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Pore Size Distribution of Clayey Soils and Its Correlation with Soil Organic Matter

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ABSTRACT

Soil pore size distribution (PSD) directly influences soil physical, chemical, and biological properties, and further knowledge of soil PSD is very helpful for understanding soil functions and processes. In this study, PSD of three clayey soils collected from the topsoil (0–20 cm) of Vertisols in Northern China was analyzed using the N_2 adsorption (NA) and mercury intrusion porosimetry (MIP) methods. The effect of soil organic matter (SOM) on the PSD of clayey soils was also evaluated. The differential curves of pore volume of clayey soils by the NA method exhibited that the pores with diameter < 0.01 µm accounted for more than 50% in the pore size range of 0.001 to 0.1 µm. The differential pore curves of clayey soils by the MIP method exhibited three distinct peaks in pore size range of 60 to 100, 0.3 to 0.4 and 0.009 to 0.012 µm, respectively. In the three clayey soils, the ultramicropores (5–0.1 µm) were determined to be the main pore class (on average 35.5%), followed by macropores ($>$ 75 µm, 31.4%), cryptopores (0.1–0.007 µm, 16.0%), micropores (30–5 µm, 9.7%) and mesopores (75–30 µm, 7.3%). The SOM greatly affected the pore structure and PSD of aggregates in clayey soils. In particular, SOM removal reduced the volume and porosity of 5–100 µm pores while increased those of $<$ 5 µm pores in the 5–2 and 2–0.25 mm aggregates of clayey soils. The increase in the volume and porosity of $<$ 5 µm pores may be attributed to the disaggregation and partial emptying of small pores caused by the destruction of SOM.

Key Words: mercury intrusion porosimetry, N_2 adsorption, pore volume, porosity, soil aggregate, Vertisol

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INTRODUCTION

Pore structure of soils affects many physical, chemical and biological properties, such as gas diffusivity, water transmission and storage, mechanical resistance, carbon dynamics, microbial habitat, and root penetration (Pagliai *et al*., 2004; Hajnos *et al*., 2006; Oorts *et al*., 2007; Smucker *et al*., 2007; Munkholm *et al*., 2012; Sleutel *et al*., 2012). The shrinkage/swelling of expansive clayey soils has been proven to dynamically change the soil porosity and pore size distribution (PSD), and deteriorate soil structure (Balbino *et al*., 2002; Alaoui *et al*., 2011). Poor pore structure of clayey soils is believed to be a major threat to soil physical quality and crop sustainable production. Thus, the analysis of soil pore structure is very important for understanding many functions and processes occurring in clayey soils. The PSD is an important parameter for describing soil quality and developing the theoretical models of the soil water, gas, and solute transport properties in clayey soils (Ehlers *et al*., 1995; Perrier *et al*., 1996).

The porous system of clayey soils is affected by a number of factors such as soil organic matter (SOM), type and content of clay minerals, water regime, compaction, and soil management (Fox *et al*., 2004; Horn, 2004; Kutílek *et al*., 2006; Wairiu and Lal, 2006; Chun *et al*., 2008; Churchman *et al*., 2010). Improvement of pore structure by organic matter, especially in clayey soils, is a traditional soil management practice (McCarthy *et al*., 2008; Papadopoulos *et al*., 2009; Grosbellet *et al*., 2011). Introduction of organic manures into soils generally increases the total porosity and alters the PSD of soils. Laboratory and field experiments have demonstrated that the organic matter increased the number of larger pores in soils and promoted the formation and stabilization of biogenic macropores (Pagliai *et al*., 2004; Oorts *et al*., 2007; Grosbellet *et al*., 2011). This preferential increase of larger pores can potentially change many of the most important soil processes, such as transmission and storage of water,

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plant root penetration and microbial activities. Knowledge on the effect of SOM on soil pore structure is needed for better soil management practices.

