Chapter 9 : Utilizing mineralogical and chemical information in PTFs.

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Soil structure is known to reflect mineralogical composition of clay fraction and soil chemical composition. Because soil hydraulic properties are likely to depend on soil structure, chemical and mineralogical composition have long been expected to be important predictors of soil ability to retain and transmit water (Rawls et al., 1991). Nevertheless, the quantitative, pedotransfer-type information about the effect of clay mineralogy and chemistry of soil solution on soil hydraulic properties remains relatively scarce. This chapter summarizes available data and ideas that may show future research directions in this field.

Mineralogical composition of the clay fraction. When the pressure head h decreases, the proportion of water increases that is retained within the porosity controlled by the arrangement of the clay-sized particles. As a result, the percentage of water retention variations accounted for by the clay content increases when h decreases. This proportion varies according not only to the clay content, but also according to soil clay characteristics such as the predominant clay mineral, the size of elementary particles and the nature of cations at the surfaces of the particles (Tessier and Pédro, 1987; Quirk, 1994).

Tessier (1984) and Tessier et al. (1992) studied water retention properties of pure clays and demonstrated that the clay fabric at a given water potential was closely related to the characteristics of the elementary clay particles. They also showed that the differences between the water retention of kaolinite, illite and montmorillonite decreased with h. Ali and Biswas (1968) demonstrated that the difference between water retention of montmorillonite and illite is not large (about 9%) at −1500 kPa but amounts to 240 % at −10 kPa suction. Bruand and Zimmer (1992) studied water retention properties of clayey soils and discussed the role of both the clay mineralogy and stress history.

Clay mineralogy was recognized by Williams et al. (1983) as a source of grouping criteria before developing PTFs for Australian soils. The mineralogy of the clay-size fraction was accurately described by X-ray diffraction thus enabling quantification of illite, montmorillonite, kaolinite, interstratified material, quartz, iron oxides, vermiculite and halloysite content. Results showed that the presence of montmorillonite, often in quite small amounts, could serve as a discriminating property. On the opposite, Puckett et al. (1985) studied the water retention properties and K_s of soils in the Lower Coastal Plain of Alabama and showed no significant correlation between these hydraulic properties and mineralogical properties of the clay fraction. As emphasized by Puckett et al. (1985), this lack of correlation might be related to the small variation of mineralogical composition of the clay-size fraction of these soils that consisted of hydroxy interlayered vermiculite, kaolinite, and gibbsite. Danalatos et al. (1994) discussed the interest of using mineralogy as grouping criteria and did not find any significant difference with no grouping the 105 horizons from Greek soils.

Gaiser et al. (2000) investigated the effect of contrasting clay mineral composition on water retention and PTFs characteristics for soils from semiarid tropical regions. They analyzed water retention at −33 kPa and −1500 kPa of 663 horizons from NE Brazil and SE Niger. They showed that PTFs for soils containing predominantly low activity clay (CEC<24 cmol/kg clay, LAC soils) differed considerably from those established for non LAC soils. Hodnett and Tomasella (2002) used a set of 771 horizons from the IGBP-DIS soils database from ISRIC in Wageningen and compared the van Genuchten soil retention parameters for temperate and tropical soils. They showed differences between montmorillonitic and kaolinitic soils and suggest to include predictors related to mineralogy in PTFs.

Bruand and Tessier (2000) studieded the water retention properties of clayey subsoils horizons according to the variation of clay characteristics. The horizons developed on a large range of age and facies of calcareous or calcium saturated clayey sediments. Results showed

that the water retention properties of the clay varies greatly from one soil to another with respect to the clay fabric that depends on the *CEC*, the size of elementary particles and hydric stress history of the clay.

Content of free iron oxides was a dominating property that affect soil water retention in the work of El Ashkar et al. (1956). Positive correlations were found between the content of free iron oxide and the water retained at −33 and −150 kPa and the water retained at −150 kPa increased more rapidly with increase in free iron oxides than it did at −33 kPa.

Cation exchange capacity. In soils with a small organic carbon content, the cation exchange capacity can be used as an estimator of the clay mineralogy. The cation exchange capacity usually increases as the swelling clays content does.

