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ESTIMATING WATER RETENTION OF SOME NATAL SUGAR BELT SOILS IN RELATION TO CLAY CONTENT

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Abstract

The expansion of sugarcane land under irrigation has created a greater need to make a fast assessment of field capacity (FC), permanent wilting point (PWP) and plant available moisture capacity (AMC) of soils. Currently the most rapid method is a laboratory determination performed on undisturbed core samples using moisture retention equipment, which could take between two and four weeks, depending on the soil texture. Mathematical models to predict these parameters would be useful. Existing models have not been evaluated for use in the sugar industry. Data from 65 orthic topsoil and subsoil layers were used to determine the non linear relationship between clay content and the water holding properties (FC and PWP) used to calculate AMC. The Michaelis Menten equation was found to be the most suitable for describing the relationships between clay content and the dependent variables (FC and PWP), giving r^2 values of not less than 0,83 and 0,91 respectively. The values increased to 0,91 and 0,93 where the data for the firm gley layer of the Longlands and Westleigh soil forms were omitted from the regression. It was also determined that the optimum AMC occurs in soils containing between 20 and 40% clay or between 30 and 50% clay plus silt.

Introduction

The expansion of sugarcane land under irrigation in South Africa has created a need to determine the plant available water capacity (PAWC) of soils quickly. The equivalent of the term PAWC used in the South African sugar industry is available moisture capacity (AMC). AMC is calculated from the difference between field capacity (FC) and permanent wilting point (PWP). The most rapid method of determining these is in the laboratory, using a ceramic plate and pressure membrane extractor on undisturbed core samples, at pressures of 10 and 1500 kPa respectively (Richards, 1941). Although this method is widely used, it has the disadvantage of taking between two and four weeks to get a result, depending on the soil texture. Thus, if the AMC for a soil is not known, sound irrigation advice cannot be given quickly. However, AMC can be estimated using models that predict FC and PWP from one or more of the values of the soil's clay, silt, bulk density and organic matter content. The existing models are either linear or are based on multiple regression equations that produce curves for FC and PWP, where the distance between these two curves increases with increasing clay content (Maud, 1962; Mottram *et al.*, 1981; Beukes, 1985; Schulze *et al.*, 1985; Boedt and Laker, 1986; Hutson, 1986). This means that AMC increases with increasing clay content. However, data reported by Richardson (1947), Olson (1970), Johnston (1973), Hall *et al.* (1977) and van Rensburg (1988) suggest that the relationship between FC & PWP and texture is not linear. van Rensburg (1988) used a power function to describe the relationship between FC and clay plus silt content.

The purpose of this paper is to provide agriculturalists in the South African sugar industry with a guide for estimating a soil's field capacity, permanent wilting point and available moisture content from its clay content, with a view to improving irrigation scheduling and drying off procedures.

Methods and Procedures

The techniques used to take undisturbed soil samples and to determine particle size distribution and soil water retention properties are described by Johnston (1973). Bulk density was calculated by dividing the mass (g) of oven dried soil (105°C for 24 hours) by the volume (cm3) of the undisturbed soil core. The units for FC and PWP (volumetric %) and AMC (mm/m) were selected for easy interpretation and to conform with the units most widely used in the sugar industry.

The investigation was divided into two phases: (1) derivation of equations to describe the relationship between clay content and FC & PWP, and (2) validation of these equations using data from independent sources.

Calibration

As the purpose of this project was to provide equations for the South African sugar industry, only data originating from within the industry were considered. Soils with organic, humic, vertic and melanic topsoils (MacVicar *et al.*, 1977) were not used, as multiple factors are needed to reduce variability in FC and PWP. About 85% of the soils found in the sugar industry can be described as having an orthic topsoil (Meyer, 1984). Data used to develop the equations were obtained from the SASEX soil physics laboratory, including that published by Johnston (1973).

