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AGGREGATE STABILITY AND SUSCEPTIBILITY TO EROSION OF SOME HIGHLY WEATHERED SOILS IN PENINSULAR MALAYSIA

H. GHULAM MOHAMMED*

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RINGKASAN

Walaupun tanah terluluhawa di rantau tropika lazimnya dianggap sebagai tanah yang beragregat baik, terdapat beberapa perbezaan penting dalam ciri-ciri agregat tanah tersebut. Sifat-sifat dan kestabilan agregat mempengaruhi keupayaan tanah untuk menahan hakisan. Keputusan kajian mengutarakan dua faktor penting untuk kestabilan agregat, iaitu kandungan liat yang mencukupi dan nisbah kandungan bahan organik dan kandungan liat yang tinggi.

Empat siri tanah diuji dengan hujan tiruan selama satu jam dengan intensiti 35 mm sejam. Semuanya mengalami hakisan percik. Tetapi hakisan tersebut lebih tinggi bagi tanah yang kurang stabil, iaitu siri Munchong I dan siri Bungor. Hujan tiruan berturut-turut meningkatkan hakisan percik bagi tanah yang kurang stabil, tetapi tidak memberi sebarang kesan pada tanah yang stabil, seperti siri Rengam dan siri Kuantan. Tanah yang stabil ini tidak mengalami perceraian agregat semasa kajian ini dijalankan.

INTRODUCTION

The soil erosion process is made up of three important phases: detachment, transportation and deposition (ELLISON, 1947). The initial and essential step, detachment, depends greatly on the inherent properties of the soil aggregates, specifically on their stability against the force of raindrops and of running water (GREENLAND, 1977). In addition, the property of the soil to swell and slake when wetted also affects its ability to resist detachment by raindrops or by runoff. This is especially important when the soil is subjected to several rainstorms within a few days.

The stability of soils against detachment is particularly relevant to the Malaysian agricultural scene. This is because of the continuing soil erosion problems being experienced. Erosion in Peninsular Malaysia is attributed to two main factors. Firstly, the tropical rainfall regime with high annual total, high intensity and frequent occurrence of wet spells (DALE, 1960; NIEUWOLT, 1981) is highly erosive. Secondly, erosion is accelerated by the continuing replacement of the forest vegetation with agricultural crops and by rapid urban development.

The most serious erosion affects the sedentary soils which are mostly found in the inland areas, where slopes are a common topographic feature. They are highly weathered and leached, and belong to the Ultisol and Oxisol orders of Soil Taxonomy. The highly weathered soils of the tropics have often been described as having very stable aggregation associated with high contents of clay and the hydrous oxides of iron and aluminium. However, a more detailed check will reveal that, among this group of soils, there are some which are unstable. This may be due to one or more of the binding substances being present in small amounts only. A study of the aggregate stability of nine soil types by SOONG (1973) revealed that some topsoils, for example the topsoil (0–15 cm) of the Serdang series containing 15% clay, are significantly less stable than others such as the topsoils of Kuantan, Segamat and Prang series with clay contents ranging from 44% to 64 per cent. Subsoils (15 – 30 cm) were found to be less stable than topsoils (0 – 15 cm) because of lower organic matter and hydrous oxide contents. Areas where the

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*Central Research Laboratories Division, MARDI, Serdang, Selangor, Malaysia.

subsoil is exposed due to cultivation and other causes, are observed to suffer severe soil erosion.

The aim of this paper is to provide further information on the aggregation of some sedentary soils in Peninsular Malaysia. Although it is generally known that soils of lower stability are relatively more erodible, certain characteristics of soil aggregates and soil moisture content modify this relationship. Some of the main points arising from a laboratory study on aggregate stability and soil erosion are discussed.

SOILS

The soils of Peninsular Malaysia can be broadly classified into three groups *i.e.*, sedentary, reworked and alluvial. The alluvial soils occupy the coastal plains and river flood plains, whereas the sedentary soils are generally found in the inland areas. Since there are genetic differences between these groups, their physical characteristics also differ. This paper focusses on a number of the sedentary soils.

