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Effects of delay in compaction on compressive strength of soil cement and soil-lime-cement mixtures

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EFFECTS OF DELAY IN COMPACTION ON COMPRESSIVE STRENGTH OF SOIL CEMENT AND SOIL-LIME-CEMENT MIXTURES

by

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A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Soil Engineering

Signatures have been redacted for privacy

Iowa State University
Of Science and Technology
Ames, Iowa

1965

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INTRODUCTION

The year 1965 marks the thirtieth anniversary of the first scientifically controlled soil-cement road built in the United States. This road is still carrying traffic near Johnsonville, South Carolina, and at a volume far in excess of what was expected at the time of its construction.

When portland cement is added in sufficient quantity to soil, and the mixture moistened, compacted, and cured, a hard, durable soil-cement mixture results. When soil-cement is correctly compacted during construction, it does not deform under traffic load or develop soft spots and is resistant to deterioration caused by moisture and weather.

Addition of lime to soils greatly improves their workability and increases the strength of the mixtures, although strength gains are not as great as those due to addition of cement. Lime is usually used with clayey soils because it flocculates the clay and improves plasticity. Cementation eventually results due to slow pozzolanic reaction. Cement will also flocculate clay by reason of its free lime content but does not require clay in a soil for fast and effective cementation. Both lime and cement may be added to a soil, the lime to facilitate mixing, and the cement to contribute strength and durability.

Time lapses between mixing and compaction vary depending upon the construction method employed. With single-pass mix-in-place procedures the delay is about two minutes. However, thirty minutes or more delay may occur when mixing is done in a stationary plant on the site, and from two to three hours delay may occur with multi-pass mix-in-place methods.

The purpose of this investigation is to study the effects of delays between the time of addition of cement or cement and lime to soils and compaction of the mixtures. The immersed, unconfined compressive strength of the cured specimens was used to evaluate the effects of the time delays.

REVIEW OF LITERATURE

The use of portland cement as an additive to improve the performance of soils in roads was started at the beginning of this century. However, relatively little was known about principles of soil composition, and it was not until 1935 that the South Carolina Highway Department constructed a test road whose field performance clearly demonstrated that soil and cement are compatible materials and that they can be mixed to form a usable base course for a road (2). The use of soil-cement is now commonplace in this country and in foreign lands, the annual square yardage constructed rivalling that of portland cement concrete. Extensive researches, principally by the Portland Cement Association, were the basis for the rapid and widespread acceptance of soil-cement.

The Portland Cement Association developed tests for the design of soil-cement mixtures and the criteria for establishment of the minimum cement requirements to produce a hard, durable soil-cement (15). The American Society for Testing Materials adopted these tests in 1944 and the American Association of State Highway Officials did likewise in 1945. The tests were revised by both organizations in 1957 (1). Cement requirement criteria are based primarily on the resistance to artificial weathering produced by wet-dry and freeze-thaw tests, with supplemental compressive strength tests to determine the rate and degree of hardening.

Another approach has been the correlation of cement requirements with the U. S. Department of Agriculture soil classification system (15). Generally, clayey soils have been found to require more cement than sandy soils.

Laboratory molding of specimens is an attempt to reproduce field construction procedures. However, field conditions obviously are not the same as those in the laboratory. One of the differences is time: field operations are done sequentially over large areas, and take much longer. Of particular interest in the present study is the effect, if any, of prolonged mixing and/or a time delay between mixing and compaction of the soil-cement mixture. Previous investigations report that increasing the mixing period increases the optimum moisture content, reduces the resistance to wet-dry and freeze-thaw cycles, reduces maximum density, and decreases the compressive strength (8).

