

## Aggregate Stability of Tropical Soils in Relation to Their Organic Matter Constituents and Other Soil Properties

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### ABSTRACT

This study was carried out to determine the distribution of organic matter and its constituents, as well as other soil properties, in various aggregate size fractions for four soil types in Malaysia, and to investigate the relationship and relative importance of these soil properties on aggregate stability. The four soil series with contrasting particle size distributions used were Munchong (Typic Hapludox), Melaka (Xanthic Hapludox), Rengam (Typic Paleudult), and Bungor (Typic Paleudult). The top soil, i.e. 0-15 cm of the soils of the four soil series was sampled and analyzed for their particle size distribution, aggregation, aggregate stability, organic matter, humic acids (HA), fulvic acids (FA), polysaccharides, functional groups of HA and FA (carboxylic, COOH, and phenolic-OH), and free Fe and Al oxides. Multiple linear regression revealed that silt, followed by free Fe oxides, fine sand, FA-OH, and HA-COOH, were the most important soil constituents to explain the observed differences in the aggregate stability between the four soil types. Generally, as the aggregate size decreased, the amount of clay, silt, OM, and free Fe oxides would also increase, while the aggregation and the amount of sand would decrease. As for the Rengam and Bungor series, the aggregate stability would generally increase with the decreasing aggregate size. Meanwhile, the observed differences in the amounts of HA, FA, and polysaccharides were mainly due to the differences in the soil types.

**Keywords:** Aggregate size, aggregate stability, fulvic acids, humic acids, humic substances, organic matter, polysaccharides

### INTRODUCTION

Aggregate stability is a measure of soil aggregates resistance to breakdown by the destructive forces of water or wind. Consequently, aggregate stability is an important soil property used to evaluate the risk of soil erosion and deterioration of soil structure. Aggregate stability is dependent on many factors, particularly on organic matter, soil texture, and oxide contents (Zhang & Horn, 2001).

Although the importance of organic matter to improve soil aggregate stability is well known (Chenu *et al.*, 2000; Boix-Fayos *et al.*, 2001; Six *et al.*, 2004; Noellemeyer *et al.*, 2008), the

experiments showing the beneficial effects of organic matter on aggregate stability have been varied. For instance, some workers (Chaney & Swift, 1984; Christensen, 1986) found a significant correlation between organic matter and aggregate stability, while others (Hamblin & Greenland, 1977; Dormaar, 1983; Li *et al.*, 2010) observed that it was the constituents of organic matter (polysaccharides, humic acids, or fulvic acids), rather than the total organic matter that were important to aggregate stability. There are also differences in the results in term of the type of organic matter constituents responsible for aggregate stability. Mehta *et al.* (1960) and

Acton *et al.* (1963) noted that polysaccharides correlated positively with aggregate stability, but Chaney and Swift (1984, 1986) ascribed it to humic acids. Fortun *et al.* (1989), however, found that the combination of humic acids, whereas fulvic acids was the most effective in increasing aggregate stability. These varied results reveal the diverse nature of organic matter.

In addition, aggregate stability is also affected by aggregate size. As aggregate increases in size, its mass will rise more rapidly than its surface area because the surface area increases with the square of the radius, and the volume with the cube of the radius. Hence, gravity, counteracting adhesion, rises in proportion to the aggregate mass. Therefore, as the aggregate size increases, the adhesive forces remain constant, but the counteracting forces increase. Consequently, larger aggregates will eventually become increasingly less stable (Tisdall & Oades, 1982; Brady, 1990). Moreover, there is a difference between cementing agents responsible for the stability of macroaggregates (those larger than 250  $\mu\text{m}$ ) and microaggregates (<250  $\mu\text{m}$ ). Microaggregates are stabilized by persistent aromatic humic material associated with amorphous Fe and Al compounds, whereas the stability of macroaggregates are stabilized by the transient or temporary binding agents such as roots, hyphae, and microbial- and plant-derived polysaccharides (Tisdall & Oades, 1982). Nwadiolo and Mbagwu (1991) used principal component analysis to reveal that the microaggregate stability of seven Italian soils of different pedogenesis was related mainly to soil mineralogy, while organic matter had been shown to have little effect.

The effects of organic matter constituents were found to vary between temperate and tropical soils. In the temperate soils, for instance, humic acids are more effective in increasing aggregate stability than fulvic acids, but in tropical soils including soils in Malaysia, it is fulvic acids that are usually more effective (Soong, 1980; Tajuddin, 1992; Theng *et al.*, 1989). Fulvic acids may perform better than humic acids for the tropical soils, and this is

simply because there are more fulvic acids in the tropical soils than in the temperate soils (which have more humic acids than in tropical soils) (Theng *et al.*, 1989). In Peninsular Malaysia, for example, fulvic acids consist 75-90% of the organic carbon (Zainab, 1977). The humic acids are converted into fulvic acids at a faster rate in the tropical soils because of the higher organic matter turnover rate in tropical soils than in the temperate soils (Greenland *et al.*, 1992).

