Moisture-Density, Moisture-Strength and Compaction Characteristics of Cement-Treated Soil Mixtures

DONALD T. DAVIDSON, GEORGE L. PITRE, MANUEL MATEOS, and KALANKAMARY P. GEORGE, Respectively, Professor of Civil Engineering, Iowa State University; 1st Lieutenant, Corps of Engineers, U.S. Army; and Research Associate and Graduate Assistant, Iowa State University

A laboratory investigation was conducted to find relationships between strength and density for cement-treated soil mixtures compacted at different moisture contents. A dune sand and three clays were used to prepare sand-clay mixtures having different amounts and dominant kinds of clay minerals. Test specimens of each cement-treated mixture were molded to near standard and modified Proctor density, moist cured 7 or 28 days, and then immersed in water for 24 hour before being tested for unconfined compressive strength.

Test results show that the optimum moisture content for maximum density and the optimum moisture content for maximum unconfined compressive strength of cement-treated sand-clay mixtures are not necessarily the same. The moisture contents for maximum strengths are to the dry side for sand-clay mixtures dominant in sand, and to the wet side for sand-clay mixtures dominant in clay. As clay content increases, the optimum moixture content for both maximum density and maximum strength values decrease. Also presented are the increase in density and in strength for the different soils when the compaction effort is increased from standard to modified. The influence of different kinds of clay minerals on the relationships studied does not appear to be significant.

• THE COMPACTING MOISTURE CONTENT recommended in soil stabilization with cement is the one that gives a maximum density. A standard method used to find the optimum moisture content of soil-cement mixtures is that given in ASTM Designation D 558-57 and also in AASHO Designation T 134-57.

The optimum moisture for maximum density has sometimes been found not to be the same as the optimum moisture for maximum strength. For instance, Felt (1) reported that compressive strength increases to a maximum at slightly less than optimum moisture for maximum density for a sandy soil and a silty soil, and at greater than optimum for a clay soil.

This investigation was conducted to find, primarily, the relation between the moisture-density and the moisture-strength relationships in several basic soils or their mixtures. A sand and three clay soils (a kaolinitic, an illitic, and a montmorillonitic), alone or in sand and clay combinations were treated with different amounts of cement.

The soil-cement mixtures were compacted with the standard AASHO compaction and a few selected mixtures also with the modified AASHO compaction.

MATERIALS

Four soil samples were used: a dune sand, two commercially produced clays, and a highly plastic clay soil. The dune sand is clean, uniformly graded, and found in the Iowa drift plain in east central Iowa. The kaolinite clay, a naturally occurring Kaolin clay, is hydraulically mined and water processed from a deposit located in north central Florida by the Edgar Plastic Kaolin Company of Edgar, Fla. The illite clay, very rich in illite, is produced by the Illinois Clay Products Company of Chicago, Ill. The montmorillonite clay is Kansan gumbotil; in Iowa this gumbotil is believed to be a highly weathered fossil B horizon developed on Kansan glacial till. The physical and chemical properties of these soils are given in Table 1.

TABLE 1

CHARACTERISTICS OF SOILS USED

Property	Dune Sand	Kaolinite Clay	Illite Clay	Montmorillonite Clay
Lab Desig.	S-6-2	Kaolin	AR-9	528-8
Sampling location	Benton Co., Iowa	North central Fla.	Goose Lake region, Ill.	Keokuk Co., Iowa
Horizon	C	Probably C	Probably C	Fossil B
Sampling depth (in.)	18-132	Unknown	Unknown	78-102
Mechanical analysis (%):				
Sand (2-0.074 mm)	94.4	0.0	6.4	17.5
Silt (74-5µ)	1.6	18.0	18.6	8.5
Clay (<5µ)	4.0	82.0	75.0	74.0
Clay (<2µ)	3.8	60.0	59.3	71.0
Physical:				
Liquid limit (%)	19.0	51.0	54.8	87.1
Plastic limit (%)	NP	29.0	27.1	34.5
Plasticity index	NP	22.0	27.7	52.6
Std. Proctor density (pcf)	110.0	93.0	100.0	95.0
Opt. moist. content (%)	12.3	27.0	22.0	28.0
Spec. gravity	2.64	2.66	ND	ND
Chemical:				
CEC (No. 10 sieve) (meq/100 g)	-	ND	19.1	ND
CEC (No. 40 sieve) (meq/100 g)	-	ND	ND	45.3
pH	6.50	5.5	5.5	6.5
Carbonates (%)	0.02	ND	1.9	0.8
Organic matter (%)	0.04	ND	1.5	0.2
Predom. clay mineral	Montmorillonite and illite interlayer	Kaolinite	Illite	Montmorillonite
Classification				
Textural	Sand	Clay	Clay	Clay
AASHO	A-3(0)	A-7-6(16)	A-7-6(18)	A-7-5(20)
Unified	SP-SM	CH	CH	CH

Type I normal portland cement, obtained from the Penn-Dixie Cement Corporation of Des Moines, Iowa, was used in this investigation. This type of cement was selected because it is commonly used in soil-cement construction. The water used in all mixtures and tests was distilled water.

LABORATORY PROCEDURES

Proportioning of Mixtures

To compare the relative effects of various sand to clay ratios and the three kinds of clay minerals on optimum moisture contents, maximum density, and maximum 7- and 28-day strengths, the dune sand was used in the preparation of the sand-clay mixtures given in Table 2 with each of the clays.

These mixtures were molded at the standard AASHO compaction and those of 100 percent sand or clay and 75 percent sand plus 25 percent clay were also molded with the modified AASHO compaction.

The cement contents selected for study with each different combination of sand and clay were 8, 12, and 16 percent, dry weight of soil basis; some of the mixtures made with montmorillonitic clay were also treated with 20 percent cement. These cement contents bracketed the minimum cement requirements for soil-cement for each mixture. Each mixture was prepared at four or five different moisture contents, varying from dry to very wet.

Preparation of Mixtures

Predetermined amounts of air dry sand and clay passing the No. 10 sieve were weighed and dry mixed by hand (trowel); this step was not necessary in 0 percent sand or 0 percent clay batches. Next, the desired amount of cement was added to the soil and dry mixed by hand. Then the desired amount of distilled water was added and wet mixing was done in a modified Hobart kitchen mixer, Model C-100 at low speed for 1.5 min (4). Finally the mixing bowl was scrapped and the mixture hand mixed for about 30 sec to break up any clods that might have formed.

Molding and Testing of Specimens

Test specimens 2 in. in diameter by 2 in. in height were molded in the Iowa State compaction apparatus (2, 4, 5). The procedures that produce compactive efforts comparable to standard or modified AASHO tests are given elsewhere (2, 5).

Nine specimens were molded from each mixture; the first three were tested for unconfined compressive strength after 7 days curing, the second three specimens after 7 days curing plus 1 day immersion in distilled water, and the last three after 28 days curing. After each specimen was molded, it was wrapped in wax paper to reduce loss of moisture and placed in a humidity room for curing. The relative humidity and temperature maintained were 95 ± 5 percent and 71 ± 4 F.

The unconfined compressive strength test was made at a constant rate of loading of 0.1 in. per min. The strength and density values reported are averages of three test specimens.

RESULTS

Moisture-Density-Strength Relationships

The data obtained are presented in Figures 1 through 13. For a given mixture the same moisture content does not necessarily give both maximum density and maximum strength. The moisture contents for maximum strength are generally on the dry side for the sand-clay mixtures dominant in sand, and on the wet side for mixtures dominant in clay (Table 3).

