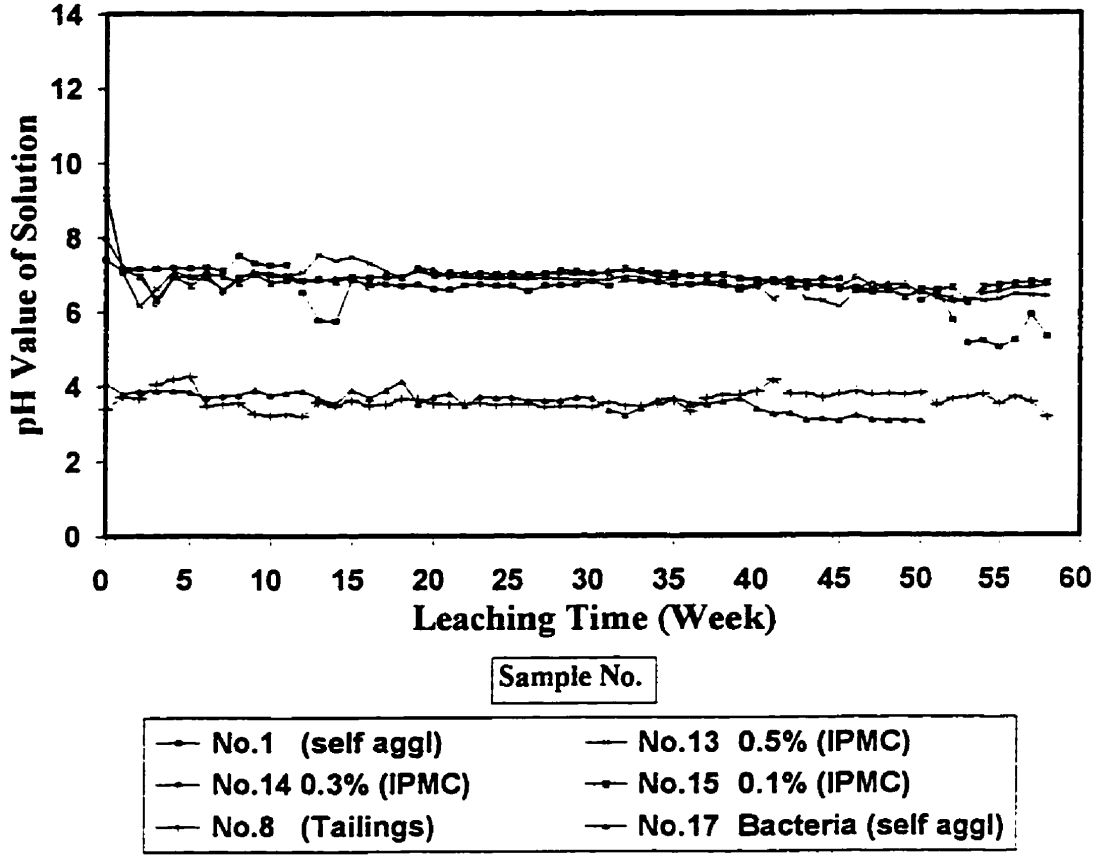


Figure D4. pH vs Leaching Time

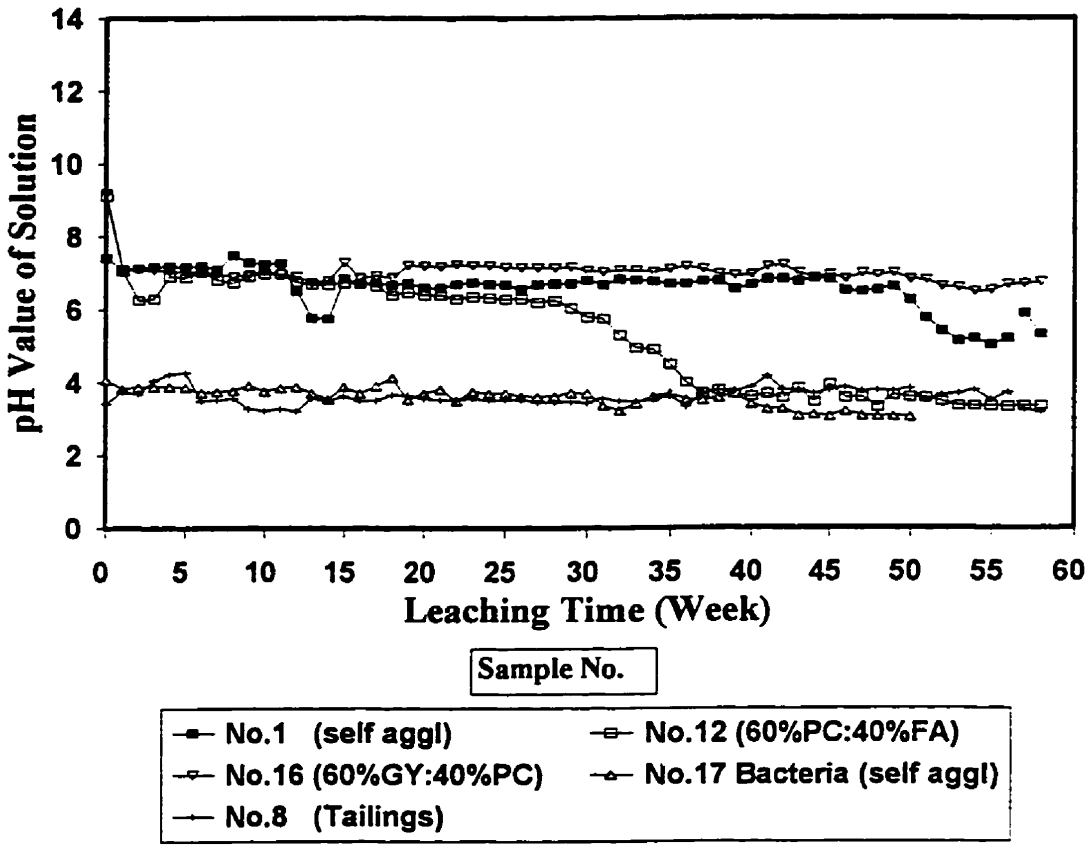


Figure D5. pH vs Leaching Time

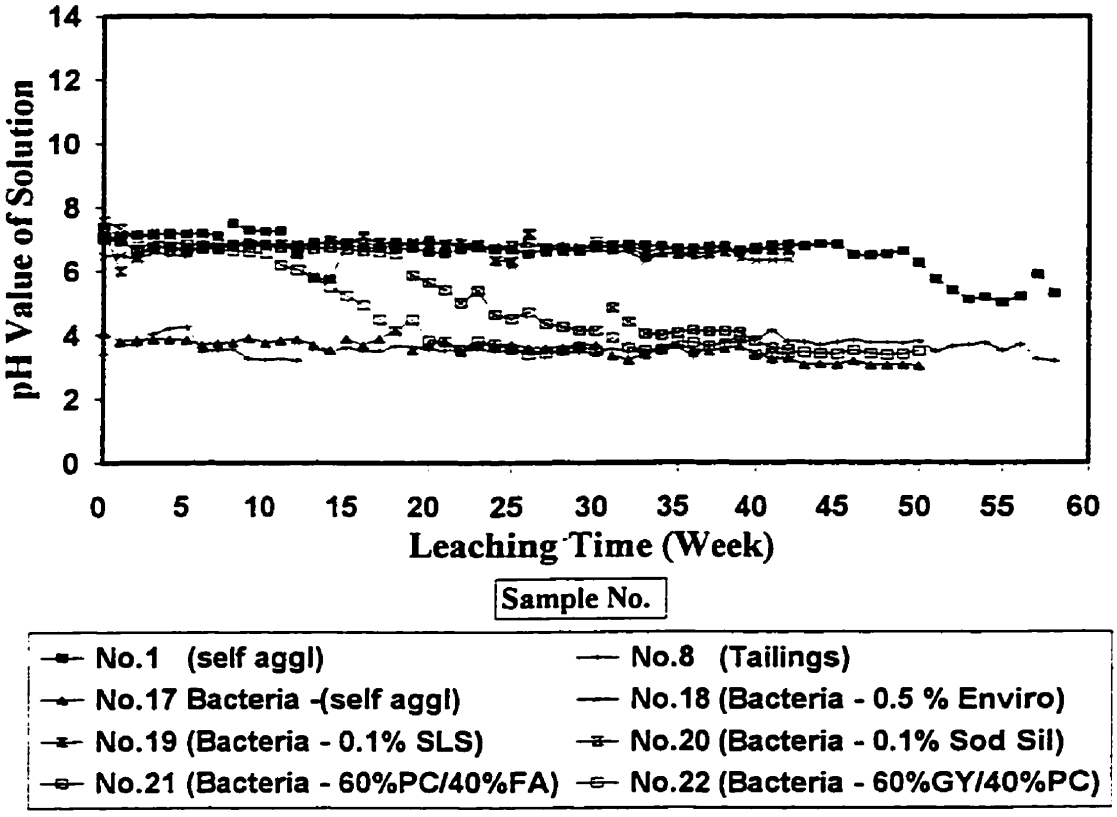


Figure D6. pH vs Leaching Time

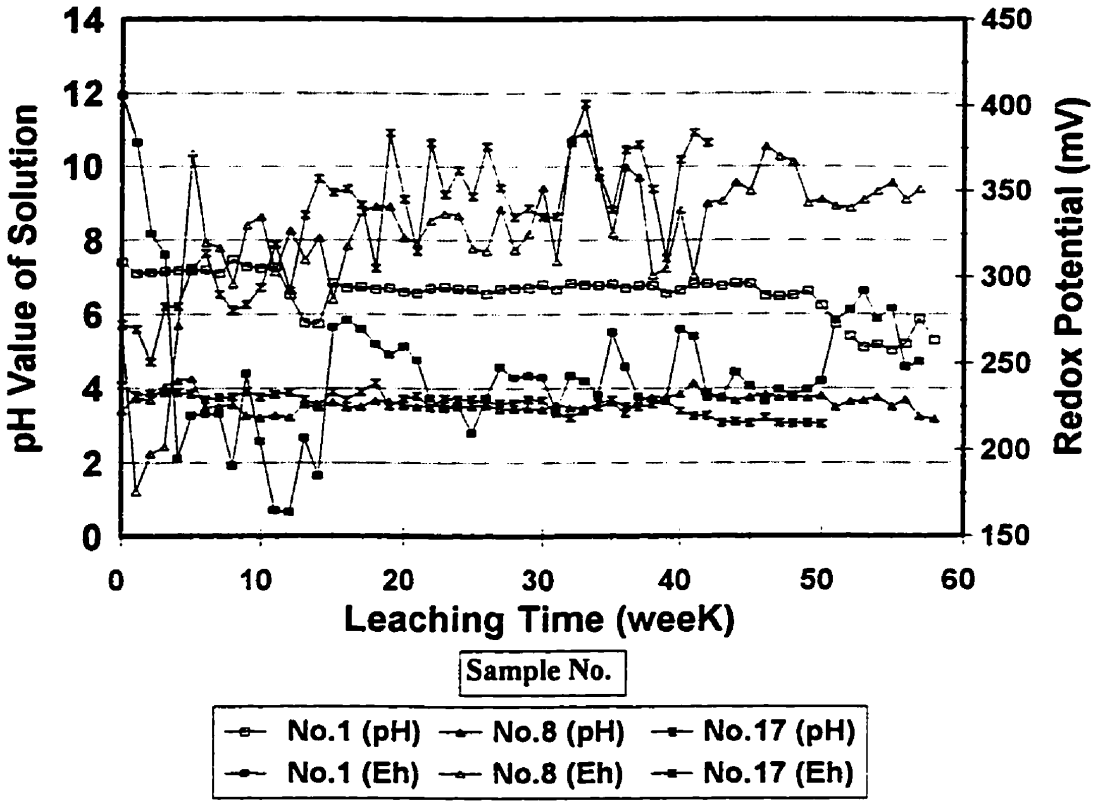


Figure D7. pH/Redox Potential vs Leaching Time

APPENDIX (E)