Unfortunately, the relationship between aggregate stability and organic matter constituents are seldom studied for the soil series in Malaysia. Consequently, the objectives of this study were: 1) to determine the distribution of organic matter and its constituents, as well as other soil properties, in various aggregate size fractions for four soil types in Malaysia, and 2) to determine the relationship and relative importance of these soil properties on aggregate stability.

## MATERIALS AND METHODS

Four soil series, commonly found in Malaysia, namely Munchong (Typic Hapludox), Melaka (Xanthic Hapludox), Rengam (Typic Paleudult), and Bungor (Typic Paleudult) were selected for this study. Based on the preliminary analyses, these soil series were selected because their particle size distributions are different from one another. The Munchong soil series (73% clay, 18% sand; land use: oil palm) and Melaka soil series (53% clay, 21% sand; land use: pine) were sampled from the farms at Universiti Putra Malaysia (2° 59' 59" N and 101° 42' 45" E), whereas the Rengam (41% clay, 52% sand; land use: rubber) and Bungor soil series (30% clay, 65% sand; land use: grassland) were sampled from the experimental sites of the Malaysian Rubber Board at Sungai Buloh (3° 9' 30" N and 101° 33' 33" E). Each soil series was sampled at the soil depth of 0-150 mm randomly around the field, bulked, and then air-dried for one week before any laboratory analysis was done.

Each of these four selected soils was then separated into three macro- and microaggregate size fractions, respectively, which were: 1) 1000-

2000  $\mu\text{m}$ , 2) 500-1000  $\mu\text{m}$ , 3) 250-500  $\mu\text{m}$ , 4) 150-250  $\mu\text{m}$ , 5) 50-150  $\mu\text{m}$ , and 6) <50 $\mu\text{m}$ . Each aggregate size fraction was analyzed for the following (with three replications each): 1) particle size distribution (pipette method; Gee & Bauder, 1986), 2) aggregation, 3) aggregate stability, 4) organic carbon (Walkley-Black dichromate titration method, with organic matter content taken as  $1.72 \times$  organic carbon; Walkley & Black, 1934), 5) humic substances (humic acids and fulvic acids), 6) polysaccharides, 7) functional groups of humic substances, and 8) free Fe and Al oxides.

Aggregation was expressed in percentage, determined from the fraction of weight of a given aggregate size fraction to the weight of all the aggregates sized below 8.0 mm.

Meanwhile, aggregate stability was expressed using the index WDCS (water dispersible clay and silt). The method of Soil Survey Laboratory Staff (1992) was employed in the present study. Five grams of uncrushed soil (<2 mm) was added to 50 ml distilled water (ratio soil to water was 1:10), and end-over-end shaking for 30 minutes and 40 rounds-per-minute (rpm). The contents were then poured into a 1-liter measuring cylinder, and the volume was made up to one litre. The solution was gently stroked up-down to distribute the contents, and then left for four minutes for the undispersed aggregates and sand particles to settle to the bottom. The clay and silt particles were then siphoned at 10 cm depth using a 25 ml pipette. At the appropriate settling time, the clay particles were then siphoned at 10 cm depth using a 25 ml pipette. Later, these values were used to calculate the stability index WDCS in the following manner:

$$WDCS = \frac{\% \text{ dispersed clay and silt}}{\% \text{ clay and silt (from particle size analysis)}} \times 100$$

The method by Norhayati and Verloo (1984) was used to extract, fractionate, and purify the humic substances (humic acids and fulvic acids) and polysaccharides. This method is also described in detail by Tajuddin (1992).

The extracted humic acids and fulvic acids were each analyzed for the functional groups COOH and phenolic-OH, as described by Schnitzer (1986). Meanwhile, the phenolic-OH groups were determined indirectly by subtraction. Total acidity of the humic material was determined first (Schnitzer, 1986), and this was followed by calculating the phenolic-OH in the following manner: meq total acidity/g humic material - meq COOH groups/g humic material = meq phenolic-OH groups/g humic material.

Free iron and aluminium oxides were simultaneously extracted with citrate-bicarbonate-dithionite (CBD) solution, as described by Mehra and Jackson (1960). However, because the Al content was low, it was determined calorimetrically using the Aluminon method. The Al amount was read using the UV-Visible spectrophotometer at wavelength 530 nm.

Data was analyzed as a 4 x 6 CRD (Completely Randomized Design) factorial experiment: four soil series and six aggregate size fractions. For each of the parameters studied, the analysis of variance (ANOVA) was used to detect any significant effect of the main effects and their interaction. In order to determine the relationship between each of the three aggregate stability indices with the soil constituents, the multiple linear regression was used. All the statistical analyses (including ridge trace) were done using SPSS for Windows version 6.0 (SPSS Inc., Chicago).

