ISSN: 1394 7990
Malaysian Journal of Soil Science Vol. 9: 1-13 (2005)
Malaysian Society of Soil Science

Aggregate Breakdown Rates of Some Malaysian Soils and Relation to Aggregate Properties

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ABSTRACT

The objectives of this study were to determine the rate of aggregate breakdown of three aggregate sizes from three highly-weathered Malaysian soils and relate the aggregate breakdown rate with several aggregate constituents. Bungor, Munchong and Serdang soils (from orders Ultisol and Oxisol) were used. For each soil type, three macro-aggregate size fractions were separated: 3-5, 1-2 and 0.3-0.5 mm. Each aggregate size fraction was wet-sieved for six time durations to determine breakdown rate of aggregates with time. Each aggregate size fraction was also analysed for its texture, organic carbon, total nitrogen, cation exchange capacity, free iron oxides, humic acids, fulvic acids and polysaccharides. Results showed that the breakdown rate of aggregates followed an exponential relationship with time. This meant that aggregates would be particularly sensitive to disruptive forces during the initial periods of erosion by water. The breakdown rate of aggregates was primarily related to the amounts of clay, sand and fulvic acids. However, whether aggregates stability increased or decreased with aggregate size depended on both the soil type and aggregate size in question. This was because the distribution patterns of the aggregate constituents were dissimilar to each other, and their distribution patterns depended on both soil type and aggregate size. For a given soil type, the distribution of clay, silt and sand differed among the macro-aggregate size fractions. Though the distributions of other aggregate constituents (organic carbon, total nitrogen, cation exchange capacity, free iron oxides, humic acids and polysaccharides) among the aggregate sizes were statistically similar, they differed according to soil type.

Keywords: Aggregate stability, erosion, organic matter, wet-sieving

INTRODUCTION

Theoretically, larger aggregates should be less stable than smaller aggregates (Brady 1990; Tisdall and Oades 1982) for two reasons. Firstly, to break up an aggregate, the external force must exceed the internal forces within the aggregate (Allison 1968). But as an aggregate increases in size, its mass will rise more rapidly than its surface area because surface area increases with the square of radius, and the volume with the cube of the radius. Hence, as the aggregate size increases, the adhesive forces remain constant but the counteracting forces increase. Secondly, there is a sort of hierarchical order of aggregate assembly, where larger aggregates are assemblages of smaller aggregates, and these smaller aggregates are, in turn, assemblages of even smaller aggregates (Baver 1956; Hadas 1987). This hierarchy of aggregate assembly means that if a given energy is large enough to break an aggregate size of, say, 1 mm, then this energy has already exceeded the amount of energy required to break down any aggregates larger than 1 mm. Subsequently, all aggregates larger or equal to 1 mm will be destroyed, but those smaller than 1 mm will persist.

However, this notion that progressively larger aggregates are increasingly less stable ignores the influence of aggregate constituents on aggregate stability. The stability of an aggregate depends not only on its aggregate size but also on the amount, distribution and type of its constituents such as organic carbon and its components (humic substances), free iron oxides, polysaccharides and texture. Not surprisingly then, this kind of hierarchical order of aggregate destruction is absent in highly weathered soils of Oxisols, as discovered by Oades and Waters (1991), and Stevenson (1982).

Aggregate stability is thus affected by a complex relationship between the various aggregate constituents with aggregate size. As aggregate size decreases, for example, the amount of organic matter often decreases. However, the organic matter in the smaller aggregates is older and more highly processed than those in the larger aggregates (Elliott 1986; Puget *et al.* 1995). This means that the stability of large aggregates is due to the transient and temporary binding agents of organic matter. It is also evident that small aggregates, in particular those smaller than 0.25 mm, are stabilised less by organic matter and more by inorganic components, polyvalent cations and clay (Krishna Murthi *et al.* 1977; Monreal *et al.* 1995).

Thus, the objectives of this study were: (i) to determine the rate of aggregate breakdown of three aggregate sizes from three typical, highly-weathered Malaysian soils; and (ii) to relate the aggregate breakdown rate with several aggregate constituents. This study aims to give an indicative picture of the stability of highly weathered Malaysian soils, in particular if there is any trend in aggregate stability with decreasing aggregate size, and if this aggregate stability trend could be explained by any of the aggregate constituents.

