Geotechnical properties of nickel laterite heap leached ore (ripios) and plant residue

Mark E. Smith, Brazilian Nickel Ltd, USA

Monte Christie, Geo-Logic Associates, USA

Abstract

Laterite geology presents unique challenges for geotechnical engineers, which increase when these materials are subjected to acid leaching. In the design of nickel laterite heap leach facilities, two byproduct materials are of key importance to the geotechnical engineer: the leached ore and the plant residues produced from separating nickel and cobalt from iron, magnesium, and other impurities. Lateritic ore can undergo dramatic physical and chemical changes during months of leaching and rinsing, with weight loss of 15 to 25% and acid consumption of 150 to 500 kg per tonne of ore.

For dynamic heaps, the spent ore is disposed of in a dump, often comingled with the plant residue. As these materials interact within the dump, physically and chemically, further changes can be expected. Plant residues are principally composed of precipitated gypsum, iron and magnesium compounds (sulfates and oxides) and are often filtered separately or comingled before disposal. While the ore has been leached and rinsed and thus is generally at chemical equilibrium, the plant residues often are undergoing active chemical reactions when discharged to the dump; if the various residues and leached ore are discharged in a co-disposal facility then seeping pore fluids of various chemistries can also create complex changes in the dump. The authors will present data, observations and suggestions for further work related to these and related issues.

Introduction

Laterites are soils or weathered rock formations rich in iron, magnesium and often aluminum. These are most commonly formed in tropical or formerly tropical climates, though there are ample examples of deposits outside of the tropics. An essential mechanism is cyclic wetting and drying, which is why lateritic geology is most common in the tropics (Schellmannk, n.d.; Dalvi et al., 2004). Nickel-bearing laterites are generally sourced from ultramafic rock containing the ferromagnesian minerals amphibole, olivine, and pyroxene. The term laterite is used for both ferruginous deposits and for soft, clay-rich profiles with strong iron segregation (Fookes, 1997). Laterite profiles will often be capped with a limonite layer and underlain by saprolite. Limonites are generally formed from the weathering of amphibole, olivine, and pyroxene, with the iron occurring as $FeO(OH) \cdot nH_2O$. The limonite can occur

as a distinct capping layer or as pockets and inclusions within the laterite. Saprolites are chemically weathered rocks, which Fookes defined as "weak, friable chemically weathered material (usually crystalline), in which the original structure and fabric are preserved because of pseudomorphic replacement."

The concept of heap leaching of nickel laterites was first proposed by Agnatnizi-Leaonardou and Demaki (1978) who achieved robust recoveries from column leach testing using sulfuric acid. More extensive research has been conducted by BHP Billiton, European Nickel, Vale, Brazilian Nickel and others on ore deposits in the Philippines, Indonesia, New Caledonia, Brazil, Colombia, Guatemala, Turkey, Australia and elsewhere. BHP introduced the concept of two-stage heap leaching, using a lead and a lag heap, to reduce both acid consumption and iron residue production (Duyvestyn et al., 2001; Steemson and Smith, 2009; Smith and Steemson, 2009). In the last decade the nickel industry has seen increasing interest in heap leaching with advanced studies, some including pilot or demonstration plants, being performed for Çaldağ (Turkey), Piauí (Brazil), Cerro Matoso (Colombia), Acoje (Philippines), Jaguar (Guatemala), Nickel West (Australia), Gag Island and Pearl (Indonesia), as well as two commercial-scale operations, Murrin Murrin in Australia and Yuanjiang in China (Smith and Oxley, 2014).

Lateritic ores tend to be of relatively low permeability and strength as compared to gold and copper ores, though there are ample examples gold and copper ores with lower permeability or shear strength (Saavedra, 2014; Ulrich et al., 2003). Nickel laterite ores have very high acid demand, typically in the range of 150 to 500 kg of sulfuric acid per dry tonne of ore, which is about ten times the typical demand for copper. This is caused by the dissolution of 15 to 25% of the solids in the ore, which also results in a complete degradation of the agglomerate structure. It also means that conventional multilift heaps require interlift liners to limit acid consumption, as is common for copper oxide leaching. Unlike other heap leach operations, nickel plants produce a considerable volume of wastes from the impurity removal in the wet plant, which are generally called plant residues and occasionally referred to as tailings (though they are chemical precipitants rather than ground rock). The volume of plant residues will often equal the volume of leached ore (referred to as "ripios" in South America and that term is adopted herein). Most commonly, the plant residues are filtered (to improve metal recovery) and dry stacked in a residue storage facility (RSF), often referred to as a dump.