The sedentary soils are developed by the *in-situ* weathering of a variety of parent materials, including various types of igneous, metamorphic and sedimentary rocks. The intense weathering under the humid tropical climate of Peninsular Malaysia results in bases being leached, silica solubilised, and iron, aluminium and manganese preferentially retained. Thus, the soil profiles are normally low in bases and silica, but rich in iron and aluminium. The quantities of these substances present depend on the composition of the parent rock. For example, Kuantan series soil, derived from basalt, is very rich in both iron and aluminium, whereas Serdang series, derived from sandstone, has relatively lower amounts of those substances.

Humid tropical weathering conditions and time have brought about mineralogical changes through physical disintegration and chemical reaction resulting in the formation of clays. Thus, because of the advanced stage of weathering, the clay content tends to be high. However, this property is sometimes altered by terrain and the nature of the parent material. Soils derived from sandstone or granite, for example, tend to contain relatively higher amounts of quartz which is normally of sand size. Those located on steep slopes tend to lose a larger proportion of the finer material through erosion.

The soils used in this study are some sedentary soils of Peninsular Malaysia such as Bungor, Kuantan, Munchong, Rengam and Bukit Temiang. These soils show differences in parent material, texture and pedogenetic features as expressed by their classification according to Soil Taxonomy *(Table 1)*. The topsoil layer (0–15 cm), the layer most vulnerable to erosion, was investigated on.

METHODS

Mechanical Analysis

The soil sample which had passed through a 2–mm sieve, was used for the determination of particle size distribution. Organic matter was oxidised by hydrogen peroxide. A mixture of sodium hexametaphosphate and sodium carbonate was used as dispersant, and the samples were physically agitated. Clay and silt were determined by the pipette method (BLACK, EVANS, ENSMINGER, WHITE and CLARK, 1965).

Organic Matter Content and pH

The organic matter contents of the soils were determined by the Walkley and Black method. The values of soil pH in water were determined in a 1:5 soil to water ratio.

Iron and Aluminium Contents

'Total' iron and 'total' aluminium were extracted by aquaregia (COTTENIE, VERLOO, VELGHE and KIEKENS, 1979). 'Free' iron and 'free' aluminium were extracted by the dithionite-citrate-bicarbonate method (MEHRA and JACKSON, 1960). Iron and aluminium in solution were determined by atomic absorption spectrophotometry.

Table 1. Sampling location, classification, particle size distribution, pH and organic matter content of the topsoil layer (0–15 cm)

Soil series	Sampling site	Classification according to Soil Taxonomy	Particle size distribution (%)				Soil pH (in water)	OM content (%)	OM:Clay ratio
			Clay <2μm	Silt 2–20 μm	Fine sand 20–200 μm	Coarse sand >200 μm			
Bungor	Serdang, Selangor	Typic Palaeudult	42.1	1.7	33.3	22.9	4.8	2.80	0.066
Kuantan	Bukit Goh, Pahang	Haplic Acrorthox	63.5	25.3	6.5	4.7	4.7	4.53	0.071
Munchong I[+]	Serdang, Selangor	Tropeptic Haplorthox	71.3	6.8	11.4	10.5	4.5	2.87	0.040
Munchong II[+]	Serdang, Selangor	Tropeptic Haplorthox	67.1	13.4	11.5	8.0	5.6	3.48	0.052
Rengam	Sg. Buloh, Selangor	Typic Palaeudult	49.6	6.1	7.7	36.6	4.5	3.68	0.074
Bukit Temiang	Changkat Bruas Estate, Perak	Orthoxic Tropudult	22.3	10.9	14.8	52.0	4.8	1.92	0.086

[+] Munchong I and Munchong II were collected from two different sites. Some earth-moving activity appeared to have taken place at the site of Munchong I. It is expected that Munchong II would be more likely to exhibit the characteristics of the topsoil of a benchmark Munchong.

