

Shahid Azam, PhD¹, Rick J. Chalaturnyk, PhD², and J. Don Scott, PhD³

Geotechnical characterization of laterite slurries for sedimentation evaluation

ABSTRACT: Laterites are the main source of economic metals such as nickel and cobalt. In many parts of the globe, these metals are extracted using the pressure acid leach operation. An efficient rate of sedimentation and a high solids content of the sedimented material are two prerequisites of this process. To understand the geotechnical behavior of laterite slurries under ambient process conditions, a comprehensive laboratory characterization protocol was developed. Results indicate that due to changes in material characteristics, sedimentation behavior of laterite slurries is improved during the metal extraction process. The rate and amount of sedimentation are directly related for this class of materials.

KEYWORDS: Laterite, Slurries, Ore, and PAL

Introduction

Laterites are the key source of economic metals such as nickel (Ni) and cobalt (Co). These residual soils contain 80% of known Ni reserves on land with sizeable amounts of Co (Golightly 1979). The pressure acid leach (PAL) process is the most widely used method for extracting metals from laterite ores due to its high recovery, low environmental risk, and economic viability (Motteram et al. 1996). This process uses selective metal dissolution in an acidic medium at elevated temperature and pressure (Chalkley & Toirac 1997). The method requires the conversion of the raw ores to slurries prior to the leaching operation that, in turn, generates slurries possessing a significantly different set of engineering characteristics. Given the increasing demand for Ni and Co, there was an exigent need to conduct a comprehensive study of these materials.

To obtain Ni and Co from the pregnant liquor in the slurry, the extraction process requires an expedient separation of the solid phase from the liquid phase. An efficient rate of sedimentation and a high solids content of the sedimented material are two prerequisites of the pressure acid leach operation. The subject matter of this research is a geotechnical assessment of various types of laterite ores used as input and of laterite PALs obtained as output in the hydrometallurgical operation for metal extraction.

The main objective of this study was to develop a fundamental understanding of the sedimentation behavior of laterite slurries under ambient process conditions by highlighting the influence of ore geology and of the PAL process. For this purpose, a specialized laboratory characterization protocol was developed owing to the various peculiarities associated with this class of materials. Routine testing procedures were modified because: (1) laterites have been reported to illustrate variations in engineering properties when dried by heating or by exposure to air (Townsend 1985); (2) dealing with heavy and fine-grained slurries with sometimes opaque

¹ Geotechnical Engineer, Klohn Crippen Consultants Limited, 500 Virtual Way, Vancouver, BC, Canada V5M 4X6.

² Associate Professor, Dept. of Civil & Environ. Eng., University of Alberta, Edmonton, AB, Canada T6G 2G7.

³ Professor Emeritus, Dept. of Civil & Environ. Eng., University of Alberta, Edmonton, AB, Canada T6G 2G7.

pore fluids is entirely different from soils generally encountered by engineers during routine geotechnical investigation; and (3) of the indispensable requirement to capture the expected changes in material characteristics during the metal extraction process.

Based on laboratory investigations, this paper presents the engineering characteristics of laterite slurries at two stages of the metal extraction process: ore slurries and PAL slurries. At the outset, an overview of material characteristics such as mineralogy of the solid phase and chemistry of the pore fluid is presented. This is followed by providing geotechnical appraisal of laterites originating from different parts of the globe using index properties. Finally, all of these data are used to understand the sedimentation behavior of both laterite ore and laterite PAL slurries.

Materials and Handling

The Metallurgical Technologies Division of Dynatec Corporation, Canada, provided laterite slurry samples. These included underflow ore slurries from the storage thickener and underflow PAL slurries from the first thickener of the multi-stage counter current decantation (CCD) wash circuit. Four laterite ore slurries were selected for geotechnical characterization from various parts of the globe: Cuba, Philippines, Australia and Indonesia. The Cuban sample represented a limonite ore whereas the Indonesian sample denoted a saprolite ore; the Philippines and the Australian samples corresponded to two distinct varieties of limonite and saprolite blended ores. For these ore slurries, the corresponding PAL slurries were obtained using consistent process conditions: temperature, 245-250 °C; pressure, 4000-4100 kPa; reaction time, 50-60 min; and pH < 1.

Table 1 gives the characteristics of laterite slurries under ambient process conditions and indicates that the pore fluid in the ore slurries was mainly neutral whereas that in the PAL slurries was highly acidic. According to the Workplace Hazardous Materials Information Systems (WHMIS), the latter type of materials is considered hazardous. To work safely, a WHMIS training course was attended under the auspices of the Office of Environmental Health and Safety, University of Alberta.

TABLE 1— Characteristics of laterite slurries under ambient process conditions

Process Stage	Parameter	Sample Type and Origin			
		Limonite	Limonite-Saprolite		Saprolite
		Cuba	Philippines	Australia	Indonesia
Ore Slurries	Color	Pinkish Red	Pink	Dark Gray	Red
	w, %	193	163	173	305
	s, %	34	38	37	25
	pH	7.1	7.2	7.5	7.3
	EC, $\mu\text{S}/\text{cm}$	156	744	1250	442
	Minerals*	G, H, M	G, H, M, C	C, G, H, M, A	C, A, G
PAL Slurries	Color	Brown	Dark Brown	Brown	Light Brown
	w, %	177	119	131	261
	s, %	36	46	43	28
	pH	0.8	0.4	0.5	0.6
	EC, $\mu\text{S}/\text{cm}$	>10000†	>10000†	>10000†	>10000†
	Minerals*	H	H	H, S, A	H, S, A

* Mineral quantity decreases from left to right

A = Amorphous materials, C = Clay minerals, G = Goethite, H = Hematite, M = Maghemite, and S = Sulfates

† Upper limit of the measuring device

Protective measures consisted of means of preventing direct contact with the samples. This included chemical resistant laboratory coats and hand gloves, safety glasses, face shields, and respiratory protection. Laboratory space was well ventilated by exhaust fans to minimize exposure to acid vapors. To cope with emergencies, eyewash and shower, a first aid box and doctor's telephone contact were made accessible. Minor spills and leaks were usually diluted and neutralized with soda ash or lime whereas larger spills were contained. The waste materials were stored in an isolated and confined area to minimize the possibility of contaminating the environment. All materials were eventually disposed of in a landfill in accordance with the regulatory criteria.

Laboratory Protocol

General

To characterize laterite slurries under ambient process conditions, a comprehensive laboratory investigation protocol was devised. This section gives a detailed account of the various testing procedures modified after standard methods specified by the American Society for Testing and Materials (ASTM). Similarly, this section presents the sedimentation test specifically designed for these fine-grained slurries composed of heavy particles and opaque pore fluids.

Laterites are prone to changes in properties caused by drying and exposure to air (Townsend 1985). Air-drying at ambient temperature can cause changes that cannot be reversed by re-wetting (Fourie 1997). Similarly, oven-drying leads to partial or complete dehydration of the clay minerals present in the soil thereby resulting in significant variations in engineering properties (Frost 1976). To preclude the possible occurrence of any permanent changes, air-drying was completely avoided in this research; oven-heating was avoided as far as possible. For all laboratory tests involving the use of material drying, heating was conducted at an oven-temperature lower than that usually specified in routine ASTM test procedures. Other test specific alterations are described where appropriate.

The metal extraction process requires that the ores be converted to fine-grained slurries; the resulting PAL slurries are also fine-grained. Due to their heavy particles and the expected high settling rates of these slurries and because of the dark color of the pore fluid in the PAL slurries, the movement of the sedimenting material was digitally recorded. This greatly improved discerning of the fast moving and sometimes vaguely visible solid-liquid interface of the slurry. The facility to electronically enlarge and refine the captured interface minimized any possible observational error.

Water Content

Water content (w) is defined as the ratio of the mass of water in a given volume of soil to that of the soil particles in the same volume. Expressed as a percentage, water content is generally determined according to the ASTM Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D 2216-98). In this method, the sample is oven-dried at a temperature of 110 ± 5 °C, which can cause removal of structural water from residual soils (Holtz & Kovacs 1981). Therefore, water content was determined at a temperature of 50 °C as suggested by Fourie (1997). Although, this reduced oven temperature could result in an underestimation of water content, such discrepancies were considered negligible owing to the large amount of water present in the slurries.

