The Calcium-Magnesium Ratio in Soil-Lime Stabilization

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Preliminary studies of soil-lime stabilization with loess pointed up the fact that different limes give widely varying strength results, and strengths seemed to be related to Ca:Mg ratio and to the use of quicklime vs hydrated lime. Now additional data are available verifying this fact for loess, glacial till, dune sand, and an alluvial backswamp clay. Mixtures of pure chemicals were used to certify the trends, and results generally supported those obtained with commercial limes. Dolomitic lime usually gives higher strengths, particularly when added in amounts greater than 4 percent by weight of the soil. The dihydrate dolomitic lime (Type S) prepared by autoclave process is not so effective as the monohydrate (Type N) in which Mg occurs as the oxide. This also was reaffirmed using pure chemicals. Highest strengths were realized with dolomitic quicklime, the strength advantage over other limes being 50 to 100 percent or more with 6 or 8 percent admixture. The difference was found to depend on the kind of soil, but the difference was significant with all soils tested.

Practical value of the soil-lime results is emphasized by the CBR and wet-dry and freeze-thaw data. CBR values for lime stabilized loess and till were frequently doubled by use of dolomitic quicklime, and CBR's with 4 to 9 percent dolomitic lime ran from 100 to over 200 after 28 days moist curing. In these and other tests all molded specimens were wrapped to prevent killing of the lime by CO_2 from the atmosphere.

Use of dolomitic lime gives the first important indication of soil-lime having a satisfactory resistance to weathering. Stabilized loess and till specimens cured 1 to 12 weeks were found in many cases to gain strength through 12 cycles of wet-dry. Freeze-thaw specimens showed only slight decrease in strength or in some cases gained strength through 12 cycles. The best results were again obtained with dolomitic quicklime. Freeze-thaw results with calcitic lime were much less favorable, and most specimens lost strength rapidly after the first few cycles.

• RECENT RESEARCH done on soil-lime stabilization and reported to the ASTM (*1*) showed that limes differ in effectiveness in their reaction with loess, a common silt material in the central U. S. This difference in cementation appeared to be related mainly to chemical composition of the lime. Objectives of the present research were to gain more information to illuminate this problem, and to prove or disprove the superiority of certain limes not only for loess, but for a sand, a glacial till, and an alluvial clay as well.

The Ca-Mg Ratio

Commercial lime is produced by crushing and calcining limestone to drive off CO_2, leaving the calcium oxide or quicklime. Many producers also burn dolomite, a carbonate rock similar to limestone but containing magnesium. The resulting lime is calcium oxide plus

magnesium oxide, and is termed dolomitic quicklime. Differences in the two types of limes were recently recognized in the plaster industry and have been given much emphasis in the past few years. Unless dolomitic quicklime is given special hydration treatment, the high-calcium or calcitic[1] lime is preferred to prevent cracking. Whereas calcium oxide hydrates quickly, magnesium oxide at normal temperature hydrates very slowly, and hydration over the years produces expansion and cracking of walls (*2*). At present this is eliminated by a forced autoclave hydration of the magnesium oxide, converting it to hydroxide.

There are two chemical types of quicklime: Calcitic, CaO; and dolomitic, CaO + MgO. There are three chemical classes of hydrated lime: calcitic, $Ca(OH)_2$; dolomitic monohydrate, $Ca(OH)_2 + MgO$; and dolomitic dihydrate, $Ca(OH)_2 + Mg(OH)_2$. The degree to which a lime is calcitic or dolomitic can be expressed in the calcium-magnesium mole ratio, Ca/Mg. In pure calcite, $CaCO_3$, the ratio is infinity; in pure dolomite, $CaMg(CO_3)_2$, it is one. Limes are also classified on the basis of plasticity as Type N (normal) or Type S (special or slick). At present most Type S lime is dolomitic dihydrate, although Type S can be a calcitic lime.

[1] The term calcitic is taken from calcite, the common $CaCO_3$ mineral in limestones. The mineral dolomite is $CaMg(CO_3)_2$.

MATERIALS

Soil Materials

A brief description of the soil samples is given in Table 1. Properties of these soils are shown in Table 2.

Loess. Of the five soil samples studied, two are loess samples from western Iowa. Loess is a silty soil material showing systematic areal variations in particle size and soil profile development. The two samples represent a friable, calcareous C-horizon loess classifying as a silty clay loam, and a plastic, noncalcareous C-horizon loess classifying as a silty clay. The major clay minerals are montmorillonite and illite.

Glacial Till. A C-horizon sample from southern Iowa was selected as a representative Kansan age calcareous glacial till. The till sample classifies texturally as a clay but contains significant amounts of sand and silt. The predominant clay minerals are montmorillonite and illite.

