

A Quick Test to Determine Lime Requirements For Lime Stabilization

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The use of hydrated lime, $\text{Ca}(\text{OH})_2$, for modifying, upgrading, and stabilizing soils is increasing greatly. This means highway laboratories have had their work loads increased, and in many instances, more than doubled for a particular job. Before the advent of the use of lime, the laboratory was finished with testing when a soil was classified as unsuitable. Now the same soil is tested and retested to find the percentage of lime required to bring the soil within specifications. In most cases the percentage is determined by compressive strength tests, Atterberg limits tests, or both.

The reaction of lime and soil can be described as a series of chemical reactions. The results of these reactions are expressed as a change in the plasticity, swell, shrinkage or compressive strength of the soil. Therefore, a quick or simple test is needed to show the amount of lime required to react chemically with a soil to bring about these physical changes to an optimum degree.

Laboratory tests, involving mineralogical, physical and chemical characteristics of untreated and lime-treated soils have proven that pH tests can be used to determine the optimum lime requirements of a soil.

•THE USE of hydrated lime, $\text{Ca}(\text{OH})_2$, for modifying, upgrading, and stabilizing soils is increasing greatly. Lime stabilization, having started as an aid in maintenance work, now covers all highway construction. This includes Interstate highways, farm-to-market roads, shoulders and parking lots as well as non-highway uses such as airport runways, building foundations, and railroad subgrades.

The occasional job calling for lime stabilization does not impose a hardship on testing laboratories. If it is a matter of upgrading a soil by decreasing the percentage of fines or reducing the plasticity index of a soil, then samples are cured with varying percentages of lime and sieve analysis or Atterberg limits tests are repeated. However, finding the optimum amount of lime for new construction jobs where the soil classification changes frequently, or for a number of jobs at the same time, greatly increases the work load. A simple and quick test to determine the lime requirements for a soil is a major goal of the soils testing engineer.

The reaction of lime and soil is a chemical reaction or rather a series of chemical reactions. The reactions are basically the reaction of calcium and the organic and inorganic compounds making up the soil. Maclean and Sherwood (7) have reported on the calcium absorption of the hydroxy-quinones, which are found in soils. Besides the absorption of calcium on the exchange sites of the clays, soils may also contain such components as soluble silica which has not been leached from the soil, alumina which is left behind in the weathering profile, sulfates from the decomposition of pyrites, and phosphates if cultivated fields are being drained toward the highway. Therefore, to

determine the amount of lime needed to stabilize a soil, it is necessary to know how much lime will be needed to satisfy all of the reactions. The aforementioned reactions, except for the absorption of calcium on the exchange sites, are instantaneous upon contact with calcium. Results of research at the University of Illinois with radioactive cesium and pure clay minerals proved, for the most part, that ion exchange is complete in one hour. Therefore, it is only necessary to know the amount of lime consumed by any soil in one hour at room temperature. However, since lime is so very alkaline (pH 12.4 at 25 C), the silicates, especially the clays (3), will be attacked, freeing silica and alumina with which the calcium reacts to form calcium silicates—as long as a high alkaline condition is maintained. The lime requirements for this continued reaction could be determined under varying conditions of time and temperature.

One of the objectives of lime stabilization research at the University of Illinois has been to devise a quick and simple test for determining the lime requirements for soil stabilization. Since most of the soils laboratories in the United States have been concerned with proving the merits of lime stabilization, little time has been devoted to test methods. In 1960, Hilt and Davidson (5) reported on research using plastic limits to determine what they termed "lime fixation." This test is satisfactory for showing the lime requirements; however, it is time consuming and an experienced man is needed to roll the silty soils after lime is added. A chemical analysis, such as ASTM C-25-58 (rapid sugar test), on a reacted soil after any given period could be used, but it is also time consuming and only results to the nearest percent are needed.

As stated earlier, lime is a strong base with a very low coefficient of solubility in water, giving a pH of 12.4. Therefore, it was felt that a pH test on soil-lime mixtures, after an hour or any given period of time, could be used to determine the optimum amount of lime for the reactions. Such a test could be performed with unskilled workers.

DESCRIPTION OF MATERIALS

Soils

Approximately one hundred soils have been tested under the conditions of this investigation, and since all of the soils followed the same pattern only the results of four soils are reported. The choice of these soils was based on the type of clay minerals and the Bureau of Public Roads soil classification. The four soils are as follows:

1. A glacial till from Champaign County, Ill., which classifies as an A-4(6). The clay minerals are predominantly illite with a smaller amount of chlorite.
2. Glacial till from Ottawa, Ill., which classifies as an A-6(9). The clay minerals are also illite and chlorite, but chlorite is predominant with mixed layering.
3. Porter's Creek clay, from Kemper County, Miss., which classifies as an A-7-6(20). The clay minerals are illite and montmorillonite.
4. Pierre shale from South Dakota, which also classifies as an A-7-6(20), and the clay mineral is montmorillonite.

Lime

A commercially produced Ca(OH)_2 , hydrated lime, meeting ASTM specification C 207-49, with 98.4 to 99.0 percent passing a No. 325 sieve, was used throughout the testing program.

