THE FACTORS INFLUENCING CONE PENETROMETER RESISTANCE AS A MEASURE OF COMPACTION IN MINESPOILS[1]

by

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Abstract. Cone penetration resistence as a measure of compaction was used to evaluate minespoils from the Luscar geological formation of the Alberta Rocky Mountain Foothills across the plant available moisture range. Three soil textures, two salinity levels and six moisture tensions were tested. There was a well defined relationship between cone penetration resistence, or strength, and moisture tension. Average minespoil strength at 1/3 and 3 bars moisture tension was 40% and 72% of that at 15 bars tension, respectively. Because each minespoil has a different range of cone penetration resistence, depending mainly on texture, an absolute relationship between moisture tension and strength could not be developed. By normalizing the strength values, whereby all values were divided by that obtained at 15 bar moisture tension, a predictive equation relating strength to moisture tension is reported ($r^2 = 0.92$) that is applicable to a wide range of minespoil textures. Clay content and salinity had a significant effect on minespoil strength. Penetration resistance was 2.5 times greater at 33% clay content than at 8% clay. Minespoil strength of saline spoils was 1.25 times that of non-saline spoils. The salinity effect increased as salts precipitated upon drying the minespoil: strength at 15 bars moisture tension in saline minespoils was 1.4 times that of non-saline minespoils.

Additional Key Words: compaction, strength, effect of moisture tension, effect of salts.

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Introduction

The effective reclamation of coal minespoils involves the rapid establishment of a healthy vegetation cover. Problems such as poor seedbed conditions and lack of nutrients are overcome by covering spoils with a layer of topsoil and by fertilization. This allows germination and seedling establishment, but further development of the cover is largely dependent on subsoil (spoil) conditions. The lack of organic matter in spoils does not promote good soil structure, and a poorly structured spoil with relatively high bulk density can result. The spoil can have high strength values which are directly related to reduced root growth (Barley 1963, Taylor and Gardner 1963, Thacker and Johnson 1988).

Measurements to identify subsoil compaction are not routinely taken because of problems of collecting and interpreting strength data. Strength can be measured inexpensively and rapidly by a newly developed cone penetrometer (James 1988), but readings are highly dependent on soil moisture (Greacen 1960, Singh and Ghildyal 1977). If the relationship between moisture and penetration resistance was defined, it would allow strength readings made at one moisture tension to be used to estimate strengths at other moisture tensions. The need for remedial action could be assessed by comparing measured and estimated strengths in the plant-available moisture range to known values at which root growth is limited.

Research has shown that penetration resistance values are dependent on moisture tension, soil type and bulk density (Taylor and Gardner 1963, Ayers and Perumpral 1982), which makes necessary a calibration curve for each soil or spoil. However, changes in strength, normalized to account for the differences due to water holding capacity, may be independent of soil type and density. If this were the case there would be no need for calibration curves for each soil or spoil. A single graph or equation showing the relative change of strength due to the change in moisture tension could be used for a wide range of soils and spoils.

The purpose of this paper is to define the relationship between strength and moisture tension in minespoils of different clay and salt contents to determine whether a single moisture-strength relationship is valid over a range of minespoil conditions.

Materials and Methods

Seventeen minespoils from the Luscar geological formation of the Rocky Mountain Foothills were air-dried and crushed to pass a 2 mm sieve. The methods used to determine chemical and physical data for these samples along with a comprehensive listing of results is described by Thacker (1987). The chemical and physical data presented in this paper are summarized from those results.

Three minespoils chosen to represent fine, medium and coarse textures were selected. Particle size analyses were done in triplicate.

Five kilogram subsamples of each minespoil were used for salinization and desalinization. The goal was to end up with high and low electrical conductivities in saturation extracts. The average chemical composition of saturation extract solutions from the saline spoils of the Luscar formation (Thacker 1987) was duplicated in the salinizing solution. On a milliequivalent basis cations in the extracts were: 95% sodium, 2% calcium, 2% magnesium and 1% potassium. Chloride was the dominant anion. A 500 millequivalent per litre stock solution was made with this composition.

To determine the amount of solution needed to salinize the minespoils, various amounts of the solution were added to 150 g samples of minespoil, the sample was moistened with distilled water, mixed, left overnight and a saturation paste extract made and analyzed the next day. When the correct volume of solution was determined for each minespoil, the salinization treatment was performed on the remaining spoil, with mixing accomplished by rotating the sample for 3 hr in a rotating-drum mixer. The spoil was then oven-dried, ground to pass a 2 mm sieve and thoroughly remixed.

