Determining soil plasticity characteristics from physico-chemical properties

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ABSTRACT
Numerous pedological soil classification systems have been developed worldwide. These include an internationally accepted system and various national systems, some of which have been incorporated into databases which include maps. Such information is used primarily for agricultural purposes. Various physical and chemical soil properties are used for classifying soils according to these pedological systems. This paper proposes an approach, based on an extensive research project, which may be used to statistically determine the plasticity characteristics of soils from the physical and chemical properties that are used by pedological classification systems, such as the South African System. These plasticity characteristics may be used to establish the engineering soil classification groups which may, in turn, be used as a means of rapidly determining the general suitability of areas for proposed developments, particularly during the preliminary stages of transportation route locations and township developments, with a resultant saving of time and money.

RÉSUMÉ
Un certain nombre de systèmes de classification pedologique de sols ont été développés depart le monde entier. Ceux-ci incluent celui internationalement accepté ainsi que divers autres nationaux dont certains ont été incorporés dans les bases de données incluant des cartes. Selon ces systèmes pedologiques, différentes propriétés physiques et chimiques sont utilisées pour classifier les sols. Cet article propose une approche qui peut statistiquement être utilisée de façon significative pour déterminer les caractéristiques de plasticité de sols à partir des propriétés physiques et chimiques utilisées par les systèmes de classification pedologique, comme le Système Sud-Africain. Ces caractéristiques de plasticité peuvent être utilisées pour établir les groupes de classification de sol de construction mécanique qui peuvent à leur tour être utilisés comme un moyen de détermination rapide de la conformité générale de régions pour les développement proposés, avec une économie résultante en temps comme en argent.

1 INTRODUCTION

1.1 Pedology

Pedology is a branch of soil science which deals with the study of soils as natural phenomena including their formation, morphological, physical, chemical, mineralogical and biological constitution.

1.2 Pedological Classification Systems

A number of pedological soil classification systems have been established worldwide and used as a basis for mapping soils. Such systems include an internationally accepted system and many national systems. The International accepted system, which is endorsed by the International Union of Soil Sciences, is the World Reference Base for Soil Classification (WRB, 1998). This system replaced the Food and Agriculture Organisation (FAO) system, which was originally developed as a legend to the Soil Map of the World in 1974.

National systems include the Canadian System of Soil Classification (CSSC) (SCWG, 1998), the United States Department of Agriculture System (USDA, 2010), and the South African Binomial Classification System (Mac Vicar et al., 1977). These national systems are also utilised by private organisations.

1.3 Pedological Databases

Various international, regional and national databases of pedological data have been established. Such databases include the SOTER (Soil and Terrain) digital databases for many, mainly developing, countries of the world (Batjes, 2002). This collection, which places emphasis on soils and adopts the WRB (1998) classification classes, comprises more than 20000 articles, country reports, books and maps. The map collection comprises in excess of 6000 small scale (1:250 000 or smaller) maps. The physical and chemical properties included in the database are very detailed. This information, which is accessible through the internet, has also been regionalized. For example the SOTERSAF database (Batjes, 2004) pertains to eight Southern African (SADC) countries.

An example of a national database is the *land type* survey database which was established for the entire country by the South African government's Institute for Soil, Climate and Water (formerly the Soil and Irrigation Research Institute).

The soil data included in the *land type* survey include the pedological properties and pedological classification in accordance with the South African Binomial system (after MacVicar et al., 1977).

The data acquired in the course of the *land type* survey are published in the form of maps (at a scale of 1:250 000), known as *land type* maps, and accompanying documents which are known as *land type* memoirs. The *land type* maps show land types determined on the basis of terrain form, soil pattern and climate. These maps and their accompanying data can be purchased at an insignificant cost.

Pedological data are used extensively and successfully primarily for the optimization of agricultural land for crop production – so much so that pedology is often incorrectly regarded as part of agricultural science.