Validation

The equations developed were validated using moisture retention and textural analysis from Hill (1965), Maud and von der Meden (1966) and Olson (1970). This data source was diverse, originating from Natal, eastern Transvaal and eastern South Dakota (USA). Only data from the first 12 soil profiles from Olson's study were used, and data from soils containing either organic, humic, vertic or melanic topsoils (MacVicar *et al.*, 1977) were excluded from all three sources. FC and PWP were estimated from the clay content of each data source to calculate the estimated AMC (see equation 1). A linear regression was performed to quantify the relationship between measured and estimated values for FC, PWP and AMC. The slope and r^2 values were used as validation criteria.

The technique of Willmott (1982) was used to obtain additional statistical information. A summary of the properties of the soils used for this study is presented in Table 1. The soils used by Johnston (1973) were reclassified according to the binomial system of classification for South Africa (MacVicar *et al.*, 1977).

Results

Calibration

The literature is not clear on the matric potential limits that should be used to determine the AMC of a soil (Gard-

Table 1

Summary of physical properties for soils with an orthic topsoil horizon

Soil form	Symbol	No. of samples	Clay range %	Silt range %	BD range g/cm^3	FC range %	PWP range %	AMC range mm/m
Hutton	H	14	7-31	2-12	1,34-1,69	12,6-32,0	3,0-18,6	85-160
Shortland	S	11	39-75	10-19	1,19-1,33	32,1-45,2	19,8-35,0	77-150
Estcourt	E	4	6-45	4-11	1,51-1,74	16,9-35,5	5,8-24,8	103-136
Glenrosa	G	7	17-45	5-10	1,39-1,74	18,1-36,4	8,6-22,9	95-153
Fernwood	F	4	5-7	3-4	1,49-1,66	11,9-15,9	1,4-3,3	88-118
Cartref	C	4	7-9	3-5	1,44-1,60	10,0-15,3	1,6-4,3	74-110
Longlands	L	4	18-62	4-14	1,60-1,82	16,4-42,2	8,0-32,0	42-201
Kroonstad	K	2	20-34	8-11	1,68-1,68	23,9-31,9	11,1-24,0	79-128
Swartland	T	2	38-60	11-14	1,35-1,54	31,3-43,7	18,6-32,7	111-126
Westleigh	W	12	23-58	8-10	1,23-1,70	26,7-43,2	-	-

BD = Bulk density
FC = Field capacity
PWP = Permanent wilting point
AMC = Available moisture content

ner, 1971; Mottram, 1981), but the use of -10 and -1500 kPa in the laboratory to determine FC and PWP respectively is well established in the sugar industry (Maud, 1962; Hill, 1965). The good relationship obtained between FC determined *in situ* and the -10 kPa measurements made in the laboratory is shown in Figure 1. We can therefore accept that the use of 10 and 1500 kPa pressure limits to determine FC and PWP respectively is justified for sugarcane.

Although better agreement between texture and matric potentials is usually obtained where clay plus silt rather than clay content alone are used, the latter was selected for this study because it is relatively easy to measure or estimate and is also a well known physical property of soil. Maud (1962) has shown that highly significant correlations exist between clay content and soil water retention properties. This was also confirmed in this study by the highly significant relationship obtained between the laboratory determined FC and clay content (Figure 2) and PWP and clay content (Figure 3) using the data shown in Table 1. Regression analysis revealed that the linear, power, logarithmic and Michaelis Menten functions fitted the data satisfactorily (Ta-

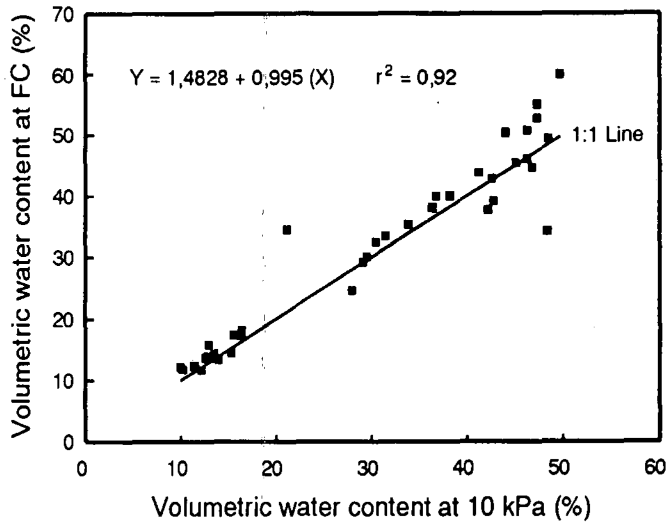

FIGURE 1 Relationship between field water capacity (FC) measured *in situ* and in the laboratory using a pressure of 10 kPa on a range of soils.

