Classification, strength and water retention characteristics of laterite subsoil materials in the Darling Range, Western Australia

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Abstract

Regolith materials beneath lateritic bauxite in the Darling Range of Western Australia mostly consist of highly weathered granite and dolerite. They are poorly described and are generally recorded as the "mottled" or "pallid" zone. These regolith materials become the media for re-establishment of jarrah-marri forests after bauxite mining. A classification system has been developed for bauxite mine floor regolith, and relationships of regolith material type with water retention, strength, bulk density and field hand texture have been discussed. Mottled zone materials are generally quartz rich with loamy sand to sandy clay textures and have weakly developed lenticular pedality. Pallid zone materials are generally clay rich with silty loam to silty clay textures and angular blocky pedality. Plant available water within the mottled and pallid zone regolith materials occupies 27% to 34% of total porosity compared to 24% and 21% for granitic and doleritic saprolite above bedrock. Plant unavailable water occupies 39% to 52 % of the total porosity compared to 61% and 70% for granitic and doleritic saprolite above bedrock. Pedogenic processes within mottled and pallid zones have thus increased porosity in the plant available water range. Clay content increases dry and wet strength of regolith materials. Grain supported fabrics are more responsive to changes in water content and matric potential. Materials cemented by iron oxides have higher dry and wet strengths and are almost unaffected by changes in water content or matric potential. The strength of these materials is more sensitive to differences in texture and iron oxide cements than it is to changes in bulk density.

Keywords

Regolith, strength, bauxite, pallid zone, mottled zone, waterholding capacity

Introduction

The subsurface regolith materials of lateritic bauxites derived from granite and dolerite in the Darling Range of Western Australia are poorly described and are commonly recorded as the "mottled" or "pallid" zones. Recommended terminologies for deeply weathered profiles were published by Anand and Paine (2002) but these do not adequately describe the observed morphological properties of mottled and pallid zone materials. Some relationships between intrinsic physical properties and regolith material type can not be identified using the current terminology.

In-situ pedogenic processes may produce hard regolith materials. Fabiola *et al.* (2003) found that micromorphological features in kaolinitic soils were related to compaction, increased tensile strength, penetrometer resistance, bulk density and hardsetting behavior. Robertson *et al.* (1998) described the transformation of granitic saprolite into a sandy arenose material by disaggregation of quartz grains and redistribution of kaolinite resulting in volume loss. Fine particles of silt and clay form structural connections between sand particles and as the material dries the strength of these connections increases (Mullins *et al*. 1987; and Lamotte *et al*. 1997a). We hypothesise that a combination of disaggregation of quartz grains, volume loss, redistribution of clay and silt and the formation of structural bridges is responsible for the hardness of some Darling Range regolith materials. Cementation by iron oxides also produces hard regolith materials.

Ripping of Darling Range bauxite mine floors using instrumented bulldozers has shown that hardness of these materials is highly variable. Structureless hard materials will limit root growth of re-established plants. We propose that a newly developed classification system can be used to predict physical properties including the hardness of mine floor regolith materials, thereby providing a basis for more effective rehabilitation of bauxite mines.

Methods

Study area and material sampled

The study has been conducted at the Alcoa World Alumina Australia, Huntly Bauxite Mine site, which is located 80km south of Perth in the Darling Range, Western Australia. The mine has an elevation of 270m above sea level at Latitude:-32.7103^{o} S and Longitude: 116.0594^{o} E. The mean max daily temperature is 15ºC in winter and 30ºC in summer. Annual rainfall is approximately 1260 mm and mostly occurs in winter.

Regolith material was sampled from Mullian 3 and Chipala 9 mine pits after land restoration. This process involves battering of the edges of the mine pit and leveling of the surface. The mine pit floor is ripped to a depth and spacing of 1.5m, additional leveling is conducted and overburden and topsoil are returned. A total of 20 trenches were excavated at Mullian 3 and 16 at Chipala 9 to a depth of 3m, which is below the depth of pre-ripping operations. Regolith profiles were described using standard soil survey techniques as described in McDonald *et al.* (1990).

