Effect of Density on Strength of Lime-Flyash Stabilized Soil

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The strength of an artificially cemented soil mass, such as soil-cement or soil-lime-flyash, is theoretically highly dependent on the intimacy of grain-to-grain contact. The controlling factor here should be degree of compaction. With this in mind, various soil-lime-flyash mixes were compacted at four different controlled densities and the specimens were moist cured at normal temperature and tested. Three soils were used: an Iowa silt (loess), a Kansas dune sand, and a Texas coastal plain clay. The lime was calcitic (high calcium) hydrated lime. Mixes were prepared with 25 percent lime-flyash and with different ratios of lime to flyash. Specimens were soaked in water and tested after 7 and 28 days.

Evaluation of the compressive strength data shows that density is indeed a highly important variable. Compaction to above standard Proctor density increased 7-day strengths on the average 100 percent and 28 day strengths, 70 percent. A higher compaction to modified Proctor density raised the average increases to 120 and 110 percent. Compaction to a super-modified Proctor increased the averages to 150 and 130 percent over strengths previously realized at standard Proctor density. It is concluded that density is not only important but that it may also be an economical consideration in design. The silt also showed influence from overcompaction, but the influence vanished on 28-day curing. The clay gave the best response to increased compaction, and strengths with modified Proctor density were approximately three times those obtained at standard Proctor. With modified density all soils showed 28-day strengths of the order of 600 to 1,000 psi with ordinary room temperature moist curing.

Attendant with this investigation was an evaluation of an optimum lime-flyash ratio. With most soils the ratio was not critical, but highest strengths were realized with a lime-flyash ratio of 1:9 or 2:8. A ratio of 1:9 was nearly a universal optimum for all three soils regardless of compactive effort.

● OBJECTIVES of this research were to study the effect of degree of compaction on the strength of lime-flyash-soil mixtures. Four compactive efforts were chosen: one to give densities equivalent to standard Proctor, one to give densities between standard and modified Proctor, one to duplicate modified Proctor, and one to give densities greater than modified Proctor (Table 1). A second objective was to determine the effect of a variable compactive effort on the selection of an optimum line-flyash ratio.

MATERIALS

Soils

Three soils were selected for this study: a sand, a silt and a clay. The sand is from a stable dune area associated with the Arkansas River in south central Kansas. The silt is a friable, calcareous loess from the deep loess area in western Iowa. The clay is a deltaic deposit from the coastal plain region in Texas; it was sampled a few miles south of Houston. Field information on the three soil samples is in Table 2, and laboratory data are given in Table 3. ASTM procedures were followed for laboratory testing except where otherwise noted.

Lime and Flyash

The hydrated lime is a calcitic lime from the Linwood Stone Products Co., Buffalo, Iowa. A laboratory analysis furnished by the manufacturer is given in Table 4. The flyash is a fine ash with low loss on ignition; it is from Paddy's Run Station, Louisville Gas and Electric Co., Louisville, Kentucky. Data by the Robert W. Hunt Co., Chicago, are given in Table 4.

METHODOLOGY

Correlation Study

Because of the advantage of small specimen size for rapid molding and testing, the 2-in. diameter by 2-in. high size was used in this study. The 2-in. height gives the advantage of molding in one layer, the compactive effort being applied at both

TABLE 1

DESIGNATIONS OF COMPACTIVE EFFORT

Compaction	Density Obtained
A	Standard Proctor density
B	Between standard and modified
C	Modified Proctor density
D	Above modified