ANALYTICAL PROCEDURE

Preparation of Materials

The soils were air dried to the point where they could be disaggregated with as little manipulation as possible to pass a No. 10 sieve. Since these soils were predominantly clays, a portion of the minus No. 10 was selected, using a sample splitter, and allowed to completely air dry before further disaggregation to pass the No. 40 sieve for liquid and plastic limit tests. The bulk samples were stored in closed containers so that a uniform moisture content could be maintained.

TABLE 1
PROPERTIES OF SOIL

Property	Glacial Till A-4(6)	Glacial Till A-6(9)	Porter Creek Clay A-7-6(20)	Pierre Shale A-7-6(20)
Textural composition:				
Passing No. 10 sieve	100.0	100.0	100.0	100.0
Passing No. 40 sieve	82.7	93.5	91.7	95.7
Silt (74-5 μ)	33.3	48.1	27.9	7.6
Clay (5 μ)	39.6	31.0	55.0	84.5
Clay (2 μ)	22.8	25.2	37.4	67.0
Physical properties:				
Liquid limit	20.0	28.6	78.8	161.2
Plastic limit	14.5	16.5	31.5	34.5
Plasticity index	5.5	12.1	47.3	126.7
Predominant clay mineral	Illite- chlorite	Illite- chlorite	Illite- montmorillonite	Montmorill- onite

Treatment of Soil

Samples of the minus No. 40 fraction equaling 20 gm of oven-dry soil were weighed to the nearest 0.1 gm and placed in two series of 150-ml plastic bottles with screw-top lids. Varying percentages of lime weighed to the nearest 0.01 gm were added to the two series of bottles. To the lime and soil, 100 ml of CO₂-free distilled water was added, and the three components were mixed by shaking the bottle until all ingredients were thoroughly mixed. One series of bottles was treated at room temperature, the other at 140 F. Curing times varied from one hour to 3 yr for both temperatures. The bottles were shaken for 30 sec every 10 min for the first hour.

Just prior to a pH determination, about 30 ml of the slurry was transferred to a 50-ml plastic beaker for measurement. Immediately after taking the reading, the slurry was returned to the plastic bottle; pH measurements were made at the end of 30 min, 1, 2, 4, 6, 12, 24, 48, 72, and 96 hr. The pH of the slurries of A-4(6) soil was determined at the end of 15 and 30 days. The A-6(9) soil was checked up to 15 days. The Pierre shale was checked every day for 30 days and then at the end of each month for 6 months, and finally once a year for 3 years.

Optimum moisture and standard Proctor density measurements were made for each untreated soil, and for each of the lime contents which had been used for the pH determinations. For the A-4(6) soil the lime contents were 2, 4, 6, and 8 percent; for the A-6(9) soil, 1, 3, 5, 7, and 9 percent; for the Porter Creek clay, 1, 3, 5, 7, and 9 percent; for the Pierre shale, 5, 10, 13, and 15 percent.

At each lime content and curing condition, enough soil for four 2- by 4-in. specimens was blended in a dry state to obtain a uniform mixture. Distilled water was then added to the dry mixture to bring it to its optimum moisture content. The material was then compacted in 2- by 4-in. molds to standard Proctor density. The specimens extruded from the molds were wrapped in damp paper towels and sealed in polyethylene bags to prevent moisture loss and carbonation, and then were stored either at room temperature or in a humidity cabinet at 140 F. A temperature of 140 F was used because Eades, Grim and Nichols (4) showed the correlation between 72 hr at 140 F laboratory curing and field strength after one year.

In the case of the Pierre shale the same procedure as above was followed, except CBR specimens were prepared. The oven-cured specimens were sealed with sheets of rubber and caps made from plate steel. CBR tests were used so that the relationship of swell to the optimum lime content, as determined by pH, could be shown along with strength increases.

EXPERIMENTAL METHODS

Unconfined Compression Test

The soil test specimens were tested unconfined, using a model AP-170 Stability Testing Machine. Loads were indicated on a 2,000-lb or 10,000-lb proving ring, depending on the strength of the sample, which has a dial reading to 0.0001-in. deflection. Strain was applied to the test specimens at a constant rate of 0.05 in./min.

California Bearing Ratio Test

CBR was used to test the Pierre shale. The same equipment that was used for unconfined compression test was used for the CBR test. A 10,000-lb proving ring was used with a 3-sq in. piston. All CBR specimens, regardless of cure, were soaked 4 days before testing. The swell was measured just prior to the test.

Liquid and Plastic Limits

ASTM Methods D-423-61T and D-424-59 were followed, except that the lime-treated samples were taken from the unconfined compression test specimens. The soil from the treated test specimens was broken down into pieces passing a No. 4 sieve and allowed to air dry. Then ASTM Method D-421-58, "Dry Preparation of Soil Samples for Grain-Size Analysis and Determination of Soil Constants," was followed for preparing the treated sample.

The plastic limit of each of the lime-treated samples was determined as the average moisture content of the three threads rolled.