1.4 Objectives of this Paper

This paper is based on an extensive research project that was initiated on the premise that the physical and chemical properties of a soil, which are manifested in the pedological class of a soil, have a bearing on the engineering properties of a soil.

In this paper, relationships are established for determining the engineering plasticity characteristics (liquid limit, plasticity index and linear shrinkage) of soils deriving from a range of pedological classes of the South African Binomial System (after MacVicar et al., 1977) from their physical and chemical properties which are determined for pedological classification purposes. These physico-chemical properties include the clay content, the percentage of the different exchangeable base cations and the cation exchange capacities (CEC).

2 THE SOUTH AFRICAN BINOMIAL CLASSIFICATION SYSTEM

2.1 Structure

The Binomial Classification System uses morphology (the science of form and structure) and composition of soils as criteria for differentiation in soil classification. This system, which groups soils according to the similarity of the properties used in the identification, employs two categories, namely an upper or general level consisting of SOIL FORMS, and a lower, more specific one, comprising SOIL SERIES.

2.2 Soil Forms

The upper level consists of 41 soil forms, each defined by a unique vertical sequence of diagnostic horizons or materials, not more than four in number, occurring in the uppermost 1,2 m of the soil profile.

2.3 Soil Series

Each soil form is sub-divisible into a number of soil series, varying from two to 36. A total of 504 soil series constitute the lower category of the classification system. Soil series have in common the properties of the relevant form (that is, the prescribed horizon sequence) but are differentiated within the form according to a variety of criteria.

The criteria used for series differentiation within each soil form include the clay content, sand grade (where the clay content is less than 15 percent), pH, base status (which is a measure of the degree to which the soil has been leached), presence or absence of free calcium carbonate and colour.

2.4 Revisions

A revised version of the South African Binomial Classification System, referred to as the “Taxonomic System for South Africa”, was published by the Soil Classification Working Group (SCWG) in 1991. This system is a more specific extension of the South African Binomial Classification System. Many persons have found the newer system to be “unnecessarily complicated” and hence have not adopted it (www.itc.nl).

Nevertheless, in this paper consideration is only given to the South African Binomial Classification System which has been solely adopted for soil classification in the *land type* survey (which was incorporated into the SOTER database) and which is still being used in South Africa.

3 RESEARCH PROCEDURE

3.1 Research Area

The area studied is intersected by Longitude 25° 45' South Latitude 25° 45'. The area, which is located approximately 150 kilometres north of the City of Rustenburg in South Africa, is approximately 4200 square kilometres in extent. The area was selected for its diversity of soil types.

3.2 The Soils Investigated in this Project

A number of soil types occur in the area, differing from one another as a result of different parent materials and/or the different soil forming processes to which they had been subjected. The research was confined to the dominant soil series which adequately cover the range of soil types occurring in the area.

The soil forms and series of each soil type selected for the research are shown in Table 1.

3.3 Fieldwork

The soils at 63 randomly selected sites within the study area were classified according to the South African Binomial System (after Mac Vicar et al., 1977).

A total of 111 disturbed soil samples, taken from the A and B (where present) diagnostic horizons of these soil profiles, were tested to determine the physical and chemical properties which are used as criteria for pedological classification. In view of the fact that the physical and chemical properties of C horizons are not reflected in the pedological classifications of profiles which contain C horizons, C horizons were not sampled.

Table 1. Soil forms selected for research purposes.