Alluvial Clay. A sample of alluvial clay from the Missouri River floodplain in western Iowa represents recent flood or overflow sediments denoted geologically as backswamp deposits or slack water sediments. Weathering is in its initial stages, and the clay is calcareous. A rather high organic matter content suggests that recently eroded topsoil has been incorporated in the deposit. From differential thermal analysis the major

TABLE 1
BRIEF DESCRIPTION OF SOILS USED

Soil	Friable Loess (Lab. No. 20-2, IV)	Plastic Loess (Lab. No. 44A-1)	Glacial Till (Lab. No. 411)	Alluvial Clay (Lab. No. A1-1)	Dune Sand (Lab. No. S-6-2)
Location	Harrison County, SW Iowa	Page County, SW Iowa	Page County, SW Iowa	Woodbury County W Iowa	Benton County, E Iowa
Geological description	Wisconsin age friable loess, oxidized; thickness over 100 ft	Wisconsin plastic loess, oxidized, leached; total thickness 15-20 ft	Kansan glacial till, oxidized, calcareous	Recent backswamp clay from Missouri River	Wisconsin aeolian sand, fine-grained, oxidized, leached
Soil series	Hamburg	Marshall	Shelby	Luton	Carrington
Horizon	C	C	C	C	C
Sampling depth, ft	39-40	4-5	3-23	0-2	6-11

TABLE 2

PROPERTIES OF SOILS USED

Soil	Friable Loess	Plastic Loess	Glacial Till	Alluvial Clay	Dune Sand
Textural composition, %[a]:					
Gravel (2.0 mm)	0	0	0	0	0
Sand (2.0-0.074 mm)	0.4	0.2	25.2	1.5	94.4
Silt (74-5μ)	82.2	58.0	31.8	24.2	1.6
Clay ($< 5\ \mu$)	17.4	41.8	43.0	74.3	4.0
Colloids ($< 1\ \mu$)	12.5	31.0	32.5	55.1	3.5
Predominant clay mineral[b]	M and I[c]	M and I	M and I	M and I	M and I
Probable predominant exchangeable cation	Calcium	Calcium	Calcium	Calcium	—
Specific gravity 25°C/4°C	2.68	2.72	2.66	2.65	2.64
Chemical properties:					
Cat. ex. cap., m.e./100 gm[d]	13.4	28.2	20.0	39.4	—
Carbonates, %[e]	10.5	0	13.0	7.0	0
pH	7.8	6.2	7.9	7.3	6.5
Organic matter, %	0.2	0.5	0.1	1.7	0.04
Physical properties:					
Liquid limit, %	32.9	53.1	41.8	71.0	19.0
Plastic limit, %	21.1	25.7	14.9	24.5	—
Plasticity index	11.8	27.4	26.9	46.5	N.P.
Shrinkage limit, %	22.0	19.9	12.3	10.2	—
Centrifuge moist. equiv, %	19.0	21.3	23.9	48.7	—
Field moist. equiv, %	26.4	53.6	31.0	38.4	—
Textural classification	Silty clay loam	Silty clay	Clay	Clay	Sand
Engineering (AASHO)	A-4 (8)	A-7-6(18)	A-7-6(15)	A-7-6 (20)	A-3 (0)

[a] Dispersed by air-jet with sodium metaphosphate dispersing agent.
[b] From differential thermal analysis of fraction passing No. 200 sieve.
[c] Montmorillonite and illite.
[d] Fraction passing No. 40 sieve.
[e] From differential thermal analysis.

clay minerals appear to be montmorillonite and illite.

Dune Sand. The sand sample is from one of the local deposits of stable dune or eolian sands on the Iowan (early Wisconsin) drift plain in eastern Iowa. The sample is C-horizon, being taken from below the major soil profile. The sand is rather fine and nearly all one size, therefore poor for compaction. A small percentage of clay occurs as grain coatings.

Lime

Commercial limes were selected to represent the various chemical classes mentioned previously. Chemical analyses furnished by the lime producers are given in Table 3. In the dolomitic limes the Ca:Mg ratio is 1.7; in the calcitic limes it is 147 and 168.

Synthetic limes were prepared from purified grade $Ca(OH)_2$, $Mg(OH)_2$ and MgO. These were mixed in various proportions to duplicate the three classes of commercial hydrated lime.

METHODS

Mixing and Molding

Soil-lime mixes were proportioned and mixed dry; then optimum water content for maximum density was added and the materials machine mixed for 5 minutes. Although most specimens were then molded immediately, some of the sand-quicklime mixes were allowed to hydrate for various times before molding. A double plunger drop-hammer molding apparatus was used to mold 2-in. by 2-in. specimens to approximate standard Proctor density. CBR specimens also were

TABLE 3
CHEMICAL ANALYSES OF COMMERCIAL LIMES USED

Kind of Lime	Calcitic Lime		Dolomitic Lime		
	Quicklime	Hydrated	Quicklime	Monohydrate	Dihydrate
Silicon dioxide	0.38	0.52	0.67	0.6	0.57
Iron and aluminum oxide	0.28	0.18	1.00	1.1	1.06
Total calcium figured as CaO	96.45	74.21	56.59	48.3	42.21
Total magnesium figured as MgO	0.68	0.59	40.41	33.2	29.72
Total sulphur	ND[a]	ND	0.04	ND	ND
Sulphur trioxide	ND	ND	ND	ND	0.11
Carbon dioxide	1.27	0.62	ND	ND	2.90
Loss on ignition	2.03	24.52	1.70	ND	27.06
Ca:Mg ratio	168:1	147:1	1.7:1	1.7:1	1.7:1

[a] ND = Not determined.

prepared at standard Proctor density (*3*).

