

FINAL REPORT

REACTIONS IN PORTLAND CEMENT-CLAY MIXTURES

by

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Highway Materials Research Analysts

(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Highway Research Council
A Cooperative Organization Sponsored Jointly by the Virginia
Department of Highways and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

October 1970
VHRC 70-R13

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INTRODUCTION

Every day large quantities of soil are removed from highway construction sites because of an inability to stabilize the strata. Still other vast tonnages of soil are effectively utilized after treatment with portland cement. The reason for some soils being effectively stabilized with cement while others are not is complicated. It has long been thought that the physicochemical reactions of clay with cement somehow effect the soil stabilization process, but aside from the findings from a few investigations (Bezruk, 1950 — Handy, 1958 — Herzog and Mitchell, 1963) the nature of these reactions is not known. It was the purpose of this research to gain insight into the reactions of portland cement-clay mixtures by studying:

- (1) The reaction products of the mixture,
- (2) the rates of reaction of the mixtures,
- (3) the deterioration or lack of deterioration of clay minerals in the mixtures, and
- (4) the development of strength in the mixtures.

The objectives were sought through a purely laboratory approach. Specimens of relatively pure clays and portland cement, and later of soils and portland cement, were prepared and cured for varied time periods. The properties of these specimens were studied.

MATERIALS INVESTIGATED

Cements

Type I and type II portland cement were utilized in the studies made with relatively pure clays; only type I was used in the studies made with soils. The physical and chemical properties of these cements are given in Table I.

TABLE I

CHEMICAL AND PHYSICAL ANALYSES OF CEMENTS UTILIZED*

<u>Oxide Analysis</u>	Percent	
	Type I	Type II
SiO ₂	21.20	22.62
Al ₂ O ₃	5.90	3.32
Fe ₂ O ₃	2.34	3.36
CaO	64.44	63.63
MgO	2.83	2.58
SO ₃	2.18	2.21
Ign. Loss	.68	.85
Na ₂ O	.12	.09
K ₂ O	.73	.00
Na ₂ O Equiv.	.60	.48
Free CaO	1.00	.67
<u>Compounds (Calculated)</u>		
C ₃ S	52.0	53.5
C ₂ S	21.6	24.5
C ₃ A	11.68	3.12
C ₄ AF	7.11	10.21
CaSO ₄	3.71	3.76
<u>Fineness</u>		
% Passing #325 Mesh	91.8	93.9
Blaine (cm ² /gm.)	3396	3396

*Cements and analyses courtesy of Standard Lime and Cement Division of Martin-Marietta.

Clays

Eight relatively pure clays were originally investigated in this project. In the later stages of concentrated investigation, however, it was decided that in order to allow more testing time per specimen so that each specimen might be more intensively studied, only three clays, Anna kaolinite, Fithian illite, and Aberdeen montmorillonite would be used. The properties of these three clays are given in Tables II and III. A detailed discussion of all eight clays is given in phase report number one (Sherwood and Noble, 1965).

TABLE II
PHYSICAL PROPERTIES OF CLAYS

Properties	Anna Kaolinite	Fithian Illite	Aberdeen Montmorillonite
Size Ranges -- Microns			
> 16	20.6%	23.5%	20.0%
16 - 8	6.0	14.2	7.2
8 - 4	12.0	11.1	10.4
4 - 2	10.6	6.6	3.5
2 - 1	13.6	9.5	14.9
< 1	37.2	35.1	44.0
Cation Exchange			
Capacity me/100 gm.	18	28	64.7
Maximum Density			
lb./cu. ft.	116.8	103.9	70.1
Optimum Moisture Content, %			
	13.82	20.84	46.48

TABLE III
CHEMICAL ANALYSES OF CLAYS

Oxides	Anna Kaolinite	Fithian Illite	Aberdeen Montmorillonite
SiO ₂	57.60%	56.85%	56.66%
Al ₂ O ₃	22.50	9.75	14.00
Fe ₂ O ₃	0.98	6.00	4.70
TiO ₂	1.43	2.22	0.57
CaO	0.24	0.30	2.66
MgO	1.26	3.30	4.44
SO ₃	0.46	0.89	0.12
Na ₂ O	0.58	3.55	0.85
K ₂ O	0.25	4.90	0.77
Ign. Loss	9.81	11.08	11.51
Total	95.11	98.84	96.26

Soils

Three soils commonly found in Virginia were continuously sampled down the profile. The properties of those samples most intensively studied are given in Tables IV through VIII. Detailed profile studies related to the composition and weathering of the soils are given in phase report number three (Plaster, 1969).

TABLE IV
SOIL SAMPLE DESIGNATIONS

Sample Number	Depth Sampled	Soil Horizon
<u>Frederick</u>		
F-1	0 - 1.9'	A
F-2	1.9 - 3.8'	B
F-4	5.6 - 7.5'	C
F-8	13.1 - 15.0'	C
F-12	20.6 - 22.5'	C
<u>Iredell</u>		
I-1	0.7 - 1.3'	A ₂
I-2	1.3 - 2.0'	B
I-5	3.3 - 4.0'	C
<u>Lloyd</u>		
L-1	0.5 - 2.2'	B ₁
L-3	4.3 - 6.4'	B ₂
L-5	8.5 - 10.6'	C
L-9	16.9 - 19.0'	C

TABLE V
MINERALOGY OF THE SOILS

Sample Number	Sand Fraction*	Clay Fraction**
<u>Frederick</u>		
F-1	Fine grained quartz, limonite, ferruginous quartz aggregates.	Quartz, illite, mixed layer clay, kaolinite, montmorillonite goethite.
F-2	Like F-1.	Mixed layer clay, quartz, illite, kaolinite.
F-4	Like F-1 except for a few chert fragments.	Illite, quartz, mixed layer clay, kaolinite.

(Continued on next page.)

TABLE V (Continued)

MINERALOGY OF THE SOILS

Sample Number	Sand Fraction*	Clay Fraction**
F-8	Like F-4.	Quartz, illite, kaolinite, mixed layer clay.
F-12	Like F-4 except for a slight increase in ferruginous material.	Quartz, illite, kaolinite, mixed layer clay, montmorillonite, goethite.
<u>Iredell</u>		
I-1	Quartz, limonite, chlorite, talc, hornblende, feldspar, biotite, ferruginous quartz aggregates.	Vermiculite, quartz, illite, chlorite, kaolinite.
I-2	Biotite, chlorite, quartz, limonite, hornblende, feldspar, epidote.	Illite, vermiculite, quartz, chlorite, kaolinite.
I-5	Chlorite, biotite, hornblende, feldspar, quartz, many gabbroic fragments.	Montmorillonite, illite, vermiculite, quartz, chlorite, kaolinite.
<u>Lloyd</u>		
L-1	Mica, quartz, feldspar, limonite.	Kaolinite, illite, mixed layer clay, quartz.
L-3	Mica, limonite, quartz, feldspar.	Like L-1.
L-5	Mica, limonite, quartz.	Kaolinite, illite, quartz, mixed layer clay, montmorillonite.
L-9	Quartz, mica, feldspar, several gneiss fragments.	Kaolinite, illite, mixed layer clay, quartz, montmorillonite

* Minerals listed in order of decreasing abundance.