Determination of pH Value

Jackson (6) states that the most valid pH measurement of soil is made in the field moist condition, and as soil suspensions are diluted, the pH rises. In spite of his recommendations, a ratio of soil to water of 1 to 5 was used for several reasons. The pH of the lime solution completely changes the soil moisture and absorbed ion relationship, and the problem becomes one of determining the amount of $\text{Ca}(\text{OH})_2$ needed to maintain a saturated system for a given period. If the ratio is 1 to 2, the soil sticks to the electrodes, which must then be cleaned between each test. Furthermore, when the samples are stored at elevated temperature and some evaporation takes place, the bottles do not have to be watched as closely to make sure the reaction is continuing.

After the unconfined compression tests, pH determinations were made on the treated slurries and on slurries composed of the treated test specimens. The soil from the test specimens was mixed with CO_2 -free distilled water in the same proportion as the soil, lime and water to form the treated slurries. A Coleman Companion pH Meter, model 31, with a Hyalk glass electrode was used with a pH range of 14.

Tests of Solutions With $\text{Ca}(\text{OH})_2$

Since the pH of $\text{Ca}(\text{OH})_2$ at 25 C is 12.40, the electrode and meter should be standardized with a 12.00 pH buffer. When the electrode is unused for a few days, it should be soaked in the buffer before the meter is standardized. The electrode should be washed with CO_2 -free distilled water between each reading to keep the electrode from becoming coated in CaCO_3 due to the carbonation of the lime.

Occasionally it is necessary to soak the electrode in 0.1 N HCl for a few seconds to remove the CaCO_3 . The electrode should be thoroughly rinsed with distilled water to remove the acid. Sometimes, after this treatment, the needle will drift, in which case dip the electrode in a solution of Beckman's "Descote." Descote is an organo-silicon product which removes sorbed water from silicate surfaces, leaving a water-repellent coating.

TABLE 2
ONE-HOUR pH RESULTS VS PLASTICITY INDEX

Percent Lime	Glacial Till A-4(6)		Glacial Till A-6(9)		Porter Creek Clay		Pierre Shale	
	pH	PI	pH	PI	pH	PI	pH	PI
1	12.4	N. P. ^a	11.85	8.3	10.20	49.6	—	—
2	12.4	N. P.	—	—	—	—	—	—
3	—	—	12.3	N. P.	11.85	28.5	—	—
5	—	—	12.4	N. P.	12.20	19.2	11.90	56.7
7	—	—	12.4	N. P.	12.30	N. P.	12.20	28.2
9	—	—	—	—	—	—	12.3	N. P.

^aNonplastic

RESULTS

One-Hour pH Results as Related to Plasticity Index

The plasticity index of all soils tested was decreased with each increase in the percentage of lime until the material became nonplastic (5). For the Champaign glacial till, the pH was 12.40 at the one-hour reading and the soil was nonplastic (Table 2). Since the plasticity index (Table 1) was only 5.5 in the untreated state, this is not surprising.

Ottawa glacial till had a PI of 12.1 in the untreated state and a pH of 12.30 with 3 percent lime, and tested nonplastic (Table 2). Again, this is a marginal soil, and one might expect that 3 percent would reduce the PI. However, the pH test for 1 percent lime was 11.85 and the soil still had a PI of 8.3.

The Porter Creek clay sample was quite plastic in the natural state with a PI of 47.3 (Table 2). At the end of the one-hour pH test it was learned that 7 percent lime was required to hold the pH at 12.3; however, 7 percent held the pH at 12.30 for 48 hr, showing there was still quite a bit of lime in the system. Probably 6 percent lime would be enough to stabilize the soil. The plastic limit test showed that samples treated with 7 percent lime were nonplastic. For this particular soil the pH would not go above 12.30, even with 10 percent lime. This phenomenon occurs with soils which are holding univalent ions such as Na^+ in the exchange position, and as the ions are replaced by the calcium, the electrode becomes sensitive to these ions along with the H^+ ion.

The Pierre shale, which contains only the montmorillonite mineral in the clay fraction, has a PI of 126.7. Seven percent lime held the pH at 12.20 for almost an hour, but it only reduced the PI to 28.2 (Table 2). Nine percent lime held the pH at 12.30 for 24 hr, and the soil tested nonplastic. Here again the pH could not be pushed above 12.30 with additional lime.

Each of the 4 soils became nonplastic when they were combined with the lowest percentage of lime, which resulted in free lime in the system after one hour. The lime percentage was based on the lowest percent of lime required to hold the pH of the lime soil slurry at 12.30 to 12.40 for one hour at room temperature. This is to say that when the Calcium (Ca^{++}) absorbing chemical components of the soil (including the exchange capacity of the soil) were satisfied, the physical characteristics of the soil were altered.

