LIME REACTIVITY OF TROPICAL AND SUBTROPICAL SOILS

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Research to determine the factors that significantly influence lime pozzolanic reactions in soils has been fairly well restricted to soils of temperate regions. Extrapolation of these data to tropical soils was not justified without additional investigation. Selection and sampling of tropical and subtropical soils in this study were accomplished so that representative cross sections of soil characteristics were provided. The laboratory investigations included the use of standard techniques to determine physical, chemical, and mineralogical properties of the 26 soils. Development of lime pozzolonic reactions was measured by maximum increases in the unconfined compressive strength of the lime-treated soils after various curing periods. It was concluded that soil pH, cation exchange capacity, base saturation, silica sesquioxide ratio, silica-alumina ratio, and pedologic order influence the development of lime pozzolanic reactions in Ultisols and Oxisols. Strength increases after 28 days of curing at 73 F varied from 22 to 606psi. Different indexes of lime reactivity and weathering were found to be valid within the Ultisols (soil pH) and within the Oxisols (silica sesquioxide ratio).

•LIME stabilization of soils for use in construction of pavements can often be beneficially and economically utilized. In most cases, however, sufficient knowledge is not yet available for evaluating the probable effects of lime stabilization of a soil without extensive testing of the individual soil. This situation is particularly prevalent in tropical and subtropical regions, where soil stabilization research has been quite limited.

In the tropics and subtropics, soil types can be broadly categorized as either residual soils developed from the in situ weathering of rock or as alluvial/colluvial soils. Surficial soils characterized as lateritic cover much of the tropics and subtropics. Within the United States, the southeastern states are extensively covered by "lateritic" and red-yellow podzol soils of both alluvial and residual origin. The soil chemistry and mineralogy of soils that have been subjected to advanced weathering processes appear to be significantly different from those of young soils, such as the glacial soils of the central United States or the azonal soils of the western United States, and thus warrant special consideration in formulating criteria for lime stabilization.

The addition of small quantities of lime (3 to 7 percent by weight) to practically any fine-grained soil whose clay-size fraction includes clay minerals will initiate a reduction in plasticity, a decrease in shrinkage potential, an increase in workability, an increase in CBR, and an increase in the modulus of deformation of the compacted soil. In some cases a marked increase in "strength", termed the pozzolanic reaction, also occurs. Thompson suggested (19) that the lime reactivity be defined as the increase in the unconfined compressive strength (lime-treated soil compared to natural soil) after 28 days' curing at 73 F at the optimum (maximum strength) lime content. This definition was used in the current study.

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Within the past decade, extensive research concerning the mechanisms of lime-soil stabilization and the significant factors influencing the lime-soil reaction has been accomplished in the United States. Based on this research, it is possible to forecast qualitatively the lime reactivity of certain classes of surficial soils on a worldwide basis. This type of research and correlation has been restricted, however, to soils derived from relatively unweathered tills and loessial materials of the central United States and some corroborating data on similar soils in Europe. Available data concerning lime reactivity of advanced-weathered soils are conflicting and indicate a lack of systematic investigation of the significant factors influencing lime stabilization of such soils.

The need for expedient, economical means of construction utilizing indigenous materials in the tropics and subtropics, where strongly weathered soils predominate, is of importance from the standpoint of development of highway systems, airfields, and other facilities required for the operation of transport and supply systems. Thus, the objectives of this research program were to determine the factors that influence the lime reactivity of soils that have been subjected to advanced weathering processes and, if feasible, to identify soil index properties by which qualitative forecasts of lime reactivity could be made reliably.

IDENTIFICATION OF FACTORS INFLUENCING LIME REACTIVITY AND SOIL SAMPLE SELECTION

The characteristics and technology of tropical and subtropical soils and the principles of lime stabilization of soils as reflected in the published literature were extensively reviewed and are summarized elsewhere (4). Factors considered to be of importance in the lime-soil pozzolanic reaction included type and amount of lime, curing conditions, mixture density, and natural soil properties such as type and amount of organic carbon, exchange complex characteristics, free carbonates, free sulfates, sodium enrichment, amounts of silica, alumina, and iron oxides (total and extractable), amount and plasticity of $<2\mu$ clay, clay mineralogy, and pedology. The vast majority of published data concerning the least controllable factor, namely soil properties, deals with soils of the temperate zones.

It was believed that a representative sample suite of tropical and subtropical soils that have been subjected to the advanced weathering process of laterization and podzolization should be about evenly divided between the two predominant soil orders resulting from these processes, Ultisols and Oxisols. [For convenience and simplicity, the nomenclature of the U.S. Department of Agriculture's 7th Approximation (13) was adopted in this study.] Well-characterized soils that had been extensively studied by soil scientists and engineers were thought to have particular merit, since common grounds of communication could be established readily for such soils. The Ava soil was included as a reference sample to previous temperate-zone soil research.

Table 1 gives the general characteristics of the soils in the sample suite. All samples except the Ava and the Vietnam soils were shipped to the laboratory in sealed containers to permit evaluation of the field moisture content.