Intact clod samples measuring approximately 30cm by 30cm were collected from regolith materials then sealed in plastic and hessian bags for transport to the laboratory.

Bulk density determination

Bulk density was determined on 10, approximately 100 g, paraffin wax coated clods broken from each of the intact clods (McKenzie 2002).

Water retention measurements and unconfined compression strength measurements

Intact clods sampled from trenches at Mullian 3 and Chipala 9 were cut into 2 cm intact cubes on a Boort diamond saw. Forty four clods measuring 30cm by 30cm and representing 9 regolith classes were cut at a low moisture content that did not induce smearing on the surface of cubes. A total of 3520 cubes were cut from the 44 clods, with 80 cubes equilibrated at 8 matric potentials (10 cubes per matric potential) for each of the 44 clods. The number of clods and cubes used for water retention and unconfined compression strength measurements per regolith class were Zm1, 2 clods, 160 cubes; Zm2, 11 clods, 880 cubes; Zm3, 7 clods, 560 cubes; Zp1, 1 clod, 80 cubes; Zp2, 8 clods, 640 cubes; Zp3, 7 clods, 560 cubes; Zh3, 4 clods, 320 cubes; Zg12, 2 clods, 160 cubes, Zg21, 2 clods, 160 cubes. The cubes were placed on ceramic plates in trays of deionised water allowing slow wetting to prevent slaking. Each cube was placed on top of a bed of < 1mm pallid zone kaolinite which was placed on Advantec, type 2, 42.5 mm filter paper. Intact cubes were allowed to saturate for 48 hours and then equilibrated at matric potentials of 0, 10, 50,100, 500, 1500 kPa using pressure plate equipment (McKenzie *et al.* 2002). Industrial nitrogen gas was used within the pressure chamber. NaCl and NaOH saturated salt solutions in glass desiccators were used to equilibrate intact cubes at matric potentials of 39,000 kPa and 400,000 kPa respectively.

Intact cubes were weighed after equilibration and then subjected to unconfined compression strength measurements (UCS) using a Mecmesin Basic Force Gauge BFG 1000N. Cubes at near saturation (0 kPa) were too wet to be measured. The intact cube was placed between the base plate and a disc (2.5cm diameter) which was lowered at a constant speed of 0.2 mm/s. Fracture strength was recorded as the value of strength (kN/m^2) at the first sign of cracking of the cube. The cube was then oven dried at 105ºC for 24 hours and the gravimetric water content determined.

Results and Discussion

Regolith Classification system for bauxite mine floor materials

Table 1 shows a morphological classification system that has been developed for bauxite mine floor regolith materials in the Darling Range, Western Australia. The classification is based on hand texture, structure, colour and coarse fragment content - all features that can be readily distinguished in the field. The definition of a zone of regolith relates to a part of the regolith having a distinct character, distinguishing it from adjacent parts (Eggleton 2001). The use of the term zone has been adopted as it implies a continuous body which differs in some respect from adjacent bodies of material. It does not imply that a layered or horizontal arrangement of materials exists. This approach is able to classify spatially complex assemblages of materials resulting from the process of *in-situ* isovolumetric weathering of multiply fractured, compositionally diverse granitiods in the Darling Range, such as those described by Anand and Paine (2002). A complex three dimensional organization of zones occurs with no persistent relationship to the current landform. Zones presumably reflect the assemblages of minerals that were present in zones in the parent rock, their interactions with water and oxygen that promoted weathering and neoformation of materials together with effects of diverse eluviation and pedoturbation processes.

Table 1. Classification system for bauxite mine floor regolith, Darling Range, Western Australia.