Table 2

Summary of the data used to select the equation used for estimating FC and PWP

Regression type	Equation	Field capacity (FC)			Permanent wilting point (PWP)		
		r^2	D-index$^+$	RMSE^{++}	r^2	D-index$^+$	RMSE^{++}
Linear	Y = A + BX	0,81**	0,95	4,31	0,90**	0,97	3,26
Power	Y = AX^B	0,89**	0,97	3,32	0,92**	0,98	3,00
Logarithmic	Y = A + BLn(X)	0,89**	0,97	3,12	0,90**	0,97	3,15
Michaelis Menten	Y = AX/(B + X)	0,91**	0,98	2,99	0,93**	0,98	2,77

$^+$ Index of agreement (Willmott, 1982) $^{++}$ Root mean square error (Willmott, 1982)
** Significant at 0,01% level

ble 2). The parameters used to evaluate the performance of the equations were r^2, D-index (Willmott, 1982) and root mean square error (RMSE). All four equations provided satisfactory results but it was the non-linear equations that gave the closest fit to the data. The Michaelis Menten equation was selected as providing the best fit. Table 3 summarises the regression analysis for the relationships between FC & PWP and clay content using the Michaelis Menten equation.

Figure 4 shows the relationship obtained between AMC and clay content. This appears to be non-linear, with the AMC reaching an optimum value at a clay content of between 20 and 40%. This is probably because the relative proportion between micro and meso pores responsible for retaining soil water is optimum between these limits. Substitution of clay for clay plus silt did not improve the regression with AMC meaningfully, since $r2$ increased from 0,41 to 0,42. The curve describing AMC in Figure 4 was calculated from the following equation:

$$\mathrm{AMC}_e = (\mathrm{FC}_e - \mathrm{PWP}_e)\ 10 \qquad \ldots\ldots(1)$$

where

AMC_e = estimated available moisture capacity (mm/m)

FC_e = estimated field capacity (volumetric %)

PWP_e = estimated permanent wilting point (volumetric %)

The relationship between estimated and measured AMC values was initially poor (r^2 = 0,11), but improved (r^2 = 0,33, D = 0,69, RMSE = 19,1, slope = 0,60) after sub-surface layers classified as soft plinthic, lithocutanic and firm gley (MacVicar *et al.*, 1977) were eliminated.

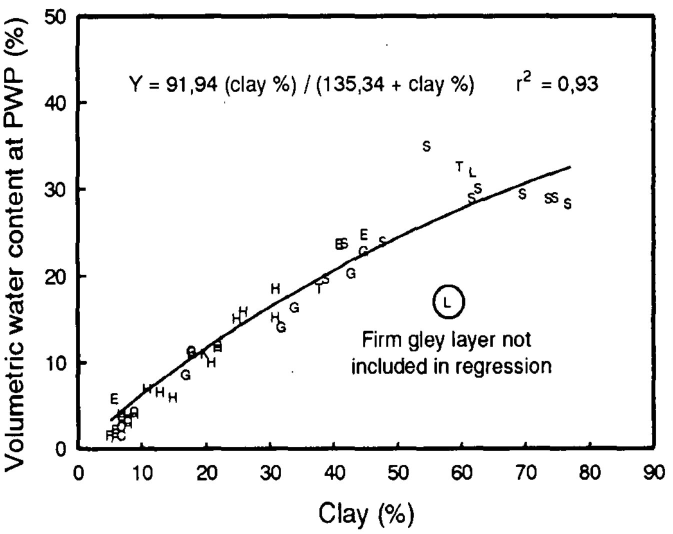

FIGURE 3 Relationship between laboratory measured permanent wilting point (PWP) and clay content for soils with an orthic topsoil. The symbols designate the various soil forms used (legend in Table 1). The firm gley layer of the Longlands form soil is encircled.

