Before and after: the make-up of native and disturbed mine soil materials.

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Abstract

The bulk-handling of native soil materials during mining operations may contribute to an increase in soil strength (hardsetting) in minesoils. The penetration resistance (PR) of soil materials from a mineral sands mine was measured to assess whether disturbance of these materials affected soil strength. The penetration resistance curve was empirically characterised using 6 parameters from which summary curve parameters were derived. There were clear relationships between the summary curve parameters Average Force (N) and Maximum Strength (N), and VWC % for individual mine soil materials. The mine soil materials that are high in clay are stronger and strength is more sensitive to water content. Interpretation of thin sections of native and disturbed mine soil materials, and the quantification of their fabric descriptions in ImageJ, indicated that physical disturbance changed the fabric of the native soil materials. The parameters that best identify variations in soil fabric were established from principal component analysis of the measured soil properties and the ImageJ parameters. These results have implications for the management of mine soil materials and encourage specific handling of soil materials based on their clay content.

Keywords

Minesoils, hardsetting, penetration resistance, soil fabric, ImageJ, principal component analysis.

Introduction

The appropriate management of mine soil materials is a key component of successful landscape reconstruction and the proper placement of soil or unconsolidated material should result in the development of a stable soil structure (Toy and Black 2000). The bulk-handling of native soil materials during mining operations tends to destroy soil structure and can lead to an increase in soil strength (hardsetting) in the newly constructed soils (minesoils) of a reconstructed landscape. While the relationships between hardsetting, soil strength and soil moisture are well documented (Mullins and Panayiotopoulos 1984; Harper and Gilkes 1994), the effects of disturbance during land rehabilitation on these soil properties are not clearly understood. In this research we measured the penetration resistance of soil materials from a mineral sands mine to assess whether disturbance of these materials affected soil strength.

Methods

The mine soil materials

We collected eight mine soil materials representing the native, constructed and overburden soil materials of a mineral sands mine located on the Swan Coastal Plain in south-west Western Australia. A further two materials, tailings sands and clay slimes, were also examined. These are by-products of the mineral extraction process and are often used in post-mining landscape reconstruction. The properties of each mine soil material were described using methods specified in McDonald *et al.* (1998) and Rayment and Higginson (1992).

Sample preparation

The mine soil materials were packed into plastic rings to an approximate dry bulk density of 1.6 g/cm^3 and placed on a Whatman Grade No. 5 filter paper. The samples were placed on a dry kiln tile in a wetting tray for slow wetting by capillary action. When the samples showed free water on their surface for a period of 24 hours, they were weighed and transferred to ceramic plates previously saturated with degassed, deionised water for equilibration at -10, -33, -300, or 1500 kN/m^2. Once the samples had equilibrated they were removed from the plate and weighed immediately prior to measuring the penetration resistance.

Measuring penetration resistance (PR)

The PR (strength) of each sample was measured using a Basic Force Gauge (BFG) fitted with a 6mm flat-end probe. The BFG does not have the capacity to measure sleeve friction so the PR is the total resistance, including sleeve friction, during penetration (Liu *et al.* 2006). The BFG was attached to a Mecmesin UltraTest Stand and, in single cycle mode, the penetration velocity was controlled at 12.5 mm/ hr. A graph of the resistance to the advancing probe over time was plotted using Dataplot™ software (Figure 1).

Image analysis
Thin sections of the mine soil materials were examined under an optical microscope with plain and polarised light. Optical micrographs (OM) and scanning electron micrographs (SEM) were obtained from each thin section (Figure 2). The fabric of each sample was described using a flow chart for OM description of soils adapted from Bullock *et al*. (1985) and the fabric descriptions were quantified in ImageJ, a public domain Java image processing program (Rasband 1997-2009). The OM and SEM images were edited, analysed and processed prior to applying the standard algorithms for analysing particles.