	Class
Material is loose or weakly structured (deposited during site preparation)	
Surface material	A1
First overburden return material	Ap
Mixed material	AZ
3D body of regolith material that remains after bauxite mining	
Mottled quartz- rich material	*Zm*
Loamy sand (LS) to light sandy clay loam (LSCL	Zm1
Sandy clay loam (SCL) to clay loam (CL	Zm2
Sandy clay(SC)	--- Zm3
Pallid clay- rich material	*Zp*
Silty Loam (ZS)	Zp1
Silty clay loam (ZCL)	Zp2
Silty clay(ZC)	Zp3
Red brown iron oxide-rich material	*Zh*
Less than 50% coarse fragments	Zh1
50% to 80% coarse fragments	Zh2
greater than 80% coarse fragments	Zh3
Prior root channels	*Zr*
Preserved granitoid material	*Zg*
LS to LSCL, with <50%CF; 50-80%CF; >80%CF	Zg11; Zg12; Zg13
SCL to CL, with <50%CF; 50-80%CF; >80%CF	Zg21; Zg22; Zg23
SC, with <50%CF; 50-80%CF; >80%CF	Zg31; Zg32; Zg33
Preserved doleritic material	*Zd*
ZL, with <50%CF; 50-80%CF; >80%CF	Zd11; Zd12; Zd13
ZCL, with <50%CF; 50-80%CF; >80%CF	Zd21; Zd22; Zd23
ZC, with <50%CF; 50-80%CF; >80%CF	Zd31; Zd32; Zd33

Water retention characteristics

The relationship between volumetric water content (m^3/m^3) and log matric potential (pF) is shown in figure 1. Water retention curves for 8 regolith materials from Mullian 3 and Chipala 9 mine pits are compared with published curves for saprolitic granitic (GPZ) and doleritic (DPZ) pallid zone from the Jarrahadale area (McCrea *et al.* 1990). GPZ material has formed 2 to 5 m above a complex bedrock consisting of gneissic granite, quartz-feldspar-mica pegmatite and adamellite, while DPZ has formed 1 to 3 m above bedrock consisting of quartz-diorite and metaquartz-dolerite (McCrea *et al*. 1990). The great diversity of these curves indicates that the pore size distribution of regolith is extremely variable and although much water is retained at field capacity (pF 2), only a small to moderate proportion is likely to be available to plants (pF 2 to pF 4.2).