LABORATORY INVESTIGATION

Each of the 26 soils in the sample suite was analyzed for chemical, physical, and mineralogical properties according to established procedures. Table 2 gives the properties determined and the procedures used in the determination. Table 3 summarizes the test results for each soil.

Details of the testing procedures have been presented elsewhere (4). The procedures were based on accepted practices (12, 19, 20) that have been widely used in other studies.

To study the effects of soil properties on lime-soil reactivity, the effects of soil properties must be experimentally isolated. Thus, other factors that affect the lime reactivity, such as lime type, lime quantity, curing conditions, and specimen density, must be made "constant". Certain procedures were employed to accomplish this requirement, as noted in the following paragraphs.

Table 1. Soil sample suite.

Soil No.	Soil Series	Soil Order	Horizon	Sample Site	Parent Material	Profile Reference[a]
1	Appling	Ultisol	B22t	South Carolina	Granite residuum	–
2	Cecil	Ultisol	B21t	North Carolina	Acidic rock residuum	–
3	Davidson	Ultisol	B22t	South Carolina	Basic igneous/ metamorphic rock	–
4	Greenville	Ultisol	B22	Georgia	Coastal plain residuum	(14)
5	Norfolk	Ultisol	B21	Georgia	Coastal plain residuum	(14)
6	Ava	Alfisol	B2	Illinois	Weathered loess	–
7	Surinam Red Earth[b]	Oxisol	B2	Surinam	Acidic metamorphic rock	–
8	Chudleigh	Oxisol	B	Jamaica	Limestone	(1)
9	St. Ann	Oxisol	B	Jamaica	Limestone	(1)
10	Talparo	Unknown[c]	B	Trinidad	Clay and clay shales	–
11	Woodford Hill	Unknown[d]	B	Dominica	Volcanic residuum	–
12	Aibonito	Ultisol	B22	Puerto Rico	Volcanic residuum	(16)
13	Bayamon	Oxisol	B22	Puerto Rico	Transported sediments	(16)
14	Catalina	Oxisol	B22-23	Puerto Rico	Flow breccia	(10)
15	Cialitos	Ultisol	B21t	Puerto Rico	Volcanic residuum	(16)
16	Corozal	Ultisol	B22t	Puerto Rico	Volcanic conglomerate	(16)
17	Coto	Oxisol	B22-23	Puerto Rico	Limestone/sand sediments	(16)
18	Jagueyes	Ultisol	B22t	Puerto Rico	Plutonic rock residuum	(16)
19	Los Guineos	Ultisol	B22t	Puerto Rico	Volcanic residuum	(16)
20	Matanzas	Oxisol	B21	Puerto Rico	Unknown	(16)
21	Nipe	Oxisol	B21	Puerto Rico	Serpentinite	(16)
22	Matanzas	Oxisol	B22	Puerto Rico	Unknown	(16)
23	Nipe	Oxisol	B22	Puerto Rico	Serpentinite	(16)
24	Vietnam Laterite[b]	Unknown	Unknown	Vietnam	River terrace sediments	–
25	Panama Howard[b]	Unknown	Unknown	Panama Canal Zone	Unknown	–
26	Panama Albrook[b]	Unknown	Unknown	Panama Canal Zone	Unknown	–

[a] For profile sites that have been characterized in published literature; number refers to those in reference list. References (2) and (17) also give general information for soils No. 1 through 5.
[b] Real series designation unknown.
[c] Probably Ultisol.
[d] Probably Oxisol.

Table 2. Test procedures for determination of soil properties.

Soil Property	Test Method Reference[a]	Remarks
Grain size distribution	ASTM D-422	
Liquid limit	ASTM D-423	
Plastic limit	ASTM D-424	$I_w = L_w - P_w$
Optimum moisture content and maximum dry density	AASHO T-99-57 (Method A)	See Ref. 4 for modifications
Natural moisture content	ASTM D-2216	Determined upon receipt of sample
Clay mineralogy	X-ray diffraction	Details in Ref. 4
Calcium carbonate	Qualitative. Method 6E2a	
pH	Method 8C1a	Coleman pH meter
Organic carbon	Wet combustion. Method 6A1a	
Cation exchange capacity	Na O Ac (pH = 8.2), Method 57.3	Isopropyl alcohol used Flame photometer
Exchangeable bases	NH_4 O Ac (pH = 7.0). Method 57.2-1	Flame photometer (Na and K) and atomic absorption (Ca and Mg)
Exchange acidity	Titration. Method 6H1a	
Total silica, alumina, iron oxides	X-ray fluorescence	
Activity	Computational	$\text{Activity} = \frac{I_w}{\text{percent} < 2\mu \text{ clay}}$
Calcium-magnesium ratio	Computational	$\text{Ca/Mg} = \frac{\text{Exchangeable calcium}}{\text{Exchangeable magnesium}}$
Silica sesquioxide ratio	Computational	$\text{SSR} = \frac{\frac{\text{percent silica}}{60.6}}{\frac{\text{percent alumina}}{101.94} + \frac{\text{percent iron oxide}}{159.70}}$
Silica-alumina ratio	Computational	$\text{Si/Al} = \frac{\frac{\text{percent silica}}{60.6}}{\frac{\text{percent alumina}}{101.94}}$
Percent base saturation	Computational	$\text{Percent base sat.} = \frac{\Sigma \text{ exch. bases}}{\text{CEC} \times 100 \text{ percent}}$
Unconfined compressive strength	Unconfined compression test	1-in.-diameter × 2-in. specimens compacted at optimum moisture content to maximum dry density