Early research in additives to soil was in attempt to improve the stabilization of some organic soils that exhibited retarded setting or produced unusually low strengths when mixed with Portland cement. The most efficient additive for these cases was found to be calcium chloride (12). Later studies of additives found lime to be effective in either reducing the cement requirement or improving the properties of soil-cement when used with clayey soils that are normally reactive with cement. When lime is mixed with moist soil, three types of reactions take place (5). First is a reduction in plasticity of cohesive soils. The mechanism is either a replacement of calcium ions for the ions naturally adsorbed by the clay, or adsorption of additional calcium ions onto the clay. These processes act to change the electric charge density around the clay particles, causing the clay particles to become electrically attracted to each other, resulting in flocculation or aggregation. As a result, the clay occurs as flocs or aggregates and behaves like a silt, being more friable and more easily worked. A second chemical reaction is a carbonation of lime by carbon dioxide of the air, producing calcium carbonate, a weak cement and deleterious for the overall strength. A third chemical reaction is a slower cementation, called pozzolanic reaction, which is responsible for the long-term strength of compacted mixtures of lime and soil. The latter reactions apparently involve interactions between hydrated lime and the siliceous and aluminous clay minerals in the soils, producing hydrated calcium silicates and aluminates similar to those produced by the hydration of portland cement. However pozzolanic reactions are slower, and more time is required to produce high strengths.

In England in 1951, a study was made of the addition of lime to soil-cement mixtures in which the organic matter of soils was deleterious for the hydration of the cement (4).

The lime was found to be beneficial, probably reacting with and neutralizing the organic matter, though not as efficient as calcium chloride.

The U. S. Army Corps of Engineers used lime in cement treatment of plastic soils in 1950. The addition of lime in this case facilitated pulverization and mixing, and also increased compressive strength and resistance to loss of weight in the wet-dry tests. The amount of cement used could be decreased from 10 percent to 6 percent with the use of 2 percent lime, while achieving equal results in the wet-dry tests. Lime was mixed with the soil prior to the addition of cement (9). Another study with a heavy clayey soil in England showed successful stabilization with 2 percent lime and 15 percent cement. Increases in both strength and resistance to loss of strength upon immersion in water were reported (13).

When portland cement is added to a soil, definite changes in properties and structure of the soil are apparent. The interaction of portland cement and soil has been described by Catton (3) as follows:

> ...each cement grain picks up a varying number of soil grains (depending on the grain size of the soil) and as the cement hydrates and crystallizes, a new or larger soil grain or agglomeration is produced. As more and more cement is added, more soil grains lose their identity to become larger soil grains or agglomerations. ...and when enough cement has been added to link all agglomerations together, with pockets of trapped soil, the mixture becomes a structural material rather than a soil (3, p. 854).

Wang and Handy (16) indicate that the cementing materials in both soil-lime and soil-cement are similar. The main compounds in cement are tricalcium silicate, dicalcium silicate and tricalcium aluminate. These compounds react with water to yield calcium silicate and calcium aluminate hydrates and lime. The lime thus formed in the initial reaction later reacts with clay mineral present in the soil to form additional calcium silicate and calcium aluminate hydrates in a secondary and slower pozzolanic reaction. The calcium silicate hydrate is a tobermorite-like material having a large surface area of meshed fibrous crystals and is usually referred to as tobermorite gel. This tobermorite gel is the main cementing agent in portland cement concrete.

Under field conditions a delay between the mixing process and compaction is usually unavoidable. Earlier research has established that the effects of delay in compaction is more noticeable when the mixture is left undisturbed than when it is intermittently mixed (8). It is also known that the effects of the delay can be reduced by increasing the moisture content above the optimum at time of mixing (6).

MATERIALS

Soils

The three soils used in the investigation varied texturally from sand to silty loam with montmorillinite as the predominent clay mineral in each. Two of the soils contained large amounts of carbonates, while the third, a sand, was non-calcareous. The soil physical and chemical properties are given in Table 1 along with other pertinent data.

The friable loess was sampled from thick loess bordering the Missouri River floodplain in Harrison County, Iowa. The sand-loess mixture was obtained from the blended material used in the soil-cement base course of Iowa Route 117, north of Colfax, Iowa. The sand was obtained in Benton county, Iowa, and is a Wisconsin age, fine grained, eolian sand. These three soils are representative of readily available materials for stabilized road construction in Iowa and other midwestern states.

Cement

Type I portland cement manufactured by the Penn Dixie Cement Corporation, Des Moines, Iowa, was used in all mixtures in the study. The bagged cement was stored in a metal barrel with a tight fitting cover. Properties of the portland cement are given in Table 2.