Result of Redox Potential

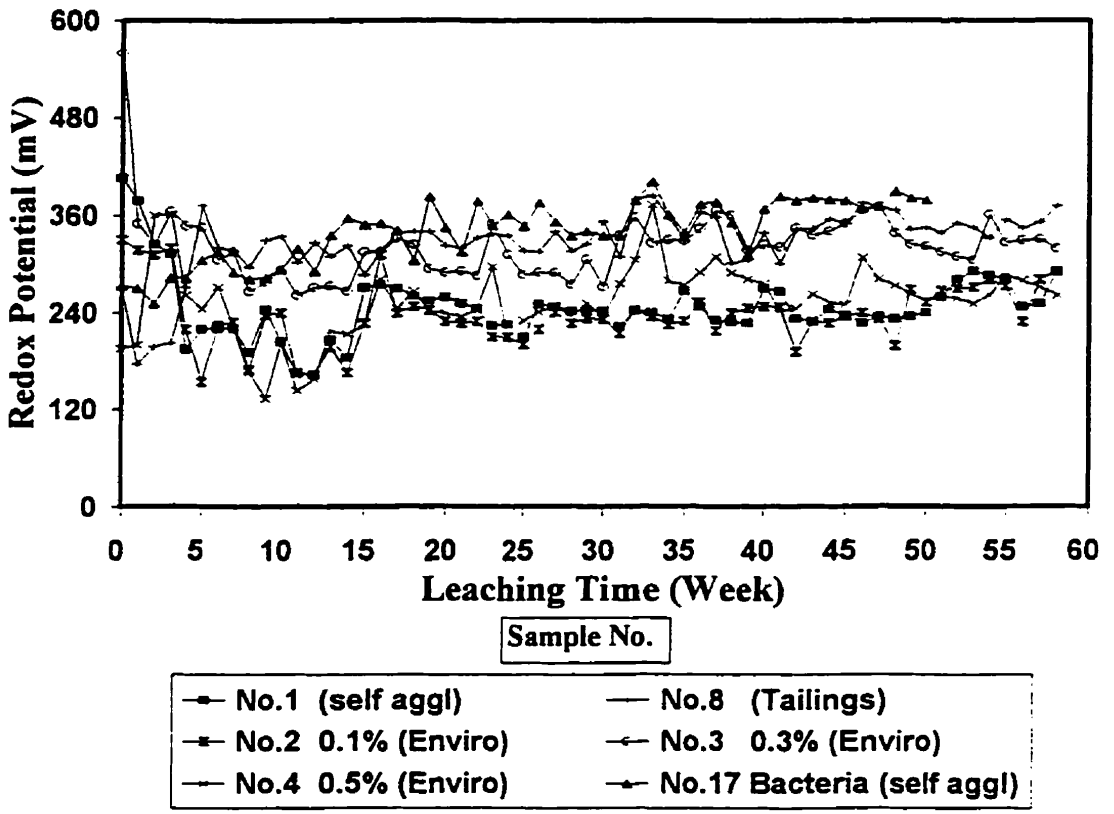


Figure E1. Redox Potential vs Leaching Time

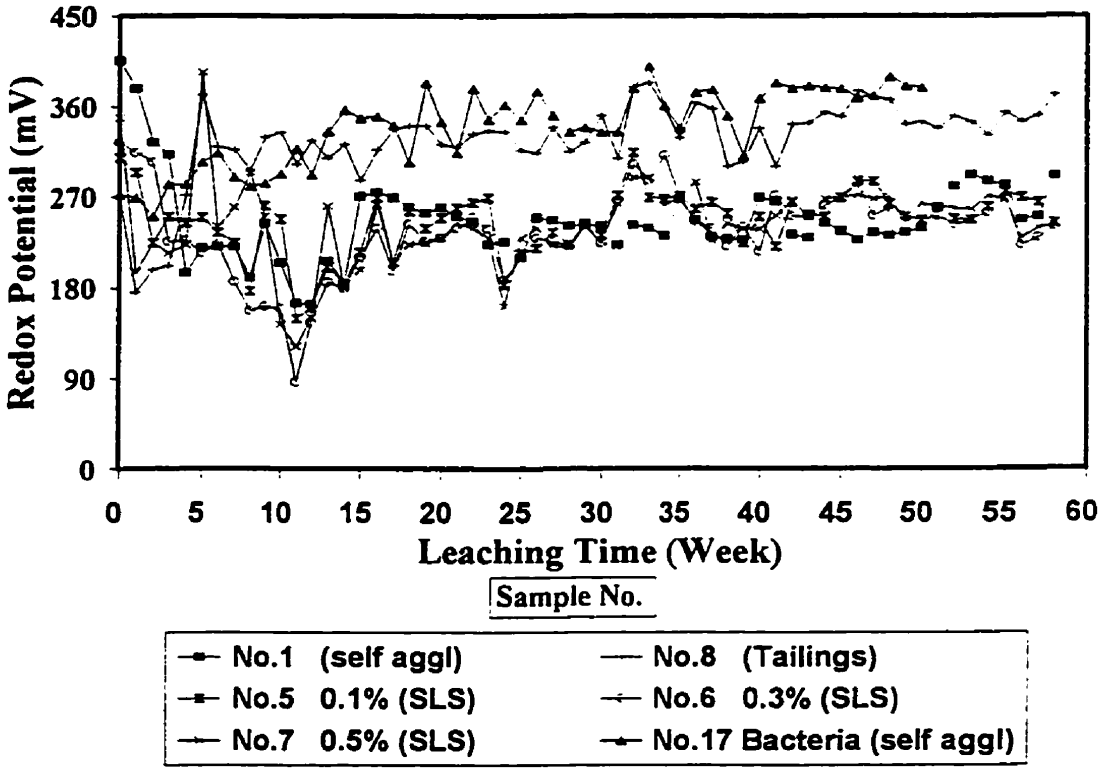


Figure E2. Redox Potential vs Leaching Time

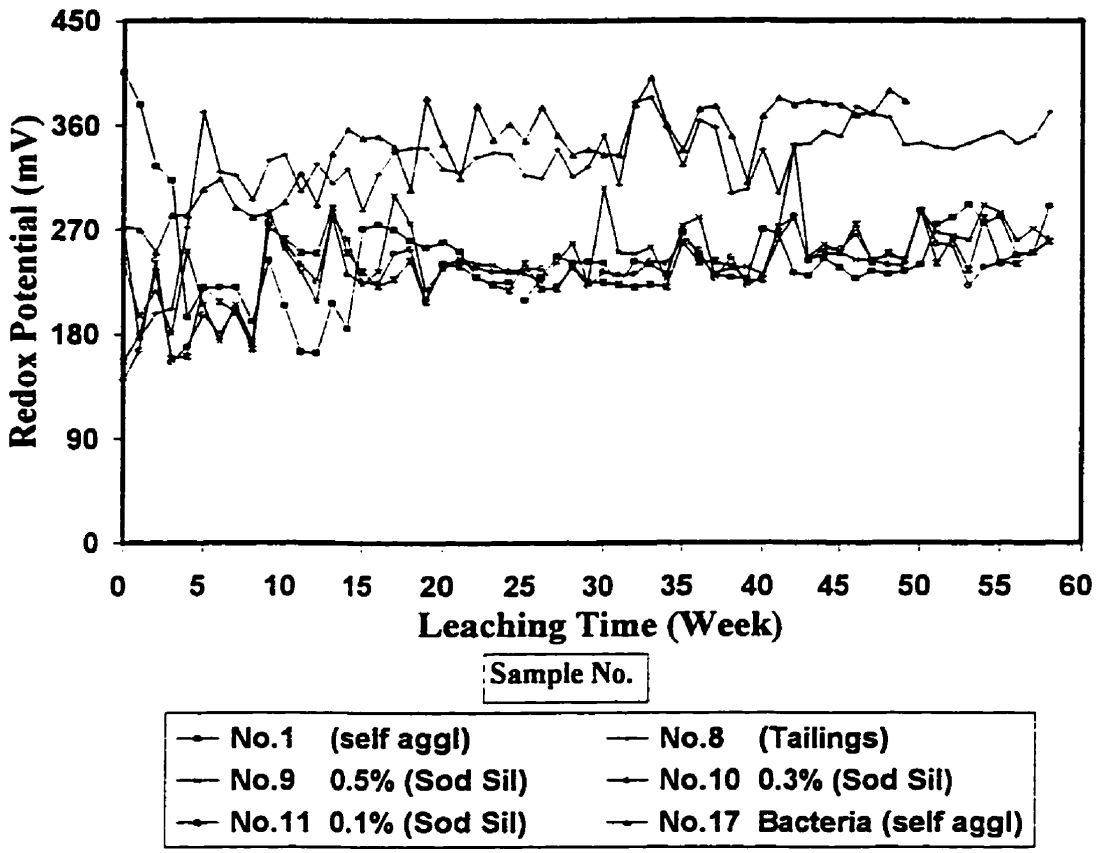


Figure E3. Redox Potential vs Leaching Time

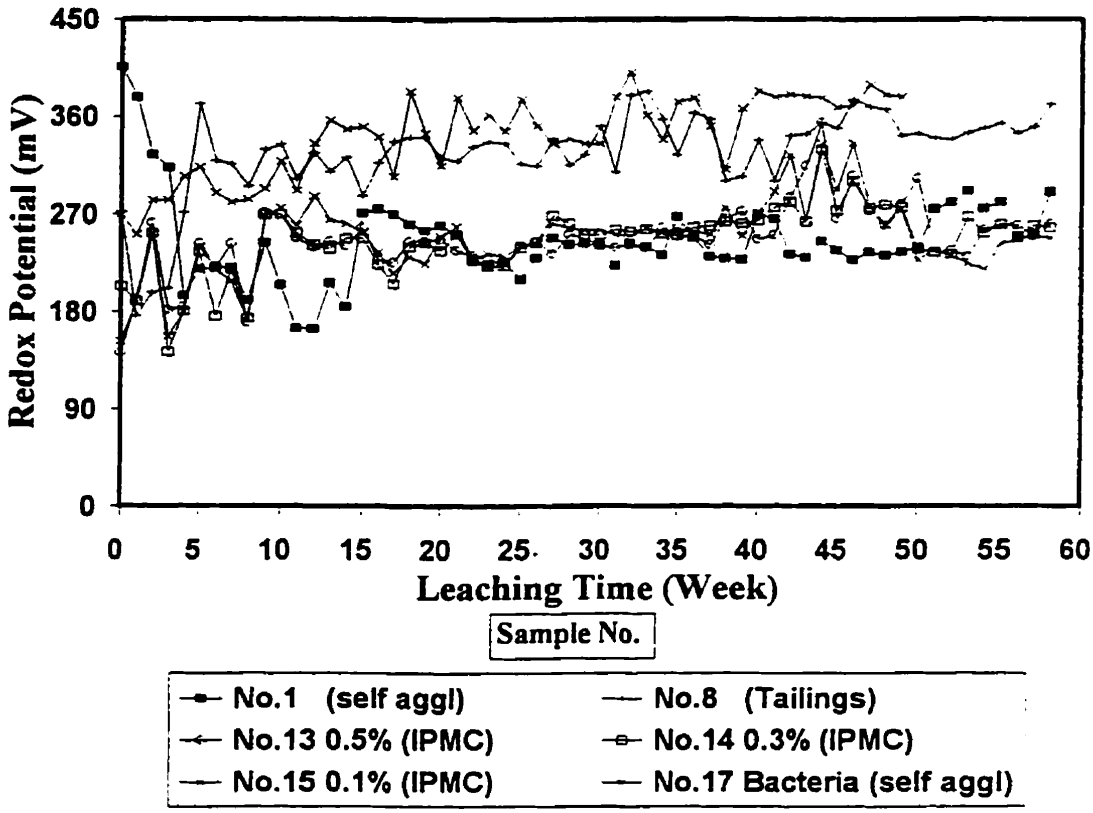


Figure E4. Redox Potential vs Leaching Time

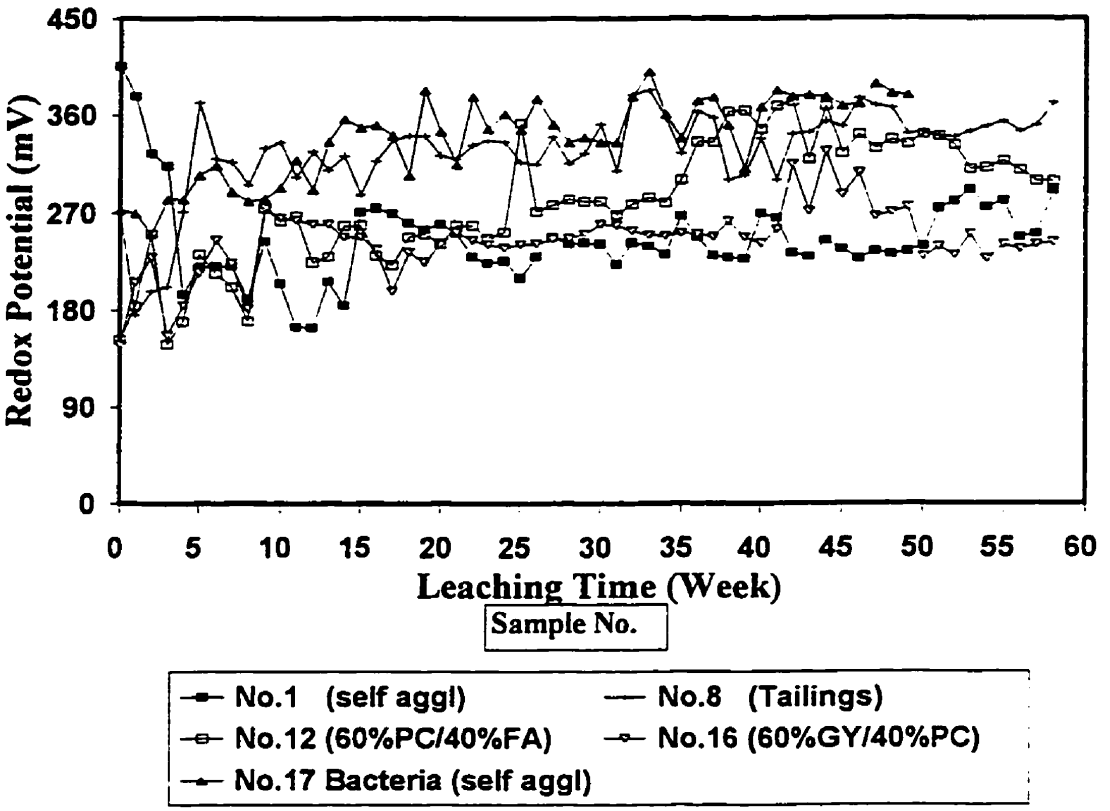


Figure E5. Redox Potential vs Leaching Time

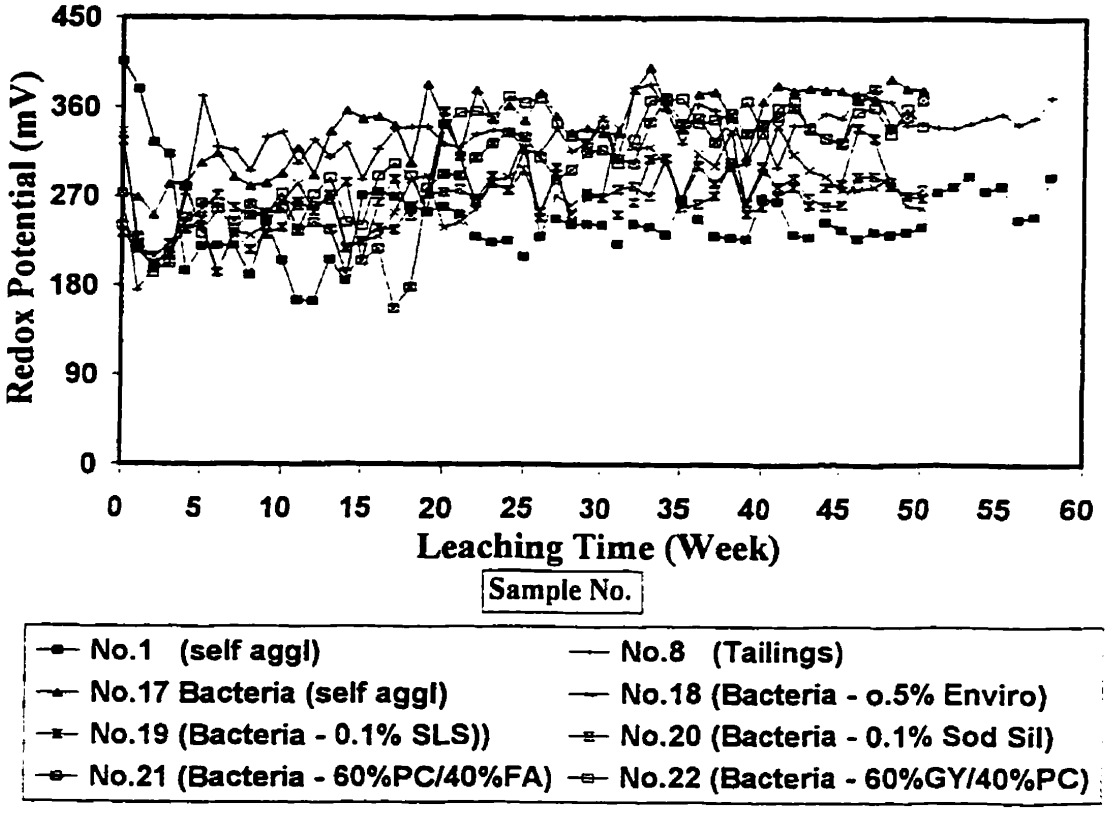


Figure E6. Redox Potential vs Leaching Time

APPENDIX (F)

Conductivity Results

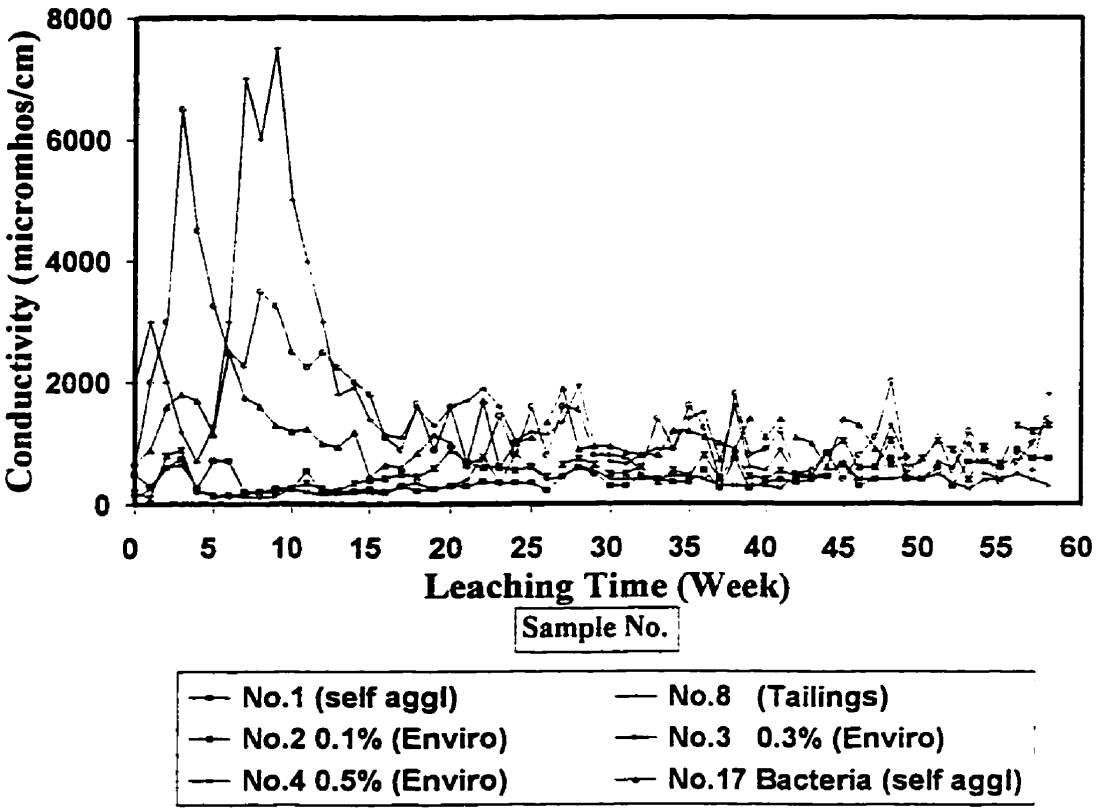


Figure F1. Conductivity vs Leaching Time

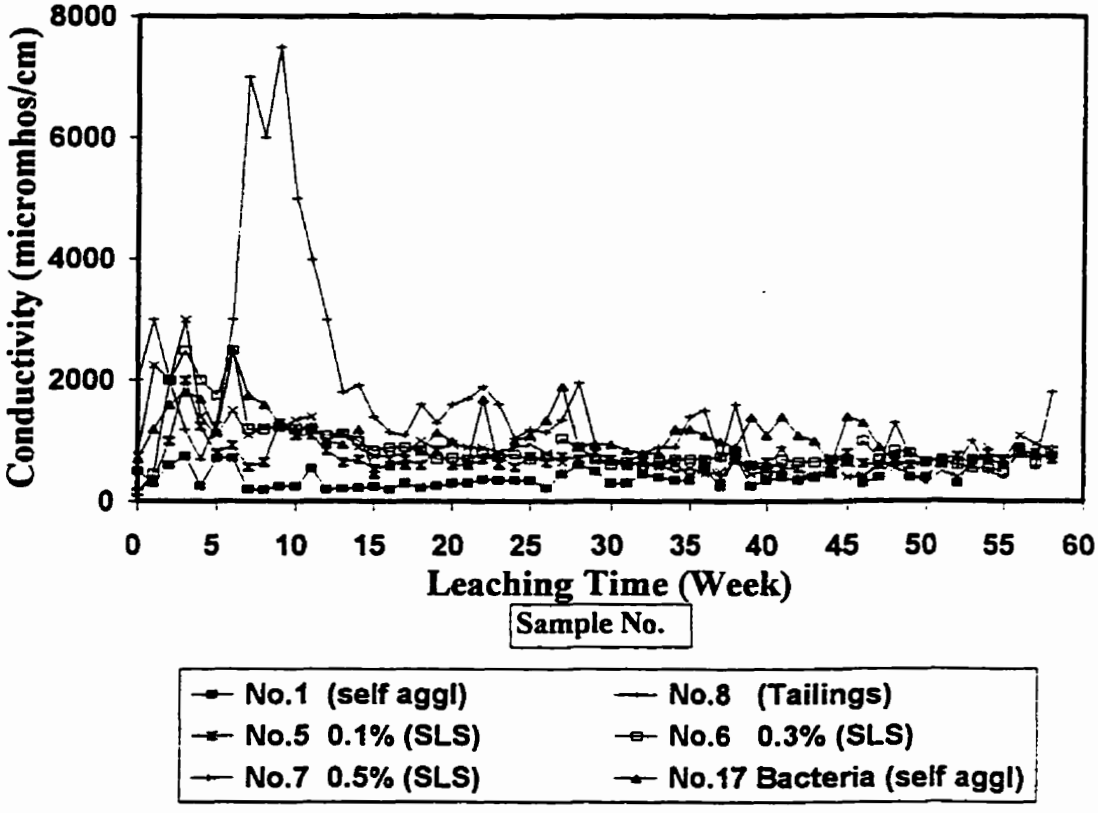


Figure F2. Conductivity vs Leaching Time

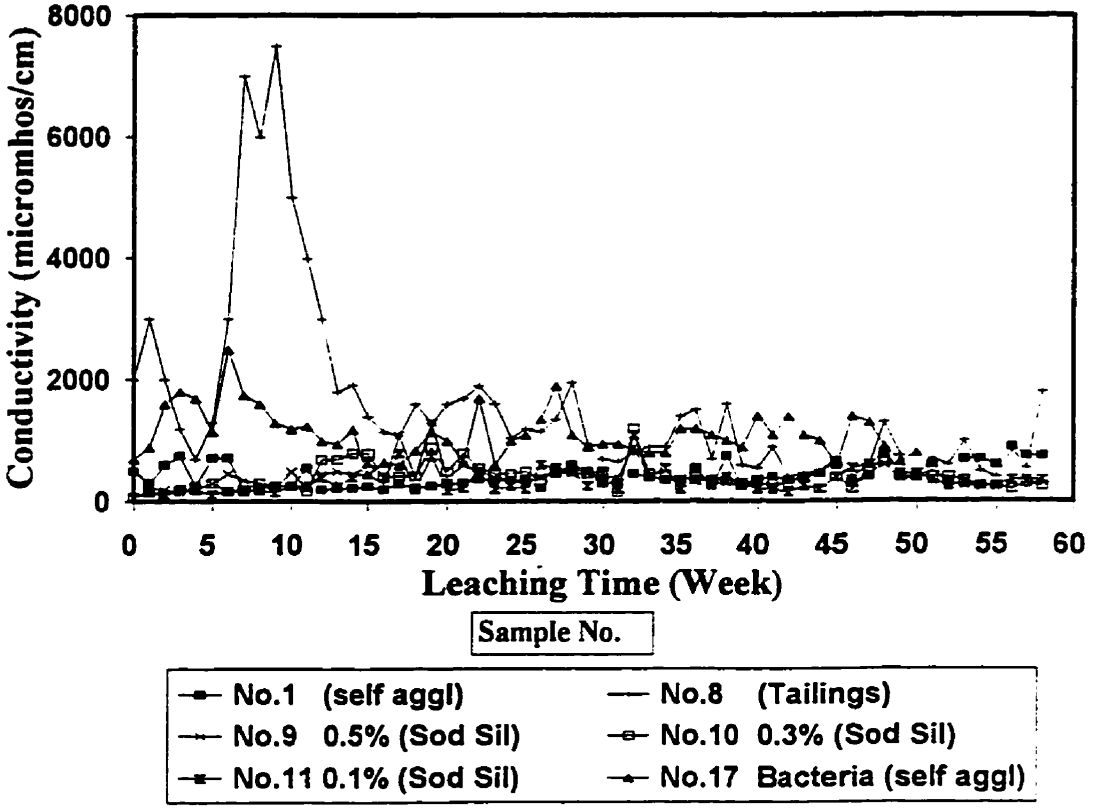


Figure F3. Conductivity vs Leaching Time

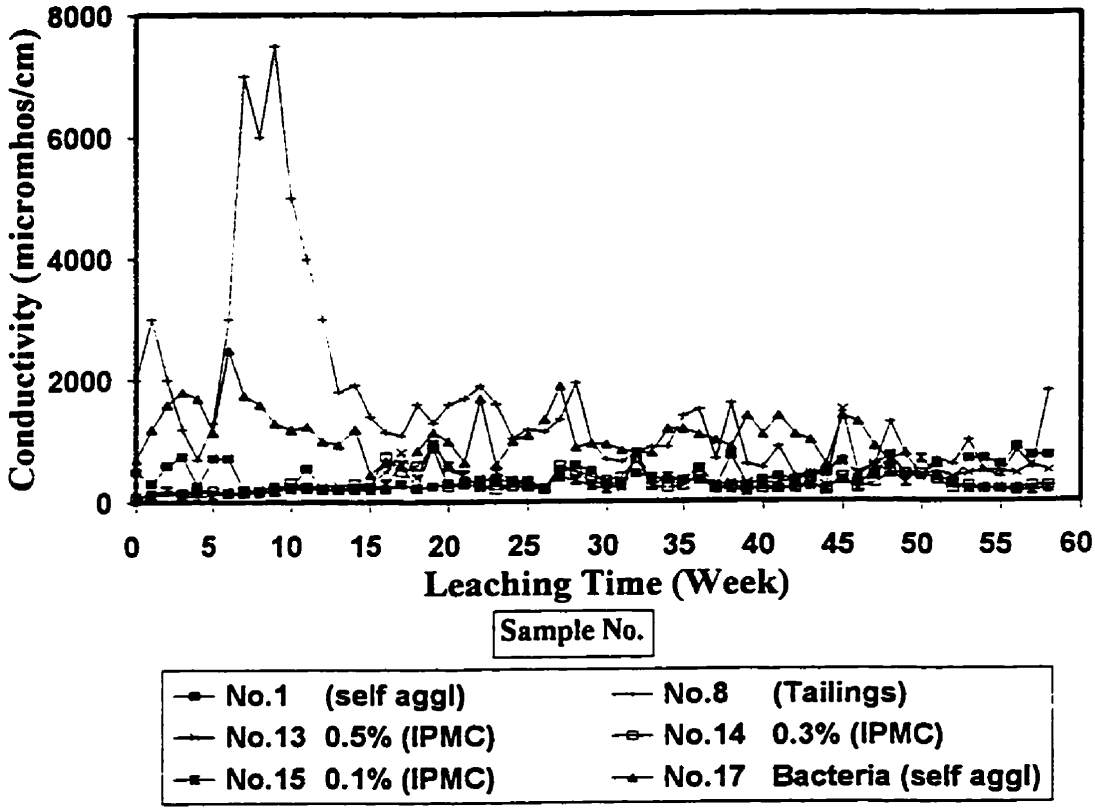


Figure F4. Conductivity vs Leaching Time

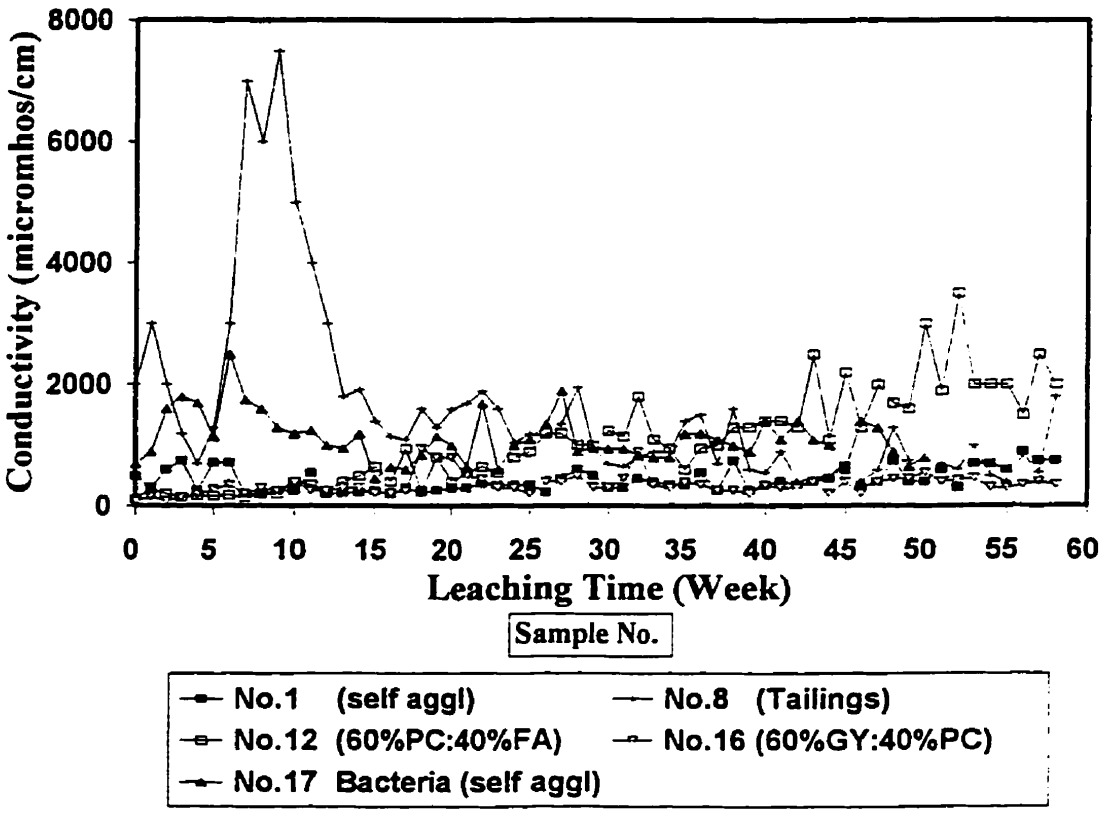


Figure F5. Conductivity vs Leaching Time

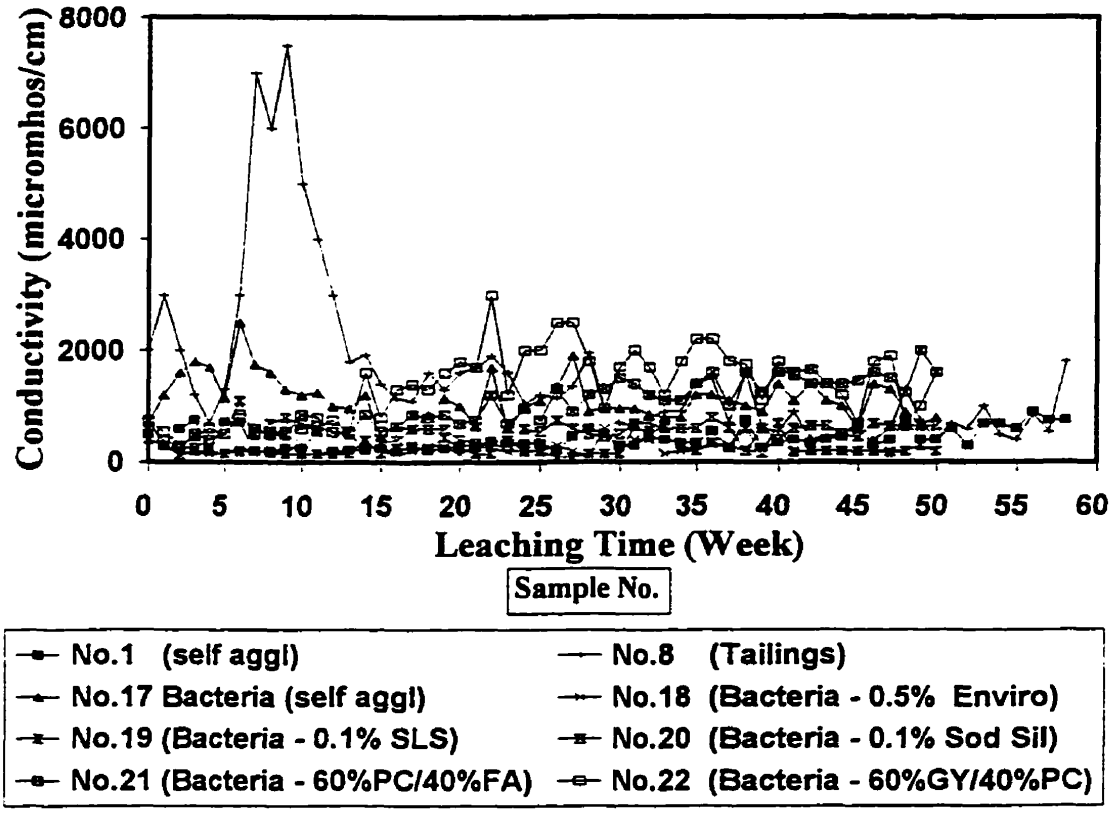


Figure F6. Conductivity vs Leaching Time

APPENDIX (G)