Soil Form	Diagnostic Horizons			Soil Type	General Correlation		
	A -Horizon	B- Horizon	C-Horizon		WRB[1]	USDA[2]	Canadian
Hutton	Orthic	Red Apedal		Ferrallitic and Fersiallitic (not characterised by the dominance of smectitic clay minerals)	Ferralsols and Arenosols	Oxisols, Inceptisols, Aridosols, Entisols and Ultisols	Brunisolic
Shortlands	Orthic	Red Structured		Fersiallitic (characterised by the dominance of smectitic clay minerals)	Luvisols	Alfisols	Luvisolic
Valsrivier	Orthic	Pedocutanic	Unconsolidated Material	Red Series - Fersiallitic (characterised by the dominance of smectitic clay minerals) Non-red Series – Planosolic		Alfisols and Aridisols	
Swartland	Orthic	Pedocutanic	Saprolite				
Arcadia	Vertic			Margallitic	Vertisols	Vertisols	Vertisolic

[1] Correlations according to Fey (2010)

[2] Correlations according to MacVicar et al., (1977)

Details of the results, methods of analysis adopted, references to the relevant methods as well as brief discussions on the significance of each property determined are given in the work of Fanourakis (1999).

A total of 99 samples were analysed for the determination of their liquid limit, plasticity index and linear shrinkage, in accordance with TMH1 (1986).

The number of soil profiles and number of samples tested for the determination of their plasticity properties for the soils of each form are shown in Table 2.

Table 2. Number of samples tested for their engineering properties

Soil form	Number of profiles	Plasticity characteristics
Hutton	28	48
Shortlands	3	4
Valsrivier	11	23
Swartland	4	7
Arcadia	17	17

4 ANALYSIS

4.1 Investigation of possible relationships

The effect of quantitative chemical properties such as the different exchangeable base cations (Ca, Mg, Na, K), S-value, base saturation, exchangeable sodium percentage (ESP), exchangeable magnesium percentage, exchangeable potassium percentage, and exchangeable calcium percentage on the plasticity characteristics of the soils constituting each soil form were evaluated with reference to liquid limit, plasticity index and linear shrinkage.

The combined effect of each of the abovementioned chemical characteristics in conjunction with physical characteristics such as the clay content, silt content, and percentage finer than 0,075 mm on the plasticity characteristics of the respective samples were also evaluated.

In the evaluation of the above, the fact that the physico-chemical properties were determined using the fraction finer than 2,0 mm and the plasticity characteristics using the fraction finer than 0,425 mm was accounted for.

A list of the possible relationships between the plasticity characteristics and the various chemical and physico-chemical properties of the soils of each form investigated is given in the work of Fanourakis (1999).

4.2 Statistical Methods

None of the data was transformed and no multiple regression procedures were adopted.

The regression equations and correlation coefficients not significant at the five percent level were rejected.

The least squares method was used for curve fitting purposes.

Significance tests were carried out for each relationship established using tables of Student's t-distribution to determine the probability that the correlation coefficient could have arisen by chance in a sample of the size dealt with.

Fisher's Z-transformation technique was used to combine independent correlation coefficients, which were significant at the five percent probability level, to obtain an estimate of the average (pooled) correlation coefficient.

This procedure took into account each correlation coefficient and the corresponding number of sets of values on which it was based.

5 RESULTS AND DISCUSSION

5.1 The Effect of Exchangeable Magnesium

In the case of the soils of each form studied, the magnitude of the liquid limit (LL), plasticity index (PI) and linear shrinkage (LS) each correlated significantly, linearly and positively with the amount of magnesium present in the clay-size portion of the fraction of the samples finer than 0,425 mm. This quantity which, in the succeeding discussion, will be referred to as *"magnesium in the clay-size fraction"*, is defined by Equation 1 and expressed in milli-equivalents per 100 g of soil finer than 0,425 mm.

$$\text{Exch. Mg (me\%)} * P0{,}002mm/P0{,}425mm \qquad [1]$$

The quantity referred to in Equation 1 was defined specifically for the purpose of this discussion and should not be confused with either of the quantities termed "exchangeable magnesium" or "exchangeable magnesium percentage (EMgP)".

The *magnesium in the clay-size fraction* is calculated by multiplying the value of the exchangeable magnesium (expressed in milli-equivalents per 100 g of soil finer than 2 mm, me%) by the ratio of the percentage by mass of the fraction of the total sample finer than 0,002 mm (P0,002mm) to the percentage by mass of the fraction of the total sample finer than 0,425mm (P0,425mm).