To desalinize spoils five kilograms of each spoil were placed in 25 cm diameter pots with several layers of Whatman #40 filter paper covering the drainage holes. The spoils were leached slowly with 10 L of calcium chloride solution (50 g $CaCl_2$/L) and then flushed slowly with approximately 20 L of distilled water until the water draining from the pots had an electrical conductivity less than 0.1 dS/m. The spoils were then oven-dried, ground and mixed as for the salinized spoil.

Minimum and maximum bulk density values were measured for each minespoil. The minimum bulk density was defined as the bulk density obtained after pouring air-dry, loose spoil into a container and tapping lightly to allow settling. The maximum bulk density was obtained by compressing moist spoil into a 15.2 cm diameter, 3 cm deep, PVC ring by means of a three tonne hydraulic jack until no additional spoil could be forced into the volume. Small holes in the PVC ring allowed drainage during compaction. The bulk density used in the experiment was the average of the minimum and maximum bulk densities for each spoil (to the nearest 0.05 g/cm^3); compression was done in the PVC rings described above.

A pressure-plate apparatus is not effective for moisture equilibration when soil is held in rigid-walled containers because the soils often shrink slightly upon drying causing loss of contact between the soil and pressure-plate. To overcome this problem 18 gypsum blocks were individually calibrated in a bed of medium textured, Chernozemic soil in a pressure-plate at 1/3, 1, 3, 5, 10 and 15 bars moisture tension. One of the gypsum blocks was buried in the centre of each ring of compacted spoil just below the spoil surface and was used to monitor the increase in moisture tension of the spoil as it air-dried. By air-drying the spoils the salt content remained constant throughout the experiment.

Strength was measured as penetration resistance at 1/3, 1, 3, 5, 10 and 15 bars moisture tension by manually pushing a 30°, 0.5 in^2 penetrometer cone into the spoil until the base of the cone was flush with the spoil surface. The ring of compacted spoil rested on an electronic balance which was used to monitor the applied force. The force was converted from kilograms to megaPascals (MPa) of pressure based on the basal area of the penetrometer cone.

The experiment was designed to allow an analysis of variance using three replicates of 36 treatments (3 spoils x 2 salinity levels x 6 moisture levels = 36 treatments). Strength was the response variable.

Results and Discussion

Chemical and physical data for the samples are presented in Table 1. The three minespoils have distinctly different clay, silt and sand contents providing a considerable range of texture to evaluate the moisture-strength relationship. The medium textured minespoil has a much lower minimum bulk density (1.07 g/cm^3) than either the coarse (1.42 g/cm^3) or fine (1.41 g/cm^3) minespoils. This also results in a much lower average bulk density for the medium minespoil. The electrical conductivity of the non-saline minespoil is <2 dS/m; the saline minespoil has an electrical conductivity of >7 dS/cm. Minespoil pH is not affected by the addition or removal of soluble salts, but the medium texture spoil has a much lower pH than the other two.

An analysis of variance was done to identify factors and interactions that influence minespoil strength (Table 2). Minespoil type, moisture tension and electrical conductivity (salt content) all have a significant effect on strength.

The significant effect of minespoil type on strength must be related to differences in particle size distribution and related changes in bulk density. The possibility that the effect is due to changes in clay mineralogy is unlikely. For minespoils originating from the Rocky Mountains, a change in mineralogy is often associated with a corresponding change in saturation percent (Thacker 19B7). In this case the increase in saturation percent parallels the increase in clay content (Table 1); and therefore mineralogy can be ruled out as a major factor causing differences in minespoil strength. The fine textured minespoil has the highest mean strength (1.42 MPa), and the coarse minespoil has the lowest mean strength (0.57 MPa).

Table 1. Chemical and physical data for minespoils.

Property	Minespoil		
	coarse	medium	fine
Clay (%)	8	18	33
Silt (%)	13	21	43
Sand (%)	80	61	24
Texture	loamy sand	sandy loam	clay loam
Min. B.D.[a] (g/cm^3)	1.42	1.07	1.41
Max. B.D. (g/cm^3)	1.70	1.65	2.00
Average B.D. (g/cm^3)	1.55	1.35	1.70
Non-saline E.C. (dS/m)	0.7	1.6	1.1
Saline E.C. (dS/m)	11.1	7.1	8.2
Non-saline pH	7.9	4.9	8.0
Saline pH	8.0	5.0	8.4
Saturation (%)	31	38	42

Table 2. Analysis of variance for minespoil strength.