Curing and Testing

Curing was at 70 deg ± 3 F with a relative humidity of not less than 90 percent. The curing time was varied. Specimens for certain investigations such as long curing were double wrapped in waxed paper and aluminum foil to better preserve moisture and prevent entry of carbon dioxide from the air.

At the end of the specified curing period some specimens were tested immediately but most were immersed in distilled water for one day. Specimens were tested for unconfined compressive strength using a load travel of 0.10 in. per minute. Tests were run in triplicate and the average strengths reported.

CBR tests were run after specimens were soaked in water for four days. The CBR readings were made at 0.1-in. and 0.2-in. penetration and the larger value reported.

Tests for Durability

Cured 2-in. by 2-in. specimens were subjected to alternate wetting and drying or to alternate freezing and thawing. Each period of immersion wetting and air drying was for one day. Freezing was for 23 hours at −10 deg F; thawing was in the open air for two hours and in the moist-cure cabinet for 23 hours. In either sequence a cycle takes two days. Specimens were tested for compressive strength after 1, 3, 6, 9, and 12 cycles wetting and drying or freezing and thawing.

SYNTHETIC LIMES

Use of synthetic limes made from prepared chemicals allows isolation of the Ca:Mg ratio as an independent variable. Other work has shown close correlations between results with chemicals and those with commercial limes (*1*). In the present work the Ca:Mg ratio was varied between the two end limits, and mixtures were prepared to represent both the monohydrate and dihydrate types of hydrated dolomitic lime. CaO quicklime was not included in the study.

Typical results with synthetic hydrated lime mixtures and one soil are shown in Figures 1 and 2; in this and other cases highest 28-day strengths were obtained with about 6 to 8 percent lime. Apparently excess lime can act as a weak filler, subtracting from strength.

The relation between strength and Ca:Mg ratio may be illustrated by plotting strengths at one lime content. Strengths with 8 percent lime and varying Ca:Mg ratio are shown in Figures 3, 4 and 5. Strengths with pure $Ca(OH)_2$ are at the left; by tracing the curves to the right one sees the effect of decreasing the $Ca(OH)_2$ with a complementary increase in either MgO, as in monohydrate dolomitic lime, or $Mg(OH)_2$, as in the dihydrate.

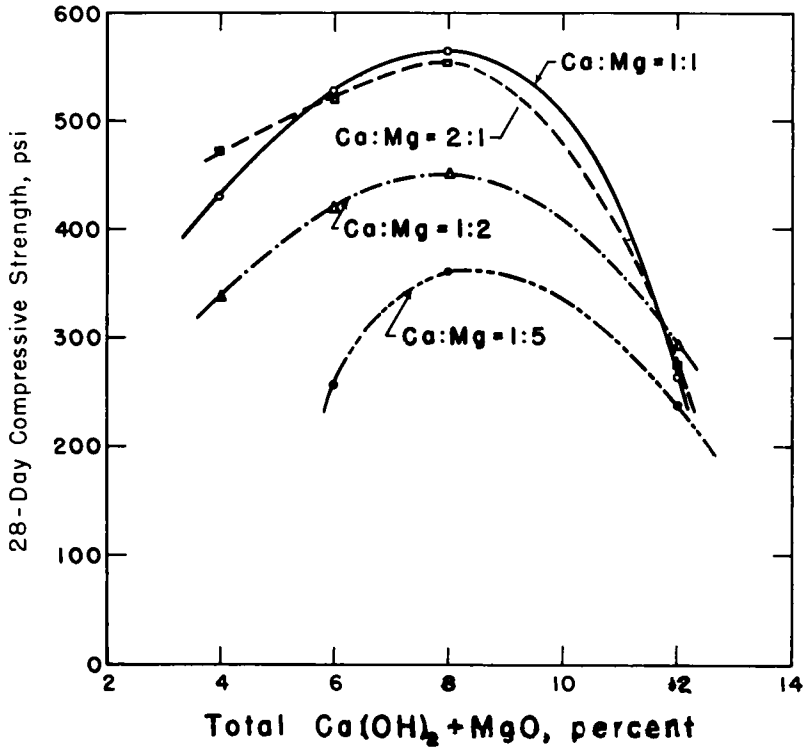

Figure 1. Immersed strengths of glacial till stabilized with limes synthesized from $Ca(OH)_2$ and MgO.

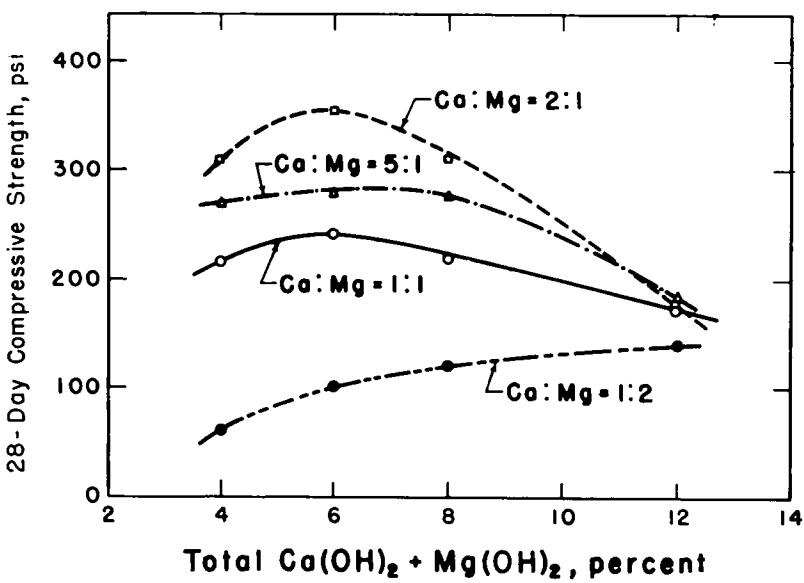

Figure 2. Immersed strengths of glacial till stabilized with limes synthesized from $Ca(OH)_2$ and $Mg(OH)_2$.