Water content was translated to solids content (s), which is the mass of soil solids divided by the total mass of the soil, and is also expressed as a percentage. Based on basic relationships, such conversion was made according to the following equation:

$$s = \frac{1}{1 + w} \quad (1)$$

Specific Gravity

Specific gravity (G_s) is the ratio of the mass of a unit volume of a material at a standard temperature (4 °C) to the mass in air of the same volume of gas-free distilled water at the stated temperature. This parameter is usually determined according to the ASTM Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer (D 854-00). To preclude pre-test drying, Fourie (1997) proposed that the dry mass of the specimen should be calculated at a temperature of 50 °C after the test; air removal was achieved by vacuum and did not involve heating. These two alterations were adapted to the standard ASTM procedure during this study.

The specific gravity of the soil was used to calculate void ratio (e), which is the ratio of the volume of voids to the volume of solids. Assuming complete saturation and using unity for the specific gravity of water, void ratio was calculated from a knowledge of solids content according to the following expression:

$$e = G_s \left(\frac{1-s}{s} \right) = G_s w \quad (2)$$

Grain Size Distribution

Grain size distribution analyses are generally performed according to the ASTM Standard Test Method for Particle-Size Analysis of Soils (D422-63(1998)). This procedure was modified to account for the initial dry mass of the slurry that was unknown because pre-test drying had to be avoided. Therefore, the soil sample was divided into two sub-samples; one for determining dry mass of the soil and the other for grain size analyses (Dusseault & Scott 1983). Hydrometer analysis was performed on slurry specimens after dispersing the soil mass by agitation with dilute alkaline sodium hexametaphosphate (Wintermeyer & Kinter 1954). Dispersion was ensured only for the ore slurries because of the expected presence of clay minerals, which tend to flocculate and form clods thereby accelerating free fall under gravity (Lamb 1951). Due to the highly acidic pore fluid and the anticipated decay of clay minerals under harsh environmental conditions, no dispersing agent was used for laterite PAL slurries. This ensured in obtaining actual grain size distribution before and after metal extraction. To preclude the effect of hindered settling during the hydrometer test, 25 g of soil, on dry mass basis, was used in the test. Based on experimentation, this amount was found to be appropriate for both ore and PAL slurries. The hydrometer test was followed by a sieve analysis on the same material washed with distilled water.

Results of the combined hydrometer and sieve analyses yield important parameters. The sand size fraction was defined as the percentage of mass finer than 0.075 mm in the total mass of soil solids whereas the clay size fraction (%) was defined as the amount of mass finer than 0.002 mm in the total mass of soil solids; between these limits is the silt size fraction that is also expressed as a percentage. The sand size determines mechanical properties of a soil slurry whereas the clay size governs the physico-chemical phenomena between the solid and the liquid phases (Mitchell 1993).

To corroborate the results of the combined hydrometer and sieve analyses, grain size distribution was studied in conjunction with visual observation of laterite particle structure (shape, size and texture) using scanning electron microscopy (SEM). For this purpose, the microscope (model JSM-6301FXV) manufactured by Japan Electron Optics Limited (JEOL), was used. The micrographs were taken at an enlargement of 10000 times.

Consistency Limits

The presence of water is one of the key factors influencing the behavior of fine-grained soils. Expressed as percentage, the liquid limit (w_l) and plastic limit (w_p) are water contents at critical stages in soil behavior and provide a standardized scale for efficient comparison of this behavior. These limits were determined according to the ASTM Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (D 4318-00). Related to and derived from consistency limits is the plasticity index (I_p), which is a useful parameter for the identification and classification of fine-grained soils. Indicating the range of water contents over which a soil is plastic, I_p is numerically equal to the difference of the liquid limit and the plastic limit.

Consistency limits for laterite ores are mainly affected by pre-drying and mixing time (Rouse et al. 1986). The effect of drying prior to testing is attributed to increased cementation due to hydrated oxides of iron and aluminum (Townsend 1985). The consistency limits were determined by gradual drying of the high water content slurries at an oven-temperature of 50 °C. This greatly reduced the effect of water addition, pre-drying and mixing on soil consistency. To further minimize the breakdown of clay clusters in the soil, mixing time was restricted to five minutes as suggested by Fourie (1997). Incidentally, no published data was found on the consistency limits of laterite PALs and, as such, additional issues with these latter materials could not be identified. To facilitate an easy comparison between various samples, the influence of increasing concentration of various ions in pore water during drying was not taken into consideration.

Water Chemistry and Mineralogy

To appreciate the influence of physico-chemical interactions on geotechnical behavior, the solid and liquid phases of laterite slurries were characterized. This involved the determination of pH and electrical conductivity (EC) of soil water and mineralogy of soil solids. An Accumet 50 instrument that allowed an accuracy of ± 0.1 units was used for measurement of both pH and EC. The pH was determined according to the ASTM Standard Test Method for pH of Soils (D4972-01). Similarly, EC was measured as per ASTM Standard Test Methods for Electrical Conductivity and Resistivity of Water D1125-95(1999). Mineral composition was investigated by X-ray diffraction (XRD) analysis using a Phillips diffractometer, Model Pw 1710. To obtain a tangible mineralogy, the grain size distributions of the XRD specimens were kept identical to those under ambient process conditions. This was obtained by oven-drying the slurry samples at 50 °C and subsequent manual grinding in a porcelain mortar pestle to powdered form.

Sedimentation

Sedimentation tests were conducted using 8.5 cm diameter graduated cylinders due to the limited amount of material obtained from various parts of the globe. To facilitate visual observation of the fast moving interface through opaque fluids, the initial sample height was kept as 8.5 cm. The resulting height to diameter ratio of 1.0 at the start of the test was found to have no significant wall effects. To mimic process conditions and to facilitate easy comparison, the

initial solids content was kept at 15%. For all of the investigated materials, this initial solids content pertained to negligible segregation. Based on consultations with the chemical and the mining industry, the 15% initial solids content was the highest value at which interactions between laterite colloids and the pore fluid are at a maximum.

Figure 1 shows the experimental system for conducting the sedimentation test. The slurry sample was poured into the graduated cylinder up to a height of 8.5 cm and was allowed to settle under self-weight. The solid-liquid interface movement was captured at equal intervals of time using a camcorder with macro lenses that allowed image magnification of up to 7 times. The figure shows that the camcorder was connected to a computer that stored the captured frames in a digital format. On the computer screen, the figure illustrates a magnified version of the focused area containing the solid-liquid interface. After the completion of the sedimentation test, the enlarged digital frame files were carefully viewed and the observed data were recorded as interface height versus time.