Aggregate Stability

Aggregate stability was initially assessed by subjecting aggregates to pressure between the thumb and forefinger. Then, it was determined by two other methods, namely dry-and-wet sieving (De Leenheer and De Boodt, 1967) and prolonged immersion in water.

One hundred aggregates in the size range of 2 mm to 8 mm were subjected to maximum pressure between the thumb and forefinger. The number of aggregates broken was noted to provide a preliminary assessment.

In the dry-and-wet sieving method, 1 500 g of air-dried soil (diameter < 8 mm) was sieved to obtain four size fractions, *i.e.*, 4.76–8.00, 2.83–4.76, 2.00–2.83 and < 2.00 millimetres. From here the aggregation percentage, that is the percentage of soil aggregates ≥ 2.00 mm diameter, was then calculated. For the wet sieving, 100 g of the fractions of 2.00–2.83, 2.83–4.76 and 4.76–8.00 mm in the same proportion as obtained in dry sieving, were used. Each of the three fractions was placed in a nickel cup and was wetted by large water drops falling from a height of 50 centimetres. Sufficient numbers of drops were added to bring the soil moisture content to field capacity. The wetted soil aggregates were kept in a high-humidity chamber for 24 hours.

The aggregates were then sieved under water for five minutes. Sieves with the following aperture sizes: 4.76, 2.83, 2.00, 1.00, 0.50 and 0.297 mm were used. The amount of soil retained on each sieve was dried and weighed.

The mean weight diameter (MWD) was calculated according to the formula of De Leenheer and De Boodt (1967).

$$\text{MWD} = \sum \begin{matrix}\text{\% weight}\\ \text{of soil}\end{matrix} \text{ x } \begin{matrix}\text{mean diameter of}\\ \text{the size fraction}\end{matrix}$$

The instability index is given by the difference between the MWD values of the dry aggregate distribution and the wet aggregate distribution.

To complement the results of the dry-and-wet sieving method in characterizing soil aggregate stability, the extent of dispersion and slaking of the soils was also assessed.

For each soil, about 300 aggregates in the size range of 3 mm to 5 mm were immersed in water for one week. It was observed earlier that the largest amount of stable aggregates was in this size range. Slaking and dipersion in water were allowed to take place without any disturbance. This was followed by drying according to the procedure described by GREENE-KELLY (1973).

The water was carefully replaced with a solution of an organic solvent, methanol. The concentration of the methanol solution used was progressively increased from 25%, 50%, 75% to 100 per cent. The solution was changed every 24 hours. The 100% methanol solution was replaced with ether which was allowed to evaporate giving dry soil aggregates.

The methanol conferred hardness to the aggregates, allowing size separation by sieving. The fractions of sizes obtained were 0.3–0.5, 0.5–1.0, 1.0–2.0, 2.0–2.8, and 2.8–4.7 millimetres.

Soil Erosion and Runoff

In order to measure soil loss and runoff, simulated rainfall was applied to aggregates <8 in diameter. Four of the soils, namely, Munchong I, Bungor, Kuantan and Rengam were selected for this investigation. These soils were chosen to represent a wide range of aggregate stability. The Munchong I was preferred over Munchong II because it is much less stable than Kuantan, Bungor and Rengam. The Bukit Temiang was left out so that the influence of high amounts of coarse sand and gravel in the erosion process was excluded in this study.

The air-dried soil sample was gently packed into a soil pan (30 x 30 x 5 cm) and tilted to a slope of 33 per cent. Slopes of such steepness are considered as serious limitations to crop growth and are common in the inland areas.

Free subsurface drainage from the soil pan was facilitated by a fritted false bottom underneath the soil sample. The density of packing was 1.1 g per cubic centimetre.

Simulated rain was applied at an intensity of 35 mm/h for an hour using a rainfall simulator which had been described by GABRIELS, DE BOODT and MINJAUW (1973). Runoff, splash and percolation were collected at regular intervals.

Runoff was collected at the end of a triangular-shaped runoff concentrator attached to the front of the soil pan. Soil material splashed onto the sides of the pan was collected by placing metal splash boards at about 6 cm away from each side of the pan. Percolation was collected through openings at the bottom of the pan.

