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Factors Contributing to the Clay Dispersion and Aggregate Stability of Thai Oxisols

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Abstract

Aggregate stability tends to give a better availability of soil water. Clay dispersion makes the soil dense, difficult for root penetration. The better understanding of these two soil properties is necessary to evaluate the suitability of soils for plant production. We collected soil samples from 10 sites from the southeast coast and northeast plateau of Thailand, at upper (0 - 5 cm depth) and lower (5 - 20 cm depth) levels for under udic and ustic Oxisols soil samples. The objective of this study was to investigate the contribution of major aggregate binding agents such as soil organic carbon (SOC), Fe and Al oxides, clay minerals and kaolin crystal size to the stability of soil aggregates. Soils were acidic (pH < 6.5), low to medium cation exchange capacity (3.34 - 14.40 cmol kg^{-1}), SOC ranged from 2.08 - 4.56 % for udic and 1.11 - 1.56 % for ustic soils. The udic soils showed higher contents of crystalline, non-crystalline, and organic forms of Fe and Al than those for ustic soils. The mean coherently scatterings domain (CSD) values for kaolin crystal size were 115 and 152 nm for udic and ustic soils, respectively. The mean water dispersible clay (WDC), water dispersible silt (WDSi), and dispersion ratio (DR) were 92, 43 g kg^{-1}, and 0.17 for udic soils, and 218, 45 g kg^{-1}, and 0.30 for ustic soils, respectively. Mean weight diameters (MWD) were 1.01 and 0.62 mm for udic and ustic soils, respectively. The clay flocculation index (CFI) and aggregated silt and clay (ASC) were 0.83 and 650 g kg^{-1} for udic soils and 0.66 and 619 g kg^{-1} for ustic soils. The SOC, non-crystalline, organic form of Fe and Al oxides, and crystalline Al oxide showed positive correlation to MWD and CFI. A negative correlation between crystal size of kaolin and aggregate stability was found.

Keywords: Soil moisture regimes (SMRs), soil properties, clay dispersion, aggregate stability, Thai Oxisols

Introduction

Many researchers have discussed procedures to characterize aggregate stability [1-5]. They showed that aggregate stability depended on SOC, clay minerals and Fe and Al oxides [5] and that soil organic carbon (SOC) acted as a binding agent for aggregate stability. It was a nucleus in the formation of aggregate. In case of low SOC in tropical soil, the SOC could not exert any role on the microaggregate formation [3]. Fe and Al were the main binding agents especially in highly weathered soils. Different forms of Fe and Al oxide influenced the aggregate stability level. [6] indicated that Al was more important than Fe oxide as an aggregating agent. Pinheiro-Dick and Schwertmann [7] found that the total, oxalate and dithionite citrate bicarbonate (DCB) of Mn oxide were shown to be the best aggregating agent in flooded soils from eastern Nigeria. Only noncrystalline Fe and Al oxides play an important role in aggregating oxide rich soils [8].

The type of clay minerals also affected aggregate stability. Their surface area, cation exchange capacity (CEC), charge density, dispersibility and flocculation mainly influenced aggregate stability [9]. Morgan [10] reported that montmorillonite more readily form aggregate but can show extensive intra crystalline swell and dispersion on contact with water. According to Oster *et al.* [11], illite were very dispersive probably due to their crystal shape [12]. Stern *et al.* [13] suggested that kaolinitic or illitic soils with small amount of smectite were dispersive. Many researchers have studied only the effect of the type of clay mineral on aggregate stability, but none or few studies have determined clay mineral properties particularly the size of clay mineral influenced on aggregate stability.

Mean weight diameter (MWD) is an index that characterizes the structure of the macroaggregate by integrating the aggregate size class distribution into one number. The MWD is also often used to indicate the effect of different management practices on soil structure [14].

The stability of soil microaggregate opposed to its dispersion is a very important soil phenomenon that checks degradation. Clay flocculation index (CFI) and aggregated silt and clay (ASC) indicate the ability of the soils to resist dispersion in water. Igwe *et al.* [15] reported that CFI and ASC indices can predict potential soil loss in some southeastern Nigeria soils. The water dispersible clay (WDC), water dispersible silt (WDSi) and dispersion ratio determine the clay and silt dispersibility in the water. The high WDC, WDSi and DR soils are weak in their structure and easily eroded. These indices are the inverse of CFI and ASC indices.

Oxisols of Thai soils occurred under udic and ustic SMR. These conditions support a high rate of chemical and physical degradation, thus it is necessary to study dispersibility and aggregate stability. The kaolin crystal size, Fe and Al oxide also involved in the aggregate stability under udic and ustic SMRs were not investigated. The objectives of this study were to (i) identify dispersibility, macro and micro-aggregate stability of the soils using indices (ii) determine amount of cementing agent namely SOC concentration, Fe and Al oxide forms, amount and type of clay, kaolin crystal size, relating to dispersibility and aggregate stability.