Table 1. Properties of soils

Property	Friable loess (Lab. no. 20-2)	Dune sand (Lab. no. S-6-2)	Sand-loess (Colfax mix)
Textural composition,[a] %			
Gravel (above 2.0 mm)	0.0	0.0	0.0
Sand (2.0 - 0.074 mm)	0.4	94.0	70.7
Silt (0.074 - 0.005 mm)	80.0	4.0	22.3
Clay (below 0.005 mm)	19.6	2.0	7.0
Clay (below 0.002 mm)	16.0	-	6.0
Predominant clay mineral	Montmorillinite	Montmorillinite (trace)	Montmorillinite
Physical properties			
Liquid limit	30.8	-	18.9
Plastic limit	24.6	-	16.4
Plasticity index	6.2	Non-plastic	2.5
Chemical properties			
Cat. ex. cap.[b], m.e/100g	13.4	1.0	11.0
Carbonates,[c] %	10.2	Non-calcareous	11.6
pH[d]	8.7	6.6	8.0
Organic matter,[e] %	0.2	0.1	0.2
Classification			
Textural[f]	Silt loam	Fine sand	Sandy loam
Engineering (AASHO)	A-4 (8)	A-3 (0)	A-2-4

[a] For fraction passing no. 40 sieve.

[b] Ammonium acetate (pH=7) method on soil fraction below 2 mm.

[c] Versenate method for total calcium.

[d] Glass electrode method using suspension of 15 gm soil in 30 cc distilled water.

[e] Potassium bichromate method.

[f] USDA textural classification.

Table 2. Properties of the portland cement used

Chemical analysis, percent by weight:		
Silicon dioxide	(SiO_2)	21.62
Aluminum oxide	(Al_2O_3)	5.05
Ferric oxide	(Fe_2O_3)	2.97
Calcium oxide	(CaO)	64.05
Magnesium oxide	(MgO)	2.90
Sulfuric trioxide	(SO_3)	2.26
Insoluble residue		0.16
Loss on ignition		0.58
Specific surface		
Turbidimeter (Wagner)		1855 sq cm/gm
Air permeability (Blaine)		3395 sq cm/gm
Computed compound composition, percent by weight:		
Tricalcium silicate	C_3S	51.2
Dicalcium silicate	C_2S	23.3
Tricalcium aluminate	C_3A	8.3
Tetracalcium alumino-ferrite	C_4AF	9.0
Magnesium oxide	MgO	2.9

Lime

Calcitic hydrated lime from the U. S. Gypsum Company (brand name Kemikal) was used in the tests. The lime was stored in a cardboard drum on a dry shelf. An analysis of the lime is given in Table 3.

Water

Distilled water was used in all the mixes and for immersing the 2 in. dia. x 2 in. high specimens before compression tests.

Table 3. Properties of hydrated lime used

Chemical analysis, percent by weight:		
Silicon dioxide	(SiO_2)	0.3
Aluminum and ferric oxide	($Al_2O_3 + Fe_2O$)	0.6
Calcium oxide	(CaO)	73.8
Magnesium oxide	(MgO)	0.6
Sulfuric trioxide	(SO_3)	0.3
Loss on ignition		24.1
Fineness		
Passing no. 325 sieve		95.5

METHODS OF INVESTIGATION

Soil Preparation

Samples of soil were air-dried, passed through a jaw crusher, and sieved through a number 10 sieve before being used. Lumps retained on the sieve were pulverized or discarded. The soil passing the sieve was then mixed to insure uniformity and stored in closed wooden bins until used.

Specimen Preparation

Mixing

Sufficient air-dried soil was weighed out to make up an 800 gram batch after correction for hygroscopic water. This was placed in the bowl of a Hobart Model C-100 electric mixer. The necessary cement and lime (if used) was also weighed out and added to the soil in the mixing bowl, the cement and lime quantities being expressed as percentages of the dry weight of the total batch. The dry ingredients were mixed at slow speed for one minute, then the bowl was hand scraped briefly to insure mixing of ingredients at the sides and bottom of the bowl.