Many methods have been developed for quantitative determination of the pore volume and PSD of soils, including the direct methods (*e.g.*, micromorphologic analysis and computed tomography) and indirect methods (*e.g.*, soil water retention curve, gas adsorption and mercury intrusion porosimetry (MIP)) (Fiès and Bruand, 1990; Fiès, 1992; Pierrier *et al.*, 1996; Echeverría *et al.*, 1999; Lipiec *et al.*, 2007, 2012; Dexter *et al.*, 2008; Paz Ferreiro *et al.*, 2010). The soil pore structure is composed of numerous continuous pores in a wide diameter range from several nanometers to centimeters. Up to date, there is not a single method capable of determining the soil PSD across the full size range (Rouquerol *et al.*, 1994; Hajnos *et al.*, 2006; Rasa *et al.*, 2012). The soil pore spaces were most commonly measured using the adsorption methods, such as the adsorption of liquid N_2 at −196 °C and CO_2 at 0 °C (Echeverría *et al.*, 1999). Recently, the ^{129}Xe NMR spectroscopy of adsorbed xenon has been adopted to measure the porosity of the soil-related materials (Filimonova *et al.*, 2006), and the X-ray computed tomography (CT) scanning technique has shown to be very powerful in visualizing and quantifying the pore space in a millimetric or micrometric resolution (Fiès and Bruand, 1990; Papadopoulos *et al.*, 2009; Munkholm *et al.*, 2012).

The MIP method has been reported to determine soil PSD for a wide diameter range (Fiès, 1992; Echeverría *et al.*, 1999; Hajnos *et al.*, 2006; Paz Ferreiro *et al.*, 2010; Lipiec *et al.*, 2012). The MIP method also has been widely used to evaluate the PSD in response to soil tillage system (Fox *et al.*, 2004; Wairiu and Lal, 2006), land use type (Hajnos *et al.*, 2006), and compaction (Kutílek *et al.*, 2006; Lipiec *et al.*, 2007). In some studies, the MIP results have been used as a reference standard for the quantification of soil PSD (Hajnos *et al.*, 2006). The N_2 adsorption (NA) and water desorption isotherms are able to measure the pores with equivalent diameters in the order of one magnitude smaller as compared with the MIP method. However, the soil moisture characteristic curves cannot be used to determine the PSD of expansive clayey soils because the water lost is not only related to the drainage but also to pores' shrinkage. In addition, the changes in bulk density during soil wetting and drying also alter the pores' geometry, which may result in a reversible change in the pore volume and size. Since the gas adsorption and MIP methods do not alter the pore geometry, they are advantageous over other techniques in determining the PSD of expansive clayey soils.

In spite of the fact that the pore structure importantly affects the soil functions and plant growth, there is a lack in qualitative description of soil pore system. The aims of this work were to quantitatively measure the pore characteristics of clayey soils over a wide range of equivalent pore diameters using the NA and MIP methods, and to evaluate the impact of SOM on soil PSD by comparing the PSD of soil aggregates before and after SOM removal.

MATERIALS AND METHODS

Soils

The study was conducted on three clayey soils located in Huaiyuan, Anhui Province (32°50′54.2″ N, 117°12′37.3″ E), Xiyi, Jiangsu Province (34°17′39.4″ N, 118°25′32.2″ E), and Runan, Henan Province (33° 7′31.5″ N, 114°26′17.3″ E), China. They are designated as AH, JS, and HN, respectively. The three clayey soils were classified as Vertisols according to USDA soil taxonomy (Soil Survey Staff, 2006). At each site, soil samples were collected from the 0–20 cm depth using a steel cylinder to avoid compaction and smearing of field-moist soil clods. Each soil was taken in three replications. The soil samples were air-dried by spreading the soil in a dry and ventilated room. After drying, aggregates of about 2 mm in size were gently separated using a sieve and used for the PSD analysis. The basic soil properties were determined on the disturbed samples passed though a 2-mm sieve according to the standard procedure (ISSCAS, 1978). Soil organic carbon (SOC) was determined by the dichromate oxidation method. Soil particle size distribution was measured by the pipette method. Soil pH was measured using a glass electrode with a 1:2.5 soil:water ratio. Soil cation exchange capacity (CEC) was measured by the ammonium acetate method. The consistency limits of soils were determined according to the ASTM D4318 procedure (ASTM, 1995). Coefficient of linear extensibility (COLE) of soils was determined using the method of Schafer and Singer (1976). The clay fraction (< 2 μm) of soil was separated using the sedimentary method. The powder samples were placed on a glass slide. The clay mineralogical composition was determined by a Rigaku X-ray diffractometer (D/Max 2550 PC, Rigaku Corption, Japan) using Cu$K\alpha$ radiation (45 kV, 300 mA). The measured results are summarized in Table I and Fig. 1.

NA method

The N_2 adsorption (NA) isotherms were used to de-