Compressive Strength Test as Related to pH

The compressive strength results for the glacial till A-4(6) are given in Table 3. As the curing period increased, so did the compressive strength. However, the optimum strength for a particular lime content did not occur just as the pH dropped below 12.40 or 12.30, but at about a pH of 11.0. Specimens treated with 8 percent lime and

TABLE 3
 COMPRESSIVE STRENGTH VS pH FOR GLACIAL TILL
 A-4(6) CURED AT 140 F

Time (days)	2% Lime		4% Lime		6% Lime		8% Lime	
	psi	pH	psi	pH	psi	pH	psi	pH
1	78	12.30	60	12.40	—	12.40	—	12.40
2	110	12.25	88	12.40	73	12.40	68	12.40
3	133	12.00	118	12.40	101	12.40	82	12.40
4	131	11.80	133	12.30	123	12.40	109	12.40
15	233	11.20	560	11.50	536	11.80	459	12.05
30	240	10.90	800	11.10	764	11.35	748	11.50

Note: Glacial till + 2 percent lime at room temperature for 144 hours gives a pH of 12.40.

TABLE 4
 COMPRESSIVE STRENGTH VS pH FOR GLACIAL TILL A-6(9)

Time (hr)	1% Lime		3% Lime		5% Lime		7% Lime		9% Lime	
	psi	pH	psi	pH	psi	pH	psi	pH	psi	pH
(a) Room Temperature										
1	41	11.85	42	12.30	45	12.40	45	12.40	43	12.40
6	39	11.85	42	12.30	43	12.35	43	12.35	47	12.40
12	38	11.70	41	12.25	41	12.30	41	12.35	46	12.35
24	43	11.70	45	12.25	46	12.30	45	12.30	40	12.35
(b) Moist Cured at 140 F										
12	43	11.45	72	12.15	82	12.30	82	12.30	83	12.35
24	45	11.30	79	12.05	93	12.20	91	12.25	105	12.30
48	44	11.20	188	11.90	210	12.10	194	12.20	195	12.25
72	54	11.05	211	11.70	301	11.80	258	11.85	255	12.10
96	—	—	—	—	306	11.70	332	11.70	282	11.85
120	—	—	—	—	312	11.60	408	11.60	350	11.70
192	—	—	—	—	343	11.45	415	11.45	417	11.50
264	—	—	—	—	384	11.35	454	11.35	489	11.35

cured for 4 days at 140 F still had a pH of 12.40, showing that the system still contained $\text{Ca}(\text{OH})_2$.

The unconfined compressive strength for specimens with 8 percent lime and cured for four days was only 109 psi, while specimens with 2 percent lime cured for four days had an unconfined compressive strength of 131 psi. As curing continued and the lime was consumed, the pH dropped; in the case of the 2 percent lime-treated specimen, the pH at 15 days was 11.20 and the unconfined compressive strength was 233 psi. At the end of 30 days, the samples treated with 8 percent lime had a pH of 11.50 and the unconfined compressive strength had increased to 748 psi.

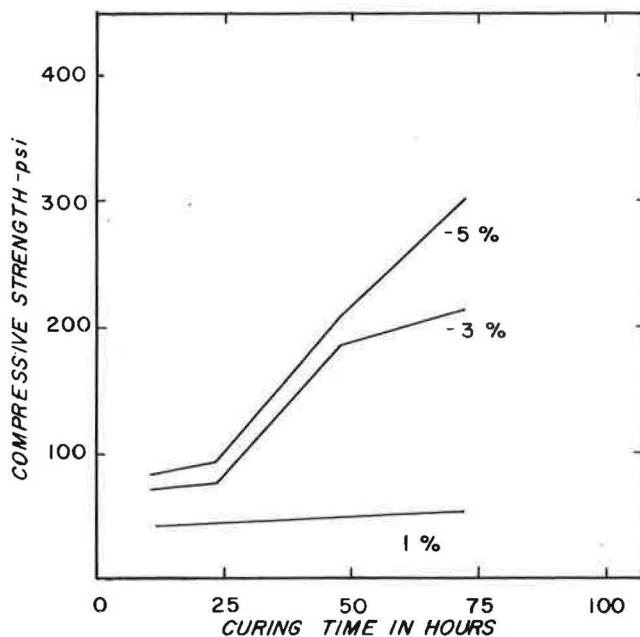


Figure 1. Lime-treated glacial till moist cured at 140 F.

Table 4 shows that there is little or no change in the strength for the first 24 hr, if the A-6(9) specimens are cured at ambient temperature. This can be explained by the fact that lime kills the plasticity of the soil, and 24 hr at ambient temperature is too soon to receive benefits from the formation of calcium silicates. However, when the specimens were moist cured at 140 F for 24 hr, the strength was doubled.

One percent lime did not improve the soil from the standpoint of strength even with prolonged curing. The pH for the 1 percent lime soil mixture after one hour was 11.85, showing that all of the lime had reacted; therefore, calcium silicates could not be formed. As the pH test for one hour had indicated, 3 percent lime killed plasticity. There was also an increase in the unconfined compressive strength from 42 psi for the 6-hr room cured samples to 211 psi for the samples cured at 140 F for 72 hours.

As shown by Figures 1 and 2 for each percentage of lime added to the glacial till A-6(9) soil there was a maximum strength increase, which was related to a definite curing time. The chemical reactions of the soil and lime after the initial reaction are dependent on time and temperature. Five percent lime gave a greater strength for 24 hr curing at 140 F than 3, 7, and 9 percent. Likewise, 7 percent lime exceeded the strength of 5 and 9 percent after 96 hr curing, and 9 percent exceeded 7 percent at 192 hr curing. In every case the specimens gained strength as the pH decreased. Three percent lime was adequate for stabilizing the soil, and increased the strength four-fold, but additional lime resulted in a longer reaction with additional strength.