TABLE 2

SAND-CLAY MIXTURE PROPORTIONS

Sand (% by wt)	Clay (% by wt.)
100	0
75	25
50	50
25	75
0	100

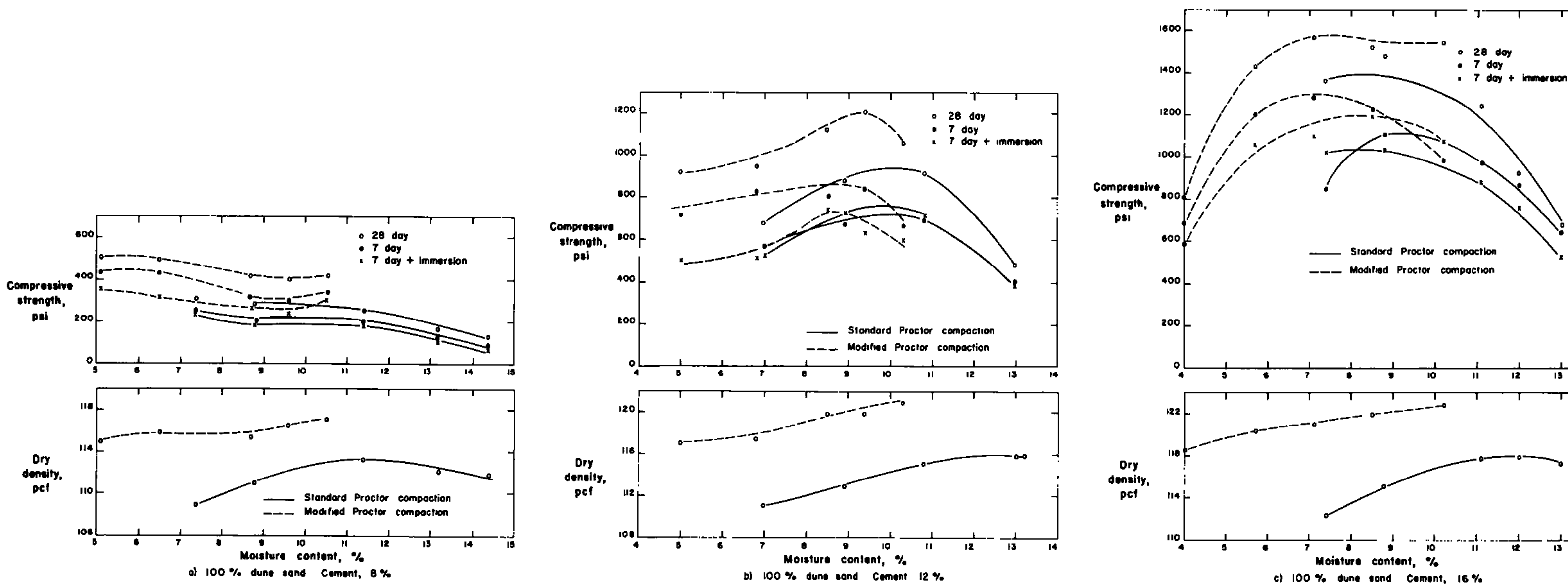
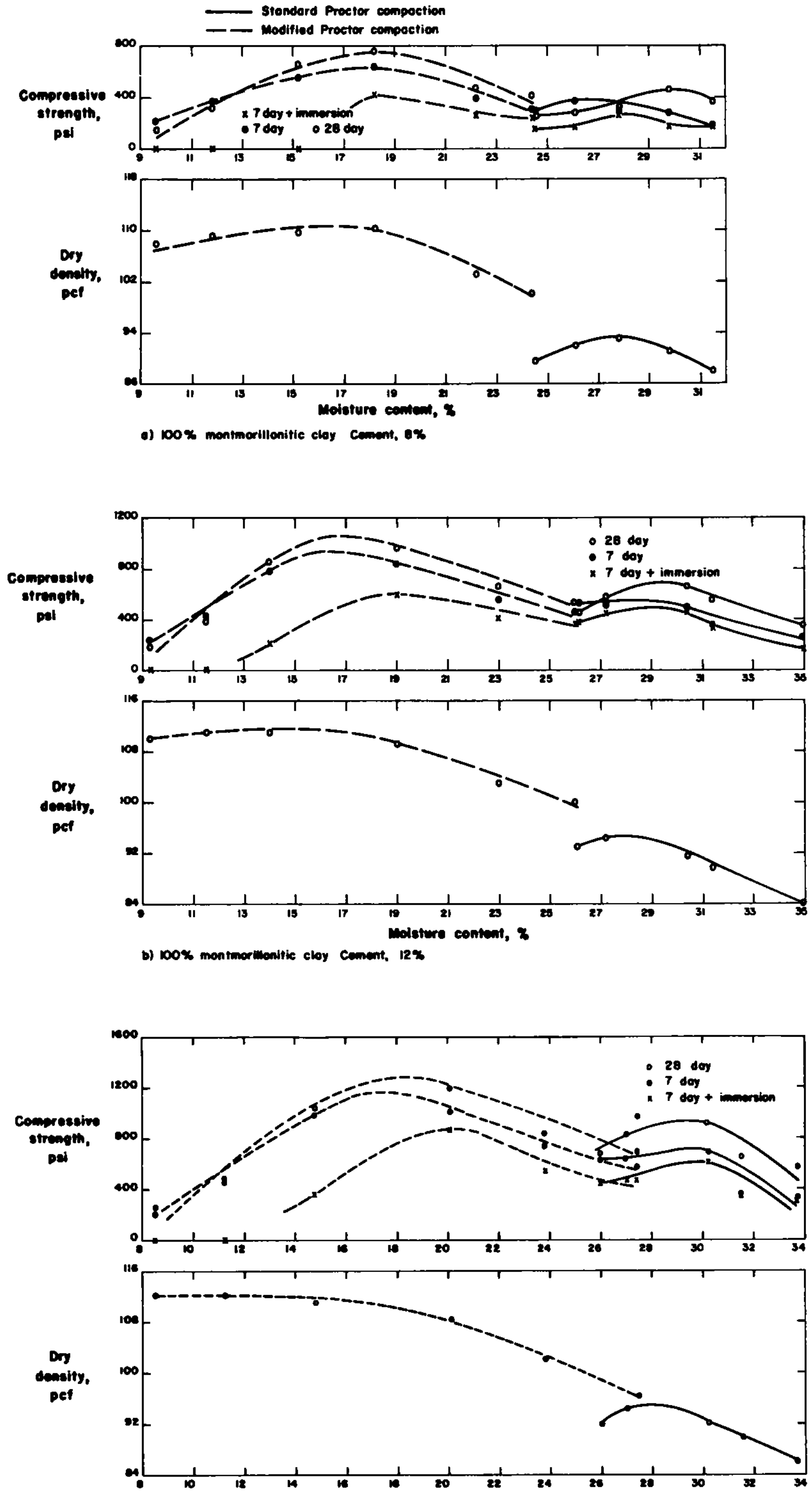

Compressive strength, psi
Dry density, pcf
28 day
7 day
7 day + immersion
Standard Proctor compaction
Modified Proctor compaction
Moisture content, %
a) 100 % dune sand Cement, 8 %
b) 100 % dune sand Cement 12 %
c) 100 % dune sand Cement, 16 %

Figure 1.

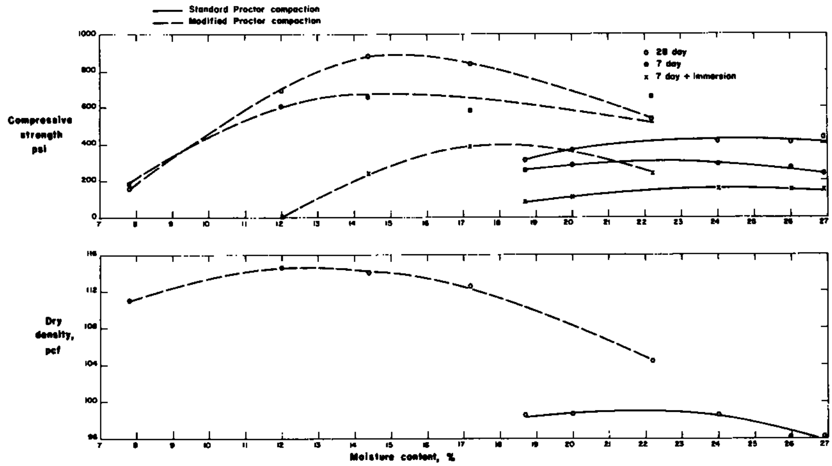


a) 100% montmorillonitic clay Cement, 8%

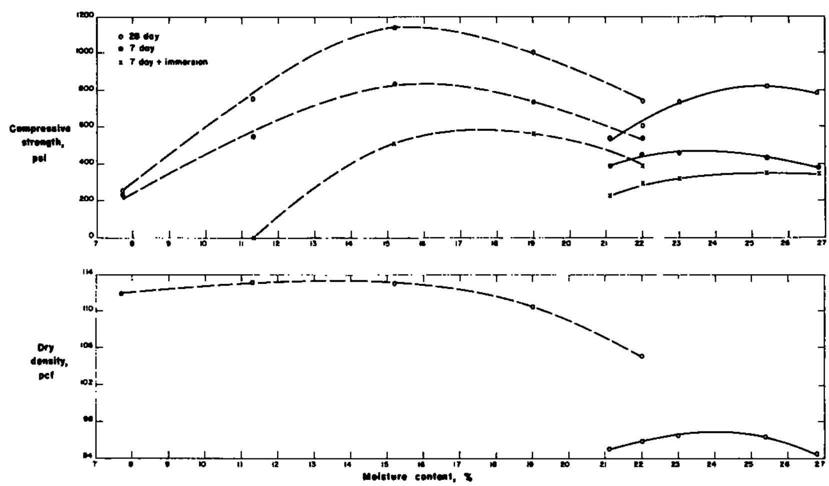
b) 100% montmorillonitic clay Cement, 12%

c) 100% montmorillonitic clay Cement, 16%

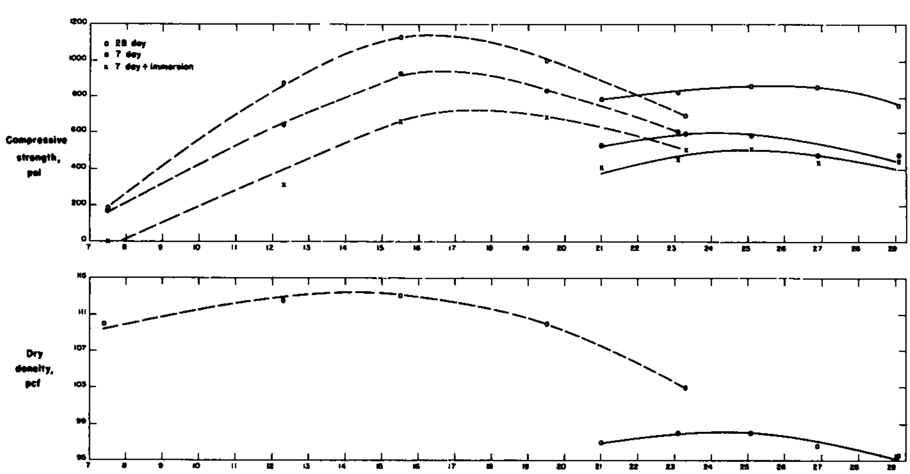
Figure 2.