** Minerals listed in order of decreasing X-ray intensity.

TABLE VI
CHEMICAL ANALYSES OF THE SOILS

	<u>Frederick</u>				
	F-1	F-2	F-4	F-8	F-12
SiO ₂	74.50%	68.00%	69.33%	67.50%	72.00%
Al ₂ O ₃	12.07	15.43	14.38	14.47	12.98
Fe ₂ O ₃	5.27	6.68	6.38	5.98	5.80
CaO	0.14	0.26	0.00	0.10	0.06
MgO	2.10	1.85	2.06	2.31	1.76
Na ₂ O	1.74	0.16	1.01	1.55	1.88
K ₂ O	1.95	1.96	2.01	2.43	2.56
Ign. Loss	4.28	5.70	5.48	5.63	4.98
Total	102.05	100.04	100.65	99.97	102.02

	<u>Iredell</u>		
	I-1	I-2	I-5
SiO ₂	54.40%	49.92%	45.89%
Al ₂ O ₃	10.40	21.33	17.07
Fe ₂ O ₃	23.89	14.93	10.67
CaO	1.43	1.88	7.90
MgO	0.00	1.34	10.09
Na ₂ O	2.60	2.06	1.61
K ₂ O	0.67	0.68	1.55
Ign. Loss	6.65	9.31	3.64
Total	99.94	101.45	98.42

	<u>Lloyd</u>			
	L-1	L-3	L-5	L-9
SiO ₂	39.36%	43.67%	42.03%	60.43%
Al ₂ O ₃	30.55	25.22	23.43	19.05
Fe ₂ O ₃	16.33	18.44	18.46	6.36
CaO	0.28	0.00	0.14	0.22
MgO	0.00	0.79	1.28	0.00
Na ₂ O	0.34	0.58	1.16	2.13
K ₂ O	1.53	2.41	3.48	5.30
Ign. Loss	11.75	10.03	8.65	6.41
Total	100.14	101.14	98.63	98.12

TABLE VII

GRAIN SIZE ANALYSES OF THE SOILS

Sample Number	Size Ranges in Microns										Σ	
	>2000	2000 420	420 62	62 31	31 16	16 8	8 4	4 2	2 1	Σ ∞	Σ ∞	<1
<u>Frederick</u>												
F-1	0.23%	0.49%	3.31%	11.58%	12.33%	12.62%	9.54%	7.64%	5.82%	5.82%	36.44%	
F-2	0.95	1.47	4.67	6.27	7.49	10.62	8.89	8.05	6.35	6.35	45.24	
F-4	0.87	1.02	4.26	8.68	10.43	8.93	7.42	7.36	5.19	5.19	45.84	
F-8	0.68	1.06	4.60	10.35	9.11	10.51	10.15	13.26	7.97	7.97	32.31	
F-12	0.62	1.96	3.22	9.90	7.96	10.25	10.15	10.15	6.78	6.78	39.01	
<u>Iredell</u>												
I-1	23.58	24.81	8.94	4.15	3.07	7.29	5.61	4.89	3.92	3.92	13.74	
I-2	2.71	7.01	6.78	3.60	2.26	4.97	3.29	3.37	4.51	4.51	61.50	
I-5	13.70	29.71	32.61	7.26	2.52	2.72	1.50	1.19	0.80	0.80	7.99	
<u>Lloyd</u>												
L-1	0.42	0.89	19.03	4.53	4.71	5.30	4.06	2.47	3.02	3.02	55.57	
L-3	0.77	0.91	43.50	5.66	8.15	6.90	5.12	2.89	1.66	1.66	24.44	
L-5	0.36	1.80	53.03	10.03	10.86	6.89	4.21	2.39	1.77	1.77	8.66	
L-9	1.43	7.35	45.71	17.35	8.54	7.27	3.52	1.97	1.21	1.21	5.65	

TABLE VIII
ENGINEERING PROPERTIES OF THE SOILS

Sample Number	Liquid Limit	Plastic Limit	Plasticity Index	Optimum Moisture Content	Maximum Dry Density	Engineering Classification
<u>Frederick</u>						
F-1	38%	23%	15%	21.0 %	102.4 pcf	—
F-2	47	30	17	24.8	97.3	A-7-5 (12)
F-4	46	28	18	26.3	96.1	—
F-8	43	27	16	24.4	98.4	A-7-5 (11)
F-12	42	26	16	23.7	99.1	—
<u>Iredell</u>						
I-1	32	22	10	15.5	121.8	—
I-2	84	32	52	29.5	91.0	A-7-5 (20)
I-5	35	24	11	14.1	124.2	A-6 (8)
<u>Lloyd</u>						
L-1	51	—	0	26.6	95.2	A-5 (10)
L-3	—	—	0	27.5	92.4	—
L-5	—	—	0	26.3	92.9	—
L-9	—	—	0	21.6	96.8	A-4 (0)

EXPERIMENTAL PROCEDURES

The experimental methods employed are discussed at length in phase reports one, two, and three (Sherwood and Noble, 1965 — Noble, 1966 — Plaster, 1969).