MATERIALS AND METHODS

Three soil types from soil orders Ultisol and Oxisol were sampled from several Universiti Putra Malaysia agriculture farms (3°01'N, 101°42'E). The soil types were Bungor (Typic Paleudult), Munchong (Typic Hapludox) and Serdang (Typic Paleudult) Series (Paramananthan, 1998). Soils were sampled randomly from the field at soil a depth 0-150 mm, bulked, and then air-dried for a week. Each soil type was dry-sieved into three macroaggregate sizes: 3-5, 1-2 and 0.3-0.5 mm. Wet-sieving according to the method described by Kemper and Rosenau (1986) was used to determine the aggregate breakdown rate with time. Before wet-sieving, aggregates were pre-wetted to saturation by fine mist sprays of water. Wet-sieving was for six time durations: 3, 6, 10, 20, 30 and 45 minutes.

Each aggregate size fraction for each soil type was also analysed for texture (Gee and Bauder 1986), total nitrogen (N) using the macro-Kjedahl method (Bremner 1965), organic carbon (OC) using the dichromate oxidation procedure (Walkley and Black 1934), polysaccharides (Norhayati and Verloo 1984), exchangeable cations (CEC) (Rhodes 1982), and free iron oxides (Fe_2O_3) as extracted using the citrate-bicarbonate-dithionite solution (Mehra and Jackson 1960). The components of organic matter, the fractions of humic acids (HA) and fulvic acids (FA), were analysed using the method by Norhayati and Verloo (1984).

All data were subjected to analysis of variance (ANOVA) for a 3 (soil types) x 3 (aggregate size fractions) factorial Completely Randomised Design (CRD). Duncan's Multiple Range Test was used to separate the significant means. Simple linear correlation was used to relate aggregate constituents to each other, and multiple stepwise regression analysis was also used to relate aggregate breakdown rate with the aggregate constituents. All analysis was done using the statistical package SPSS version 13.0 (SPSS Inc., Chicago).

RESULTS AND DISCUSSION

Aggregate Breakdown Rate

This study found that for all the three soil types, each of their three aggregate size fractions would break down with time according to the exponential relationship:

$$w_i \propto \exp(-b_i t) \qquad (1)$$

where w_i is the weight of water-stable aggregates, at time t, of aggregate size fraction i; and b_i is the rate of aggregate breakdown for aggregate size fraction i. Smaller b values indicate slower breakdown of aggregates, thus, denoting greater aggregate stability. The aggregate breakdown rates are shown in Table 1. Eq. (1) reveals that large amounts of aggregates would break down during the initial period of disruptive forces. However, aggregates would become progressively more resistant to breakdown by water with time. In practice, this means that aggregates will be particularly sensitive to disruptive forces during the initial periods of erosion by water.

More importantly, ANOVA revealed that the aggregate breakdown rate was a function of the interaction between aggregate size and soil type ($p<0.01$). This meant that whether stability increased or decreased with decreasing aggregate size depended on both the soil type and size of aggregate in question. This study observed that for Munchong and Bungor Series their larger aggregates (> 1 mm) were more stable than their smaller aggregates (0.3-0.5 mm), and their aggregates of sizes 1-2 and 3-5 mm had generally comparable stabilities. But for the Serdang Series, there were no significant differences ($p<0.20$) among the stabilities of the three aggregate size fractions.

To explain these patterns of aggregate stability among the soil types and aggregate sizes, it was important to determine the distribution of the aggregate constituents among the aggregate size fractions.

Distribution of Aggregate Constituents in the Macro-aggregate Sizes

Table 1 shows the distribution of several aggregate constituents in the three macro-aggregate size fractions of the three soil types. ANOVA revealed that of all the aggregate constituents, only texture (clay, silt and sand) was a function of the interaction between the soil type and aggregate size ($p<0.05$). This meant that the distribution of clay, silt and sand particles depended on both the soil type and aggregate size. For Munchong and Bungor soils, clay content increased with the aggregate size. For Serdang Series, however, the largest aggregate size (3-5 mm) had the highest clay content, but the clay content in the 1-2 and 0.3-0.5 mm aggregates were similar. Not surprisingly, the distribution of sand was opposite that for clay because the distribution of clay and sand are often inversely related to each other. The distribution of silt was less clear in this study. Generally, silt content was higher in the larger aggregates.