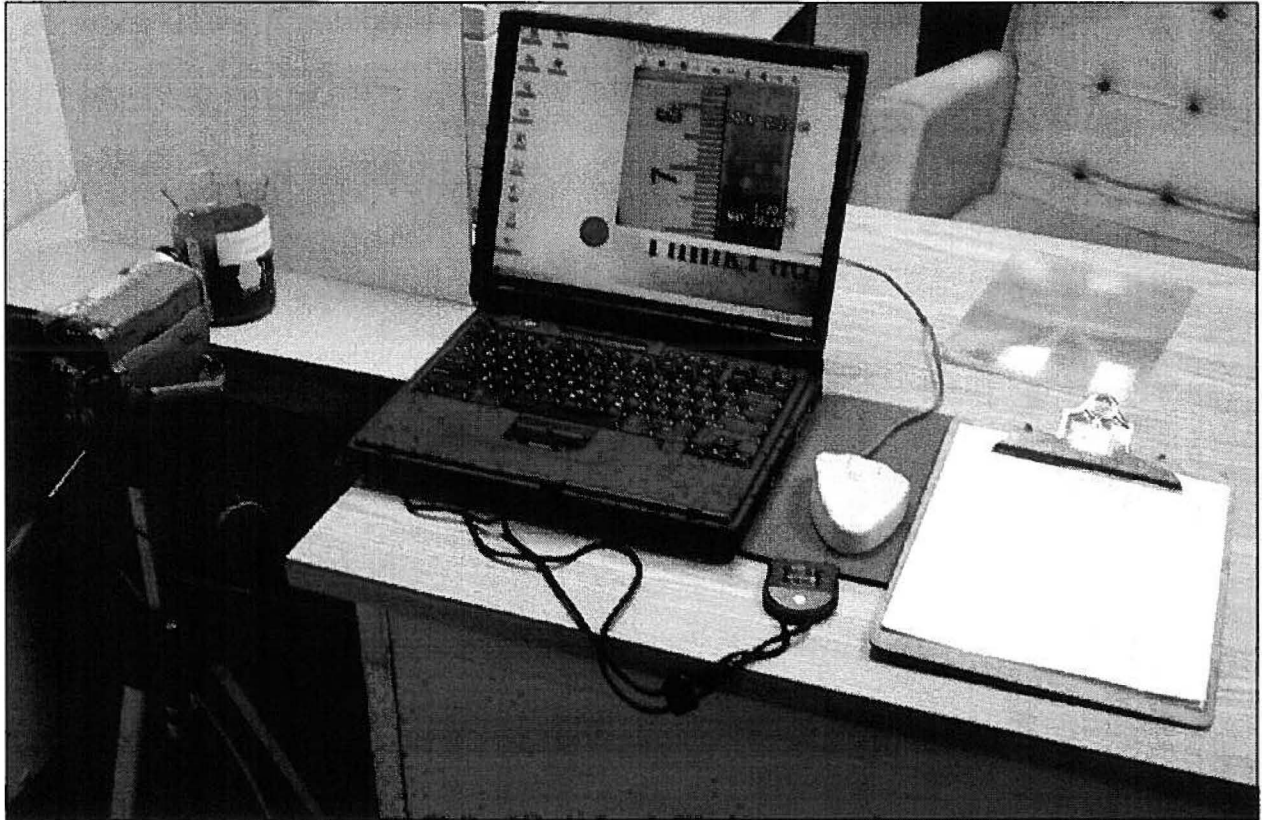


FIG. 1— *Experimental system for sedimentation test*

The slope of the initial straight-line portion of the sedimentation curve was used to determine the initial hydraulic conductivity (k_i) according to the theoretical formulation given by Pane & Schiffman (1997). Using the settling velocity (V_s) of the grains and the unit weights of soil solids (γ_s) and water (γ_w), k_i was determined according to the following equation:

$$k_i = \frac{\gamma_w V_s (1 + e)}{\gamma_s - \gamma_w} \quad (3)$$

The sedimentation data was further translated to void ratio-time and solids content-time curves using equation 2. First, the initial void ratio (e_0) was calculated from knowledge of the initial solids content (s_0). Then, the void ratio (e_i) pertaining to the next time reading was obtained by multiplying the initial void ratio with the interface height at that time reading. In turn, the next solids content (s_i) that corresponded to e_i was calculated by rearranging equation 2, and so on.

Results and Discussion

Material Characteristics

Table 1 summarizes the material characteristics of laterite ore and PAL slurries. This table indicates that the color of various laterite ores range from pink to red and even dark gray. All of these colors are invariably transformed to various shades of brown under the severe conditions of the PAL process. Derived either from the in situ geology or from the autoclave operation, the color of these samples denotes their composition that affects their distinct set of engineering characteristics.

Table 1 gives the water content of different laterite underflow slurries from the storage and CCD thickeners. The table indicates that all ore slurries are associated with high water contents, which is attributed to the high water requirement for slurry preparation. The amount of water required to prepare suitable plant feed from laterite ores depends on the bond strength of particles, size of aggregates and mineral composition (Schramm 1996). Removal of the strong sesquioxide coating on soil particles in these ores during wet screening is the key factor contributing to their high water demand (Golightly 1981). The table indicates lower values of water content for PAL slurries suggesting a lower water requirement for the PAL operation. According to Carlson & Simmons (1960), the amount of water required in the autoclave mainly depends on availability that, in turn, is determined by the economics of the metal extraction process.

The water content of the limonite-saprolite thickener underflow is lower than that of both the limonite and the saprolite. This is attributed to the possible presence of some mineral types in these samples containing adsorbed and/or structural water that cannot be removed at a temperature of 50 °C (Mackenzie 1957). Some of these materials include clay minerals formed in relatively arid climates, amorphous silica gels possessing water adsorbing properties, and various forms of magnesium sulfates containing structural water.

The corresponding solids content of laterite underflow slurries from the thickeners gives an insight into their dewatering behavior. Table 1 indicates a variable amount of released water for the investigated slurries despite the fact that the initial solids content is generally of the order of 15%. The limonite-saprolite slurries release more water than the other two slurries. This shows that the former slurries obtained from blending limonite and saprolite materials, coalesce the positive characteristics of both ore types and their subsequent PALs. Table 1 shows a general improvement in underflow solids content by 2 to 8% during the metal extraction process. This indicates changes in both the solid and the liquid phases as well as in the resulting colloid-electrolyte interactions in the ore and the PAL slurries.

Table 1 indicates that the water used in slurry preparation is generally neutral to slightly basic. On the other hand, this table indicates the extreme degree of acidity of the pore water by reporting pH values less than 1 for all of the laterite PAL slurries. The EC measured for pore water of various ore slurries varies between 150 and 1250 $\mu\text{S}/\text{cm}$ whereas that for the pore fluid

of all PAL slurries reaches the maximum limit of the measuring device and measures 10,000 $\mu\text{S}/\text{cm}$. This means that the pore fluids of the latter materials are rich in multivalent ions. Azam (2003) determined that H^+ , Ca^{2+} , Mg^{2+} , Mn^{2+} , Al^{3+} , Fe^{3+} , Ni^{3+} , Co^{3+} and SO_4^{2-} are the major ions in the pore fluids of the PAL slurries.

Table 1 shows that the ores are mainly composed of minerals such as goethite, hematite and maghemite. Clay minerals and amorphous materials such as silica and iron oxides are also present in sizeable amounts in ores derived from saprolite. Due to the high temperature and pressure and acid treatment in the autoclave, goethite and maghemite are converted to hematite whereas the clay mineral species have completely decayed. Magnesium sulfates are formed by reaction between sulfuric acid and the released Mg^{2+} from the ores. Because of the difficulty in identification by XRD, amorphous substances in the PALs may or may not be identical to the ores.

Geotechnical Index Properties

Table 2 provides a summary of the geotechnical index properties of laterite slurries. This table indicates that the specific gravity of laterite ores is higher than most sedimentary soils and falls within the range 2.9 to 3.2, common for residual soils. The G_s for laterite PALs is even higher and ranges between 3.2 and 3.6. Such high G_s values are attributed to the presence of heavy iron oxides in these materials (Gidigas 1976) and contribute to a high solids content of the sedimented slurries as observed earlier in Table 1. This is substantiated by the higher underflow solids content (Table 1) of the limonite-saprolite slurries because of their slightly higher values of G_s . Using these values of G_s and the observed underflow solids content in equation (2), the void ratio was calculated. The corresponding void ratios depicted in Table 2 reflect the underflow solids content in the storage and the CCD thickeners used in the metal extraction process.

TABLE 2— Geotechnical index properties of laterite slurries

Process Stage	Parameter	Sample Type and Origin			
		Limnolite	Limonite-Saprolite		Saprolite
		Cuba	Philippines	Australia	Indonesia
Ore Slurries	G_s	2.92	3.16	2.92	2.92
	e	5.7	5.2	5.0	8.7
	- 0.075 mm, %	93	93	92	92
	- 0.002 mm, %	20	35	56	19
	w_l , %	60	83	95	108
	w_p , %	44	42	48	53
	w_s , %	35	25	29	29
PAL Slurries	G_s	3.22	3.56	3.22	3.22
	e	5.7	4.2	4.2	8.4
	- 0.075 mm, %	70	71	69	72
	- 0.002 mm, %	6	7	12	19
	w_l , %	26	27	50	83
	w_p , %	17	16	30	42
	w_s , %	15	14	18	25

Figure 2 gives the grain size distribution of various laterite slurries. This figure shows that the amount of sand size material is only up to 8% for laterite ores and material finer than 0.075 mm is about 92%. This means that similar slurry preparation procedures are adopted throughout

the world and therefore the resulting laterite ore slurries are generally fine-grained. The amount of sand size material is only 28 to 31% for the corresponding laterite PALs and material finer than 0.075 mm is in the range of 69 to 72%. Due to negligible dissolution of the fine material, this fourfold increase in sand size is primarily attributed to grain size growth during the PAL operation (Tindall & Muir 1998).