Figures 3, 4, and 5 show the relationship of pH and unconfined compressive strength for Porter Creek clay. Seven percent gave a pH of 12.30 for 48 hr when cured at room temperature; therefore, 6 percent is probably enough to kill the plasticity (Fig. 3). A plot of the unconfined compressive strength for specimens cured for 72 hr at 140 F shows 6 percent should give a strength of about 200 psi. However, if strength was the aim of the stabilization, lime in a percentage greater than 10 would be reacted in 72 hr at a temperature of 140 F, since 10 percent gave a pH of only 11.10 (Fig. 4). In most cases, additional strength above that obtained from the reaction resulting from the amount of lime required to hold the pH at 12.40 for one hour at room temperature is not needed.

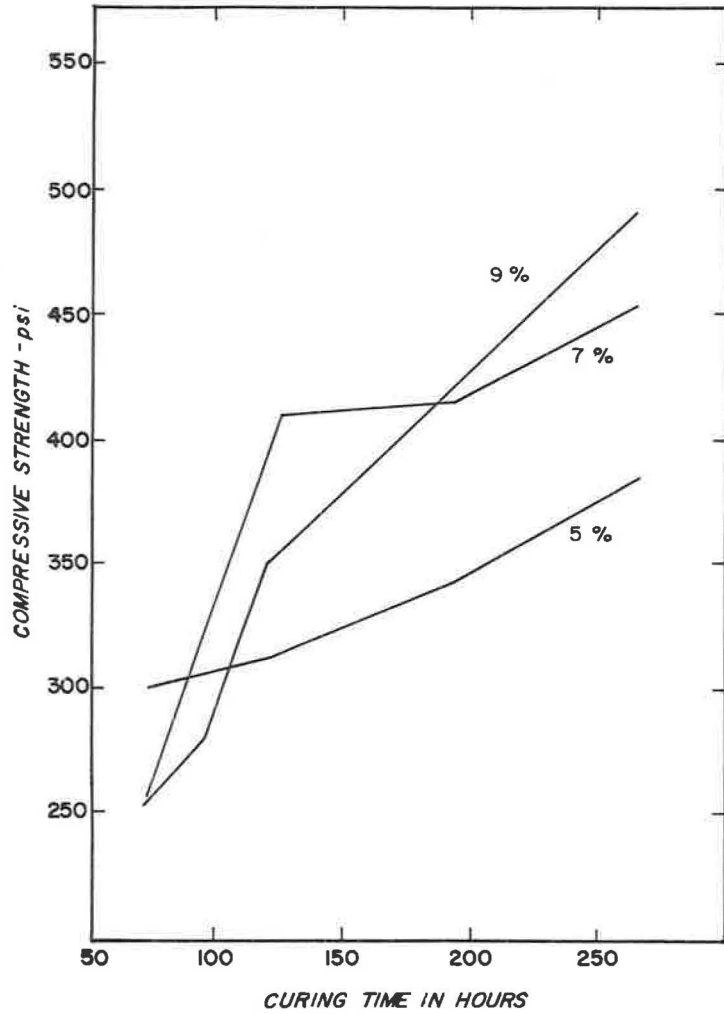


Figure 2. Lime-treated glacial till moist cured at 140 F.

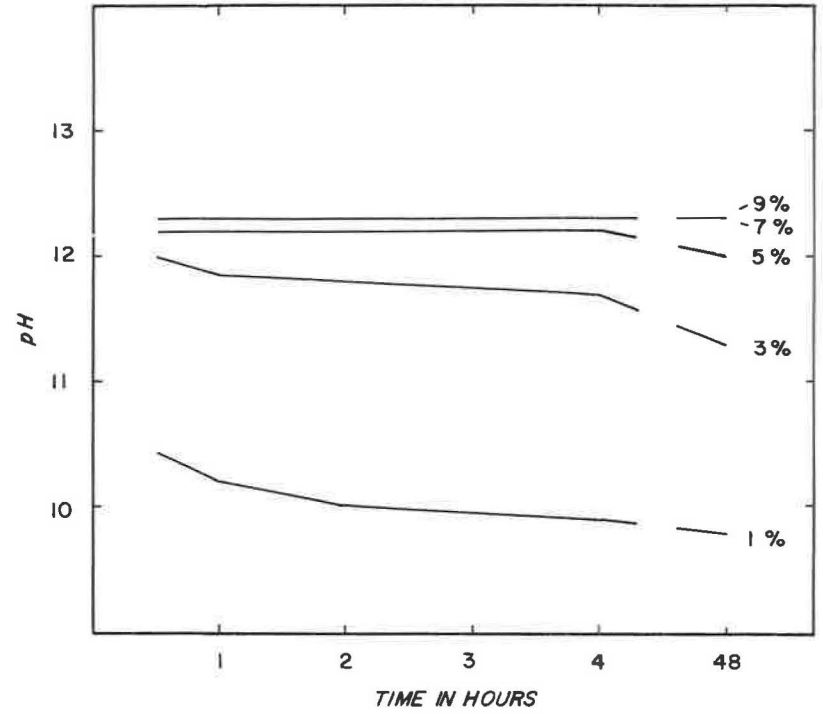


Figure 3. Porter Creek clay and lime, pH results at room temperature.