a) 100% Illitic clay Cement 8%

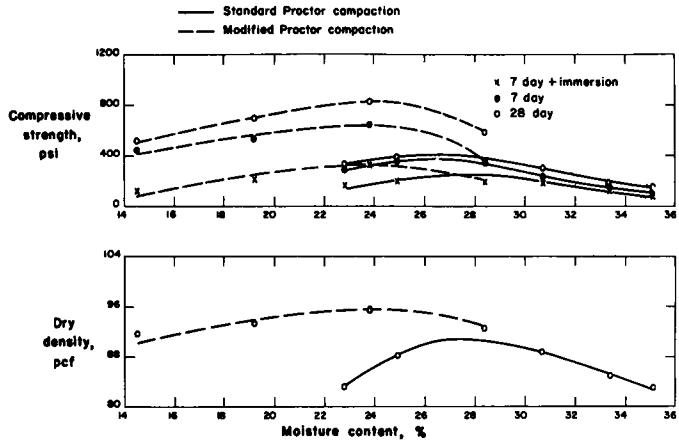


b) 100% Illitic clay Cement 12%

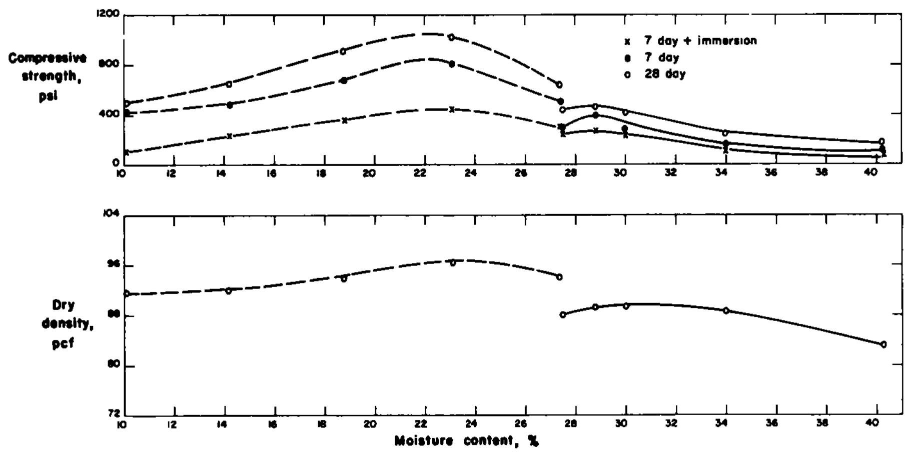


c) 100% Illitic clay Cement, 16%

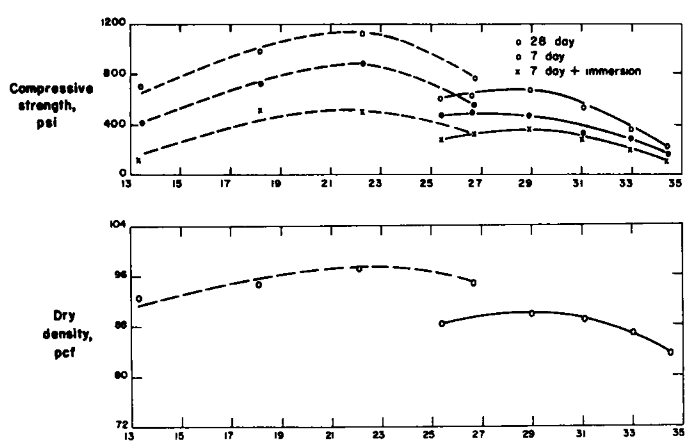
Figure 3.



a) 100% kaolinitic clay Cement, 8%

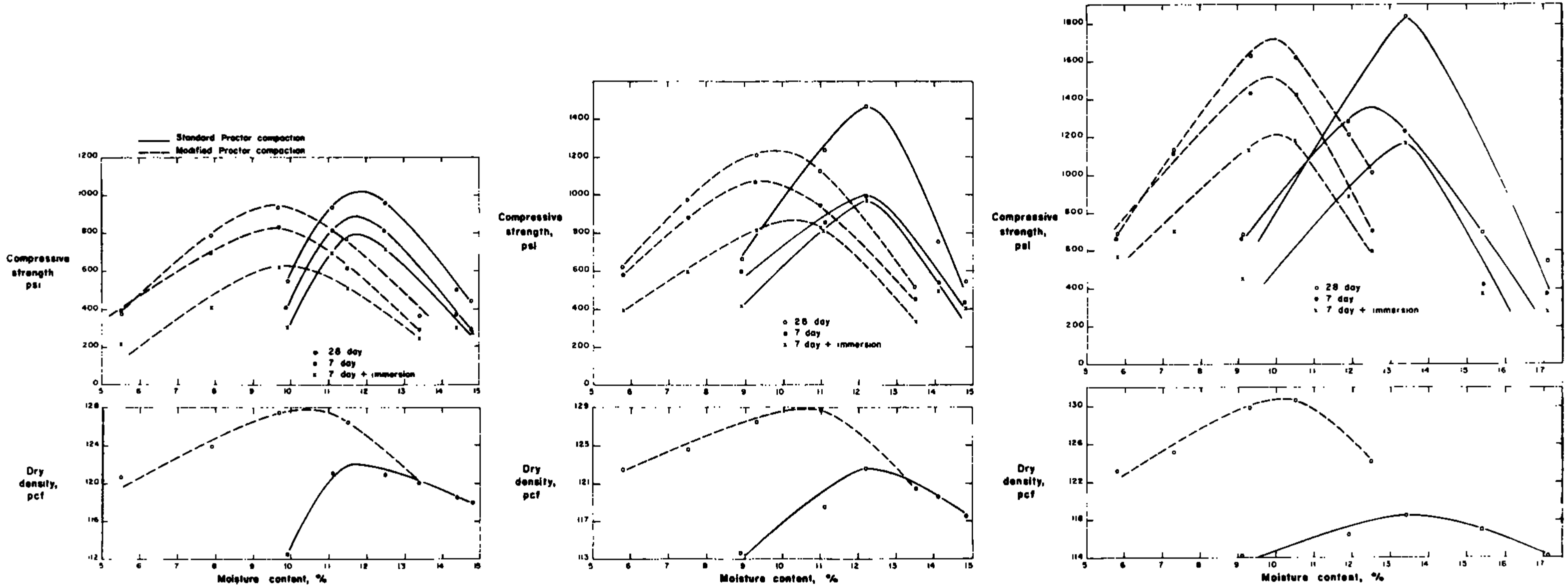


b) 100% kaolinitic clay Cement, 12%



c) 100% kaolinitic clay Cement, 16%

Figure 4.