Results of the Leachate Sulphate and Cumulative Sulphate

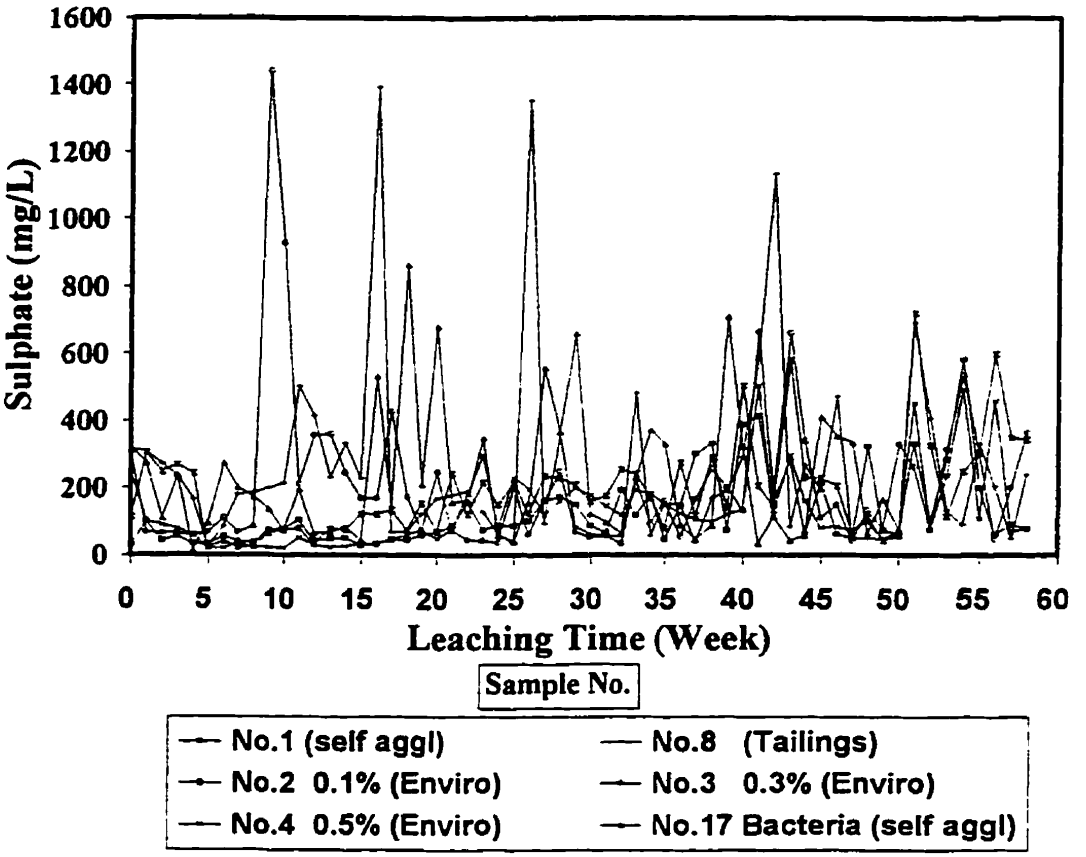


Figure G1 Sulphate vs Leaching Time

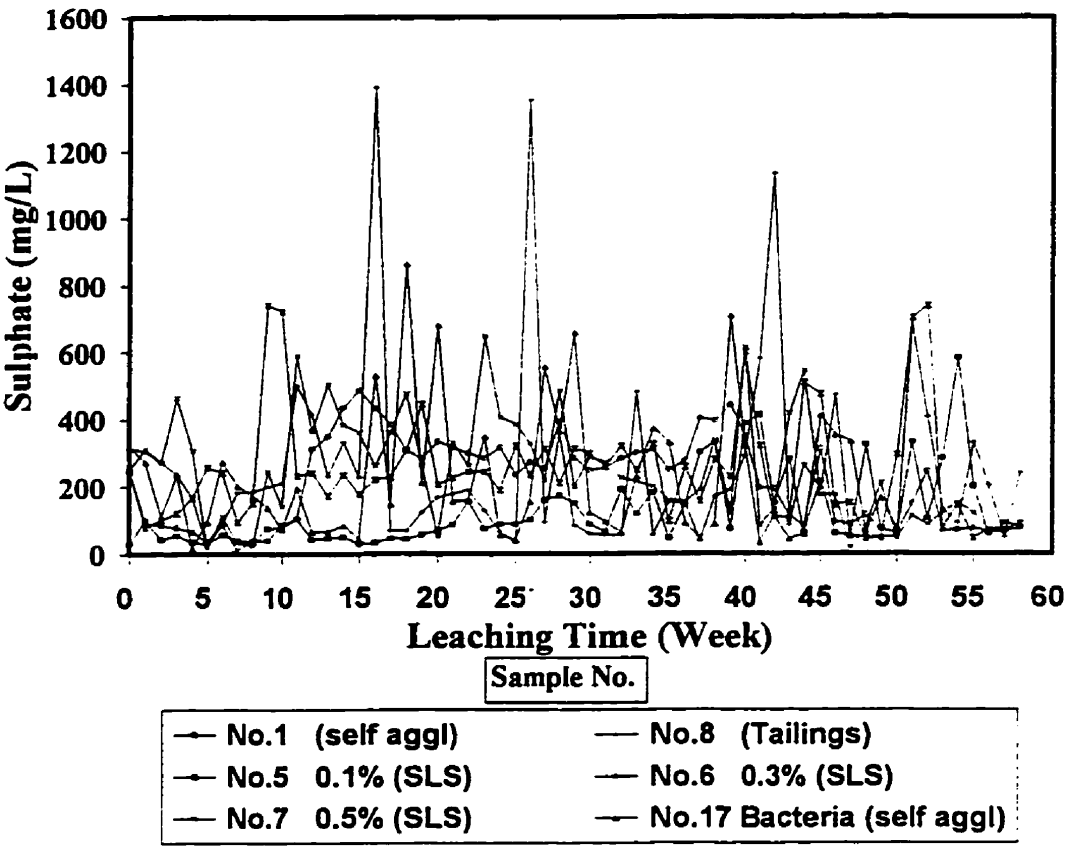


Figure G2. Sulphate vs Leaching Time

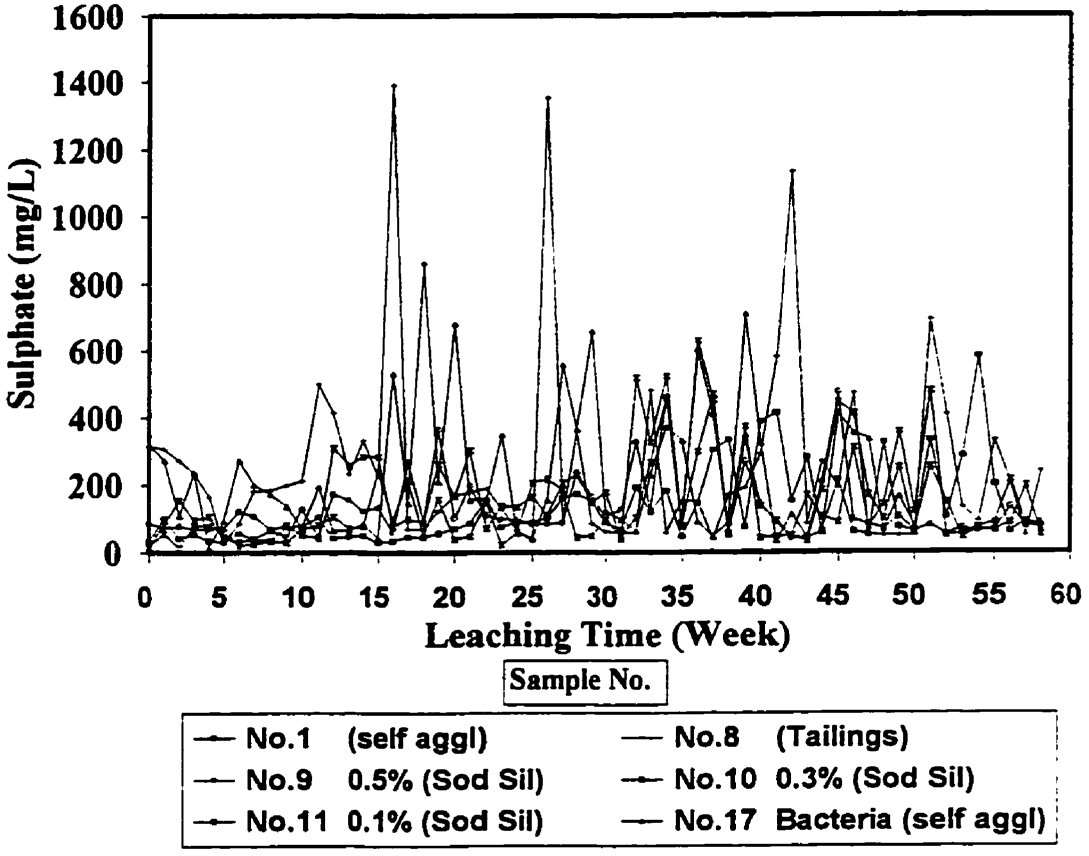


Figure G3. Sulphate vs Leaching Time

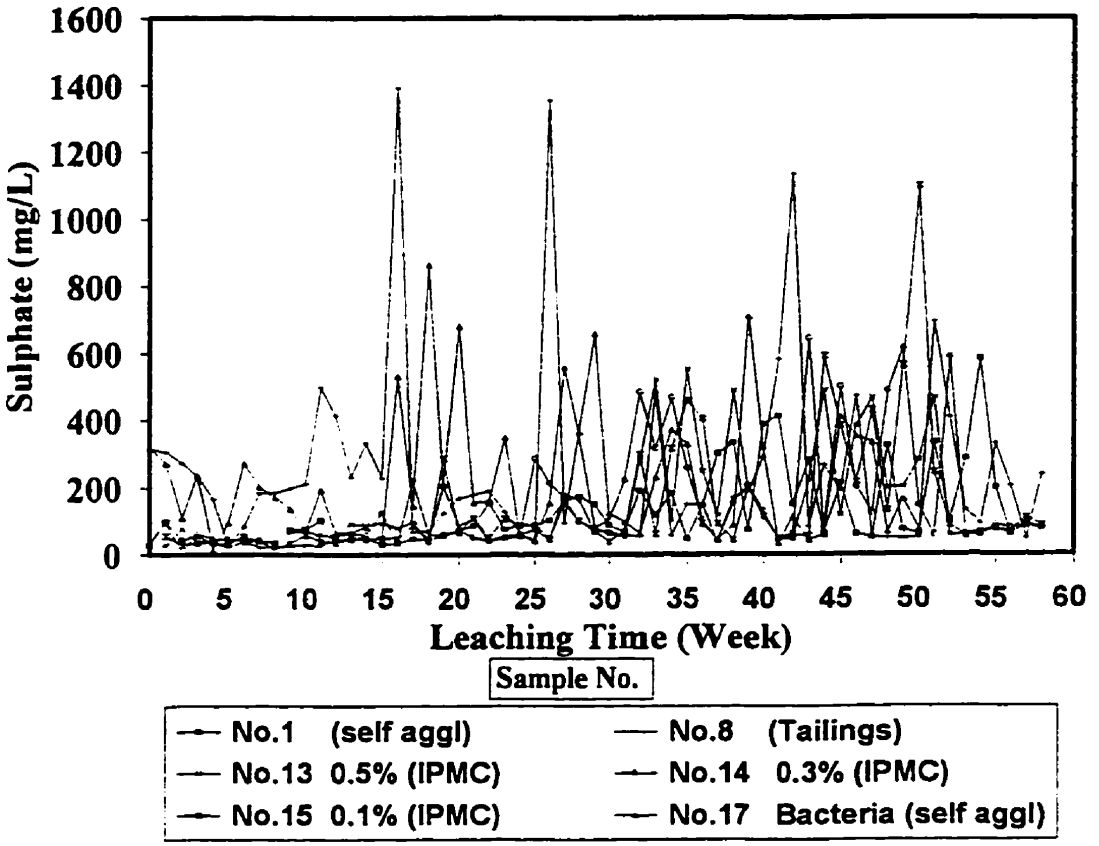


Figure G4. Sulphate vs Leaching Time

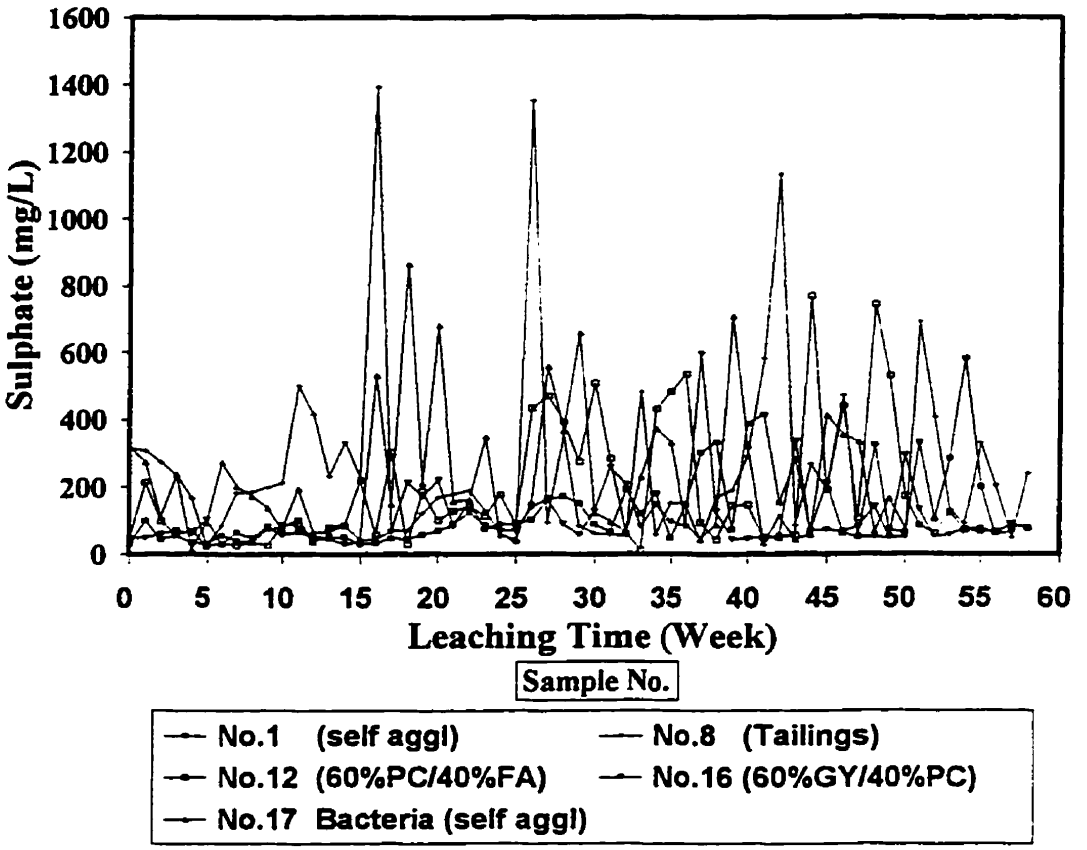


Figure G5. Sulphate vs Leaching Time

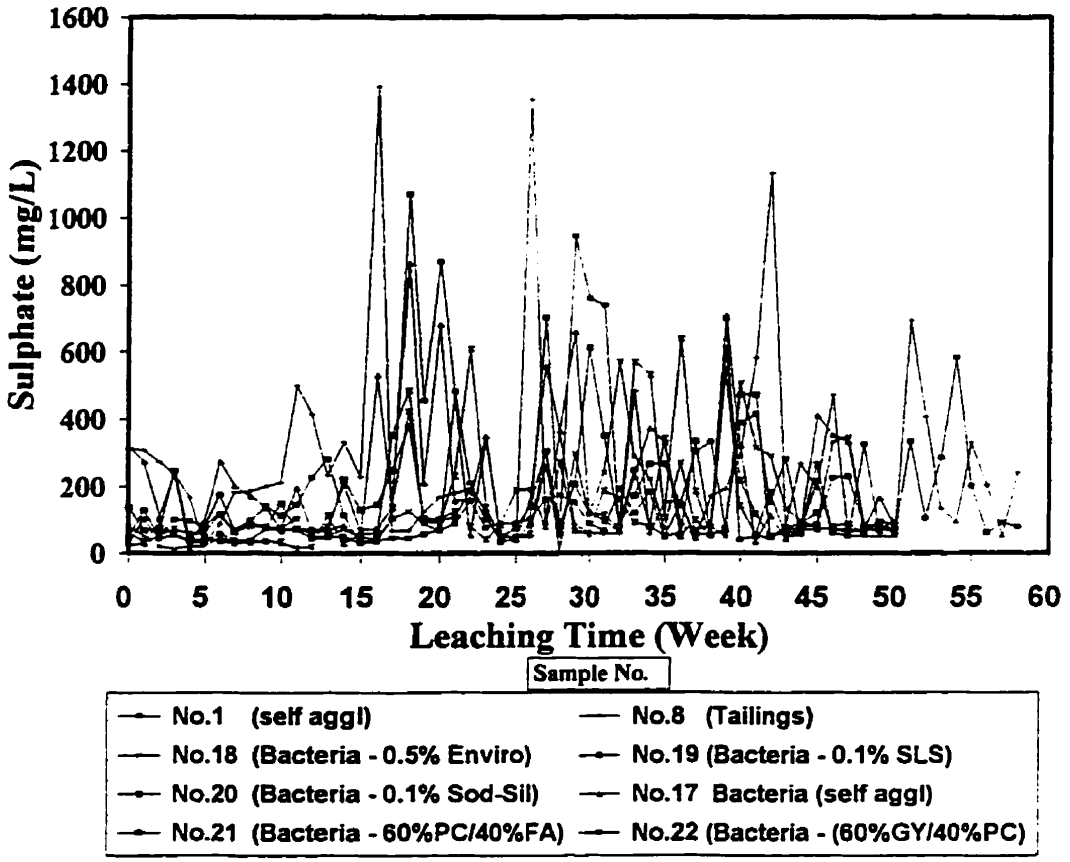


Figure G6. Sulphate vs Leaching Time

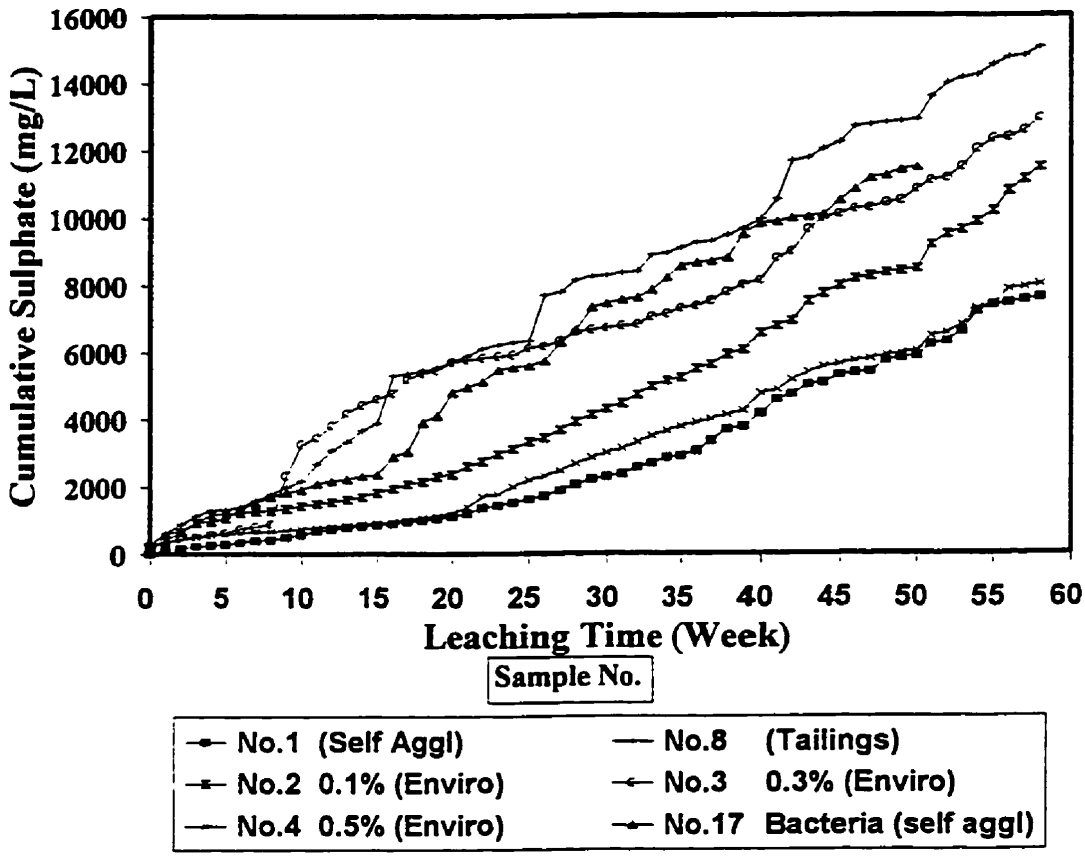


Figure G7. Cumulative Sulphate vs Leaching Time

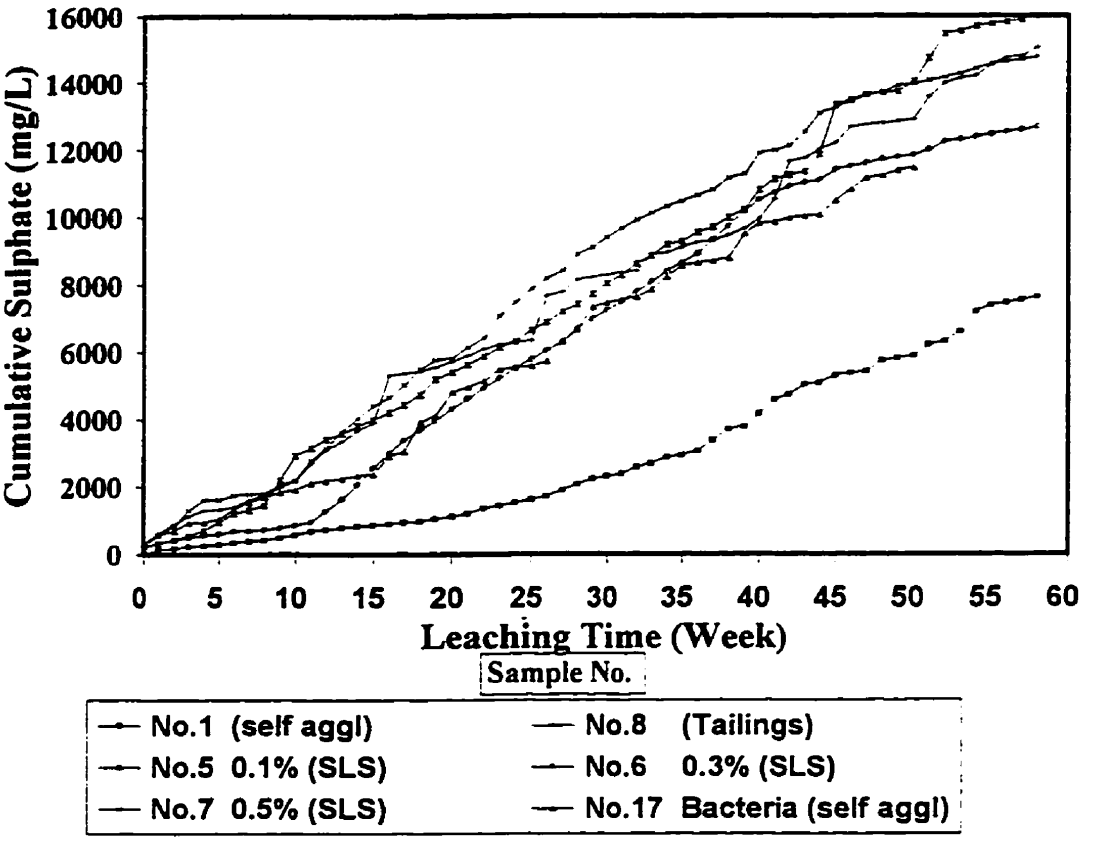


Figure G8. Cumulative Sulphate vs Leaching Time

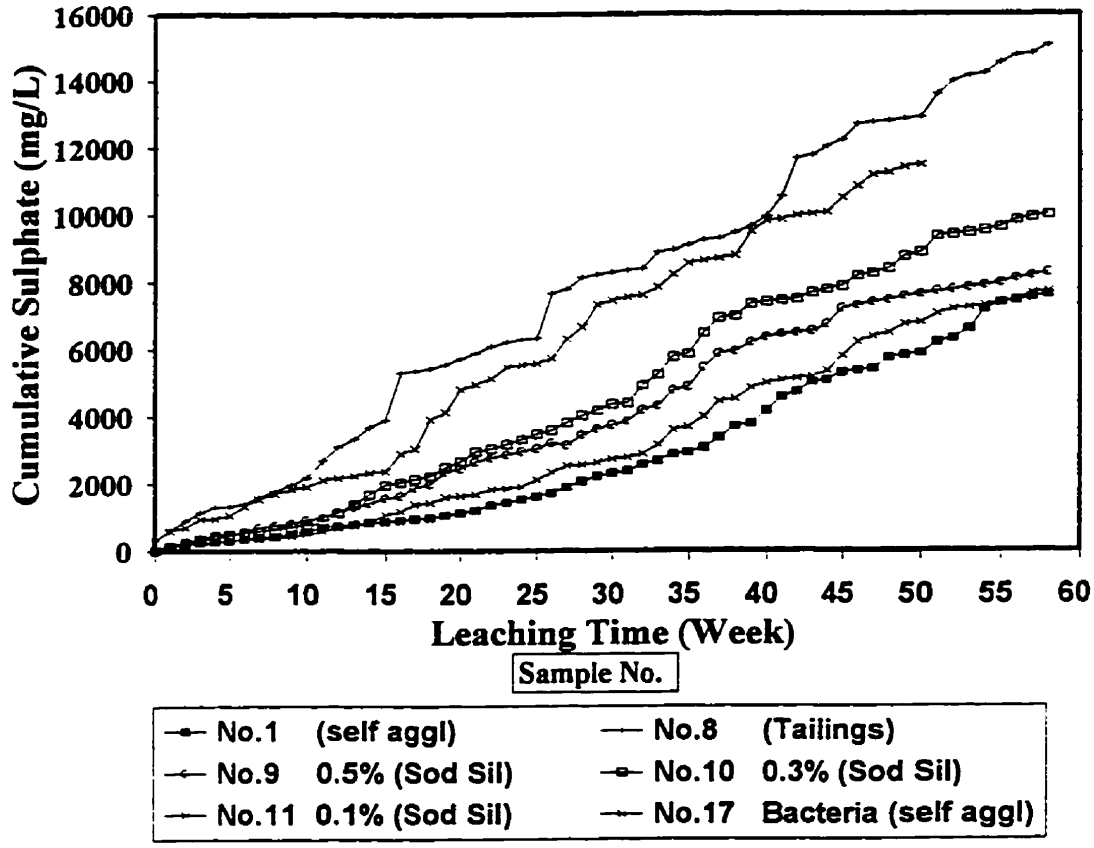


Figure G9. Cumulative Sulphate vs Leaching Time