Rainfall intensity was calculated based on readings of field rain gauges.

RESULTS AND DISCUSSION

General Characteristics of the Soils

Particle size analysis, pH, organic matter content and other information are given in *Table 1*. Contents of iron and aluminium are given in *Table 2*. Brief notes on the soils are given in *Appendix 1*.

Characteristics of Aggregate Stability

The values of mean weight diameter (MWD), instability index and aggregation percentage are shown in *Table 3*. The narrow range in MWD (dry) indicates a close similarity in the distribution of soil aggregates in the air-dried state. A relatively large proportion of these aggregates, ranging from 34.9% to 54.1% are larger

Table 2. Iron and aluminium contents of the soils under study

Soil series	Iron content (%)		Aluminium content (%)	
	Aquaregia extract	DCB extract	Aquaregia extract	DCB extract
Bungor	3.10	3.18	2.65	0.87
Kuantan	19.26	11.24	10.24	3.11
Munchong I	5.58	5.00	6.12	1.38
Munchong II	4.79	3.93	5.71	1.71
Rengam	1.61	1.57	3.27	0.50
Bukit Temiang	0.69	0.62	3.57	0.19

DCB = Dithionite-citrate-bicarbonate

Table 3. Aggregate stability data obtained by dry-and-wet sieving

Soil series	Aggregation (%)	Mean wt. diameter		Instability index
		Dry	Wet	
Bungor	45.43	4.41	2.60	1.81
Kuantan	34.90	4.29	3.07	1.22
Munchong I	40.10	4.40	1.80	2.60
Munchong II	52.70	4.42	2.78	1.64
Rengam	49.10	4.51	3.23	1.28
Bukit Temiang	54.10	4.60	2.82	1.78

Table 4. Distribution of 3–5 mm aggregates after immersion in water for one week

Soil series	Distribution (% w/w) of 6 aggregate sizes (mm)					
	2.8–4.7	2.0–2.8	1.0–2.0	0.5–1.0	0.3–0.5	<0.3
Bungor	48.3	15.5	10.8	9.1	8.7	7.6
Kuantan	68.5	10.2	6.8	2.7	6.1	5.7
Munchong I	30.8	11.5	15.4	6.8	19.8	15.7
Munchong II	56.7	10.3	12.1	9.2	6.4	5.3
Rengam	50.5	12.5	14.1	5.4	11.1	6.4
Bukit Temiang	18.4	7.9	24.0	10.1	23.3	16.3

than two millimetres. This is a favourable soil structural characteristic.

The stability of the soils against the forces employed in the sieving method, that is water drop impact and agitation in water, is shown by the values of MWD (wet) and instability index. These values show more variation than the values of MWD (dry). Kuantan series was shown to be very stable, whereas Munchong I series was relatively unstable.

However, in interpreting these results, one must also consider the different textural composition of these soils. High gravel and coarse sand content, as in Bukit Temiang series, tends to increase the values of MWD as well as aggregation percentage. Thus, the high MWD values and low instability index obtained for Bukit Temiang, contradict the findings during an initial assessment of stability by pressing air-dried aggregates between the thumb and forefinger *(Appendix 2)*. Therefore, a more complete assessment of the aggregate stability has to be made by also taking into account the extent of aggregate dispersion that occurred after the air-dried aggregates were immersed in water for a week.

Table 4 shows the percentages of 3–5 mm aggregates which have broken down into the various size fractions. Soils with higher percentages of smaller-sized aggregates are considered to be less stable than those with lower percentages of such aggregates. A careful examination of the data reveals that Bukit Temiang and Munchong I are relatively less stable, whereas Kuantan is the most stable *(Appendix 2)*.