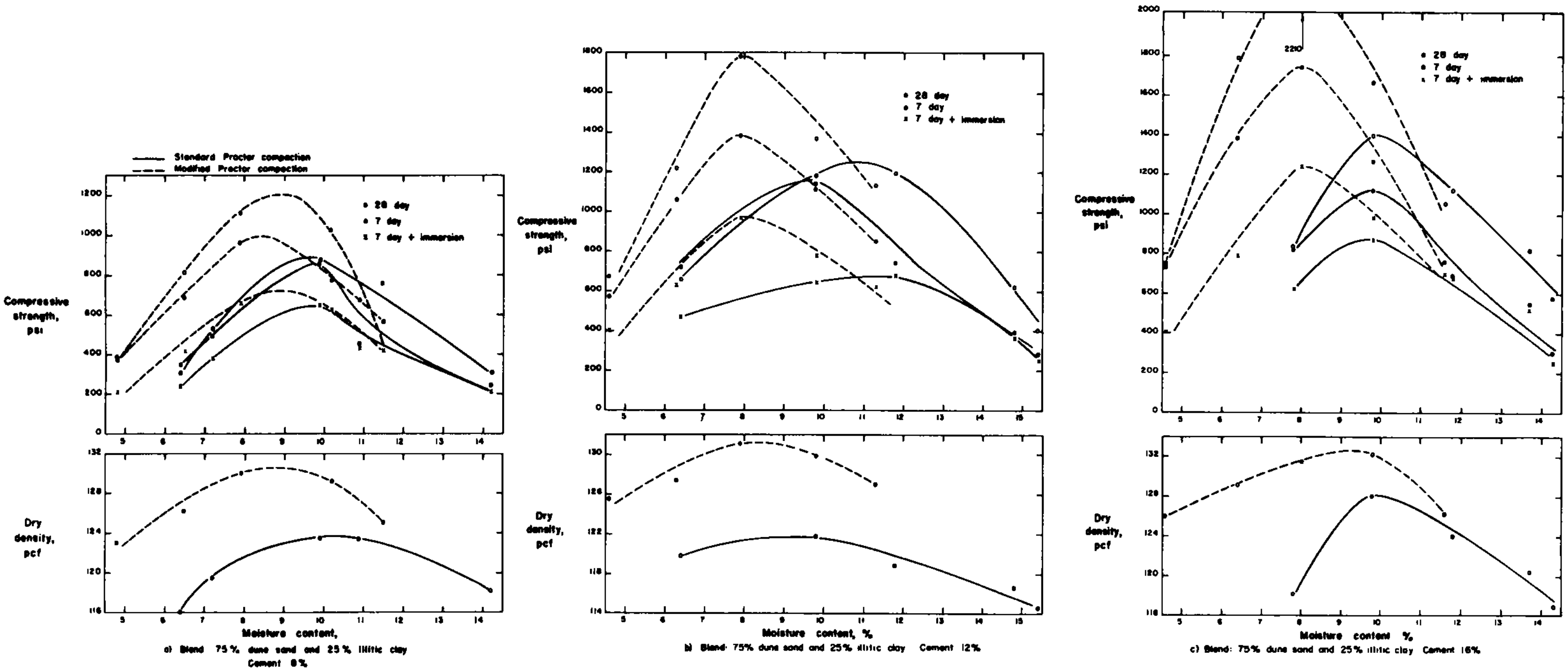


a) Blend 75 % dune sand and 25 % montmorillonitic clay Cement 8 %

b) Blend 75 % dune sand and 25 % montmorillonitic clay Cement 12 %

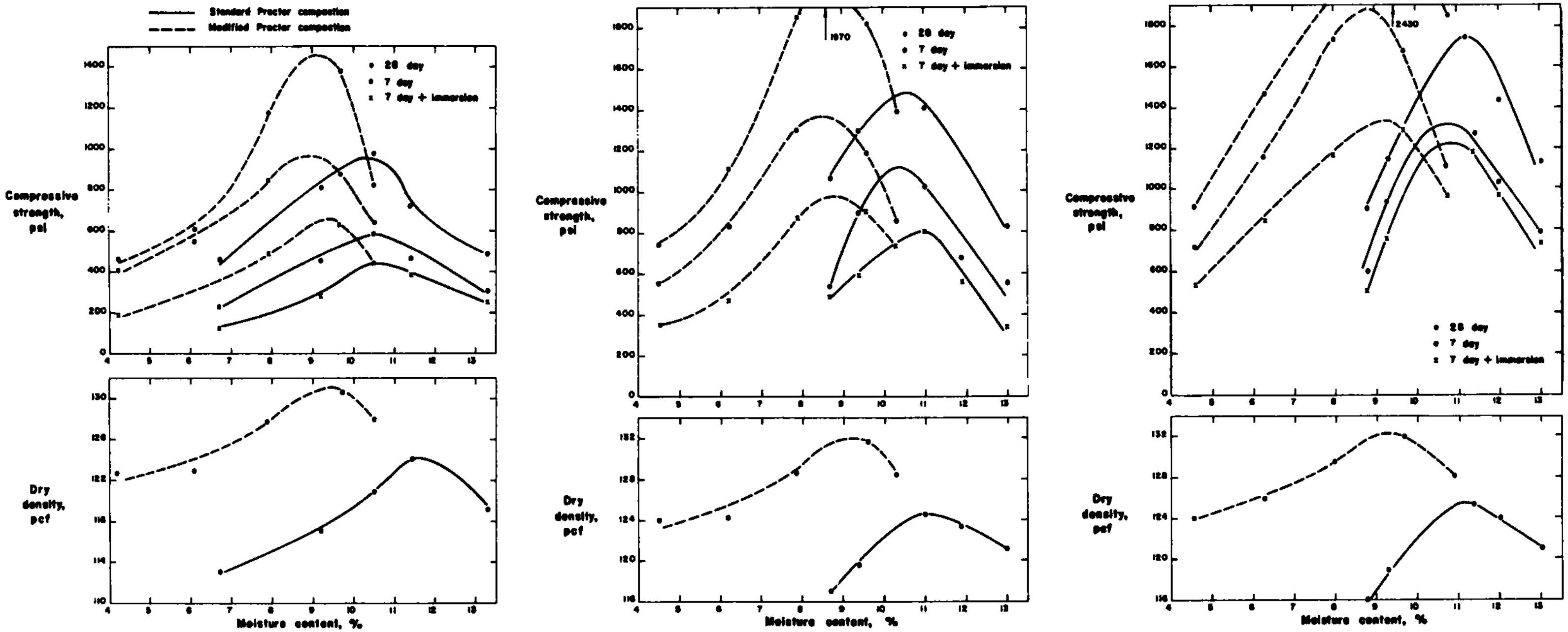
c) Blend 75 % dune sand and 25 % montmorillonitic clay Cement 16 %

Figure 5.



Standard Proctor compaction
Modified Proctor compaction
28 day
7 day
7 day + immersion
Compressive strength, psi
Dry density, pcf
Moisture content,
Moisture content, %
2210
a) Blend 75% dune sand and 25% illitic clay Cement 8%
b) Blend: 75% dune sand and 25% illitic clay Cement 12%
c) Blend: 75% dune sand and 25% illitic clay Cement 16%

Figure 6.

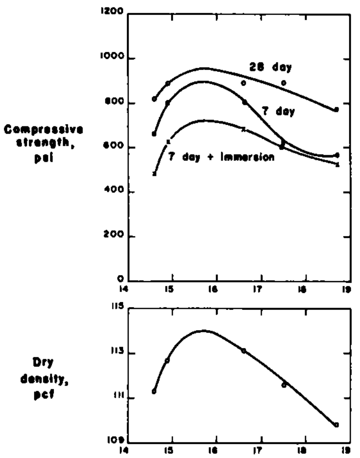


a) Blend: 75 % dune sand and 25 % kaolinitic clay. Cement content, 8 %

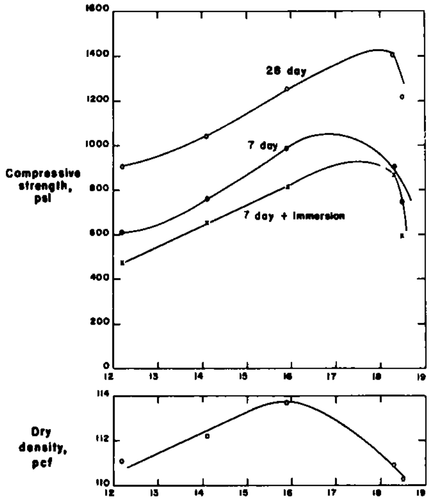
b) Blend: 75 % dune sand and 25 % kaolinitic clay. Cement content, 12 %

c) Blend: 75 % dune sand and 25 % kaolinitic clay. Cement content, 16 %

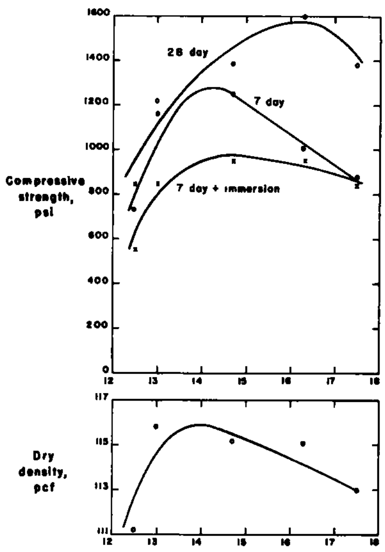
Figure 7.



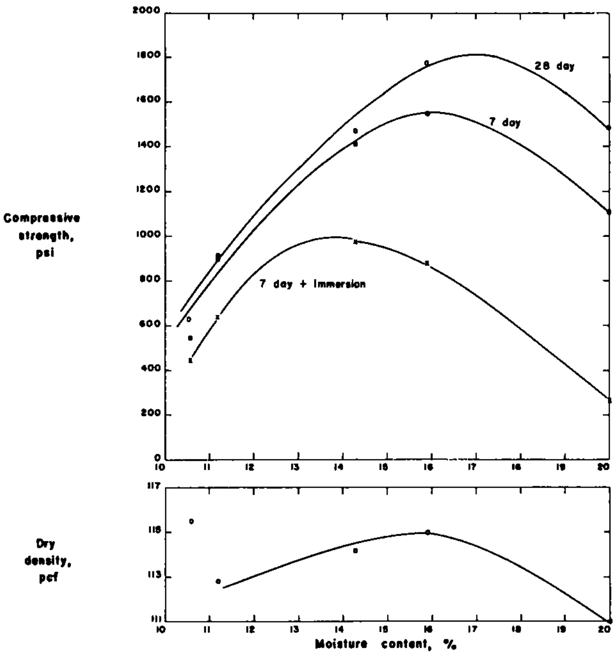
a) Blend: 50 % dune sand and 50 % montmorillonic clay
Cement, 8 %