## RESULTS

Some of the measured soil parameters had to be transformed as they violated the assumptions of normality and homogeneity of variance. The following variables were transformed to correct these violations (skewness followed by kurtosis values are shown in brackets): silt (1.13, 0.82), very fine sand (2.61, 7.46), fine sand (2.34, 6.86), humic acids (HA) (1.82, 4.42), fulvic acids (FA) (2.66, 8.96), aggregation (0.98, -0.04), and WDCS (1.09, 0.57). These variables were transformed by  $\ln(2X+e)$ , where X is the variable to be transformed and e is the natural

logarithm. However, the carboxylic functional group of humic acids (HA-COOH) (0.75, -0.82) was transformed by  $\ln(X)$ .

The physical and chemical characteristics of the six aggregate size fractions for the four soil types are shown in Table 1. Meanwhile, the partial ANOVA results of the main and interaction effects are shown in Table 2, where  $\eta^2$  (eta-squared), which is the proportion of the variation accounted for by the main and interaction effects,

are shown in brackets. In short,  $\eta^2$  measures the strength of an experimental effect.

The observed differences in the particle size distribution (clay, silt, and the various sand size fractions), organic matter (OM), and free Fe oxides were significant due to the three experimental effects (Table 2). This means that the amounts of clay, silt, sand, OM, and free Fe oxides in an aggregate would depend on the aggregate size, as well as the type of soil.

TABLE 1  
Mean characteristics of the six aggregate size fractions for the four soil types (all values are in percentages, unless otherwise stated)

Soil series and aggregate size fractions ( $\mu\text{m}$ )	clay < 2 $\mu\text{m}$	silt 2-20 $\mu\text{m}$	sand > 50 $\mu\text{m}$	very fine sand 50-100 $\mu\text{m}$	fine sand 100-250 $\mu\text{m}$	aggregation	WDCS	free Fe oxides	free Al oxides
<b>MUNCHONG</b>									
1000-2000	71.15	7.67	21.19	2.34	5.41	12.24	11.93	3.92	0.16
500-1000	72.47	7.46	20.07	2.50	5.24	11.28	9.84	3.48	0.19
250-500	74.61	7.08	18.31	2.09	7.32	7.41	10.28	3.73	0.18
150-250	69.95	15.33	15.02	2.46	12.56	3.92	12.63	3.52	0.16
50-150	83.51	8.29	8.21	5.82	2.39	4.94	24.91	3.59	0.21
< 50	87.95	12.05	-	-	-	0.77	84.66	4.36	0.22
<b>MELAKA</b>									
1000-2000	49.42	21.72	28.86	5.53	6.00	9.02	44.33	3.26	0.14
500-1000	41.81	21.14	37.05	4.34	4.56	5.05	46.60	2.42	0.12
250-500	48.80	22.95	28.25	4.31	6.63	2.03	40.51	3.04	0.15
150-250	51.84	22.84	25.32	3.75	21.56	1.35	39.81	2.87	0.15
50-150	54.88	22.73	22.39	16.50	5.89	2.14	44.06	2.97	0.12
< 50	61.73	38.27	-	-	-	0.49	52.60	3.15	0.16
<b>RENGAM</b>									
1000-2000	37.28	1.13	61.59	1.88	5.38	21.91	35.06	1.36	0.05
500-1000	38.50	1.86	59.63	1.80	4.84	22.96	32.35	1.23	0.08
250-500	52.78	2.16	45.06	2.36	12.08	10.24	27.42	1.66	0.12
150-250	66.65	3.07	30.28	4.43	25.85	4.03	27.83	1.87	0.15
50-150	80.68	3.19	16.13	10.38	5.75	2.46	29.65	2.20	0.14
< 50	91.92	8.08	-	-	-	0.22	85.47	2.44	0.13
<b>BUNGOR</b>									
1000-2000	31.79	2.33	65.88	8.00	26.38	9.53	18.56	1.91	0.12
500-1000	25.79	1.49	72.71	5.64	17.16	18.91	15.15	1.55	0.13
250-500	22.52	2.09	75.38	4.11	24.87	23.23	16.25	1.42	0.11
150-250	30.13	2.52	67.35	6.32	61.03	11.12	12.86	1.82	0.18
50-150	50.33	4.08	45.58	26.69	18.89	7.46	10.90	2.60	0.15
< 50	82.18	17.82	-	-	-	0.98	74.17	3.38	0.20

TABLE 1 (continued)