Table 3

Summary of the coefficients and statistical data to describe the fit of the Michaelis Menten equation to the FC and PWP data in relationship with clay content

Soil property	A coefficient	B coefficient	r^2	D-index	RMSE
FC (including the firm gley layer of Longlands and Westleigh)	50,19	21,04	0,83**	0,95	3,99
FC (excluding the firm gley layer of Longlands and Westleigh)	54,70	24,53	0,91**	0,98	2,99
PWP (including the firm gley layer of Longlands and Westleigh)	85,73	125,71	0,91**	0,97	3,09
PWP (excluding the firm gley layer of Longlands and Westleigh)	91,94	135,34	0,93**	0,98	2,77

** Significant at the 0,01% level

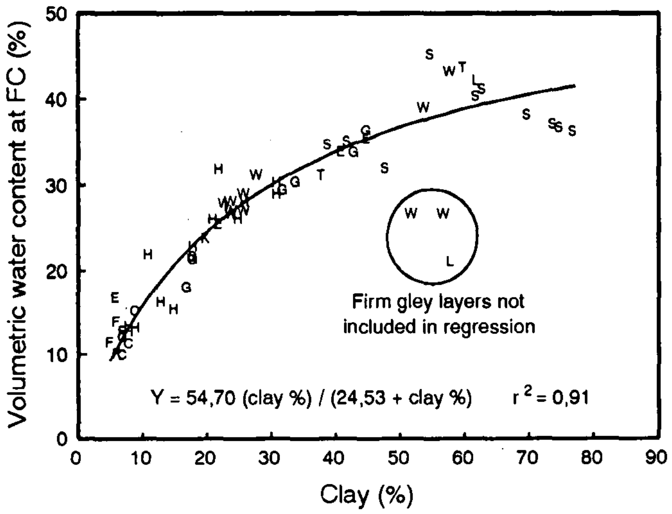

FIGURE 2 Relationship between laboratory measured field water capacity (FC) and clay content for soils with an orthic topsoil. The symbols designate the various soil forms used (legend in Table 1). The firm gley layers of the Longlands and Westleigh form soils are circled.

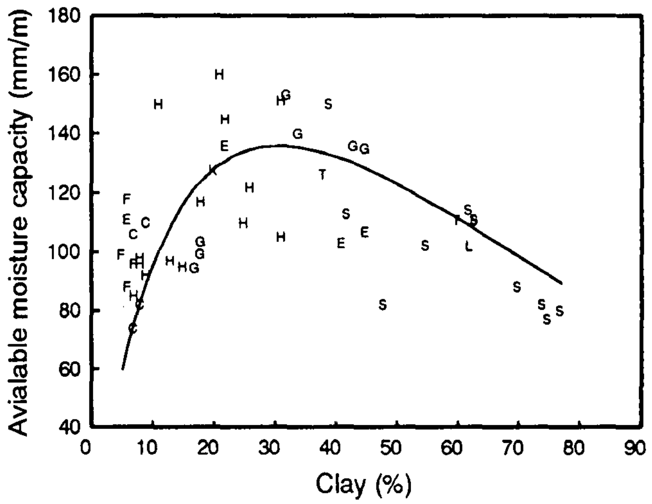

FIGURE 4 Relationship between available moisture capacity (AMC) and clay content. AMC designated by the symbols was calculated from the difference between laboratory measured FC and PWP. AMC represented by the line was calculated from the difference between estimated FC and PWP (legend in Table 1).