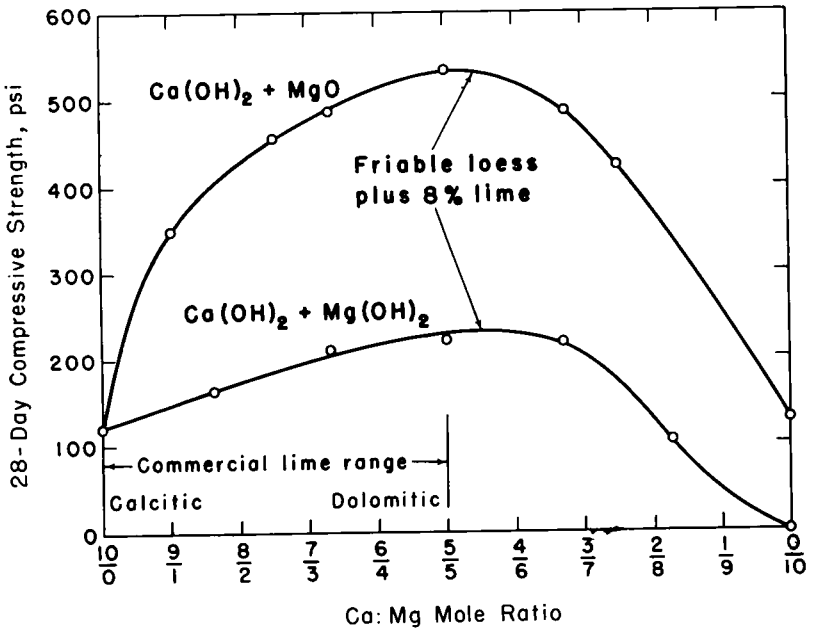

Figure 3. Effect of Ca:Mg ratio on immersed strength of friable loess with 8 percent synthetic hydrated lime.

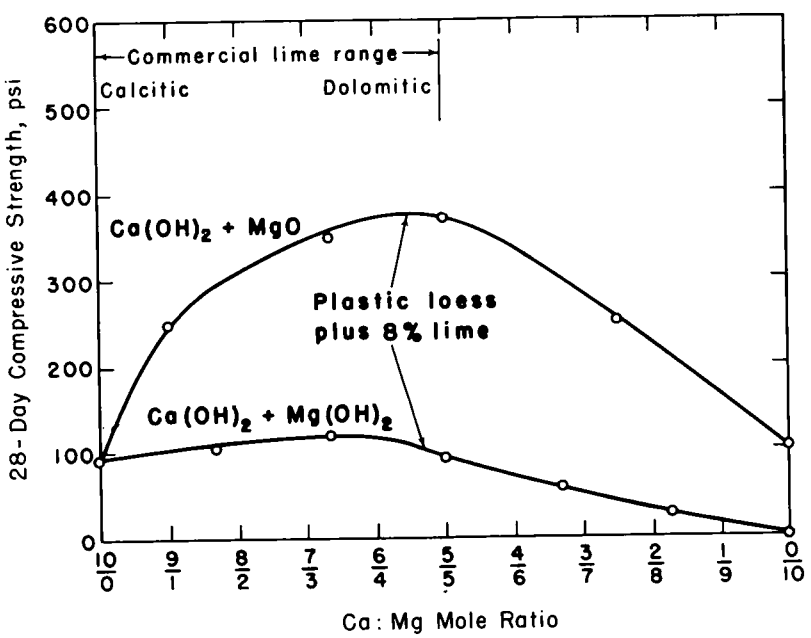

Figure 4. Effect of Ca:Mg ratio on immersed strength of plastic loess with 8 percent synthetic hydrated lime.