Bruand and Zimmer (1992) showed that the pore volume resulting from clay-particles packing in clay soils (clay content > 30 %) was closely related to the *CEC* of the clay phase. The pore volume developed by the clay phase (v_v^{clay} in cm^3 per gramme of clay) was shown to be increasing with the cation exchange capacity of the clay phase (cec^{clay} in cmol$_+$ per gramme of clay) as indicated by the following relationship:

$$v_v = 0.275 + 0.067 \, cec^{clay}$$

As a consequence, when cec^{clay} does not vary for a group of soils, Bruand (1990) showed that PTFs can be established with clay content as single predictor. Arrouays and Jamagne (1993) investigated the water retention properties of loamy soils and recorded a positive correlation between the water content at field capacity or permanent wilting point and *CEC*. Tessier et al. (1999) showed that the *CEC* can be considered as a parameter characterizing the amount and nature of the < 2 µm fraction in a soil. Relationships between the water retained at a given water potential and *CEC* were established (Figure 1). The closeness of these relationships increased when the water potential decreased. Pachepsky and Rawls (1999) found the *CEC* of

clay fraction to be essential predictor of water retention at -33 and -1500 kPa. In addition, Karathanasis and Hajek (1982) and Lenhard (1984) showed that the mineralogical compositions becomes a dominant factor when the water content at very small h (i.e. $< -10^5$ kPa) is studied.

Soil chemical properties. Consequences of chemical and mineralogical characteristics on soil hydraulic properties are often linked, the effect of chemical characteristics on hydraulic properties being closely related to the mineralogical composition of the clay fraction.

Rajkai and Varallyay (1992) showed that for salt-affected soils, water retention was primarily affected by soil chemical properties, while soil physical variables were found to play only a secondary role. PTFs for water retention were developed with the exchangeable sodium Na_{exc} and bulk density as predictors for $-1 > h > -50$ kPa, with Na_{exc} and the clay content for $h = -250$ kPa and the total salt content and the clay content for $h = -1500$ kPa. Thus, they found chemical properties and bulk density but not the textural components to be the only necessary inputs in their PTF to estimate water retention in salt-affected soils.

To estimate the effect of salinity and solution composition on soil hydraulic properties, values of the *SAR* and total electrolyte concentration C or solute ionic strength I were used. Ninety five percent of variation in changes in water retention of clay samples could be estimated from *SAR* and C values in the work of Lenhard (1984). Changes in soil water retention were attributed to soil mineralogical composition in the work of Jayawardane and Beattie (1978). Lima et al. (1990) demonstrated that values of C and *SAR* affect parameters of van Genuchten's equation (van Genuchten, 1980) in a regular manner and can be in principle used to modify these parameters. Baumer et al. (1994) suggested to include the product of *SAR* and clay content in PTFs to estimate residual water contents and water content at $-$

1500 kPa, and to include *SAR* in the PTF to estimate the bubbling pressure in the Brooks-Corey equation.

Nashshineh-Pour et al. (1970) studied the effect of electrolyte composition on K_{sat} of several soils in Texas. They concluded that the most significant single soil characteristics would be soil mineralogy. Changes in K_{sat} as affected by sodium adsorption and electrolyte concentration were related to clay mineralogy, clay content and bulk density in the work of Frenkel et al. (1978). Result showed plugging of the pores by dispersed clay particles was the major cause of reduced K_{sat}. The sensitivity to excessive exchangeable sodium and small electrolyte concentration increased with clay content and bulk density. The kaolinitic soil was less sensitive than montmorillonitic and vermiculitic soils, the difference between the latter remaining small.