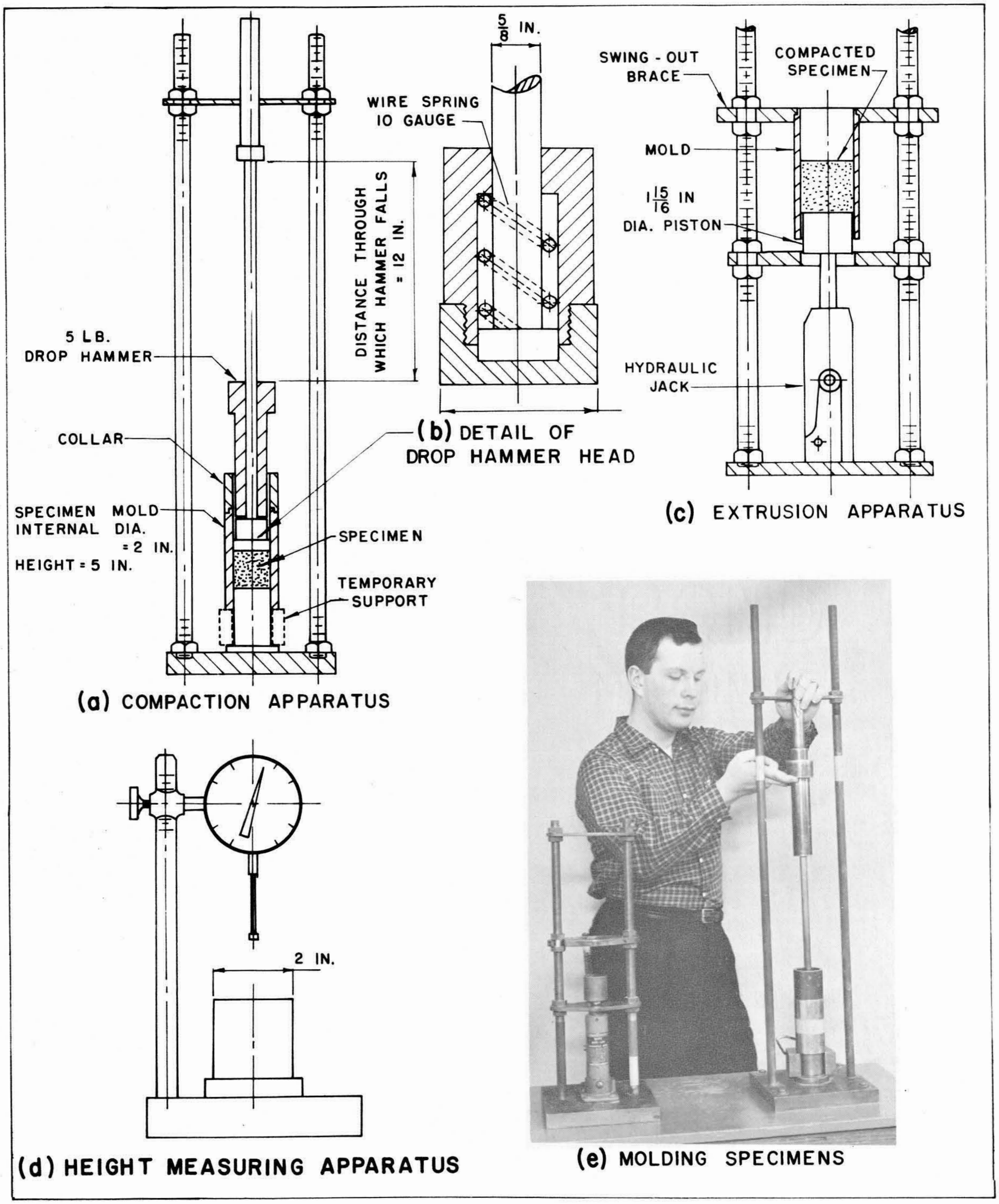
Sufficient distilled water was added to the mixture to bring it to the desired moisture content. Mixing at slow speed for one minute, scraping sides and bottom of the bowl by hand, and additional mixing at slow speed for one minute completed the blending of the ingredients.

If the batch was to be molded immediately, the bowl was covered with a damp cloth to deter evaporation. If the batch was not to be molded until after a time delay, the mixture was placed in a two-pound capacity metal can, covered with a tight fitting lid, and set aside.