[a] References to ASTM and AASHO refer to recommended test procedures of the American Society for Testing and Materials and the American Association of State Highway Officials respectively. Methods of the form "6E2a" are procedures outlined in SSIR No. 1 (15), and those of the form "57.2-1" are procedures outlined in Methods of Soil Analysis (7).

Table 3A. Soil properties.

Soil No.	Soil Type	Field ω, Percent	Moisture-Density: Natural $(\gamma_d)_{max}$, pcf	Natural ω_{opt}, Percent	Lime-Modified Soil $(\gamma_d)_{max}$, pcf	Lime-Modified Soil ω_{opt}, Percent	Atterberg Limits: LL, Percent	PL, Percent	PI, Percent	Percent <2μ Clay	Soil Activity	Classification: AASHO	UC	pH	Percent OC
1	Appling sandy loam	24.7	100.5	24.0	94.3	25.8	71	33	38	50.0	0.76	A-7-5(17)	CH	5.4	0.27
2	Cecil sandy loam	19.6	110.7	18.3	105.5	19.7	53	26	27	40.6	0.66	A-7-6(13)	CH	5.4	0.04
3	Davidson clay loam	25.3	95.8	25.8	93.1	28.6	70	36	34	53.5	0.64	A-7-5(20)	MH	5.1	0.08
4	Greenville fine sandy loam	16.4	116.0	14.5	109.9	16.3	35	12	23	39.3	0.59	A-7-6(10)	CL	6.0	0.19
5	Norfolk fine sandy loam	17.0	124.9	11.4	116.0	13.7	28	10	18	26.5	0.64	A-7-6(5)	SC	5.7	0.04
6	Ava silt loam	Unknown	109.8	16.6	102.8	18.8	35	19	16	27.0	0.59	A-7-6(10)	CL	5.6	0.08
7	Surinam red clay loam	32.2	96.2	28.0	92.2	28.5	60	32	28	59.8	0.47	A-7-5(19)	MH	5.0	0.27
8	Chudleigh clay loam	33.7	92.0	30.6	82.2	33.8	68	30	38	92.0	0.41	A-7-5(20)	CH	8.0	0.35
9	St. Ann clay loam	25.1	95.3	28.5	87.5	34.5	58	25	33	92.0	0.36	A-7-6(20)	CH	7.7	0.39
10	Talparo clay	29.9	96.0	24.5	90.5	27.8	88	25	63	78.2	0.81	A-7-6(20)	CH	5.0	1.01
11	Woodford Hill clay	40.6	81.6	38.6	78.5	39.5	99	38	61	76.3	0.80	A-7-5(20)	CH	5.7	0.39
12	Aibonito clay	28.9	91.2	29.1	85.5	32.7	80	30	50	70.5	0.71	A-7-5(20)	CH	4.8	0.82
13	Bayamon clay	31.5	88.8	30.0	84.2	34.2	86	33	53	83.2	0.64	A-7-5(20)	CH	5.3	0.43
14	Catalina clay	42.9	84.8	36.4	80.2	37.4	83	40	43	87.2	0.49	A-7-5(20)	MH	5.0	0.55
15	Cialitos clay	42.4	84.7	33.6	83.9	35.8	81	41	40	67.7	0.59	A-7-5(20)	MH	4.9	0.58
16	Corozal clay	33.4	88.2	31.1	83.4	33.8	92	36	56	72.0	0.78	A-7-5(20)	CH	4.5	0.47
17	Coto clay	26.3	100.2	24.3	94.0	27.9	51	23	28	67.7	0.41	A-7-6(20)	CH	6.8	0.58
18	Jagueyes silty clay loam	16.1	113.8	14.7	106.7	18.4	54	23	31	36.1	0.86	A-7-6(10)	SC	4.7	0.23
19	Los Guineos clay loam	36.7	93.2	29.3	84.6	32.4	74	34	40	54.3	0.74	A-7-5(20)	CH	4.8	0.66
20	Matanzas clay (B21)	24.5	94.3	30.8	86.4	32.9	58	30	28	89.2	0.31	A-7-5(20)	CH	7.8	0.97
21	Nipe clay (B21)	30.0	97.7	28.8	93.4	31.1	48	31	17	81.7	0.21	A-7-5(20)	ML	5.4	1.09
22	Matanzas clay (B22)	25.2	95.5	29.2	87.7	32.2	58	29	29	89.2	0.32	A-7-5(20)	CH	7.8	1.01
23	Nipe clay (B22)	24.1	109.7	23.9	103.8	27.0	42	28	14	46.0	0.30	A-7-6(8)	ML	5.6	1.01
24	Vietnam laterite	Unknown	129.3	12.7	121.3	15.0	44	19	25	16.2	1.54	A-2-7(2)	SC	5.0	0.35
25	Panama Howard	36.5	90.8	30.3	85.8	32.5	82	32	50	48.0	1.04	A-7-5(19)	CH	7.2	0.31
26	Panama Albrook	33.7	88.4	30.9	85.2	33.2	76	35	41	57.2	0.72	A-7-6(20)	CH	5.3	0.35