Table 4

Results from the three data sources used in the validation with r^2 and slope as criteria

Source	No. of points	Field capacity		Permanent wilting point		Available moisture capacity	
		r^2	Slope	r^2	Slope	r^2	Slope
Hill (1965)	8	0,93**	1,33	0,97**	1,34	0,75*	0,98
Maud and von der Meden (1966)	24	0,96**	1,10	0,95**	1,15	0,01	−0,05
Olson (1970)	73	0,53**	0,57	0,63**	0,61	0,24*	0,16

* Significant at 0,5% level ** Significant at 0,01% level

Evaluation

Three independent sources of data (Hill, 1965; Maud and von der Meden, 1966; Olson, 1970) were used to validate the equations quoted in Figures 2 and 3. A linear regression was used to test the fit of estimated to measured values for FC, PWP and AMC (Table 4). The aim was to obtain slope and r^2 values of 1.00. The estimated FC, PWP and AMC fitted the data of Hill (1965) satisfactorily, but FC and PWP values were slightly overpredicted. The FC and PWP data of Maud and von der Meden (1966) were well estimated but measured and predicted AMC values showed little agreement. The most likely reason for this is that the relationships between measured FC and PWP against clay content were linear and not curvilinear. These two relationships were also parallel with each other. This implied that there was no change of AMC with increasing clay content. The FC and PWP data of Olson (1970) were significantly predicted from clay content but generally underestimated.

Discussion and Conclusions

Field capacity (FC) and permanent wilting point (PWP) can be estimated from clay content alone with a high degree of certainty. Available moisture capacity (AMC) calculated from the difference between measured FC and PWP varied considerably in relation to clay content and the situation did not improve when clay plus silt was used on the abscissa. Other factors will have to be included to reduce the large variability in AMC. Elimination of the soft plinthic, lithocutanic and firm gley subsoils from the data has reduced this variability. Hall *et al.* (1977) reported that bulk density could explain 50% of the variation of AMC in the topsoil, and fine silt and bulk density could account for 45% of the variation in the subsoil. Calculation of AMC from estimated FC and PWP values should give the user a reasonable idea of the true value. However, estimated AMC values should be used only where moisture retention data are not available.

Table 5

Field guide to estimate field capacity (FC), permanent wilting point (PWP) and available moisture capacity (AMC) from clay content of soils with orthic A horizons in Natal

Clay (%)	≤ 5	6–15	16–25	26–35	36–45	46–55	≥ 56
FC (%)	9,3	13,5	25,1	29,4	34,3	36,8	38,8
PWP (%)	3,3	5,2	12,2	15,9	21,2	24,6	27,6
AMC mm/m	≤ 60	50–110	100–160	110–170	100–160	90–150	80–140
ERD* (mm)	Total available moisture (MM)						
400	≤ 24	20–44	40–64	44–68	40–64	36–60	32–56
600	≤ 36	30–66	60–96	66–102	60–96	54–90	48–84
800	≤ 48	40–88	80–128	88–136	80–128	72–120	64–112
1000	≤ 60	50–110	100–160	110–170	100–160	90–150	80–140
1200	≤ 72	60–132	120–192	132–204	120–192	108–180	96–168
1400	≤ 84	70–154	140–224	154–238	140–224	126–210	112–196
1600	≤ 96	80–176	160–256	176–272	160–256	144–240	128–224
1800	≤ 108	90–198	180–288	198–306	180–288	162–270	144–252
2000	≤ 120	100–220	200–320	220–340	200–320	180–300	160–280

Equation 1 was used to calculate available moisture content (AMC). AMC and total available moisture (TAM) must be used with caution as the values obtained with undisturbed samples has revealed a large variability (see Figure 4)

* Effective rooting depth

It is nevertheless meaningful to note that the relationship between clay content and AMC does not increase linearly, and that an optimum value for AMC is reached in the clay content range of 20 to 40% or a clay plus silt content of 30 to 50%. The independent data of Olson (1970) confirmed that the relationships between FC, PWP and AMC on the one hand and clay content on the other, are non-linear.

A field guide was developed for soils with orthic topsoils to estimate FC and PWP from clay content, enabling AMC to be calculated from the difference between FC and PWP (Table 5). A constant AMC has been used for soils with a clay content higher than 56% because of the relatively high variability in predicting FC and PWP in the high clay range (Figures 2 and 3). The results of this investigation indicate that previously AMC was slightly overestimated in the sandy clay loam to clay range. A similar exercise for soils with vertic and melanic horizons is planned. The merits of these relationships for possible use in the CANEGRO crop growth model is also under consideration.

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