A categorization of these soils according to aggregate stability is carried out. This categorization takes note of both the results of dry-and-wet sieving and prolonged immersion in water of 3–5 mm aggregates, the initial stability assessment by pressing air-dried aggregates as well as the textural differences of the soils. A scoring scheme was devised for this purpose *(Appendix 2)*. The aggregate stability categories were:

Very stable	– Kuantan
Stable	– Munchong II, Bungor, Rengam
Moderately stable	– Munchong I
Unstable	– Bukit Temiang

The process of aggregation depends on the existence of clays. If the bathing liquid has a sufficiently high ionic concentration and a large proportion of divalent ions such as Ca^{++}, clays tend to flocculate (RUSSELL, 1973). The aggregation process is initiated when the clays flocculate and cluster to form domains. Substances which are said to bind domains together include organic matter and sesquioxides. Thus, the high stability of Kuantan series may be attributed to the high content of these substances *(Tables 1* and *2)*. These constituents interact with each other and are strongly held together by a combination of electrostatic, Van der Waals and hydrogen bonds, as suggested by EL-SWAIFY (1980).

The other soils, namely Rengam, Munchong II and Bungor, are also stable but relatively less so than Kuantan. The binding of soil contituents in these soils is probably less intense because of the relatively lower contents of the mentioned constituents *(Table 2)*.

However, high amounts of clay and sesquioxides alone do not necessarily ensure high aggregate stability. The relative ease of dispersion of Munchong I seems to point to a low organic matter: clay ratio (unpublished information). It appears that its high clay content (71%) requires a relatively high organic matter content to aid in the binding of all the clay domains. This indicates that the role of organic matter is very important in stabilising aggregates.

However, it is evident from the literature (BAVER, GARONER and GARDNER, 1972; RUSSELL, 1973) and from this study that a prerequisite for the formation of stable aggregates is the presence of clay particles. Their active surfaces enable them to react with ions and the binding agents as well as with each other. Thus, one finds the soil with low clay content, Bukit Temiang, exhibiting the lowest aggregate stability.

However, in the case of Bukit Temiang series, a small proportion of its large aggregates was found to exhibit a stability similar to that of the other soils, when pressed between the fingers. When these large and stable aggregates were specially selected and analysed for textural composition, the clay content was found to be reasonably high compared with that of the whole sample. *Table 5* gives a comparison between the clay contents of selected 5–8 mm aggregates and those of the whole samples. This substantiates the above comment that a considerably high clay content is a prerequisite for stable aggregation.

Erosion and Runoff Resulting from Consecutive Rainstorms

Table 6 gives the erosion and runoff data obtained after applying simulated rain of intensity 35 mm/h and of one-hour duration for three consecutive days on initially air-dried soil samples. During each storm, soil splash occurred almost immediately. The measured side splash erosion (SSE) generally increased as a rainstorm progressed *(Figure 1)*. Runoff occurred only in the Munchong I and Bungor series soils, starting on the first day

Table 5. Particle size distribution of 5–8 mm aggregates and clay content of whole samples

Soil series	Particle size distribution (% w/w)				
	5–8 mm aggregates				Whole sample
	Clay < 2 μm	Silt 2–20 μm	Fine sand 20–200 μm	Coarse sand > 200 μm	Clay < 2 μm
Bungor	43.4	6.4	30.5	19.7	42.1
Kuantan	63.2	26.8	5.1	4.9	63.5
Munchong I	70.7	6.5	12.0	10.8	71.3
Munchong II	69.4	12.4	11.8	6.4	67.1
Rengam	64.9	8.2	9.0	17.9	49.6
Bukit Temiang	43.4	12.6	12.9	31.1	22.3

Table 6. Erosion and runoff from three rainstorms applied on consecutive days

Variable	Bungor	Kuantan	Munchong I	Rengam
Side splash erosion (g)				
1st rainstorm	3.16	0.79	7.04	0.16
2nd rainstorm	7.30	1.19	17.78	0.22
3rd rainstorm	12.72	1.84	22.17	0.25
Total	23.18	3.82	46.99	0.63
Soil wash (g)				
1st rainstorm	0	0	1.13	0
2nd rainstorm	0.10	0	2.56	0
3rd rainstorm	0.78	0	3.18	0
Total	0.88	0	6.87	0
Runoff (cm^3)				
1st rainstorm	0	0	36	0
2nd rainstorm	40	0	804	0
3rd rainstorm	558	0	1 278	0
Total	598	0	2 118	0