Most of the specimens used were composed of 40 percent cement, mixed at a solids to liquid ratio of one to one, cured at room temperature in a nitrogen atmosphere for varied periods, and oven dried at a temperature less than 80°C. Early in the study it was thought that accelerated curing might be necessary to produce detectable differences in the rates of reaction. Therefore, two series of specimens were cured at 79° C, and 100 percent relative humidity for 43 and 100 days. The tests performed with a statement of purpose are listed below:

- (1) Test: Distilled water leachates of cement-clay and cement-soil powders.
 Purpose: To determine the amount of easily soluble calcium in the cement-clay and cement-soil specimens, as a measure of the extent or rate of cement hydration.
- (2) Test: Hydrochloric acid leachates of cement-clay and cement-soil powders.
 Purpose: To determine any increases or decreases in acid soluble silica, alumina, and ferric oxide in the clays and soils after cement treatment as a measure of reaction of the clay and soil constituents.
- (3) Test: pH determination of dilute suspensions of cement-clay mixtures.
 Purpose: To detect the change with time of the alkalinity of the cement-clay systems as a measure of the presence of $\text{Ca}(\text{OH})_2$.
- (4) Test: X-ray analysis of cured cement-clay and cement-soil powders.
 Purpose: To identify and determine any changes with curing time in crystallinity and quantity of clay, soil, and cement constituents.
- (5) Test: Petrographic investigation of cement-clay thin sections and powders and cement-soil thin sections.
 Purpose: To study the structure (particle to particle orientation) and composition of the cement-clay and cement-soil specimens.
- (6) Test: Seven day unconfined compressive strengths.
 Purpose: To determine any strength gain of the clays and soils after treatment with ten percent cement.

RESULTS AND DISCUSSION

The principal thrust of this discussion will be toward elucidation of the reactions and strength development and how they relate to the properties of the clays and soils in the cement-clay and cement-soil mixtures. Therefore, only those test results that contribute to the purpose stated above will be discussed, which excludes the results of the pH determinations and the petrographic investigations. Furthermore, discussion of the various clay and soil properties and how they relate to each other will be omitted, and only those properties that lend themselves to the purpose stated above will be or have been tabulated.

It is hoped that consideration of the results and their discussion will support a recommendation concerning the use of accelerating techniques when investigating the nature of reactions in cement-clay and cement-soil mixtures.

Cement-Clay, Cement-Soil Reactions

Water Leaches

The percentages of potential $\text{Ca}(\text{OH})_2$ leached from the various specimens are listed in Table IX. Based on the rate of hydration suggested by Copeland, et al (1962), for the three compounds that make up 85 percent of the Type I portland cement used, the data in Table IX demonstrated that:

- (1) In the heat cured cement-clay specimens, either the cement did not hydrate or virtually all of the $\text{Ca}(\text{OH})_2$ was consumed in reaction with the clays.
- (2) In the cement-clay specimens cured at approximately 25°C , hydration and the concomitant production of $\text{Ca}(\text{OH})_2$ along with the possible consumption of $\text{Ca}(\text{OH})_2$ occurred at various rates. Hydration was slightly faster than normal in the kaolinite specimens, slightly slower than normal in the illite specimens, and either much slower than normal or accompanied by considerable consumption in the montmorillonite specimens. All the specimens experienced some consumption of $\text{Ca}(\text{OH})_2$ after 56 days of curing as evidenced by a slight decrease in leached $\text{Ca}(\text{OH})_2$.

Noble (1967) suggested that neither cation exchange nor pozzolanic action could account for the differences in $\text{Ca}(\text{OH})_2$ leached from the kaolinite, illite, and montmorillonite specimens, and thus the only plausible explanation seemed to be restricted hydration caused by encapsulation of the cement grains by clay particles.

- (3) In the cement-soil specimens cured at approximately 25°C for two days the rate of hydration for most of the specimens appeared to be slightly slower than normal. Cement hydration was much slower than normal for the clay rich B-horizon of the Iredell (I-2) and the saprolitic C-horizon of the Iredell (I-5) and the Lloyd (L-9), while the clay rich B-horizon of the Lloyd (L-1) experienced slightly faster than normal cement hydration.

TABLE IX
 PERCENT OF POTENTIAL $\text{Ca}(\text{OH})_2$ WATER LEACHED

Temperature Cured	79° C			Approximately 25° C															
	A.K.	F.I.	Ab.M.	A.K.	F.I.	Ab.M.	F-1	F-2	F-4	F-8	F-12	I-1	I-2	I-5	L-1	L-3	L-5	L-9	
Specimen																			
Days Cured																			
1				56	30.9	7.4													
2							33	31	37	27	35	32	18	21.5	51.5	29.5	34.5	21	
3				63.6	47.4	14.6													
7				69.4	53.3	13.5													
14				69.2	53.6	16.1													
43	3	5	3.5																
56				72.4	55.3	11.9	51	44	47	65	56	37	17	15.5	20.5	14	28.5	18	
100	3	5.3	4.3																
112				66.1	50.4	10.4													
Difference	0	0.3	0.8				18	13	10	38	21	5	-1	-6	-31	-15.5	-6	-3	

After 56 days of curing, the Frederick specimens maintained their slightly slower than normal rate of hydration and showed, on the average, an increase of 20 percent in potential $\text{Ca}(\text{OH})_2$ leached. Such an increase indicates that, at the least, the production of $\text{Ca}(\text{OH})_2$ exceeds the consumption. Only a very slight increase for the C-horizons and for all the Lloyd specimens indicates that consumption of $\text{Ca}(\text{OH})_2$ has occurred in these specimens.

Plaster and Noble (in print) attempted to correlate the difference in percent of potential calcium hydroxide leached by water from the 2 day and 56 day cured cement-soil specimens with the mineralogy and magnitude of their clay size fraction. As shown in Table X, the gross mineralogical composition of the Frederick clay size fraction was relatively constant, although traces of montmorillonite and goethite were in F-1 and F-12. However, the relative quantities of the minerals varied slightly. With quartz and illite the dominant clay size minerals in F-8, the greatest increase in leached calcium hydroxide occurred. The principal variation in F-1 and F-12 as compared to F-8 was the presence of montmorillonite, and the difference in leached calcium hydroxide decreased. Without montmorillonite but with the relative abundance of quartz decreased and the total clay size fraction increased, as in F-2 and F-4, the difference in calcium hydroxide leached further decreased. It is apparent that even extremely fine grained quartz neither impeded the formation of nor contributed to the consumption of calcium hydroxide. However, with a significant increase in the relatively inactive illite as well as the mixed layer clay, or with the appearance of montmorillonite, either the production of calcium hydroxide is hindered or some calcium hydroxide is consumed.