Materials and methods

Site description

Two contrasting types of soil moisture regime were chosen for this study, i.e. udic SMR for 4 sites (site 1 to site 4) and ustic SMR for 6 sites (site 5 to site 10). The udic SMR is the culture of durian (*Durio zibethinus*) and rubber (*Hevea brasiliensis*) trees, while the ustic SMR is mango (*Mangifera indica)*. Soils in the study areas are Oxisols, i.e. acidic, clayey, deep and well drained with dark reddish brown (5YR3/4) to dark red (2.5YR3/6) of B horizon. The boundary between epipedon and sub-soil ranges from abrupt to clear, while boundaries between subsurface horizons range from clear to diffuse. The subsoils have strong fine granular structure. The soils from udic SMR were located in the southeast coastal region of Thailand. The climate is Tropical Monsoon with an average temperature ranging between 26.5 - 28.5 °C, and an average annual rainfall of 2,852 mm. The soils are Kandiudox. The soils from ustic SMR were located on the northeast plateau of Thailand with a Tropical Savanna climate with an annual average temperature ranging between 23.1 - 30.0 °C, and an annual rainfall of 1,035 mm. The Oxisols under this soil moisture are Kandiustox. Parent materials for both southeast coast and northeast plateau sites are either basalt or limestone and/or associated with shale (**Table 1**). Soils of these 10 sites have been often severely degraded and highly weathered. Soil samples were taken from 0 - 5 and 5 - 20 cm depths. These depths represented the active root zone for the crops under study. Soil samples were air dried, sieved through a 2 mm mesh and analysed as described below.

Table 1 Environmental setting of soil samples.

Site	Taxonomic name	SMR*	Land use	Rainfall mm yr^{-1}	Slope %	Parent material	Coordinate	
							N	E
1	Typic Hapludox	Udic	Durian	2,852	2	Basalt	481416222	48175321
2	Typic Kandiudox	Udic	Durian	2,852	3	Limestone	481415292	48175486
3	Typic Hapludox	Udic	Rubber	2,852	1	Basalt	481448651	48184325
4	Typic Kandiudox	Udic	Rubber	2,852	1	Limestone	481415497	48175783
5	Typic Kandiustox	Ustic	Mango	1,035	1	Basalt	481605525	48215479
6	Rhodic Kandiustox	Ustic	Mango	1,035	2	Limestone/shale	471620264	47749647
7	Typic Kandiustox	Ustic	Mango	1,035	1-2	Basalt	481606519	48217266
8	Rhodic Kandiustox	Ustic	Mango	1,035	1	Limestone/shale	471632949	47752758
9	Typic Kandiustox	Ustic	Mango	1,035	2-3	Basalt	481615936	48206757
10	Rhodic Kandiustox	Ustic	Mango	1,035	2	Limestone/shale	471618289	47750014

*SMRs = Soil moisture regimes.

Soil properties analyses

Soils samples from each site and depth were analyzed for their properties. Soil pH was determined with a pH electrode in a 1:1 (w/w) soil/water ratio. Soil carbon concentration was determined by a dry combustion method using a CN analyzer (Vario Max CN Macro Elemental Analyser). Cation exchange capacity (CEC) was determined by the NH_4OAc method [16]. Crystalline, non-crystalline and organic forms of Fe and Al were extracted respectively by dithionite-citrate-bicarbonate solution (DCB), 0.2 *M* ammonium oxalate solution at pH 3.0, and sodium pyrophosphate [17-19]. Dissolved Fe and Al were measured using atomic absorption spectrophotometry. Total Fe and Al (Fe_t, and Al_t) were determined by X-ray fluorescence spectrometry of fused samples [20].

Particle size distribution of the fine earth fractions was determined using the sieve and pipette method [21]. Total clay (TC) and total silt (TS) obtained by the use of chemical dispersant. Water dispersed clay (WDC) and water dispersed silt (WDSi) were obtained by the same method but no chemical dispersant was used. The indices of dispersibility and microaggregate stability were calculated using the relationships stated below:

$$DR = (WDC + WDSi)/(TC + TS)$$
$$ASC\ (g\ kg^{-1}) = [TC + TS] - [WDC + WDSi]$$
$$CFI\ (g\ kg^{-1}) = [(TC - WDC)/TC]$$

DR = Dispersion ratio; ASC = Aggregated silt and clay; CFI = Clay flocculation index