Table 3B. Soil properties (continued).

Soil No.	Cation Exchange Capacity, Meq/100 g	Exchange Bases, Meq/100 g: Ca	Mg	K	Na	Exchange Acidity, Meq/100 g	Ca/Mg	Percent Base Sat.	Basic Constituents: SiO_2	Al_2O_3	Fe_2O_3	Silica Sesqui-oxide Ratio	Si/Al	Clay Minerals[a]	Unconfined Compressive Strength, psi: Natural Soil	Lime-Modified Soil: 7-Day Cure	28-Day Cure	56-Day Cure
1	24.9	0.6	1.3	0.46	0.27	22.5	0.46	11	64.0	26.1	4.3	3.73	4.11	K, I, M, V, Q, Gi	92	224	410	550
2	16.6	0.6	1.3	0.14	0.00	15.3	0.46	12	67.2	16.7	5.5	5.59	6.75	K, I, Q, Gi	71	198	273	297
3	38.6	0.2	0.8	0.27	0.00	20.2	0.25	3	52.2	25.8	13.4	2.55	3.40	K, Go, Q, M, H	112	210	347	477
4	15.6	2.4	0.8	0.08	0.00	15.5	3.00	21	84.0	11.6	4.2	9.89	12.15	K, V, Q, Gi, Go, H, MI	83	318	620	995
5	10.8	1.9	1.1	0.03	0.00	16.3	1.73	28	83.5	7.4	4.6	13.50	18.85	K, Q, Gi, C	67	246	406	534
6	18.8	7.5	4.2	0.17	0.00	26.5	1.79	63	81.6	10.0	4.8	10.52	13.74	K, I, M, Q, C	107	150	219	268
7	32.6	0.1	0.5	0.00	0.00	24.1	0.20	2	55.7	24.2	11.9	2.93	3.86	K, I, M, Q, C, Gi	72	152	186	218
8	35.6	9.3	1.4	0.07	0.00	12.8	6.64	30	22.5	42.5	17.2	0.71	0.89	K, Gi, B, Bo	55	299	302	310
9	24.4	7.5	1.3	0.10	0.00	18.4	5.77	36	7.3	49.9	18.3	0.20	0.25	Gi, Bo, K	119	448	580	592
10	51.5	16.2	5.3	0.49	0.00	28.0	3.06	43	57.3	24.6	10.1	3.11	3.92	K, Q, M, I	90	166	191	214
11	27.4	2.8	6.9	0.48	0.48	20.9	0.41	39	44.8	32.0	14.9	1.81	2.35	K, I	107	310	450	555
12	43.0	0.1	0.9	0.13	0.00	34.7	0.11	3	65.0	18.3	10.1	4.41	5.95	K, Q, Mi	85	117	141	195
13	35.1	3.5	1.6	0.00	0.22	18.8	2.19	15	41.3	28.0	14.0	1.87	2.47	K, M, Q, Go, Gi	108	129	190	353
14	41.2	1.9	0.9	0.11	0.00	18.6	2.11	7	30.4	32.0	19.7	1.15	1.60	K, M, Q, Gi	91	120	217	225
15	34.8	0.1	0.8	0.01	0.00	21.6	0.13	3	39.2	32.0	19.2	1.49	2.06	K, M, Go	107	105	138	233
16	44.4	3.6	0.6	0.06	0.00	25.0	6.00	10	60.0	24.4	10.7	3.23	4.14	K, Q, Mi	91	122	151	231
17	22.0	2.8	1.4	0.54	0.00	11.4	2.00	22	55.1	22.7	15.0	2.86	3.79	K, Go, I	81	160	195	273
18	23.1	0.2	0.5	0.10	0.00	9.9	0.40	3	78.7	17.4	3.0	6.84	7.60	K, M, I, Q	98	126	227	389
19	35.4	2.3	0.8	0.03	0.00	40.7	2.88	9	68.0	18.6	7.9	4.83	6.12	K, Go, C, Q	85	96	107	166
20	29.8	9.2	0.9	0.01	0.00	11.7	10.23	34	34.0	36.2	17.9	1.20	1.58	K, Bo, Gi, C	75	161	228	412
21	34.9	2.2	0.5	0.00	0.00	19.1	4.40	8	12.3	26.5	49.0	0.36	0.78	K, Gi, C	55	242	520	660[b]
22	29.6	9.4	0.6	0.00	0.00	8.3	15.67	34	35.3	36.3	18.5	1.23	1.64	K, Bo, Gi	117	133	239	420
23	25.8	0.2	0.5	0.06	0.00	15.9	0.40	3	7.0	23.4	64.3	0.18	0.50	K, Gi, Go, Bo, C	67	300	605	675[b]
24	16.2	0.1	0.5	0.00	0.00	6.9	0.20	4	49.1	11.2	34.8	2.47	7.36	K, Gi, Q, C	120	131	203	290
25	23.1	18.0	7.5	0.06	0.20	8.5	2.40	100	44.3	28.7	15.3	1.93	2.59	K, Gi, I	106	245	712	800[b]
26	21.0	6.4	2.9	0.03	0.00	11.8	2.21	45	45.5	28.8	15.8	1.96	2.65	K, Go, Q, M	111	147	325	365