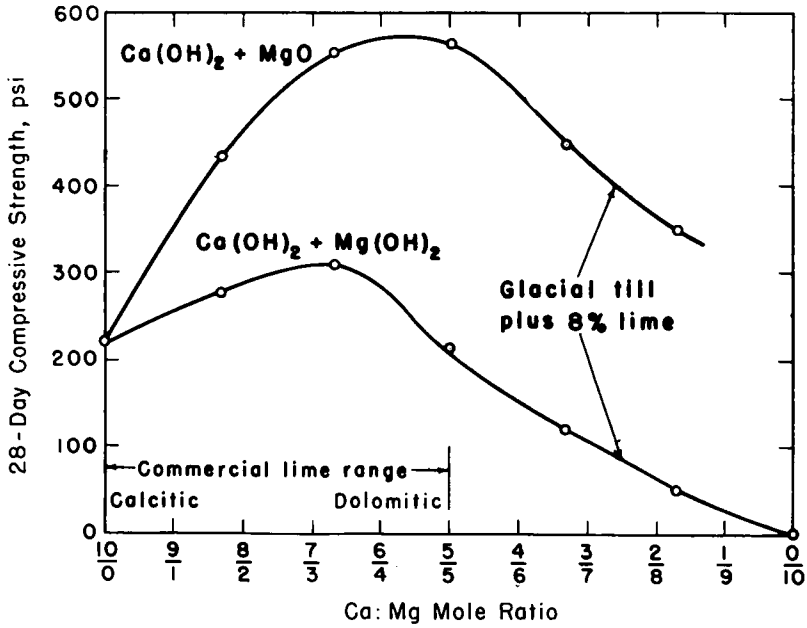

Figure 5. Effect of Ca:Mg ratio on immersed strength of glacial till with 8 percent synthetic hydrated lime.

Strengths tend to be higher with dolomitic lime, but the vast and most significant increase is with the monohydrate. With monohydrate lime the optimum Ca:Mg ratio approximates that of pure dolomitic lime. A further increase of MgO is not possible with commercial limes, but neither is it desirable, as strengths go down. It is of academic interest to note that some strength is realized with pure MgO, whereas specimens molded with pure Mg $(OH)_2$ slaked when put in water. Twenty-eight day strengths with dolomitic monohydrate lime are of the order of two to four times those obtained with calcitic hydrated lime, the greatest difference being with lower clay content. The lime-stabilized loesses give double or triple strength with only a very small addition of MgO. The glacial till has the highest clay content and is least sensitive to replacement of $Ca(OH)_2$ with MgO.

COMMERCIAL LIMES

Seven-day strengths with different percentages of commercial limes are shown in Figures 6 through 8. In general the curves reflect trends previously found with synthetic limes. Monohydrate dolomitic lime gave higher strengths than dihydrate, and dihydrate gave higher strengths than calcitic lime except in the low lime content range. It will be noted however that strength differences between mono and dihydrate are not nearly so pronounced as they were with synthetic chemical limes. Related to this is the fact that strengths with monohydrate lime are not as high as they should be. For comparison, mixes were prepared using quicklime. Use of dolomitic quicklime raised the strengths up to those previously realized with the synthetic monohydrate lime (Table 4). This is also true if lime contents are expressed on a molar equivalent basis.

MgO is most effective when added as a pure chemical or in quicklime and its effectiveness is reduced in commercial monohydrate lime; therefore, a possible relation to the hydration process is suggested. Hydration of dolomitic quicklime after it is mixed with soil is a "cold" process, and in the small batches used

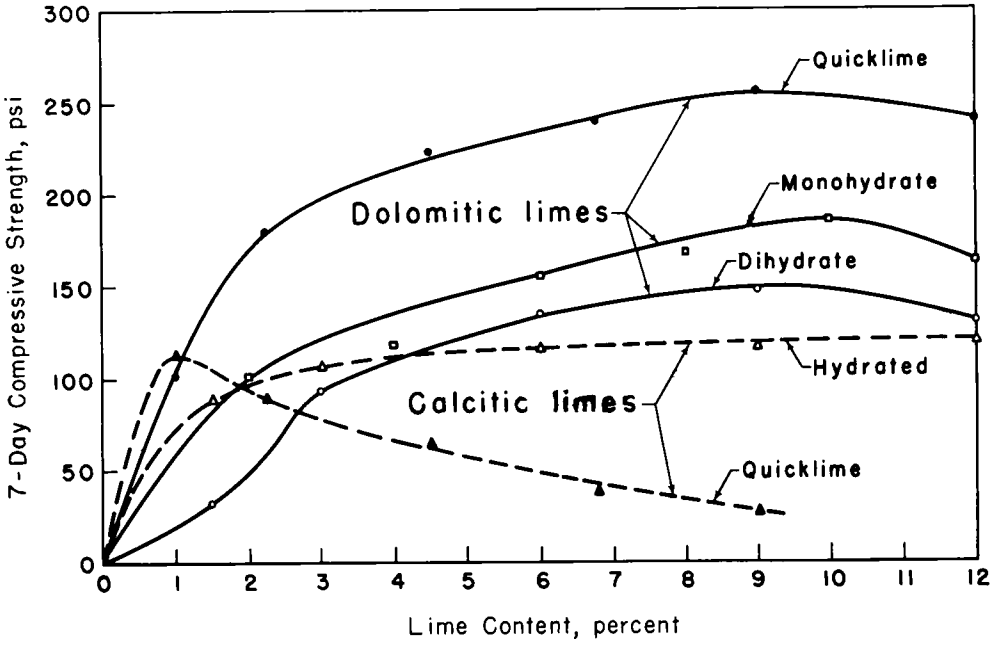

Figure 6. Immersed strength of friable loess with commercial lime.