Statistical analysis
Statistical summaries for the quartz, clay matrix, organic material, heavy mineral and void fabric components were calculated prior to principal component analysis (PCA). The initial dataset consisted of five statistical measures (mean, median, standard deviation, skewness and kurtosis) of the seven particle, aggregate and void properties (area, perimeter, ellipse major, ellipse minor, ellipse angle, circularity and Feret's diameter). Due to the large number of variables (35), PCA was performed separately on each of the fabric components. Further analysis was then performed on a reduced dataset with all the fabric components.

Results

The properties of the mine soil materials

Table 1. The physical and chemical properties of the mine soil materials.

Soil material	Sand %	Silt %	Clay %	Bulk density	pH ($CaCl_2$)	EC (mS/m)	Exch. Cations Ca	Mg	Na	K	ECEC meq/100g	ESP	Total C %
Native Subsoil 1	85	1	14	1.6	6.6	14	0.2	0.1	0.0	0.0	0.4	8.3	0.0
Native Subsoil 2a	77	1	22	1.7	4.5	4.1	1.3	0.4	0.1	0.1	1.9	3.8	0.3
Native Subsoil 2b	71	1	28	2.0	4.4	2.3	0.6	0.3	0.1	0.0	0.9	5.3	0.1
Native Overburden	59	1	40	1.9	4.3	3.2	0.2	0.1	0.1	0.0	0.4	22	0.1
Constructed Subsoil 1a	88	1	11	1.6	5.7	11	1.6	0.5	0.1	0.1	2.2	2.2	0.2
Constructed Subsoil 1b	88	2	10	1.7	4.5	10	0.6	0.4	0.2	0.0	1.2	17	0.3
Stockpiled Subsoil 1a	84	1	14	1.8	5.3	31	1.2	0.9	0.6	0.1	2.8	21	0.3
Stockpiled Subsoil1b	75	1	24	1.8	5.7	3.9	1.0	0.2	0.1	0.1	1.3	4.5	0.3
Tailings sand	98	1	1.0	1.7	5.8	23	1.7	3.9	0.4	0.1	6.1	7.0	0.0
Clay slimes	18	1	81	NA	5.4	14	1.2	4.9	0.6	0.1	6.8	8.6	0.1

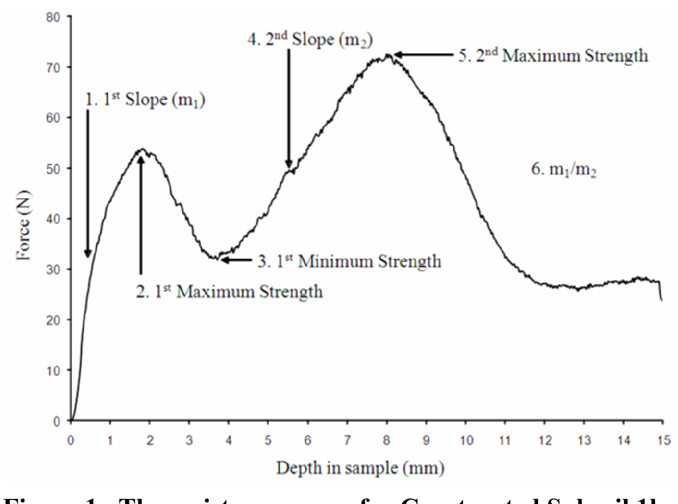

Figure 1. The resistance curve for Constructed Subsoil 1b and definitions of the 6 curve parameters.

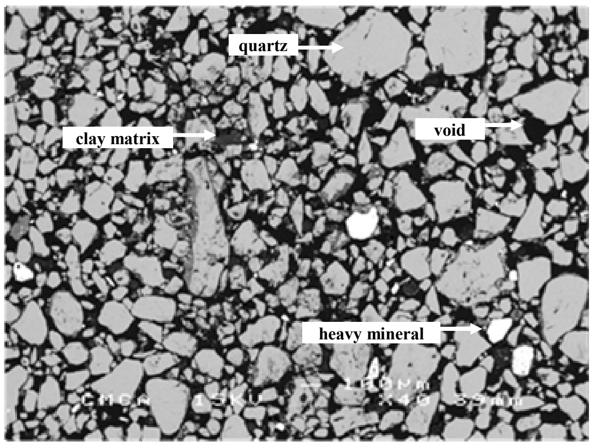

Figure 2. SEM of Constructed Subsoil 1b, identifying each of the fabric components.