Note: All soils were noncalcareous.

[a] Symbols used are: B = Bayerite; Bo = Boehmite; C = Chlorite; Gi = Gibbsite; Go = Goethite; H = Hematite; I = Illite; K = Kaolinite; M = Montmorillonite; Mi = Mica; MI = Mixed Layer; Q = Quartz; V = Vermiculite

[b] Based on extrapolation of test data.

One lime, a commercial high-calcium hydrated lime manufactured by the Mississippi Lime Company of Ste. Genevieve, Missouri, was used in the study. All the lime used was taken from a single batch. A typical analysis furnished by the lime company showed 96.2 percent available calcium hydroxide, with approximately 95 percent of the lime passing the No. 325 sieve.

Each of the soils was treated with 3, 5, 7, and 9 percent lime (nominal, by weight of soil solids). In cases when a leveling off of the confined compressive strength with increasing lime content after 28 days' curing was not obtained with the stated lime quantities, additional specimens were made up with lime contents as great as 16 percent. In some soils, slightly different combinations such as 3-6-9-12 percent, or 3-6-8-10 percent, were used, to assure leveling off of the strength in cases where soil quantities were very limited. In all soils, a minimum of 4 different lime levels was used.

Curing was accomplished in a constant-temperature cabinet at 73 F ±4 F. Curing periods used in this investigation were 7, 28, and 56 days. Specimens were sealed in plastic bags to prevent lime carbonation and to minimize loss of moisture. Strength specimens of the natural soil were cured for 7 days to allow for thixotropic effects.

At the end of each curing period, the selected specimens were tested in unconfined compression in a Riehle hydraulic testing machine. Loads were applied at a constant rate of deformation of 0.05 in. per minute. The maximum load was recorded, and a moisture-content sample was taken from each test series. The average strength of the 4 specimens was recorded as the unconfined compressive strength. The maximum unconfined compressive strength for each curing period was determined by inspection of the plot of the unconfined strength versus the amount of lime. The maximum strength increases, including the lime reactivity (28-day cure), were then determined by subtracting the natural soil compressive strength from the maximum unconfined compressive strength as taken from the curve of strength versus lime content. Table 3 includes a summary of the strength increases for the various curing periods. Complete strength test results are reported elsewhere (4).

STATISTICAL ANALYSIS

Twenty of the 26 soils included in this study were pedologically described in sufficient detail to permit classification as either Ultisols (10 soils) or Oxisols (10 soils). This distinction was capitalized on in the analyses to investigate the possible influence of soil development factors on the lime reactivity.

The response of the soils in this study to lime as measured by the lime reactivity varied from 22 psi to 606 psi. To facilitate statistical analyses, the entire suite of 26 soils was divided into 5 convenient, arbitrary reactivity groups:

Reactivity Group Identification	Strength Increase, psi (28-day cure)
1	0-60
2	61-125
3	126-250
4	251-500
5	>500

When statistical analysis was performed within the individual soil orders, the number of arbitrary lime reactivity groups was reduced to 3, to ensure a statistically significant population in each reactivity group. Reactivity groups used in these analyses (U = Ultisols, O = Oxisols) were as follows:

Reactivity Group Identification	Strength Increase, psi (28-day cure)
U-1 and O-1	0-125
U-2 and O-2	126-250
U-3 and O-3	>250

Detailed curves of strength versus lime content are presented elsewhere (4).

Statistical analyses (standard analytical methods referred to as analysis of variance and Duncan's multiple-range test) and simple correlation were performed. Simple correlation results are given in Table 4. Analysis-of-variance and Duncan's multiple-range test results are presented elsewhere (4).

DISCUSSION AND INTERPRETATION

Based on the premise that all soils, due to the chemical presence of silica and/or alumina in the clay fraction, can potentially react with lime (18) to form hydrated calcium aluminosilicates or perhaps calcium ferroalumino-silicates (11), the intent of this research was to identify those soil properties that affect the rate of reaction and the maximum potential reaction of the lime and the soil. The discussion in the following paragraphs summarizes those soil properties examined in this investigation.