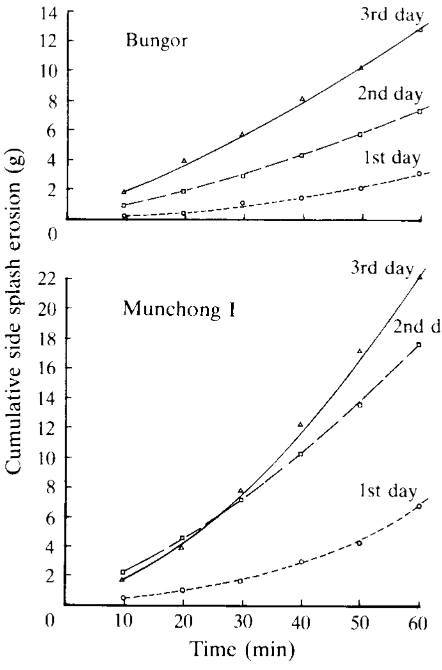

Figure 1. Increase in side splash erosion with the progress of rainstorms for Bungor and Munchong I series soils.

for Munchong I and on the second day for Bungor. The time to incipient runoff decreased on each successive day. For Munchong I, the times taken were 48, 5 and 3 minutes for the first, second and third day respectively. For Bungor, the durations were 50 and 5 minutes for the second and third day respectively.

Under natural conditions in many areas in the humid tropics, the peak intensity of rainstorms may greatly exceed 35 mm/hour. For example, 28% of the rainstorms recorded between July 1978 and August 1980 in Serdang, Selangor had maximum 30-minute intensity (I_{30}) values of 40 mm/h or more (GHULAM MOHAMMED and ZAKI, 1981). The peak intensity values would be much higher. The rainfall records also show that, during rainy periods, storms occur on a number of days successively. Thus, it is common for high-intensity rain to fall on wet ground and, increase runoff and erosion on soils of relatively low stability.

The results also show that soil splash takes place on all four soils, indicating that under natural conditions this phenomenon is experienced on soils over a wide range of aggregate stability, if they are not protected by vegetation or mulch.

The Effect of Initial Moisture Content on Runoff and Erosion

The effect of initial moisture content on splash erosion is shown in *Figure 2.* The initial moisture content increases on each successive day because of the moisture received from earlier rainstorms. *Table 6* shows the increases in runoff and erosion on each successive day.

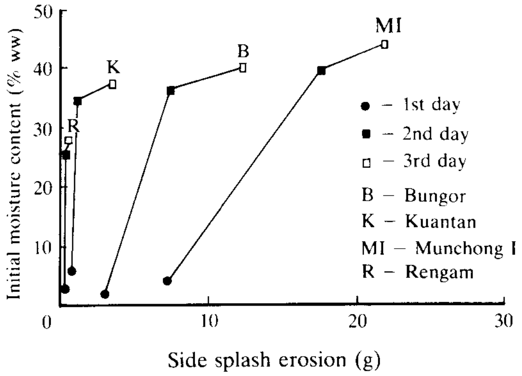

Figure 2. Effects of initial moisture content on side splash erosion.

When initially dry aggregates are suddenly wetted, water enters the pores and causes 'air explosion' (Bolt and Koenigs, 1972) due to trapped air escaping from the pores. This results in either weakening or slaking of the aggregates. The extent of weakening and the possibility of slaking taking place, depend on how strongly the soil particles are held together by the aggregating agents. In soils which are susceptible to this weakening process, erosion will take place more readily when they are further subjected to the impact of raindrops. This behaviour is shown by Munchong I and Bungor.

Besides the increase in erosion recorded on each successive day *(Figure 2* and *Table 4)*, the phenomenon is also shown in *Figure 1* and *Table 7* where increases in erosion and runoff are observed during the progress of each individual storm.