The definition of *magnesium in the clay-size fraction* by Equation 1 is based on two premises, first, that the exchangeable magnesium occurs almost exclusively in the fraction finer than 0,425 mm and second that the exchangeable magnesium is distributed uniformly within this fraction. These premises were regarded as applicable to all the soils investigated in this project regardless of the degree of base saturation.

To test the validity of these premises, sets of relationships between exchangeable magnesium and plasticity characteristics were established based on each of the following two assumptions:

Firstly, that the magnesium cations are uniformly distributed within the soil fraction finer than 2 mm and, secondly, that the magnesium cations are uniformly distributed within the minus 0,075 mm fraction.

The relationships established were not all significant and it can, therefore, be concluded that the upper size limit of the soil fraction in which the exchangeable magnesium predominates must be of the order of 0,425 mm. However, it must be emphasized that this is not because the engineering plasticity analyses are performed on the fraction finer than 0,425 mm of the soil.

The exchangeable cations in a soil are adsorbed onto the negatively charged clay particles (Brady, 1974). In view of this fact, the relationships established between the plasticity characteristics and the *magnesium in the clay-size fraction* indicate that the soils researched must contain clay particles which are larger than 0,002 mm in size. Furthermore, these relationships indicate that only the exchangeable magnesium which is adsorbed onto the clay particles which are finer than 0,002 mm in size has an effect on the plasticity.

It is not unusual for soils to contain clay mineral particles which are larger than 0,002 mm in size. A study of the mineralogy of five weathering profiles developed from Archaean Granite, conducted by Buhmann (1990), revealed that particles of clay minerals such as biotite occurred in the silt and sand size fractions.

The relationships established between the plasticity characteristics and the *magnesium in the clay-size fraction* were re-established after grouping the soils of each soil form according to two different arbitrarily selected ranges of cation exchange capacity per 100 g clay. This grouping was not carried out in the case of the soils of the Shortlands form of which a sufficient number of soil samples to warrant grouping was not available. The cation exchange capacity range limits were selected such that, for the soils of each form, an approximately equal number of samples fell within each of the two ranges. The relationships obtained after grouping into two ranges of cation exchange capacity per 100 g of clay resulted in correlation coefficients of a higher order and corresponding levels of significance of decreased probability than before the grouping. In general, the greater the cation exchange capacity per 100 g clay, the greater the plasticity displayed by the soil for a given quantity of exchangeable magnesium cations in the clay fraction. This is especially true of soils of the Arcadia form which had a mean activity of 1,2 and in which montmorillonite clay particles, which have a high affinity for water, are known to occur. As shown in the work of Baver (1930), the affinity of soil for water and its capacity for swelling increase as the cation exchange capacity of the clay increases.

The correlations determined for the soils of each soil form are discussed in the succeeding paragraphs.

5.2 Discussion of Results

5.2.1 Soils of the Hutton Form

The mean activity of the soils of the Hutton Form was 0,47. Of the 48 soil samples of the Hutton form analysed, a total of 30 samples displayed plasticity. Examination of the grading and plasticity characteristics of these soils revealed that on the average soils with a clay content of less than 12 percent did not display plasticity. This absence of plasticity is thought to be as a result of a low content of 1:1 clays in the soils.

Sixteen of the samples displaying plasticity had a cation exchange capacity within the range 13 to 30 milli-equivalents per 100g of clay and 14 had a cation exchange capacity within the range of 33 to 62 milli-equivalents per 100 g clay.

The regression equations and statistics pertaining to these relationships are given in Table 3.