TABLE X
LEACHED $\text{Ca}(\text{OH})_2$ AND CLAY SIZE DATA

Samples Listed in Order of Increasing Clay %	Clay Size Mineralogy	% Clay of Material Passing No. 230 Sieve	Difference in Leached $\text{Ca}(\text{OH})_2$ 56 day minus 2 day
<u>Frederick</u>			
F-8	Q, I, K, ML	45.0	+38
F-1	Q, I, ML, K, M, G	44.2	+18
F-12	Q, I, K, ML, M, G	49.5	+21
F-2	ML, Q, I, K	55.5	+13
F-4	I, Q, ML, K	55.4	+10
<u>Iredell</u>			
I-5	M, I, V, Q, Ch, K	34.8	- 6
I-1	V, Q, I, Ch, K	42.4	+ 5
I-2	I, V, Q, Ch, K	79.5	- 1
<u>Lloyd</u>			
L-9	K, I, ML, Q, M	17.2	- 3
L-5	K, I, Q, ML, M	20.0	- 6
L-3	K, I, ML, Q	48.2	-15.5
L-1	K, I, ML, Q	73.7	-31.0

Abbreviations: Q - quartz, I - illite, K - kaolinite, ML - mixed layer, M - montmorillonite, G - goethite, V - vermiculite, Ch - chlorite.

Correlation of the data for the Iredell specimens was not as straightforward as for the Frederick. The most coarse grained Iredell specimen (I-5, C-horizon) consumed $\text{Ca}(\text{OH})_2$, while the slightly finer grained I-1 (A-horizon) experienced an increase in leached $\text{Ca}(\text{OH})_2$ and the finest grained of all the soil specimens (I-2, B-horizon) consumed only a very small quantity of $\text{Ca}(\text{OH})_2$. The dominance of montmorillonite in the clay size mineralogy of I-5 and the chemically unstable nature of saprolitic materials seem to explain the consumption of $\text{Ca}(\text{OH})_2$ by I-5. I-1 from the thoroughly leached relatively stable A-horizon and with a clay size mineralogy somewhat similar to that of the Frederick specimens, might be expected to leach additional $\text{Ca}(\text{OH})_2$. Vermiculite and chlorite, which are in the Iredell and not in the Frederick specimens, are crystallographically more closely related to illite than to montmorillonite and have a much smaller total surface area than montmorillonite; thus, they might be considered to be less reactive than montmorillonite. The extremely high clay content of I-2 explains why some $\text{Ca}(\text{OH})_2$ was consumed despite the similarity in mineralogy between I-1 and I-2.

As mentioned previously, the Lloyd soil leached less $\text{Ca}(\text{OH})_2$ from the specimens cured for 56 days than those cured for 2 days. This relationship indicates that calcium hydroxide was originally formed and then was consumed in some manner. This consumption process was more pronounced in some specimens, especially the clay rich ones, than in others (see Table X). The clay size mineral suites of the Frederick and Lloyd soils are so similar that they permit evaluation of the effect of kaolinite on the difference in quantity of leached calcium hydroxide with curing time. Very small quantities of kaolinite were present in the Frederick specimens and the difference in quantity of leached calcium hydroxide increased with curing time, i. e., calcium hydroxide accumulated. Kaolinite is the dominant clay in the Lloyd specimens and the negative difference in the quantity of calcium hydroxide leached became greater as the clay content increased. Thus the rate of calcium hydroxide consumption must have exceeded the rate of production, and did so to a greater extent with kaolinite than with any other clay mineral present.

Acid Leaches

It was anticipated that at least the clay minerals and possibly other constituents of the clays and soils would be reactive in the hydrating cement environment. Changes in the response of the clays and soils to hydrochloric acid leaching subsequent to portland cement treatment (stabilization) might be interpreted as a measure of the magnitude and nature of these reactions. Therefore, acid leaches were made of the clays, soils, cement-clay and cement-soil mixtures.

The quantity of Al_2O_3 , SiO_2 , or Fe_2O_3 expected to be leached from the cement-clay or cement-soil mixtures was defined as the amount leached from the untreated clay or soil plus the amount in the cement. The data reported in Tables XI, XII, and XIII are the percentages of Al_2O_3 , SiO_2 , or Fe_2O_3 in excess of the expected quantity that was leached subsequent to cement treatment, and that was considered to be directly related to the response of the clay and soil constituents to the hydrating cement environment.

TABLE XI

PERCENT Al_2O_3 IN EXCESS OF EXPECTED AMOUNT — HCl LEACHED

Temperature Cured	79°C			Approximately 25°C															
	A. K.	F. I.	Ab. M.	A. K.	F. I.	Ab. M.	F-1	F-2	F-4	F-8	F-12	I-1	I-2	I-5	L-1	L-3	L-5	L-9	
Days Cured																			
1				14	—	20.8													
2							2.9	2.18	4.1	3.2	5.1	1.6	4.28	5.0	10.6	8.9	6.0		6.7
3				2.2	—	13.1													
7				7.2	—	17.2													
14				8.2	—	23.2													
21							2.5	2.2	2.7	1.5	6.1	8.0	9.75	9.4	20.2	12.3	4.9		13.3
43	41.2	23.6	27.0																
56				0.32	27.6	18.1	4.5	6.0	5.8	4.5	5.3	7.0	13.7	12.0	25.1	14.5	7.4		22.8
100	53.8	27.1	30.6																
112				—	—	25.2													

TABLE XIII
 PERCENT Fe_2O_3 IN EXCESS OF EXPECTED AMOUNT — HCl LEACHED

Temperature Cured	79°C						Approximately 25°C												
	A. K.	F. I.	Ab. M.	A. K.	F. I.	Ab. M.	F-1	F-2	F-4	F-8	F-12	I-1	I-2	I-5	L-1	L-3	L-5	L-9	
Days Cured																			
1				—	—	—													
2							4.0	3.9	8.5	3.2	7.7	1.9	6.0	20.6	4.9	4.5	6.3	6.8	
3				—	—	—													
7				—	—	—													
14				—	—	—													
21							6.1	5.2	9.9	2.2	7.7	3.2	11.9	29	5.6	4.8	6.2	5.7	
43	—	—	—																
56				—	—	—	7.5	8.4	11.9	4.4	6.1	2.8	14.1	40.8	6.4	6.5	7.4	10.0	
100	—	—	—																
112				—	—	—													

The relationship of the SiO_2 and Fe_2O_3 data for the cement-clay specimens was rendered questionable because of laboratory procedures which were later modified. Thus these data were not presented because discussion of them would not contribute to any meaningful conclusions.

Cement-Clay Accelerated Curing

Large quantities of the total Al_2O_3 in the clays were leached from the heat cured specimens; they ranged from 49 to 64 percent over both the 43 and 100 day cured specimens. This rather narrow range of variability belies the actual differences in response that became obvious when the values for the untreated clays were subtracted. It is quite apparent from the values in Table XI that the Anna kaolinite suffered the greatest deterioration, almost twice that of the least deteriorated clay, Fithian illite. The data for both the Fithian illite and the Aberdeen montmorillonite are quite similar. Considering their basic similarity of being three layer clays characteristic of an intermediate stage of soil development, the similarity in the magnitude of their reaction to cement is not too surprising. However, the similarity does not seem to correlate with the difference in their particle size distribution; montmorillonite, generally considered as one of the finest grained clays with an extremely high surface area, would be expected to be more reactive than illite.