Methodology

The authors have participated in the studies of 17 nickel laterite heap leach studies. The levels of these studies ranged from preliminary economic assessments to definitive feasibility studies and detailed engineering. Project sites were located in North, South and Central America, central Europe, Australia, Indonesia, New Caledonia and the Philippines. These studies provided the data presented in this paper.

Fresh and leached ore

Nickel laterite ores are generally crushed and then agglomerated with sulfuric acid. Agglomeration is used to improve several key operating parameters, including permeability of as-stacked ore, reducing fines migration during irrigation, speeding early leach kinetics, and shortening the leach cycle. The properties of the fresh laterite ores vary greatly depending upon the geology and location, as well as the manner in which they are crushed and agglomerated. Much has been written about laterite agglomeration (Nosrati and Addai-Mensah, 2012; Janwong, 2012). This paper will not provide much detail on either fresh ore or agglomeration. Rather, the authors focus on the properties of the ore at the end of the leach cycle (i.e., the ripios).

Acid dosage rates during agglomeration of 25 to 75 kg acid per dry tonne of ore are typical in the agglomerator. Total acid consumption (agglomeration plus leaching) is almost entirely driven by dissolution of gangue minerals (including Fe and Mg compounds). This dissolution affects the physical and mechanical properties of both the ripios and the plant residues (since it is the subsequent precipitation of those gangue minerals which produce the residues). These effects could be compounded by the difference in the original contents of Fe and Mg in heaps, variations in their extraction rates, and the acidity of the extraction process including whether reprecipitation of Fe in the heap is accomplished.

Figure 1: Sample of fresh agglomerated ore (left) and ripios from pilot heap (Piaui mine, Brazil)

Plant residues

Iron precipitate (IP) is the outcome of the first stage of precipitation during the impurity removal process and consists of oxidized iron at a relatively low pH of 3 to 4. IP is predominantly composed of iron compounds (typically goethite and jarosite), gypsum, amorphous materials, and traces of quartz. The IP can be dominated by gypsum with minor goethite or jarosite. The volume of IP produced can be over half the total. Neutralization precipitates 1 and 2 (NP1 and NP2) are produced in the second and third stages of impurity removal. NP1 typically contains iron hydroxide and gypsum based precipitates at a medium pH of 6 to 8 for NP1. NP1 is predominantly composed of gypsum and calcite, with minor amounts of amorphous materials, goethite or jarosite, and traces of quartz. NP2 is a magnesium hydroxide and gypsum based precipitate with little to no iron and generated at a pH of 9 to 11. NP2 can be predominantly composed of bassanite with minor amounts of amorphous materials, brucite, calcite,

and traces of quartz. NP1 and NP2 will frequently be comingled in the plant before discharge to the RSF.

Some plants will produce a final residue is very small quantities, from either treating bleed water or as a final polishing step. When this is produced it will commonly be comingled in the plant with either NP1 or NP2, and tends to be of very high pH. This group of plant residues has not been included in any of the authors' testing programs.

Figure 2: Sample of IP coming off of belt filter (South America)

The plant residues may be blended with each other or with ripios. Tests have been conducted to investigate the effects of blending plant residues in various proportions. These results were used to improve understanding of the geotechnical properties of the blends, which can be critical for predicting long-term stability of the RSF. For instance, in one program when acidic and alkaline plant residues were blended they produced a significant volume of carbon dioxide gas. Such off-gassing can create a wide range of operational problems from worker safety issues (effectively creating "confined space" hazards at the working face) to inducing excess pore pressures and aggravating liquefaction concerns (Davies et al., 2002).