Penetration resistance of the mine soil materials
A diverse range of resistance curves was observed for the mine soil materials. The curves were empirically characterised using 6 parameters (Figure 1) from which summary curve parameters were derived. Average force (AF) in Newtons (N) was chosen as the primary summary curve parameter because it is the average of

the maximum and minimum strength parameters, and it has a strong relationship with the maximum strength (MS) in Newtons (N) recorded for each sample) ($r^2 = 0.98$). A linear correlation matrix was generated to establish the relationships between the summary curve parameters and the sample properties of bulk density (BD g/cm^3), volumetric water content (VWC %) and clay (C %). Bivariate plots indicated that there are no clear associations across all samples between the resistance curve parameters and the sample properties for the normal or ln transformed data. There are, however, clear relationships between the summary curve parameters and VWC % for individual materials. Of these, AF and MS show the strongest associations.

The regression coefficients dry strength (D) and sensitivity to water content (W) were derived from linear regression of VWC % against AF (Figure 3) for the normal and ln transformed data. The relationship between AF and VWC % for Constructed Subsoil 1b (Figure 3) is summarised by the equation y = 0.79x + 5.01 where the intercept (5.01) is ln D and the slope (-0.79) is W. The strength of the mine soil material increases as water content decreases and the functional form is best described by the ln/ln relationship. A summary of the regression coefficients for the ln/ln relationship indicates that a systematic relationship between ln D and W exists for the mine soil materials (Figure 4).

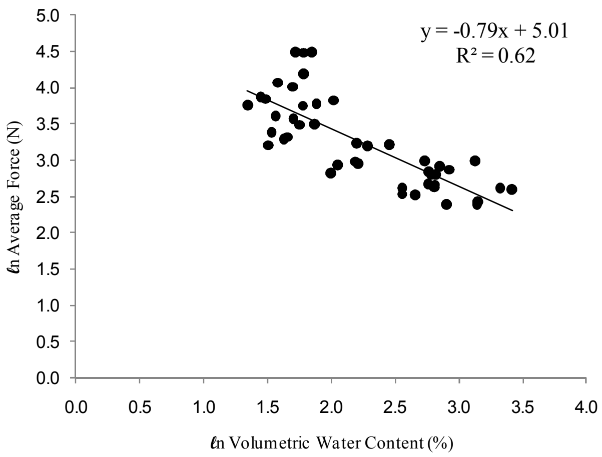

Figure 3. Relationship between ln AF (N) vs. ln VWC % for Constructed Subsoil 1b.

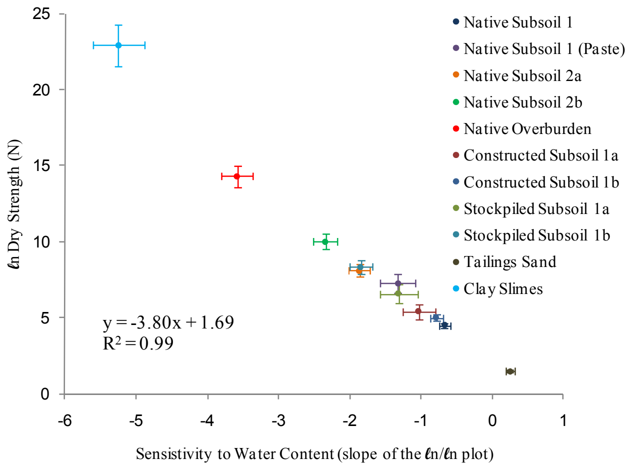

Figure 4. Relationship between ln D vs. W (slope of the ln/ ln **plot) with SE bars for the mine soil materials.**