Saturated hydraulic conductivity of soil decreased with decreasing C and increasing SAR values in studies of McNeal and Coleman (1966), Lagerwerff et al. (1969), Pupisky and Shainberg (1984) and Russo and Bresler (1977). Pachepsky (1989) assembled a data base of published experimental data and found that the combined effect of the exchangeable sodium content and ionic strengths of solution on saturated hydraulic conductivity could be expressed using a single variable, the excessive thickness of hydrated layer, $\varDelta$, that he defined in terms of the proportion of exchangeable sodium in the sum of exchangeable cations Y_{Na} and ionic strengths I, mol L^{-1} as:

$$\varDelta = Y_{Na}(12 / I^{0.37} - 5).$$

The saturated hydraulic conductivity K_{sat} changed as a function of $\varDelta$:

$$K_{sat} = \frac{K_{sat,0}}{1 + \left(\dfrac{\Delta}{\Delta_{0.5}}\right)^{q}}$$

where parameters Δ, $\Delta_{0.5}$ and q were soil-specific, $K_{sat,0}$ was the hydraulic conductivity in absence of exchangeable sodium. Dane and Klute (1977) and Lima et al. (1990) observed the decrease in unsaturated hydraulic conductivity as the total concentration decreased.

Concluding remarks. Soil water management remains the utmost important issue in the regions of the World where soil salinity and alkalinity is developed or is developing. Much needs to be done to provide water management models with reliable estimates of interrelations between water and salt movement in soils of these regions.

REFERENCES

Arrouays, D. and Jamagne, M., 1993. Sur la possibilité d'estimer les propriétés de rétention en eau des sols limoneux lessivés hydromorphes du sud-ouest de la France à partir de leurs caractéristiques de constitution. C.R. Acad. Agric. Fr., 79: 111-121.

Bruand, A., 1990. Improved prediction of water-retention properties of clayey soils by pedological stratification. J. Soil Sci., 41: 491-497.

Bruand, A. and Tessier, D., 2000. Water retention properties of the clay in soils developed on clayey sediments: Significance of parent material and soil history. Eur. J. Soil Sci., 51: 679-688.

Bruand, A. and Zimmer, D., 1992. Relation entre la capacité d'échange cationique et la volume poral dans les sols argileux: incidences sur la morphologie des assemblages élémentaries. C. R. Acad. Sci., 315: 223-229.

Danalatos, N.G., Kosmas, C.S., Driessen, P.M. and Yassoglou, N., 1994. Estimation of the draining soil moisture characteristics from standard data as recorded in soil surveys. Geoderma, 64: 155-165.

El Ashkar, M.A., Bodman, G.B. and Peters, D.B., 1956. Sodium hyposulfite-soluble iron oxide and water retention by soils. Soil Sci. Soc. Am. Proc. 20: 352-365.

Frenkel, H., Goertzen, J.O. and Rhoades, J.D., 1978. Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J. 42: 32-39.

Gaiser, Th., Graef, F. and Carvalho Cordiero, J., 2000. Water retention characteristics of soils with contrasting clay mineral composition in semiarid tropical regions. Aust. J. Soil Res., 38: 523-536.

Hodnett, M.G. and Tomasella, J., 2002. Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: a new water retention pedo-transfer functions developed for tropical soils. Geoderma, 108: 155-180.

Jayawardane, N.S. and Beattie, J.A., 1978. Effect of salt solution composition on moisture release curves of soils. Aust. J. Soil Res. 17: 89-99.

Karathanasis, A. D. and Hajek, B.F., 1982. Quantitative evaluation of water absorption on soil clays. Soil Sci Soc. Am. J. 46:1321-1325.

Lenhard, R.J,. 1984. Effects of Clay-Water Interactions on Water Retention in Porous Media. Ph.D. Thesis. 145 pp. Oregon State University, Corvallis, OR.

Nashshineh-Pour, B., Kunze, G.W. and Carson, C.D., 1970. The effect of electrolyte composition on hydraulic conductivity of certain Texas soils. Soil Sci., 110: 124-127.

McNeal, B. L. and Coleman, N.T., 1966. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Am. Proc., 30: 308-312.

Pachepsky, Y.A., 1989. Effect of the composition of soil solutions and exchange cations on water retention and hydraulic conductivity. Soviet Soil Sci., 21: 90-103.

Pachepsky, Y.A. and Rawls, W.J., 1999. Accuracy and reliability of pedotransfer function as affected by grouping soils. Soil Sci. Soc. Am. J., 63: 1748-1759.

Puckett, W.E., Dane, J.H. and Hajek, B.F., 1985. Physical and mineralogical data to determine soil hydraulic properties. Soil Sci. Soc. Am. J., 49: 831-836.