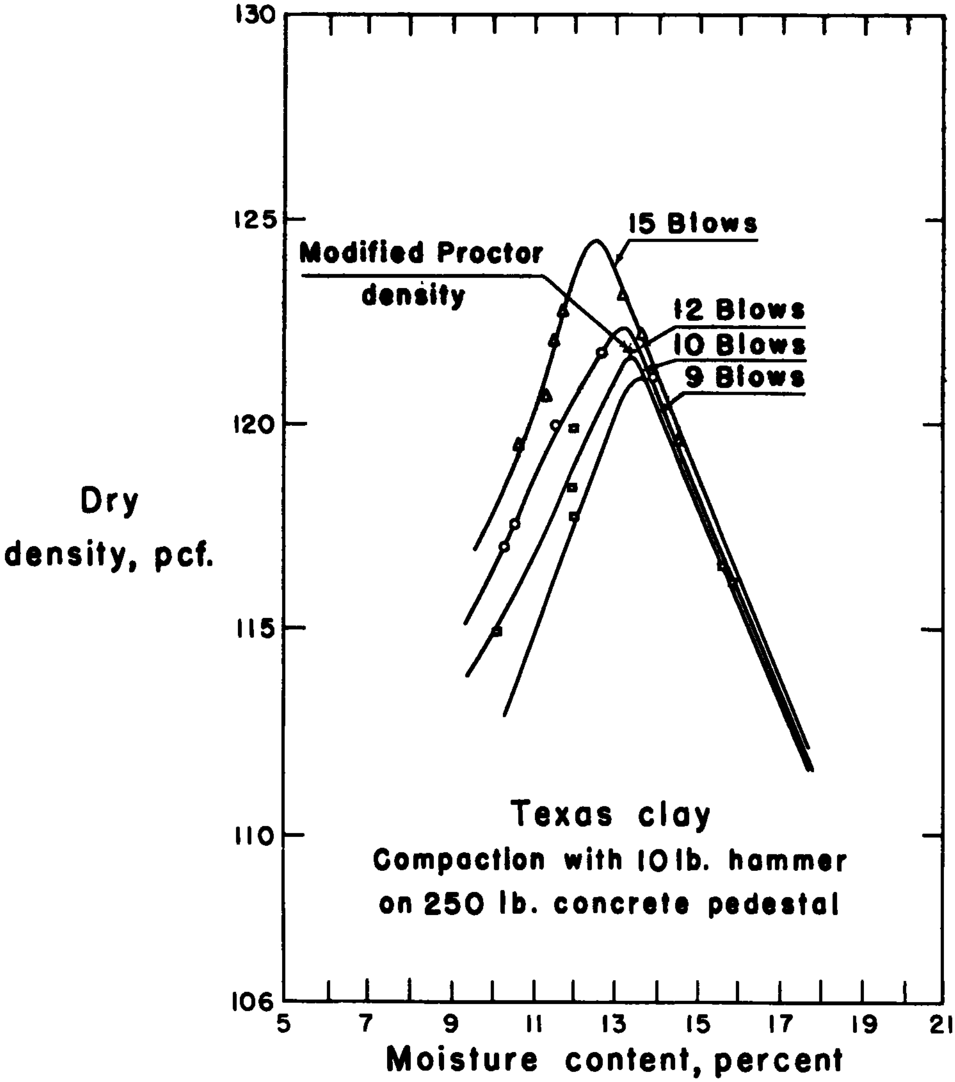

Figure 1. Typical moisture-density relationships from 2-in. x 2-in. specimens. Ten blows with a 10-lb drop hammer give a maximum density and optimum moisture content close to modified Proctor.

TABLE 2

FIELD INFORMATION ON SOIL SAMPLES

Sample:	Kansas Sand	Iowa Silt	Texas Clay
Geological origin:	Recent dune sand from the Great Bend tract	Wisconsin age loess from near Missouri River	Deltaic (Beaumont fm.) clay from coastal plain
Soil Series:	Pratt	Hamburg	Lake Charles
Horizon:	C	C	C
Location:	28 mi S of Great Bend	In the town of Missouri Valley	South of Houston
Sampling depth, ft:	1½ - 3½	49-50	3¼ - 12 (Composite)

TABLE 3

PROPERTIES OF SOIL SAMPLES

Sample:	Kansas Sand	Iowa Silt	Texas Clay
Textural composition, %[a]			
Gravel (> 2 mm)	0	0	0
Sand (2-0.074 mm)	86.4	0.7	7.7
Silt (74-5 μ)	4.0	78.3	48.2
Clay (< 5 μ)	9.6	21.0	44.1
Colloids (< 1 μ)	8.6	15.8	36.8
Predominant clay mineral[b]	Montmorillonite	Ca montmorillonite	Ca montmorillonite
Specific gravity 25C/4C	2.67	2.68	2.67
Chemical properties:			
Cat. ex.cap., m.e./100 gm[c]	7.3	13.4	25.5
Carbonates, %[d]	0	10.5	0
pH	5.6	7.8	5.9
Organic matter, %[c]	0.4	0.2	0.6
Physical properties:			
Liquid limit, %	-	32	57
Plastic limit, %	-	25	20
Plasticity index	NP	7	37
Shrinkage limit, %	18	25	14
Centrifuge Moist. Equiv., %	5	15	21
Field Moist. Equiv., %	21	26	21
Classification:			
Textural	Sand	Silty clay loam	Clay
Engineering (AASHO)	A-2-4(0)	A-4(8)	A-7-6(20)

[a] Dispersed by air-jet with sodium metaphosphate dispersing agent.

[b] From differential thermal analysis of fraction passing No. 200 sieve.

[c] Fraction passing No. 40 sieve.