The aggregate size distribution was measured by wet sieving through a series of four sieves (2.00, 1.00, 0.50 and 0.25 mm) according to Elliott [22]. A 100 g subsample was submerged in deionized water for 5 min at room temperature, on top of the 2.00 mm sieve. Aggregate separation was made by moving sieves up and down with a 3 cm stroke with 50 repetitions during a period of 2 min. The stable > 2.00 mm aggregates were then gently backwashed off the sieve into an aluminum pan. Floating organic material (> 2.00 mm) was decanted and discarded. Consequently, five size fractions were produced: (i) > 2.00 mm, (ii) 2.00 - 1.00 mm, (iii) 1.00 - 0.50 mm (iv) 0.50 - 0.25 mm, and (v) < 0.25 mm (silt and clay particles). The four aggregate fractions (i - iv) were oven dried (50 °C), weighed, and stored at room temperature. A correction for the sand content of each size fraction was determined by weighing the material that was retained on a 53 µm screen sieve after dispersion of aggregates [23]. Mean weight diameter (MWD) was used as an index of macroaggregate stability and was calculated by summing the mass weighted proportions of four aggregate fractions [24].

Mineralogical analyses

X-ray diffraction (XRD) analyses of the pretreated clay fraction were carried out using a computer driven Philips PW-3020 diffractometer with a graphite diffracted beam monochromator and Cu Kα radiation obtained at 50 kV and 20 mA. Coherently scattering domain (CSD) size of kaolins referred to as kaolin crystal size was calculated from the width at half height of XRD reflections using the Scherrer equation [25].

Data analysis

Data analysis was performed by correlation of dispersibility and aggregate stability with SOC, kaolin crystal size and different forms of Fe, Al and Mn oxides using regression module of the SPSS package. Multiple comparisons of means for each parameter were performed using Duncan's Multiple Range Test at the significance level (α) = 0.01 and 0.05.

Results

Soil properties

Clay contents of collected soils from any sites ranged from 320 - 844 g kg^{-1}. The soils were extremely to strongly acidic with pH ranging from 3.64 - 6.51 (**Table 2**). Soils for site 5, site 9 and site 10 were the most acidic. CEC values ranged from 3.34 - 14.42 cmol kg^{-1} which were high for depth of 0 - 5 cm and lower for 5 - 20 cm for all sites (**Table 2**). Site 5 to site 10 had lower CEC values than did site 1 to site 4 which may reflect differences in carbon concentration and the properties of clay minerals between sites. Site 1 to site 4 had high values of SOC for the 0 - 5 cm (3.73 - 4.56 %), but values sharply decreased with depth (**Table 2**). The values were much higher than those for site 5 to site 10.

Table 2 Selected soil chemical properties and soil mineralogy.

SMRs	Site	Depth cm	pH 1:1	CEC cmol kg^{-1}	Clay g kg^{-1}	SOC %	Clay minerals$^{/1}$
udic	1	0-5	5.08	14.42	320	4.45	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{++}, Gib^{tr}
		5-20	4.82	8.66	555	2.41	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{++}, Gib^{tr}
udic	2	0-5	4.77	12.38	480	3.73	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{++}
		5-20	4.93	7.43	620	2.33	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{+}
udic	3	0-5	5.22	11.82	336	3.79	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{++}, Gib^{tr}
		5-20	5.42	8.29	450	2.08	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{++}, Gib^{tr}
udic	4	0-5	4.54	10.21	532	4.56	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{++}
		5-20	4.57	9.71	684	3.15	Kao^{+++}, Goe^{+}, Hem^{+}, Qtz^{+}
		Mean	4.92	10.37 ^{b}	497	3.31^{b}	
		CV %	5.86	21.27	24.06	27.35	
ustic	5	0-5	4.15	7.12	608	1.18	Kao^{+++}, Goe^{tr}, Hem+, Qtz^{+}
		5-20	4.04	5.63	676	1.11	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{+}
ustic	6	0-5	6.51	7.05	744	1.54	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{tr}
		5-20	6.33	5.94	788	1.39	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{tr}
ustic	7	0-5	5.64	6.37	844	1.23	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{tr}
		5-20	5.46	4.64	600	1.23	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{tr}
ustic	8	0-5	5.31	5.65	576	1.56	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{+}
		5-20	5.52	6.13	680	1.34	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{tr}
ustic	9	0-5	3.64	3.53	592	1.17	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{++}
		5-20	3.65	3.34	680	1.15	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{tr}
ustic	10	0-5	4.25	6.20	424	1.14	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{++}
		5-20	4.21	4.46	524	1.17	Kao^{+++}, Goe^{tr}, Hem^{+}, Qtz^{++}
		Mean	4.89	5.51 ^{a}	645	1.27^{a}	
		CV %	19.92	21.79	17.21	11.77	

$^{/1}$ $^{+++}$ = dominant, $^{++}$ = moderate, $^{+}$ = small, tr = trace
Kao = kaolinite, Goe = goethite, Hem = hematite, Qtz = quartz, Gib = gibbsite.