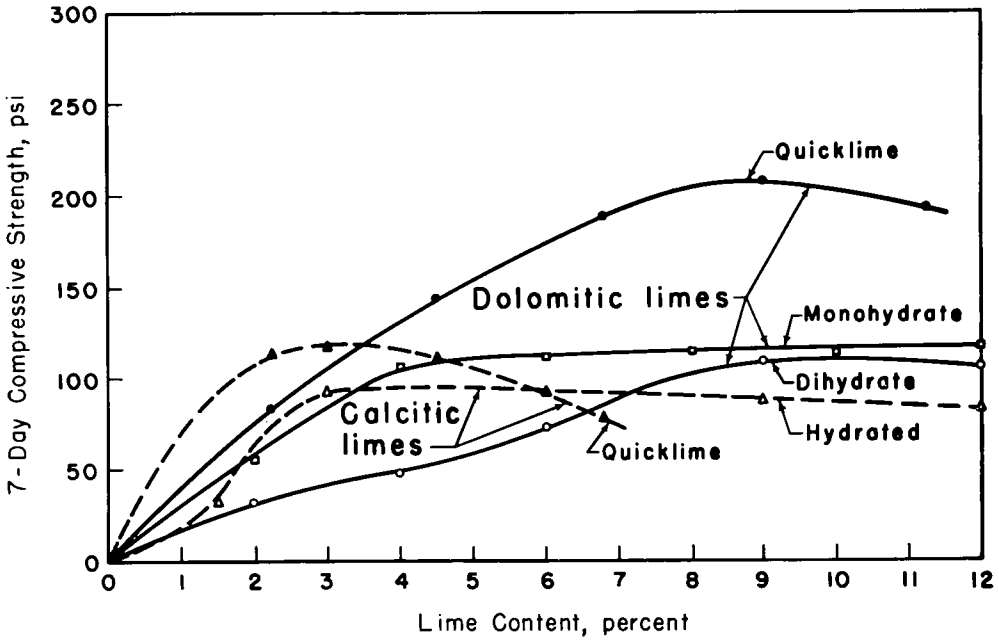

Figure 7. Immersed strength of plastic loess with commercial lime.

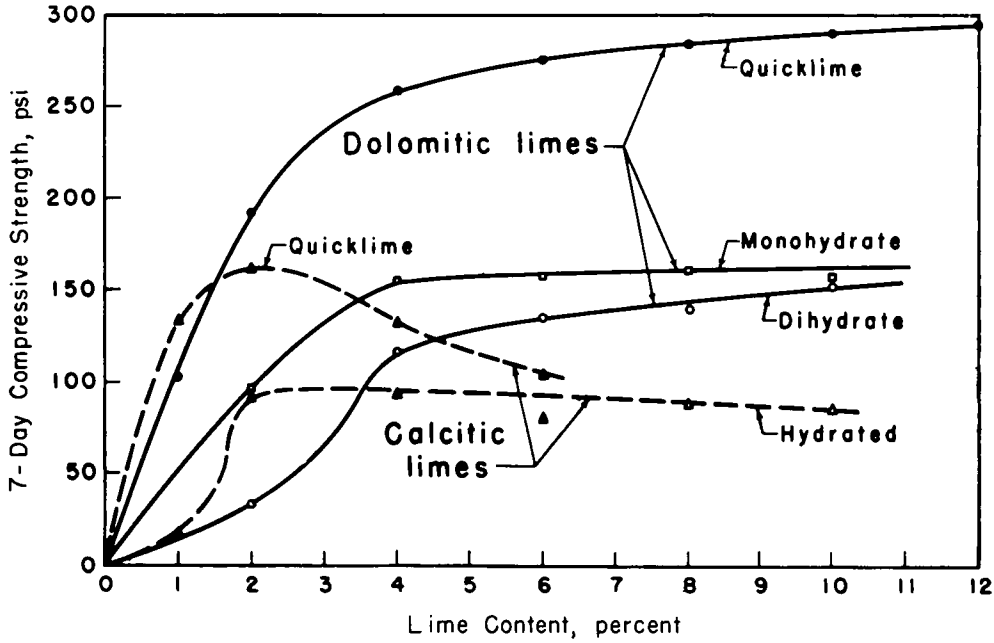

Figure 8. Immersed strength of glacial till with commercial lime.

TABLE 4

COMPARATIVE 28-DAY STRENGTHS WITH DIFFERENT KINDS OF DOLOMITIC LIME.*

Lime	Immersed Strength, psi	
	Friable Loess	Plastic Loess
Synthetic monohydrate	506	356
Commercial monohydrate	274	122
Quicklime	588	312

* Lime contents 8 to 9 percent.

the heat was quickly dissipated in the mixing bowl. There is probably little conversion of MgO. Commercial hydration on the other hand involves much heat, depending on the process, and perhaps commercial processes result in MgO being coated with a thin layer of hydroxide, in effect partially "killing" the MgO in the lime. It is known that if heat and pressure are raised high enough MgO will completely convert to the hydroxide, as in the autoclave manufacture of dihydrate lime. This might explain various differences in effectiveness of different brands of monohydrate dolomitic lime.

Calcitic quicklime strengths are highest with about 1 to 3 percent lime, and quicklime strengths exceed those with calcitic hydrated lime. At higher lime contents the quicklime strengths drop off, the greatest drop being with the least clay. Hydration in the molded soil-lime specimen may be a significant factor with these higher contents of calcitic lime. The factor is not so much one of heat as one of pressure built up by expansion of hydrating lime. In some cases expansion and cracking of the specimens was observed. The more friable samples, having less clay and lower cohesive tensile strength, would be most sensitive to this type of destruction.