Soil series and aggregate size fractions ( $\mu\text{m}$ )	OM %	HA mg /g	FA mg /g	HA-COOH meq /100g	HA-OH meq /100g	FA-COOH meq /100g	FA-OH meq /100g	Polysaccharides mg /g
<b>MUNCHONG</b>								
1000-2000	4.84	0.75	5.68	4.01	3.63	2.38	0.33	19.47
500-1000	4.91	1.11	9.05	2.35	3.51	1.53	1.37	11.34
250-500	4.79	1.04	2.08	2.48	3.39	7.38	1.34	8.06
150-250	5.04	1.44	3.06	2.54	2.93	3.67	0.44	12.98
50-150	5.60	1.13	2.62	2.57	2.92	2.71	2.28	8.44
< 50	6.21	0.57	2.39	4.38	3.58	3.40	4.80	7.77
<b>MELAKA</b>								
1000-2000	3.12	3.18	2.70	2.47	4.61	5.47	4.19	9.83
500-1000	2.92	7.62	2.94	1.97	2.20	6.05	1.45	6.18
250-500	2.87	4.57	3.15	2.25	3.00	3.07	2.31	6.09
150-250	2.61	2.01	2.24	2.62	4.78	6.08	4.22	9.81
50-150	2.76	2.36	2.62	2.69	5.28	3.85	0.47	8.13
< 50	3.11	2.47	2.55	2.53	3.03	6.46	6.57	11.68
<b>RENGAM</b>								
1000-2000	2.01	0.47	2.35	5.00	6.43	2.48	2.99	8.54
500-1000	2.10	0.32	2.50	4.74	1.07	4.39	1.03	7.41
250-500	2.75	0.39	2.18	4.76	3.86	4.97	8.19	7.05
150-250	3.65	0.64	2.08	4.21	8.02	6.72	5.46	10.17
50-150	4.54	0.50	2.60	5.56	0.25	5.22	3.49	14.43
< 50	5.30	0.57	2.38	4.76	1.25	6.13	0.28	10.25
<b>BUNGOR</b>								
1000-2000	3.57	2.50	2.04	2.90	5.24	5.01	5.61	8.52
500-1000	2.50	2.21	2.02	2.96	5.39	6.14	3.13	10.69
250-500	2.34	1.72	1.67	2.84	5.30	5.92	3.97	17.91
150-250	2.82	2.11	1.83	3.17	5.64	4.81	5.69	12.76
50-150	4.54	3.54	2.17	3.11	4.54	6.73	3.40	14.14
< 50	6.90	3.64	2.14	3.18	5.87	5.88	5.93	12.20

Generally, as the aggregate size decreased, the amount of clay, silt, OM, and free Fe oxides would increase (Table 1). As expected, the distribution of sand was the opposite of the distribution of clay. For all the soil series, the aggregate size fraction 50-150  $\mu\text{m}$  had the highest amount of very fine sand, whereas the aggregate size fraction 150-250  $\mu\text{m}$  had the highest amount of fine sand.

Like free Fe oxides, the observed differences in free Al oxides were also significantly affected by the three experimental effects (Table 2), but its distribution was less varied than that of free Fe oxides. Within the same soil, there was a

weaker, less clearer trend that the amount of free Al oxides would increase with the decreasing aggregate size (Table 1). For the Melaka series, moreover, the amount of free Al oxides between the six aggregate size fractions were statistically similar to one another (Table 2), and that there was no significant differences in the amount of free Al oxides between the four soils in the aggregate size fraction 150-250  $\mu\text{m}$ .

Aggregation (that is, the proportion of an aggregate size fraction to the whole soil <8 mm) would progressively decrease with the reducing aggregate size (Table 1). However, for all the soil series, the differences in the aggregation

for the smallest aggregate size fraction <50  $\mu\text{m}$  between the four soils were not significant (Table 2).

Aggregate stability (WDCS) showed that the Melaka series was the least stable (Table 1). As for the average across all the six aggregate size fractions, the Bungor soil series was the most stable (that is, having the lowest WDCS), followed by the Munchong, and Rengam soil series. The least stable was the Melaka series. Additionally, the stability found in all the six aggregate size fractions in the Melaka soil series was insignificantly different from one other (Table 2). For all the soil series (except for the Melaka soil series), the WDCS would steeply increase for the smallest aggregate size fraction <50  $\mu\text{m}$  (Table 1). As for the Rengam and Bungor series, there was a general trend that with decreasing aggregate size, aggregate stability would increase.

Nevertheless, aggregate size did not significantly influence the amount of humic acids in the soils (Table 2). The observed differences in the amount of humic acids between the soils and aggregate size fractions were only due to the main effect and the interaction effect of the soil series. Moreover, within the Munchong and Rengam series, the amount of humic acids was not significantly different between the six aggregate size fractions. Within the same soil series, the amount of humic acids between the six aggregate size fractions was generally similar to one another (Table 1). This is considering the fact that the soil series main effect could explain more of the total variation of humic acids than the interaction effect (Table 2). The observed differences in the amount of fulvic acids were significantly caused only by the differences in the soil series. Within the same soil, there were no significant differences in the amount of fulvic acids between the various aggregate size fractions. This was indicated by the insignificant effects by both the aggregate size main effect and the interaction effect.

