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Evaluation of soil aggregate microstructure and stability under wetting and drying cycles in two Ultisols using synchrotron-based X-ray micro-computed tomography

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Soil structure and the soil pore system are important for many soil environmental processes. However, little is known about the influence of intra-aggregate microstructure on aggregate stability. The objective of this study was to evaluate the effect of soil pore characteristics on wet aggregate stability and aggregate tensile strength (*TS*) using synchrotron-based X-ray micro-computed tomography (SR-μCT) under wetting and drying cycles. Undisturbed topsoils (200 cm^3) derived from shale (S) and Quaternary red clay (Q) were submitted to three wetting and drying treatments under controlled laboratory conditions. 3–5 mm aggregates were collected from different treatments and scanned at 3.7 μm voxel-resolution for the reconstruction of 3D micro tomography images. The wet aggregate stability and *TS* were measured after each treatment. The relationships among pore characteristics, wet aggregate stability, and *TS* were analyzed using partial least squares regression (PLSR). The results indicated that porosity (*P*), percentage of pores >100 μm ($Pd_{>100}$), and fraction of elongated pores (*FEP*) all significantly increased with an increasing number of wetting and drying cycles, while the opposite trends were observed for the total number of pores (*TNP*), the percentage of pores with a diameter of 75–100, 30–75, and <30 μm. Decrease in wet aggregate stability and *TS* of both soils was mainly due to higher *P*, a more extensive and complex pore network, which caused increased air pressure, increased rate of water entry, and high probability of crack propagation and interaction. The *TNP*, Pd_{75-100}, *P*, and $Pd_{>100}$, were identified as the primary factors controlling the wet aggregate stability and *TS* according to PLSR. The pore characteristics and soil clay content accounted for as much as 99% of the variation in wet aggregate stability and *TS*. This study provides insights for improved understanding of the change in topsoil microstructure; however, the effect of pore characteristics on the aggregate breakdown mechanism requires further investigation.

1. Introduction

A good soil structure is essential for supporting life, ensuring sustainable agriculture, and moderating environmental quality. Stable aggregates are regarded as an indicator of the soil structure, playing an important role in the maintenance of soil structure and fertility, reducing detachment by raindrop impact, abrasion in overland flow, and the formation of surface crusts and seals, and facilitating water filtration and root development (Six et al., 2000; Lado et al., 2004; Madari et al., 2005; Wang et al., 2013). In a broader sense, aggregate size and stability, as well as the amount, distribution, and size of pore space between and inside the aggregates, characterize the soil structure (Six et al., 2004). Studies of soil structure are usually conducted on bulk scales and mostly use bulk density, porosity (*P*), or soil friability to describe the soil structure (Munkholm et al., 2002, 2012). Knowledge of detailed

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aggregate microstructures, however, is very limited. To better understand the microstructure characteristics in soil aggregates, it is advantageous to conduct research at the aggregate scale and to investigate aggregate stability as well as soil quality directly (Zhou et al., 2012).

Soil strength and friability are criteria that are often proposed to assess the consequences of soil compaction on agricultural tillage, seeding emergence, root growth and yield. Experimental results have confirmed the strong influence of pores on soil fragmentation and tensile strength (*TS*). Hallett et al. (1995a) reported that structural pores in aggregated soils intensify external loads and reduce the surface energy of the failure surfaces. Munkholm et al. (2002) found the *TS* of soil cores measured by direct tension test was negatively correlated to the macroporosity (pores > 30 μm) of the soil, whereas the ease of soil fragmentation measured by soil drop test was positively correlated to pore continuity. Schäffer et al. (2008) applied uniaxial compression tests to repacked samples in which artificial cylindrical pores of two diameters (2 and 4 mm) and two orientations ('vertical': inclination angle of 0° from the vertical, 'oblique': 30°) were created, and observed that cylindrical macropores did not significantly affect the pre-compression stress and compression indexes of bulk soil. This finding is in contrast to the results reported by Hartge and Sommer (1980), who indicated that vertically arranged macropores decreased the compressibility of bulk soil. Munkholm et al. (2012) found significant and positive correlations between the soil pore characteristics assessed on the whole soil cores and soil friability assessed using the drop shatter method. They pointed out that the morphology of the air-filled pore space played a significant role in relation to soil friability. A soil aggregate is a basic unit of soil structure. Mechanical properties of soil aggregates play a key role in the soil system, referring to tillage, compaction, and plant growth. One of the most useful mechanical properties of soil aggregates and a very sensitive indicator of soil structural stability is the *TS*. Aggregate *TS* is defined as the stress, or force per unit area required to cause a soil aggregate to fail in tension, that is, to break into smaller particles. However, little is known regarding the relationship between aggregate *TS* and soil pore characteristics, emphasizing the need to study the relationship between aggregate *TS* and aggregate pore characteristics.