Table 7. Side splash erosion during the progress of rainstorms for the relatively more stable soils, Kuantan and Rengam series

Time after initiation of rainstorm (min)	Cumulative side splash erosion (g)		
	1st day	2nd day	3rd day
Kuantan			
10	0.04	0.25	0.37
20	0.07	0.42	0.74
30	0.13	0.60	0.98
40	0.36	0.72	1.23
50	0.51	0.89	1.47
60	0.79	1.19	1.84
Rengam			
10	0.02	0.03	0.02
20	0.04	0.07	0.05
30	0.07	0.12	0.09
40	0.10	0.15	0.16
50	0.13	0.19	0.22
60	0.15	0.22	0.25

The Influence of Aggregate Stability on Erodibility

The two soils with relatively lower aggregate stability, Bungor and Munchong I, suffered runoff and soil wash (sheet erosion) in addition to splash erosion, whereas the other two soils, Kuantan and Rengam suffered only minimal splash erosion *(Table 6)*. The difference in soil erosion of these two pairs of soils is much larger than their differences in instability index would suggest. Thus, soils which deteriorate upon being subjected to rain, rapidly lose their stability when further stresses are applied. Those which are initially resistant, maintain their stability, as exemplified by Kuantan and Rengam.

A plot of instability index against splash erosion suggests a linear relationship *(Figure 3)*. However, an anomaly occurs with respect to Rengam. This could be

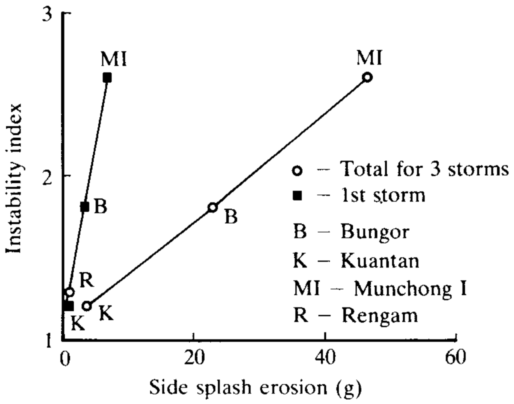

Figure 3. Relationship between instability index and side splash erosion.

explained by the generally larger aggregates of Rengam when compared with those of Kuantan *(Table 8)*. Larger aggregates are less easily splashed.

The splashed Kuantan soil are fine aggregates and not dispersed material. The amount of splash increases slightly with higher moisture content *(Table 7)* because the finer aggregates are splashed together with the puddled water.

It is clear that aggregate dispersion occurred only in Munchong I and Bungor. This dispersion led to crust formation and the onset of runoff.

CONCLUSIONS

As many factors influence soil aggregation and aggregate stability, no one single method can completely compare the soils according to their aggregate characteristics. Many factors have to be taken into account when the relative stabilities of the soils are studied. The factors include texture, instability index obtained by dry-and-wet sieving, and aggregate stability under submerged conditions. It was found that, when the clay content was sufficiently high, aggregate stability was influenced by the ratio of organic matter content to clay content.

Aggregate stability is related to erosion resistance, with soils of low stability suffering greater erosion. However, in the higher range of stability, aggregate size also plays a role, there being less splash erosion where aggregates are larger.

Aggregates with a high initial moisture content are more easily eroded because they are less cohesive when wet. However, this is only true for the relatively less stable soils. The more stable ones have greater cohesion and suffer minimal splash erosion regardless of the moisture content.

For a high resistance to erosion, this study showed that a prerequisite was a

Table 8. Field description and laboratory data on aggregate size

Soil series	Structural units described in the field			Distribution+ (% w/w) of 4 sizes (mm)			
	Type & class	Size (mm)	Grade	4.76–8.00	2.83–4.76	2.00–2.83	< 2.00
Bungor	Medium & coarse SAB	10–20 20–50	Moderate	15.89	19.86	9.68	54.58
Kuantan	Fine & medium granules	1–2 2–5	Strong	12.08	13.95	9.02	64.95
Munchong I	Fine & medium SAB	5–10 10–20	Moderate	14.82	15.16	10.04	59.98
Rengam	Medium granules & fine SAB	2–5 5–10	Strong	20.43	17.39	11.06	51.13

+Laboratory data
SAB = Subangular blocks

sufficiently high clay content. But this alone is no guarantee. A wide organic matter: clay ratio and large aggregates are also necessary.