[d] From differential thermal analysis.

ends. Specimens were molded with a drop hammer molding apparatus, and extensive correlation work was done to determine the proper hammer weights and numbers of blows for standard and modified Proctor densities. Figure 1 gives a typical set of curves for one soil and one hammer weight. In this case modified Proctor density was approximated by 10 blows on each end of the 2-in. by 2-in. specimen. The closeness

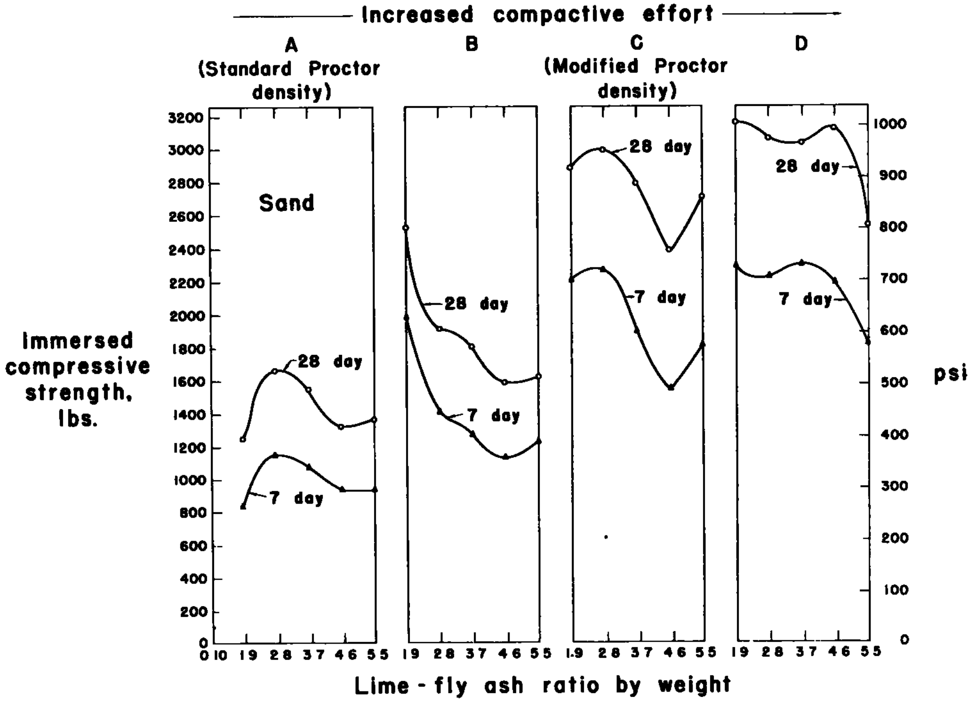

Figure 2. Effect of compactive effort on strength of Kansas sand stabilized with 25 percent lime-flyash in varying ratios.

TABLE 4

PROPERTIES OF LIME AND FLYASH

Material	Linwood Hydrated Lime	Louisville Flyash
Specific gravity	2.29	2.67
Fineness		
Passing No. 325 sieve, Percent	99.00	94.30
Specific surface, sq. cm./gm.		3,470
Chemical analysis, Percent		
Total $Ca(OH)_2$	97.82	
Available $Ca(OH)_2$	97.38	
MgO	0.49	0.52
$CaCO_3$	0.77	8.36
Fe and Al oxides	0.82	Not determined
SiO_2	0.80	38.90
Al_2O_3		22.92
SO_3		2.0
Free water		0.17
Loss on ignition	24.56	2.10

to which modified Proctor density can be duplicated with different soils is illustrated in Table 5. These results were obtained with 20 blows (10 on each end) with a 10-lb hammer dropping a distance of 1 ft, the molding apparatus being mounted on a concrete pedestal. Other compactive efforts used are B (Table 1) obtained by 10 blows with the same arrangement and D obtained with 30 blows. Standard Proctor density (density A) was duplicated by 10 blows from a 5-lb hammer falling 1 ft, the apparatus resting on a wooden bench.

Constants and Variables

To reduce the number of variables, a constant percentage of lime-flyash was used in all tests, the lime plus flyash making up 25 percent of the dry weight of the mixtures. Previous work has shown that 25 percent is both a satisfactory and an economical content (1).

Compaction is the major variable, as previously discussed. The moisture contents were adjusted to the optimums for each mixture and for each compactive effort. The optimum moisture contents of mixtures with different ratios of lime to flyash were read from a triangular chart in which optimum moisture contents of soil, of 75/25 soil-flyash, and of 75/25 soil-lime are plotted at corners of the triangle and intermediate values are found by interpolation (1, p. 81).