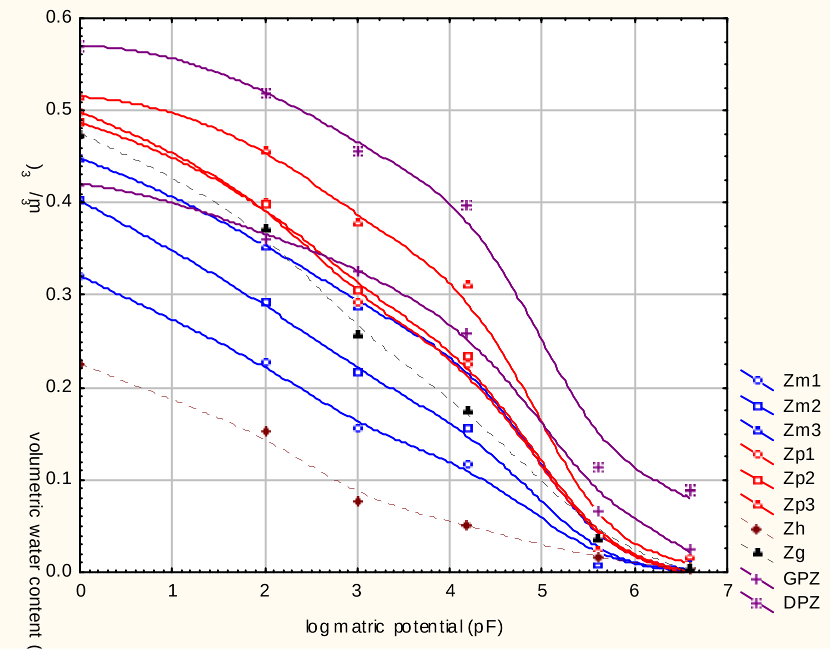

Figure 1. Water retention curves for regolith materials

By measuring the water content at near saturation (pF 0), the total porosity (m^3/m^3) of materials can be ranked as follows: 0.52 (Zp3) > 0.50 (Zp1) > 0.49 (Zp2) > 0.47 (Zg) > 0.45 (Zm3) > 0.40 (Zm2) > 0.32 (Zm1) > 0.23 (Zh3). The high total porosity of Zp materials is due to a matrix dominated by silty loam to silty clay textures with low percentages of sand size quartz grains being present (<30%). Zm materials contain higher and more variable percentages of quartz grains (usually >30%) resulting in a grain supported sandy loam (Zm1) matrix ranging to a clay supported sandy clay (Zm3) matrix. The total porosity decreases as clay content decreases and considerable variation in pore size distributions occurs due to a quartz dominated grain support matrix occurring in many materials. Zg material has a soft granitic fabric consisting of a sandy loam to silty clay loam textures with unaltered (disaggregated) quartz grains in varying amounts, giving a total porosity between values for Zm and Zp materials. Zh materials are cemented by various amounts of iron oxides which produce a matrix with a pore size distribution concentrated in the mesopore range and a lower total porosity than for other materials.

The shape of the water retention curves for GPZ and DPZ materials (McCrea *et al.* 1990) and regolith materials differ due to differences in texture and structure. Salter and Williams (1965a,b) concluded that undisturbed intact cores should be used to determine moisture characteristic as structure influences the curve and is altered by packing of disaggregated soil. They also demonstrated that moisture content at field capacity and permanent wilting point increases as soils become finer. McCrea *et al.* (1990) using thin sections demonstrated that relict rock fabric is present within saprolitic GPZ and DPZ materials due to isovolumetric alteration, with all major primary minerals except quartz being replaced by a fine-grained isotropic clay matrix with minor amounts of sesquioxides. The relict rock fabric with its fine clay matrix for GPZ and DPZ materials produces a different shape water retention curve with a greater proportion of total porosity occurring in micropores where water is retained beyond wilting point (pF 4.2). Where saprolitic materials have been subject to pedogenic restructuring processes, regolith gives water retention curves with lower total porosity beyond permanent wilting point. Materials (Zp) with finer texture (silt and clay) have water retention curves similar to the DPZ curve, whereas quartz rich (Zm) and porous (Zh) materials contain a greater proportion of total porosity within the plant available range (pF 2 to 4.2).

Figure 2 shows a differential plot of volumetric water content per 1 pF unit and the corresponding pore sizes. The curves for GPZ and DPZ material (McCrea *et al.* 1990) show that most retained water is unavailable to plants, being retained at matric potentials greater that pF 4.2. The DPZ material has a maximum water content of 0.26 m^3/m^3/pF at pF 5 (pore size of 0.03µm) and GPZ material has a maximum of 0.18 m^3/m^3/pF at pF 5.5 (pore size of 0.01µm). The curves for regolith materials classified as Zm2, Zm3 and Zp3 have water contents lower than those for GPZ material. Water within these latter materials is gradually extracted at tensions ranging from near saturation (pF 0) to plant wilting point (pF 4.2) and the curves generally lie above those of GPZ and DPZ materials in this range. The bimodal pore size distribution may also be related to the extent of structure development (Bullock and Thomasson 1979). The peak in the DPZ curve at pF 3 is due to intraped porosity of the more structured (pedal) doleritic PZ material (McCrea *et al.* 1990). This material is similar to that classified as Zp which has a moderate to strong angular blocky pedality. The peak at pF 2.5 (pore size of 10µm) for Zg, Zh and Zm2 regolith materials is related to the fabric of the materials. Zg regolith materials have a coarse grained fabric dominated by quartz and unweathered feldspar grains. Zh regolith materials are the product of the *in-situ* weathering of granite. They consist of a porous "boxwork" fabric cemented by iron oxides around the original boundaries of the completely altered mineral grains. Zm2 regolith material is characteristic of reorganised material where clay translocation has resulted in increased concentrations of quartz and large pore sizes (10 µm, pF 2.5). This process of relative quartz concentration in granitic saprolite was outlined by Robertson *et al.* (1998).