Geochemical and mineralogy characterization

One study looked in detail at the geochemical composition of the ripios and plant residues. Of particular interest is the presence and nature of hydrated carbonate and sulfate minerals, acid-base reactivity, and availability of constituents that may be of concern for geotechnical and geochemical stability. The geochemical program tested for a variety of metrics, including: net acid generation, acid-base accounting, synthetic precipitation leaching protocol, x-ray diffraction (XRD), and x-ray fluorescence. However, a detailed discussion of these results is beyond the scope of this paper.

Testing determined that the plant residues are altered in a standard 110°C drying oven (ASTM D-2216), which renders the resulting moisture content measurements unreliable. This is consistent with the presence of hydrous and hydrated phases in these particular samples. Therefore, the geotechnical program considered both 110°C and 55°C oven temperatures for determining moisture contents and it is recommended that other investigators determine, early in their program, whether their samples are sensitive to the oven drying temperature. The crystalline structure of the plant residues is described in general as comprised of a loose-packed crystal "mush" of well-developed bladed monoclinic crystals forming an open framework, with a very fine-grained interstitial (inter-crystalline) matrix (identified by XRD as calcite) within a glutinous mass of hydroxides. It is these hydrous and loose crystalline structures surrounded by the mush that lead to some of the unique geotechnical properties described herein.

Geotechnical characterization

A key to understanding the geotechnical properties of leached nickel laterite ores (ripios and plant residues) is the fact that the fresh agglomerated ore undergoes a 15% to 25% loss of mass during leaching. This drastic reduction in mass due to leaching leads to significant material degradation and change in geochemical and geotechnical properties. In addition, degradation of the plant residues can also be affected by comingling different plant residues with each other or with ripios. For example, the various types of plant residue have pHs ranging from a low of about 3 (for IP) to a high of around 11 (NP2). When comingled, the resulting change in acidity may adversely affect the geotechnical properties. Further, to the extent that there are significant quantities of $MgSO_4$ present along with migrating acidic pore fluids in the RSF, continued dissolution and the resulting physical changes can be expected. Therefore, there is value in including some sort of semi-coupled geochemical and geotechnical modeling to accurately predict the long-term behavior of the comingled plant residue-ripios waste mass within the RSF.

Moisture content

Table 1 shows the range in moisture contents for plant residues samples at two oven temperatures. Moisture content will be affected by the method of filtration (belt filter, pressure filter, disc filter, etc.), chemical composition, and post-filtration handling. Many nickel projects are in the tropics and thus moisture contents can increase between the filter and the RSF. An important note about the way moisture content is reported herein: in geotechnical engineering (and in this paper) it is standard practice to report moisture content as a percentage of the dry weight of the material. This contrasts to how metallurgical labs tend to report moisture, which is based on the wet weight of the material.

Samples of ripios from three projects were tested for moisture content at the end of the leach cycle (both column and pilot heap samples were tested). The results ranged from 18 to 76% with an average of 37% and standard deviation of 15. For the project in Brazil, 17 ripios samples were tested and the

resulting moisture content ranged from 18 to 60% with an average of 33% and standard deviation of 15. For this project, the standard Proctor (ASTM D-698) optimum moisture content ranged from 15 to 32% with an average of 23% and standard deviation of 7. For another South American project, 13 samples were tested with moisture contents ranged from 20 to 75%, an average of 44% and standard deviation of 18. For this project, the standard Proctor optimum moisture content ranged from 18 to 34% with an average of 25% and standard deviation of 5.

Table 1: Moisture content of plant residues

Plant residue	55°C Oven	110°C Oven
Iron precipitate	48 – 68	72 – 92
Neutralization precipitate 1	25 – 28	28 – 38
Neutralization precipitate 2	45 – 52	60 – 70

Specific gravity

Specific gravities (ASTM D-8454) ranged from 2.2 to 3.6, with the majority of the samples ranging from 2.75 to 3.2. The specific gravity of solids is the highest for IP, ranging from 2.8 to 3.6, with NP1 and NP2 ranging from 2.6 to 2.8 and 2.2 to 2.6, respectively. The ripios ranged from 2.76 to 3.17. The agglomerated ore ranged from 2.3 to 3.2.