Source of variation	df	Sum squares	F
Total	107	2715	32.1*
Error	72	164	
<u>Treatments</u>			
Minespoil	2	1517	333.9*
Moisture	5	646	56.9*
Salinity	1	115	50.4*
<u>Interactions</u>			
Minespoil/Salinity	2	91	20.1*
Minespoil/Moisture	10	124	5.4*
Salinity/Moisture	5	40	3.5*

[a] Treatments designated with an asterisk (*) are significant at a 95% confidence level. Unmarked figures are not significant at 95%.

There is a non-linear relationship between clay content and minespoil strength (data not shown).

The greater penetration resistance associated with increased clay content can be attributed to an increase in the number of small soil pores. Strength is determined by frictional forces, cementing agents and the strength and number of moisture bonds between particles (Aitchison 1961, cited by Mirreh and Ketcheson 1972). As moisture tension increases large pores are drained, and smaller pores control water retention. The water in the small pores has much greater curvature radii which markedly increases interparticle cohesion (Gardner 1961, cited by Mirreh and Ketcheson 1972). The greater the number of small pores, the greater is the cohesion (strength) as the soil or spoil dries.

The two salinity levels result in significantly different penetration resistance; values of the saline spoils (>7 dS/m) are 1.25 times those of the non-saline minespoils (<2 dS/m). However, the effect on strength amounts to only one sixth that caused by changes in clay content or moisture (data not shown).

The significant interaction between minespoil and electrical conductivity indicates that salinity has a different effect on penetration resistance in different spoils. Strength values at high salinity (>7 dS/m) were 2.3 times those at low salinity (<2 dS/m) for the coarse textured spoil (0.80 vs. 0.35 MPa); 1.2 times for the medium textured spoil (0.75 vs. 0.63 MPa); and only 1.03 times for the fine textured spoil (1.44 vs. 1.40 MPa). In the coarse minespoil less water is present at all moisture tensions than in the spoils with finer textures, so the coarse spoil has the greatest content of precipitated salts and the most pronounced effect of salt cementation.

There is also a significant interaction of moisture and salinity on strengths indicating that the effect of salinity on strength is dependent on moisture. Apparently, the salt-cementation effect only becomes substantial when salts are precipitated in relatively dry soils. In moist soils salts are dissolved, and cementation is less obvious.

Moisture tension, as expected from a review of the soil compaction literature (Graecen 1960, Taylor and Gardner 1963 Ayers and Persumpral 1982), has a significant influence on penetration resistance (Table 2). Average minespoil strength at 15 bars moisture tension is 2.6 times that at 1/3 bar tension. This is similar to the increase associated with an increase in clay content from 8% to 33%, where strength increased 2.5 times.

The significant interaction between minespoil type and moisture (Table 2) indicates that the effect of moisture on penetration resistance is different in different minespoils. This is illustrated in Figure 1 where the moisture-strength curves differ between minepoils. Compared to strength at field capacity, values at wilting point are 2.4 times as great for the low-clay spoil, 3.3 times as great for the medium-clay spoil and 2.5 times as great for the high-clay spoil.

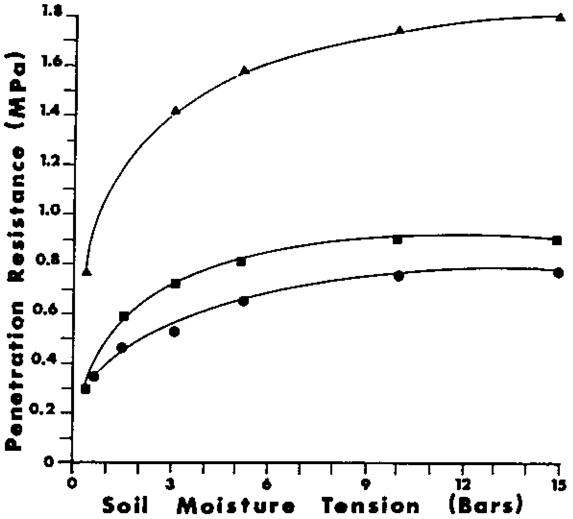

Figure 1: Penetration resistance vs. moisture tension in fine(▲), medium(■), and coarse textured (●) minespoils.