Generally, there should be more fulvic acids than humic acids in tropical soils due to the higher organic matter turnover rate (Greenland *et al.*, 1992) which would convert humic acids into

fulvic acids at a faster rate in the tropical soils than that in the temperate soils (Mendonça *et al.*, 1991). This study, however, showed that the amount of fulvic acids was significantly greater than humic acids for only the Munchong and Rengam soil series ( $t=4.405$ ;  $df=11$ ;  $p<0.001$ ), but there were no significant differences between their amounts ( $t=2.078$ ;  $df=11$ ;  $p<0.062$ ) for both the Melaka and Bungor soil series.

For the carboxylic functional groups in humic acids (HA-COOH), only the soil series main effect could explain the total observed variation (Table 2). Once again, this reveals that the observed differences in the HA-COOH amount were only due to the differences in the soil series. On the other hand, the amount of carboxylic groups in fulvic acids (FA-COOH) was influenced by the three experimental effects, of which the interaction effect was the greatest (Table 2). Generally, the amount of the COOH groups in fulvic acids was more than those of humic acids (Table 1). The COOH groups in fulvic acids ranged from 1.53 to 7.38 meq/100g soil, whilst the COOH groups in humic acids ranged from 1.97 to 5.56 meq/100 g soil.

Note that ANOVA was not done on phenolic-OH groups for either humic acid (HA-OH) or fulvic acids (FA-OH). As stated earlier, the amount of phenolic-OH groups was determined by subtracting the amount of COOH groups from total acidity. As the means of the three replications were used for the subtraction, phenolic-OH determination would not have any replications. Therefore, the explained variance ( $\eta^2$ ) was also not done.

Finally, the observed differences in the amount of polysaccharides were significantly caused only by the differences in the soil types (Table 2); that is, the main effect of the soil series was significant at 5% level, which is in contrast to the insignificant aggregate size main effect and interaction effect.

Meanwhile, the correlations between aggregate stability and the soil constituents showed that very few constituents correlated significantly with aggregate stability (WDCS) (Table 3). In particular, only silt and polysaccharides correlated significantly with

TABLE 2  
 Partial ANOVA results of the main effects and interaction effect (measure of the experimental effect or *eta*-squared,  $\eta^2$ , in brackets)

Parameter	MSE	Main effect		Interaction	Insignificant simple effects at 5% level
		Soil series (S)	Aggregate size (A)	(S x A)	
		F-statistic	F-statistic	F-statistic	
Clay	3.78	1118.85** (0.986)	624.42** (0.985)	86.25** (0.964)	None
Silt	0.03	455.48** (0.966)	61.28** (0.865)	9.03** (0.738)	None
Sand	1.47	4507.49** (0.997)	771.46** (0.987)	132.83** (0.976)	None
Very fine sand	<0.01	1149.07** (0.989)	1535.87** (0.994)	74.11** (0.957)	None
Fine sand	<0.01	1748.66** (0.992)	995.55** (0.990)	38.65** (0.921)	None
Aggregation	0.04	81.81** (0.836)	185.50** (0.951)	12.89** (0.801)	(S) within <50 $\mu$ m
WDCS	0.02	189.25** (0.922)	147.74** (0.939)	20.32** (0.864)	(A) within Melaka
Free Fe oxides	0.03	452.64** (0.966)	60.14** (0.862)	11.00** (0.775)	None
Free Al oxides	<0.01	23.14** (0.591)	7.60** (0.442)	2.20* (0.407)	(S) within 150-250 $\mu$ m; (A) within Melaka
OM	0.01	1487.93** (0.989)	769.63** (0.988)	165.89** (0.981)	None
HA	0.03	117.66** (0.880)	1.57 <sup>ns</sup> (0.141)	5.89** (0.648)	(A) within Munchong and Rengam
FA	0.05	7.19** (0.310)	1.86 <sup>ns</sup> (0.163)	1.01 <sup>ns</sup> (0.240)	All
HA-COOH	0.03	35.62** (0.817)	2.41 <sup>ns</sup> (0.334)	1.44 <sup>ns</sup> (0.474)	All
FA-COOH	1.50	10.86** (0.404)	3.24* (0.252)	4.79** (0.600)	(A) within Bungor
Polysaccharides	20.94	2.81* (0.149)	0.65 <sup>ns</sup> (0.064)	1.82 <sup>ns</sup> (0.362)	All

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; <sup>ns</sup> not significant at 5% level

the WDCS. Their signs indicated that greater amounts of silt and polysaccharides would decrease and increase aggregate stability, respectively.

However, Lapin (1993) explained that the correlations and simple linear regressions do not reveal joint contributions of factors on the

dependent variable. This also means that a factor may not correlate significantly to aggregate stability, but yet when its contribution is included with the effects of other factors, its contribution to aggregate stability may become significant. One way to reveal such joint contributions is by multiple linear regression.