The high strengths with calcitic quicklime in the low lime content range are rather difficult to explain. One possibility is that hydration and the accompanying forced crystal change in lime while it is being mixed with soil may benefit the soil-lime interface contact and allow a more efficient use of lime for chemical

bonding. Chemical precipitation of lime in lime-soil mixtures as a result of higher temperature has been found to increase strengths of both soil-lime (*1*) and soil-lime-fly ash, probably because of improved intimacy of grain contact (*4*).

Use of dolomitic and calcitic quicklime with an alluvial clay and a dune sand was investigated (Figure 9). Highest strengths were with dolomitic lime, although low percentages of calcitic quicklime gave high strengths with the clay. Results with the alluvial clay are not substantially different from those with the other clayey soils. Results with the sand show a necessity for high lime contents, probably because of the lack of fine-grained material to give suitable grain contact area for cementation.

DURABILITY OF SOIL-LIME

A durability test without brushing was used with soil-lime: 2- by 2-in. specimens were subjected to 12 cycles of wet-dry or freeze-thaw and the final compressive strength measured. This strength was compared to that obtained from specimens moist-cured to the same total age but not subjected to wet-dry or

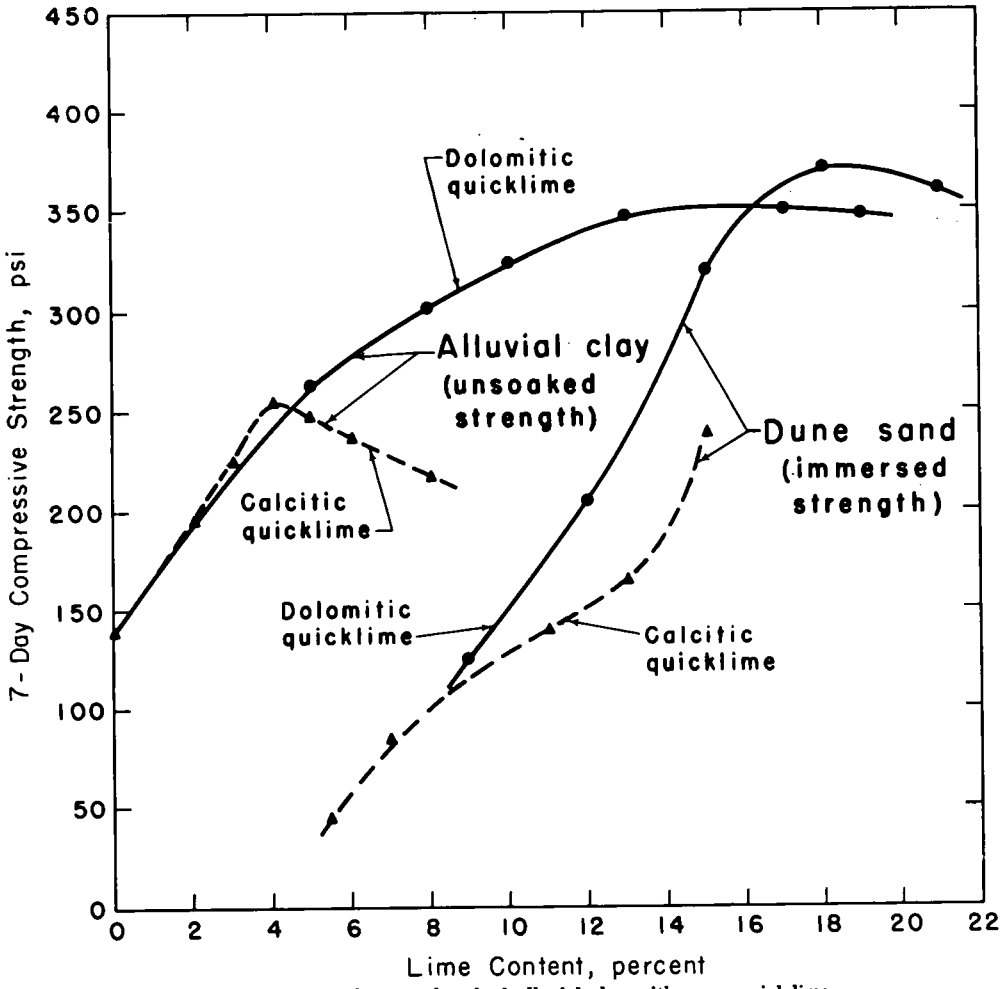

Figure 9. Strengths of dune sand and of alluvial clay with commercial lime.

freeze-thaw. The reference specimens were immersed in water one day prior to testing in order to duplicate the saturated condition of the weathered specimens. The result of weathering can be expressed as a durability ratio, or the ratio of strength after weathering to the strength of reference specimens the same age. A similar ratio was used by Maclean in freeze-thaw testing of soil-cement (*5*). A durability ratio of 1.0 indicates no adverse effect from weathering; a durability ratio of 0.0 denotes failure due to weathering.