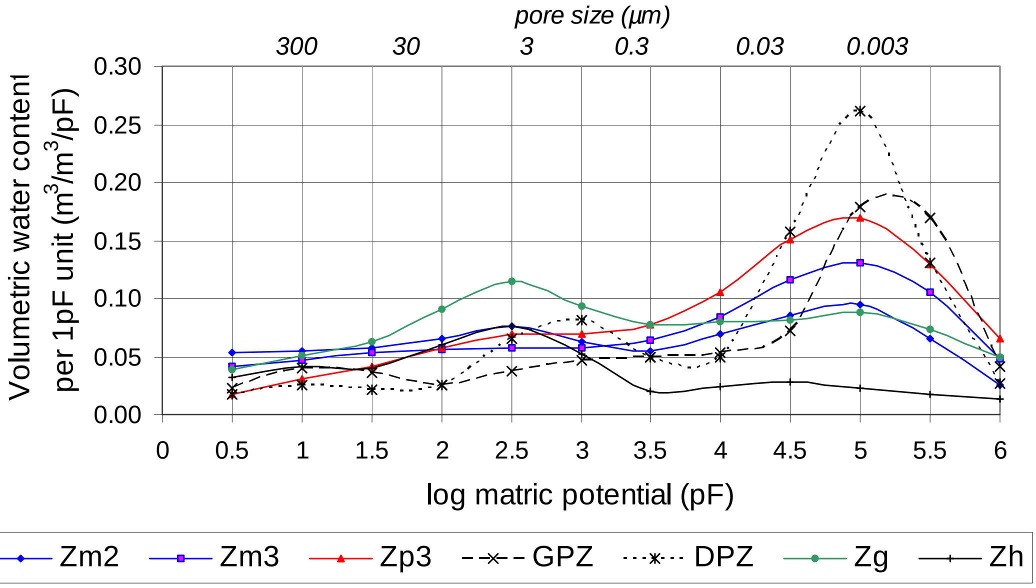

Figure 2. Differential plot of volumetric water content per 1 pF unit for regolith materials

Plant available water occupies 27% to 34% of total porosity within Zm2, Zm3 and Zp3 materials compared to 24% and 21% respectively in GPZ and DPZ material. The water in micropores that is unavailable to plants (pF greater than 4.2) is 39% to 52% of total porosity for Zm2 and Zm3 regolith materials, compared to 61% of total porosity for GPZ material. Similarly, Zp3 regolith materials have 61% of total porosity occupied by water that is unavailable to plants compared to 70% in DPZ material. There are positive linear relationships for regolith materials between clay % and volumetric water content at pF 2 (r^2=0.56) and pF 4.2 (r^2=0.64), but no relationship between clay % and plant available water (pF 2-4.2)(r^2=0.0004). As shown in figure 3, water content at pF 5 increases as clay content increases for regolith and saprolitic materials (Zm2 to DPZ). Total water content in this range is closely related to clay content. GPZ and DPZ materials have average clay contents of 35% and 60% respectively (McCrea *et al.* 1990). The clay contents of regolith materials are shown in table 1 and correspond to the texture classes of (McDonald *et al.* 1990). The increase in percentage of total water in the plant available range and the decrease in water in the unavailable range for bauxite mine floor regolith materials relative to saprolitic GPZ and DPZ is presumably a consequence of pedogenic processes involving clay translocation and causing meso-structure development in materials present in the mine floor.