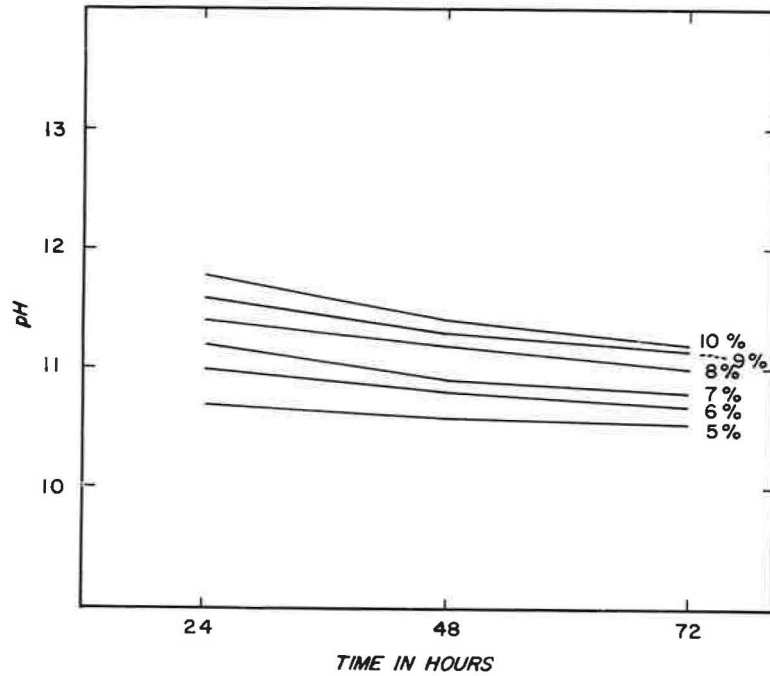


Figure 4. Porter Creek clay and lime, pH results moist cured at 140 F.

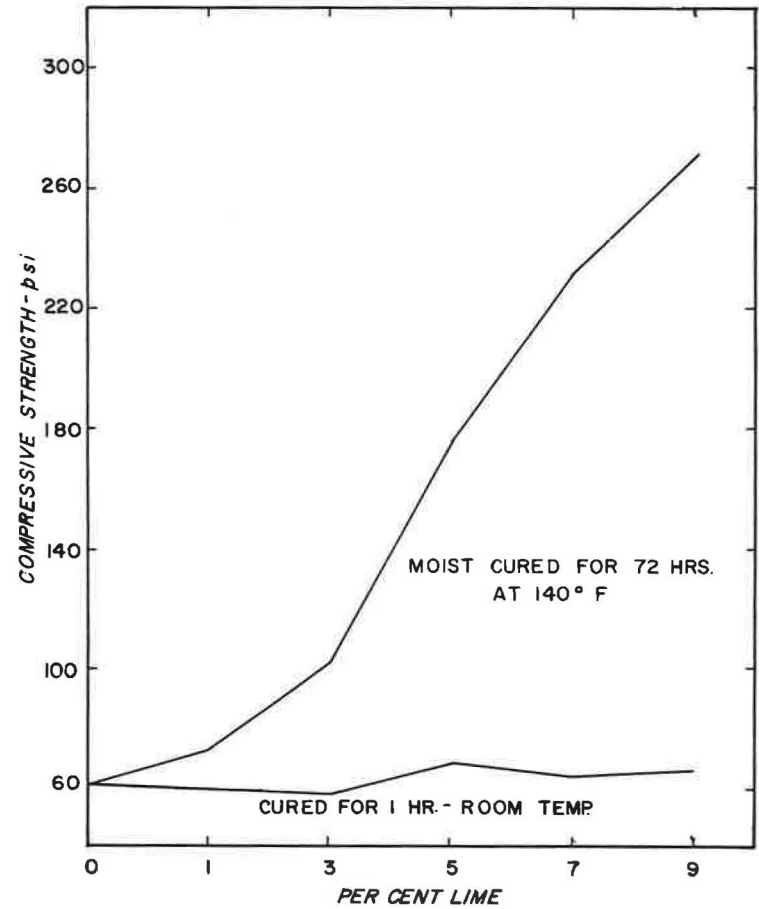


Figure 5. Lime-treated Porter Creek clay, room temperature vs oven cured.