Table 3. Statistics pertaining to the correlation of plasticity characteristics with *magnesium in the clay-size fraction* for soils of the Hutton form

P*	CEC/ 100g Clay (me)	Regression Equation	r	P
LL	13-30	y = 20,338 + 0,077x	0,914	1E-06
	33-62	y = 19,711 + 9,159x	0,951	1E-06
PI	13-30	y = 10,527 + 4,309x	0,662	5,212E-03
	33-62	y = 6,917 + 5,351x	0,869	5,472E-05
LS	13-30	y = 2,862 + 3,599x	0,877	8,047E-06
	33-62	y = 2,436 + 3,573x	0,878	3,642E-05

P* = Plasticity characteristic correlated with Exch. Mg (me %) * P0,002 mm/P0,425 mm

A relative comparison of the points representing the A horizons with those representing the B horizons (on the scatter diagrams) indicated that most B horizons occurred in the lower cation exchange capacity range. No horizon specific trends were observed for any of the relationships.

The relationships established were all highly significant, being at the 0,52 percent level of probability. The correlation was positive - an increase in the *magnesium in the clay-size fraction* was associated with an increase in each of the three plasticity characteristics.

A statistical analysis of the correlation coefficients of the six relationships referred to above and the six pairs of values from which each relationship was determined, yielded a pooled correlation coefficient of 0,874. The mean of the probability that any of the six relationships could have arisen by chance was 0,090 percent.

5.2.2 Soils of the Arcadia Form

Of the 17 soil samples analysed, all of which displayed plasticity, nine samples had a cation exchange capacity within the range 53 to 61 milli-equivalents per 100 g of clay and eight had a cation exchange capacity within the range of 63 to 90 milli-equivalents per 100 g clay.

The regression equations and statistics pertaining to these relationships are given in Table 4.

A pooled correlation coefficient of 0,826 was obtained when taking into account the correlation coefficients of the six relationships and the six pairs of values. The mean of the probability that any of these relationships could have arisen by chance was 1,3 percent.

Table 4. Statistics pertaining to the correlation of plasticity characteristics with *magnesium in the clay-size fraction* for soils of the Arcadia form

P*	CEC/ 100g Clay (me)	Regression Equation	r	P
LL	53-61	y = 35,766 + 2,752x	0,767	1,587E-02
	63-90	y = 54,827 + 1,447x	0,948	3,379E-04
PI	53-61	y = 15,865 + 1,732x	0,740	2,263E-02
	63-90	y = 29,547 + 0,721x	0,794	1,862E-02
LS	53-61	y = 9,996 + 0,672x	0,791	1,113E-02
	63-90	y = 14,622 + 0,254x	0,839	9,214E-03

P* = Plasticity characteristic correlated with Exch. Mg (me %) * P0,002 mm/P0,425 mm

5.2.3 Soils of the Shortlands, Valsrivier and Swartland Forms

The relationships between liquid limit, plasticity index and linear shrinkage respectively and the *magnesium in the clay-size fraction* for the two ranges of cation exchange capacity per 100 g of clay, of the soils of these forms were analysed according to the six groups shown in Table 5, justified by the similarity of these soils.

The soils comprising each group were sub-divided into one of two arbitrarily selected ranges of cation exchange capacities per 100 g clay (except in the case of soils of the Shortlands form). Hence a total of 36 relationships were established.

The pooled correlation coefficients as well as the minimum, maximum and mean levels of significance for the six groups are shown in Table 5.

From the pooled correlation coefficients and mean probabilities shown in Table 5, it is evident that the differences between the pooled correlation coefficients and mean probabilities of the six soil groups are so small as to be negligible. In the case of soils of the Shortlands, Valsrivier and Swartland forms, which had a mean activity of 0,52, qualitative physical characteristics such as uniform colour, predominant colour and the presence of continuous clay skins on ped faces (cutans) did not bear any relationship to the soil's plasticity characteristics.