Particle size distribution

The plant residues were comprised predominantly of fines (passing the #200 sieve), ranging from 91% to 100% of the total weight, with the balance comprised of sand-sized particles. The average fines fraction in the 22 samples tested was 98%. The material retained on the #200 sieve is comprised of, on average, 90% silt-size and 10% clay-size particles.

The ripios samples tested were comprised of particles ranging in size from silt to gravel. The gravel ranged from 11 to 56%, sand from 11 to 54%, and fines from 11 to 75%. The fresh agglomerated ore ranged with gravel from 11 to 61%, sand from 12 to 30%, and fines from 14 to 75%.

Atterberg limits

Lateritic ores tend to have low content of true clay. The plant residues are chemical precipitates and as such will be clay free. Other than a few outliers, both the plant residues and ripios clustered around the classifications of low to high plasticity silt (ML to MH). In general, the ripios are less plastic than the plant residues but there is larger scatter in the data for the plant residues. The IP, NP1, ripios, and the blends classify as ML or SM. NP2 and some of the ripios classify as MH. Figure 3 below shows the range in plasticity for both the plant residues and ripios. Especially for the plant residues, special considerations are required in interpreting the laboratory tests and deriving design parameters since correlations between Atterberg Limits and other properties, historically developed from natural soils, may not be applicable to chemical precipitates.
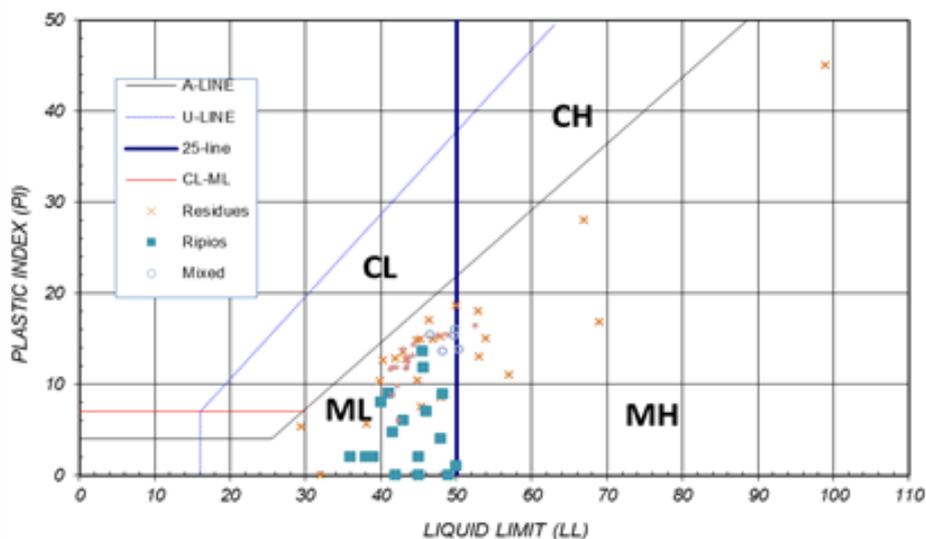
Figure 3: Atterberg limits for plant residues and ripios

Moisture-density relations

The maximum dry densities of plant residues obtained from the standard Proctor test ranges from 1.05 g/cm^3 at optimum moisture of 50% to 1.55 g/cm^3 at optimum moisture of 15%. For the modified Proctor tests (ASTM D-1557), the maximum dry densities range from 1.3 g/cm^3 at optimum moisture of 33% to 1.8 g/cm^3 with the optimum moisture of 18%. These are relatively wide ranges and demonstrate some practical difficulties and implications in selecting or specifying the design parameters for placement within the RSF. The expected as-deposited densities of plant residues are expected to be lower than for wastes from gold and copper operations.

For fresh agglomerated ore, the standard Proctor test maximum dry density varied from 1.34 g/cm^3 at optimum moisture of 35% to 1.81 g/cm^3 at optimum moisture 15%. The standard Proctor test maximum dry density of ripios varied from 1.35 g/cm^3 at optimum moisture of 33% to 2.0 g/cm^3 at optimum moisture 18%. The plant residue-ripios blended samples had lower maximum dry densities than the plant residues. As-stacked densities for nickel laterite ores are much lower than for gold and copper ores, which has been verified for pilot heaps at several operations.