Cement-Clay Room Temperature Cured

The data for the cement-clay specimens cured at approximately 25°C indicate that generally much less deterioration of the clays occurred, and that the order of severity of deterioration for the clays changed. Deterioration of the Aberdeen montmorillonite was the most severe. The degree of deterioration of the Anna kaolinite was about half that of the montmorillonite and the Fithian illite suffered the least.

Both the change in the magnitude of the reaction and the change in the order of deterioration are of considerable interest. The implications of these changes as they relate to the study of cement-soil systems will be discussed after the discussion of the X-ray diffraction results.

Cement-Soil Room Temperature Cured

The cement-soil specimens reacted with considerable variability to the hydrating cement environment. The quartz, illite rich Frederick specimens leached the slightest percentage of their Al_2O_3 and Fe_2O_3 . Rich in illite, vermiculite, quartz and biotite, the Iredell specimens leached considerable Al_2O_3 , SiO_2 and especially Fe_2O_3 . The Lloyd specimens, with a mineralogy dominated by kaolinite, illite, quartz, mica and feldspar leached a significant percentage of their Al_2O_3 and SiO_2 , but leached Fe_2O_3 only to the same extent as did the Frederick specimens.

With the exception of the relatively uniform Frederick soil, there was also considerable variation within the specific soil profiles. As might be expected, the clay rich illuvial horizons (I-2 and L-1) were particularly reactive and leached significantly larger quantities of Al_2O_3 and SiO_2 than did most of the specimens, especially the heavily leached, eluvial I-1. I-2 was derived from a metagabbro which contains minerals with a large quantity of iron and thus it also leached a significant quantity of Fe_2O_3 . Somewhat unexpectedly, the saprolitic horizons (I-5 and L-9), which were in a state of incipient mineralogical change, were also quite reactive. Because of their proximity to the parent material within the weathering cycle, the leachate from the saprolitic zones reflects the mineralogy of the parent material to the greatest degree. Thus I-5 leached a moderate percent of its Al_2O_3 , more SiO_2 and a very high percent of its Fe_2O_3 . L-9, which was derived from a granite-gneiss rich in feldspar, quartz, and mica, leached a high percentage of its Al_2O_3 and only a moderate percentage of its SiO_2 and Fe_2O_3 . Any variation within the Frederick profile was so subtle as not to be attributable to any specific differences other than perhaps a slight change in the magnitude of the clay size fraction.

X-ray Investigations

Tobermorite gel, the principal strength producing compound in hydrating cement, is poorly crystalline and not easily detected by X-ray diffraction. Therefore, the primary emphasis in the interpretation of the diffractograms was placed on observing any changes in the crystallinity of the clay minerals, since these minerals were thought to be the ones most likely to react with cement, and the increases or decreases in the quantity of calcium hydroxide. Quartz occurring in the clays and soils was used as an internal standard. The occurrence and amount of $\text{Ca}(\text{OH})_2$ was taken as a semi-quantitative indication of the combined effect of the cement hydration ($\text{Ca}(\text{OH})_2$ production) and $\text{Ca}(\text{OH})_2$ consumption.

All the clays suffered a loss of crystallinity because of cement treatment, but the degree to which they suffered was difficult to estimate solely on the X-ray diffraction data.

Cement-Clay Accelerated Curing

Based on work done subsequent to what was done for this particular phase, it is now obvious that accelerated curing had a considerable effect on the magnitude of the reactions occurring in the mixtures. No dicalcium silicate or tricalcium silicate

reflections were observed; their hydration seems to have been complete. No calcium hydroxide reflections were observed in most of the mixtures, and only in several of the kaolinite and an illite mixture did a very weak reflection appear at the sites of the most intense calcium hydroxide reflections. Only one reflection could confidently be attributed to calcium silicate hydrate. However, this reflection indicated that the hydrated calcium silicate was well developed.

Thus, preliminary indications are that hydration was complete and that re-action involving calcium hydroxide was extensive and resulted in the almost complete consumption of the calcium hydroxide. The question as to whether this same course of events would have occurred without accelerated curing needs to be answered, and will be addressed later.

Cement-Clay Room Temperature Cured

No dicalcium silicate, tricalcium silicate, or calcium silicate hydrate reflections were observed for the specimens cured from 1 to 112 days. That the anhydrous silicates were not detected after only one day of hydration needs explanation. There are limits to the process of accelerated hydration, and it is extremely unlikely that the cement could hydrate in one day to the extent that the remaining anhydrous silicates could not be detected. It is more probable that the anhydrous grains were shielded by the adhesion of clays and hydration products to their surfaces. Such an early absence of the anhydrous silicates on the X-ray diffractograms seems to support the encapsulation hypothesis mentioned earlier.

The rate of apparent accumulation of Ca(OH)_2 in the several mixes was quite varied. In the Anna kaolinite mixtures, crystalline Ca(OH)_2 reached its maximum concentration by 14 days and maintained that level through 112 days. The specimen cured 2 years also yielded a sharp, intense Ca(OH)_2 peak.* Such data certainly do not suggest any strong reaction of the Ca(OH)_2 with the kaolinite. The water leachate data support the suggestion that no strong reaction occurred between the Ca(OH)_2 and the kaolinite.

There is a pronounced increase in crystalline Ca(OH)_2 in the Fithian illite mixtures up to the 7 day curing period; this is followed by an apparent decrease in Ca(OH)_2 at 14 days which continues to 56 days, when it reaches the level it maintained through the 112 day curing period. The specimen cured for 2 years yielded Ca(OH)_2

*During early testing, one group of specimens was set aside to cure at 100 percent relative humidity and room temperature for a long period of time. They were X-rayed after two years of curing.

reflections that were quite distinct though considerably less intense than those for the 2 year Anna kaolinite mixture. The water leachate data, which does not parallel the X-ray diffraction data, indicate that a steady state was maintained from 7 days to 56 days and that the quantity of $\text{Ca}(\text{OH})_2$ decreased slightly from 56 days to 112 days. This difference in the data can be explained by noncrystalline $\text{Ca}(\text{OH})_2$ being adsorbed on the surfaces of the clays and the recently crystallized calcium silicate hydrates such that it was not detected by the X-rays but was still susceptible to leaching by water.