One of the objectives of this study was to develop a relationship between minespoil strength and moisture tension such that one measurement of both could be used to estimate the changes minespoil strength would undergo with wetting or drying. Figure 1 makes it obvious that there is a well defined dependence of strength on moisture tension. But the large differences in absolute strength at the same moisture tension between minespoil types shows that texture must be taken into account.

By normalizing the minespoil strength values (dividing the strength at each moisture tension by the strength at 15 bars moisture tension), a precise prediction of minespoil strength can be achieved (Figure 2). After normalization the influence of minespoil type is removed; strength is shown to depend only on moisture tension.

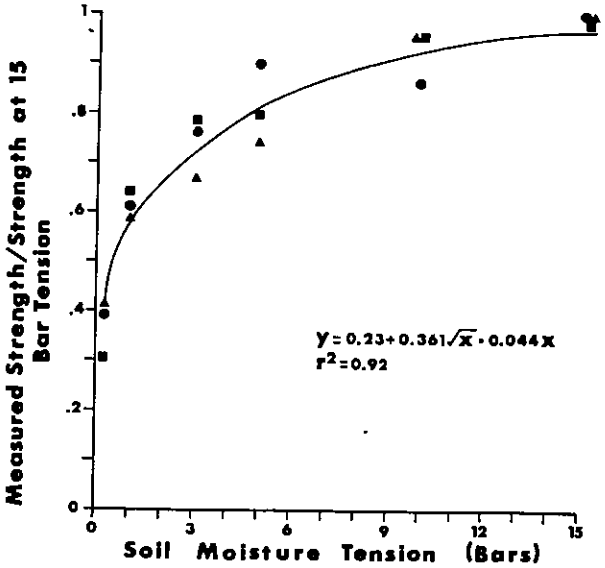

Figure 2: Normalized soil strength vs. moisture tension in fine(▲), medium(■), and coarse textured (●) minespoils.

Using this figure or the regression equation, one can predict an unmeasured minespoil strength at any moisture tension from one measured strength and one measured moisture tension:

$$Y_t = A_b \cdot \frac{Z_t}{X_b} \qquad (1)$$

where: Y_t = predicted strength at desired moisture tension

A_b = actual strength at measured moisture tension

Z_t = Normalized strength at desired moisture tension (from Fig. 2)

X_b = Normalized strength at measured moisture tension (from Fig. 2)

For example, if the measured moisture tension is 3 bars and the measured minespoil strength 2.0 MPa, then minespoil strength at 1/3 bar and 15 bars moisture tension would be:

$$Y = 2.0 \cdot \frac{0.4}{0.72} = 1.1 \text{ MPa at } 1/3 \text{ bar}$$

$$Y = 2.0 \cdot \frac{1.0}{0.72} = 2.8 \text{ MPa at } 15 \text{ bars}$$

Since the minespoils used in this experiment all came from one area of Alberta, it is important to evaluate the validity of this predictive method on spoils with a wider range of properties.

Previous studies in soils (Taylor and Gardner 1963) and spoils (Thacker and Johnson 1987) have shown that 2.5 MPa (25 bars) strength can be considered a limit to unimpeded root growth. Above this value root growth decreases rapidly. Therefore, the strength estimates generated from equation 1 can be used to evaluate the probability of minespoil compaction affecting root performance across the entire range of moisture contents.

Conclusions

Texture, moisture and salinity all exert significant effects on minespoil strength as measured by penetration resistance. Strength values at 33% clay content were 2.5 times those at 8% clay; strength at 15 bars moisture tension was 2.6 times that at 1/3 bar tension; and strength at high salinity (>7 dS/m) was 1.25 times that at low salinity (<2 dS/m).

There is a precise (r^2 = 0.92) dependence of normalized strength on moisture tension regardless of minespoil type or salinity level. (Normalized means that all measured strength values were divided by the strength value at 15 bars moisture tension). Therefore, the strength of a minespoil at any moisture tension can be predicted from only one, strength-moisture tension measurement. This allows for changes in penetration resistence (strength) due to fluctuations in moisture content to be taken into account when evaluating the effect of compaction on plant performance.

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