Permeability

To model the expected behavior of plant residue disposed of within the RSF with respect to permeability, the samples were remolded to approximately 90% of modified Proctor and permeabilities were measured using flexible wall, falling head (ASTM D-5084) methods. Some cases used tap water, while one study used simulated process water. Table 2 summarizes the measured permeabilities.

Regarding the heap leach, where permeability affects the leaching process, the permeability of column ripios generally decreased by 1 to 2 orders of magnitude over a range of simulated pile heights of 1m to 23 m, as shown in Figure 4. For every case studied, the heap designs where either dynamic

heaps with maximum ore depths of 6 m, or multistack heaps with liners between each lift, and lift thickness of 4 to 7 m. Thus, for the design of the heap, permeabilities at loads simulating 4 to 7 m of ore should be used. A permeability of 2×10^{-4} cm/sec equals an irrigation rate of 7.5 L/h/m^2 assuming full saturation and Darcy's law. Most nickel projects use or will use irrigation rates of 5.0 to 10.0 L/h/m^2.

Table 2: Range of plant residue permeabilities (cm/sec)

Plant residue	Low	High
Iron precipitate (IP)	2×10^{-8}	3×10^{-7}
Neutralization precipitate 1 (NP1)	1×10^{-6}	3×10^{-6}
Neutralization precipitate 2 (NP2)	9×10^{-6}	3×10^{-5}
Plant residue blends	8×10^{-8}	7×10^{-7}

Our database includes 218 tests, 19 reporting permeabilities equal to or less than 2×10^{-4} cm/sec at simulated heap heights of 1 to 7 m, which is about 9% of the total. The lowest permeability results resulted from ripios samples containing the highest content of limonites and lowest silica, with some ores being composed almost entirely of limonite. Generally, when limonite contents were low the laboratory permeability for simulated heap heights of 7 m were equal to or greater than 5×10^{-4} cm/sec. Subsequent testing with better agglomeration control (generally more acid) will also improve the permeability.

The reported permeability values are from end-of-leach-cycle ripios and in all cases the as-stacked ore was more permeable. All samples were disturbed either in sampling or in the lab, and thus the open matrix created in the heap through gentle stacking and leaching of gauge minerals (which increases porosity) was destroyed. Thus, the values reported in Figure 4 should be the lower bound values for good quality ores (low limonite, high silica). For any given project, the lower value results would trigger additional testing to find ways to improve permeability, which might include: crushing to a larger maximum particle size (to reduce the amount of fines generated), blending low and high permeability ores, improving agglomeration methods (perhaps through optimizing acid addition), screening or washing out some of the fines (at least three large copper projects do this to improve permeability and thus there is precedent), and stripping some or all of the limonite off the orebody (this was the plan at both Gag Island and Hallmark in Indonesia and the Philippines, respectively). The stripped limonite can then either be processed in a separate circuit or shipped directly to a smelter.
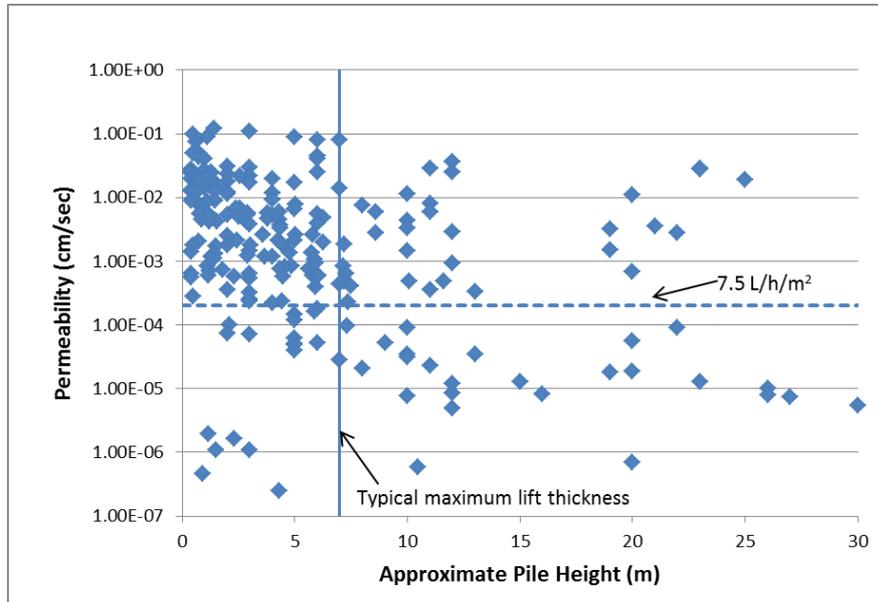
Figure 4: Ripios permeabilities