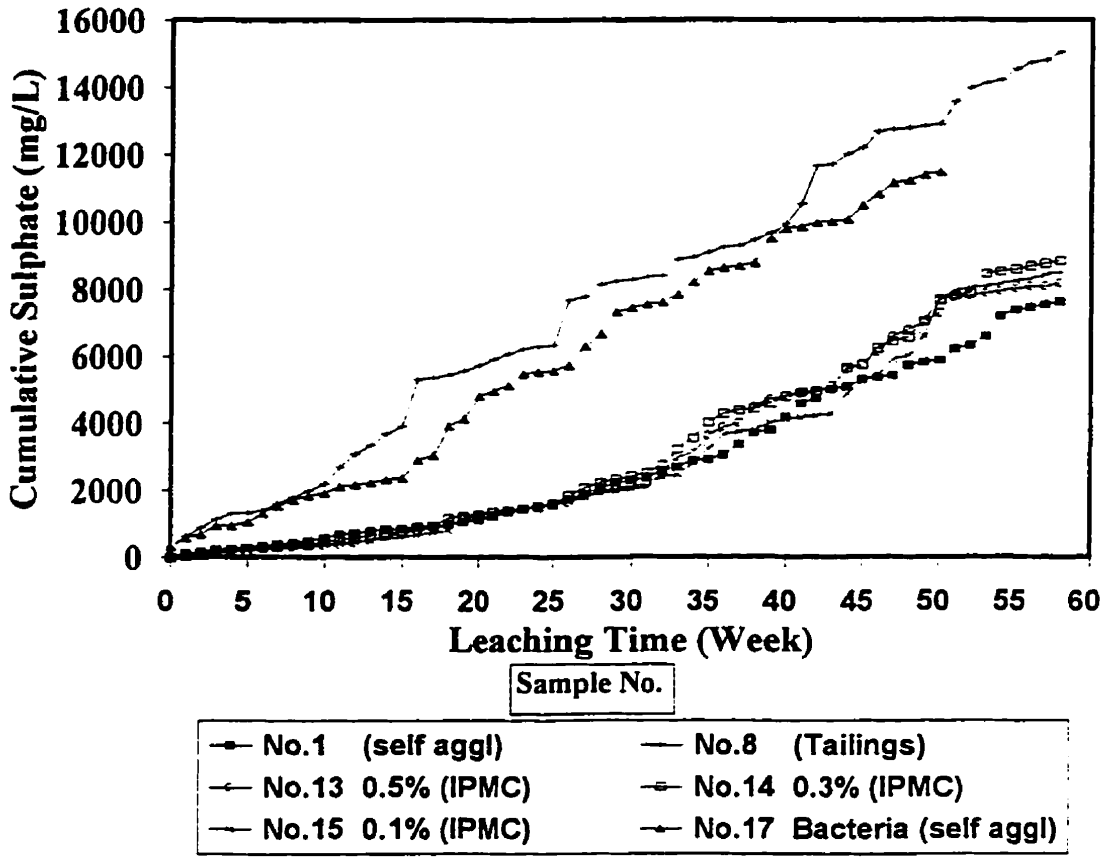


Figure G10. Cumulative Sulphate vs Leaching

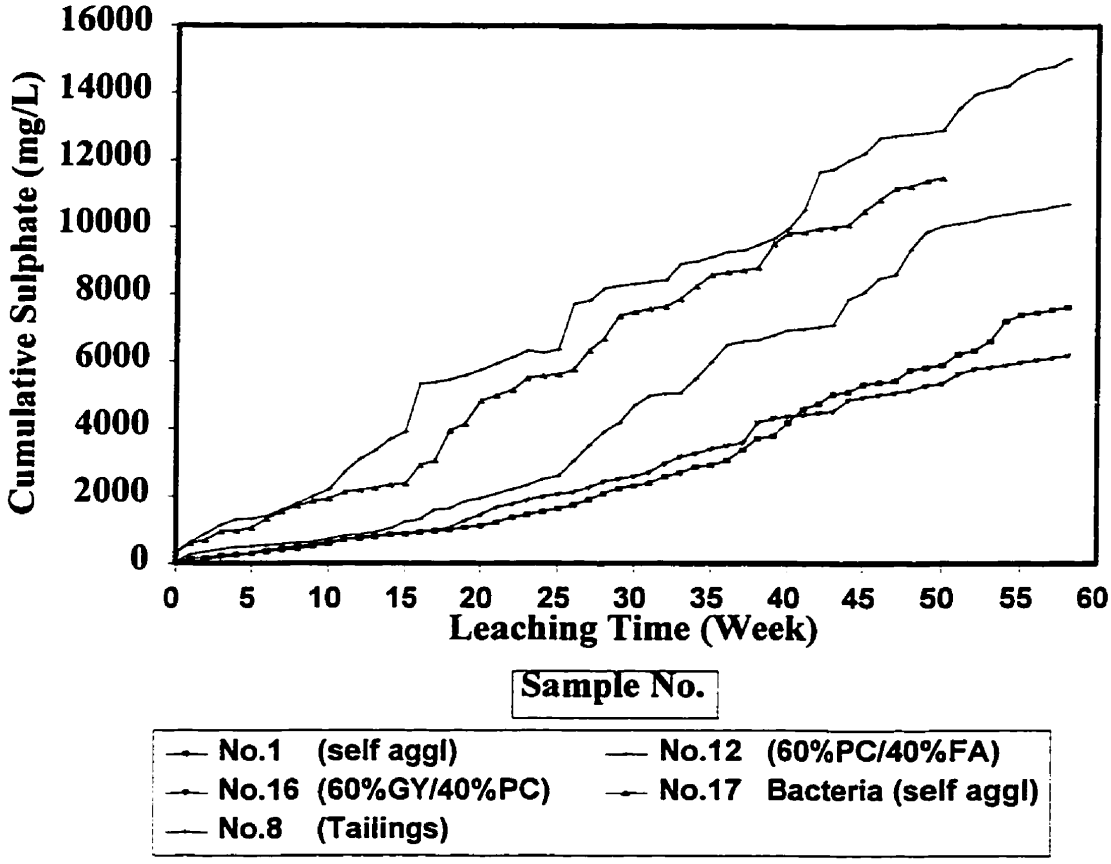


Figure G11. Cumulative Sulphate vs Leaching Time

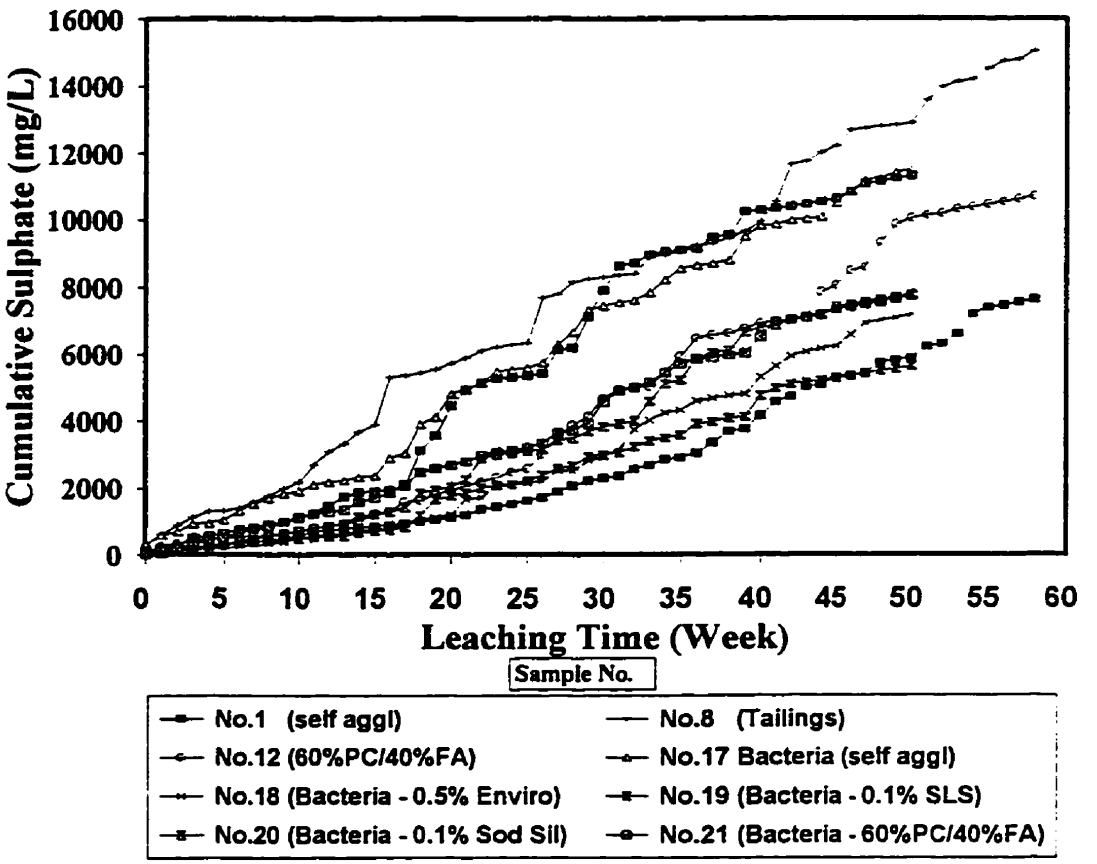


Figure G12. Cumulative Sulphate vs Leaching Time

APPENDIX (H)

Acidity and Cumulative Acidity Results

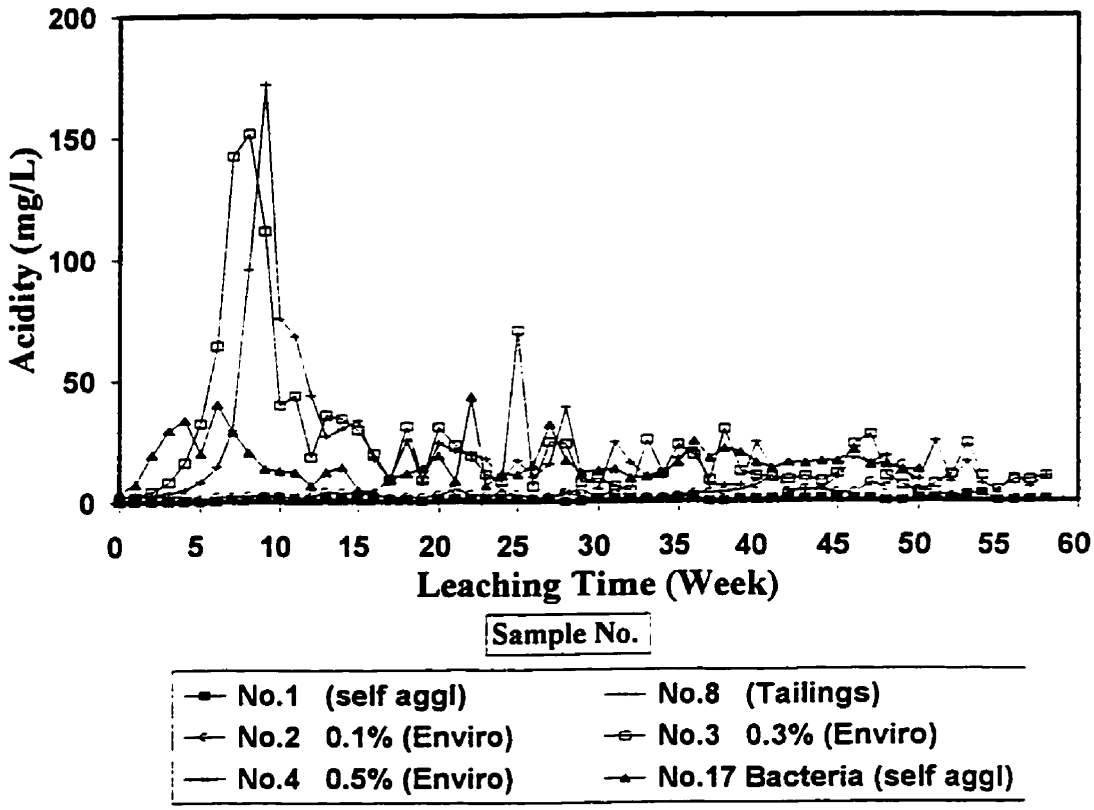


Figure H1. Acidity vs Leaching Time

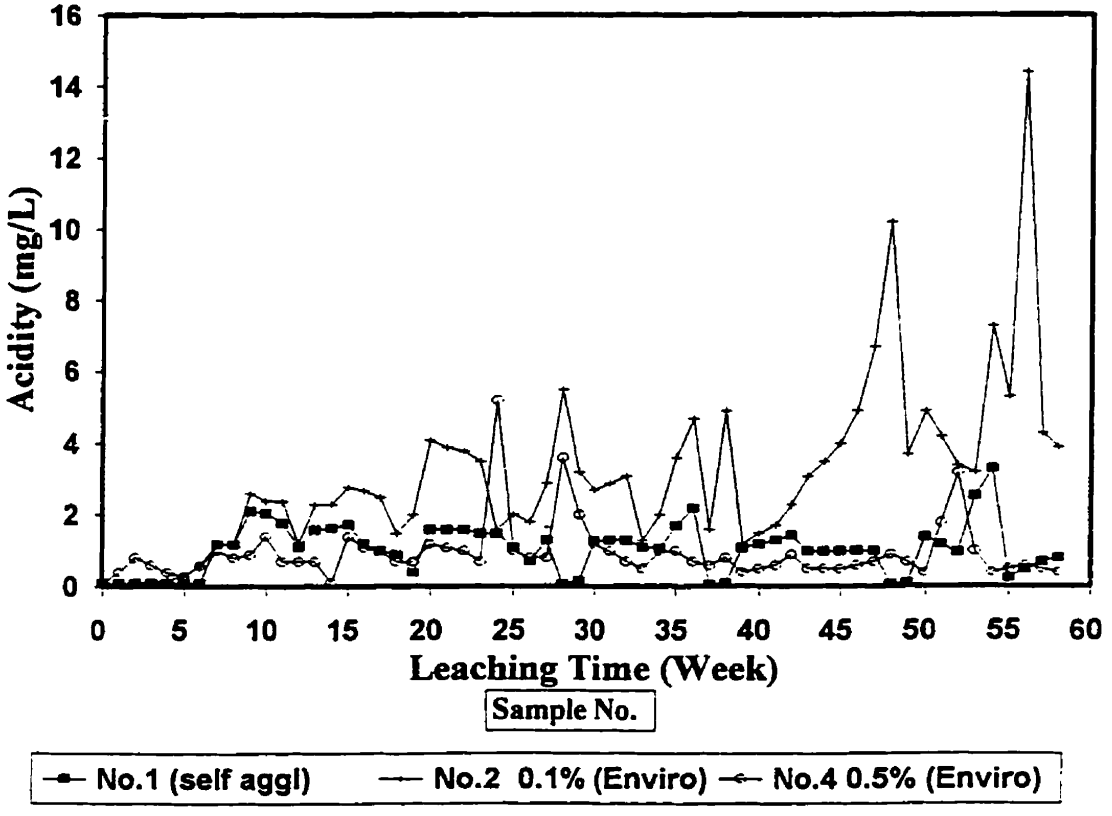


Figure H2. Acidity vs Leaching Time

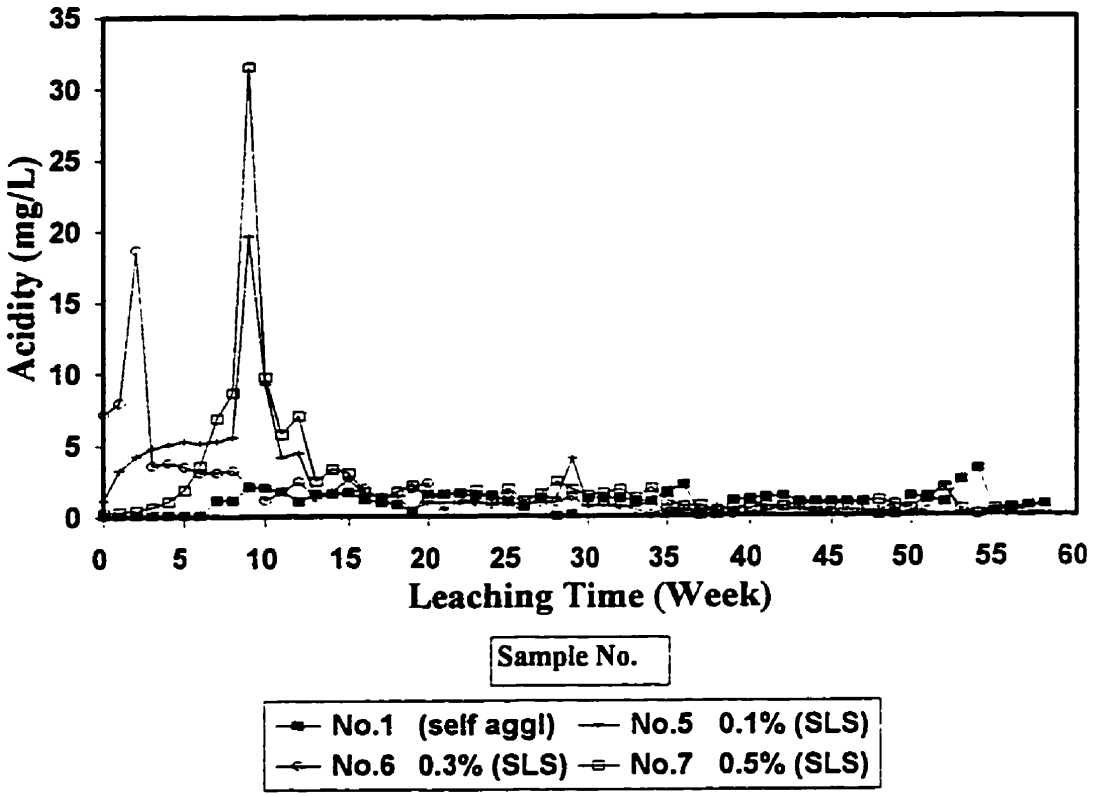


Figure H3. Acidity vs Leaching Time

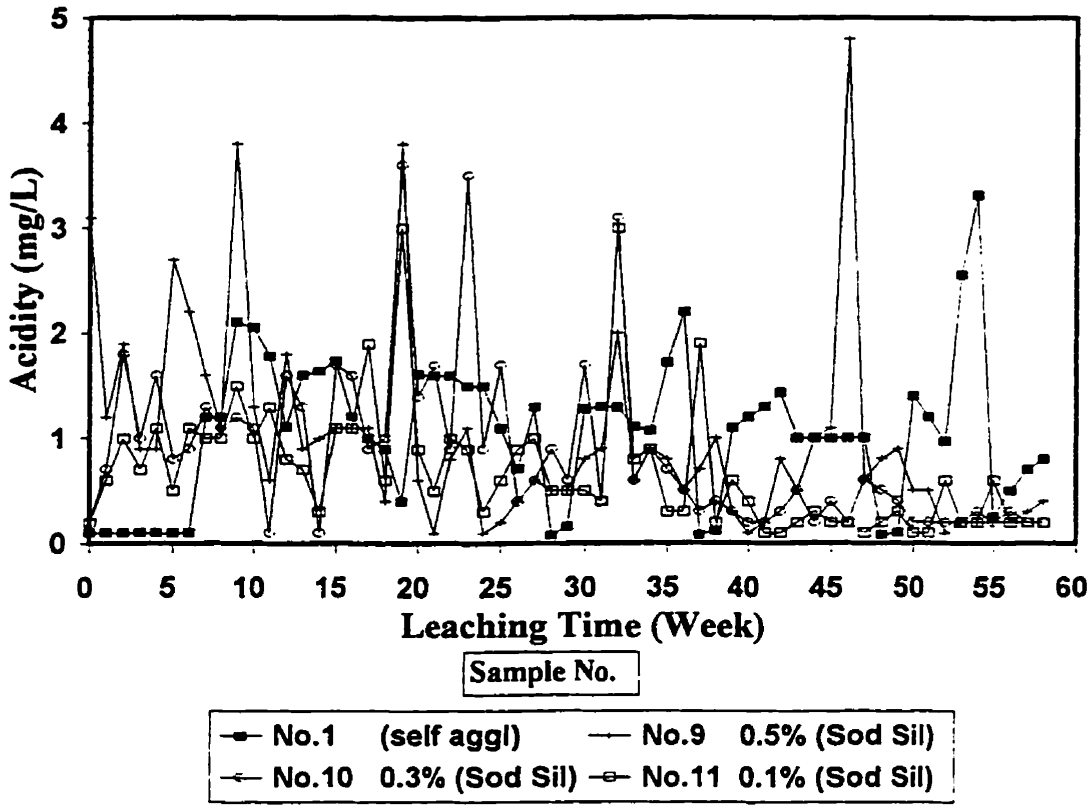
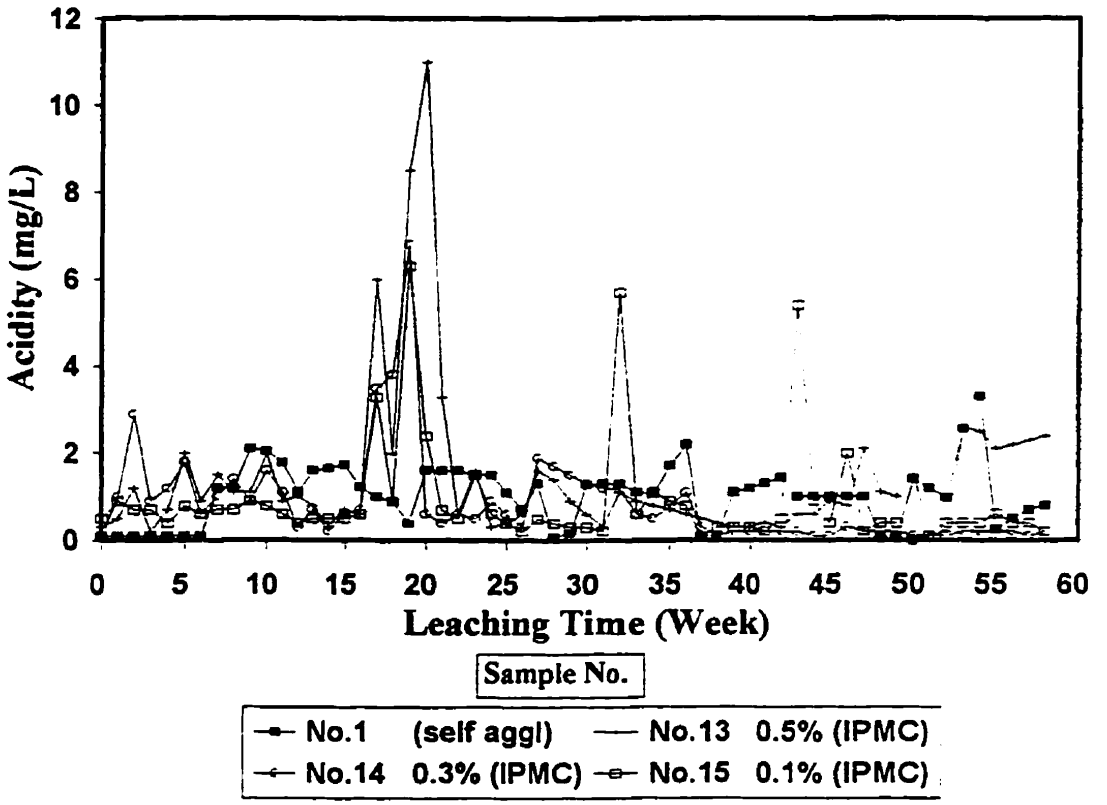


Figure H4. Acidity vs Leaching Time



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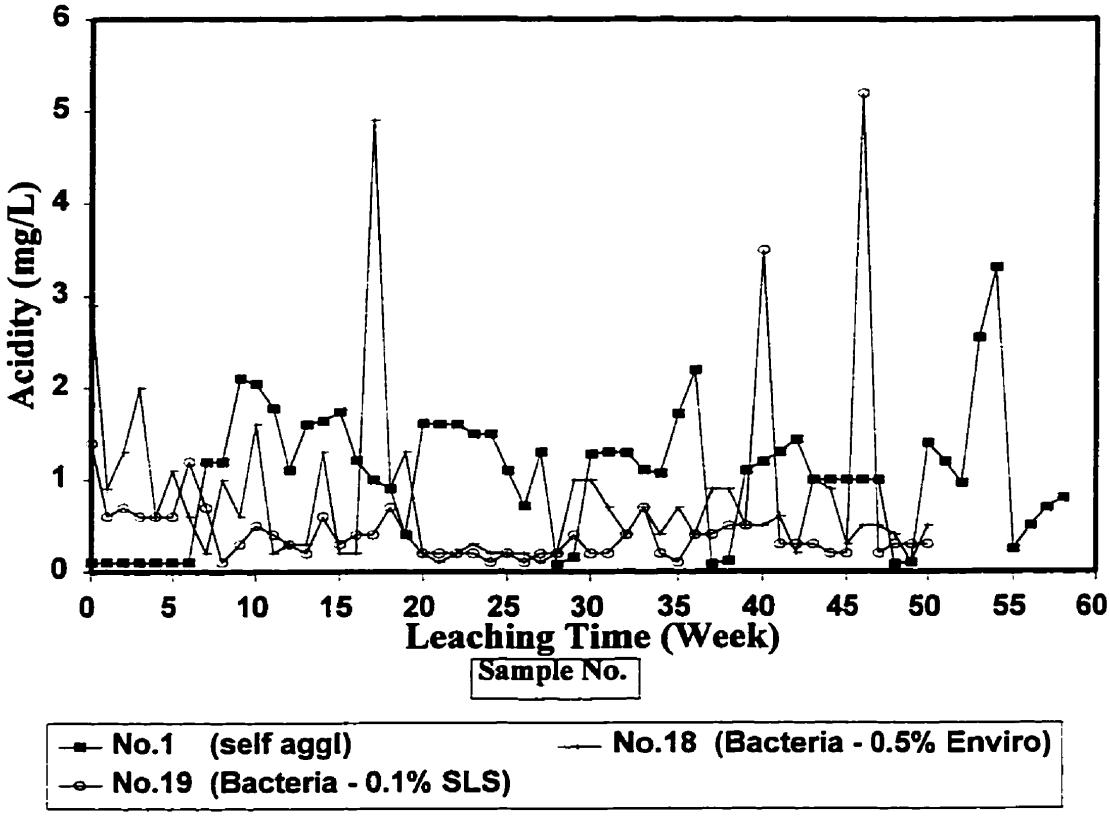