TABLE 5

COMPARISON OF MODIFIED PROCTOR DENSITIES

Sample:	Kansas sand	Iowa silt	Texas clay
ASTM test:			
Maximum dry density, pcf	128.1	121.8	118.8
Optimum moisture content, percent	9.2	13.2	13.8
2-in. x 2-in. test:			
Maximum dry density, pcf	128.9	122.0	118.9
Optimum moisture content, percent	9.3	13.3	13.7

The second major variable is ratio of lime to flyash. Testing was continued at each of the four compactive efforts to show any change in optimum ratio. The previously found optimums with these soils has been between 1:9 and 2:8 by weight of lime to flyash. In the present study specimens were molded with ratios 0:10, 1:9, 2:8, 3:7, 4:6, and 5:5.

A third variable was age. Strengths were measured after 7 and after 28 days moist curing.

Curing and Testing

Curing was done at 70 ± 3 F and with a relative humidity near 90 percent. Specimens were not wrapped, as is sometimes done to exclude carbon dioxide from the air. After curing the specified time, specimens were immersed in distilled water at 70 F for 24 hours, then removed and tested for unconfined compressive strength. The rate of strain was 0.05 in. per min per in. of specimen height. Results are expressed in pounds; if the height-diameter ratio is neglected results can be converted to pounds per square inch by dividing by 3.14.

Other measurements include absorption and volume change during curing and immersion.

RESULTS

Results are plotted in Figures 2, 3, and 4. In most cases curves are displaced upward by increased compactive effort, and 7-day strengths were on the average about 100 percent higher with compactive effort B than at standard Proctor density A. Compaction to modified Proctor density raised this to 120 percent, and compaction to beyond

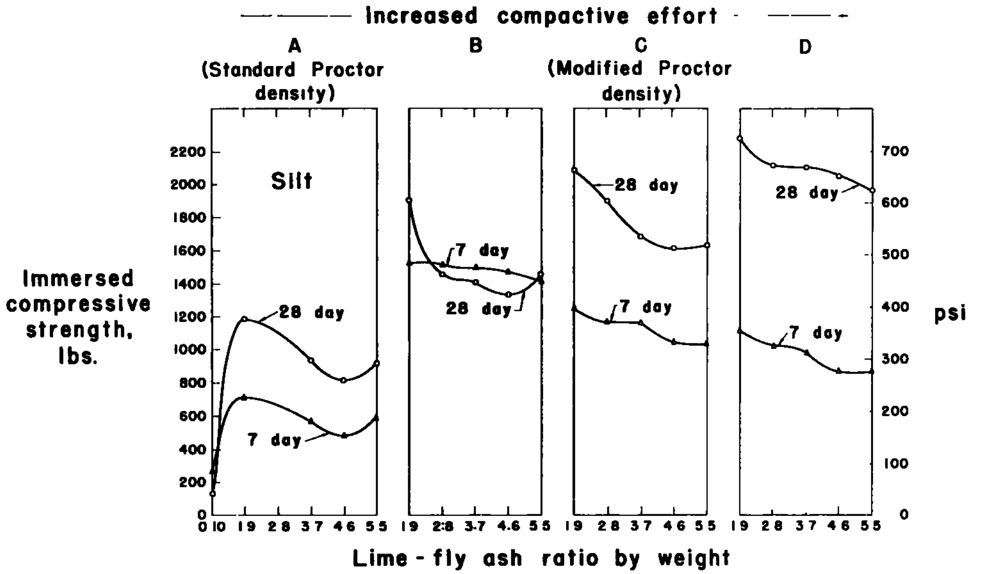

Figure 3. Effect of compactive effort on strength of Iowa silt (loess) stabilized with 25 percent lime-flyash in varying ratios.