Shear strength

Mohr-Coulomb shear strength parameters were estimated by performing consolidated undrained triaxial shear tests with pore pressure measurements. The intrinsic cohesion was found to be negligible in the majority of samples tested. The effective friction angle varied from 32 to 45 degrees for the plant residues, and 25 to 40 degrees for the ripios. A similar range was found for the plant residues/ripios blends. IP appears to have the highest shear strength with effective friction angles ranging from 37 to 45 degrees. NP1 exhibited the lowest shear strength with a 35 degree effective friction angle. The strength of IP and NP1 can be strongly influenced by the form of the iron precipitate (geothite, jarosite) and the amount of amorphous material produced, which in turn are affected by the temperature and pH in the plant. Of course, the ripios shear strengths will vary depending upon the fresh ore characteristics as well as the amount of acid used during leaching. Therefore, each sample must be tested using parameters based on the established design criteria.

The test results indicate relatively high-strength materials that should remain statically stable if proper care is taken with the rate of loading to allow adequate pore water pressure dissipation (i.e., to avoid triggering static liquefaction) in the RSF. Experience with natural geologic materials suggest that long-term slope stability can be achieved with relativly low-strength materials with proper drainage and maintenance. However, in areas of high seismicity, such as the Philippines, Indonesia, and Turkey, additional testing and analyses will be necessary to address dynamic (or psuedo-static) stability and seismically-induced liquefaction.

Consolidation

Figure 5 graphically presents the void ratio versus log of normal stress (e vs. log p) obtained from 1-dimensional, remolded, consolidation tests on plant residue and ripios samples. Blends for specific

projects have been tested, but not reported here, as the blending will be highly site specific based upon material quantities and ratios for blending. These plots show that with an initial void ratio range of approximately 2 to 2.5, consolidation under loads increasing from 10 to 2,500 kPa can produce a void ratio reduction of approximately one, with the compression index, C_c, values ranging from 0.069 to 1.34. The stability analysis must, therefore, address both the highly compressible nature of the plant residues and the potential to generate excess pore water pressures during loading. The coefficient of consolidation, C_v, ranged from 0.001 to 0.023 cm^2/sec. Figure 5 also indicates a lack of rebound when the samples were unloaded, with C_r ranging from 0.012 to 0.062. The rebound lines are nearly flat, signifying lack of elastic deformation in the range of normal load applied.
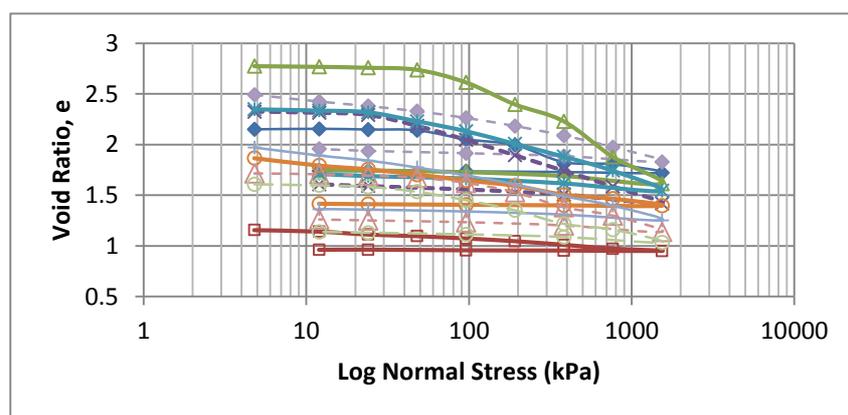

Figure 5: Typical consolidation curves showing range in compressibility, with plant residues on the high and low end and ripios in between