ABSTRACT

Although the highly weathered soils of the humid tropics are generally thought of as well-aggregated soils, there are important differences in aggregate characteristics among them. These influence their susceptibility to erosion. In the group of soils under study, the results highlighted two factors which are essential for high stability: a sufficiently high clay content and a relatively high organic matter to clay ratio.

Simulated rainfall of one-hour duration at 35 mm/h caused splash erosion on all series of soils, but to a much greater degree on the less stable ones, Munchong I and Bungor. Successive rainstorms increased soil splash considerably on the less stable soils, but produced negligible increases on the more stable ones, Kuantan and Rengam series. The stable soils did not suffer dispersion under the conditions of this experiment.

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Appendix 1. Description of the various soil series

Soil series	Description
Bukit Temiang	Coarse-grained granite derivative. Sand and gravel contents are relatively high. Clay fraction comprises kaolinite halloysite, gibbsite and traces of mica. Silt fraction comprises kaolinite, gibbsite, quartz and mica (WONG, 1976). Shallow (< 100 cm) and situated on upper slopes.
Bungor	Derived from interbedded sandstones and shales. Sand content is relatively high with a greater proportion of fine sand. Clay fraction comprises mainly kaolinite, gibbsite and goethite.
Kuantan	Derived from olivine basalts of Quartenary age, dark brown in colour, very stable microaggregation and very deep profile. Clay fraction comprises kaolinite and halloysite (35%), gibbsite (40%) and goethite and magnetite (21%). Silt fraction comprises ilmenite, magnetite, kaolinite, quartz and gibbsite (AMINUDDIN and ESWARAN, 1973). Occurs in a gently undulating landscape. (e.g. Bukit Goh Reserve, Bukit Goh Felda Scheme, Jabor Valley and Southern Terengganu).
Munchong	Derived from iron-rich shale. Occurs in undulating to rolling terrain. Clay fraction dominated by kaolinite, gibbsite and goethite.
Rengam	Derived from granite. Occurs in undulating, rolling and hilly terrain with slopes ranging from 10° to 25°. Relatively high sand content. Clay fraction comprises kaolinite, halloysite, gibbsite, goethite and quartz (WONG, 1976). Silt fraction comprises kaolinite, gibbsite, quartz and mica (WONG, 1976).

Appendix 2a. Scoring scheme for categorizing soils according to aggregate stability

Score	0	1	2	3
No. of aggregates that yield to pressure[1](%)	80–100	50–80	20 –50	< 20
Instability index[2]	> 2	2– 1.5	1.5– 1	< 1
Aggregate > 1 mm[3] (% w/w)	< 50	50–60	60 –75	75–100
Coarse sand[4] (% w/w)	> 50	40–50	20 –40	< 20

[1] Aggregate stability assessed by pressing air-dried aggregates between the thumb and forefinger.

[2] Obtained from dry-and-wet sieving.

[3] % stable aggregates after prolonged immersion in water.

[4] Textural factor (The presence of coarse particles contributes to a lower instability index. Thus, a lower score is given for a higher content of coarse sand to offset the error).

Appendix 2b. Scores for the soils used in the study

Variable	Bukit Temiang	Bungor	Kuantan	Munchong I	Munchong II	Rengam
Yield to pressure	0	2	3	1	3	3
Instability index	1	1	2	0	1	2
Aggregates >1 mm	1	2	3	1	3	3
Coarse sand content	0	2	3	3	3	2
Total	2	7	11	5	10	10

Dicetak oleh Unit Percetakan MARDI, Serdang, Selangor.
Kementerian Pertanian Malaysia.