The Aberdeen montmorillonite specimens were distinguished by their lack of crystalline $\text{Ca}(\text{OH})_2$. After 3 days of curing the strongest reflection was detected, it was weaker at 7 days, and could not be detected after 14 days curing. Both the X-ray data and the water leachate data indicate that the concentration of $\text{Ca}(\text{OH})_2$ in the several cement-clay mixtures varies. As was mentioned earlier, these very significant differences might be interpreted as indicating the extent of cement hydration provided no processes are active which tend to combine the calcium in compounds only slightly soluble in distilled water (Noble, 1967).

Interpretation of the data suggests that hydration was very rapid in the kaolinite mixtures; slower in the illite mixtures; and slowest in the montmorillonite mixtures.

Cement-Soil Room Temperature Cured

Identification or a quantitative estimation of the cement hydration products was hampered due to their poor crystallinity and the interference offered by X-ray reflections of soil minerals.

The reaction of the clay minerals in the hydrating cement environment was evidenced by such signs of distress as a decrease in the ordering of the layers, diminution of peak intensity, and shifts in layer spacing. The varied reactions of the several soil profiles depended on which clay mineral was dominant, how much clay was present and the degree of equilibrium within the weathering cycle attained by the particular horizon. Kaolinite and the somewhat hydrophilic clays such as montmorillonite and vermiculite suffered the greatest distress; illite suffered the least. The horizons with the highest clay content and the saprolitic horizons, in a state of incipient change, showed the greatest effect due to cement treatment.

Detection of crystalline $\text{Ca}(\text{OH})_2$ closely paralleled the water leachate data for all the horizons except L-1. Those horizons with the least clay, with considerable clay size material dominated by illite, or with the least reactive materials experienced the greatest development of $\text{Ca}(\text{OH})_2$; these include all the Frederick specimens and I-1. For L-1, after 2 days curing, the X-ray data do not correlate with the water leachate data in that only a slight amount of crystalline $\text{Ca}(\text{OH})_2$ was detected but a large percent of the potential $\text{Ca}(\text{OH})_2$ was leached. It is possible that large amounts of $\text{Ca}(\text{OH})_2$ were present, but the compound had not crystallized and was largely amorphous or adsorbed on the surface of the clays. It is also possible that the $\text{Ca}(\text{OH})_2$ was entirely crystalline, but the abundant clays in specimen L-1 were absorbed onto the surface of the crystals. Thus, many of the X-ray reflections of the $\text{Ca}(\text{OH})_2$ might have been masked. Specimen I-2 with the highest liquid limit and lowest maximum dry density had the slightest development of $\text{Ca}(\text{OH})_2$.

It appears that the Frederick illitic soils experienced the most rapid hydration and the Iredell montmorillonitic, vermiculitic soils the slowest. The most reactive soils were the clay rich, and the saprolitic horizons of the Lloyd and Iredell; the least reactive soil was the illitic Frederick.

Accelerated vs. Normal Curing

Most rocks, the parent material from which soils are derived, were formed under conditions quite different from the weathering environment. Thus in a general sense, soils are a very sensitive physicochemical system that are in the process of establishing an equilibrium state within the weathering environment. Moisture, pH, organics, oxygen, drainage, temperature and many other variables have a great effect on the end product of the soil producing process.

If soils are considered as part of a larger system such as soil-cement, and there is interest in the nature and magnitude of reactions which may occur slowly at relatively normal surface conditions, it might appear that the process could simply be accelerated by altering only one of the environmental conditions, such as the curing temperature. However, the data for the specimens that were heat cured and the data for the normally cured specimens demonstrate that:

- (1) Not only were the reactions greatly intensified, but
- (2) the relative magnitude of deterioration for the several clays was changed (see Table XIV).

TABLE XIV
ORDER OF DETERIORATION

<u>Degree</u>	<u>Accelerated</u>	<u>Normal</u>
1. Greatest	Kaolinite	Montmorillonite
2. Moderate	Montmorillonite	Kaolinite
3. Least	Illite	Illite

In addition, the data for montmorillonite and illite in the accelerated cured specimens were quite similar, whereas kaolinite in the normally cured specimens suffered much greater deterioration than did illite.

Strength Studies

The results of the unconfined compressive strength tests are given in Table XV. The strength gains, as discussed later, can easily be calculated by subtracting the zero cement strength from the 10 percent cement strength.

TABLE XV
SEVEN DAY UNCONFINED COMPRESSIVE STRENGTHS

<u>Specimen</u>	<u>Strength (psi)</u>	
	<u>No Cement</u>	<u>10% Cement</u>
Anna Kaolinite	70	661
Fithian Illite	80	323
Aberdeen Montmorillonite	67	237
F-1	52.9	329.1
F-2	79.2	354.2
F-4	47.8	302.3
F-8	48.4	196.5
F-12	47.4	321.2
I-1	19.6	461.3
I-2	40.0	250.2
I-5	19.8	520.6
L-1	23.6	200.1
L-3	51.5	268.0
L-5	21.2	191.1
L-9	17.0	436.4

Cement-Clay Mixtures

Strength development of the clays with type I, high C₃A cement appears to be nearly linear with cement contents up to 20 percent. The magnitudes of the strengths of different cement-clay mixtures vary over a large range with the two-layer Anna kaolinite and the three layer Fithian illite type clays developing strengths of considerably higher magnitude than the more hydrophilic three-layer and chain structured types.

The strength studies with type II cement demonstrated that despite a much lower C₃A content the mixtures developed strengths almost comparable to those developed with the type I cement, though 10 to 180 psi lower.

Comparison of Cement-Clay and Cement-Soil Mixtures

The question of whether any one of the many variables in the cement-clay and cement-soil mixtures effects principal control over the strength gained by the mixtures deserves consideration. Therefore, an attempt was made to correlate the strengths gained with some of the physical properties of the cement-clay and cement-soil strength specimens. Consideration was given to the clay mineralogy, size distribution, and optimum moisture content of the specimens.

Anna kaolinite and Fithian illite had almost identical size distributions; the kaolinite was slightly finer and might have been expected to gain less strength. However, the kaolinite gained 591 psi; the illite gained 243 psi. Other than clay mineralogy, which affects optimum moisture content, the principal difference between the two is a 7 percent higher optimum moisture content for the Fithian illite. Fithian illite and F-1 of the Frederick soil have similar mineralogies, comparable size distributions, with the Frederick being slightly coarser grained, and almost identical optimum moisture contents. The Fithian illite gained 243 psi and F-1 gained 276 psi. High strength gain cement-soil mixtures, L-9, I-1 and I-5, bear little resemblance to the high strength gain Anna kaolinite. L-9, I-1 and I-5 are much coarser grained, have lower natural compressive strengths, and their coarse grain mineralogy makes them mineralogically quite different from Anna kaolinite. Only the optimum moisture contents of I-1, I-5 and Anna Kaolinite are similar, and they had comparable strength gains, (see Table XVI).