Unlike texture, the distribution of other aggregate constituents such as OC, N, free Fe_2O_3, CEC, HA, FA and polysaccharides were a function of the soil type only $p<0.05$. For these aggregate constituents, there was no significant differences in their distribution among the three aggregate size fractions for a given soil type. In other words, their distribution only varied with the soil type.

The distributions of OC and N tend to have a similar pattern, as observed by Adesodun *et al.* (2005) and Mbagwu and Piccolo (1990). This was also observed in this study where OC and N had a moderately strong linear relationship with each other ($r=0.77$, $p<0.05$) (Table 2). However, in contrast to some studies where OC and N tended to decrease with aggregate size (Adesodun *et al.* 2005; Mbagwu and Piccolo 1990), this study found no significant differences in the amount of OC and N among the macro-aggregate size fractions for a given soil type. Adesodun *et al.* (2005) and Mbagwu and Piccolo (1990) speculated that the distribution of OC and N could be related to the specific surface area of aggregates, which is affected by the amount of clay and silt in the aggregates. They speculated that the higher silt and clay contents in the aggregates, the higher the specific surface area; thus, there is greater accumulation of OC and N.

In this study, the total clay and silt contents among the three aggregate sizes ranged from 24 to 38%, 77 to 83% and 32 to 42% for the soils Bungor, Munchong and Serdang Series, respectively. These ranges may not be wide or different enough to cause a very dissimilar specific surface area among the three aggregate sizes. This could explain why the distributions of OC and N, as well as the organic matter components (HA and FA), CEC and free Fe_2O_3, were not significantly different among the macro-aggregate sizes for a given soil type. Although ANOVA had revealed that clay and silt varied significantly with both soil type and aggregate size, the texture differences among the three aggregate sizes for a soil type may not be sufficiently large to cause a difference in the distribution of these aggregate constituents.

Expectedly, the amount of FA exceeded HA in this study (Table 1). Bungor, Munchong and Serdang Series are highly weathered tropical soils. One reason why there is more FA in tropical soils than in temperate soils is that tropical soils have a higher organic matter turnover rate (Greenland *et al.* 1992). According to the degradative genesis of humic substances, HA would be converted to FA faster in tropical soils than in temperate soils (Mendoça *et al.* 1992). One exception in this study was that for each of the three soils, there was slightly more HA than FA in the smallest aggregate size fraction, 0.3-0.5 mm (Table 1).

Relationship Between the Aggregate Constituents and Aggregate Breakdown Rate

Aggregate breakdown rate correlated significantly ($p<0.05$) with N, CEC, clay, sand and FA (Table 2). The breakdown rate did not have a significant linear relationship with OC. OC is often regarded as an important agent of aggregate stability, but several studies revealed that it is not total organic matter *per se* that is crucial to aggregate stability. Quirk and Panabokke (1962), for example, revealed that it was the disposition (or distribution) of organic matter within the aggregates that was more important. They revealed that to increase aggregate stability, organic matter must settle in certain pore classes to strengthen the walls of these pores. Porosity contributes directly to aggregate stability because some pores (in particular 15-50 µm pore size) act as conduits or fault lines of aggregate failure.

Soil organic matter when it is extracted as a whole may not correlate strongly to aggregate stability. This is because it is often found that it is the components of organic matter (such as HA and FA) rather than total organic matter that are of greater influence on aggregate stability (Dutarte *et al.* 1993; Hamblin and Greenland 1977). HA is a fraction of organic matter that is soluble in alkali but insoluble in acid. In contrast, FA is soluble in both alkali and acid. There have been many studies expressing conflicting opinions as to which of these two fractions is more important to aggregate stability (Fortun *et al.* 1989; Piccolo and Mbagwu 1990). These conflicting results, however, can be grouped into two: studies conducted using temperate soils, and those using tropical soils. In temperate soils, HA usually fares better in improving aggregate stability, but in tropical soils, including Malaysian soils, FA usually fares better (Soong 1980; Tajuddin 1992; Theng *et al.* 1989). FA fares better in tropical soils possibly because there is often more FA than HA in tropical soils. Tropical soils are more highly weathered and have higher rates of turnover of organic matter. Thus, HA in tropical soils is converted to FA at a faster rate than that in temperate soils.