b) Blend 50 % dune sand and 50 % montmorillonitic clay
Cement, 12 %

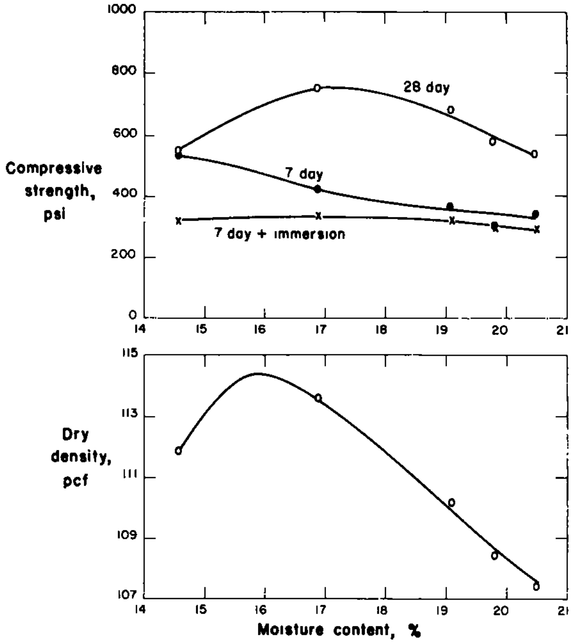


c) Blend 50 % dune sand and 50 % montmorillonitic clay
Cement, 16 %

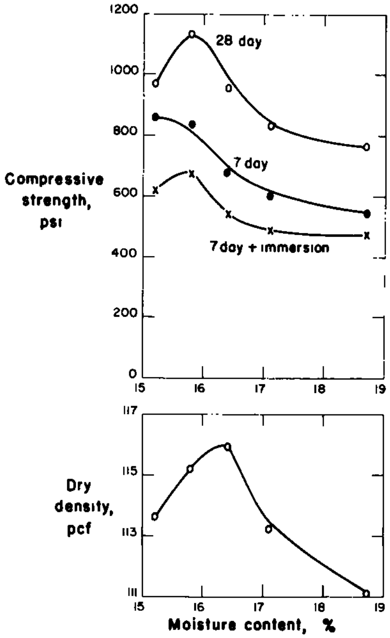


d) Blend 50 % dune sand and 50 % montmorillonitic clay
Cement, 20 %

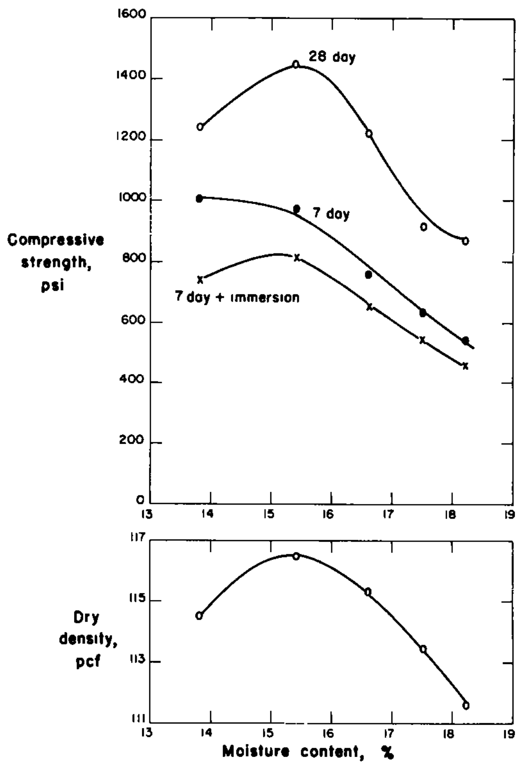
Figure 8.



a) Blend 50% dune sand and 50% illitic clay Cement, 8%

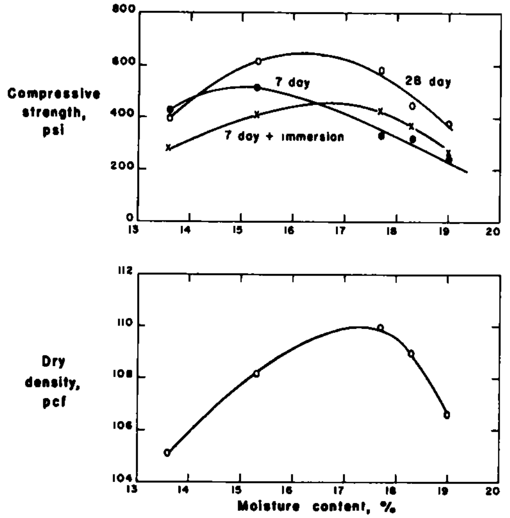


b) Blend 50% dune sand and 50% illitic clay Cement, 12%

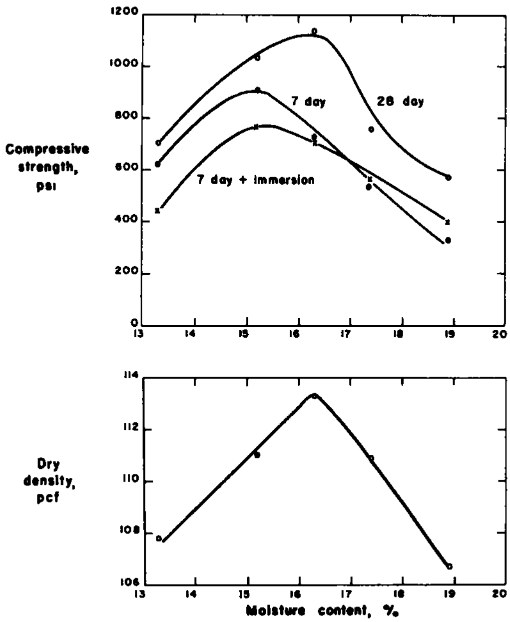


c) Blend 50% dune sand and 50% illitic clay Cement, 16%

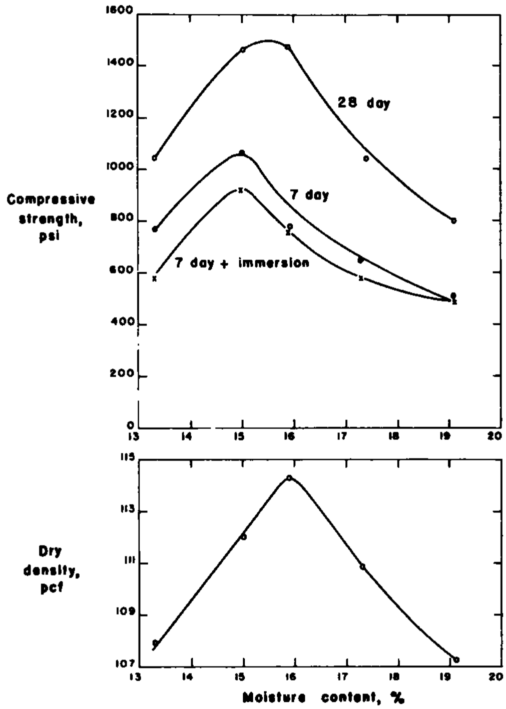
Figure 9.