Soil pH

A significant statistical correlation between lime reactivities and soil pH, such as found by Thompson (19) for the temperate-zone soils he examined (r = 0.499, 29 observations), was not found in the current investigation when the entire sample suite was considered. When the Oxisols and the Ultisols were considered by themselves, however, the results were striking, and opposite. For the Oxisols, the simple correlation coefficient was 0.003. In the Ultisols, the correlation was highly significant, as shown in Figure 1. Thus, it appears that the Ultisols, which have developed from the more "conventional" weathering process of podzolization, have lime reactivity characteristics similar to temperate-zone soils. Soil pH as an indicator of weathering also appears to be valid in the Ultisols, because the pH of the tropical Ultisols (Puerto Rico) were lower than the less weathered humid-temperate Ultisols (southeastern United States). But, within the Oxisols, soil pH did not appear to have any relationship to the degree of weathering. For example, the highly laterized bauxite soils of Jamaica had soil pH's of 7.7 and 8.0, while the average pH of all the Oxisols was 6.4.

Soil Exchange Complex Properties

Although the correlation between the cation exchange capacity (CEC) and the lime reactivity of the entire sample suite was statistically significant (r = -0.400), analysis of the data indicates that the significance of correlation may be due primarily to the strong correlation within the Ultisols (r = -0.718). Thus CEC, like soil pH, may be of value in assessing the lime reactivity within individual soil orders. A comment with regard to the sense (positive or negative) of the correlation is warranted. Ingles and Frydman (6) examined a suite of samples having a sizable number of soils with exchange capacities less than 10 Meq per 100 g and found a positive correlation between the 7-day lime-modified soil strengths and the CEC. Most of their essentially nonclay soils, however, did not react favorably with lime. The current study, on the other hand, did not have any soils with an exchange capacity less than 10 Meq per 100 g.

The percent base saturation correlated significantly with lime reactivity among the Ultisols, which again might be expected, since the soil pH was significantly correlated to lime reactivity for these soils. In general, the base saturation has a strong direct relationship with the soil pH and is inversely related to the exchange acidity (19).

Basic Soil Constituents (Silica, Alumina, Iron Oxides)

Since silica, alumina, and iron oxides are the basic chemical constituents in soils, it would seem to follow that the lime pozzolanic reaction, a chemical reaction, should be related to the concentration or state of these constituents. Studies attempting to relate silica and alumina content to lime reactivity of soils have been very limited due to the expense involved and to the requirement for sophisticated laboratory equipment to determine total silica, alumina, and iron oxide contents. Most of the early work correlating silica and alumina with lime reactivity was accomplished using lime-fly ash mixtures. The work of Thorne and Watt (21) and Hollis and Fawcett (5) indicated that the ultimate strength of lime-fly ash mixtures was significantly related to the silica and alumina content.

Silica, alumina, and iron research on temperate-zone soils has been limited primarily to that involving the extractable portions of the 3 basic constituents. Thompson (19) examined the reactivity of 2 soils from Illinois before and after removal of the extractable iron and found the after-stripping unconfined compressive strengths to be 46 percent and 303 percent greater. Moore and Jones (8) continued work on Thompson's original data by determining the extractable iron, silica, and alumina of his soils and found statistically significant relationships between the lime reactivity and the extractable iron (negative) and between the lime reactivity and the extractable silica (positive).

Examination of the correlation coefficients between lime reactivity and the amounts of silica, alumina, and iron and the empirical parameters referred to as the silica sesquioxide ratio and silica-alumina ratio for the entire soil suite of the current investigation shows none to be statistically significant. Similarly, no significant correlations among these factors and lime reactivity were found in the Ultisols. Among the Oxisols, however, correlations between the percent silica ($r = -0.866$), the percent iron oxides ($r = 0.803$), and the silica sesquioxide ratio ($r = -0.782$) were all significant at the $\alpha = 0.05$ level. Figure 2 shows the correlations of lime reactivity with the SSR and Si/Al.

Ordinarily, when one discusses the lime pozzolanic reaction, a relative abundance of silica and/or alumina is assumed. It appears, however, that the state of weathering and susceptibility to attack by the lime is of equal or greater importance in determining the lime reactivity of tropical soils, and particularly Oxisols, than any arbitrary standard of amount of total silica and/or total alumina present. [The hypothesis of Sherwood (11) regarding the reaction of lime with the iron and alumina oxides should not be discounted, but basic mineralogical research regarding calcium-ferroaluminate complexes is still lacking.] One might postulate that the silica, and possibly the alumina, in the highly laterized Oxisols is in a highly weathered state and thereby much more susceptible to dissolution and attack by the lime in the highly alkaline lime environment. Furthermore, in a suite of pedologically identified Oxisol soil samples, the silica sesquioxide ratio, at least in the range of 0.2 to 3.0, and to a lesser extent the silica-alumina ratio might then be of value as a lime reactivity index, as soil pH appears to be in the Ultisols.