Dispersibility indices

The dispersibility indices of the soils are presented in **Table 3**. The WDC, WDSi, WDC+WDSi and DR, which were used to estimate instability. Their mean values were 92, 46, 135 and 0.17 respectively for udic SMR and 218, 45, 263 and 0.30 respectively for ustic SMR. These indices were lower under udic than ustic SMR. These indices also had a negative correlation with aggregate stability indices (**Table 4**).

Table 3 Dispersibility, aggregate stability indices and kaolin crystal size.

SMRs	Site	Depth	WDC	WDSi	WDC+WDSi	DR	MWD	ASC	CFI	CSD
		cm	g kg^{-1}				mm	g kg^{-1}		nm
udic	1	0-5	81	16.8	98	0.15	1.22	575	0.75	72
		5-20	76	90.6	906	0.22	0.79	585	0.86	103
udic	2	0-5	82	42.0	420	0.16	1.15	669	0.83	92
		5-20	67	31.1	311	0.11	0.99	763	0.89	121
udic	3	0-5	61	65.2	652	0.17	1.28	603	0.82	120
		5-20	28	60.4	89	0.11	0.85	686	0.94	116
udic	4	0-5	68	28.2	282	0.12	1.30	708	0.87	109
		5-20	60	20.9	209	0.10	1.16	773	0.91	106
		Mean	92^{a}	43	135^{a}	0.17^{a}	1.01^{b}	650	0.83^{b}	115^{a}
		CV %	60.9	53.2	41.4	40.2	23.8	11.7	10.2	22.5
ustic	5	0-5	180	54.8	235	0.29	0.60	573	0.70	146
		5-20	219	20.6	240	0.30	0.72	569	0.68	171
ustic	6	0-5	301	0.30	301	0.40	0.81	455	0.60	143
		5-20	209	50.7	260	0.27	0.70	687	0.73	155
ustic	7	0-5	284	41.5	325	0.35	0.59	595	0.66	157
		5-20	224	40.5	264	0.33	0.63	527	0.63	176
ustic	8	0-5	186	60.2	246	0.26	0.73	708	0.68	142
		5-20	166	50.1	216	0.23	0.67	703	0.76	140
ustic	9	0-5	239	40.4	279	0.34	0.55	541	0.60	131
		5-20	177	80.4	257	0.29	0.52	638	0.74	188
ustic	10	0-5	210	50.1	260	0.28	0.54	661	0.50	149
		5-20	182	40.7	223	0.25	0.48	673	0.65	135
		Mean	218^{b}	45	263^{b}	0.30^{b}	0.62^{a}	619	0.66^{a}	152^{b}
		CV %	19.8	41.9	11.9	16.6	16.3	13.2	11.3	11.4

WDC = Water dispersed clay; WDSi = water dispersed silt; DR = Dispersion ratio; ASC = Aggregated silt and clay; CFI = Clay flocculation index; CSD = coherently scattering domain.

Table 4 Pearson correlation coefficients (r) relating dispersibility to aggregate stability indices, soil organic carbon, forms of Fe and Al oxide, and kaolin crystal size of all soil samples.

	WDC+WDSi	WDC	WDSi	DR	MWD	ASC	CFI	Clay
SOC	-0.81^{**}	-0.74^{**}	-0.19	-0.75^{**}	0.95^{**}	0.24	0.62^{*}	-0.57
Al$_t$	0.29	0.35	-0.25	0.32	-0.26	-0.24	-0.31	0.26
Fe$_t$	-0.71^{**}	-0.70^{**}	0.10	-0.67^{*}	0.68	0.30	0.70^{**}	-0.33
Fe$_d$	-0.28	-0.37	0.36	-0.30	0.10	0.26	0.34	-0.21
Al$_d$	-0.90^{**}	-0.91^{**}	0.13	-0.84^{**}	0.79^{**}	0.33	0.84^{**}	-0.53
Fe$_o$	-0.90^{**}	-0.91^{**}	0.08	-0.84^{**}	0.82^{**}	0.27	0.80^{**}	-0.62
Al$_o$	-0.91^{**}	-0.90^{**}	0.03	-0.84^{**}	0.84^{**}	0.28	0.80^{**}	-0.61
Fe$_{py}$	-0.90^{**}	-0.85^{**}	-0.10	-0.86^{**}	0.85^{**}	0.46	0.81^{**}	-0.37
Al$_{py}$	-0.86^{**}	-0.87^{**}	0.10	-0.80^{**}	0.81^{**}	0.26	0.77^{**}	-0.55
clay	0.57	0.60	-0.15	0.51	-0.29	-0.04	-0.17	1.00
CDS	0.78^{**}	0.72^{*}	0.16	0.72^{**}	-0.74^{*}	-0.25	-0.56^{*}	0.58
CFI	-0.85^{**}	-0.87^{**}	0.18	-0.85^{**}	0.66^{*}	0.56		
ASC	-0.53	-0.56	0.15	-0.71^{**}	0.26			
MWD	-0.82^{**}	-0.72^{**}	-0.29	-0.75^{**}				