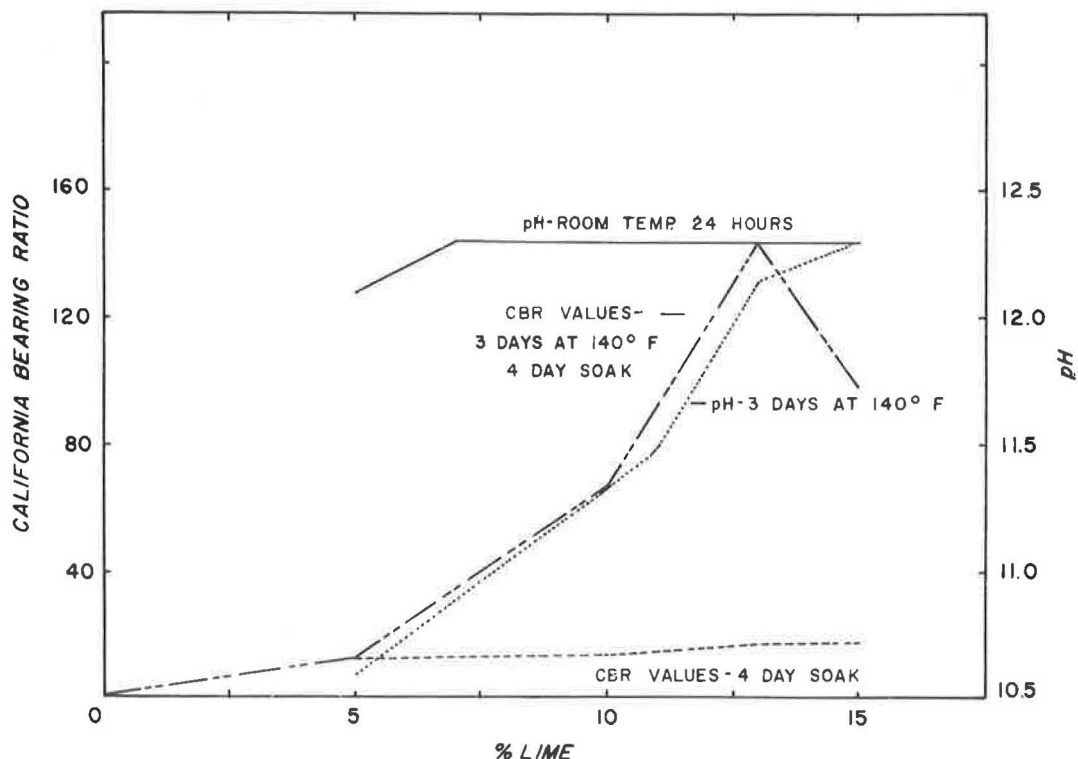


Figure 6. Lime-treated Pierre shale.

Figure 6 shows the relationship of pH results for room-cured slurries, slurries treated at 140 F for 72 hr, CBR values for specimens cured at 140 F for 72 hr, and CBR values for specimens cured only by the 4-day soak period. Nine percent lime is needed to hold the pH at 12.30 for one hour, but 15 percent is needed to hold the pH at 12.30 for 72 hr at 140 F; i.e., at 140 F just under 15 percent lime would be consumed in the soil reactions in 72 hr. This does not mean the greatest strength would be obtained from 15 percent in 72 hr. The greatest CBR value was obtained after 72 hr cure at 140 F with 13 percent lime (Fig. 6). However, the lime requirement of 9 percent as determined by the one-hour pH test increased the CBR value from 2 percent to 45 percent after curing for 72 hr at 140 F. A CBR value of 12 percent was recorded for specimens treated with 9 percent lime and cured only by soaking for 4 days at room temperature.

Figure 7 shows the relationship between pH values for slurries of Pierre shale kept at room temperature and those kept at 140 F for 3 yr. The pH for the slurry treated at 140 F for 72 hr was within a 0.05 pH of the sample maintained at room temperature for 365 days. This correlates with field results of Eades, Grim, and Nichols (4).

Research by Eades and Grim (3), and Diamond (2), offered proof that the clay minerals are destroyed with calcium silicate hydrates, resulting in new minerals when clays and soils are treated with lime. It seems reasonable to assume that a gel phase precedes the crystalline phase as reported by Brand (1). Therefore, if the pH of a soil-lime mixture is below 12.40, and the unconfined compressive strength increases until the pH is around 11.00, it must be due to the crystallization of the gels and the liberation of excess Ca^{++} . The released calcium would combine with silica ions which would be in equilibrium with the high pH of the system and increase strength.