Molding

An amount of the mixture necessary for preparation of a 2-inch diameter by 2-inch high specimen was weighed out on a balance. The mixture was poured into the specimen mold shown in Figure 1. The molding cylinder rests on two temporary supports. The drop hammer assembly was placed in position in the cylinder, the five pound drop hammer raised through the controlled 12 inch distance and released. The temporary support was removed and the hammer was dropped four more times. The mold was then inverted and the hammer dropped five times. The compacted specimen was extruded from the mold with a modified hydraulic jack. The specimen was immediately weighed to the nearest 0.1 gram and its height measured to the nearest 0.001 inch. All specimens were required to have a height of 2.000 ± 0.050 inches or they were discarded. Three specimens were molded from each batch for the 7-day, 28-day, and 90-day curing periods.

A sample of the mixture left over after molding was tested for moisture content.



(a) COMPACTION APPARATUS

(b) DETAIL OF DROP HAMMER HEAD

(c) EXTRUSION APPARATUS

(d) HEIGHT MEASURING APPARATUS

(e) MOLDING SPECIMENS

Figure 1. Molding equipment.

Curing

Each specimen was wrapped in wax paper and sealed with cellophane tape immediately after being weighed and measured. They were then stored in a curing room wherein the relative humidity was maintained at 95 ± 5 per cent with the temperature at 70 ± 5 degrees F.

Testing

After the predetermined curing time the specimens were removed from the curing room and immersed in distilled water for 24 ± 1 hours. They were then compressed to failure to determine their unconfined compressive strength. The apparatus used to apply the compressive load was a Model AP-170 Stability Testing machine as manufactured by Soiltest, Inc., Chicago, Illinois. With this apparatus, strain is applied to the specimen at a constant rate of 0.1 inch per minute. The loads are indicated by measuring the deflection of a 10,000 pound capacity proving ring by means of an attached dial indicator.

PRESENTATION AND DISCUSSION OF RESULTS

Unconfined Compressive Strength

The effects of compaction delay on unconfined compressive strength of three soil-cement and two soil-lime-cement mixtures are shown in Figures 2 through 19. Detailed data are presented in Tables 5 through 9 in the Appendix. All figures are plots of unconfined compressive strength versus moisture content at variable curing periods and variable delay times.

Sand-loess (Colfax mix)

The compressive strength of this soil-8 per cent cement mixture increases with increasing moisture until an optimum moisture content is reached, beyond which a decrease in strength occurs. However, the optimum moisture for maximum strength varies according to the delay period, successively higher moisture contents being necessary to achieve maximum strength at increasing lengths of delay (Figures 3, 4, and 5). The maximum strength shows a marked decrease between no delay and 2 hour delay and then much lesser decreases between subsequent delays. For example, the maximum strengths for the 90 day curing period are as follows: 1560 psi at no delay, 980 psi at 2 hour delay, and 740 psi at both the 6 hour and 24 hour delays. These maximums occur at 9.6, 11, 13, and 16 percent moisture, respectively. Similar trends are exhibited at 7 day and 28 day curing periods.

Friable loess

The strength curves for this soil mixed with 8 per cent cement are shown in Figures 6, 7, 8, and 9. The strength-moisture relationships, discussed above in relation to the sand-loess soil, follow similar patterns for the friable loess. However, the reduction in maximum strength, as evidenced by the 90 day curing curve, is not as great with this soil as with the sand-loess. The maximum strength at 6 hour delay is only about 100 psi (or about one-eighth) less than for the no delay case, whereas for the sand-loess, the reduction was about 800 psi (about one-half). The mixtures prepared for 2 hour and 24 hour delays were not carried out to high enough moisture contents for a peak to appear in the compressive strength curves.

As with the sand-loess, higher moisture contents are required for this soil with increasing time delays of compaction to achieve maximum strength. A moisture content of approximately 26 per cent is required at 6 hour delay versus only 18 per cent at no delay.

Dune sand

Results of unconfined compressive strength tests of sand-8 per cent cement mixtures after compaction delays of 0, 2, 6, and 24 hours and variable curing are shown in Figures 10, 11, 12, and 13. In the no delay case (Figure 10), strength appears quite high at 6.6 per cent moisture content, then decreases until 8 per cent moisture is reached and then rises continuously to 11 per cent moisture, the highest content included in the test. This strength trend is an inversion of the curves for the sand-loess and friable loess.