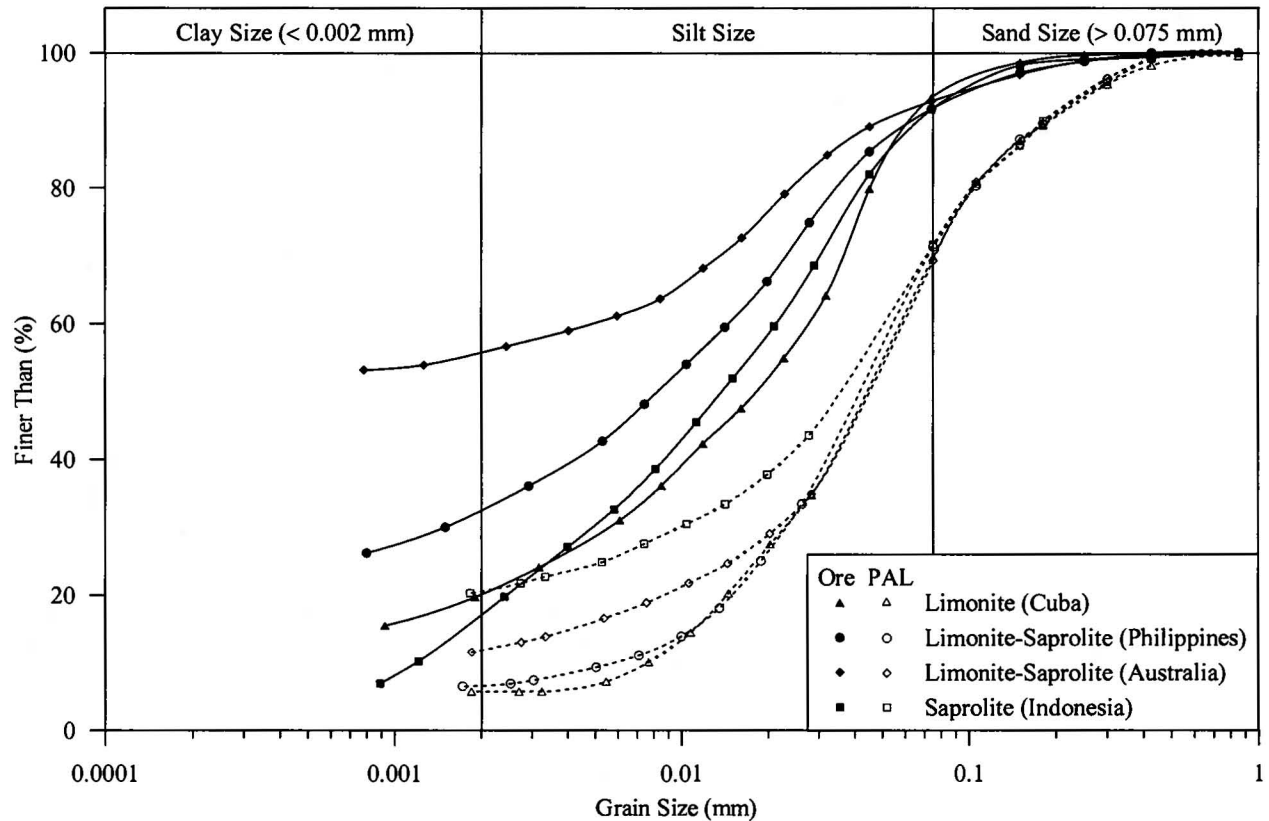


FIG. 2— Grain size distribution of laterite slurries

Figure 3 confirms the notion of grain size growth by comparing the morphology of laterite ore and PAL materials. Figure 3a is a SEM micrograph of a typical laterite ore and shows needle-shaped goethite crystals coating soil particles. Arranged in all directions similar to iron filings on a magnet, the size of individual goethite needles is of the order of 1 μm (Tindall & Muir 1998), which is half the clay size. Figure 3b is a SEM micrograph of the corresponding laterite PAL, illustrates globular hematite coating soil particles and occurring in separate but mutually conjoined colonies (Rubisov & Papangelakis 1999). Due to their inseparable fusion, the size of a singular hematite entity is difficult to ascertain. However, hematite globules with dimensions ranging between 1 and 5 μm are clearly visible in this micrograph.

Figure 2 further illustrates that the bulk of the materials in laterite slurries fall in the silt and clay size regions with variable clay size fraction. The variability in the grain size distribution curves among laterite ore and PAL slurries is due to the variable degree of coating of soil particles by sesquioxide and hematite, respectively (Golightly 1981). Removal of such a coating during wet screening or the PAL operation depends upon particle bond strength, aggregate size and mineral composition (Schramm 1996).

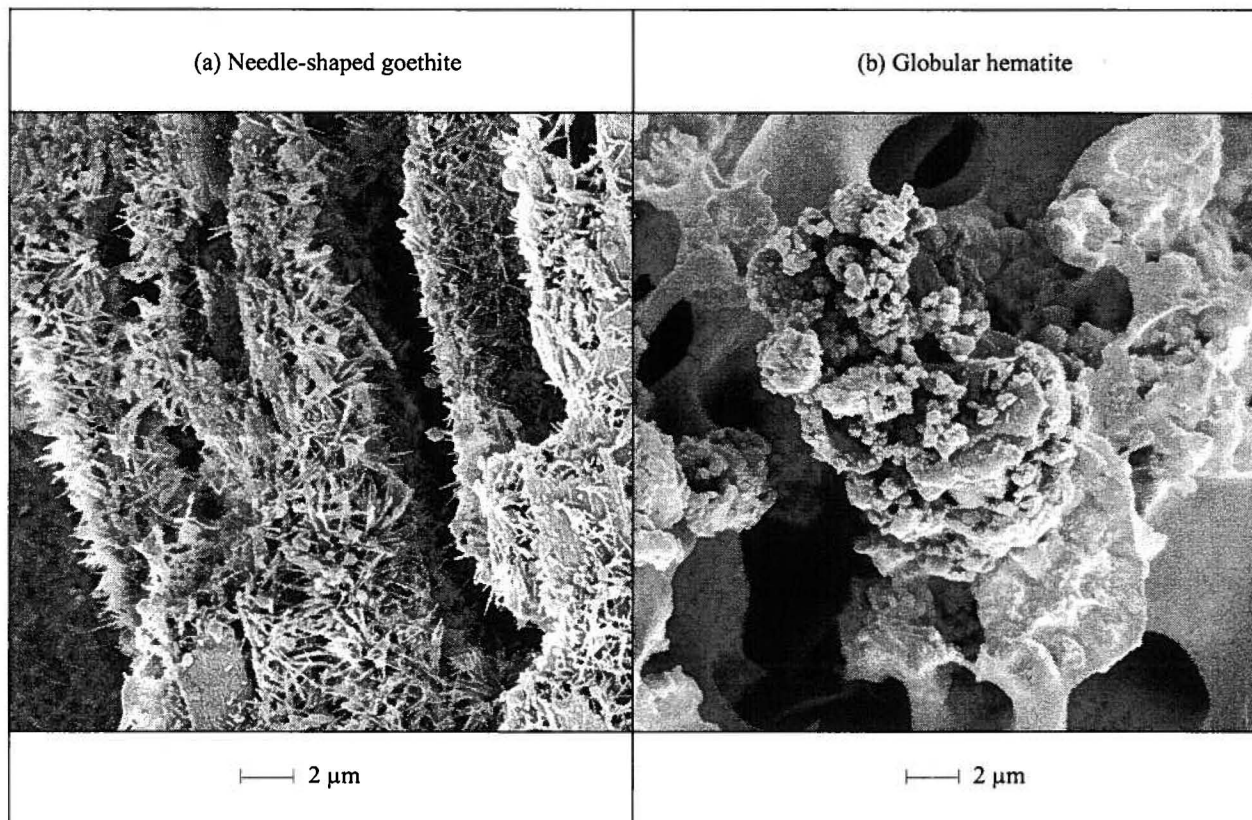


FIG. 3— *Change in morphology of laterite particles due to autoclave operation*

Among various laterite ores, the limonite slurry from Cuba is a slightly gap-graded material (concave upward gradation curve with clearly defined inflection points) and containing clay size fraction of 20%. On the contrary, the limonite-saprolite ore slurry from the Philippines is a well-graded material (relatively linear gradation curve and vague inflection points) with a clay content of 35%. The limonite-saprolite ore from Australia is a poorly-graded slurry as more than half (56%) of the material is finer than the clay size of 0.002 mm. The linear gradation curve of the saprolite ore from Indonesia indicates a well-graded slurry and an amount of clay size material equal to 18%.