TABLE XVI

COMPARISON OF OPTIMUM MOISTURE CONTENT AND STRENGTH GAIN

	<u>Percent</u>	<u>psi</u>
L-9	21.6	419
I-1	15.5	441
I-5	14.1	500
Anna kaolinite	13.8	591

L-9 with a rather high optimum moisture content, almost the same as that of F-1, seems to be anomalous. However, the size distribution of L-9 is the second coarsest of the soils and it has the least amount of material 4 microns and under. With a coarse grain fraction composed of tenaceous minerals, it is understandable that L-9 gained considerable strength. It is also interesting to note that the magnitude of the strength gain varied indirectly to the optimum moisture content.

It is not intended by the brief comparisons presented above to suggest that optimum moisture content has been thoroughly documented as the variable which effects the greatest control over strength gain in soil-cements. However, it has been demonstrated that there is a relationship between optimum moisture content and strength gain. Thus it would seem worthwhile to further investigate this relationship and also to observe the relationship of the other variables such as clay mineralogy and size distribution to optimum moisture content.

Relation of Physical Properties of Soils to Strength Gain

Inasmuch as one of the most important properties of a stabilized soil is its strength gain, analysis of the strengths gained by the various cement treated soils and whether these increases correlate with such soil parameters as size distribution, mineralogy, maximum dry density, optimum moisture content, and unconfined compressive strength was most informative.

On the basis of strengths gained, the twelve specimens tested seem to fit into four groupings. The validity of these groupings is attested to by the correspondence of the physical properties of the specimens within each group. When a specimen does not appear to fit within its strength gain grouping, the explanation for the inconsistency seems to lie in one of the parameters having such an extreme value as to greatly affect the strength gain.

The four groupings are as follows:

<u>Strength Gain psi</u>	<u>Specimen</u>
1. 400 - 500	I-1, I-5, L-9
2. 250 - 275	F-1, F-2, F-4, F-12
3. 210 - 216	I-2, L-3
4. 150 - 175	F-8, L-1, L-5

400 - 500 psi Strength Gain

Those specimens (I-1, I-5, L-9) that experienced the greatest strength gain were poorly graded with their size distributions skewed to the sand sizes and slightly greater. Mineralogically, with the exception of I-5, they were distinguished by an abundance of relatively tenaceous minerals, rock fragments, and ferruginous quartz aggregates, and by paucity of the easily cleaved micas within the sand size fraction. Their optimum moisture contents were relatively low and their natural unconfined compressive strengths were low, which indicated a lack of the cohesiveness commonly achieved by a moderate quantity of clay.

Though chlorite and biotite (mica type minerals) were in greatest abundance in specimen I-5, there were also significant quantities of relatively tenaceous minerals present, such as hornblende, feldspar, and quartz, as well as considerable granules of gabbroic rock in the sand size fraction. In addition, the size distribution data for I-5 show that it had the highest percentage (76) of coarse grain particles through the sand sizes.

250 - 275 psi Strength Gain

All the specimens (F-1, F-2, F-4, F-12) which had a moderate gain in strength were from the Frederick soil profile. The Frederick specimens are characterized by their apparent similarity. They are poorly graded and their size distributions are

skewed to the silt and clay sizes, with 50 to 60 percent of the particles being less than the equivalent spherical diameter of four microns. Mineralogically, quartz dominates both the coarse and fine fractions. Illite, mixed layer clay, and kaolinite make up the remainder of the principal clay size minerals with montmorillonite and goethite as minor constituents in a few specimens. The slight differences in the relative abundances of the clay size minerals are not of such magnitude as to explain any differences in parameters such as strength gain, though they may account for some of the chemical differences. Their optimum moisture contents averaged 10 percent higher than those of I-2 and I-5, but were only slightly higher than that of L-9. Higher natural unconfined compressive strengths (47 to 79 psi) than those of the specimens experiencing the highest strength gain seem to reflect the increase in clay content. The rather moderate gain in strength was attributed to the specimens' fine grained, somewhat hydrophilic nature, which was responsible for a moderately high optimum moisture content.

210 - 216 psi Strength Gain

Based on a comparison of their size distributions, the specimens (I-2 and L-3) that had a marginal strength gain appear to be misfits that would fit better into the previously mentioned groups. I-2 is quite fine grained and poorly graded; L-3, by contrast, is relatively coarse grained and well graded. However, their maximum dry densities are the lowest of all the specimens and indicate that other of their intrinsic properties should be examined. The cumulative percents for the size distribution curves of I-2 and the Frederick specimens have a reasonable correspondence from the coarse sizes down through the medium silt size. Through the fine silt and coarse clay sizes the Frederick specimens have more material. Comparison of the less than one micron size fractions shows that I-2 has the highest percentage (61.5) of this size material. Such a large quantity of very fine grain material, with its extremely large surface area capable of adsorbing and tying up the various cement constituents with a minimum of resultant adhesion, helps explain the marginal strength gain of I-2. In addition to the foregoing, I-2, as might be expected, had the highest optimum moisture content. The pores occupied by no strength water provided space in which the hydration products could crystallize without forming an adhesive bond at the point to point contacts of the grains. Under these conditions, cement hydration contributes the least to the strength gain of the mass. Comparison of the cumulative percents for the size distribution curves of L-3 and the other coarse grained specimens shows that L-3 is somewhat finer grained, as is reflected in its higher natural unconfined compressive strength (51 psi). In itself, an increase of 7 to 18 percent in fines less than one micron in diameter, while still having 45 percent sand or coarser, does not seem sufficient cause to explain such a marginal increase in strength. A check of the sand size mineralogy, however, reveals that there is an increase in mica with a proportionate decrease in quartz and feldspar. Because of its platy crystal structure mica has excellent basal cleavage and tends to slide or separate along these planes of weakness when under stress. This difference in mineralogy along with the increase in fines appears to explain the strength gain experienced by L-3.