Figure H6. Acidity vs Leaching Time

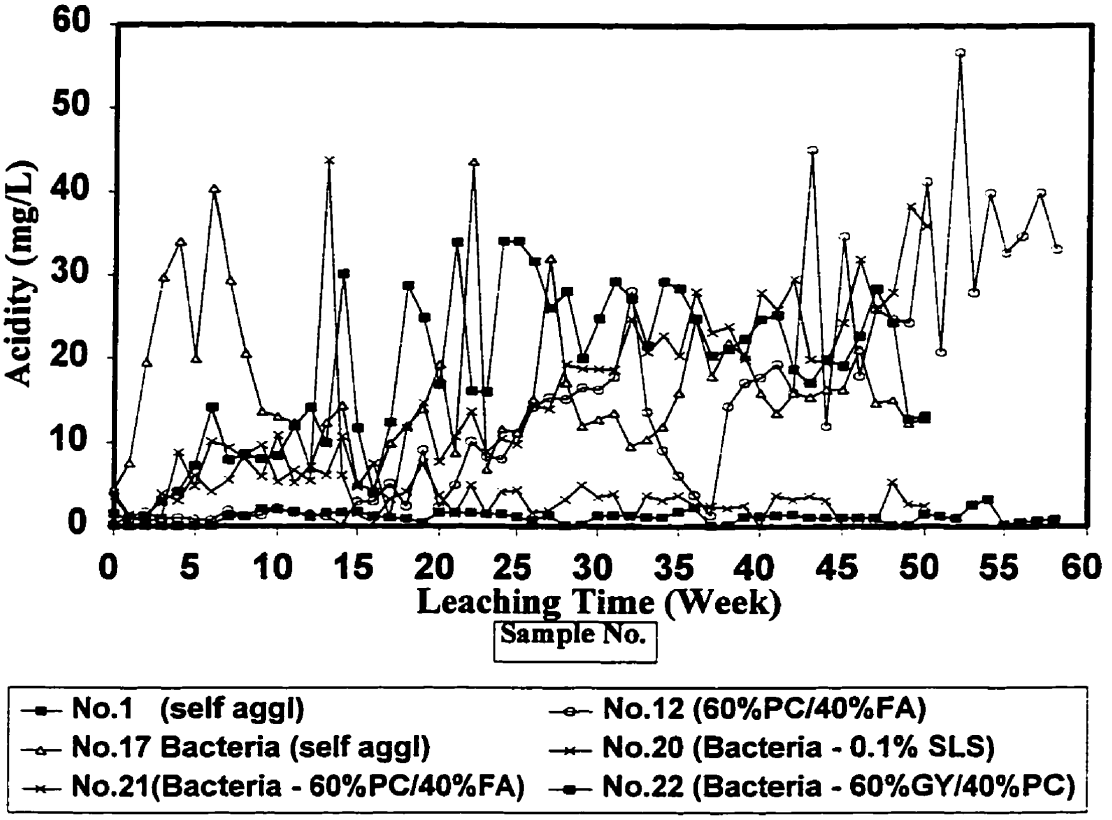


Figure H7. Acidity vs Leaching Time

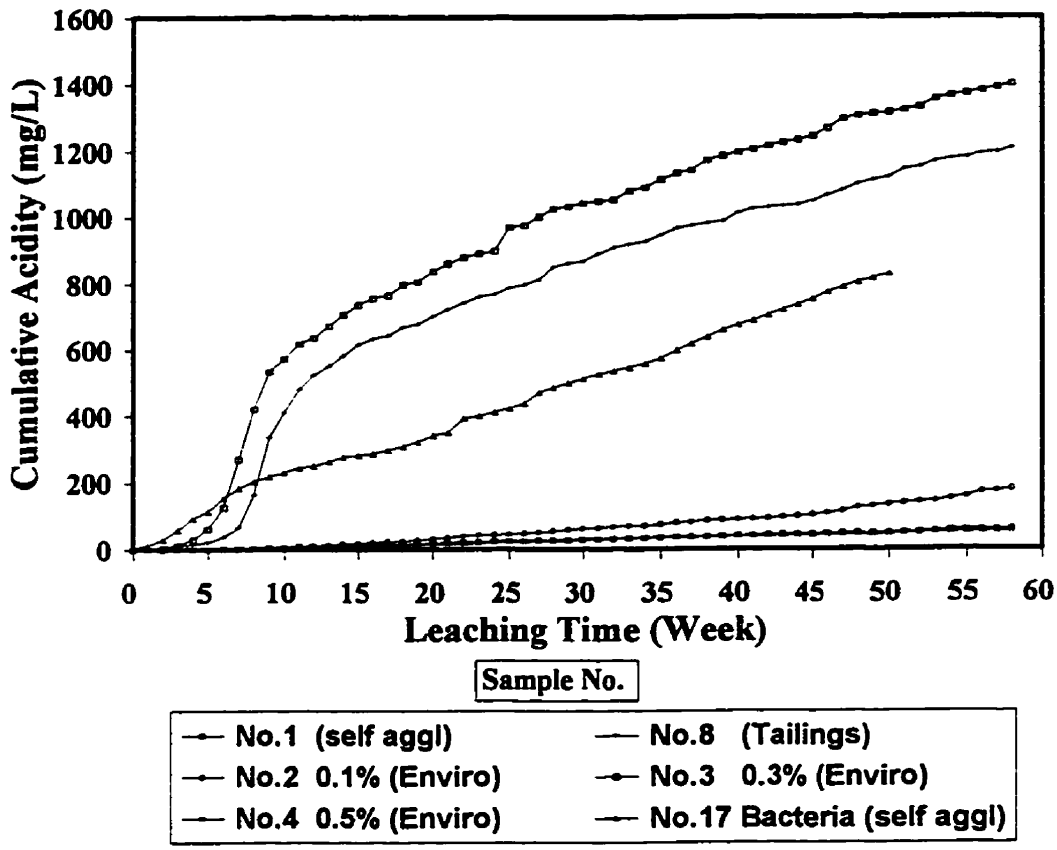


Figure H8. Cumulative Acidity vs Leaching Time

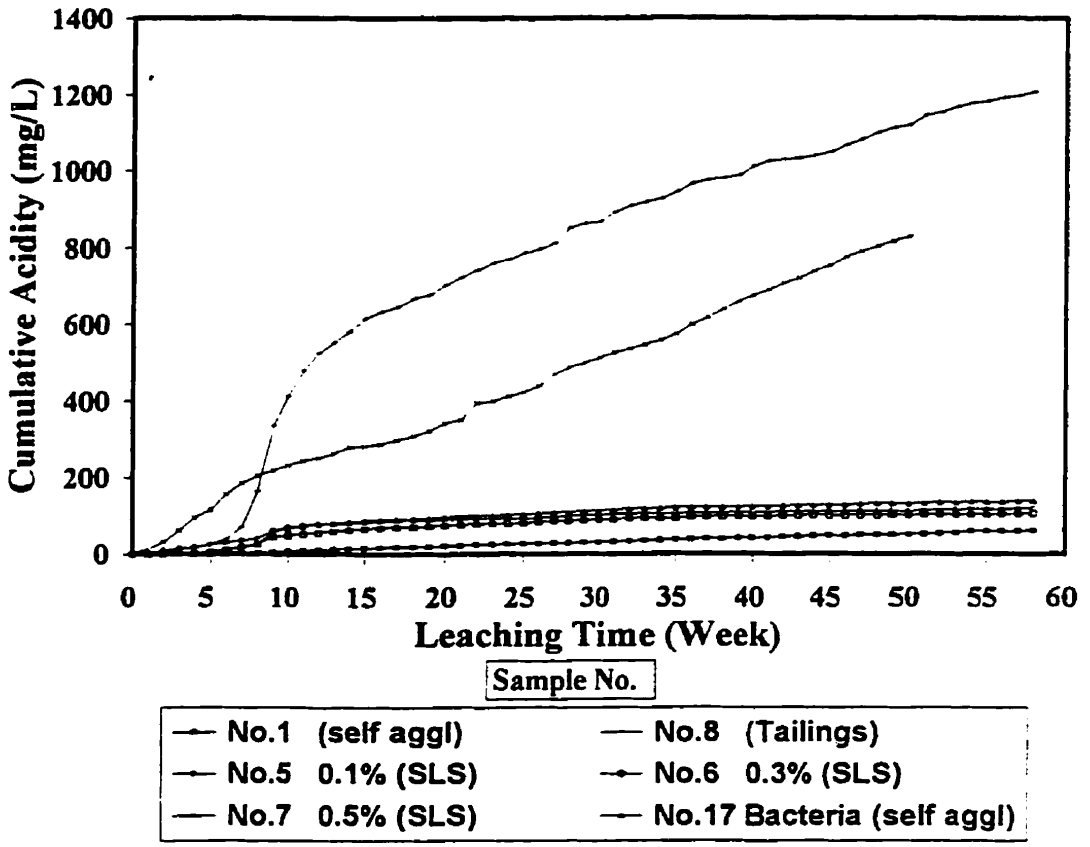


Figure H9. Cumulative Acidity vs Leaching Time

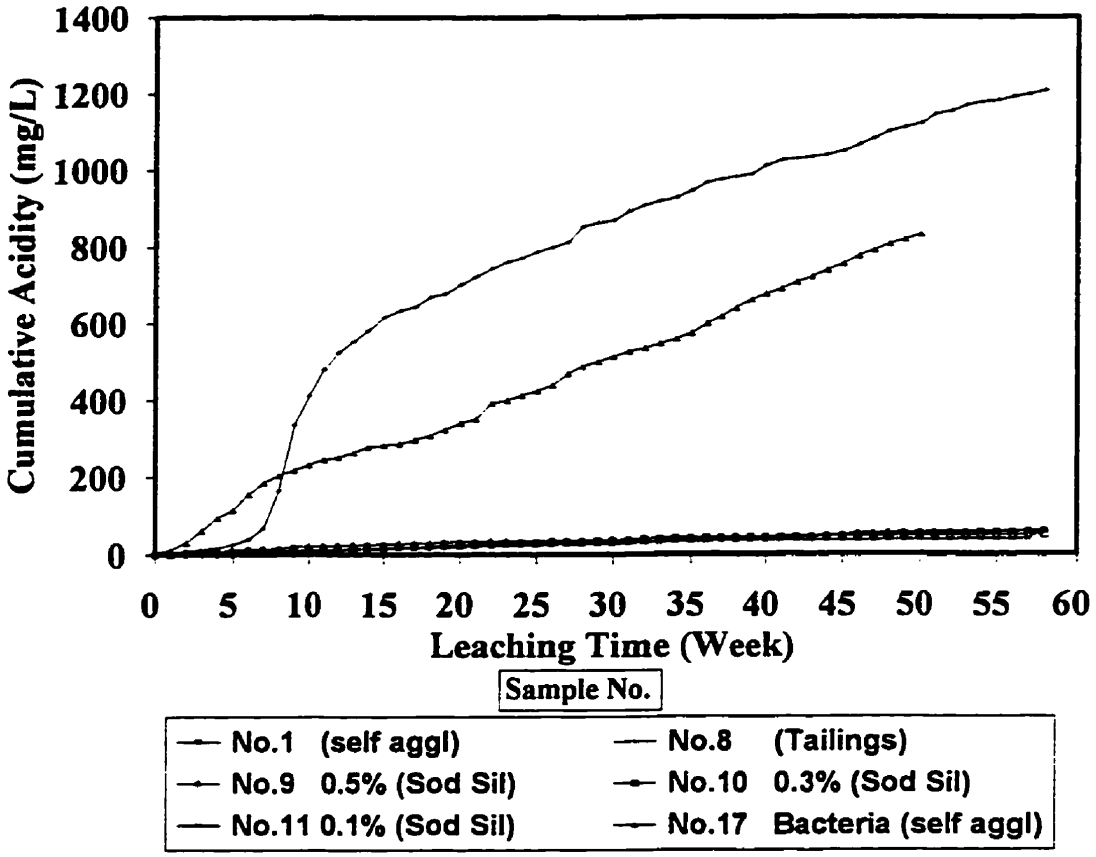


Figure H10. Cumulative Acidity vs Leaching Time

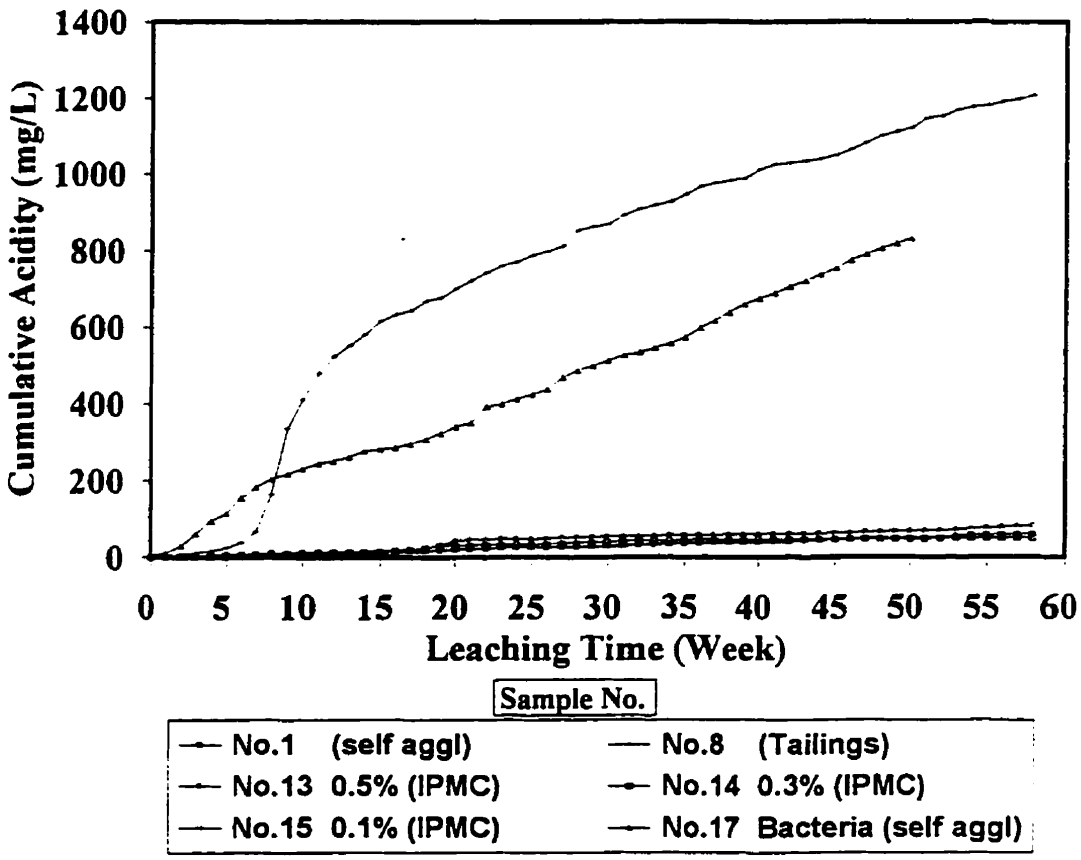


Figure H11. Cumulative Acidity vs Leaching Time

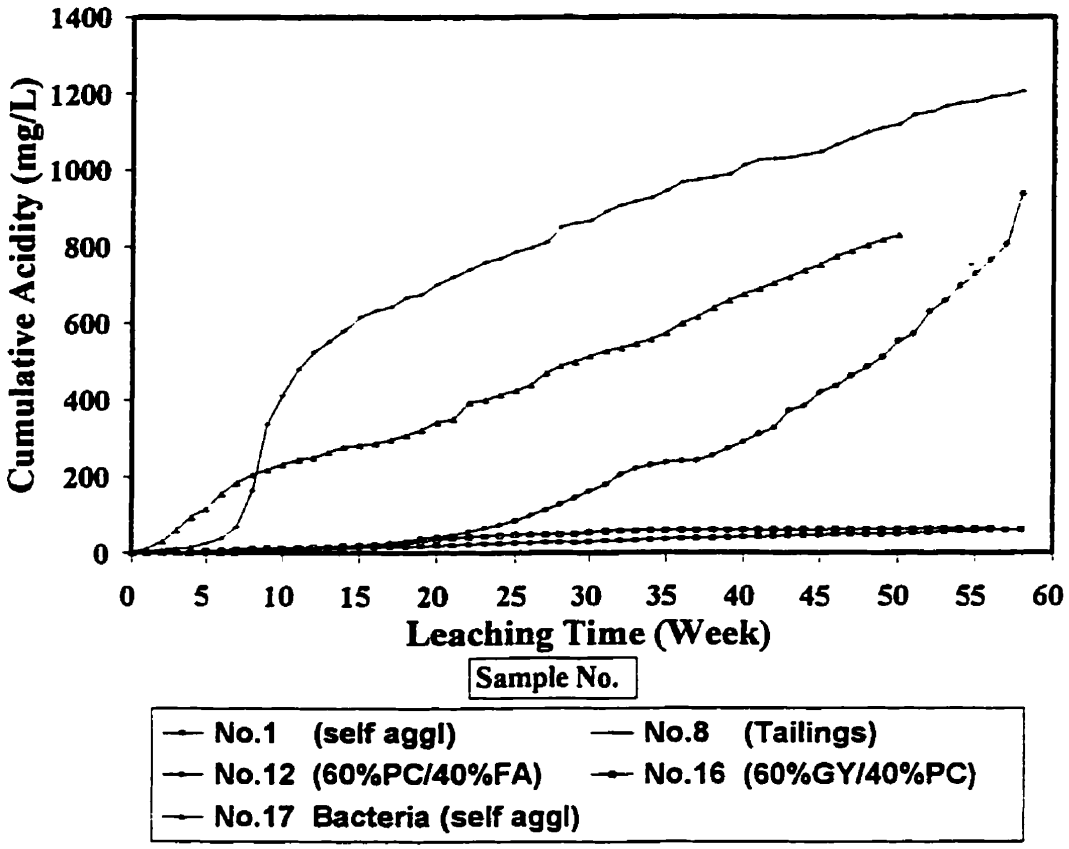


Figure H12. Cumulative Acidity vs Leaching Time

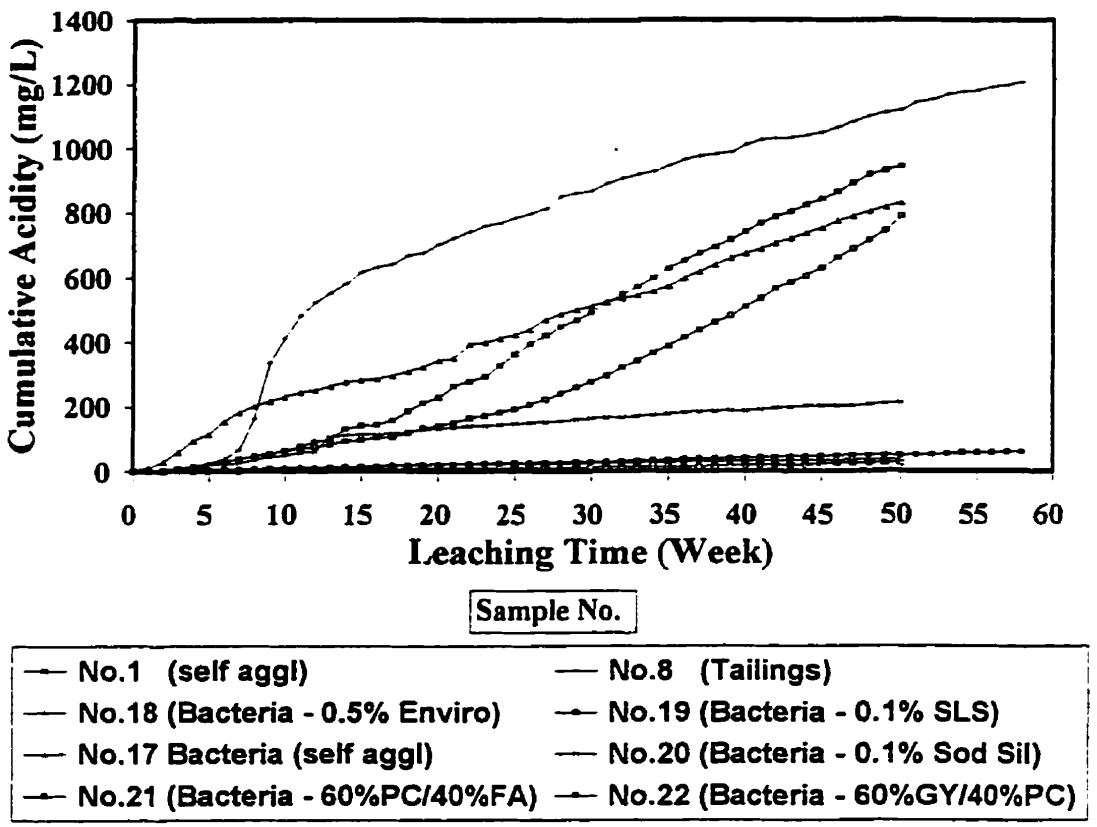


Figure H13. Cumulative Acidity vs Leaching Time

APPENDIX (I)