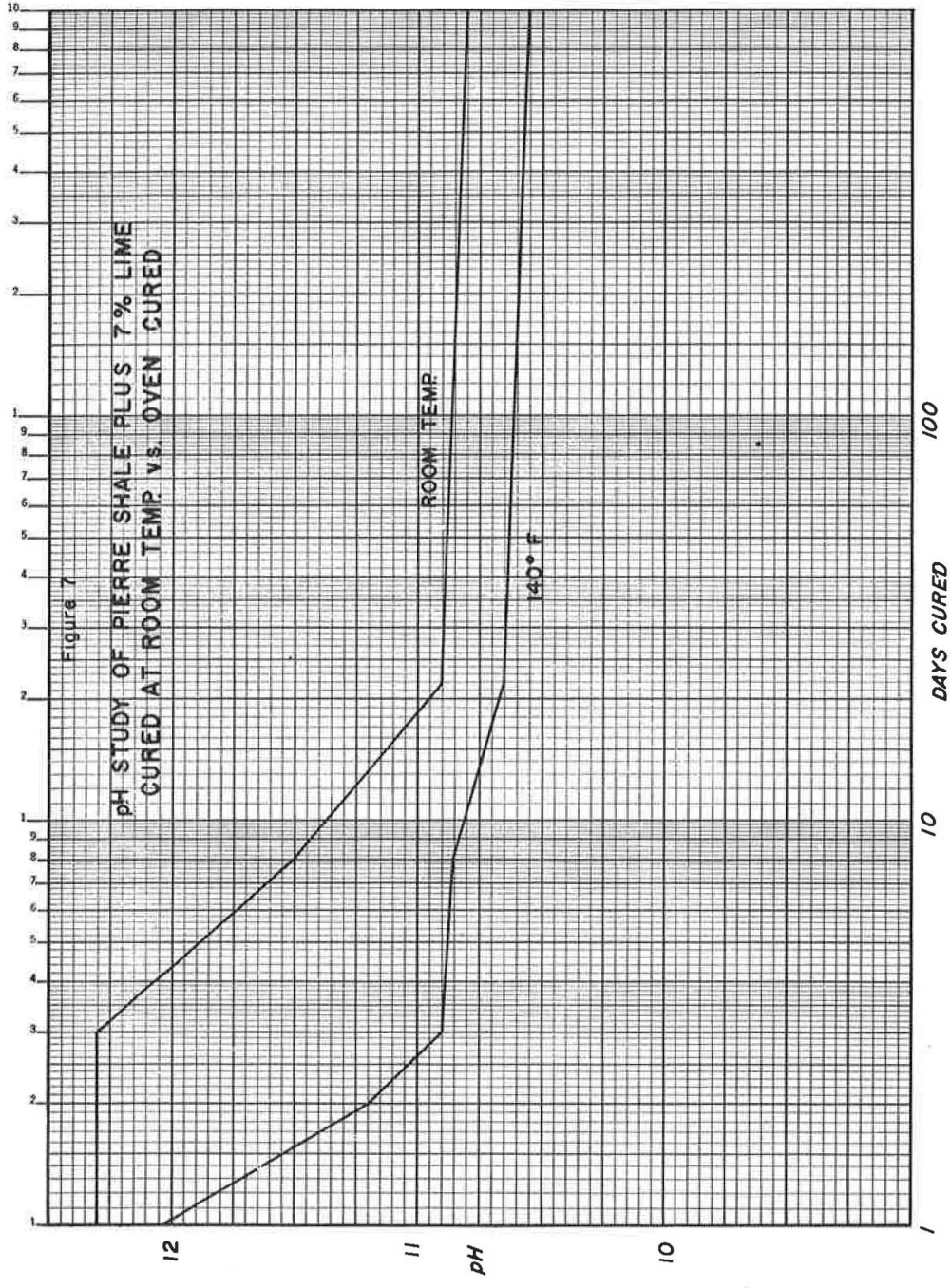


Figure 7.

SUMMARY OF TEST PROCEDURE

1. Representative samples of air-dried, minus No. 40 soil to equal 20 gm of oven-dried soil are weighed to the nearest 0.1 gm and poured into 150-ml (or larger) plastic bottles with screw tops.

2. Since most soils will require between 2 and 5 percent lime, it is advisable to set up five bottles with lime percentages of 2, 3, 4, 5, 6. This will insure, in most cases, that the percentage of lime required can be determined in one hour. Weigh the lime to the nearest 0.01 gm and add it to the soil. Shake to mix soil and dry lime.

3. Add 100 ml of CO₂-free distilled water to the bottles.

4. Shake the soil-lime and water until there is no evidence of dry material on the bottom. Shake for a minimum of 30 seconds.

5. Shake the bottles for 30 seconds every 10 minutes.

6. After one hour, transfer part of the slurry to a plastic beaker and measure the pH. The pH meter must be equipped with a Hyalk electrode and standardized with a buffer solution having a pH of 12.00.

7. Record the pH for each of the lime-soil mixtures. If the pH readings go to 12.40, the lowest percent lime that gives a pH of 12.40 is the percent required to stabilize the soil. If the pH did not go beyond 12.30 and 2 percent lime gives the same reading, the lowest percent which gives a pH of 12.30 is that required to stabilize the soil. If the highest pH is 12.30 and only 1 percent lime gives a pH of 12.30, additional test bottles should be started with larger percentages of lime.

CONCLUSIONS

A measure of the amount of lime consumed by a soil after one hour affords a quick method of determining the percent lime required for lime stabilization. A pH meter with a Hyalk glass electrode can be used to determine the percent lime which has reacted with a soil. This is accomplished by measuring the pH of lime-soil slurries to determine the minimum percent lime required to maintain a pH of 12.40.

The use of the pH meter is also applicable for determining the required percentage of dolomitic or magnesium limes for soil stabilization.

The one-hour pH or "quick test" can only be used to determine the lime requirements of a soil for stabilization. Since strength gains are related to the formation of calcium silicates, and their formation varies with the mineralogical components of the soil, a strength test is necessary to show the percentage of strength increase.

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