The most notable issue is the difference between primary and secondary consolidation processes. Primary consolidation is associated with pore pressure dissipation; secondary consolidation is associated with creep in the form of time-dependent or continued readjustment of particles, with insignificant excess pore pressures. When does primary end and secondary begin? Typically, consolidation is dominated by the primary stage, with secondary consolidation comprising only a small fraction of the total process. However, in the case of these plant residues, the primary consolidation appears to be completed quickly, whereas the secondary consolidation continues for a long time and is significant. The relatively fast primary consolidation, implying quick dissipation of excess pore pressure, will aid RSF stability during loading by limiting pore-water pressure build-up. The slow secondary consolidation will require consideration for the long-term performance of the RSF. The secondary consolidation issue is still being addressed for concerns with static liquefaction. Further geochemical testing is needed to establish if the long secondary consolidation is associated with chemical reactions that may induce leaching of salts and other chemicals from the plant residues.

California bearing ratio (CBR)

The results for 0.1-inch penetration on plant residue samples ranged from 0.03 to 18.5; results for 0.2-inch penetration range from 0.03 to 15. The variation seems to be random; the authors found no trend

based on plant residues type, blending or amendment with cement. It is the high moisture content of the plant residues that appear to produce low CBR values, which indicate potential difficulty in maneuvering conveyors and other mobile equipment when disposing of the plant residues in the RSF. Field tests on the IP produced from one pilot plant verified that moderate weight equipment was able to maneuver on top of the plant residue. Therefore, the laboratory CBR testing may not be indicative of actual field behavior.

Vibration

The samples were placed on a vibration table at moisture contents approximating the "as produced" conditions from the pilot plant filters. The specimens were then subjected to vibrations with a range of frequencies, bracketing those produce by conveyors, to determine if they liquefied. The laboratory testing showed some variation in the extent of liquefied zone within each sample. The exact frequency at which the individual samples liquefied was not recorded. It remains unclear at which frequencies and moisture contents the plant residues would liquefy. The significance of this is that conveying the plant residues may be constrained if the water content is excessive, either as produced from the filter or after stockpiling (which can allow the plant residues to either dry further or gain water from precipitation).

Figure 6: Stockpiled IP shows stable vertical cut and vibration-induced liquefied bottom

Key observations

Ripios samples were generally well behaved with engineering properties consistent with their index properties. It is important that the geotechnical program take into full account the large degree of chemical alteration which occurs during leaching. Low permeability is perhaps the most often cited limitation for heap leaching lateritic ores, but in the authors' studies all but a few of the samples exhibited permeabilities sufficiently high to allow leaching, which was consistent with the metallurgical column and pilot heap testing on the same ores. For dynamic heaps, the ripios are also generally sufficiently permeability to allow drainage within the dump. One important design consideration for dynamic heap operations is whether the ripios should be disposed of separately or co-disposed with the plant residues. As general guidance the following may be useful:

- Ripios generally have substantially higher permeabilities than plant residues and thus strategic placement of ripios in the RSF can provide internal drainage, shell armoring, and stabilizing of the top of the dump to improve equipment support.

- Ripios are less likely to undergo further chemical degradation in the dump, and thus mixing ripios with plant residues can improve the overall long-term physical and chemical stability.

- Comingling wastes makes testing and analysis more complex and can raise long-term stability issues, especially as related to continued chemical degradation. On the other hand, mixing low and high pH materials will often make sense from an environmental point of view.

- Plant residue stacking will principally be controlled by static liquefaction rather than global stability. For high seismicity locations such as Turkey, Indonesia and the Philippines, the dynamic behavior of the dump will also be a controlling factor and may require either (1) stabilizing berms or (2) partial or full encasement of the plant residues inside of either the RSF or a waste rock dump.

Unusual behavior in some of the plant residues was observed with respect to consolidation and liquefaction, including prolonged, time-dependent strains and significant strength loss upon vibration. These are not normally observed in low-plasticity materials. IP, for example, appears strong against static loads but loses shear strength upon remolding or vibration, and then regains strength relatively quickly once vibrating has stopped. These results and observed behavior must be taken into consideration in designing the RSF, especially with respect to conveying and equipment loading during stacking.

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