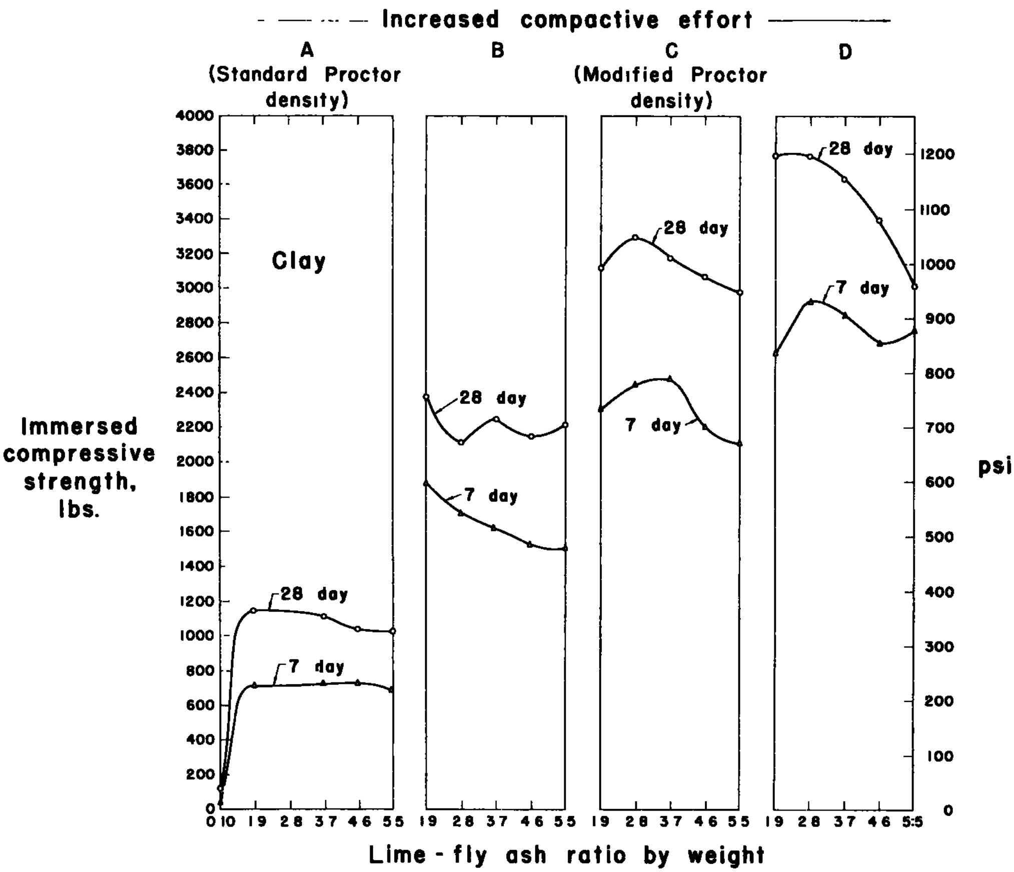

Figure 4. Effect of compactive effort on strength of Texas clay stabilized with 25 percent lime-flyash in varying ratios.

modified Proctor gave on the average a 150 percent increase in 7-day strength. Twenty-eight-day strengths reflect the same trends.

Density and Percent Solids

Density is of course dependent on compactive effort, but density also depends on lime-flyash ratio. Density is decreased by higher contents of lime because of two factors: the lime itself is less dense than soil or flyash, and lime causes aggregation of clay. The first factor is calculable and can be corrected by converting measured densities to percent solids by volume. This has been done in Figures 5, 6, and 7. In these