* = significant at p = 0.05; ** = significant at p = 0.01
WDC = Water dispersed clay; WDSi = water dispersed silt; DR = Dispersion ratio; ASC = Aggregated silt and clay; CFI = Clay flocculation index; CSD = coherently scattering domain; Fe$_t$, Al$_t$ = total Fe and Al oxide; Fe$_d$, Al$_d$ = Fe, Al oxide in crystalline form; Fe$_o$, Al$_o$ = Fe, Al oxide in noncrystalline form; Fe$_{py}$, Al$_{py}$ = Fe, Al oxide in organic form.

Macro and micro-aggregate stability

Mean MWD was high value of 1.10 mm for soils under udic SMR which was almost 2 times higher than soil under ustic SMR. It correlated with accumulation of SOC with r = 0.95 and oxides especially in the form of amorphous and organic with r > 0.80. The CFI ranged from 0.75 - 0.94 for soils under udic SMR and 0.50 - 0.76 for soils under ustic SMR. This value increased with depth for udic SMR but was quite constant for both depths in ustic SMR. The ASC value also followed the trend of the CFI value (**Table 3**). The value of ASC ranged from 575 - 773 g kg^{-1} and 455 - 708 g kg^{-1} for soils under udic and ustic SMR, respectively. The ASC of 0 - 5 cm soil depth were lower than that of 5 - 20 cm depth. Lower microaggregate indices for the surface horizon were probably influenced by land use [26].

Iron and aluminum oxides in the soils

Table 5 shows the values for the total (t), crystalline (d), noncrystalline (o) and organic (py) form of Fe and Al in the soils. Accumulation of Al$_t$, Fe$_t$ and Fe$_d$ were not significantly different between soil SMRs (**Table 5**). Others forms of oxide accumulation were different between soil moisture regimes. Accumulation of Al$_d$, Fe$_o$, Al$_o$, Fe$_{py}$ and Al$_{py}$, were high in the soils from udic SMR with a mean of 13.0, 5.46, 6.70, 3.15 and 3.78 g kg^{-1} respectively whereas their value for soils from ustic SMR ranged from 0.16 - 1.99 g kg^{-1} respectively. It is probable that these differences in the amounts and forms of Fe and Al relate to soil moisture regime rather than parent materials. These data were collected primarily to investigate the influence of these elements on aggregate stability.

Table 5 Total Fe, Al oxide content (Fe_t Al_t), Fe, Al crystalline (d), Fe, Al noncrystalline (o) and Fe, Al organic (py).

SMR	Site	Depth	Al_t	Fe_t	Fe_d	Al_d	Fe_o	Al_o	Fe_{py}	Al_{py}
		cm	$g\ kg^{-1}$							
udic	1	0-5	228	210	68	10.6	6.25	7.90	2.46	4.01
		5-20	235	212	98	15.4	5.82	6.70	2.98	5.03
udic	2	0-5	215	153	73	10.7	4.84	5.88	2.80	3.51
		5-20	237	167	91	12.2	4.79	5.71	3.42	2.85
udic	3	0-5	233	167	100	15.7	6.35	7.34	2.53	3.80
		5-20	242	173	100	14.3	6.40	7.82	1.96	3.02
udic	4	0-5	246	194	77	11.7	5.04	6.60	4.77	4.53
		5-20	258	204	92	13.5	4.19	5.65	4.28	3.49
		Mean	237	185	87	13.0^{b}	5.46^{b}	6.70^{b}	3.15^{b}	3.78^{b}
		CV %	5.08	11.53	13.78	14.49	14.56	12.80	28.40	18.19
ustic	5	0-5	248	75	58	1.84	1.19	0.77	0.31	0.44
		5-20	251	76	52	3.78	1.27	0.85	0.33	0.39
ustic	6	0-5	281	127	60	0.58	0.56	0.48	0.01	0.12
		5-20	277	126	66	1.24	0.76	0.66	0.02	0.14
ustic	7	0-5	234	103	58	1.17	0.93	0.89	0.09	0.28
		5-20	229	108	54	2.02	0.83	0.83	0.17	0.34
ustic	8	0-5	202	149	94	2.23	1.10	0.50	0.18	0.22
		5-20	206	149	97	2.24	1.32	0.55	0.20	0.21
ustic	9	0-5	269	159	138	3.31	0.94	0.90	0.13	0.81
		5-20	257	151	88	2.14	0.59	0.54	0.16	0.90
ustic	10	0-5	270	90	62	1.53	0.61	0.52	0.15	0.45
		5-20	259	88	73	1.74	0.85	0.84	0.19	0.51
		Mean	248	117	75	1.99^{a}	0.91^{a}	0.69^{a}	0.16^{a}	0.40^{a}
		CV %	10.05	25.19	32.16	42.62	27.62	23.29	57.35	59.28