TABLE 3  
Correlations between aggregate stability and soil constituents

Parameter	WDCS
Clay	0.301 <sup>ns</sup>
Silt	0.461*
Sand	-0.094 <sup>ns</sup>
Very fine sand	0.043 <sup>ns</sup>
Fine sand	-0.332 <sup>ns</sup>
Free Fe oxides	0.095 <sup>ns</sup>
Free Al oxides	-0.039 <sup>ns</sup>
OM	0.097 <sup>ns</sup>
HA	0.088 <sup>ns</sup>
FA	-0.043 <sup>ns</sup>
HA-COOH	0.203 <sup>ns</sup>
HA-OH	-0.145 <sup>ns</sup>
FA-COOH	0.100 <sup>ns</sup>
FA-OH	0.177 <sup>ns</sup>
Polysaccharides	-0.430*

\*  $p < 0.05$ ; <sup>ns</sup> not significant at 5% level

However, including all variables into a regression model was found to be inappropriate because there were symptoms of severe multicollinearity, whereby some variables were highly correlated or dependent on each other. Collinearity diagnostics were performed according to methods described by Belsley *et al.* (1980), Dougherty (1990), and Lardaro (1993). Meanwhile, VIF (variance inflation factors) were calculated for each variable, where any variables with VIF values above 4 or 5 revealed collinearity with others. The larger the VIF, the more a variable is dependent on others. This study found that more than half of the variables were affected by collinearity, with the largest being clay, OM, silt, free Fe oxides, and HA-COOH (all their VIF values exceeded 20). Moreover, the condition number of the collinearity matrix was 151.675, i.e. about five times more than the multicollinearity threshold of 30. As multicollinearity was present, the method of least squares applied to non-orthogonal (correlated) variables would produce poor estimates of the regression coefficients. One way to reduce multicollinearity is to remove unimportant variables from the regression equation. Nonetheless, usual variable selection

methods (such as stepwise regression, forward selection, and backward elimination) would be unsuitable for highly correlated variables. In this study, multicollinearity was reduced by making the regressors orthogonal or nearly so with biased estimators using the ridge trace method (Hoerl & Kennard, 1970).

TABLE 4  
Multiple regression coefficients for WDCS (criterion variable) at different stages of variable selection

Predictor	Variable selection stage	
	Full model	Final model
Clay	-0.015 <sup>ns</sup>	-
Silt	1.095*	0.794**
Very fine sand	-0.073 <sup>ns</sup>	-
Fine sand	-0.600*	-0.388**
OM	0.197 <sup>ns</sup>	-
HA	0.035 <sup>ns</sup>	-
FA	-1.183 <sup>ns</sup>	-
HA-COOH	1.466 <sup>ns</sup>	0.571*
HA-OH	0.080 <sup>ns</sup>	-
FA-COOH	-0.009 <sup>ns</sup>	-
FA-OH	0.042 <sup>ns</sup>	0.084**
Polysaccharides	-0.014 <sup>ns</sup>	-
Free Fe oxides	-0.682*	-0.599**
Free Al oxides	4.107 <sup>ns</sup>	-
Intercept	3.325*	3.607**
SSE	0.194	0.437
MSE	0.039	0.031
Standard error	0.197	0.177
Adjusted R <sup>2</sup>	0.855	0.883
F-statistic	8.985*	29.694**
c.v. (%)	4.864	4.360

\*  $p < 0.05$ ; \*\*  $p < 0.01$ ; <sup>ns</sup> not significant at 5% level

The multiple regression model for the WDCS is shown in Table 4. Although including all the variables into the model (that is, the full model) produced a significant regression model, a low SSE, and a high adjusted R<sup>2</sup>, the regression coefficients would be inaccurate, as described earlier. Following the ridge trace method, two criteria were compiled: (a) remove variables that are stable but with small prediction power, and (b) remove unstable variables that are driven to near zero values. Consequently, the following



variables were removed: clay, very fine sand, organic matter, humic acids, fulvic acids, HA-OH, FA-COOH, polysaccharides, and free Fe and Al oxides. Clay, for example, was removed as its values were unstable and were driven to almost zero value. Likewise, humic acids variable, though stable, was also removed as it had small predictive power. Meanwhile, selected variables were fitted into a new regression model. In order to further improve the model's fit, non-influential and multicollinear variables were removed, but they were tested if their removal would significantly inflate the SSE (sum of squared error) compared to the SSE of the full model before any removal. In this study, the Wald's test (Lardaro, 1993) was used. The best regression model was selected based on the following criteria; low SSE and MSE, high F-statistic, high adjusted  $R^2$ , low standard error of estimate, low standard error for each predictor variable and low correlations among predictor variables.

The final multiple linear regression model is presented in the last column in Table 4. The final model has the following variables: silt, fine sand, free Fe oxides, HA-COOH, and FA-OH. A proper variable selection greatly reduced the multicollinearity effects. The VIF values for all the variables were greatly reduced, and none of them exceeded the critical VIF value of 4 (Table 5). With multicollinearity reduced, the variables fitted better, showing improvement in the adjusted  $R^2$ , MSE, standard error of estimate, and F-statistic value (Table 4).