150 - 175 psi Strength Gain

Minimal strength gain was experienced by three (F-8, L-1, L-5) out of the twelve specimens. A very careful perusal of all the data on the Frederick specimens did not disclose any cause for the strength gained by F-8 to be 100 psi less than the strength gained by the other Frederick specimens. With no intrinsic characteristic of the specimen as the apparent cause for such a low strength gain, human error is offered as a rather poor substitute to explain this anomalous result. L-1 was quite fine grained and poorly graded, with next to the highest fraction (55 percent) of less than one micron size particles. Mineralogically the sand size fraction is predominantly mica. These two facts adequately explain the low strength gain of L-1. Specimen L-5 was coarse grained and poorly graded with 55 percent of the particles of sand size or coarser. The sand size fraction was almost entirely mica, which fact explains the low strength gain (well developed basal cleavage acts as planes of weakness), the low maximum dry density (mica tends to be resilient and will not compact as tightly as clay), and the low natural unconfined compressive strength (mica does not have cohesiveness comparable to that of most clays).

Thus it appears that size distribution and clay mineralogy, as they relate to maximum dry density, optimum moisture content, and the resultant abundance or paucity of voids, are important controlling factors of strength development in a soil-cement. Further, it seems that the Proctor test provides a quick, though not fool-proof, first step estimate as to what can be expected in strength gain for a specific soil. The less the adhesive power of the hydrating cement is wasted in filling voids and the more it is applied to the point to point contacts between grains as it crystallizes, the greater the strength that can be developed. Mineralogy is further important in strength development because of the variability in the tenacity of minerals. Weak, easily cleaved mineral grains cannot form as strong a cemented mass as can quite tough mineral grains. A highly micaceous soil does not make as strong a soil-cement as does a well graded quartz sand.

Geologic Consideration

While not discussed here at any length, the uniformity of the Frederick soil profile was noted by Plaster (1969). Because of the similarity in strength gained by four of the Frederick specimens, the uniformity of the Frederick soil as related to the parent material, Chepultepec limestone, and generally what is known about its geologic history is discussed below.

What is presently observed in the Frederick soil profile is the result of the response of two distinctly different types of materials, carbonates (calcite - CaCO_3) and silicates (clays-potassium-magnesium-calcium aluminosilicates and quartz- SiO_2), to the prevailing weathering environment. Geologically a time of carbonate deposition over broad geographic areas is considered tectonically to be a rather quiet time. A time when, because of the limited relief between the basin of deposition and the uplands of the land mass, the physical energy available for erosion is minimal. Therefore, old well developed soil profiles containing minerals that tend toward equilibrium with the weathering environment are produced and can be expected to contribute minor quantities (0 - 25 percent) of stable detritus to the basins experiencing predominantly carbonate deposition.

The carbonate depositional environment is quite different from the weathering environment which produces the stable detritus. If granted a minimal degree of diagenetic change for the silicates, when the impure limestone is eventually elevated and exposed to the weathering environment the unstable carbonates dissolve relatively easily. They leave behind a residuum of the stable, rather uniform detritus. If in a weathering environment similar to that with which it was previously in equilibrium, the residuum tends not to show any distinctive soil profile development. The uniformity of the soil profile reflects the uniformity of the processes which produced the detritus many years previously and the uniformity of the materials from which it was produced.

CONCLUSIONS

1. Accelerated curing caused rapid hydration of the cement, consumption of Ca(OH)_2 , and extreme deterioration of the clays in an order of severity that was different from the order when the specimens were cured at room temperature. It is recommended that when studying the nature and magnitude of reactions occurring in a system which commonly exists at relatively normal surface conditions it is advisable not to attempt, for the convenience of the study, to accelerate those reactions by altering one or more of the environmental conditions, such as raising the curing temperature of the system.
2. With room temperature curing hydration was slightly faster than normal in the cement-Anna kaolinite mixtures, slightly slower than normal (approximately three-fourths the hydration rate in the kaolinite) in the cement-Fithian illite mixtures and much slower than normal (approximately one-fifth the hydration rate in the kaolinite) in the cement-Aberdeen montmorillonite mixtures.
3. Considering all the cement-soil specimens except the 2 day L-1, the rate of cement hydration was at the most slightly slower than normal. The rate of cement hydration was much slower than normal in the more reactive horizons.
4. Extensive Ca(OH)_2 consumption was not documented for the cement-clay mixtures cured at room temperature. Differences in the quantity of Ca(OH)_2 in the various mixtures was attributed to restriction of hydration due to encapsulation of cement grains by very fine grained clay and recently formed gels of calcium silicate hydrate. This concept of encapsulation is a modification of the concept for encapsulation of Ca(OH)_2 crystals by an amorphous calcium silicate hydrate gel presented by Diamond (1966).
5. Consumption of Ca(OH)_2 was documented for the Iredell and Lloyd soils. The kaolinite rich Lloyd soils consumed the greatest quantities of Ca(OH)_2 .
6. The clays in the room temperature cured specimens suffered deterioration in the alkaline environment of hydrating cement from greatest to least as follows: Aberdeen montmorillonite, Anna kaolinite, and Fithian illite.
7. The Frederick soil constituents did not react appreciably with the cement, although some of the clays in the soil were slightly deteriorated after cement treatment.
8. As shown in the Frederick specimens, quartz neither impeded the production of nor contributed to the consumption of calcium hydroxide.
9. The clays and probably other constituents in the B- and C-horizons of the Iredell and Lloyd soils suffered deterioration after cement treatment, as indicated by the release of large amounts of silica and alumina and by the diminution of mineral X-ray peaks.
10. When the major clay mineral in the soils was considered, the soils appeared to suffer deterioration after cement treatment from greatest to least in the following order: montmorillonitic soils, kaolinitic soils, illitic soils.

11. It appeared that reaction of calcium hydroxide with the soil constituents was proportional to the magnitude of the clay size fraction.
12. The instability of the saprolitic horizons seemed to be related to the incipient state of change of many of the minerals.
13. The less hydrophilic, kaolinite and illite, clays appear to develop the greatest strengths.
14. An inverse relationship appears to exist between optimum moisture content and strength gain. The Proctor test is recommended as a good, quick, first step estimate of potential strength gain.
15. Some clays, such as montmorillonite, are hydrophilic and require large percents of water for adequate lubrication. Thus, soils containing large quantities of these clays have very high optimum moisture contents and poor strength development.
16. Size distribution and clay mineralogy as they relate to maximum dry density and optimum moisture content are important controlling factors of strength development.

ACKNOWLEDGMENTS

This research was conducted under the general direction of the late Dr. Tilton E. Shelburne, State Highway Research Engineer, and Mr. Jack H. Dillard, State Highway Research Engineer, and was financed by HPR funds administered by the U. S. Department of Transportation, Federal Highway Administration.

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