In contrast to the ore slurries, all of the laterite PAL slurries are well-graded materials. However, the limonite PAL from Cuba and the limonite-saprolite PAL from the Philippines can be considered slightly poorly-graded as these samples contain a clay size fraction of about 7%. The limonite-saprolite PAL from Australia and the saprolite PAL from Indonesia are well-graded materials having higher clay contents of 12 and 19%, respectively. The clay size fraction for the saprolite PAL slurry from Indonesia coincides with the ore slurry from which it is derived.

The grain size distribution influences the mechanical and the physico-chemical interactions of laterite slurries. First, the very fine gradation of these slurries is partly responsible for the high void ratios in the thickeners as indicated in Table 2. Second, well-graded materials help minimize segregation of the clay and coarse fractions. Azam (2003) reported that at an initial solids content of 15%, most laterite slurries are essentially nonsegregating. Third, the clay size fraction of these slurries governs the colloid-electrolyte interactions, which in turn, influence consistency, sedimentation and hydraulic conductivity.

Table 2 indicates that laterites have variable consistency limits. This is attributed to their distinct mineralogy, which is derived from ore geology and the PAL conditions as well as chemistry of the pore water used during slurry preparation and autoclave operations. The high consistency limits of some of the laterite ores confirm the presence of clay mineral species and amorphous materials such as iron oxide and silica (Mitchell 1993). Despite the high amount of clay size fraction, the low consistency limits of the limonite-saprolite ore from Australia indicate that the water used for feed preparation contained high concentrations of various electrolytes. These electrolytes were concentrated in the pore water during drying and fresh water was not added for the determination of liquid and plastic limits.

The lower consistency limits of all of the laterite PALs than their ore counterparts substantiate mineral transformation during the PAL process. Since, such transformation mainly occurs in sesquioxides whereas clay mineral structures collapse, the limonite-saprolite PAL from Australia and the saprolite PAL from Indonesia have higher consistency limits as they contain large amounts of amorphous materials. Further, the reported high electrolyte concentration in the pore water is also partly responsible for the low consistency limits of the laterite PAL slurries.

The plasticity chart (Casagrande 1948) gives a preliminary assessment of the mineralogical composition of soils. Figure 4 that shows the regions of various clay minerals and sand, shows various laterites on such a chart. This figure illustrates that all of the laterite ores fall in the high liquid limit zone and below the A-Line. According to Holtz & Kovacs (1981), soils plotting in this region of the plasticity chart can be classified as micaceous fine sandy and silty clays. Based on their position on the plasticity chart, these laterite ores are expected to contain micaceous clay minerals such as chlorite and hydrous mica as well as kaolinite. Despite their low amounts in the samples (Table 2), these clay minerals greatly affect the consistency limits of the materials. The corresponding laterites PALs are shifted downward and to the left on the plasticity chart. The limonite PAL from Cuba and the limonite-saprolite PAL from the Philippines are close to the region designated as *sand*. Similarly, the engineering behavior of the limonite-saprolite PAL from Australia is expected to be similar to that of the kaolinite whereas the saprolite PAL from Indonesia is still classified as micaceous fine sandy and silty clay.

Sedimentation

Figure 5 gives the sedimentation test data in the form of interface height versus time for laterite slurries. This figure shows that among the ore slurries, the limonite from Cuba has the most rapid sedimentation. This is attributed to the mechanical action of coarse particles in this slightly gap-graded material and the presence of a high amount of heavy iron oxides. This is followed by the limonite-saprolite ore slurry from the Philippines. The sedimentation behavior of this slurry is due to a well-graded material with 35% clay size content, the presence of clay minerals and reduced amount of iron oxides, and higher amount of pore water electrolytes. The sedimentation behavior of the limonite-saprolite ore slurry from Australia is dominated by the presence of a high amount of clay size fraction (56%) including clay minerals and amorphous materials and a high concentration of pore water electrolytes as indicated by an EC of 1250 $\mu\text{S}/\text{cm}$. Although, the amount of clay mineral is lower in the saprolite ore slurry from Indonesia, this material has a high amount of amorphous substances. In a near-neutral environment, the amorphous materials partially coat a significant amount of the clay platelets. This means that clayey material as well as individual clay platelets can be oppositely charged. Such incomplete coating of clays results in a voluminous cardhouse fabric that is difficult to dewater. Hence, the sedimentation behavior of laterite ore slurries follows a decreasing trend from limonite though saprolite.

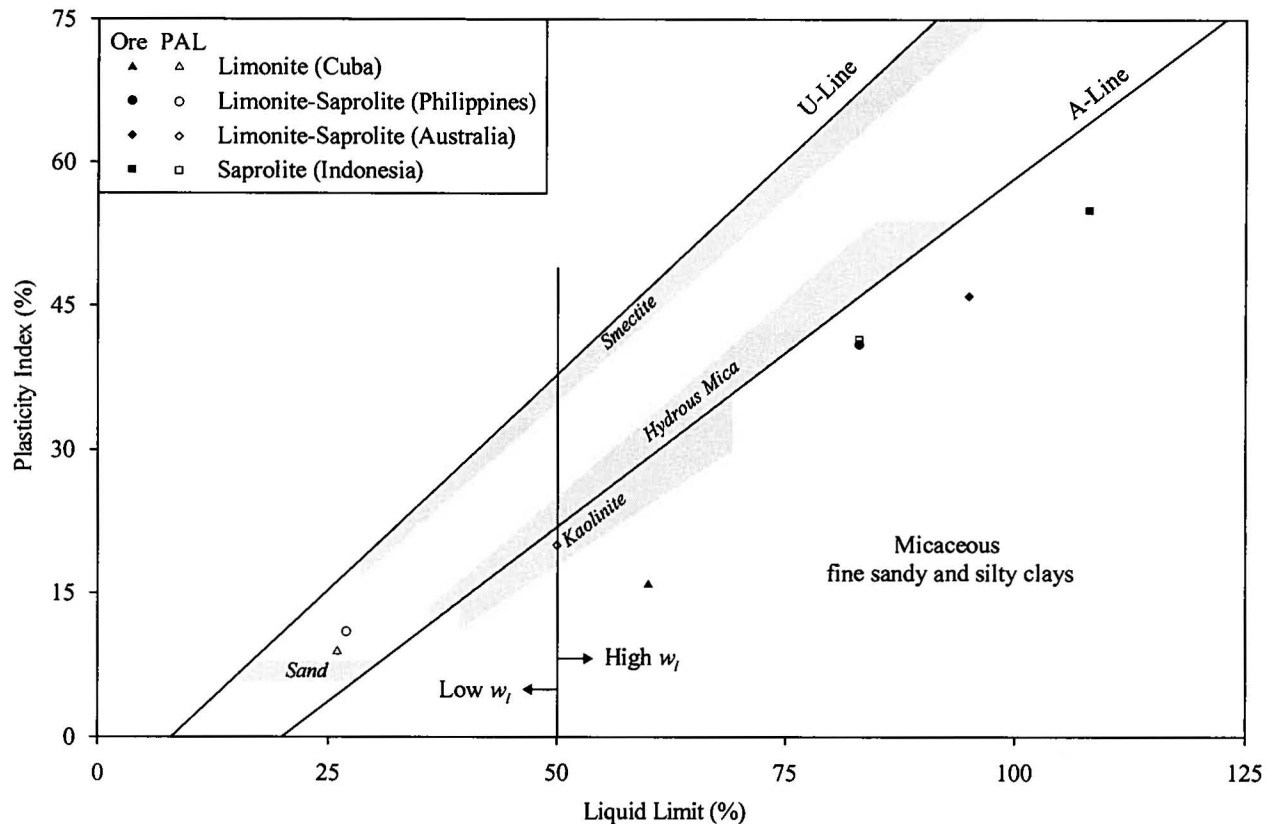


FIG. 4— *Plasticity chart for laterite slurries*

This order is generally followed by laterite PAL slurries except the limonite-saprolite PAL slurry from the Philippines, which has the most rapid sedimentation due to its highest specific gravity of 3.56. Figure 5 shows that the limonite PAL slurry from Cuba follows the limonite-saprolite PAL slurry from the Philippines. Further, the sedimentation behavior of the other two slurries is much slower and is due to the presence of significant amounts of amorphous materials and magnesium sulfate minerals. The observed variation between the limonite-saprolite PAL slurry from Australia and the saprolite PAL slurry from Indonesia is mainly attributed to the larger amount of amorphous material and magnesium sulfate in the latter material. The smaller dewatering amount of the saprolite PAL slurry from Indonesia is ascribed to the higher amount of structural water associated with the magnesium sulfate mineral present in this PAL material (Azam 2003).