Nonetheless, in equal amounts, FA should still be better than HA in promoting aggregate stability for two reasons. FA is smaller, more highly charged and more polar than HA (Hayes 1991). Firstly, the larger HA is less effective as a binding agent because it is too big, is spherical instead of linear (like FA), and because of its spherical shape, the functional groups in HA may not be free or exposed enough to attach itself to clay particles (Allison 1968). Linear shapes like FA is analogous to a network of ropes where clay particles string along the lines. Secondly, FA is more acidic than HA due to its higher concentration of carboxylic functional groups, and these functional groups together with phenolic-OH groups play a role in aggregate stability (Martin and Aldrich 1955).

TABLE 1

The properties of three aggregate size fractions of three Malaysian soils

Soil	Agg. size (mm)	N (%)	C (%)	Free Fe_2O_3 (ppm)	CEC (ppm)	Clay (%)	Silt (%)	Sand (%)	HA (mg/g)	FA (mg/g)	Polysaccharides (mg/g)	Breakdown rate, *b* *
Bungor	0.3-0.5	0.12	2.61	9.08	4.98	22.14	5.71	61.70	2.54	2.07	8.65	0.0160 (0.87)
Munchong		0.27	3.39	31.10	6.89	69.63	2.81	67.13	2.21	2.02	10.69	0.0095 (0.86)
Serdang		0.08	0.68	38.67	5.43	28.01	2.09	75.74	1.92	1.75	15.34	0.0128 (0.70)
Bungor	1-2	0.14	3.05	8.80	5.68	30.02	6.65	16.34	0.81	6.14	21.06	0.0073 (0.71)
Munchong		0.26	3.35	32.33	6.91	74.17	8.41	17.38	0.75	5.68	19.47	0.0029 (0.73)
Serdang		0.16	2.61	35.73	5.69	28.82	7.37	22.98	1.24	2.52	10.52	0.0109 (0.79)
Bungor	3-5	0.14	2.57	12.43	5.63	32.28	10.09	57.65	0.69	3.55	6.59	0.0083 (0.74)
Munchong		0.25	3.09	31.95	6.80	76.96	9.39	61.75	0.62	3.18	5.89	0.0076 (0.90)
Serdang		0.15	2.72	33.42	6.40	32.22	4.15	67.83	0.60	3.09	5.73	0.0121 (0.79)

* *b* is the aggregate breakdown rate from Eq. (1), and values in brackets denote degree of fit R^2 of Eq. (1)

TABLE 2

Correlation coefficient matrix among the aggregate properties

	N	C	Free Fe_2O_3	CEC	Clay	Silt	Sand	HA	FA	Polysaccharides
C	0.762*									
Free Fe_2O_3	0.303	-0.242								
CEC	0.905**	0.592	0.511							
Clay	0.944**	0.560	0.387	0.903**						
Silt	0.483	0.304	0.693*	0.651	0.376					
Sand	-0.953**	-0.568	-0.449	-0.934**	-0.994**	-0.476				
HA	-0.209	-0.298	-0.070	-0.395	-0.216	-0.450	0.260			
FA	0.243	0.477	-0.342	0.243	0.204	-0.033	-0.190	-0.647		
Polysaccharides	0.015	-0.027	-0.072	-0.016	0.041	-0.286	-0.003	-0.001	0.630	
Breakdown rate	-0.665*	-0.526	-0.093	-0.662*	-0.676*	-0.308	0.676*	0.652	-0.768*	-0.452

$*p<0.05$ $**p<0.01$

Consequently, in this study, of all constituents, FA had the strongest correlation to aggregate stability. The role played by HA on aggregate stability may still be important, as its correlation to aggregate breakdown rate was significant at 6%. Both HA and FA, however, had stronger correlations than OC to aggregate stability for reasons discussed earlier.