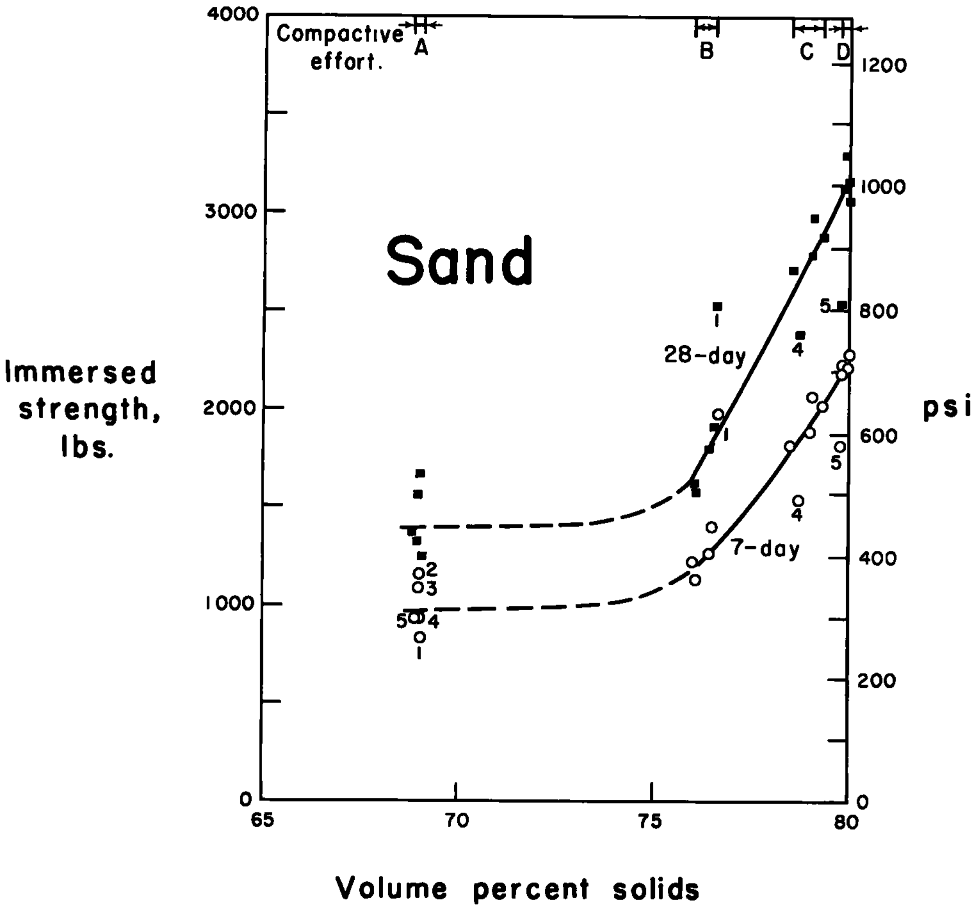

Figure 5. Relation of strength to percent solids in lime-flyash stabilized Kansas sand.

figures compressive strength has been plotted against percent solids, irrespective of the lime-flyash ratio. The fact that in most cases smooth curves are obtained indicates that the lime-flyash ratio is not critical.

In the Texas clay (Fig. 7) the influence of clay aggregation on density is found to be a maximum. As an example, points labeled 1, 2, 3, 4, 5 under compactive effort A are with lime-flyash ratios of 1:10, 2:8, 3:7, 4:6 and 5:5. A higher lime content decreases the volume percent solids. With higher compactive efforts the same trend is found, but the range in percent solids shown at the top of the graph is less for B, C and D, indicating that higher effort may break down the clay aggregates and better their compaction. This tendency is particularly pronounced with the silt (Fig. 6), in which with effort A there is a wide range in percent solids depending on the lime content. The range is progressively smaller with efforts B, C and D. It is believed that the silty soil aggregates may have less strength than those formed in the clay soil and are thus easier to break down.

The sand (Fig. 5) offers a direct contrast to this. With low compactive effort addition of more lime has practically no effect on the percent solids, as shown by the narrow horizontal range in points under A. With higher compactive efforts the range is greater, as in B and C, but the range is greatly reduced, with D the highest compactive effort. Although the reason for this is not known, it is suspected that lower lime and higher flyash contents improve the gradation of the sand for compaction.

Unconfined Compressive Strength for Evaluation of Stabilized Soils

Unconfined compressive strength is primarily influenced by cementation and does not give a true measure of the frictional strength developed in a confined state. There-

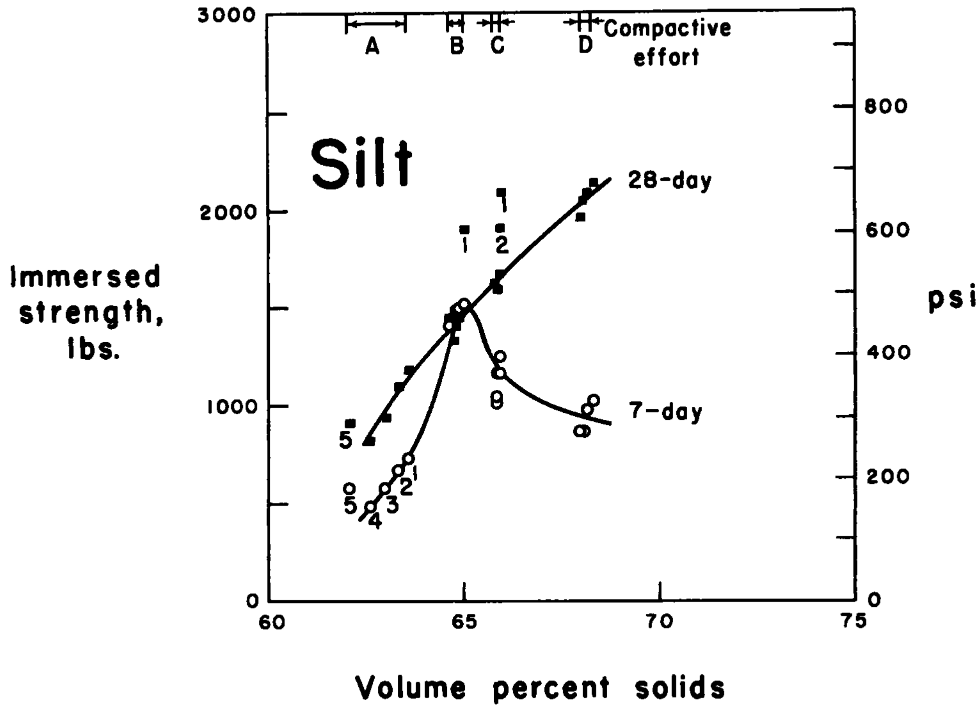

Figure 6. Relation of strength to percent solids in lime-flyash stabilized Iowa silt.