Kaolin crystal size

The XRD patterns showed that the clay samples consisted almost entirely of kaolin, small iron oxides minerals and small to moderate quartz for all samples (**Table 2**). Gibbsite can be found for only site 1 and site 3. Coherently scattering domain (CSD) size of kaolins was 72 - 127 nm with an average of 115 nm for soil under udic SMR and 131 - 188 nm with an average of 152 nm for soils under ustic SMR. CSD data in **Table 3** show a significant difference between soil moisture regimes.

Dispersibility and aggregate stability versus soil organic carbon (SOC), Fe and Al oxides and kaolin crystal size

We have used the correlation matrix between the dispersibility indices and aggregate stability indices with the aggregating agents (SOC, Fe and Al) and kaolin crystal size to portray the level of aggregate stability in the soils sample (**Table 4**). Total clay content was not significantly correlated with any soil properties. This means that clay content was not a factor contributing to aggregate stability and dispersibility. WDC, WDC+WDSi and DR negatively correlated with SOC, and almost all oxides forms (**Table 4** and **Figure 1**).

WDSi was not significantly correlated with any soil properties. MWD and CFI were significantly positive correlated with SOC, almost all forms of Fe and Al and significantly negative correlated with kaolin crystal size but some of these relationships were spurious as they were a consequence of the bimodal distribution of the Fe and Al oxides as illustrated in **Figure 2**.