Therefore, the engineering plasticity characteristics of soils of the Shortlands, Valsrivier and Swartland forms, can be determined from the *magnesium in the clay-size fraction* of each soil sample, together with the cation exchange capacity per 100 g clay of that sample by using the relationships established when the test results for the soils of all three of the above forms were grouped. This is true only for soils with physico-chemical properties within the ranges of the soils investigated, including a low exchangeable sodium percentage (ESP). The regression equations and statistics pertaining to these relationships are given in Table 6.

Table 5. Pooled correlation coefficients and corresponding levels of significance

Series	Pooled r	Levels of Significance (%)		
		Min.	Max	Mean
Shortlands	0,965	3.3	5,3	4,5
Valsrivier and Swartland	0,889	<1E-04	0,006	0,002
Red Valsrivier and red Swartland	0,828	0,003	0,025	0,978
Non-red Valsrivier and non-red Swartland	0,979	0,003	2,4	1,277
Shortlands, red Valsrivier and red Swartland	0,826	0,003	0,383	0,135
Shortlands, Valsrivier and Swartland (Luvisolic)[3]	0,885	<1E-04	0,001	0,001

[3] General equivalent according to the Canadian Classification System (SCWG, 1998).

Table 6. Statistics pertaining to the correlation of plasticity characteristics with *Magnesium in the clay-size fraction* for soils of the Shortlands, Valsrivier and Swartland forms

P*	CEC/ 100g Clay (me)	Regression Equation	r	P
LL	25-49	y = 27,639 + 3,961x	0,918	<1E-06
	52-94	y = 26,362 + 4,605x	0,913	<1E-06
PI	25-49	y = 10,830 + 2,340x	0,862	8,624E-06
	52-94	y = 10,930 + 2,172x	0,862	8,624E-06
LS	25-49	y = 5,827 + 1,335x	0,875	4,222E-06
	52-94	y = 5,351 + 1,298x	0,864	7,789E-06

P* = Plasticity characteristic correlated with Exch. Mg (me %) * P0,002 mm/P0,425 mm

Of the 34 samples included in these relationships, 17 had a cation exchange capacity within the range of 25 to 49 milli-equivalents per 100g of clay and the other half had a cation exchange capacity within the range of 52 to 94 milli-equivalents per 100 g clay.

A relative comparison of the points representing the A horizons with those representing the B horizons (on the scatter diagrams) indicated that most B horizons occurred in the lower cation exchange capacity range. No horizon specific trends were observed for any of the relationships.

6 CONCLUSIONS

This research showed that the liquid limit, plasticity index and linear shrinkage of soils can be statistically significantly estimated from the physico-chemical data of soils, for a range of pedological groups.

All the relationships established for estimating the plasticity characteristics of the soils of the Hutton form (Brumisolic Order according to the Canadian Soil Classification System - CSCS) and Shortlands, Valsrivier and Swartland forms (Luvisolic Order according to the CSCS) soils were highly significant (P < 1 %). The relationships pertaining to the Arcadia form (Vertic Order according to the CSCS) were all significant (P < 5 %).

With the aid of quantitative pedological data, the plasticity characteristics of soils, which are in turn used to classify a soil for various intended engineering usages, can be estimated. Hence this information may assist in the identification of and avoidance of large areas of unfavourable soils in projects such as township development and transportation route alignment, resulting in a saving of time and money. Conversely, areas or routes covered by favourable soils can be located, hence providing the framework for more detailed testing required for the final engineering design.

The findings of this research are valid for soils of the pedological classifications investigated and their particular physical, chemical and mineralogical properties only, since the research project was intended to serve as a pilot study. The indications are that additional similar studies covering soils of the pedological classifications researched but with different chemical properties as well soils with other pedological classifications with varying chemical properties could undoubtedly lead to the extension of this work and improvement of its universality.

Finally, it is hoped that this research has succeeded in emphasizing the interrelationships between pedogenesis and the engineering behaviour of soils and in suggesting an approach for the interpretation of pedological data for engineering purposes.

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