fore, a stabilized granular material with relatively low unconfined compressive strength may show satisfactory stability. It is known that for a given stabilized soil the CBR values are directly proportional to unconfined compressive strength (2), and it has been found that for example a lime-flyash stabilized sand with an unconfined compressive strength of 138 psi has a CBR of 213, while a stabilized clay must have an unconfined compressive strength of 705 psi to develop the same CBR (3).

Strength vs Percent Solids

Figures 5, 6 and 7 show the relationships between strength and percent solids. Points have been plotted without regard to lime-flyash ratio, and the striking feature is that most of the points fall on or very close to the curves. The exceptions are numbered to indicate their ratios, which are either very low (1:10 or 2:8) or very high (5:5).

Curves for the different soils show a similarity in that strength is approximately proportional to percent solids, and the proportionality factor indicated by the slope of the curve is much the same. An exception is noted in the case of sand, where the strength gain between efforts A and B is not nearly in accord with the increase in percent solids. Apparently cementation of the sand is not greatly improved until compaction reaches above a critical percent solids, in this case about 75 percent. For some reason a critical degree of packing is necessary before grain contact and cementation are improved.

Overcompaction and Tendency to Heal

In one curve (Fig. 6), strength loss from overcompaction is evident. This is the 7-day strength curve for the silt. The same trend can be seen in Figure 3, where the 7-day curves in B, C and D are progressively lower even though density is increased and absorption and volume change are reduced by the greater compaction. It is believed, therefore, that strength loss may be due to shearing displacements in the specimen causing intrinsic planes of weakness.

Particularly significant is that at 28 days the strength curve follows a normal pattern, and the shear planes, if they existed, have apparently healed. Such a tendency for healing of overcompaction failure planes could be of considerable importance in field construction. Presumably continued intimate contact would be necessary for failure plane healing.

Optimum Lime-Flyash Ratio

Previous work has shown that for highest strength with standard Proctor compaction the optimum lime-flyash ratio (1) is usually in the range 1:9 to 2:8.[1] In the present study,