a) Blend 50% dune sand and 50% kaolinitic clay
Cement, 8%

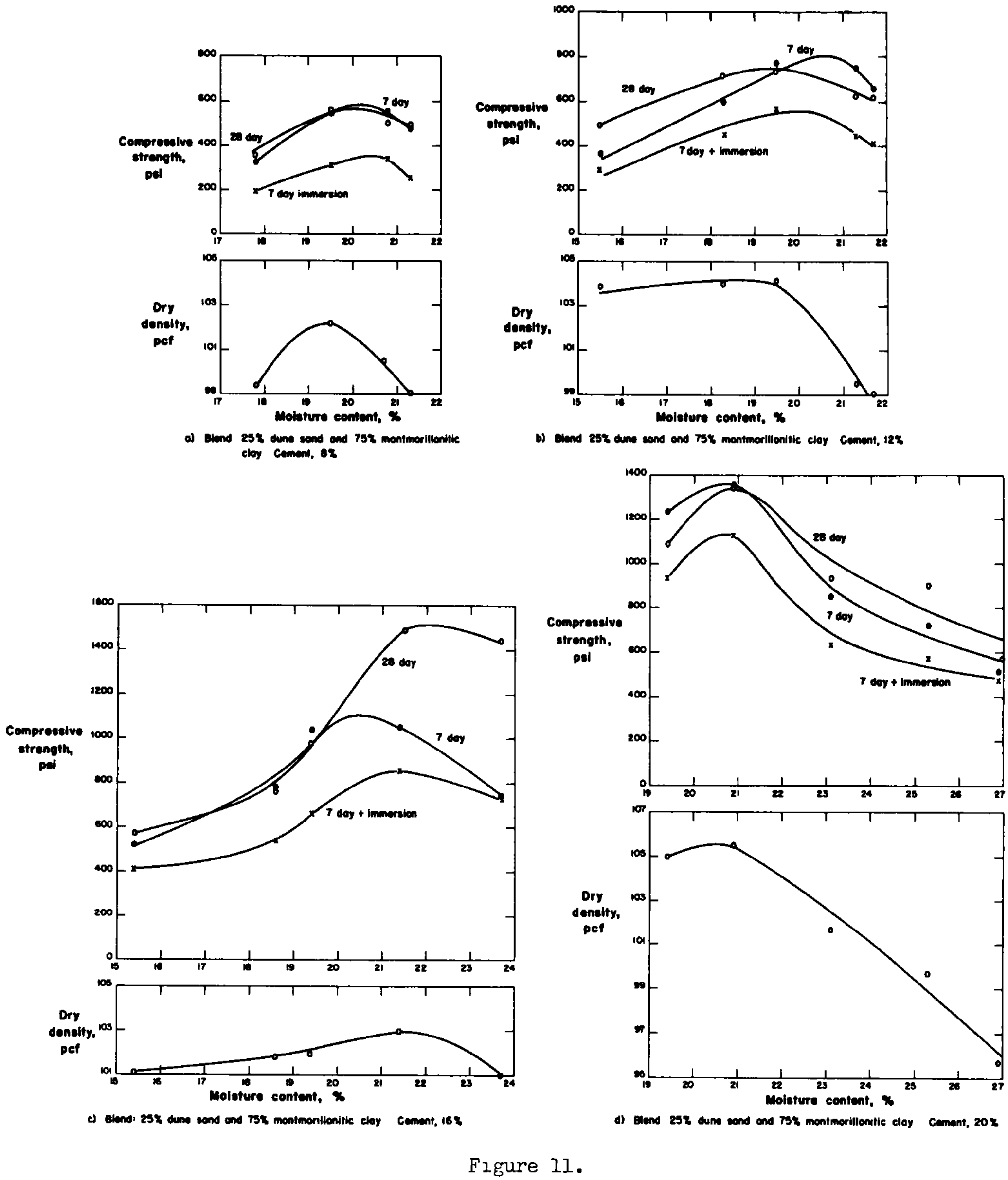


b) Blend 50% dune sand and 50% kaolinitic clay
Cement, 12%



c) Blend 50% dune sand and 50% kaolinitic clay
Cement, 16%

Figure 10.



a) Blend 25% dune sand and 75% montmorillonitic clay Cement, 8%

b) Blend 25% dune sand and 75% montmorillonitic clay Cement, 12%

c) Blend: 25% dune sand and 75% montmorillonitic clay Cement, 16%

d) Blend 25% dune sand and 75% montmorillonitic clay Cement, 20%

Figure 11.

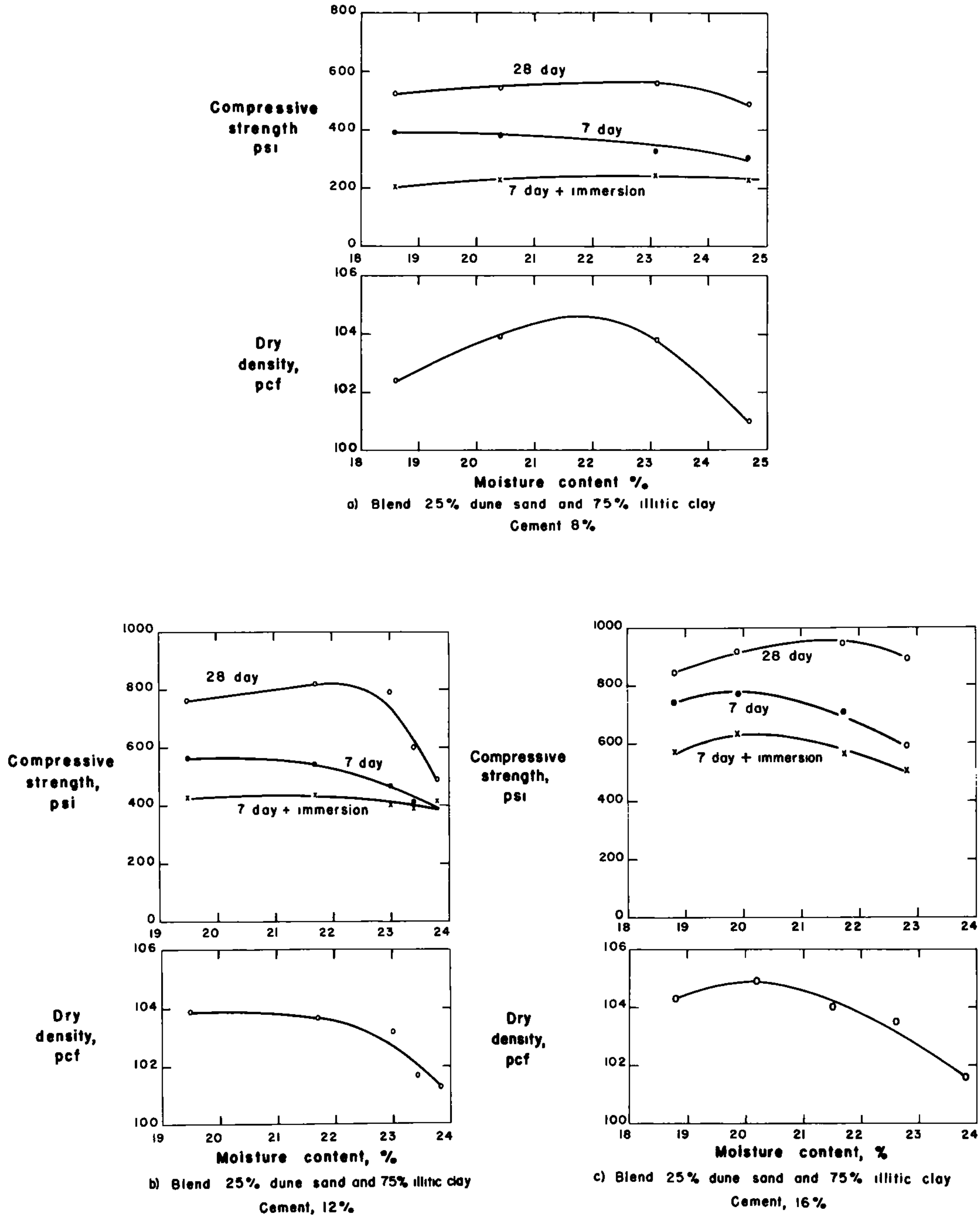
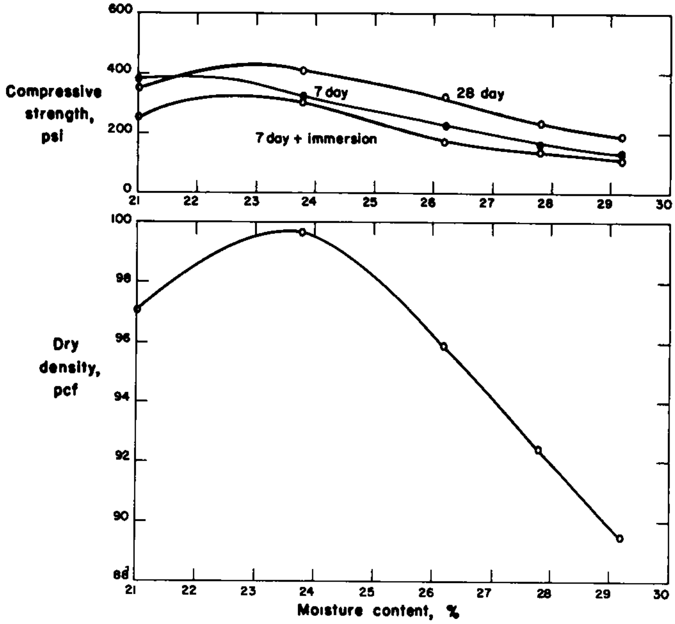
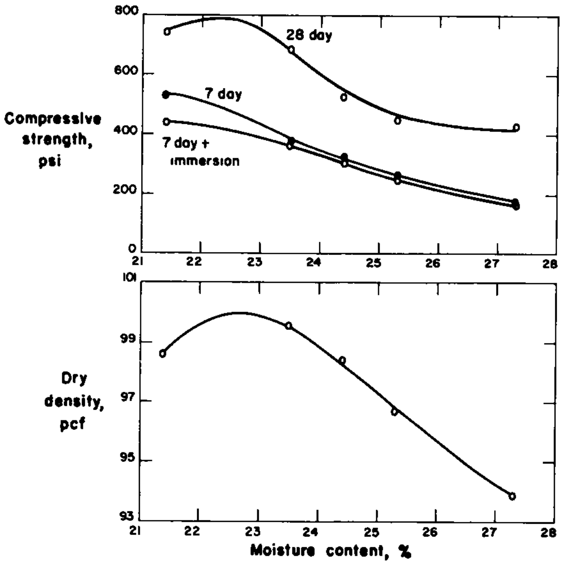

800
600
400
200
0
28 day
7 day
7 day + immersion
Compressive strength psi
18 19 20 21 22 23 24 25
106
104
102
100
Dry density, pcf
18 19 20 21 22 23 24 25
Moisture content %
a) Blend 25% dune sand and 75% illitic clay
Cement 8%
1000
800
600
400
200
0
28 day
7 day
7 day + immersion
Compressive strength, psi
19 20 21 22 23 24
106
104
102
100
Dry density, pcf
19 20 21 22 23 24
Moisture content, %
b) Blend 25% dune sand and 75% illitic clay
Cement, 12%
1000
800
600
400
200
0
28 day
7 day
7 day + immersion
Compressive strength, psi
18 19 20 21 22 23 24
106
104
102
100
Dry density, pcf
18 19 20 21 22 23 24
Moisture content, %
c) Blend 25% dune sand and 75% illitic clay
Cement, 16%

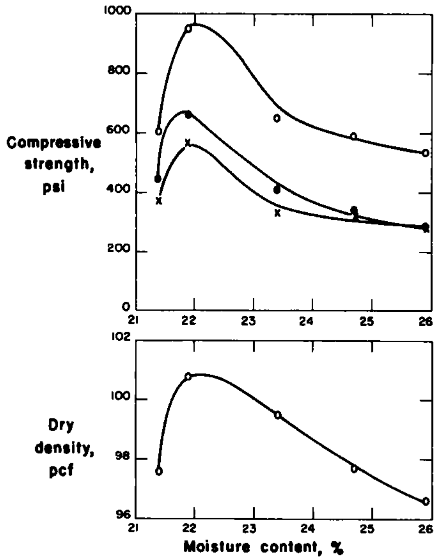
Figure 12.



a) Blend 25% dune sand and 75% kaolinitic clay Cement, 8%



b) Blend 25% dune sand and 75% kaolinitic clay Cement, 12%



c) Blend 25% dune sand and 75% kaolinitic clay Cement, 16%

Figure 13.