Leachate [Fe], [Ni], and [Cu] Results

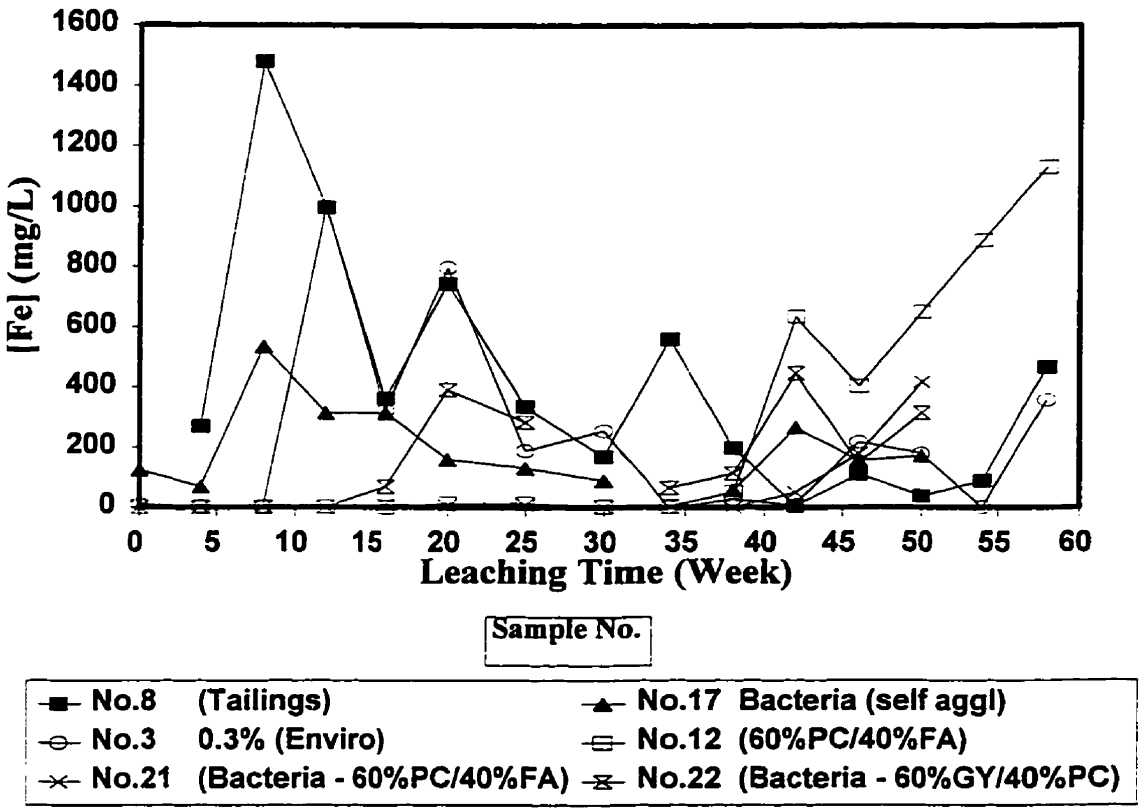


Figure I1 Leachate [Fe] vs Leaching Time

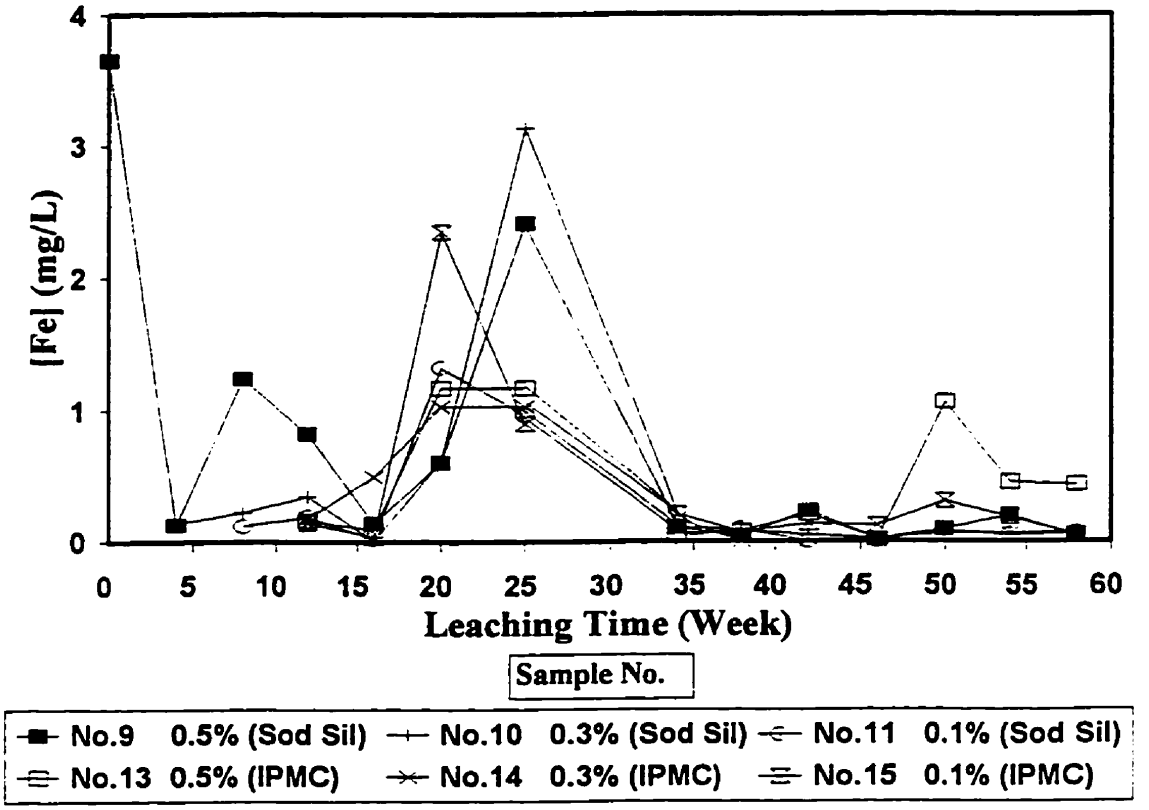


Figure I2. Leachate [Fe] vs Leaching Time

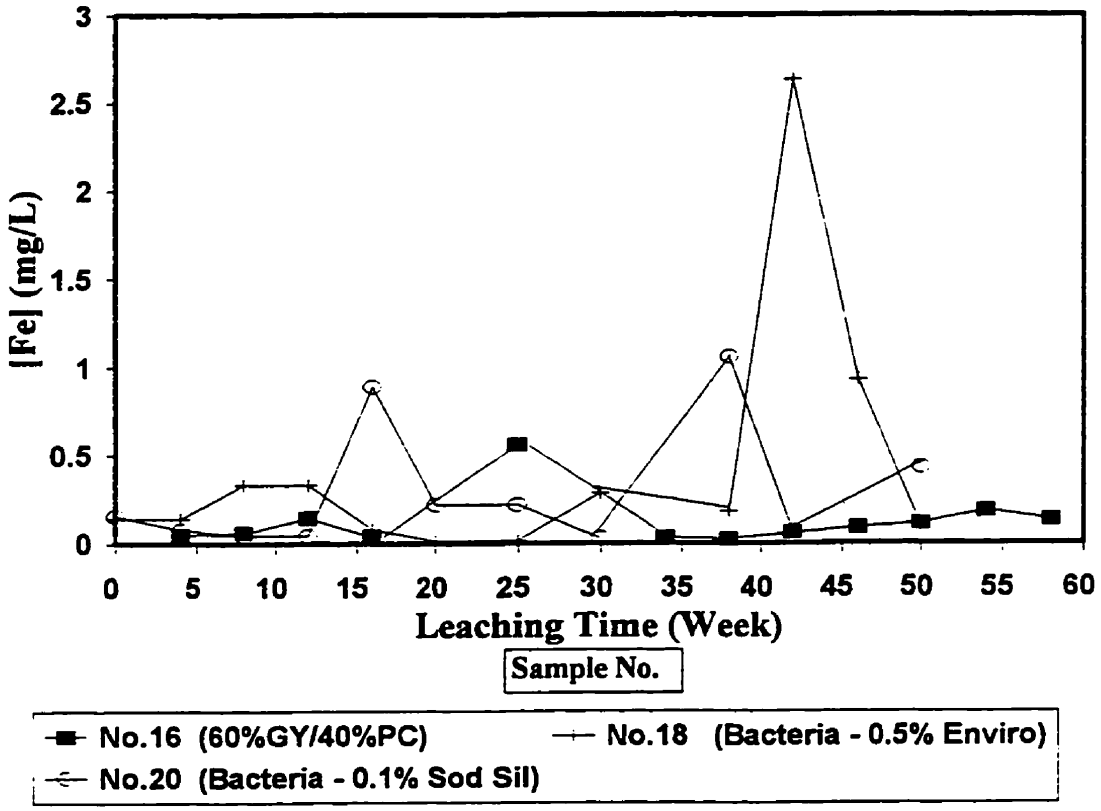


Figure I3. Leachate [Fe] vs Leaching Time

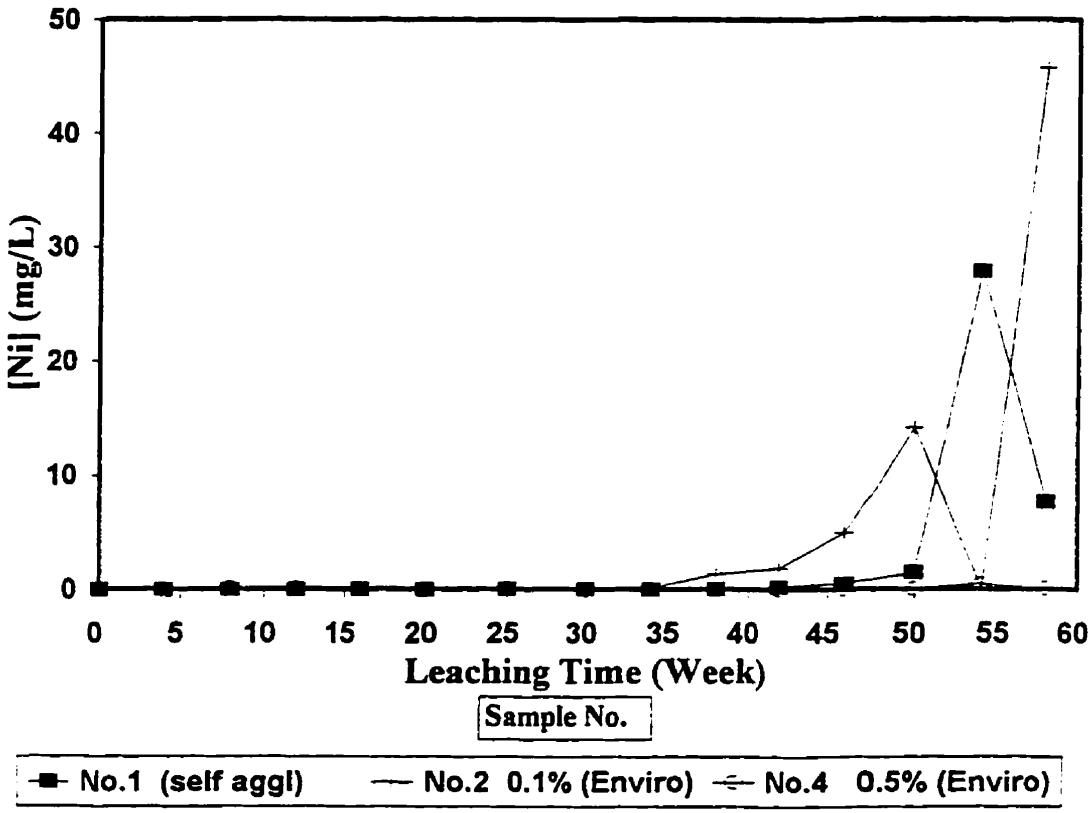


Figure I4. Leachate [Ni] vs Leaching Time

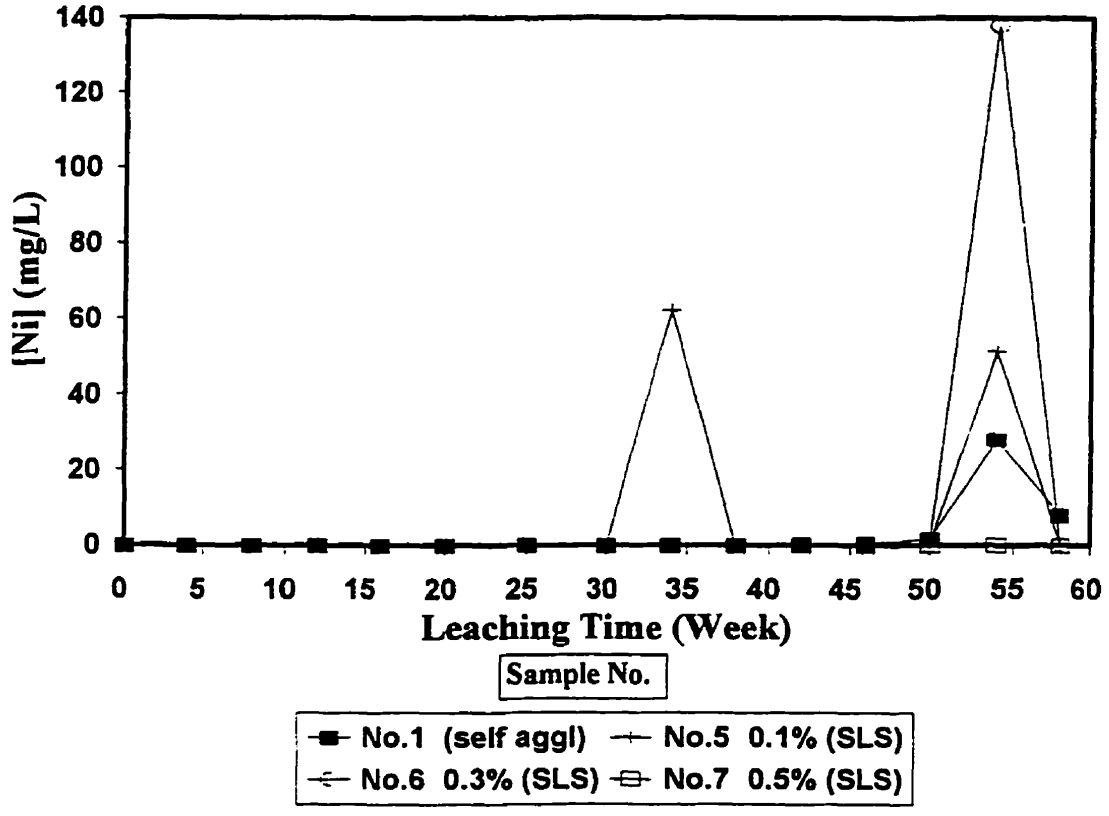


Figure I5. Leachate [Ni] vs Leaching Time

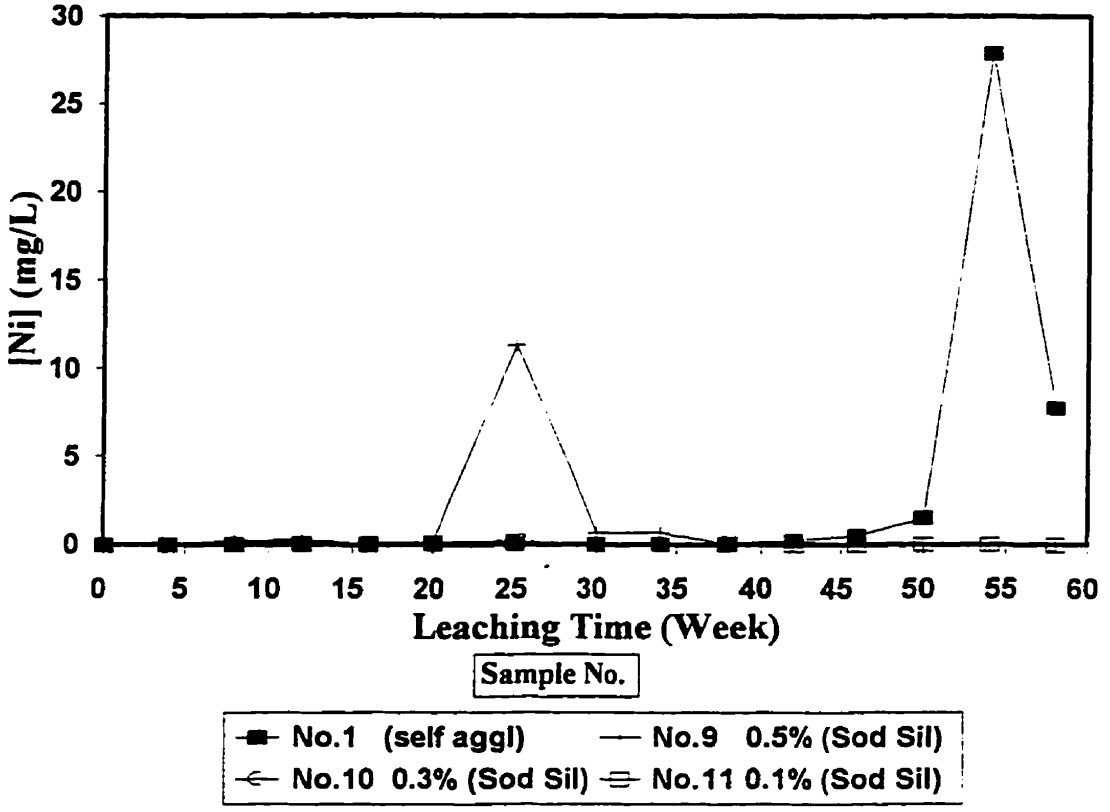


Figure I6. Leachate [Ni] vs Leaching Time

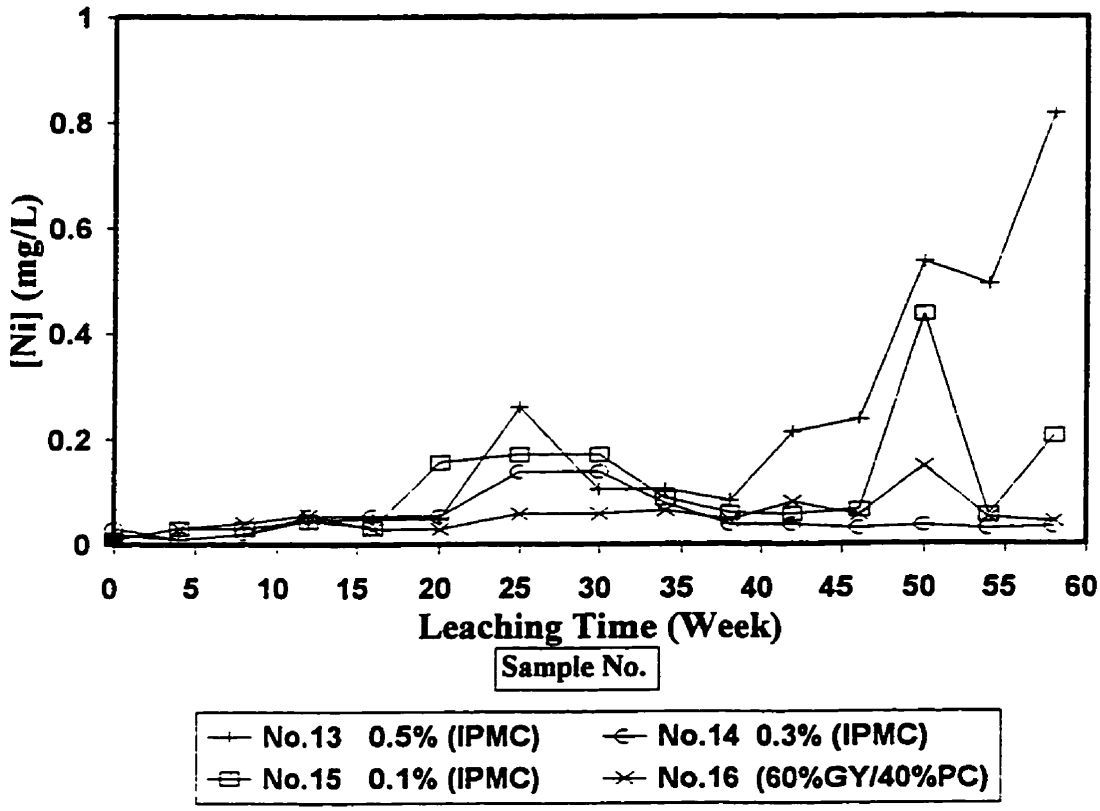


Figure I7. Leachate [Ni] vs Leaching Time

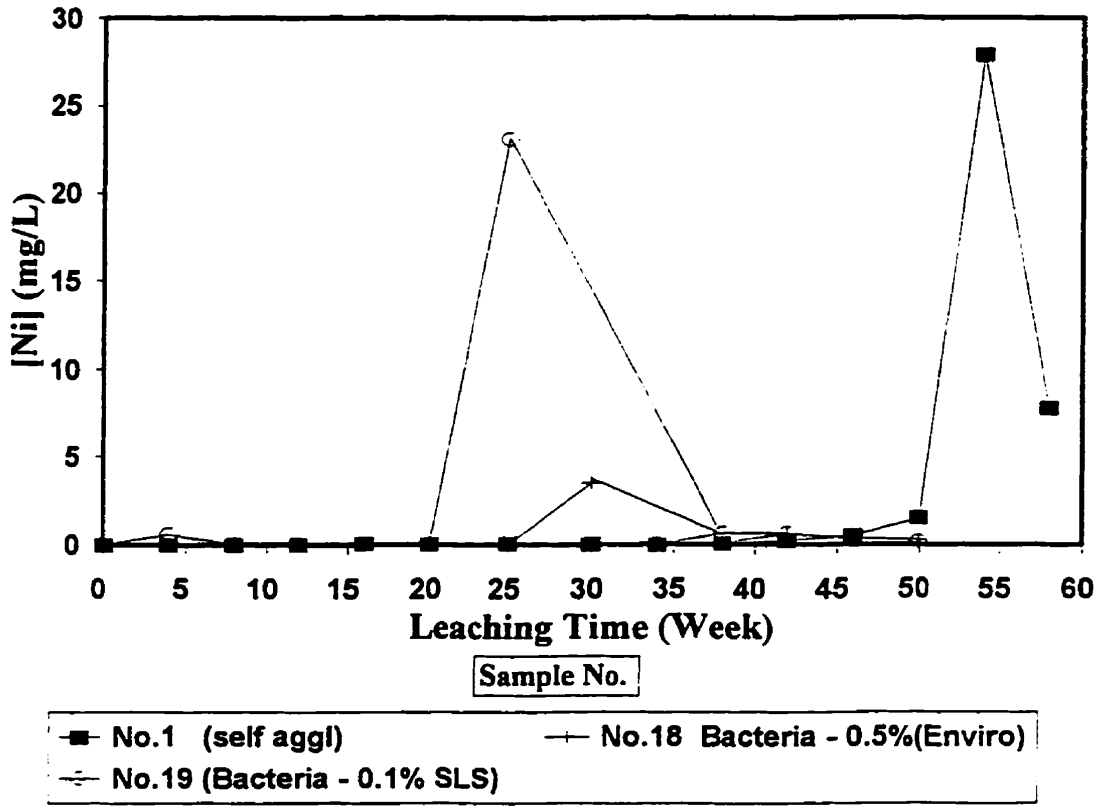


Figure I8. Leachate [Ni] vs Leaching Time

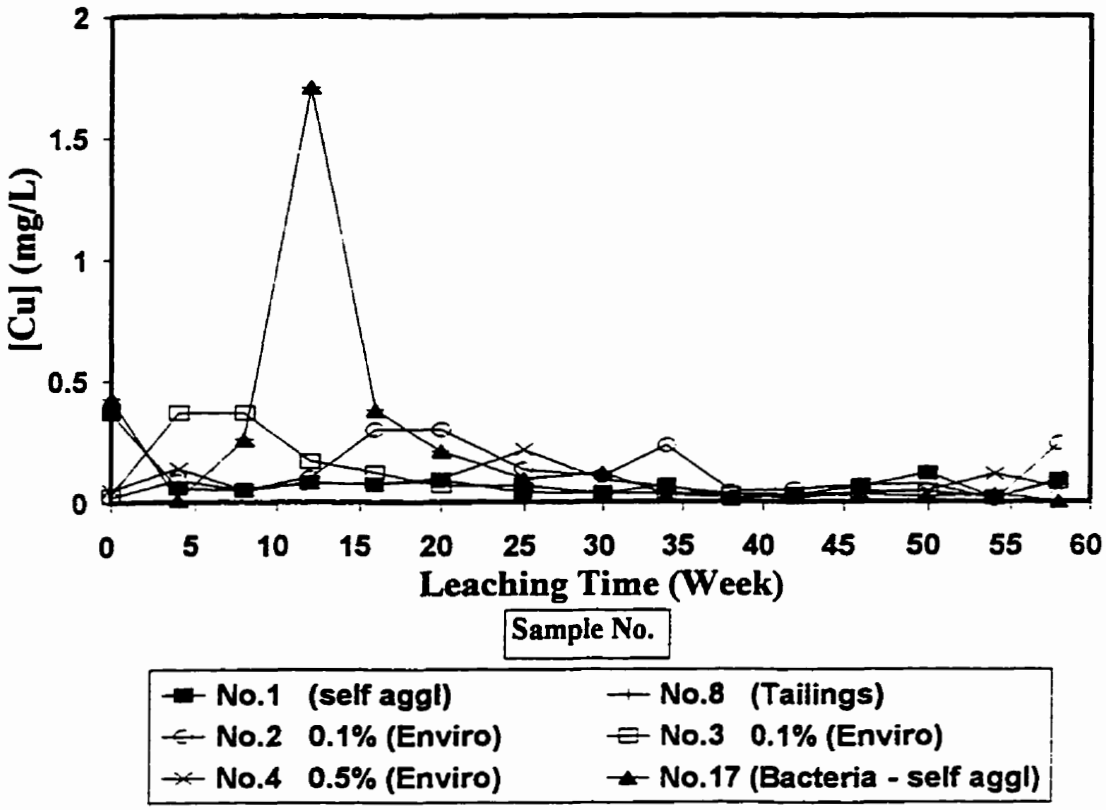


Figure I9. Leachate [Cu] vs Leaching Time

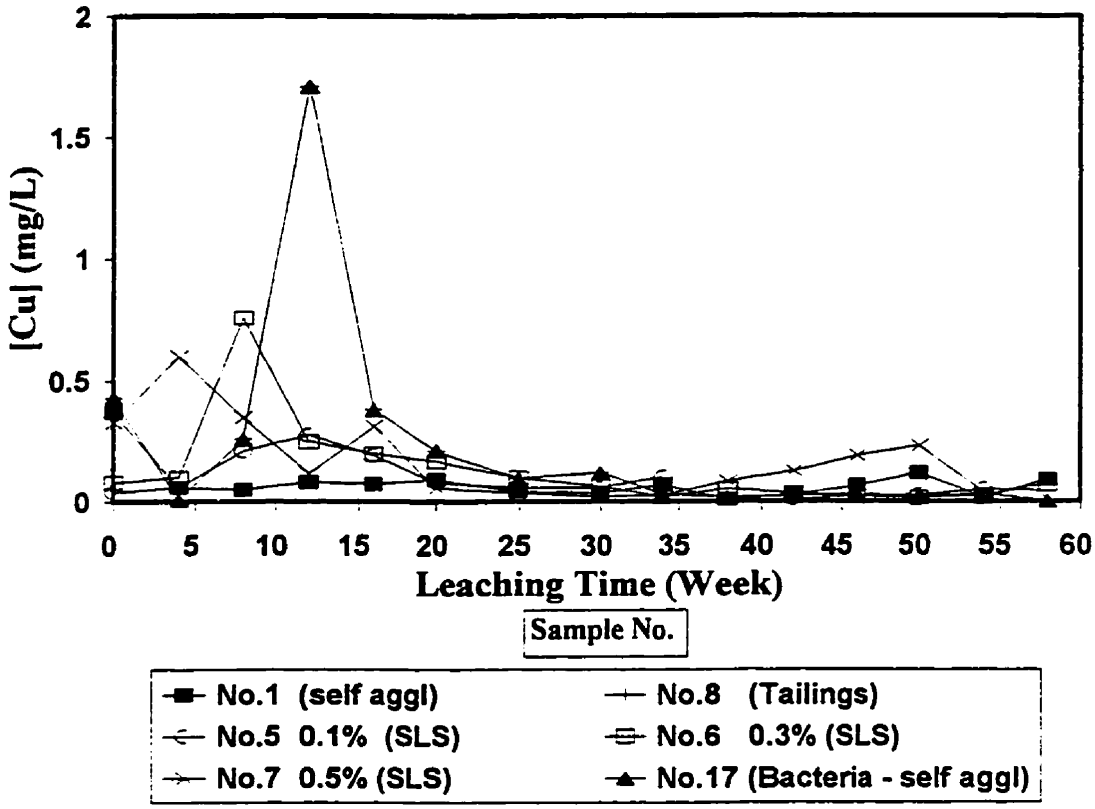


Figure I10. Leachate [Cu] vs Leaching Time

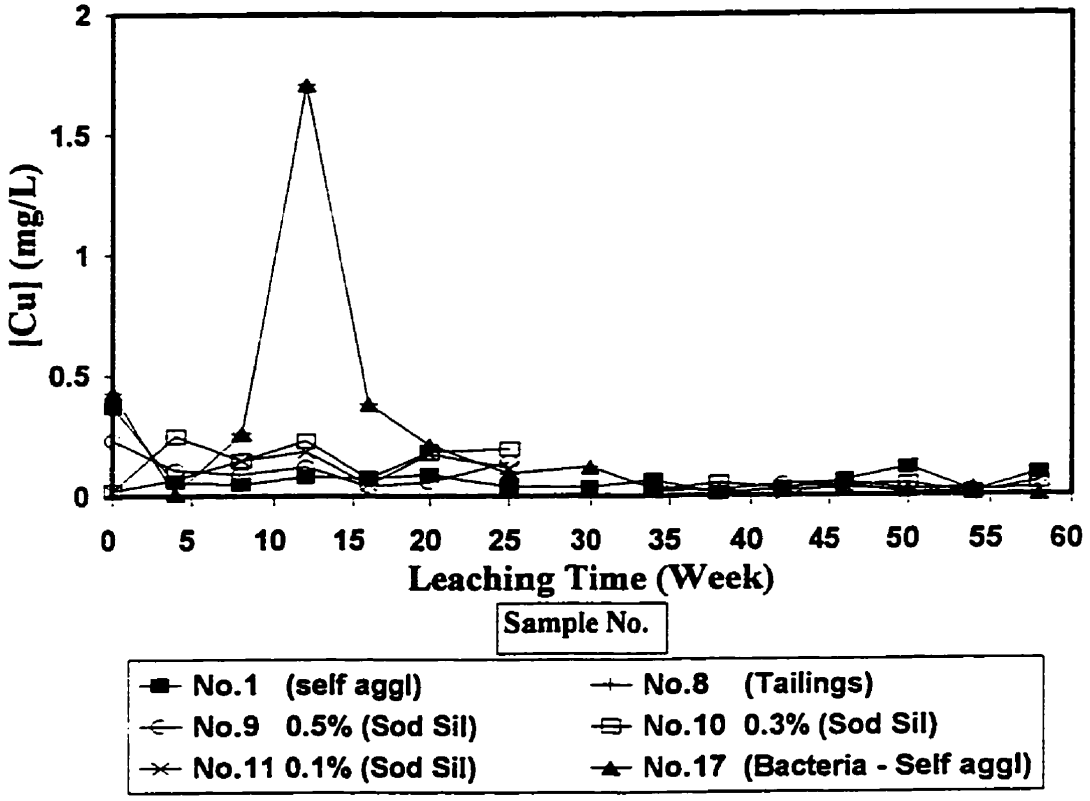


Figure I11. Leachate [Cu] vs Leaching Time

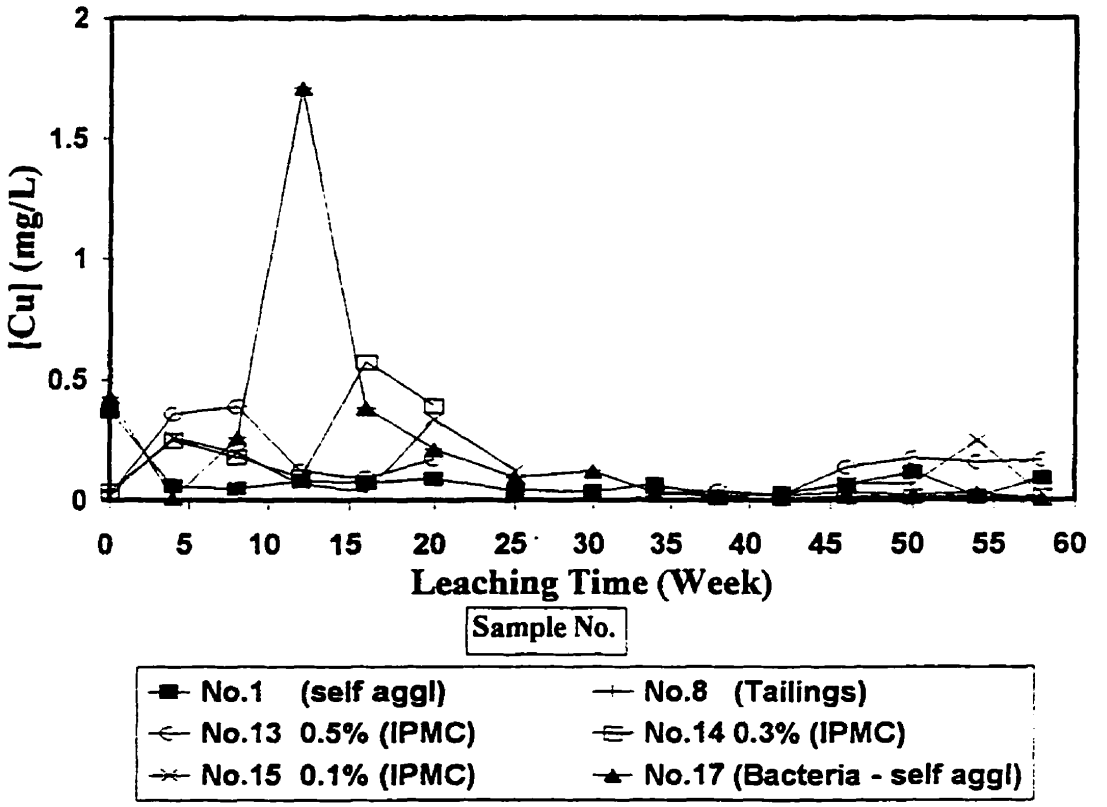


Figure I12. Leachate [Cu] vs Leaching Time

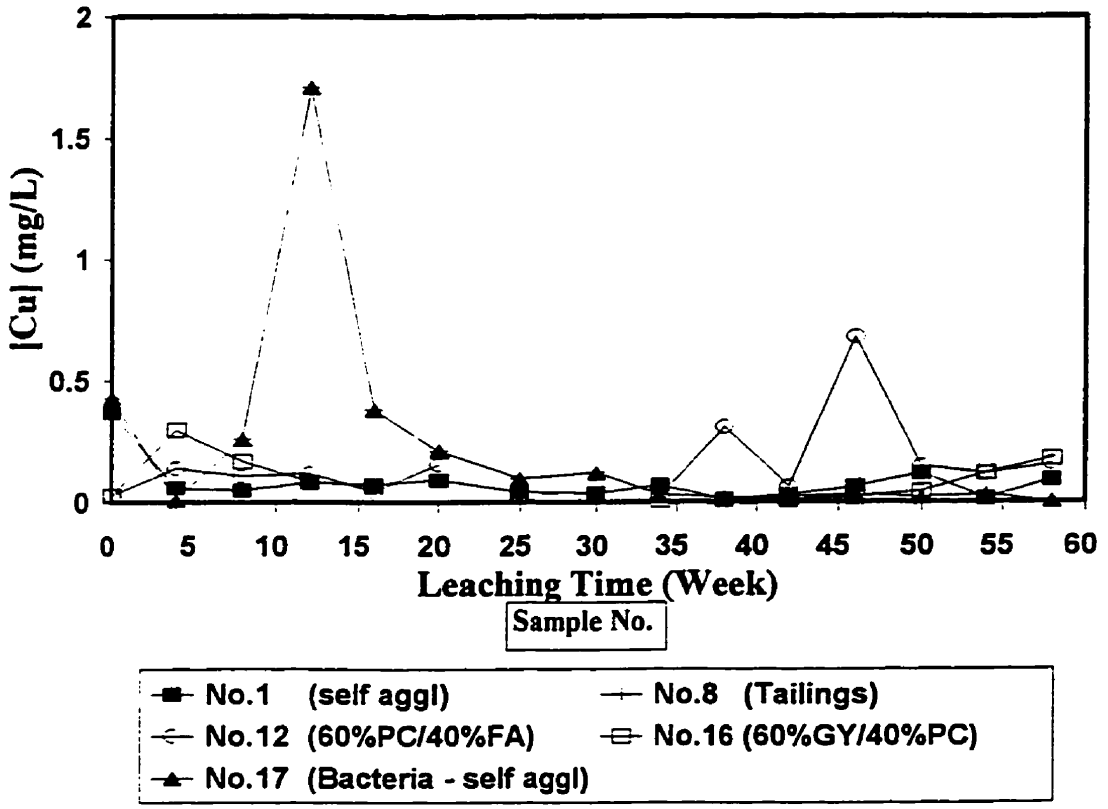


Figure I13. Leachate [Cu] vs Leaching Time

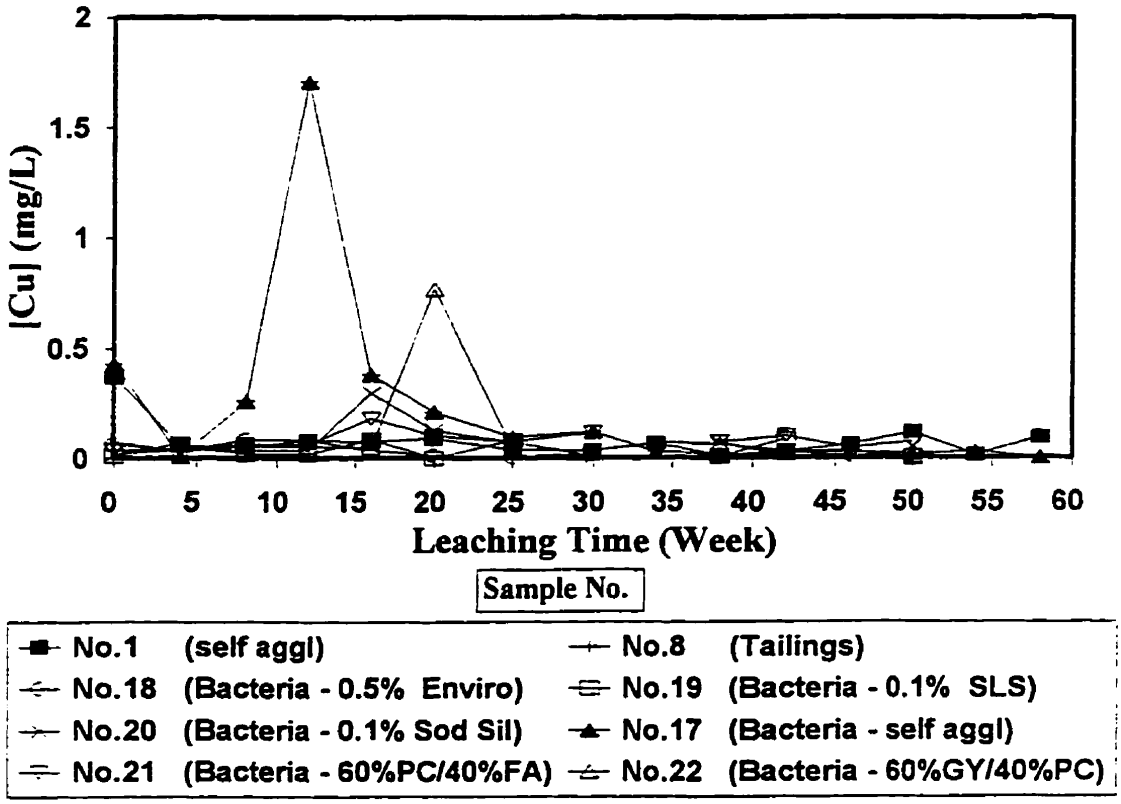


Figure I14. Leachate [Cu] vs Leaching Time

APPENDIX (K)

Description of Micrographs

Description of Micrographs

This is a description of the Scanning Electron Microscopic images of the tailings control sample, agglomerated pyrrhotite samples (i) before the accelerated weathering , (ii) during the leaching test, and (iii) at the end of the test period. The cured agglomerates and leached agglomerates were analyzed using Back Scattered Electrons (BSE) to study the surface morphology and Secondary Electron images to study the composition of samples. The Energy Dispersive Spectrometry (EDS) spectrum was also used to obtain more specific details of the composition of the samples scanned. The SEM qualitative analysis of the exterior of surface of agglomerated pellets showed the presence of Ca and S from the binders used (fly ash and cement). Al and Si were also present from the binding agents or from the silicate gangue. Fe and S from pyrrhotite were the dominant elements for most of the sample.

1) Figures J1 to J4

   Description of sample No.1 (self-agglomerated) after 7 days of curing and prior weathering test using Back Scattered Electrons (BSE) showed more details of pyrrhotite particles around the sulphides. The pyrrhotite (white) is angular and can be clearly seen in Figure J3 and J4 (light smooth areas), gangue is medium grey.

2) Figures J5 and J6

   The images for sample No.1 (self-agglomerated) after 20 weeks of leaching, showed pyrrhotite with apperance of long threads which became longer and larger compared to images from figures J3 and J4.

3) Figures J7 -J8

Images of sample No. 16 (60%GY/40%PC) without the addition of *Thiobacillus* before leaching and after 20 weeks of leaching showed similar details. However, long threads of gypsum which became more evident after 20 weeks of leaching. The Energy Dispersive Spectrometry Spectrum (EDS) illustrated the presence of iron and sulphur which became more evident with presence of Ca, and Si after 20 weeks of leaching. Al and Si are present may be from the binding agents or from the silicate gangue.

4) Figures J9 to J14