In Table 5, the five soil constituents contributed significantly to the regression model of WDCS, although each of their correlations with WDCS was low, and the highest was silt ( $r=0.37$ ). These findings illustrated the fact that a variable might not correlate strongly or even significantly with WDCS, but would still contribute significantly when other variables were accounted with it in a multiple regression model. Higher values of WDCS were associated with higher values of silt, HA-COOH and FA-OH, suggesting that any increase in dispersibility (or decrease in aggregate stability) would be attributed to higher amounts of silt, HA-

COOH, and FA-OH, but higher amounts of fine sand and free Fe oxides would be attributed to lower dispersibilities (or increases in aggregate stability).

The relative importance of a soil constituent on WDCS can only be determined by its semi-partial correlation to WDCS. Semi-partial  $r$  is the correlation of a variable to WDCS after the contributions of all other variables on WDCS are removed. The square of a variable's semi-partial  $r$  is then the decrement in  $R^2$  if this variable is eliminated from the model. Therefore, the measure of a variable's "usefulness" in a regression model is its semi-partial  $r$  to the criterion variable, not its standardized regression coefficient (Darlington, 1990). Based on the values of the semi-partial  $r$  from Table 5, silt was found to be relatively the most important soil constituent in explaining WDCS, followed by free Fe oxides, fine sand, FA-OH, and lastly, HA-COOH.

## DISCUSSION

Using the multiple regression has been shown to have improved the interpretation of the results by revealing joint contributions of soil constituents on aggregate stability. Though multicollinearity was a serious problem in this study, multicollinearity was also expected because this study dealt with many constituents that would interact or correlate with one another.

The multiple linear regression model (after correcting for multicollinearity) showed that dispersibility (WDCS) increased with the increasing amounts of silt, HA-COOH, and FA-OH. Meanwhile, the relationship between the latter two with aggregate stability contradicts with the common notion that functional groups of humic substances should reduce, not increase, dispersion.

The role by humic substances, however, is not always shown to be beneficial to aggregate stability. Several researchers have shown that increasing amounts of organic matter or its fractions (humic acids and fulvic acids) can promote dispersion (Gillman, 1974; Shanmuganathan & Oades, 1983; Mbagwu *et*

TABLE 5  
Variables in the final regression model for the WDSCS

Parameter	standard error of regression coefficient	<i>r</i>	Semipartial <i>r</i>	VIF
Silt	0.086	0.365	0.724	3.077
Free Fe oxides	0.072	-0.214	-0.655	2.455
Fine sand	0.078	-0.332	-0.391	1.934
FA-OH	0.027	0.100	0.243	1.969
HA-COOH	0.202	0.056	0.197	2.250
Intercept	0.542			

*al.*, 1993; Nelson *et al.*, 1999). Organic matter and its fractions can increase dispersion because as more organic anions are sorbed onto colloid surfaces, they increase the negative charges on these surfaces, and thus, increase the diffuse layer of cations as well (Oades, 1984). With this increase, the net negative charge on the surfaces is also increased; thus, promoting dispersion. Therefore, the functional groups of humic substances, namely COOH and phenolic-OH that are mainly responsible for the binding of the humic molecules in clay minerals (Kononova, 1966; Schnitzer & Kodoma, 1977; Theng, 1979), may instead help to increase dispersion and lower aggregate stability.

Moreover, this study revealed that the contribution of FA-OH was more adverse on aggregate stability than of HA-COOH. Nayak *et al.* (1990) observed the same results in their study on three types of soil. They explained that increasing the amount of acidic groups (such as fulvic acids) would increase the inter-particle repulsion between clay and humic molecules. Furthermore, the more acidic groups will tend to be strongly hydrated, and this hydration energy is strong enough to disrupt bonds between clay and humus. As fulvic acids are more acidic than humic acids, fulvic acids would increase the inter-particle repulsion more and would yield stronger hydration energy than as humic acids would.

Silt explained the variability of the WDSCS the most; however, its correlation was positive, indicating that increasing the amount of silt is associated with increasing dispersibility. The results from this study are in agreement with

the findings by Voronin and Sereda (1976) and Soong (1977, 1980). The role of silt in aggregate stability is actually still unclear, while the correlations involving silt with aggregate stability have either been significantly positive or negative, and at times, the correlations are insignificant. For example, Levy *et al.* (1993) discovered that when the amount of clay and silt exceeded 15%, clay dispersion would exceed 40%. The soil series with less than 15% clay and silt, on the contrary, had less than 40% clay dispersion. Wustamidin and Douglas (1985), however, found silt to correlate positively and significantly with aggregate stability.