TABLE 3

OPTIMUM MOISTURE CONTENTS FOR MAXIMUM DENSITY AND MAXIMUM 7-DAY STRENGTH FOR CEMENT-TREATED SAND-CLAY MIXTURES AT STANDARD AASHO COMPACTION

Cement Content (%)	Dominant Clay Mineral[a]	Property	Opt Moist. Content (%) for Sand-Clay Ratios of				
			100:0	75:25	50:50	25:75	0:100
8	Kaolinite	Density	11.3	11.5	17.1	23.7	27.6
		Strength	6.8	10.4	15.3	22.2	26.5
	Illite	Density	11.3	10.3	15.9	21.8	21.9
		Strength	6.8	9.8	14.5	20.0	22.3
	Montmorillonite	Density	11.3	11.7	15.6	19.4	27.8
		Strength	6.8	11.7	15.8	20.2	26.6
12	Kaolinite	Density	12.2	11.0	16.3	22.7	30.4
		Strength	9.8	10.3	15.2	21.4	28.8
	Illite	Density	12.2	9.8	16.3	19.5	24.0
		Strength	9.8	9.6	15.1	19.5	23.9
	Montmorillonite	Density	12.2	12.2	15.9	19.3	28.2
		Strength	9.8	12.2	16.8	20.6	28.8
16	Kaolinite	Density	12.2	11.2	15.9	22.2	29.0
		Strength	9.3	10.7	15.0	21.8	28.0
	Illite	Density	12.2	9.8	15.3	20.2	24.3
		Strength	9.3	9.8	14.0	20.1	24.7
	Montmorillonite	Density	12.2	13.3	13.8	21.1	27.8
		Strength	9.3	12.5	14.3	20.6	29.8

[a]In sand-clay mixtures.

The variation between the optimum moisture contents for both maximum density and maximum strength may be related to the particle size of the soils. The surface area of sands is relatively small, and most of the lubrication water provided is available for hydration of the cement. The optimum moisture for maximum density may furnish a surplus of water for the hydration reaction, causing a reduction in strength analogous to that found in concrete with a high water to cement ratio; when less water is added, the proper hydration of the cement increases the over-all strength of the mixture, even though the density is slightly less than maximum. Clays, on the other hand, have a large surface area, and much of the water provided for lubrication may be adsorbed resulting in insufficient water available for hydration of the cement. In the sand and clay mixtures dominant in clay, the additional water to obtain proper cement hydration apparently raises the moisture content for maximum strength above that required for maximum density.

For the sand-kaolinite clay mixtures and kaolinite alone, maximum strength is always on the dry side of optimum moisture for maximum density, perhaps because kaolinite has a very low capacity for adsorbing water (3), and cement hydration requirements are satisfied with less water than is needed for compaction to maximum density. For the sand-illite and sand-montmorillonite clay mixtures, the optimum moisture content for maximum strength shifts to the wet side of optimum moisture for maximum density at the higher clay contents. Compared to kaolinite, illite and particularly montmorillonite clay have high capacities for adsorbing water (3), and as the amount of illite or montmorillonite clay in sand-clay mixtures is increased, the moisture requirement for cement hydration is not completely satisfied. Consequently the optimum water content for maximum strength is greater than that required for maximum density when the amounts of clay are large.

As the cement content of a given sand-clay mixture increases, the optimum moisture for maximum density and the optimum moisture for maximum strength does not change much. This suggests that the water necessary for hydration of cement may be small in comparison with the amount needed to obtain a maximum density.

Strength Increase Between 7 and 28 Days

The strength increase in the early curing period is important. The maximum strengths at 28 days are 100 to 160 percent of those at 7 days (Figs. 1 to 13 and Tables 4 and 5). No definite relationship is found between the strength increase and type of clay or other factors. However, the strength increase of the montmorillonite clay mixtures is generally less than that shown by the illite or kaolinite clay mixtures. This may be due to the greater affinity for water of montmorillonite clay, and a resultant shortage of water for cement hydration reactions.

Immersed and Unimmersed Strengths

Because stabilized soil courses in a pavement may become saturated, specimens cured for 7 days were tested in both immersed and unimmersed conditions. The 2- by 2-in. specimens were at near saturation moisture content after immersion in distilled water for 24 hr.

The unimmersed specimens have maximum strengths of from one to two times those of the corresponding immersed specimens (Figs. 1 to 13 and Tables 4 and 5). The ratio of unimmersed to immersed maximum strength varies with the type and amount of clay in the mixture, cement content, and the kind of compaction. Every mixture tested gives a different ratio of unimmersed to immersed strength. However, with standard AASHO compaction, mixtures with illite clay are more susceptible to immersion than mixtures made with either of the other two clays.

Effect of Compactive Effort on Strength

Modified compactive effort produced higher maximum strengths than standard compactive effort with all four basic soils and with the 75 percent sand-25 percent illite clay and 75 percent sand-25 percent kaolinite clay mixtures at all cement contents (Figs. 1 to 7 and Table 4). But with the 75 percent sand-25 percent montmorillonite clay mixture, standard compaction gave maximum strengths equal to or higher than

TABLE 4

MAXIMUM COMPRESSIVE STRENGTHS OF SOIL-CEMENT MIXTURES COMPACTED WITH STANDARD AASHO AND MODIFIED AASHO COMPACTION

Mixture	Cement Content (%)	Maximum Compressive Strength (psi)					
		Standard AASHO Compaction			Modified AASHO Compaction		
		7-Day + 1-Day Immersion	7-Day	28-Day	7-Day + 1-Day Immersion	7-Day	28-Day
100% sand	8	235	250	300	350	440	510
	12	760	720	940	740	860	1,205
	16	1,035	1,120	1,400	1,200	1,300	1,580
100% montmorillonite	8	280	380	470	420	640	760
	12	485	560	680	610	940	1,060
	16	610	715	940	880	1,160	1,280
100% illite	8	160	300	425	395	670	885
	12	355	475	825	585	840	1,140
	16	510	600	870	730	950	1,145
100% kaolinite	8	260	385	405	330	640	840
	12	280	400	480	450	830	1,045
	16	360	480	680	500	886	1,120
75% sand + 25% montmorillinoite	8	880	880	1,020	630	830	950
	12	960	1,000	1,460	870	1,080	1,240
	16	1,180	1,360	1,840	1,220	1,520	1,720
75% sand + 25% illite	8	640	860	890	720	1,000	1,200
	12	680	1,140	1,260	970	1,390	1,790
	16	880	1,180	1,400	1,240	1,740	2,210
75% sand + 25% kaolinite	8	440	580	960	660	970	1,455
	12	800	1,120	1,480	980	1,370	1,970
	16	1,220	1,320	1,740	1,330	1,880	2,430

TABLE 5

MAXIMUM COMPRESSIVE STRENGTH OF SOIL-CEMENT MIXTURES COMPACTED WITH STANDARD AASHO COMPACTION

Mixture	Cement Content (%)	Maximum Compressive Strength (psi)		
		7-Day + 1-Day Immersion	7-Day	28-Day
50% sand + 50% montmorillonite	8	720	890	960
	12	930	1,045	1,420
	16	970	1,280	1,580
	20	995	1,555	1,815
50% sand + 50% illite	8	335	535	760
	12	680	860	1,125
	16	825	1,010	1,440
50% sand +50% kaolinite	8	460	520	645
	12	765	910	1,130
	16	930	1,060	1,500
25% sand + 75% montmorillonite	8	360	585	565
	12	560	805	750
	16	860	1,105	1,520
	20	1,135	1,340	1,360
25% sand + 75% illite	8	240	390	565
	12	430	565	820
	16	626	766	960
25% sand + 75% kaolinite	8	325	385	430
	12	440	530	790
	16	560	670	965

those for modified compaction (Fig. 5). This finding was at first questioned, and the experiment was carefully repeated. The results were the same. Further, more detailed studies are planned to obtain the data needed for an explanation.

Maximum strengths for modified AASHO compaction range between 71 and 247 percent of the maximum strengths for standard AASHO compaction, the highest percentage increasing occurring with 8 percent cement-treated illite clay. It is apparent that many variables affect the relationship between strength and compactive effort. It appears, however, that if maximum densities as great as those obtained by the modified AASHO compaction could be assured, soil-cement of superior quality would be produced. This is especially true for soils dominant in illite and kaolinite clays.