Obviously, this discussion ignores the presence of contaminants that interfere with the lime pozzolanic reaction. The effects of organic carbon and sulfates are discussed elsewhere (4). Extractable iron, apparently indicative of certain weathering states, either coats the clay minerals or by some other chemical means restricts the lime reactivity, as noted by Thompson (19) and Moore and Jones (8). Yet the Nipe soils of this investigation were extremely responsive to lime, and they have extractable iron contents of 15 to 20 percent (11).

Pedology

The analyses in this investigation point very definitely to the importance of pedology, and particularly the state of weathering, in the assessment of the probable lime reactivity of tropical and subtropical soils. Soil indexes of lime reactivity apparently do not cut across the boundaries of soil orders, at least in highly weathered soil profiles. On the other hand, highly significant indexes can be found within the individual soil orders.

Many of the pedologic indexes found to be significant in predicting the lime reactivities of temperate-zone soils, such as soil profile drainage (19), presence of free carbonate (10, 19), and presence of sulfates (3, 9), were not found to be of any value in the highly leached Ultisols and Oxisols. Carbonates and sulfates, being quite soluble, are apparently leached from the Oxisol and Ultisol profiles, while profile drainage appears to be a factor only in certain weathering states. Horizonation was not a factor considered in the current study because all the samples were from the mid-B horizon.

Miscellaneous Observations

The effects of organic carbon content, soil physical properties, clay mineralogy, amounts of individual exchangeable cations, calcium-magnesium ratio, and exchange acidity were not found to be of significance, generally, in their influence on lime-soil reactivity. More detailed discussion of their effects, particularly in the analysis of the Ultisols, is presented elsewhere (4).

The contention that optimum lime requirements are higher for tropical soils appears to be at least partially true on an individual soil basis. Several soils in this study (Table 5) had 28-day optimum lime contents of 10 percent or more as opposed to the 5 to 7 percent range common for the temperate soils noted by Thompson (19). The average optimum lime content for the 28-day cure was 7.4 percent for the Oxisols and 5.9 percent for Ultisols. Again, the departure from temperate-soil norms in the Oxisols is noteworthy.

Although deformations were not measured during the testing of unconfined compression specimens, a change in the stress-strain behavior was observed in all the soils due to the addition of lime. Beyond a certain "threshold" lime content, which varied from soil to soil, the modulus of deformation was noticeably greater, and the failure strain was noticeably lower, than for the natural soil. It appeared that the more ferruginous soils required higher threshold lime contents to initiate the more brittle failure characteristics.

The decrease in maximum dry density due to the addition of lime is clearly given in Table 3. In most cases this density loss does not result in a corresponding strength loss, since the cementing action of the lime more than offsets the density effect.

It should be pointed out that the moisture loss during curing in the 56-day specimens appeared to be fairly substantial in some cases, although not unreasonable. Absolute values of the unconfined compressive strength after 56 days of curing should be considered in this light.

Lime Reactivity Index

Originally it was hoped that the results of this investigation would permit the development of a reactivity index for the entire range of tropical and subtropical soils, with accompanying lime reactivity equations based on multiple-regression analysis such as those developed by Thompson (19). As shown by the investigation, however, such a simplified index system apparently does not exist. Rather, the individual soil orders appear to require individual index systems. The sample population in each order in the current study, although large enough to give statistically significant correlations, is not great enough to warrant development of prediction equations for general use.

CONCLUSIONS

Conclusions formed on the basis of this investigation were as follows:

1. The B-horizons of tropically and subtropically weathered soils, like temperate-zone soils, exhibit a wide range in lime reactivities. Furthermore, no single soil property can be used to predict accurately the lime reactivity of tropically and subtropically weathered soils. Lime reactivity index systems for such soils must be based on 2 or more soil properties or characteristics.
2. The absolute amount of silica or alumina required to sustain the pozzolanic reaction in soils appears to be relatively small. And the type of weathering process that has predominated in a soil profile significantly influences the state of the basic soil constituents and thus influences the potential lime reactivity of the soil. Therefore, Ultisols and Oxisols have different indexes of both weathering and lime reactivity.
3. Within the Ultisols, soil pH is a good index of both weathering and lime reactivity. Similarly, cation exchange capacity and percent base saturation are useful indexes of lime reactivities within the Ultisols.
4. The relative concentrations of the basic soil constituents, as measured by the silica sesquioxide ratio and to a lesser extent the silica-alumina ratio, are an excellent index of weathering and the lime reactivity of the soils of the Oxisol order.

Table 4. Simple correlation coefficients (correlation to unconfined compressive strength increase, 28-day cure).