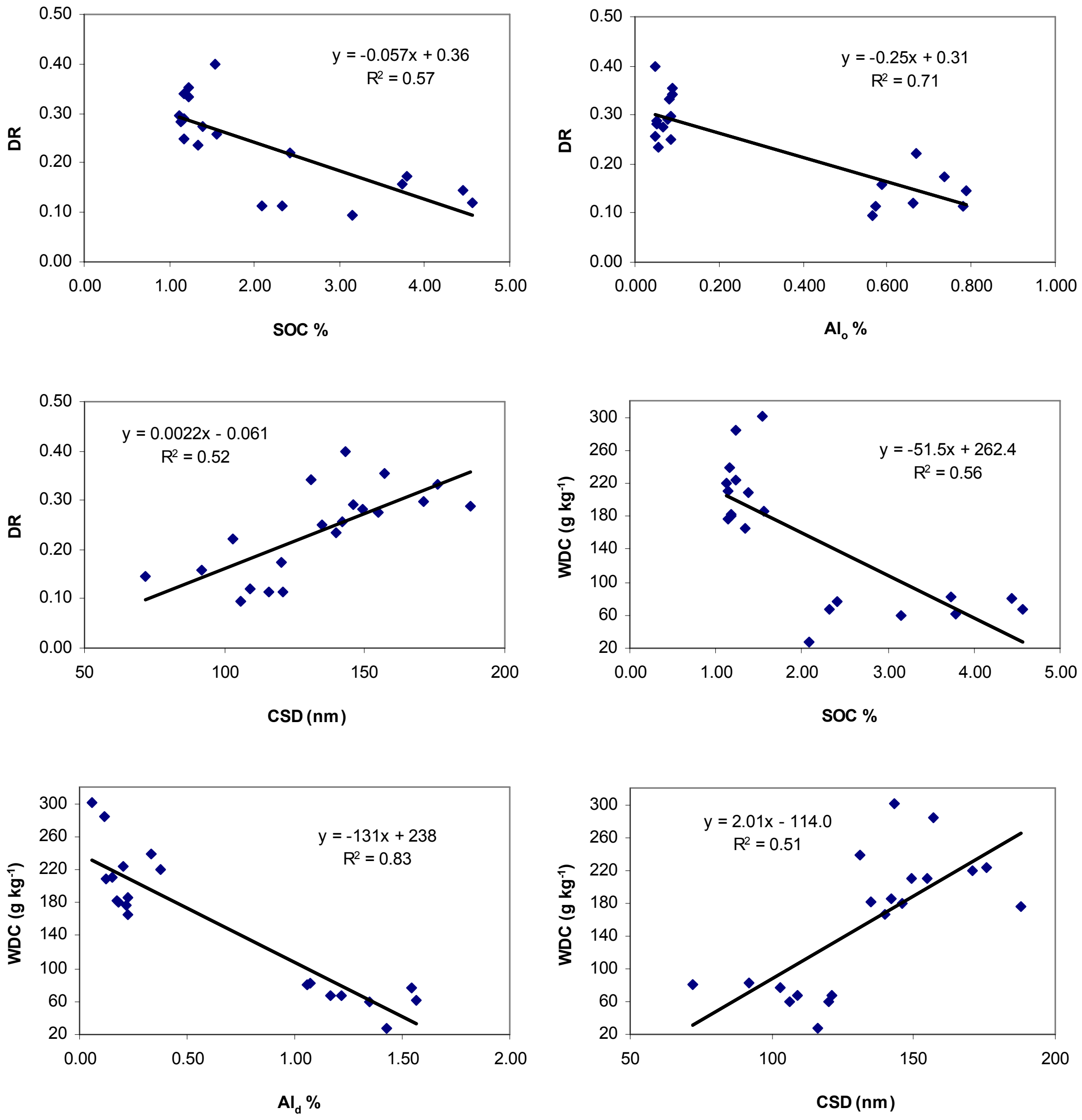

Figure 1 Some dispersibility indices plots with major cementing agents.