Changes in unconfined compression strength with increasing water content

Unconfined compression strength (UCS) of regolith materials is highly sensitive to water content and this relationship is described by a negative exponential function (equation 1).

$$Y = A\,e^{-BX} \qquad \text{eq 1}$$

Y – unconfined compression strength (kN/m^2)
X – water content (m^3/m^3)
A – represents dry UCS (strength at approximately free water content 105ºC)
B - represents the responsiveness of UCS to increasing water content, a measure of sensitivity

This relationship for selected materials is shown in figure 3 and the coefficients dry UCS (A) and responsiveness to increasing water content (B) for all materials are shown in figure 4. The dry UCS (A) values of quartz rich (Zm) and clay rich (Zp) material ranges from 1000 to 10,000 kN/m2, excluding outliers. Evidently, increasing clay content increases the dry UCS (A) of these materials.
Quartz rich (Zm) materials are more responsive to increasing water content (B) than are clay rich (Zp) materials, indicating that their strength decreases more quickly when water content is increased by equal increments. The range in response to increasing water content is large (figure 4) for both materials.

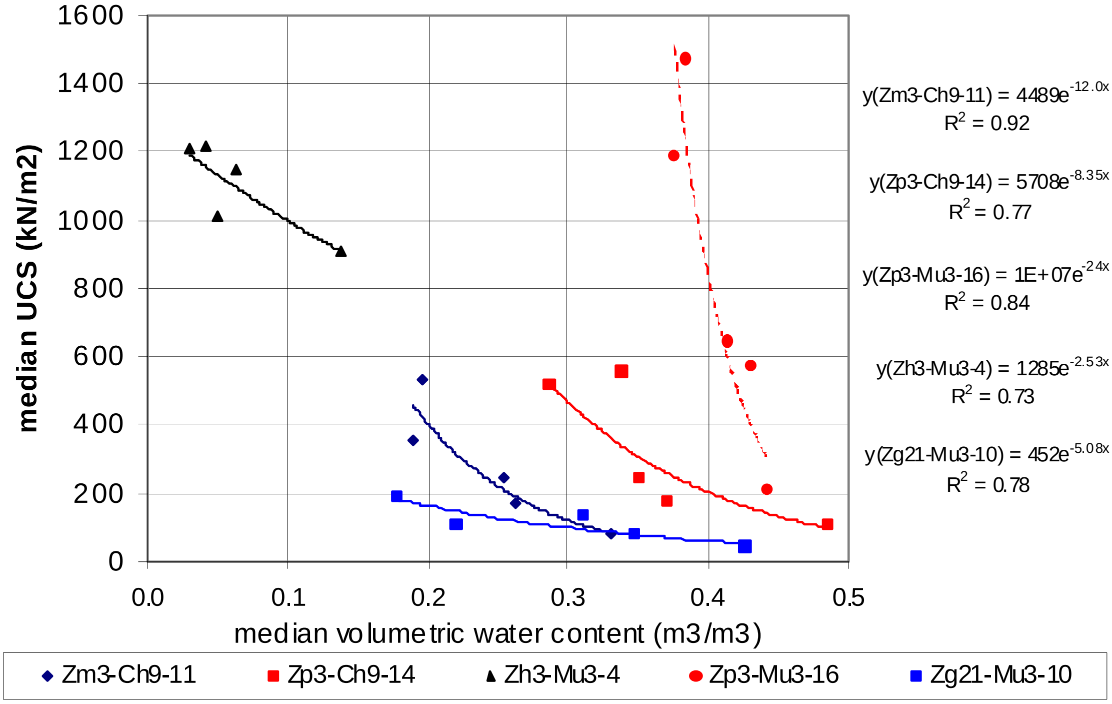

Figure3. Unconfined compression strength versus volumetric water content, median values for each material