Clay content had a significant correlation to aggregate stability (Table 2). Together with organic matter, clay plays a vital role in aggregate stability due to its very large specific surface area and its permenant negative charge. And because clay and sand contents tend to have an inverse linear relationship, sand was inversely related to aggregate stability where greater amounts of sand would decrease aggregate stability. Silt, however, did not have a significant relationship with aggregate stability probably because the three soils chosen in this study all had similar amounts of silt, ranging from 2 to 10% only. Silt particles can be important to aggregate stability due to the substantial accumulation of organic matter in the silt fractions as discovered by Ahmed (1981), Ahmed and Oades (1984), and Anderson and Paul (1984).

N and CEC also correlated significantly to aggregate stability, but their significant relationships could be due to their high linear relationships to clay ($r = 0.9$).

Free Fe_2O_3 and polysaccharides are often reported to be important agents of aggregate stability. Nonetheless, this study found no significant relationships between them and aggregate stability. The effects of iron oxides vary with different soils, and this variation itself is caused by the different amounts and nature of iron oxides in the soils, as well as to the different nature and environment of the soils' pedogenesis (Schwertmann and Taylor 1989). This could mean that iron oxides can be an inefficient agent of aggregate stability when iron oxides occur as discrete or free particles in the soil, in particular for old, highly weathered and well-oxidised soils (Greenland *et al.* 1968). Greenland *et al.* (1968) further remarked that correlating iron oxides to aggregate stability might be insufficient. Visual inspections on the iron oxide coating on the clay surfaces are necessary because iron oxides tend to form discrete, inactive particles. Moreover, even if coatings are formed, they may not be stable or continuous (Quirk 1978).

There are several possible reasons why this study found an insignificant relationship between polysaccharides and aggregate stability. The effect of polysaccharides on increasing aggregate stability is rapid, but they decompose quickly as well (Tisdall and Oades 1982). This means that polysaccharides are short-lived stability agents. Aggregate stability would be increased if there is continuous addition of polysaccharides into the soil. Just as it is the fractions of organic matter that are important to aggregate stability, several workers have shown that certain fractions of polysaccharides are more important to promote stability (Hayes and Swift 1978; Swift 1991). Moreover, current extraction methods may still leave behind significant amounts of polysaccharides in crevices or within the aggregates. If these are extracted as well, correlations between polysaccharides and aggregate stability may be found.

Multiple Linear Regression Analysis

Stepwise multiple linear regression analysis was used to identify the linear addictive contribution of one or more of the aggregate constituents on the rate of aggregate breakdown. Of all the aggregate constituents, only FA and clay were selected into the regression equation:

$$rate = 0.01894 - \underset{(0.0542)}{0.00009clay} - \underset{(0.658)}{0.00157FA}\,; \qquad R^2 = 0.87 \tag{2}$$

where all regression coefficients were significant ($p<0.01$), and the values in brackets denote the standardised coefficients for clay and FA. Eq. (2) is not so much for predictive purposes as the coefficient values would change for different soils, but rather Eq. (2) has shown that only clay and one of the organic matter components, FA, were important in explaining aggregate stability. Between clay and FA, the latter had a larger influence on explaining the aggregate breakdown rate (based on its larger standardised coefficient than that for clay).

CONCLUSION

The breakdown rate of aggregates followed an exponential relationship with time. This meant that large amounts of aggregates would break down initially, but, with time, progressively less aggregates would break down further. In practice, this means that aggregates will be particularly sensitive to disruptive forces during the initial periods of erosion by water.

The breakdown rate of aggregates was primarily related to the amounts of clay, sand and to one of the organic matter components, FA (fulvic acids). However, whether aggregate stability increased or decreased with aggregate size depended on both the soil type and aggregate size in question. This was because the distribution patterns of aggregate constituents important to aggregate stability were dissimilar to each other, and their distribution patterns depended on both soil type and aggregate size. For a given soil type, this study showed that the distribution of the primary particles, clay, silt and sand, differed among the three macro-aggregate size fractions. For a given soil type, however, the distributions of other aggregate constituents among the aggregate sizes were statistically similar. The distributions of soil constituents such as organic carbon, total nitrogen, cation exchange capacity, free iron oxides, humic acids and polysaccharides were only different according to soil type.

ACKOWLEDGEMENT

This study was funded by the Universiti Putra Malaysia Fundamental Research Grant (No. 03-07-03-065J).

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