Property	Entire Sample Suite (26 Observations)	Ultisols (10 Observations)	Oxisols (10 Observations)
Dry density, natural soil	0.173	0.715*	0.600
Optimum moisture content, natural soil	-0.098	-0.721*	-0.382
Maximum dry density, lime-modified soil	0.182	0.745*	0.558
Optimum moisture content, lime-modified soil	-0.099	-0.756*	-0.234
Liquid limit	-0.293	-0.770**	-0.607
Plastic limit	-0.229	-0.729*	-0.293
Plasticity index	-0.278	-0.717*	0.628
Percent < 2 μ clay	-0.107	-0.659*	-0.245
Soil activity	-0.177	-0.377	-0.635*
Soil pH	0.375	0.920**	0.003
Percent organic carbon	-0.075	-0.685*	0.353
Cation exchange capacity	-0.400*	-0.718*	-0.289
Exchange calcium	0.198	0.148	-0.143
Exchange magnesium	0.272	0.353	-0.301
Exchange potassium	-0.003	0.303	-0.165
Exchange sodium	0.254	0.262	-0.319
Exchange acidity	-0.338	-0.540	0.169
Percent base saturation	0.365	0.702*	-0.125
Ca/Mg	-0.030	0.002	-0.166
Percent SiO_2	-0.299	0.573	-0.886**
Percent Al_2O_3	0.122	-0.509	0.149
Percent Fe_2O_3	0.347	-0.541	0.803**
Silica sesquioxide ratio	-0.016	0.629	-0.782**
Si/Al	-0.039	0.589	-0.750*
Moisture loss during 28-day cure	0.268	—	—
Optimum lime content, 7-day cure	0.401*	-0.050	0.667*
Optimum lime content, 28-day cure	0.576**	0.580	0.682*
Optimum lime content, 56-day cure	0.438*	-0.092	0.581

*Significant correlation coefficient ($\alpha = 0.05$). **Highly significant correlation coefficient ($\alpha = 0.01$).

Figure 1. Influence of soil pH on lime reactivity of Ultisols (10 observations).

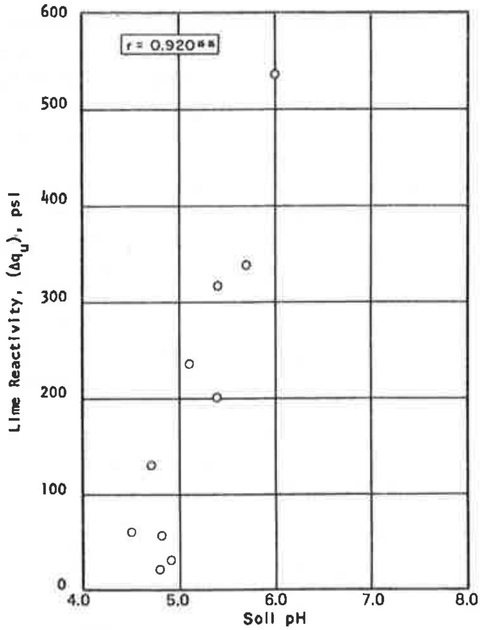

Figure 2. Influence of basic soil constituents on lime reactivity of Oxisols (10 observations).

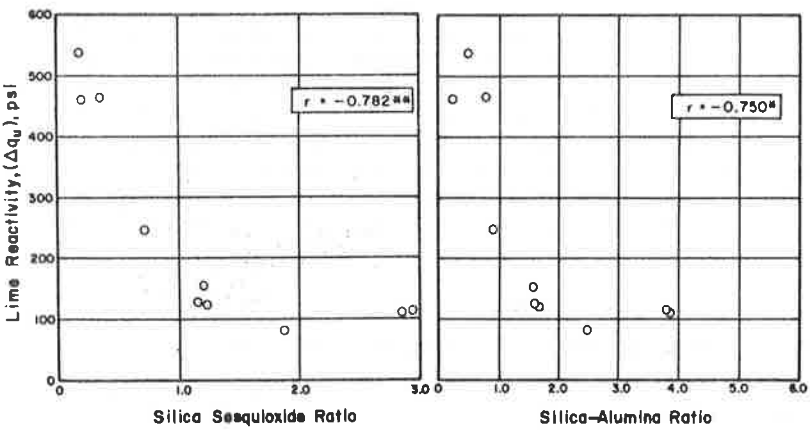

Table 5. Optimum lime content data.

Soil No.	Optimum Lime Content, Percent (28-Day Curing)
1	8
2	10
3	10
4	9
5	3
6	5
7	3
8	7
9	7
10	8
11	10
12	3
13	6
14	10
15	3
16	5
17	3
18	5
19	3
20	7
21	12
22	7
23	12
24	9
25	12
26	15

Note: Optimum lime content determined as the lowest lime content above which there is no statistically significant increase in the 28 day unconfined compressive strength.

5. Soil profile drainage, extractable iron contents, the presence of free carbonates, and the presence of sulfates generally are not of value as indexes of lime reactivity of tropically and subtropically weathered soils. In the case of carbonates and sulfates, however, the lack of value is due only to a lack of those constituents in such soils.
6. Lime requirements to maximize strengths of lime-treated soils of the tropics and subtropics are generally higher than those of temperate-zone soils.

It must be noted that this research was limited to 26 soils and required the experimental simulation and control outlined. Use of the data outside the context of this investigation must be judiciously considered.

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