When the compaction delay is 2 hours, the strength is more constant (Figure 11) over the moisture content range of the test. In the 6 and 24 hour delays (Figures 12 and 13) the strength-moisture relationships parallel those established by the sand-loess and friable loess soil-cement mixtures.

The drop in strength at 8 per cent moisture in the no delay case may be an effect of the water-cement ratio. The cement content is 8 per cent so a water cement-ratio of 1.0 exists at time of mixing. At 6.6 per cent moisture the ratio is down to about 0.8. The sand had very little clay in it, so the sand-cement-water mixture perhaps behaved like a very fine aggregate concrete. A water-cement ratio of 0.5-0.6 is common for concrete and values above this result in a decrease in strength of the concrete so the decreasing strength from 6.6 to 8 per cent moisture may be the normal curve for a concrete mixture. The rising strength from 8 to 11 per cent would then be the normal curve for soil or for soil-cement, where water-cement ratios are almost always greater than 1. According to the Proctor Theory of soil compaction, additional water allows denser compaction for a given comparative effort because of lubrication effect. Finally as the mix approaches saturation the curve trends downward, and the more water the lower the density. A batch was prepared at 13 per cent moisture, but was too wet to mold and extrude from the molding apparatus. Optimum moisture for dune sand has been reported to be 11.6 per cent (14).

The maximum compressive strength exhibited by the 90 day curing curves decreases from about 800 to 500 psi after a 2 hour delay, but does not fluctuate noticeably after longer delays of 6 and 24 hours.

Sand-loess with 2 per cent lime and 6 per cent cement added simultaneously

The unconfined compressive strength curves of sand-loess-lime-cement at no delay, 2 hour delay and 24 hour delay are shown in Figures 14, 15, and 16 respectively. In comparing the resultant maximum 90 day strengths of this mixture at no delay (Figure 14) with those of the same soil with 8 per cent cement (Figure 2) it is seen that the lime-cement has much less strength; 960 psi versus 1560 psi for cement alone. However, after a 2 hour delay the 90 day strengths are equal at 980 psi, and after a 24 hour delay the mixture containing lime has a maximum strength of 500 psi compared to 640 psi for the soil-cement mixture. The maximum strengths still occurred at the same moisture contents, i.e., 10, 11, and 16 percent, as for the soil-cement mixture with the identical delay times.

Sand-loess with 2 per cent lime and 6 per cent cement; cement added 24 hours after the lime

In this study lime was mixed with the soil, and requisite water for a desired moisture content was added and mixed. The batch was set aside in a sealed metal container for 24 hours. The cement was then added and mixed. Specimens were molded immediately and after 2 hour and 24 hour delays, the mixture being sealed during the delay periods. Brief remixing just prior to molding was required to break up the larger aggregates that formed during the delay period. The strengths are shown in Figures 17, 18, and 19.

It is seen that lower moisture contents should have been included for the cases of no delay and 2 hour delay since strengths show only to be decreasing from their values at 10 per cent moisture as higher moisture contents were used. However, in the study reported immediately above, the maximum strengths occurred at 10 per cent and 11 per cent for no delay and 2 hour delay, so for this case the peak strengths are probably at only slightly lower moisture contents. It is noticed at 24 hour delay (Figure 19) that the maximum strength occurs at 14 percent moisture versus 16 per cent when lime and cement (Figure 16) are added at the same time.

The maximum strengths are much higher when the lime is allowed to "marinate" for 24 hours before adding the cement than when the lime and cement are added at the same time. The comparisons are as follows: At no delay and 10 per cent moisture, 1500 psi versus 960 psi; at 2 hour delay, 1220 psi at 10 per cent moisture versus 980 psi at 11 per cent moisture; at 24 hour delay, 800 psi at 14 per cent moisture versus 700 psi at 16 per cent moisture. These maximums are also very close to those for the same soil at corresponding moisture contents and 8 per cent cement. Allowing the lime to "marinate" reduces the loss in strength due to delays between mixing and compaction. This is evident when comparing the maximum strengths in Figures 2, 3, and 5 with those in Figures 17, 18, and 19.