Pupisky, H. and Shainberg, I., 1984. Effect of salt content on hydraulic conductivity of a sandy soil. Soil Sci. Soc. Am. J, 48: 429-433.

Quirk, J.P. 1994. Interparticle forces: A basis for the interpretation of soil physical behavior. Advances in Agronomy, 53: 121-183.

Rajkai, K., Várallyay, G., 1992. Estimating soil water retention from simpler properties by regression techniques. In: van Genuchten, M.Th., Leij, F.J., Lunds, L.J. (Eds.). Methods for estimating the Hydraulic Properties of Unsaturated Soils. Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils, Riverside, California, 11–13 October 1989, pp. 417–426.

Russo, D., and Bresler, E., 1977. Analysis of the saturated - unsaturated hydraulic conductivity in a mixed Na-Ca soil system. Soil Sci. Soc. Am. J., 41: 706-710.

Williams, J. R., Prebble, E., Williams, W.T. and Hignett, C.T., 1983. The influence of texture, structure and clay mineralogy on the soil moisture characteristic. Aust. J. Soil Res., 21: 15-31.

Tessier, D., 1984. Etude Expérimentale de l'Organisation des Matériaux Argileux. Thèse Doctorat d'Etat, 247 pp. Université de Paris 6, France.

Tessier, D., Bigorre, F. and Bruand, A., 1999. La capacité d'échange : outil de prévision des propriétés physiques des sols. C.R. Acad. Agric. Fr., 85, 37–46.

Tessier, D., Lajudie, A. and Petit, J.C. 1992. Relation between the macroscopic behavior of clays and their microstructural properties. Applied Geochemistry, Supplement Issue No 1, 151-161.

Tessier, D. and Pédro, G., 1987. Mineralogical characterization of 2:1 clays in soils: Importance of the clay texture. In: L.G. Schultz, H. van Olphen, F.A. Mumpton (eds.)

Proceedings of the International Clay Conference, Denver, 1985, pp. 78–84. The Clay

Minerals Society, Bloomington, IN.

Van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic

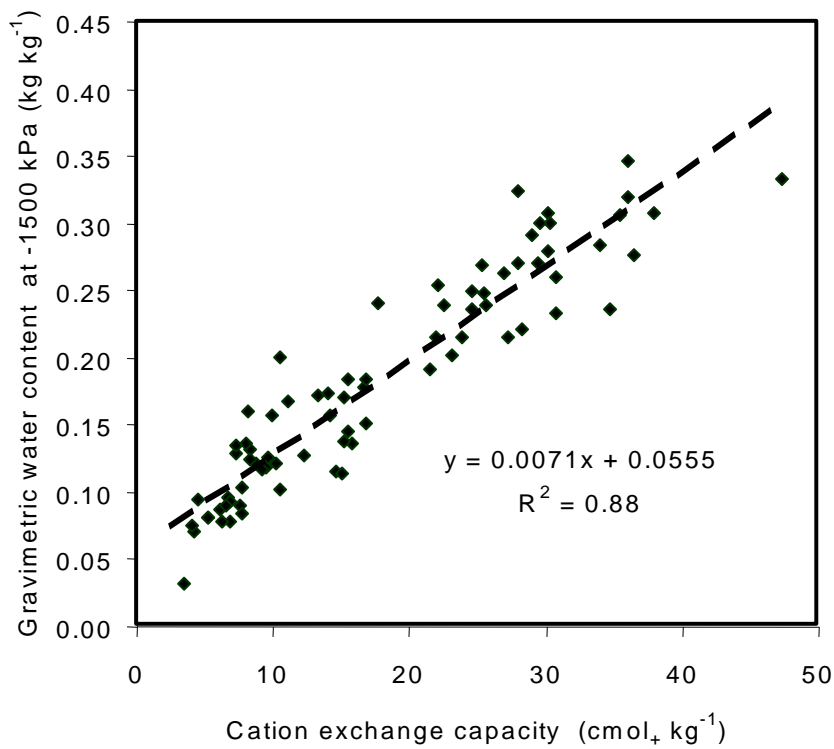conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44: 892-898.

Figure 9.1. Gravimetric water content at −1500 kPa with as a function of the cation exchange

capacity.