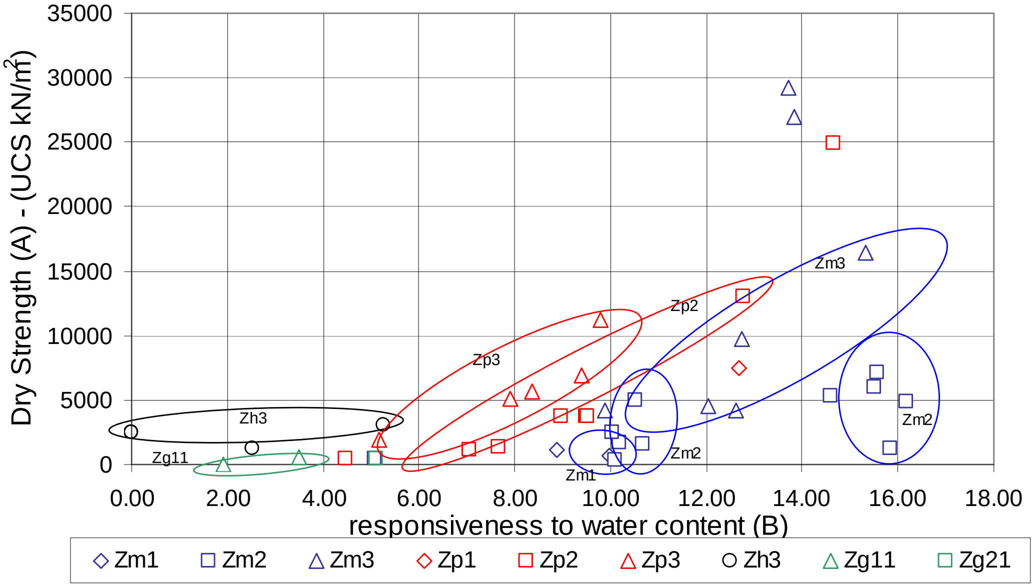

Figure 4. Dry UCS (A) versus responsiveness to water content (B). Ellipses represent classes of regolith materials

Materials indicated in figure 4, as having a high (greater than 12,000 kN/m2) dry UCS (A) have silty clay loam and sandy clay field textures. Increasing clay content and/or changes in fabric arrangement increased the dry strength of these materials. Materials with a low response to increasing water content (B), are cemented by iron oxides (Zh materials), or have a coarse grain support fabric with low clay content, with or without cementing by iron oxides (Zg materials). These materials (Zh and Zg) show minimal change in strength as water content increases, indicating that the strength of iron oxide cemented fabrics is unaffected by changes in water content.

The relationships of dry UCS (A) and responsiveness to water content (B) to clay content are shown in figure 5. Dry UCS (A) increases with increasing clay percentage and the response to increasing water content (B) shows an increase up to a maximum at approximately 30% clay for several materials.

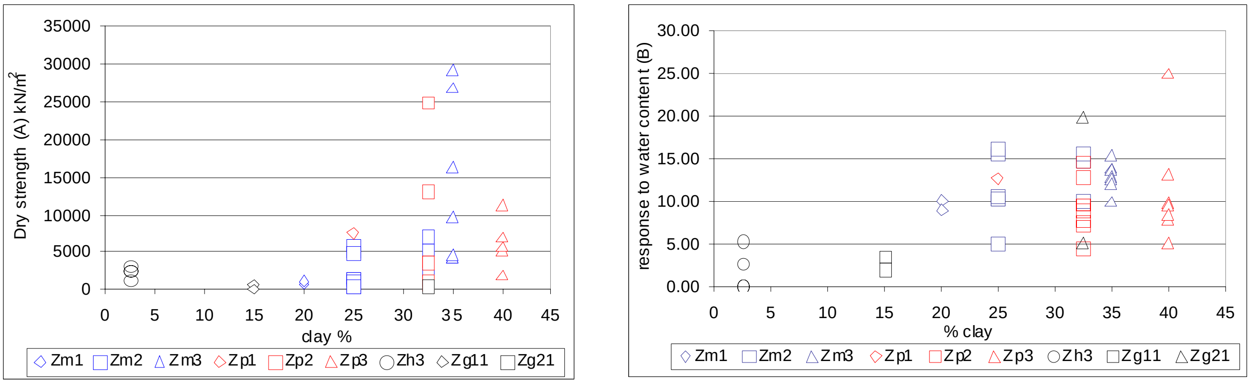

Figure 5. DryUCS (A) and responsiveness to water content (B) versus clay percentage