Results from durability tests are shown in Table 5. Lime contents for these tests were selected on the basis of 7-day compressive strength curves (Figures 6, 7, and 8) and represent percentages which either gave maximum or near maximum 7-day strength. The only lime which gives an indication of satisfactory weathering resistance to both wet-dry and freeze-thaw is dolomitic quicklime, which also gave highest compressive strength. Dihydrate dolomitic lime added in the same percentages usually gave lower durability. From compressive strength curves it would be anticipated that the monohydrate would give a durability in between, and calcitic limes added in the same amounts would give low durability. Lesser amounts of calcitic lime did give low durability but in some instances there was satisfactory resistance to wet-dry (Table 5). Many soil-lime specimens gained strength through the cycles of wet-dry. Durability in general is increased by longer curing before the initiation of wet-dry or freeze-thaw cycles. Since freezing takes place with specimens resting on wet felt, the test is probably severe.

There also appears to be a relation between durability and kind of soil; the friable loess is most durable and the glacial till is least durable.

CBR OF SOIL-LIME

The California Bearing Ratio was determined for the same soil-lime mixtures studied for durability (Table 6). Highest CBR's were gained with dolomitic quicklime. The CBR's increased with increased curing time, as would be expected from compressive strength data. For a given soil the CBR is approximately proportional to the unconfined compressive strength. The same relationship is reported for soil-cement by Maclean (*5*). There is little correlation between CBR and durability ratio. Data indicate that a satisfactory CBR can be realized after 11 days or less and the numerical gain in CBR from 11 to 32 days is only of the order of 2 to 30.

TABLE 5
WET-DRY AND FREEZE-THAW DURABILITY RATIOS OF SOIL-LIME*

Soil	Lime		Moist Cure, days			Moist Cure, days		
			7	28	56	7	28	56
	Kind	%	+ 12 cycles wet-dry			+ 12 cycles freeze-thaw†		
Friable loess	Calc. hyd.	3	0.3	0.4	1.0	0	0	0
	Calc. quick.	1	0	0	0	0	0	0
	Dol. dihyd.	9	1.0	0.7	1.0	0	0	0
	Dol. quick.	9	0.6	0.9	1.0	0.4	0.7	0.8
Plastic loess	Calc. hyd.	3	0	0.7	1.0	0	0	0
	Calc. quick.	3	0.2	0.8	0.7	0	0	0
	Dol. dihyd.	9	0	0.3	0.3	0	0	0
	Dol. quick.	9	0.7	0.8	0.9	0.1	0.4	0.6
Glacial till	Calc. hyd.	2	0	0	0	0	0	0
	Calc. quick.	2	0	0	0	0	0	0.2
	Dol. dihyd.	4	0	0.1	0.2	0	0.1	0.2
	Dol. quick.	4	0.5	0.4	0.4	0.5	0.4	0.4

$$* \text{ Durability ratio} = \frac{\text{Strength after 12 weathering cycles}}{\text{Immersed strength after moist curing to same age}}$$

† Total age = moist cure time plus 24 days.

TABLE 6
CBR OF SOIL-LIME AFTER VARIOUS PERIODS OF CURING AND 4 DAYS SOAKING

Soil	Kind of Lime	Lime, %	Pre-Soak Curing Time, days		
			0	7	28
Friable loess	—	0	9	—	—
	Calc. hyd.	3	24	57	77
	Calc. quick.	1	26	85	88
	Dol. dihyd.	9	23	104	132
	Dol. quick.	9	29	205	215
Plastic loess	—	0	5	—	—
	Calc. hyd.	3	23	38	49
	Calc. quick.	3	38	46	61
	Dol. dihyd.	9	39	52	66
	Dol. quick.	9	49	84	115
Glacial till	—	0	3	—	—
	Calc. hyd.	2	20	62	64
	Calc. quick.	2	46	105	115
	Dol. dihyd.	4	25	92	107
	Dol. quick.	4	48	120	178

CONCLUSION

In conclusion it can be stated that lime cementation of soil at ordinary temperatures is best when the lime is a dolomitic monohydrate, consisting of molar equal parts of $Ca(OH)_2$ and MgO. Except at very low lime contents any large departure from this composition resulted in lower strength and durability. Occurence of magnesium as the hydroxide, $Mg(OH)_2$, greatly reduces its effectiveness, and from strength data and comparisons with quicklimes the commercial monohydrate used may have endured partial hydration of its MgO.

With commercial limes the highest strengths were realized when dolomitic quicklime was added and allowed to hydrate with the soil, and strengths were approximately those previously reached with monohydrate lime made up from pure chemicals. The commercial hydration process may have a very significant bearing on the effectiveness of dolomitic lime; dissipation of heat during hydration might prevent partial conversion of MgO to $Mg(OH)_2$.

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REFERENCES

1. LAGUROS, J. G., DAVIDSON, D. T., HANDY, R. L., AND CHU, T. Y., "Evaluation of lime for stabilization of loess." Presented at the 59th Annual Meeting of ASTM, June, 1956.
2. National Bureau of Standards, "Investigation of failures of white-coat plaster." Building Materials and Structures Report 121. 1951.
3. American Society for Testing Materials, "Procedures for testing soils." Philadelphia, The Society. 1950. p. 386.
4. DAVIDSON, D. T., AND HANDY, R. L. Closure to special discussion by L. John Minnick on "Soil stabilization with lime-fly ash admixtures." Bulletin 129: 100-102. Highway Research Board. 1956.
5. MACLEAN, D. J., "Considerations affecting the design and construction of stabilized-soil road bases." Journal of the Institution of Highway Engineers, Vol. 3, No. 9:16-33.