Influence of Clay Content on Strength

The maximum strengths with standard compaction for different sand-clay combinations treated with 8, 12, and 16 percent cement are shown in Figure 14. For the sand-clay combinations investigated, the strength values generally reach a peak for mixtures composed of about 75 percent sand and 25 percent clay. This strength peak corresponds to a density peak for about the same combination of sand and clay. It appears, therefore, that the blends of 75 percent sand and 25 percent clay form a well-graded soil mixture giving high maximum densities and high maximum strengths.

The relative influence of the different clays in the sand-clay mixtures is seen in Figure 14. For amounts of clay greater than 25 percent, the mixtures containing montmorillonite clay gave higher maximum strengths than comparable mixtures containing illite or kaolinite clays. This may be partly due to the high surface activity of montmorillonite and its participation in the reactions producing the cementing compounds.

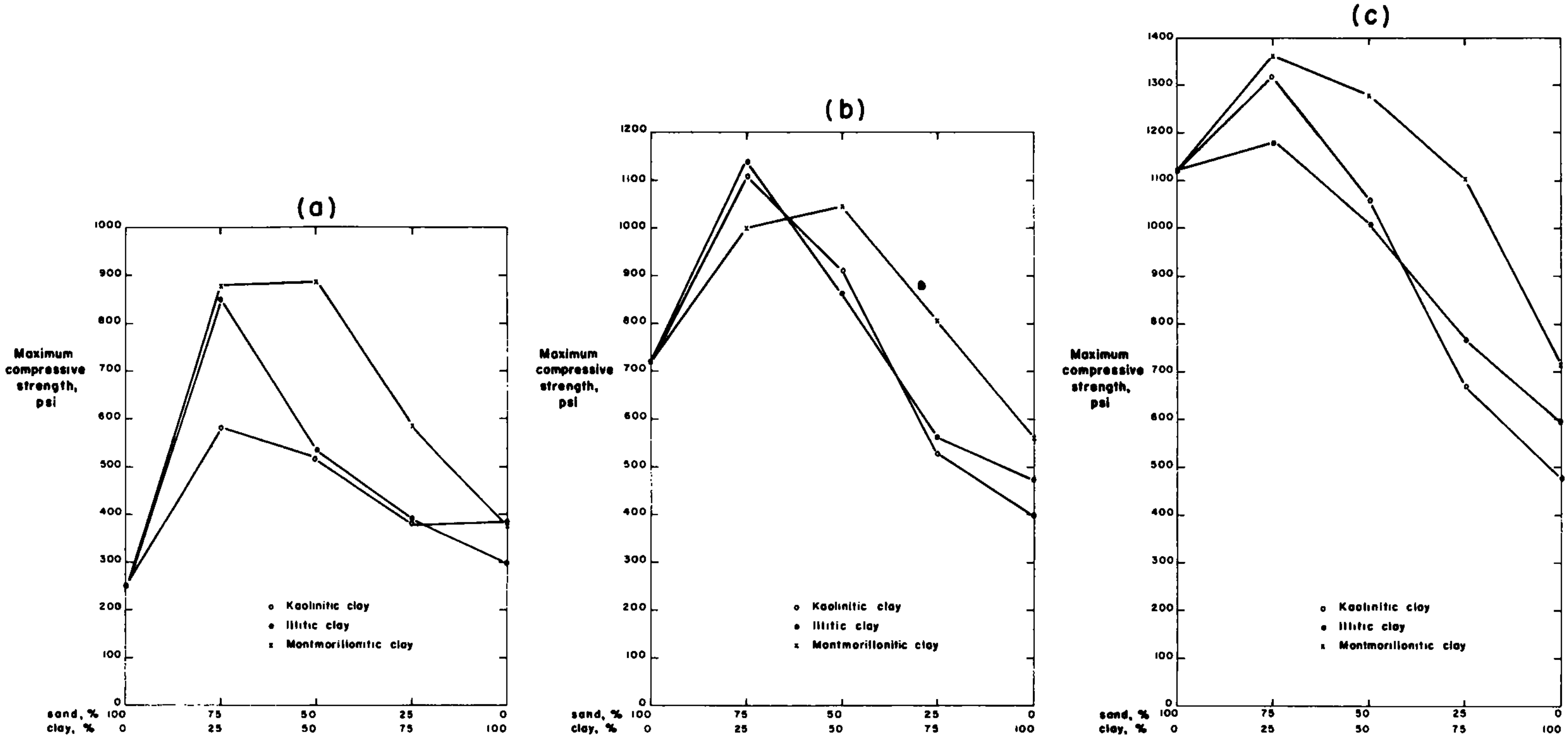


Figure 14. Maximum strengths of sand-clay mixtures compacted with the standard AASHO compactive effort and treated with (a) 8 percent concrete, (b) 12 percent concrete, (c) 16 percent concrete.

Effect of Clay Content on Density

The maximum density for a given combination of sand-clay is about the same with either montmorillonite or illite clays (Figs. 1 to 13). With these clays the densities are greater than with kaolinite clay.

Influence of Amount of Cement on Strength

The maximum strength increases with increase in cement (Fig. 14 and Tables 4 and 5), but the rate of strength increase varies for every sand-clay combination. In general, the maximum 7-day strength is increased 30 percent by increasing the amount of cement from 8 to 12 percent, from 12 to 16 percent, or, in mixtures with montmorillonite clay, from 16 to 20 percent. However, a 30 percent increase in strength with a 4 percent increase in cement can not be relied on because in some sand-clay mixtures the increase is as low as 3 percent or as high as 70 percent. An increase in cement content from 8 to 12 percent resulted in a very great improvement in maximum 7-day strength of cement treated dune sand with no clay, a threefold increase with standard compaction and a twofold increase with modified compaction.

If a minimum strength of 300 psi is required after 7 days curing and 1 day immersion, none of the four basic soils used were properly stabilized with 8 percent cement and standard AASHO compaction. However, when modified compaction is used, the four basic soils with 8 percent cement have 7-day cured, 1-day immersed strengths of over 400 psi.

All sand-clay mixtures treated with 8 percent cement and given standard compaction have 7-day cured, 1-day immersed strengths of over 300 psi, except the one composed of 25 percent sand and 75 percent illite clay.

CONCLUSIONS

The following conclusions appear applicable to the cement-treated soil or sand-clay mixtures used in this investigation:

1. The optimum moisture content for maximum density and the optimum moisture content for maximum unconfined compressive strength are not necessarily the same.
2. The moisture content for maximum strength of the sand is from 2.4 to 4.5 percentages drier than the moisture content for maximum density.
3. The moisture content for maximum strength of the sand-kaolinite clay mixtures is slightly drier than the moisture content for maximum density.
4. The moisture content for maximum strength of the sand-illite clay or the sand-montmorillonite clay mixtures is on the dry side of the moisture content for maximum density in mixtures dominant in sand, and on the wet side in mixtures dominant in clay.
5. A sand-clay mixture of about 75 percent sand and 25 percent clay is near optimum for both maximum density and maximum strength.
6. Modified compactive effort gives maximum strengths up to 247 percent higher than the standard, except with a mixture of 75 percent sand and 25 percent montmorillonite clay, for which standard compaction produced maximum strengths equivalent to or higher than those obtained with modified compaction.
7. The maximum strengths after 28 days of curing are from 100 to 160 percent greater than those obtained after 7 days of curing.
8. The maximum strengths after 7 days of curing, without immersion, are from 100 to 200 percent greater than after 7 days of curing plus 1 day of immersion.
9. It is recommended for construction purposes that the difference between optimum moisture for maximum density and optimum moisture for maximum strength be considered practically negligible for sand-clay mixtures containing about 25 percent clay or more. However for mixtures with sand alone, or sand and small amounts of clay, the optimum moisture content for maximum strength should be used.

ACKNOWLEDGMENTS

The material for this paper was obtained as part of the research being done under Project 449-S of the Iowa Engineering Experiment Station, Iowa State University of

Science and Technology. Project 449-S is under contract with the Iowa Highway Research Board of the Iowa State Highway Commission as their Project HR-82.

REFERENCES

1. Felt, E. J., "Factors Influencing Some of the Physical Properties of Soil-Cement Mixtures." HRB Bull. 108, 138-162 (1955).
2. Goecker, W. L., Moh, Z. C., Davidson, D. T., and Chu, T. Y., "Stabilization of Fine and Coarse-Grained Soils with Lime-Fly Ash Admixtures." HRB Bull. 129, 63-82 (1956).
3. Grim, R. E., and Cuthbert, F. L., "The Bonding Action of Clays." University of Illinois Engr. Exp. Sta. Bull. 50 (1945).
4. Ruff, C. G., and Davidson, D. T., "Lime and Sodium Silicate Stabilization of Montmorillonite Clay Soil." HRB Bull. 304, 76-92 (1961).
5. Viskochil, R. K., Handy, R. L., and Davidson, D. T., "Effect of Density on Strength of Lime-Fly Ash Stabilized Soil." HRB Bull. 183, 5-15 (1957).