Figure 6 shows the initial part of the interface height-elapsed time plot for the determination of initial hydraulic conductivity. The slope of the initial straight-line portion of the sedimentation curve decreases from limonite through saprolite ore slurries. Among various laterite PAL slurries, the slope is highest for the limonite-saprolite PAL slurry from the Philippines. For other materials, the slope decreases from the limonite PAL slurry (Cuba) through the limonite-saprolite PAL slurry (Australia) and finally to the saprolite PAL slurry (Indonesia). It is interesting to note that the initial hydraulic conductivity obtained using the slope values are directly proportional to the total settlement of the corresponding slurry after sedimentation is completed.

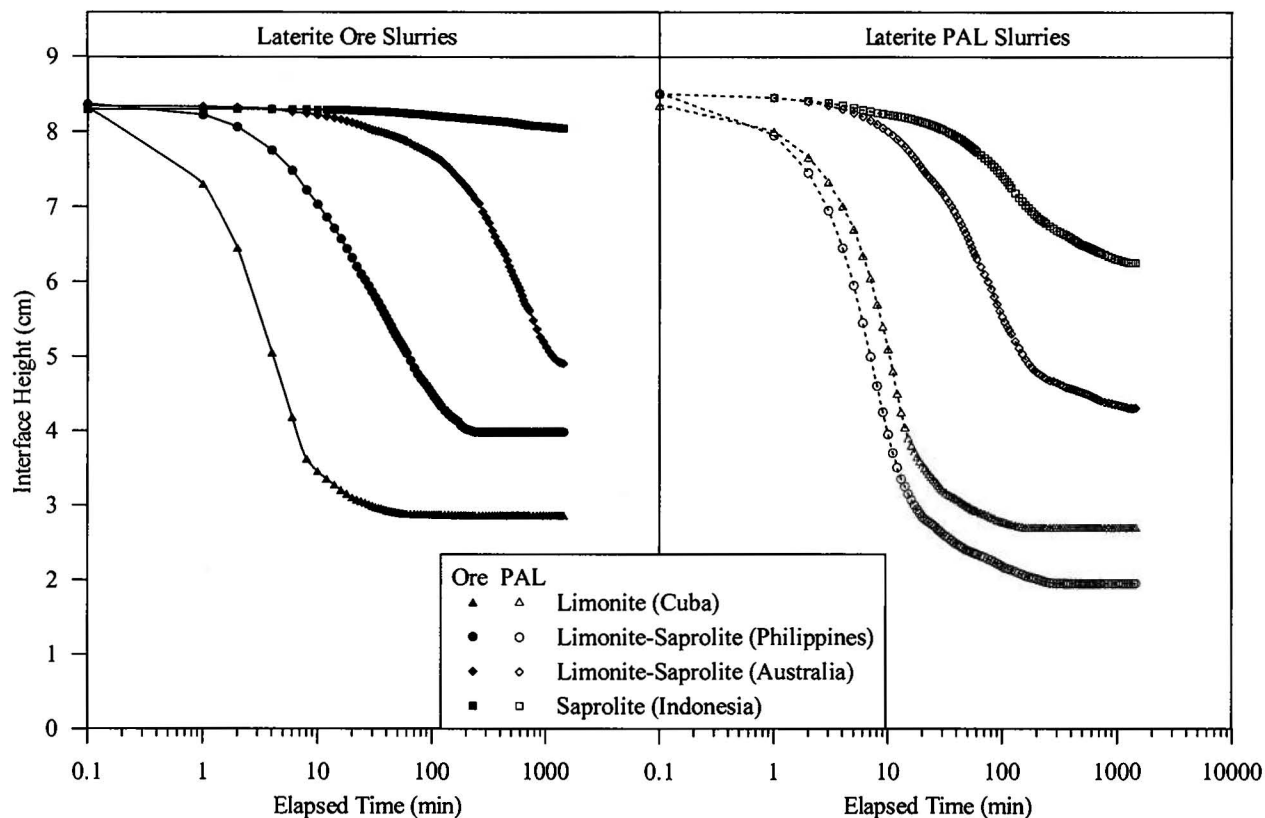


FIG. 5— *Interface height-time data during sedimentation of laterite slurries*

Table 3 summarizes the sedimentation test results by reporting the initial and the final conditions and k_i during settling. This table indicates approximately constant initial conditions at the start of the sedimentation tests. The slightly higher values for the limonite-saprolite slurries are due mainly to the high specific gravity of this material. The table shows that the initial hydraulic conductivity of laterite ore slurries varies by three orders of magnitude from 1.2×10^{-1} cm/sec for the limonite slurry from Cuba to 1.5×10^{-4} cm/sec for the saprolite ore slurry from Indonesia. Conversely, the variation in the initial hydraulic conductivity from 6.4×10^{-2} to 1.9×10^{-3} cm/sec of the laterite PAL slurries is only $1\frac{1}{2}$ order of magnitude. These values are generally higher than most sedimentary clays owing to the high G_s of laterites.

Figures 7 and 8 give the sedimentation test results in the form of void ratio and solids content as functions of time, respectively. These figures indicate that the void ratio and the solids content at the end of sedimentation of different materials follow the same order as for the initial hydraulic conductivity. This means that the rate and amount of sedimentation are directly related for the investigated laterite slurries. Examining Table 3 in conjunction with Figures 7 and 8 indicates that the sedimentation behavior is improved as a result of the pressure acid leach operation. Based on both efficiency (initial hydraulic conductivity) and yield (solids content after the completion of self-weight sedimentation), the limonite-saprolite from the Philippines is the most appropriate material for the metal extraction process. A threefold increase in the initial hydraulic conductivity and a 6.5% increase in the solids content after the completion of sedimentation under self-weight of the slurry are observed for this material during the PAL process.