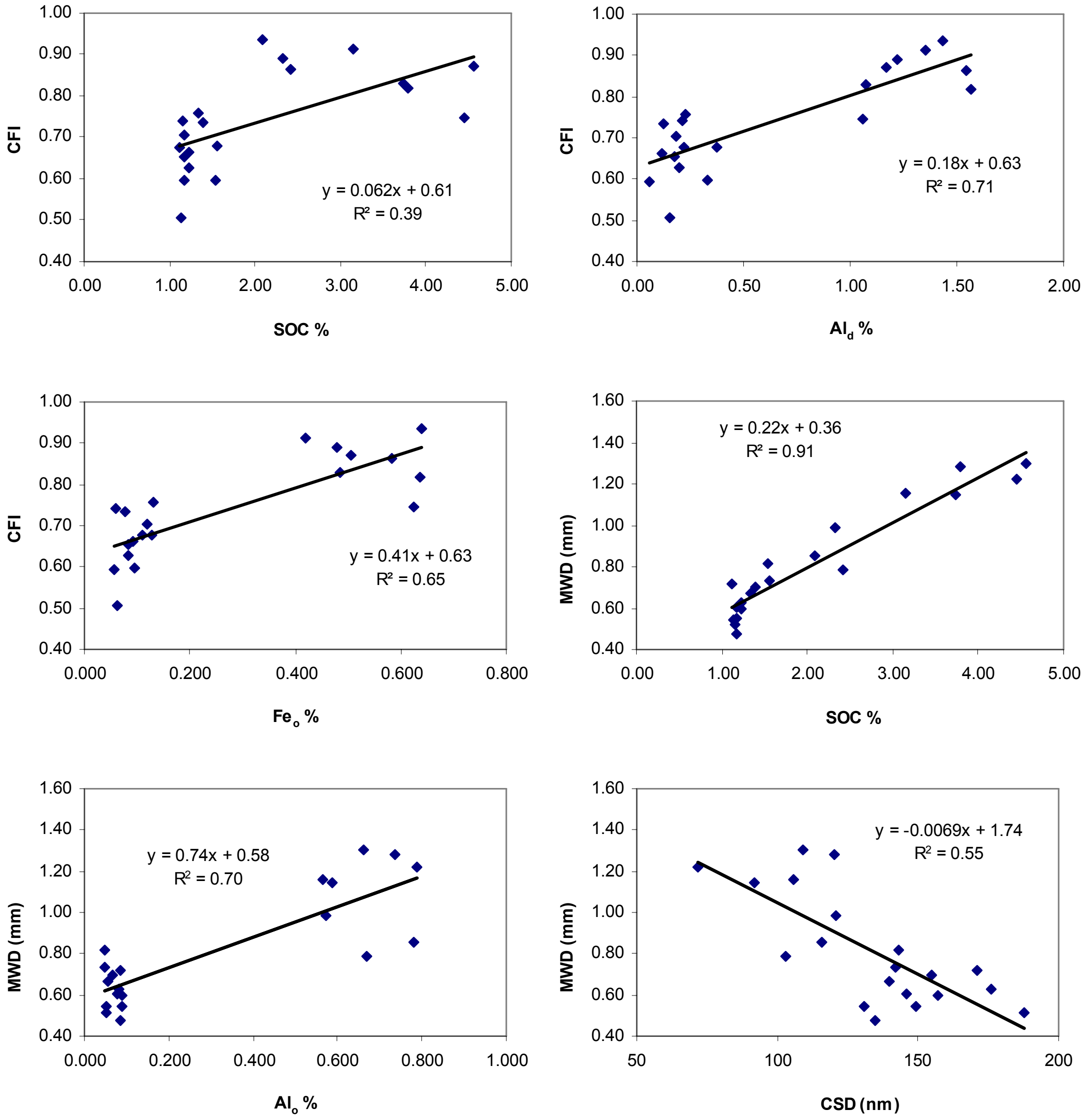

Figure 2 Some aggregate stability indices plots with major cementing agents.

Discussion

Dispersibility, macro and micro-aggregate stability of the soils

Macro and micro-aggregate stability of soils under udic SMR were higher than soils under ustic SMR whereas values of dispersibility under udic SMR was lower than those from ustic SMR. Normally high amounts of rainfall and higher humidity in the soil (udic SMR) showed higher soil weathering. This condition supports an increasing accumulation of Fe and Al oxides [27,28] which were the main bonding agents for macro and micro-aggregate stability in highly weathered soils.

Influence of SOC, forms of Fe and Al oxides and kaolin crystal size on aggregate stability

The relationship between SOC and macro and micro-aggregate stability found in this research was different from other research in the same type of soils. Generally, in highly weathered soils such as Oxisols, SOC does not play an important role as the binding agent of an aggregation [3,5] and some reports suggest that SOCs act as dispersing agents [6]. But this research indicated that SOC was the main factor in increasing aggregate stability. High enough concentrations of organic carbon in these soils studied probably increased aggregate stability and reduced dispersion [29].

The content of clay and type of clay mineral was not associated with increasing aggregate stability. The relationship between crystal size of kaolin and MWD and CFI from **Table 4** showed that the crystal size of kaolin supported aggregate stability. Size of kaolin effects cooperation bonding with polyvalent cations (Fe and Al) and SOC. Different sizes of kaolin can give different levels of aggregate stability. Trakoonyingcharoen *et al.* [30] reported that Thai kaolin crystals had specific properties within a moisture regime. Small crystal size, low crystallinity and high surface area of kaolin specified with udic SMR whereas large crystal size, high crystallinity and low surface area specified with ustic SMR. The study confirmed that soils from udic SMR had very small kaolin crystal size and contained high aggregate stability. Soils from ustic SMR showed the opposite results.

Oxides of Fe and Al also influenced aggregate stability. Strong positive correlation between aggregate stability indices (MWD and CFI) with Fe_t, Fe_o, Fe_{py}, Al_d, Al_o and Al_{py} are shown in **Table 4**. Fe_d did not relate with any aggregate stability indices. Normally, Fe_d was more correlated with aggregate stability than other properties for oxide rich soils [31] but our study indicated that noncrystalline Fe had a more significant effect on aggregate stability than crystalline Fe. This is probably due to the larger surface area of particles per gram of noncrystalline Fe than crystalline Fe oxides [4]. All forms of Al were correlated with aggregate stability since they were the most effective aggregating agents especially, at the microaggregate level [32].

Imhoff *et al.* and Six *et al.* [33,34] all confirmed that in oxide rich soils oxides can act as binding agents in three ways; organic materials adsorb on oxide surfaces or negative charged clay minerals or finally a coat of oxide on the surface of minerals forms bridges between primary and secondary particles. Edwards and Bremner [35] also explained the nature of the polyvalent bonding with the clay surfaces and organic matter in following manner: clay-(Fe and Al)-organic matter-(Fe and Al)-clay. This study also showed this linkage encourages soil aggregate stability.

Conclusion

Soils from 2 types of parent materials and 2 types of soil moisture regimes showed that soil moisture regime influenced the content of oxides and size of kaolin whereas parent materials did not. These conditions can lead to more interactions between them and SOC. The interaction between them can promote aggregate stability. The udic SMR had more soil weathering, giving higher oxide content and smaller kaolin crystal size than soils from ustic SMR. Consequently, soil aggregate stability for both macro and micro-aggregate under udic SMR was higher than those from ustic SMR although the latter had a low amount of rainfall. The climate did not have an adverse effect on soil physical properties but they did encourage an increase in soil aggregate stability for these soils.

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