Images of sample No. 5 (0.1% SLS) without the addition of *Thiobacillus.* pyrrhotite was not as clear as on the other samples but fly ash and cement is clear in lesser amounts. The images mostly revealed dark colours (fly ash) with high Ca and Al and small grains of pyrrhotite still present after 20 weeks of leaching.

5) Figures J15 and J18

BSE and Secondary electrons images of sample No. 4 (0.5% Enviroseal) showed dark material (fly ash), more silica than other samples and more sodium, calcium and aluminium due to the presence of cement and fly ash.

6) Figures J19

Images of sample No. 1 (self-agglomerated) after 58 weeks of testing using BSE. It showed more pyrrhotite with a smooth surface. ESD analysis showed an increase in the amount of iron and sulphur which may be a result of the oxidation process.

7) Figure J20

Images (BSE) of sample No. 2 (o.1% Enviroseal) after 58 weeks of leaching revealed less pyrrhotite and lesser amounts of iron and sulphur (EDS) compared to control sample No.1

8) Figure J21

Images (BSE) of sample No. 4 (0.5% Enviroseal) after 58 weeks of leaching revealed dark areas (fly ash) and less pyrrhotite particles compared to the control sample No.1.

9) Figures J22 to J24

Images (BSE) of sample No. 5, 6 and 7 (0.1%, 0.3% and 0.5% SLS) showed fly ash, cement but pyrrhotite was not as clear as the others samples. The EDS analysis revealed high amounts of sulphur and lesser amounts of iron compared to 20 weeks of leaching.

10) Figures J25 and J27

The image of sample No. 8 (tailings control sample) showed large oxidized particles of tailings agglomerated as a result of weathering after 58 weeks of testing. The BSE images showed more details of the oxidation particles while showing more white smooth surface areas (pyrrhotite).

11) Figures J27 and J28.

Images (BSE) of sample No. 17 (self-agglomerated with addition of *Thiobacillus).* The secondary electron images showed the interior oxidation of inside layer of pellet that was oxidized after 50 weeks of testing. The white particles are

pyrrhotite grains, the light grey particles are Fe-oxides and dark particles are Ca-Al silicates.

12) Figure J29

Images of sample No. 18 (0.5% Enviroseal with addition of *Thiobacillus)* revealing some pyrrhotite (white smooth surface). Less iron and sulphur were detected using EDS.

13) Figure J30

Images of sample No. 19 (0.1% SLS with addition of *Thiobacillus*) after 50 weeks of testing. Less pyrrhotite was revealed and EDS indicated that high amount of sulphur are present.

14) Figure J31

Images of sample No. 20 (0.1% sodium silicate with addition of *Thiobacillus*) after 50 weeks of testing. High amounts of Ca and Si were detected using EDS and pyrrhotite particles are shown in lesser amounts.

15) Figure J32

Images of sample No. 21 (60%PC/40%FA with addition of *Thiobacillus)* after 50 weeks of testing. Higher amounts of Ca and S were detected using EDS.

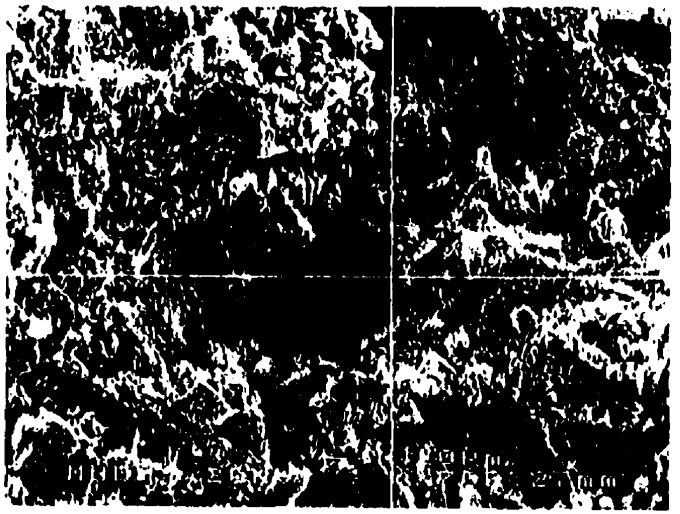


Figure J1.

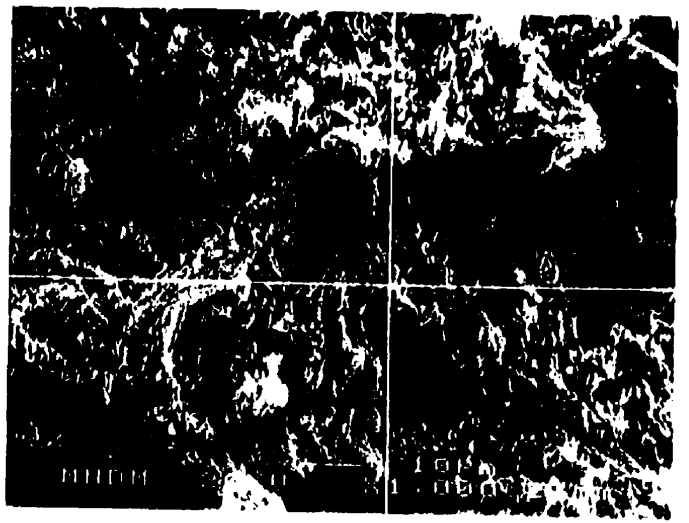


Figure J2.

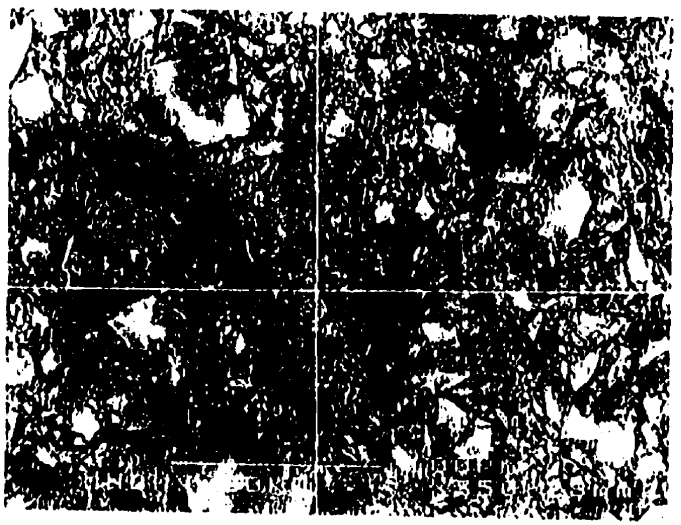


Figure J3.

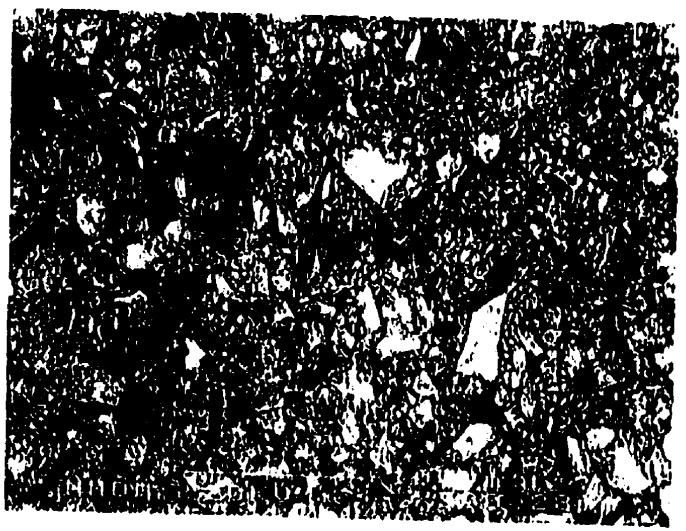


Figure J4.

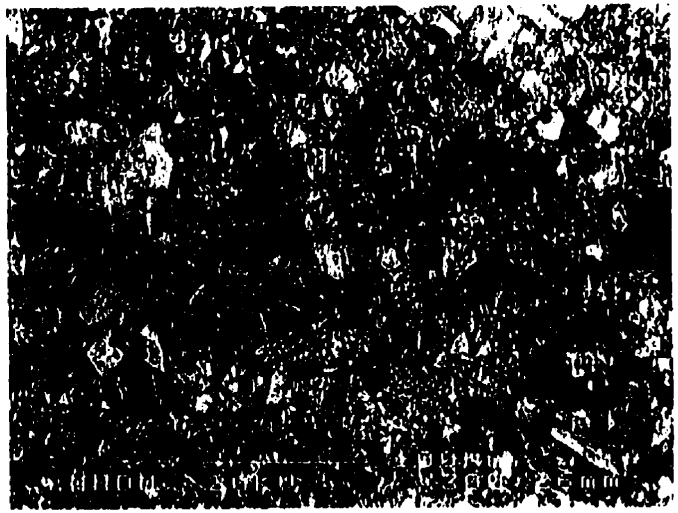


Figure J5.

Figure J6.

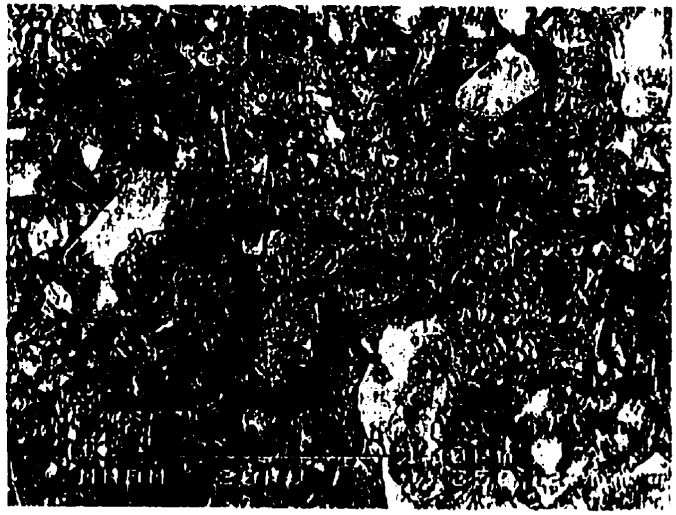


Figure J7.

Figure J8.

Figure J9.

Figure J10.

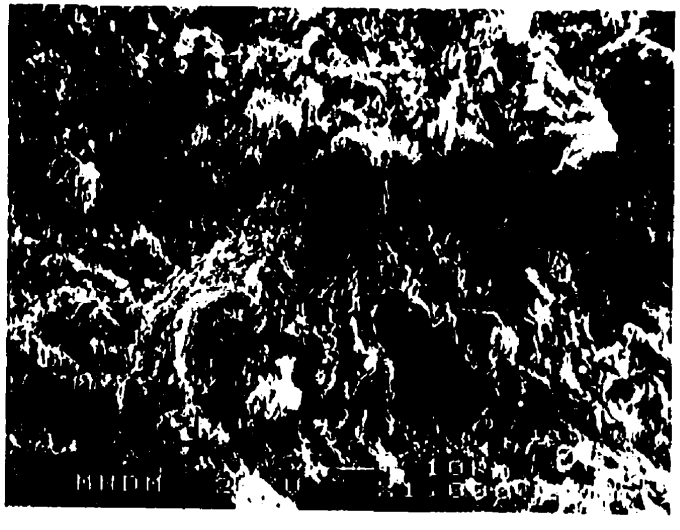


Figure J11.

Figure J12.

Figure J13.

Figure J14.

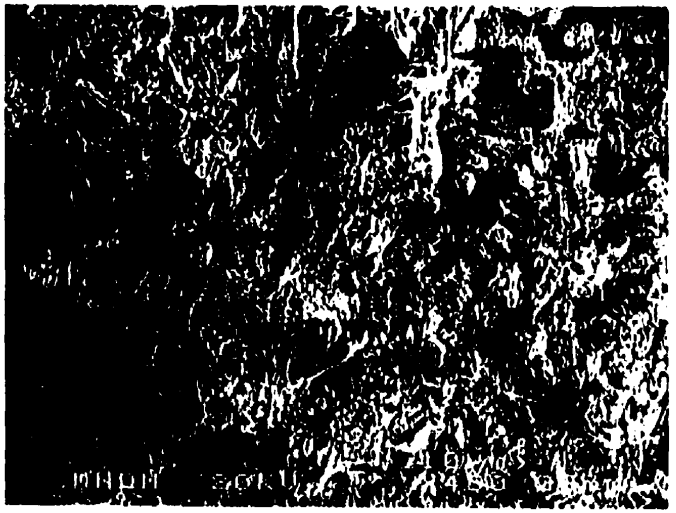


Figure J15.

Figure J16.

Figure J17.

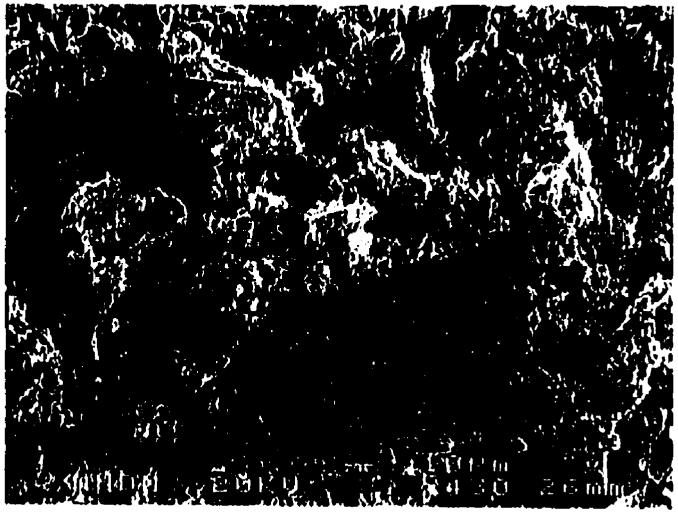


Figure J18.

Figure J19.