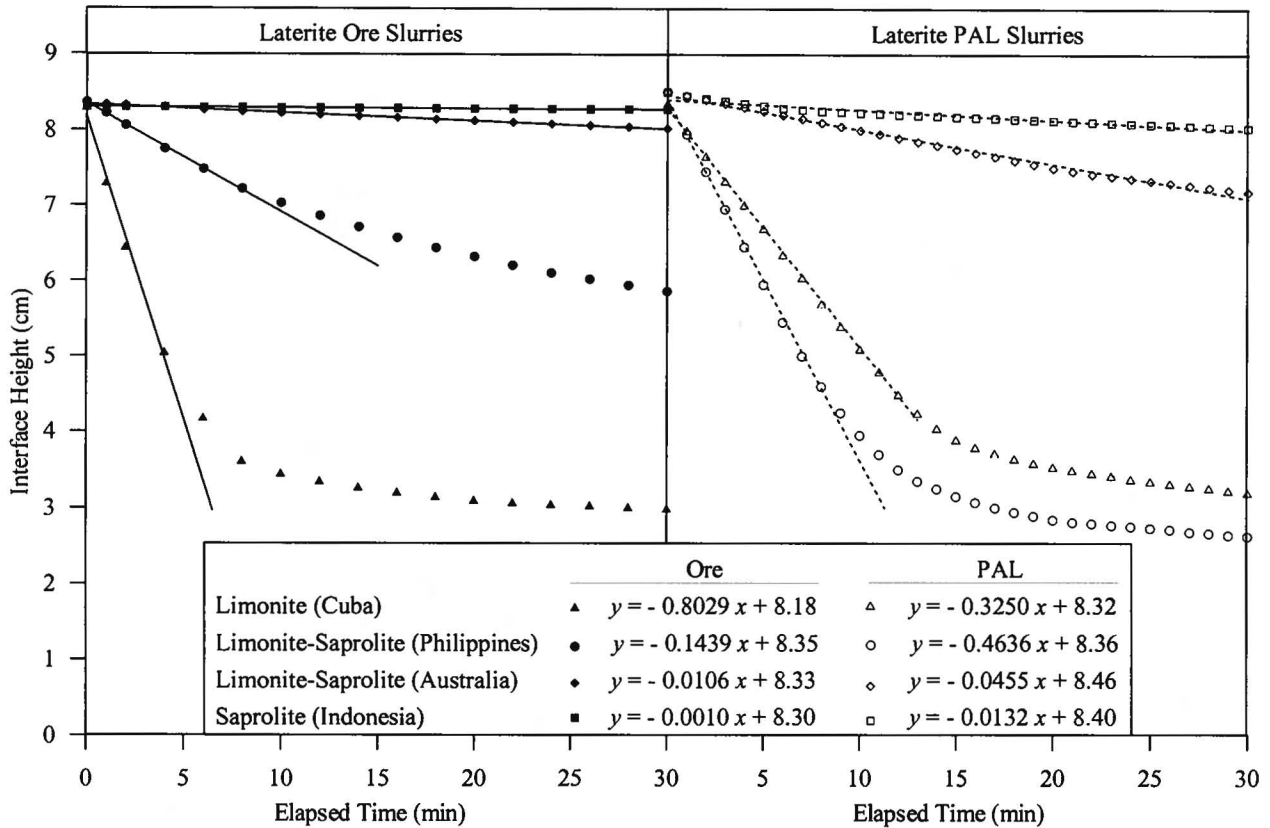


FIG. 6— Determination of initial hydraulic conductivity during sedimentation of laterite slurries

TABLE 3— Sedimentation characteristics of laterite slurries

Process Stage	Parameter	Sample Type and Origin			
		Limonite	Limonite-Saprolite		Saprolite
		Cuba	Philippines	Australia	Indonesia
Ore Slurries	H_o , cm	8.30	8.36	8.34	8.30
	s_o , %	15.1	15	15	15
	e_o	16.6	17.9	16.6	16.6
	$k_i \times 10^{-4}$, cm/s	1220	210	16.1	1.5
	H_f , cm	2.86	3.89	4.90	8.04
	s_f , %	33.9	27.0	23.1	15.4
	e_f	5.7	8.5	9.7	16.0
PAL Slurries	H_o , cm	8.35	8.50	8.50	8.50
	s_o , %	15	15.1	15.1	15
	e_o	18.3	20.0	18.3	18.3
	$k_i \times 10^{-4}$, cm/s	470	639	65.7	19.1
	H_f , cm	2.70	1.95	4.30	6.25
	s_f , %	35.3	43.5	25.9	19.4
	e_f	5.9	4.6	9.2	13.4

Summary and Conclusions

Four ore slurries were selected from various parts of the globe: Cuba, Philippines, Australia and

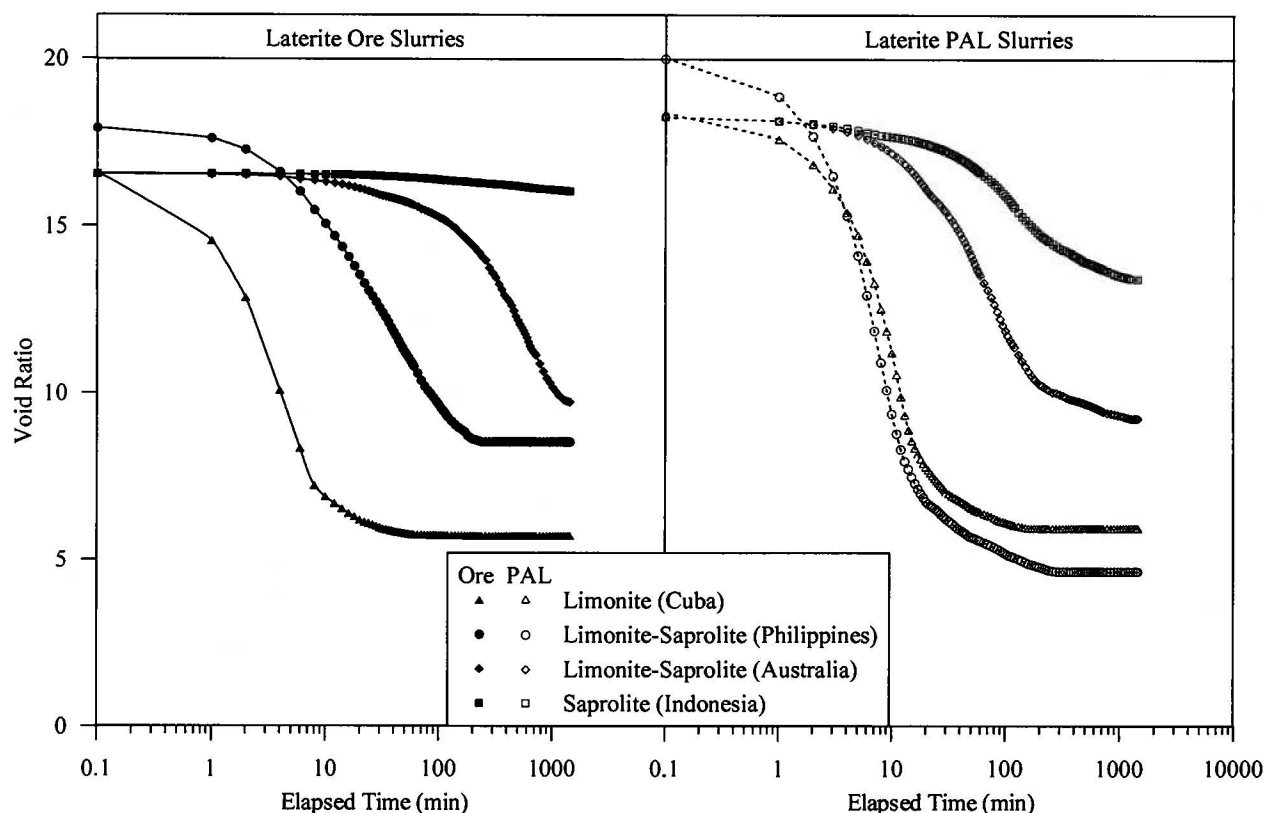


FIG. 7— *Void ratio-time data during sedimentation of laterite slurries*

Indonesia. The corresponding PAL slurries were obtained using identical process conditions during metal extraction. Laboratory investigations comprising of material characteristics, geotechnical index properties, and sedimentation, necessitated significant modifications to suit laterite slurries. Heating was avoided in most cases but where absolutely necessary, an oven temperature of 50 °C was employed. Determination of specific gravity involved the use of vacuum for air removal and dry mass calculation after test completion. Grain size analyses were conducted on 25 g of dry soil using distilled water; the ores were dispersed with calgon whereas the PALs were not altered. Consistency limits were determined by gradual drying of the high water content slurries at 50 °C; mixing time was restricted to five minutes. Sedimentation tests were conducted on 15% initial solids content slurries poured in 8.5 cm diameter graduated cylinders to an initial height of 8.5 cm. The solid-liquid interface movement was captured using a camcorder connected to a computer; digital refinement improved accuracy. The main conclusions of this study are summarized as follows:

- Laterite slurries constitute a distinct class of materials with geotechnical characteristics depending on ore geology and the metal extraction process. The ores are primarily composed of sesquioxides in a neutral environment whereas the hematite-rich PALs occur at $\text{pH} \leq 1.0$.
- Laterite ores have a G_s of about 2.9 and require a high amount of water for conversion to slurries. The corresponding PALs have a G_s above 3.2 and exhibit a high water requirement during the autoclave operation for economic metal extraction.