Aggregate disintegration caused by different mechanisms is well documented: (1) slaking, which is breakdown caused by the compression of entrapped air by the advancing wetting front; (2) mechanical breakdown caused by raindrop impact; and (3) microcracking, or breakdown caused by differential swelling (Le Bissonnais, 1996). Only a few studies have attempted to determine the effects of pore characteristics on wet aggregate stability when attempting to discern the underlying mechanisms of breakdown. Papadopoulos et al. (2009) determined the wet aggregate stability of differently managed soils by slaking and using mean weight diameter (*MWD*) as stability index. They suggested that the intra-aggregate *P* did not significantly affect the wet aggregate stability. In aggregates of organically managed soils, these authors observed a considerable number of cracks and elongated pores connected to the edges. They proposed that these pores had a positive effect, allowing entrapped air to escape during wetting and therefore reducing pressure build-up. Conversely, Lugato et al. (2010) compared the long-term effects of organic and mineral fertilizers in three contrasting soils and hypothesized that a greater volume of large pores would allow the rapid entry of water, which would cause a build-up of internal air pressure and consequent disruption of the aggregates. The pore connectivity phenomenon is also decisive for gas diffusion and saturated hydraulic conductivity. Peth et al. (2008) characterized and quantified transport relevant morphological features of the pore-space network of two contrasting soil aggregates at the microscale. They pointed out that soil solutions are more effectively transported to the aggregate's interior by the continuous, less tortuous and wider flow paths of the grassland aggregate. In combination with the wider and more continuous flow channels, this finding suggests a more enhanced fluid transport through and into the intra-aggregate pore space for the grassland aggregate. Despite the complexity of pore characteristics, which govern the variations in aggregate stability, few efforts have been devoted to understanding the role of pores and their morphological features in aggregate breakdown from a mechanistic point of view.

Ultisols (locally known as red soils) cover approximately 1.14 million km^2 in southeastern China. The region is humid and has a subtropical monsoon climate with an annual average temperature of 16.8 °C. More than 70% of the annual precipitation falls between the months of April and August. In this context, the intense wetting and drying of soils is one of the most prominent natural changes in these climatic regions and contributes to significant changes in aggregation and soil structure (Swanepoel et al., 2013). The objective of this project was to (1) evaluate the impact of wetting and drying cycles on wet aggregate stability and *TS*; (2) quantify variations in aggregate pore characteristics in terms of wetting and drying cycles using a high-resolution X-ray CT scanner; and (3) quantify the contribution of changes in aggregate pore characteristics to wet aggregate stability and *TS* using partial least squares regression (PLSR).

2. Materials and methods

2.1. Site description and sampling

The sampling plots were located in Xianning County, which is situated southeast of Hubei Province, China. The region has a subtropical monsoon humid climate with an average annual precipitation of 1572 mm. The landscape of the area is characterized by low hills that exhibit different degrees of erosion.

The two selected soils are derived from shale and Quaternary red clay, which are the main parent materials in this region. The processes of soil formation resulted in the development of similar horizons in selected soils where each soil had an *A*, B_s, and C_{sw} horizon. The *A* horizon was about 20 cm deep in forested and wild areas and 0–15 cm deep in tea gardens and croplands. The B_s horizon comprised iron and aluminum illuvial horizons and was characterized by a massive nutty structure. The C_{sw} under the *B* horizon was a reticulated mottling horizon. The soil sampling area was at the upper part of the hills. Each area of the sampling massif was about 0.1–0.3 ha. The parent material, soil sampling site, land use, and some selected properties of the soils are listed in Table 1. According to the U.S. Soil Taxonomy (Soil Survey Staff, 2010), these red soils are

Table 1
Location of sampling sites and description of Ultisols.

Sample designation	Parent material	Situation	Slope	Dominant minerals	Land use	Planted period (year)
S	Shale	N30°01′04.00″E114°19′23.9″	9–18%	Hydromica, Kaolinite	Cunninghamia	6
Q	Quaternary red clay	N30°01′19.8″E114°20′56.4″	18–20%	Hydromica, Kaolinite	Prunus	>10

S and Q indicate soils derived from shale and Quaternary red clay, respectively.