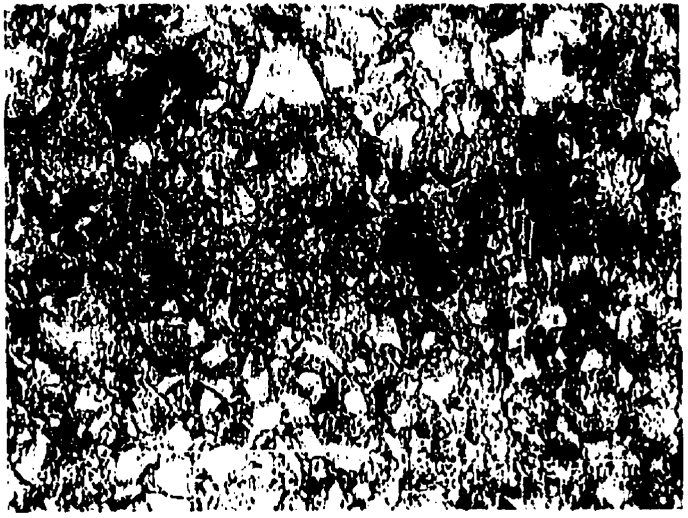


Figure J20.

Figure J21.

Figure J22.

Figure J23.

Figure J24.

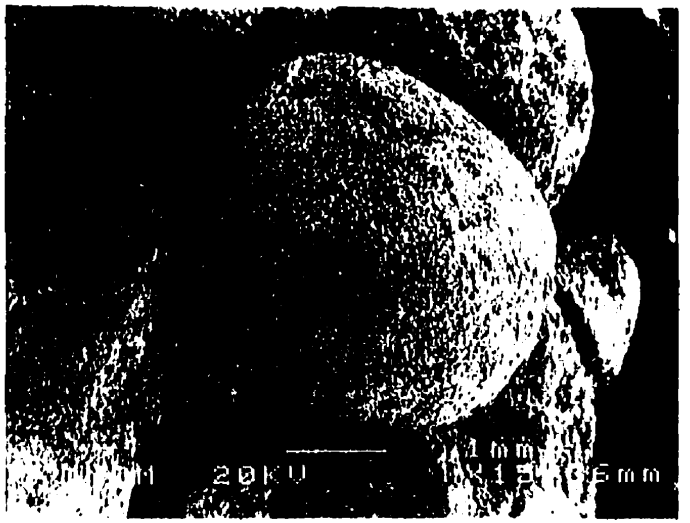


Figure J25.

Figure J26.

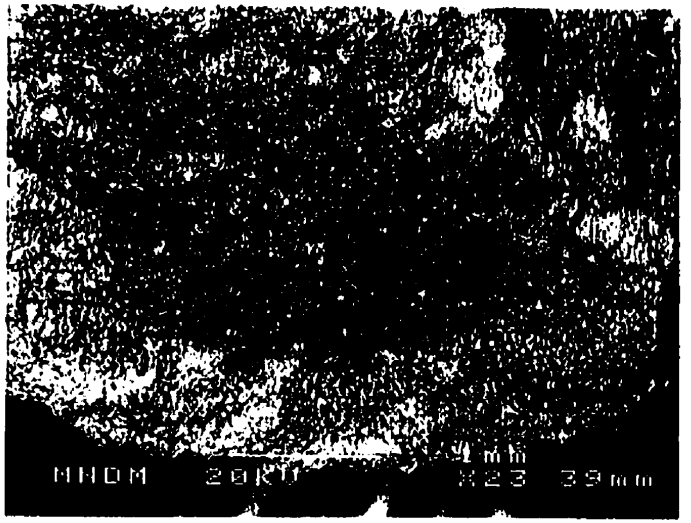


Figure J27.

Figure J28.

Figure J29.

Figure J30.

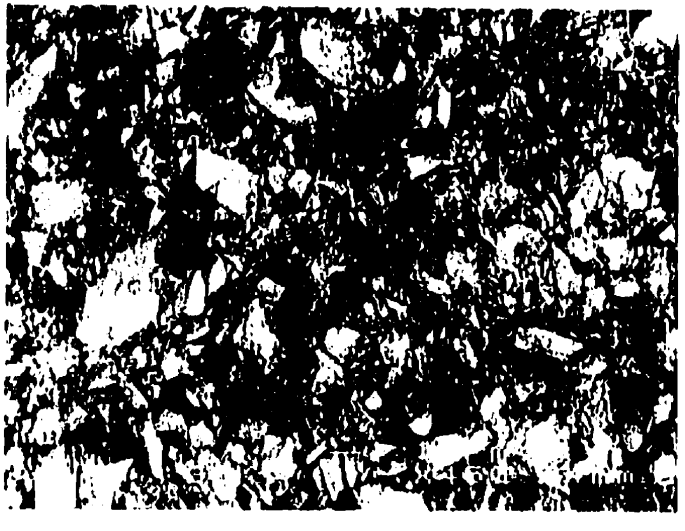


Figure J31.

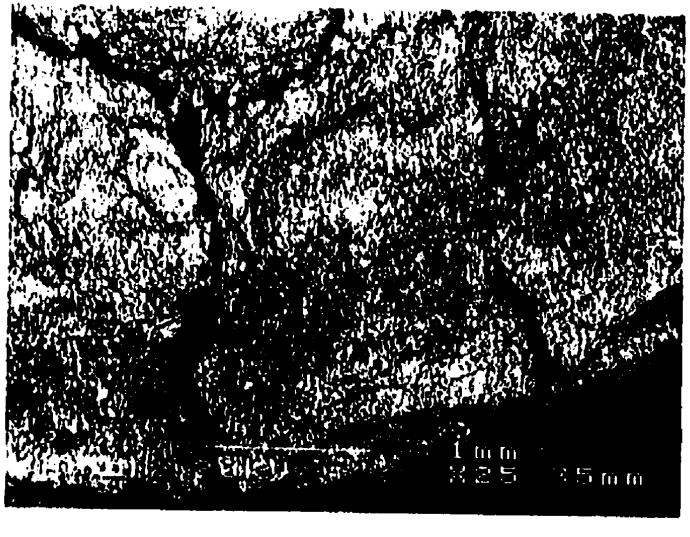


Figure J32.

APPENDIX (K)

The Results of Chemical Analysis of the Pellet Compositions

Table K1. Chemical Composition of Pellets Before Leaching and After 20 Weeks of Leaching

SAMPLE No.	Duration in Weeks	Na %	Mg %	Al %	Si %	P %	K %	Ca %	Ti %	Mn %	Fe %	SULPHUR %
GSP-1		1.99	0.57	8.06	31.22	0.12	4.58	1.45	0.39	0.03	3	0.03
1	0	0.25	0.08	0.27	2.76	0.01	0.01	0.39	0.08	0.04	37.91	24.32
2	0	0.37	0.1	1.33	5.27	0	0.06	2.08	0.17	0.04	39.59	30.22
3	0	0.14	0.05	1.17	5.1	0.01	0.05	2.48	0.17	0.04	39.8	29.64
4	0	0.17	0.21	1.29	5.31	0.01	0.05	2.51	0.18	0.04	39.5	29.52
5	0	0.17	0.43	1.33	5.48	0.01	0.05	2.44	0.18	0.04	39.33	29.72
6	0	0.12	0.08	1.04	4.98	0.01	0.04	2.53	0.15	0.04	39.91	31.55
9	0	0.23	0.19	1.4	5.9	0.02	0.09	2.43	0.17	0.04	38.42	29.08
10	0	0.26	0.04	1.43	5.76	0.01	0.09	2.88	0.17	0.04	38.42	29.46
11	0	0.62	0.31	1.38	5.72	0.01	0.08	2.63	0.17	0.04	38.58	30
12	0	1.43	0.23	1.1	5.14	0	0.07	2.83	0.15	0.04	39.04	31.75
13	0	0.03	0.19	1.4	5.63	0.01	0.08	2.85	0.16	0.04	38.55	30.92
14	0	0.31	0.12	1.31	5.37	0.01	0.07	2.44	0.16	0.04	39.22	29.8
15	0	0.38	0.14	1.33	5.49	0.01	0.08	2.55	0.17	0.04	38.85	29.83
16	0	0.29	0.43	1.47	5.87	0.01	0.09	2.72	0.17	0.04	38.29	29.33
1	0	0.1	0.6	1.41	5.86	0.01	0.07	2.62	0.19	0.04	38.33	29.22
2	0	0.03	0.46	1.47	5.95	0.01	0.07	2.68	0.19	0.04	38.23	30.12
3	20	0.09	0.12	0.65	3.95	0.01	0.03	0.69	0.12	0.02	30.13	23.16
4	20	0.36	0.36	1.45	5.92	0.01	0.08	2.7	0.19	0.04	37.27	28.41
5	20	0.3	0.48	1.41	5.92	0	0.06	2.53	0.2	0.04	38.86	29
6	20	0.2	0.22	1.45	5.88	0.01	0.06	2.73	0.19	0.04	38.85	29.02
7	20	1.49	0.51	1.47	5.9	0.01	0.06	2.48	0.2	0.04	39.12	29.72
8	20	0.13	0.17	0.64	3.84	0	0.02	0.53	0.14	0.03	34.84	22.66
9	20	0.58	0.19	1.51	6.05	0.01	0.09	2.65	0.17	0.04	37.97	28.5
10	20	0.35	0.44	1.46	5.86	0.01	0.08	2.64	0.17	0.04	38.09	28.8
11	20	0.24	0.45	1.44	5.88	0.01	0.08	2.69	0.17	0.04	38.28	29.6
12	20	0.01	0.76	0.78	4.14	0	0.04	2.52	0.12	0.04	37.46	31.29
13	20	0.25	0.1	1.31	5.4	0	0.07	2.58	0.2	0.04	38.67	29.2
14	20	0.34	0.18	1.29	5.31	0.01	0.07	2.54	0.17	0.04	39.04	29.76
15	20	0.24	0.22	1.36	5.44	0	0.07	2.62	0.17	0.04	38.97	29.89
16	20	0.14	0.27	1.52	5.9	0	0.09	2.78	0.17	0.04	38.25	28.76

Table K2. Chemical Composition of Pellets Before Leaching (week 0) and After 20 Weeks of Leaching

SAMPLE No.	Duration In Weeks	V ppm	Cr ppm	Fe %	Co ppm	Ni ppm	Cu ppm	Zn ppm	Nb ppm	Zr ppm	Y ppm	Sr ppm	Rb ppm	Ba ppm	Pb ppm
GSP-1		50.2	13.5	3	6.1	14.5	34.4	101.5	25.1	500.6	27.7	232.6	253.5	1331.8	51.8
1	0	58.1	54.7	37.1	61.3	12941.9	252	168.9	7.9	25.4	14	16.4	12.4	127.6	27.4
2	0	135.9	116.3	39.3	36.2	4473.8	307.3	153.6	9.9	36.1	18.8	193.6	29.6	501	24.5
3	0	114	136.4	39.2	37.2	4634.6	424.4	166.2	0.9	29	11.3	210.5	48.9	406.8	69.7
4	0	131.1	170.4	38.8	35.5	4544.1	367.5	182	0.4	18.8	23.9	243.9	0.2	524.7	0.1
5	0	127.4	201.4	38.9	41.9	4617.3	436.2	144.3	7.7	26.3	2.3	246.8	25.7	540.9	43.6
6	0	122.9	163.2	39.2	36.8	4629.6	371.2	172.8	7.3	25.3	6.6	127.9	50.7	183.2	69.3
9	0	101.7	195	38	38.8	4722.7	535.2	182	0.1	24.2	25.3	263.3	29.3	457.1	42.9
10	0	133.1	201	37.4	42.2	4689.9	587	183.5	6.2	48.5	0.6	256.6	33.2	433.2	16.6
11	0	116.2	146.6	38	40.8	4714.9	609.3	181	10.5	47.5	4.4	244.4	54.1	450.6	11.5
12	0	101.7	250	37.9	45.4	4709.5	563.4	162.2	12.7	22.4	15.3	153.2	7.5	188.9	62.7
13	0	110.7	438.3	37.7	40.4	4744.1	568.4	169.7	7.2	18.1	16.9	260	19.8	462.8	70
14	0	102.8	181.3	38.7	39.9	4686.6	566.9	167.6	4.7	36.6	23.3	232.2	23.8	471.1	10.6
15	0	130.5	134.6	38.2	36.4	4741.1	649.6	163.3	19	31.1	0	251	31.6	434.6	61.1
16	0	117.1	204.4	37.5	43.2	4695	569.3	160.9	7.3	25.4	6.2	282.8	48.9	511.1	1.5
1	20	120.5	137.2	37.7	39	4387.7	279.9	215	2.5	53.2	23.8	269	24.6	467.2	38.1
2	20	121.6	160.9	37.6	40.9	4402.9	271.1	194.3	10.6	38.6	6.3	260.2	31.7	521.4	89.5
3	20	87.6	96.1	27.6	69.4	2605.8	117.7	79.3	4.9	13.7	0.1	33.5	12.5	270.5	23
4	20	144.5	172.5	36.4	46.7	4234.3	250.4	194.2	5.4	46	0.6	234.6	11	490.9	35.4
5	20	118.5	127.1	38.4	42.3	4435	257.8	220.8	3.3	27.6	11.3	261	15.4	506.3	56
6	20	142.5	140.9	38.1	41.4	4392.4	236.6	190.7	12.7	37.4	14.7	263.8	28.8	514	17.7
7	20	147.1	122.4	38.8	41.4	4474.6	245.5	212.4	0.1	41.8	13.8	244.5	24.3	497.7	0.7
8	20	105.6	114.7	33	49.3	2090.1	111.8	69.1	4.1	16.9	1.2	35.4	0.4	245.1	37.2
9	20	140.3	101.3	37.2	46.2	4680.6	549.1	164.4	7	35	12.6	255.3	18.3	547.4	37.3
10	20	101.9	126.9	37.6	44.3	4684.2	602.4	159.1	0.9	28.6	17.7	283.6	46.3	455.4	54.2
11	20	131.9	96.7	37.6	44.2	4691	628.1	174.4	7.3	34.4	13.4	266.2	1.1	478.5	64
12	20	92.6	96.7	36	59.1	8674.3	458.4	170.3	-0.6	25.8	22.6	133.5	22.8	177.9	16.2
13	20	116.9	104.7	37.9	42.7	4747.5	591.3	155.3	6.5	37.3	9.6	243.1	35.2	481.4	66
14	20	115.3	189.9	38.2	40.4	4747.4	539.3	176.5	8.3	29.2	19.5	263.2	6.4	464.8	35
15	20	105.8	112	38.1	39.7	4725	608.9	145.5	7.7	30.7	17.5	234.6	54.5	476.4	18.1
16	20	103	104.1	37.4	42.2	4676.3	549.3	182.5	13.3	32.9	0.8	288.7	27.7	531.5	9.7

Table K3. Chemical Composition of Pellets After 50 Weeks and 58 Weeks of Leaching

SAMPLE No.	Na %	Mg %	Al %	Si %	P %	K %	Ca %	Ti %	Mn %	Fe %	SULPHUR %
GSP-1	1.99	0.57	8.06	31.22	0.12	4.58	1.45	0.39	0.03	3	0.03
1	0.08	0.21	1.58	6.52	0.01	0.06	1.97	0.23	0.04	38.34	29.62
2	0.1	0.15	1.38	6.3	0.01	0.05	2.01	0.21	0.04	38.4	29.59
3	0.11	0.14	0.54	4.84	0	0.03	0.43	0.14	0.03	37.18	26.61
4	0.16	0.27	1.49	6.48	0.01	0.07	2.15	0.21	0.04	37.97	29.32
5	0.11	0.21	1.23	5.93	0	0.04	1.96	0.21	0.04	38.87	28.48
6	0.08	0.3	1.5	6.57	0.01	0.05	1.49	0.21	0.04	39.36	28.57
7	0.1	0.24	1.56	6.61	0.01	0.05	1.52	0.21	0.04	39.29	28.81
8	0.14	0.11	0.61	4.97	0	0.02	0.4	0.15	0.03	40	30.16
9	0.14	0.27	1.54	6.6	0	0.08	2.15	0.17	0.04	37.84	27.87
10	0.25	0.31	1.46	6.49	0.01	0.07	2.15	0.17	0.04	38.12	29.6
11	0.22	0.31	1.48	6.57	0.01	0.07	2.37	0.17	0.04	37.92	28.81
12	0.2	0.13	0.72	5.18	0	0.03	2.28	0.13	0.03	37.98	30.84
13	0.12	0.01	1.4	6.24	0.01	0.06	2.2	0.17	0.04	38.16	30.43
14	0.2	0.14	1.34	6.15	0.01	0.06	2.36	0.17	0.04	38.65	31.21
15	0.22	0.09	1.39	6.26	0	0.07	2.22	0.17	0.04	38.36	29.45
16	0.12	0.11	1.55	6.56	0	0.08	2.12	0.18	0.04	38.22	29.14
17	0.13	0.08	0.59	4.87	0.01	0.02	0.39	0.13	0.03	38.78	31.82
18	0.16	0.3	1.23	5.94	0.01	0.05	1.78	0.18	0.04	39.24	30.22
19	0.24	0.12	1.27	5.94	0.01	0.05	1.6	0.18	0.04	39.77	30.19
20	0.16	0.08	1.32	6.1	0.01	0.04	1.89	0.19	0.04	39.1	28.89
21	0.13	0.14	1.15	5.76	0.01	0.04	1.85	0.17	0.04	39.25	28.49
22	0.23	0.07	0.6	4.98	0.01	0.03	1.91	0.13	0.03	38.87	30.18

*Samples No. 1 to 16 were tested for 58 weeks
*Samples No.17 to 22 were tested for 50 weeks

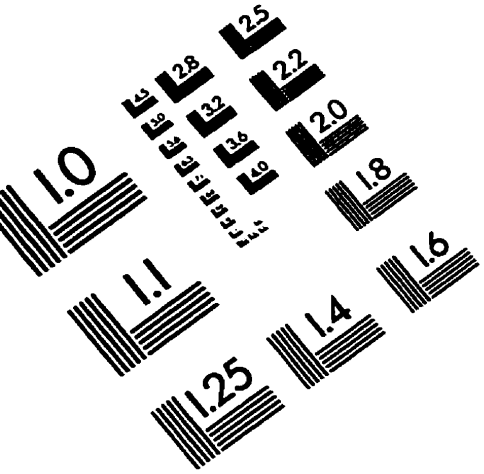
Table K4. Chemical Compositon of Pellets After 50 and 58 Weeks of Testing

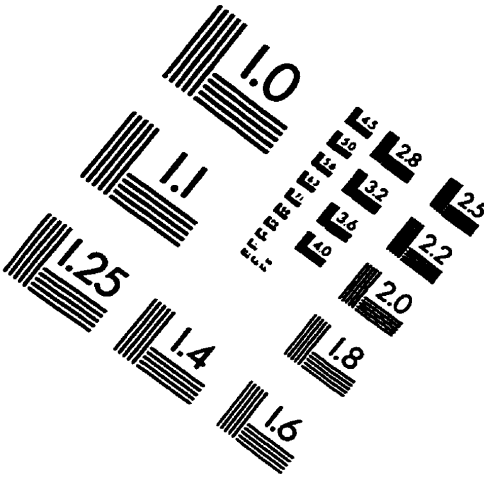
SAMPLE No.	V ppm	Cr ppm	Fe %	Co ppm	Ni ppm	Cu ppm	Zn ppm	Nb ppm	Zr ppm	Y ppm	Sr ppm	Rb ppm	Ba ppm	Pb ppm
GSP-1	50.2	13.5	3	6.1	14.5	34.4	101.5	25.1	500.6	27.7	232.6	253.5	1331.8	51.8
1	142.3	119	38.4	42.1	4530	289.7	217.8	10	29.9	14.8	258.2	20.3	478.2	50.8
2	122.6	133.5	38.3	44.2	4711	229.4	173.7	5.1	31.5	5.7	248.2	35.8	488.8	57.9
3	99.3	103.8	36.4	42.3	2467	190.5	142.5	9.3	13.1	12.6	75.3	11.7	189.2	62.1
4	129.5	113.3	37.8	46.3	4466	251.1	224	15.4	33.9	9.9	261.7	5.6	502.5	86.7
5	111.2	154.8	38.9	39.1	4792	384.2	144.4	11.1	40.4	19.8	200.9	30.8	474.9	19.1
6	135.9	169.1	40.1	36.1	4619	295	216.3	5.2	45.8	14.4	232.6	20.1	514.3	70.6
7	124	138.8	40.3	32.7	4581	246.9	235.1	4.1	28.9	19.8	220.6	28.9	487	20.8
8	126.6	103.4	39.4	31.8	1679	194.4	146.3	0.8	21.8	9.6	53.8	22.8	185	59.2
9	120.3	93.5	37.7	41.5	4723	542.4	159.6	2	26.3	15.5	242.9	14.5	548.1	30.4
10	109.6	90.7	38.1	43.6	4754	552.3	161	9.1	36.7	34.5	240.1	10.5	454.5	2.1
11	112.6	92.9	37.7	46.7	4729	585.1	180.9	0.4	44.9	12.6	273.9	17.6	480.2	45.1
12	80.9	77.8	36.5	47.8	3360	478.6	128.4	9.4	19.5	11.9	120.2	19.4	188.3	33.5
13	114.3	171.3	37.8	45.9	4935	586.6	176.5	9.8	43.3	17.4	261.6	24.2	528.2	48.8
14	126.2	104.6	38.1	42.3	4750	524.2	148.2	6.5	21.3	16.3	253.4	14.9	504.3	68
15	102.2	102.3	38.3	43.9	4743	550	158.1	13.1	18.2	20.3	251.9	13.9	489.7	2
16	126.1	102.5	38.1	48.7	4744	578.4	190.1	0.2	30.7	8.9	271.5	43.1	477	95.3
17	106.3	86.9	38.7	39.4	3678	317.2	109.7	15.8	21.9	1.4	44.8	0.1	186.9	48.6
18	115.5	106.8	39.4	32.4	4492	307.8	151.4	6.3	31.3	7.1	223.3	28.5	463.4	41.9
19	144.7	100.5	40.1	32.7	4658	390.8	155.5	9.5	35.9	14.9	193.3	25.6	461.9	51.3
20	121.9	116.5	39.3	34.3	4752	426.2	144.2	17.5	22.7	12.2	234.1	18.8	567.9	33.5
21	135.4	119.9	39.1	35.8	4492	357.8	161.2	12.7	34.2	3.6	206.9	33.2	522.6	0.2
22	87.8	80.9	37.4	37.6	2469	348.7	121.2	9	33.4	24.4	76.8	14.2	185.9	43.9

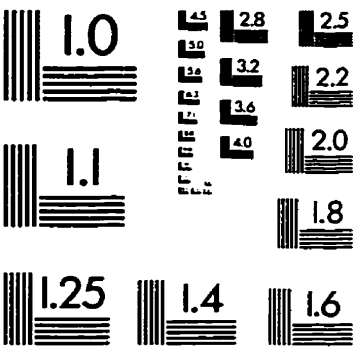
*Sample No.1 to 16 were tested for 58 weeks

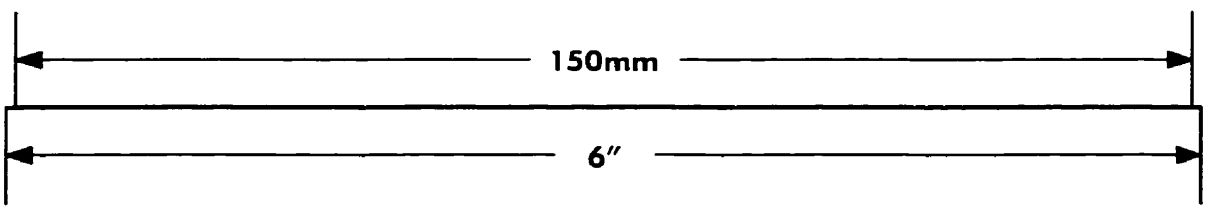
*Sample No.17 to 22 were tested for 50 weeks in presence of Thiobacillus

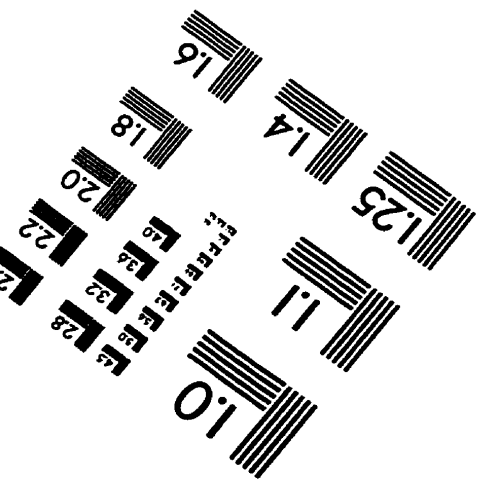
IMAGE EVALUATION TEST TARGET (QA-3)

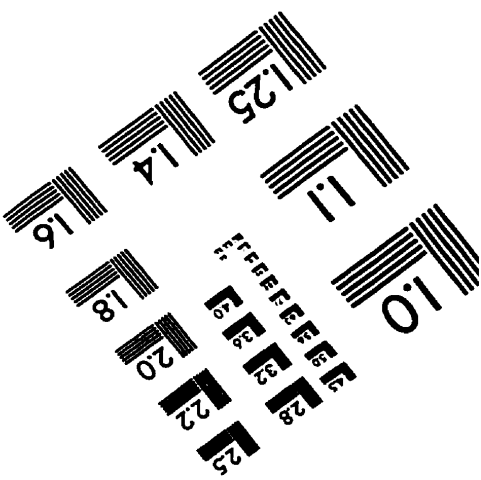












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