Principal component analysis (PCA)

PCA identified clusters of closely correlated variables for the quartz, clay and voids fabric components of the mine soil materials. Five distinct groups of variables occurred for the quartz and voids components and four for the clay matrix. The grouping of variables was consistent across the fabric components and several of these properties are strongly positively correlated. On this basis, a subset of ImageJ parameters was selected to simplify the subsequent analysis of these data. These parameters are particle, aggregate and void size (Ad), length (Jd), roundness (Cm), sorting (Js) and size distribution (Fw). The ImageJ estimates of quartz (%Q), clay matrix (%M), void (%V), organic material (%O) and heavy mineral (%H), and the variables dry strength (D), sensitivity of strength to water content (W), and laboratory measured percent clay (C) were incorporated into the statistical analysis (Figure 5).

Eigenvalues determine the number of factors required to adequately classify the materials. In this instance, a four component model is sufficient to explain 83% of the variation in ImageJ parameters and the soil property variables. The strongest positive correlation is between D and %M (r = 0.90). This, together with the strong, positive correlation between D and C (r = 0.78) and a strong, negative relationship between D and %Q (r = -0.83), show that the strength of the mine soil materials is strongly dependent upon clay content. Sensitivity of strength to water content (W) is negatively correlated with M (r = -0.67) indicating that the strength of clay rich materials is most sensitive to water content (Figure 6).

D	Dry Strength (N)
W	Sensitivity to Water Content
C	Clay (%)
%Q	Quartz (% of the image)
%M	Clay Matrix (% of the image)
%V	Voids (% of the image)
%O	Organic Material (% of the image)
%H	Heavy Mineral (% of the image)
VAd	Voids Area (mm^2) median
VFw	Voids Feret's Diameter skewness
QJd	Quartz EllipseMaJor median
QCm	QuartzCircularitymean
MAd	Clay Matrix Area (mm^2) median
MCm	Clay Matrix Circularitymean
MFw	Clay Matrix Feret's Diameter skewness

Figure 5. The reduced dataset consisting of the mine soil property variables and the ImageJ parameters.

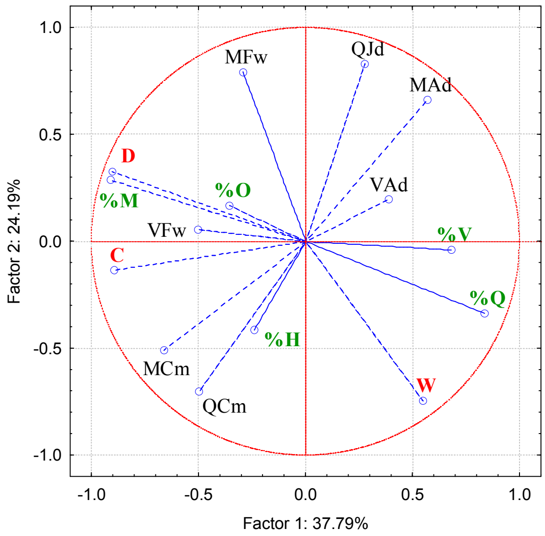

Figure 6. Relationships between the mine soil property variables and ImageJ parameters derived by PCA.

Conclusions

The parameters that best describe variations in soil fabric were established from PCA of the measured soil properties and the ImageJ parameters. The mine soil materials that are high in clay are stronger and strength is more sensitive to water content. The strong, positive relationship between laboratory measured clay content (C) and the ImageJ estimate of percent clay (M) indicates that the ImageJ analysis of thin section micrographs is a suitable tool for estimating the clay content of the mine soil materials. These results have implications for the management of mine soil materials during mining operations. The bulk-handling of mine soil materials may be necessary due to the large scale of mining operations, however these data indicate that their separate handling based on clay content may reduce the occurrence of hardsetting.

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