Figure 2. Unconfined compressive strength of sand-loess with 8 per cent cement. No delay between mixing and compaction.

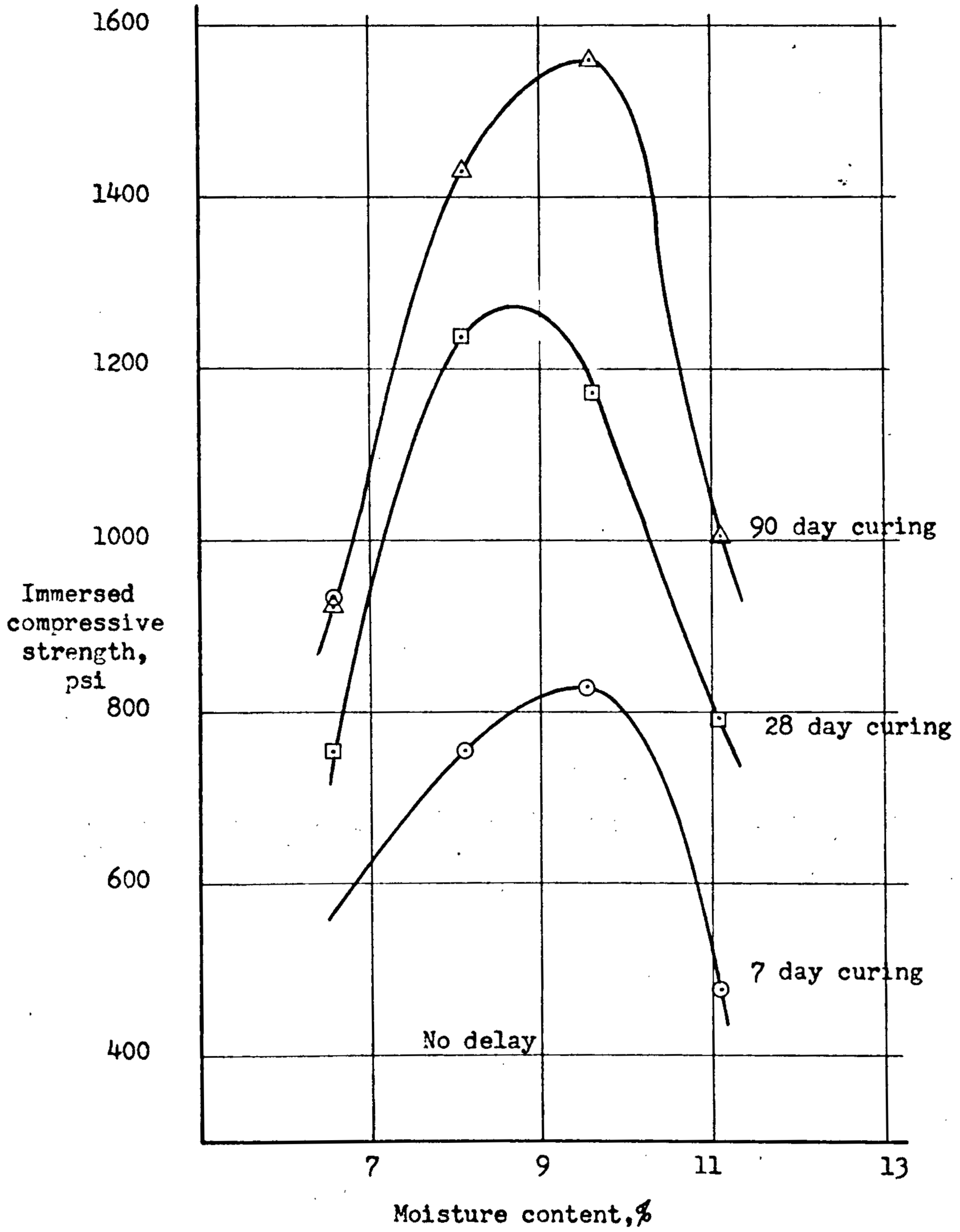

1600
1400
1200
1000
800
600
400
Immersed compressive strength, psi
90 day curing
28 day curing
7 day curing
No delay
7
9
11
13
Moisture content,%

Figure 3. Unconfined compressive strength of sand-loess with 8 per cent cement. Two hour delay between mixing and compaction.