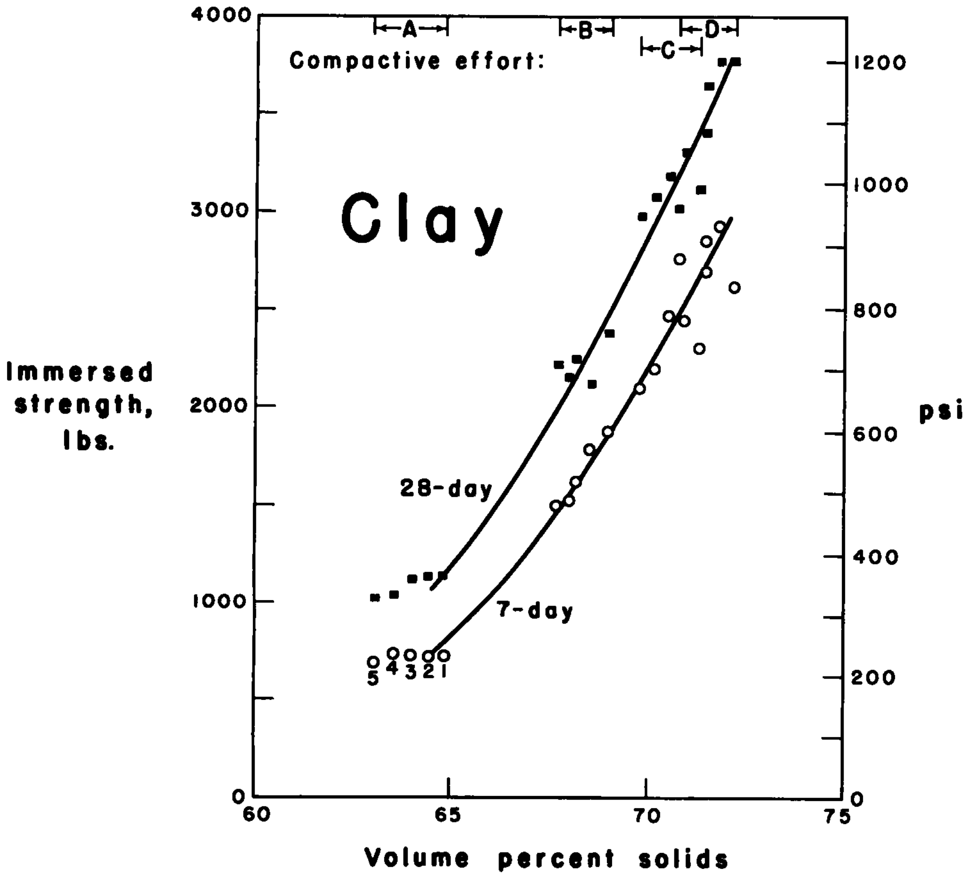

Figure 7. Relation of strength to percent solids in lime-flyash stabilized Texas clay.

increased compaction does not greatly or consistently change the optimum ratio (Fig. 2, 3 and 4). From an economic standpoint a low ratio is desirable, since the cost of

[1]An exception was noted for an halloysitic clay, which requires more lime.

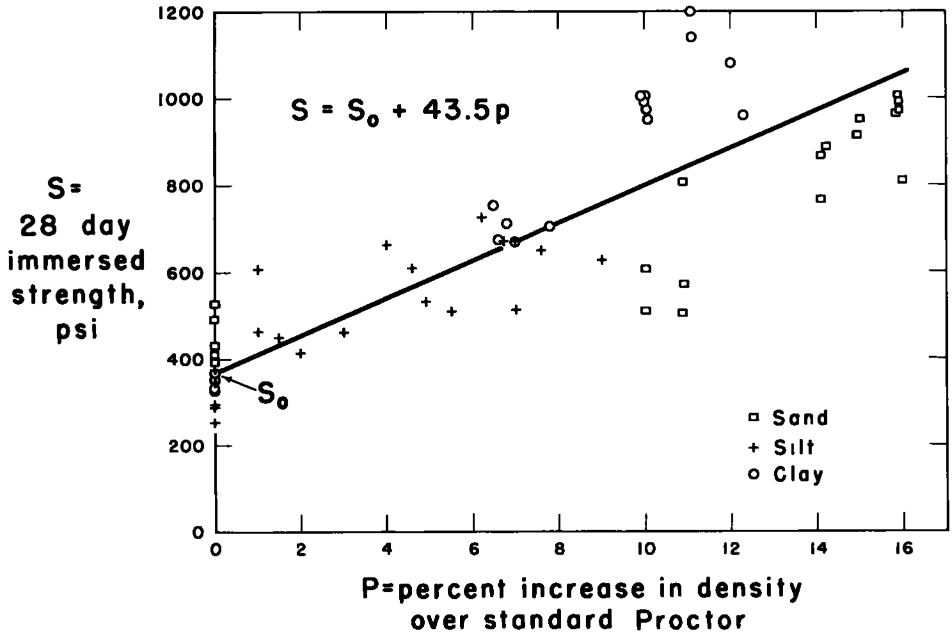

Figure 8. Average effect of increase in density on compressive strengths of a sand, a silt, and a clay.

flyash is usually a fraction of the cost of lime. A limit is imposed by difficulties in mixing and securing uniform distribution of very small percentages of lime. Experience has shown that ratios of 1:9 and 2:8 can be successfully handled in construction with a wide variety of soil textural types.

SUMMARY

A summary of the relation between compaction and compressive strength is illustrated in Figure 8. The curve represents an average for all three soils; the scatter of points is greater than in Figures 5, 6 and 7 because of disregard of other variables such as soil type and the dependence of density on percent lime. The average increase in compressive strength is 43.5 p, where p is the percent increase in density over standard Proctor. That is, $S = So + 43.5\,p$, where So is the strength in psi at standard Proctor density. On the average a 10 percent increase in density will about double the unconfined compressive strength. This density is approximately equivalent to modified Proctor for the sand and the clay; because of poor gradation it is not readily obtainable with the silt.

CONCLUSIONS

1. Strengths of lime-flyash stabilized soil after 7 and 28 days are greatly increased by increased density and compaction, but the optimum lime-flyash ratio is little influenced. The optimum ratio for these soils remained 1:9 or 2:8.

2. Increasing the additions of lime to the clay and silt soils results in a decreasing percent solids with the same compactive effort, probably because of clay aggregation by lime. The resulting decrease in strength is approximately proportional to the decreasing percent solids. This relationship was not found in the case of the sand.

3. Lowered strengths of stabilized silt due to overcompaction were evident after 7-days curing, but at 28 days the influence had vanished. It is concluded that overcompaction shear planes in lime-flyash-soil tend to heal on long curing.

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