Mullins *et al.* (1987) and Lamotte *et al.* (1997a) proposed that fine materials form bridges between sand particles and as soil dries, the strength of these bridges is increased. This process is variable within quartz rich (Zm) materials where the matrix consists of randomly packed quartz grains of variable size and abundance, providing a grain supported fabric. The differences in quartz content, size and shape, the effects of slaking, the resultant weak lenticular structure and the increase in fine silt and clay bridging material are possible explanations for the variability in the dry strength of quartz rich (Zm) material. Root growth within these materials is usually poor with only few, very fine to fine roots present compared with roots in clay rich (Zp) material with common to many medium roots along the faces of angular blocky peds.

Unconfined compression strength and bulk density

Figure 6 shows values of median bulk density of intact clods for each material plotted against unconfined compression strength (UCS) for intact cubes at matric potential pF 4.2 (-1500 kPa). There is no systematic difference in strength (100 to 700 kN/m^2) between quartz rich (Zm) and clay rich (Zp) materials despite the bulk density of Zm materials being mostly larger than for Zp materials (the quartz rich Zm materials have bulk densities of 1.80 to 1.95 g/cm^3 compared to 1.60 to 1.80 g/cm^3 for clay rich Zp materials). Clay content, degree of iron oxide cementation, fabric of the matrix and water content are clearly more predictive of UCS than is bulk density.

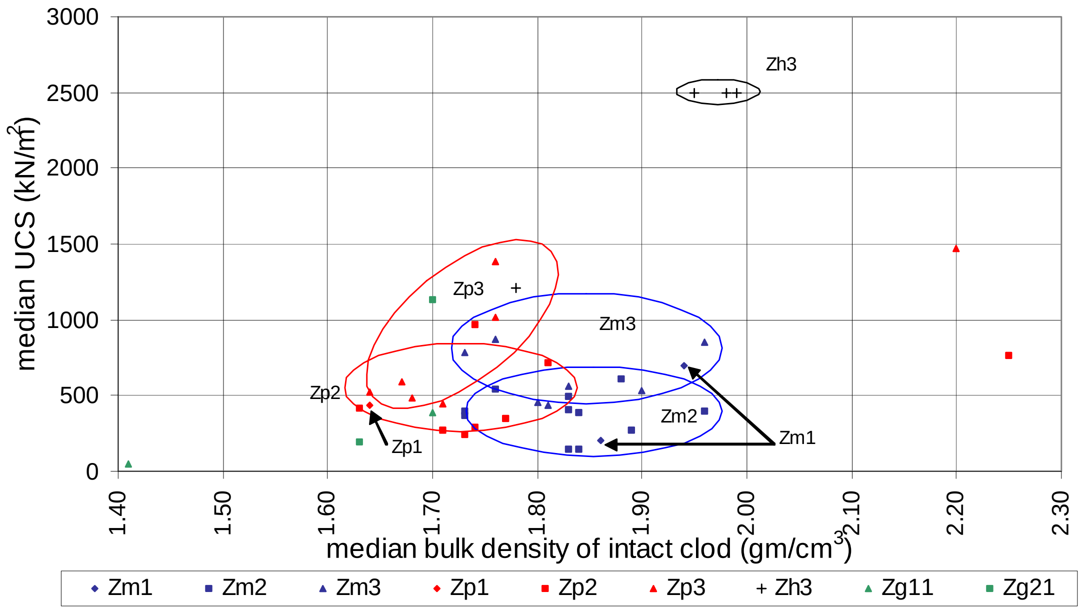

Figure 11. Unconfined compression strength versus bulk density for regolith materials. Ellipses represent classes of regolith materials

Conclusion

The field regolith classification system for bauxite mine floor regolith materials is indicative of water retention characteristics, strength and bulk density. It provides a basis for assessing the physical properties of the materials that affect plant growth and also can be used to indicate appropriate management practices including ripping.

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