Free Fe oxides were the second most important contributor to the regression model to explain WDSCS. Similarly, Zhang and Horn (2001) obtained a significant effect by free Fe oxides on aggregate stability. Free Fe oxides can increase the binding strength within aggregates by growing crystals between matrixes of particles; thus, producing a stable and non-dispersible matrix (Shadfian *et al.*, 1985). Similarly, free Fe oxides were also found to reduce the critical coagulation concentrations and clay swelling (Goldberg, 1989). The useful effects of Fe oxides have been demonstrated in many other ways, which include: 1) by significant correlations between aggregate stability and Fe oxides (Arca & Weed, 1966; Murthi & Huang, 1987); 2) by electron optical observations of Fe oxides deposits on kaolinite platelets (Fordham & Noorish, 1983; Kitagawa, 1983); 3) by the dispersion of aggregated soils after the removal of their Fe oxides with reducing agents (McNeal *et al.*, 1968); and 4) by the aggregating effect of

added synthetic Fe oxides (Blackmore, 1973). Although free Al oxides are thought to be better than Fe oxides because free Al oxides has a platy structure and is more chemically stable, free Al oxides did not contribute significantly to aggregate stability in this study. This could be due to the low variability and amount of free Al oxides among the soils and aggregate size fractions.

After silt and free Fe oxides, fine sand was the most important constituent in explaining WDCS. In this context, the negative contribution of fine sand to dispersibility also means that with increasing amount of fine sand, aggregate stability is increased. This observation follows the well-known aggregate model by Emerson (1959), whereby for the formation of stable aggregates, fine sand particles are also required.

It is now known which soil constituents contributed significantly to explain aggregate stability. This can help to relate the distribution patterns of some soil constituents with dispersibility.

For the Rengam and Bungor series, as their aggregate size decreased, dispersibility, as measured by WDCS, would generally decrease. Similarly, Zhang and Horn (2001) also observed that for several Ultisols in China, aggregate stability would increase with decreasing aggregate size. This increasing trend in aggregate stability followed the general increasing trend for the amount of fine sand and free Fe oxides. With successively smaller aggregates, the amount of fine sand and free Fe oxides would generally increase, and subsequently increase aggregate stability. Nevertheless, the smallest aggregate size fraction of  $<50 \mu\text{m}$  for all the soil series (except for the Melaka series) was exceptional because its dispersibility was, in contrast, the highest. This was due to the sharp increase in the amount of silt in this aggregate size fraction. The acute increase in dispersion could also be explained by the sudden absence of finer-sized sand particles, especially the fine sand fraction. For larger aggregate size fractions, dispersibility was much smaller, and this was probably due to the combination of clay and finer sand particles to form relatively stable aggregates.

With the absence of the finer sand particles for aggregates smaller than  $50 \mu\text{m}$ , however, the stability of aggregates would decrease drastically (dispersing very easily). The importance of silt could also be seen for the Melaka soil which had the lowest aggregate stability and the highest amount of silt among the four soils.

The contributions of the organic matter and its fractions, polysaccharides, humic acids and fulvic acids, were each insignificant to explain the WDCS. This was due to the low variability of their amounts among the aggregate size fractions. This low variability among the aggregate size fractions is contrary to some previous work. Mendonça *et al.* (1991), for example, found that the macroaggregates in Oxisols had more fulvic acids and less humic acids than in microaggregates. On the other hand, Chakraborty *et al.* (1981) observed that with increasing aggregate size until 5.0 mm, the amount of both humic acids and fulvic acids increased, but the increase of humic acids was more than of fulvic acids. The distribution pattern of humic substances in the aggregates sizes would depend on the soil type and other environmental factors (Loveland & Webb, 2003). The whole soil used by Mendonça *et al.* (1991), for example, had more fulvic acids than humic acids, but the whole soils used by Chakraborty *et al.* (1981) had more humic acids than fulvic acids.

The distribution of the acidic functional groups of either humic acids or fulvic acids did not follow a particular trend among the aggregate size fractions. This could be the reason for the relatively low contributions of HA-COOH and FA-OH on aggregate stability.

## CONCLUSIONS

In the present study, the multiple linear regression revealed that silt was the most important soil constituent to explain the observed differences in aggregate stability between the four soil types. This was followed by free Fe oxides, fine sand, FA-OH, and HA-COOH. With the increasing amounts of silt, FA-OH, and HA-COOH, aggregate stability would decrease, whereas

aggregate stability would instead increase with the increasing amounts of fine sand and free Fe oxides. Meanwhile, other soil constituents, such as clay, free Al oxides, humic acids, fulvic acids, and polysaccharides, did not significantly relate to aggregate stability.

Generally, as the aggregate size decreased, the amount of clay, silt, OM, and free Fe oxides would increase, whereas aggregation and the amount of sand would decrease. For the Rengam and Bungor soil series, aggregate stability would generally increase with the decreasing aggregate size.

The observed differences in the amounts of humic acids, fulvic acids, and polysaccharides were mainly due to the differences in soil types. Generally, within the same soil type, there were insignificant differences in the amount of humic acids, fulvic acids, and polysaccharides in the different aggregate size fractions.

Finally, the amount of fulvic acids in the Munchong and Rengam soil series was found to be significantly higher than the amount of humic acids, but the difference between their amounts was not significant for the Melaka and Bungor soil series.

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