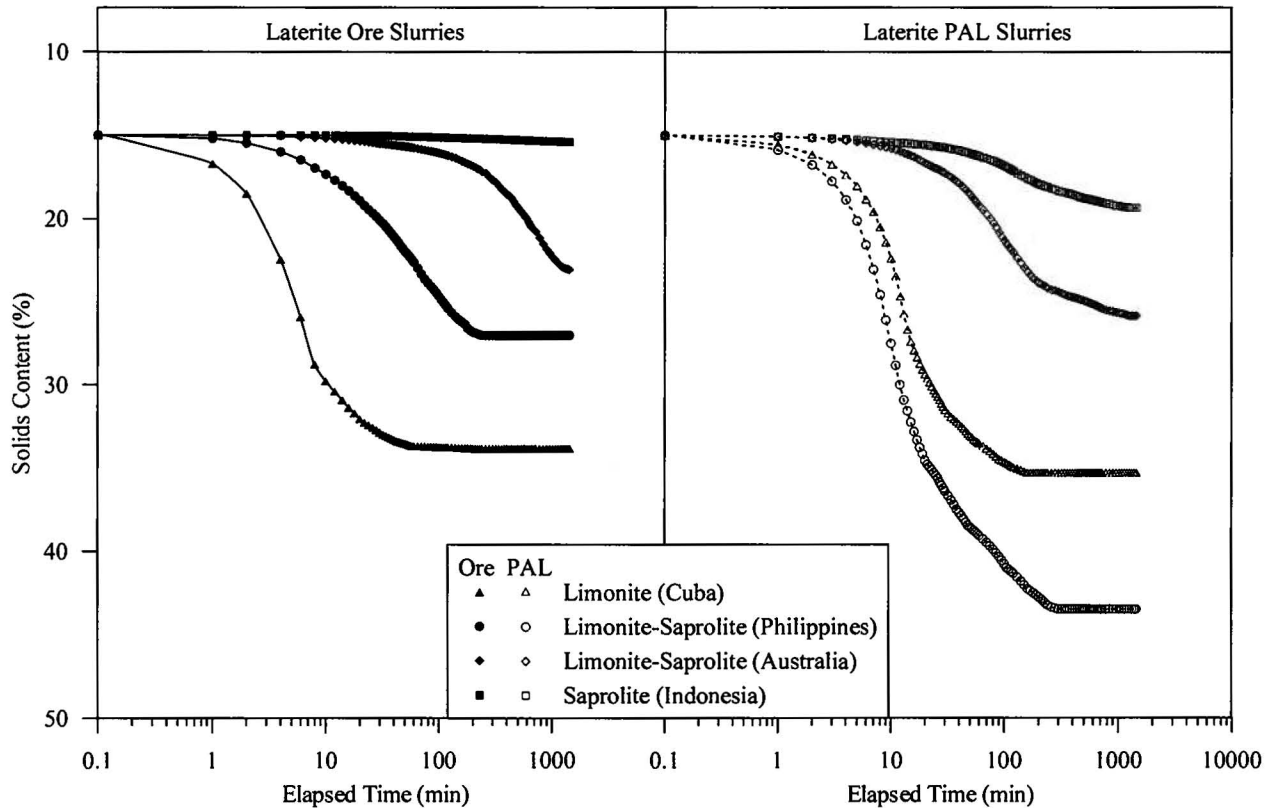


FIG. 8— *Solids content-time data during sedimentation of laterite slurries*

- More than 90% of the material in ore slurries is finer than 0.075 mm; the clay size fraction is between 20 and 60%. During the PAL operation, grains undergo size growth and only about 70% of the material is finer than 0.075 mm and the clay size fraction is reduced to 5 to 20%.
- The combined effect of variable material characteristics is vividly expressed during sedimentation under self-weight. The initial hydraulic conductivity of the ore slurries ranges between 10^{-1} to 10^{-4} cm/sec and that of the PAL slurries between 10^{-2} to 10^{-3} cm/sec.
- The engineering behavior of laterite slurries generally improves during the PAL operation. The rate and amount of sedimentation are directly related for this class of materials.

Acknowledgements

The authors are grateful to the University of Alberta for providing laboratory space and computing facilities. Thanks are given to the Materials Technologies Division of Dynatec Corporation, Canada for material support.

References

- Azam S. (2003). *Solid-Liquid Separation of Laterite Slurries*. PhD Dissertation. University of Alberta, Edmonton, Alberta, Canada.
- Casagrande, A. (1948). Classification and identification of soils. *Transactions, ASCE*. Vol. 113, pp. 901-930.

- Carlson, E.T. & C.S. Simons (1960). Acid leaching, Moa Bays nickel. *Journal of Metals*, pp. 206-213
- Chalkley M.E. & I.L. Toirac (1997). The acid pressure leach process for nickel and cobalt laterite. Part I: Review of operations at Moa. *Proceeding, Nickel-Cobalt International Symposium*. Sudbury, Ontario, Canada. Vol. 1, pp. 341-353.
- Dusseault M.B. & J.D. Scott (1983). Tailings pond behavior and characterization of oil sand tailings sludge. *Particulate Science and Technology*. Vol. 1, pp. 295-309.
- Fourie, A.B. (1997). Classification and index tests. *Mechanics of Residual Soils*, (Blight ed.). ISSMFE Technical Committee 25. Balkema, Rotterdam, The Netherlands. pp. 57-63.
- Frost, R.J. (1976). Importance of correct pretesting preparation of some tropical soils. *Proceedings, 1st South East Asian Conference on Soil Engineering*, Bangkok, Thailand.
- Gidigas, M.D. (1976). *Laterite Soil Engineering-Pedogenesis and Engineering Principles*. Elsevier Amsterdam, The Netherlands.
- Golightly, J.P. (1981). Nickeliferous laterite deposits. *Economic Geology*. Vol. 75, pp. 710-735.
- Golightly, J.P. (1979). Nickeliferous laterites-a general description. *Proceedings, International Laterite Symposium*, New Orleans, USA. Vol. 1, pp. 3-23.
- Holtz, W.G. & W.D. Kovacs (1981). *An Introduction to Geotechnical Engineering*, Englewood Cliffs, New Jersey, Prentice Hall.
- Lamb, T.W. (1951). *Soil Testing for Engineers*. John Wiley & Sons, New York, USA.
- Mackenzie, R.C. (1957). *The Differential Thermal Investigation of Clays*. Mineralogical Society, Clay Minerals Group, London.
- Mitchell, J.K. (1993). *Fundamentals of Soil Behavior*, 2nd edition, John Wiley & Sons, Inc. New York.
- Motteram, G., M. Ryan, R. Berezowsky, & R. Raudsepp (1996). Murrin Murrin nickel cobalt project. *Nickel/Cobalt Pressure leaching & Hydrometallurgy Forum*, Perth, Australia.
- Pane, V. & R.L. Schiffman (1997). The permeability of clay suspensions. *Geotechnique*. Vol. 47, No. 2, pp. 273-288.
- Rubisov, D.H. & V.G. Papangelakis (1999). The effect of acidity 'at temperature' on the morphology of precipitates and scale during sulfuric acid pressure leaching of laterites. *29th Annual Hydrometallurgical Meeting*, Montreal, Canada. Vol. 1, pp. 185-203.
- Rouse, W.C., A.J. Reading & R.P.D. Walsh (1986). Volcanic soil properties in Dominica, West Indies. *Engineering Geology*. Vol. 23, No. 1, pp. 1-28.
- Schramm, L.L. (1996). Suspensions: Basic principles. *Suspensions: Fundamentals and Applications in Petroleum Industry* (Schramm ed.), American Chemical Society. pp. 3-44.
- Tindall, G.P. & D.M. Muir (1998). Effect of E_h on the rate and mechanism of the transformation of goethite into hematite in a high temperature acid leach process. *Hydrometallurgy*. Vol. 47, No. 2-3, pp. 377-381.
- Townsend, F.C. (1985). Geotechnical characteristics of residual soils. *ASCE, Journal of Geotechnical Engineering*. Vol. 111, No. 1, pp. 77-94.
- Wintermeyer, A.M. & E.B. Kinter (1954). Dispersing agents for the particle size analysis of soils. *Highway Research Board Bulletin*. Vol. 95, No.1, pp. 1-14.