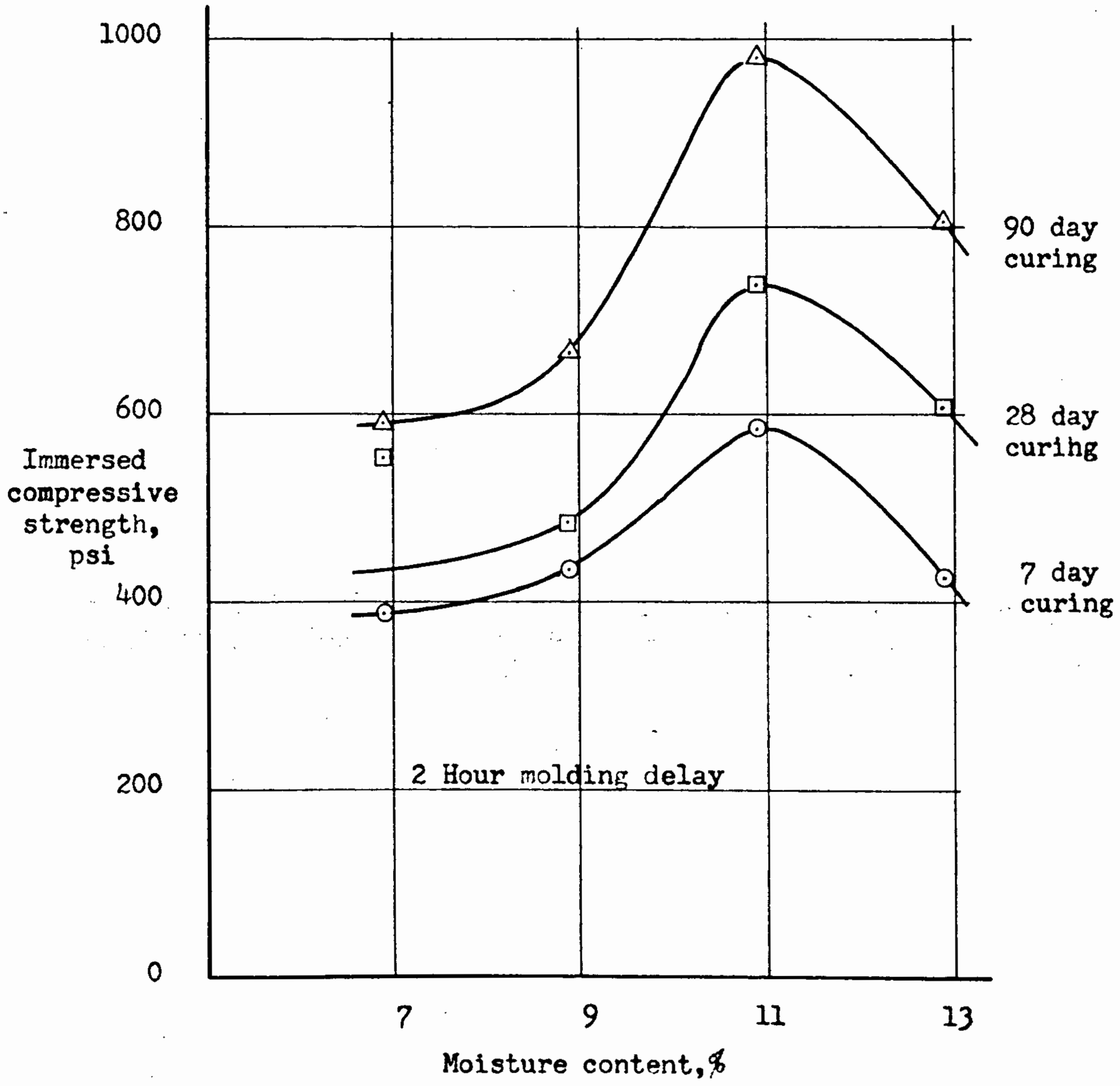

1000
800
600
400
200
0
Immersed compressive strength, psi
90 day curing
28 day curihg
7 day curing
2 Hour molding delay
7
9
11
13
Moisture content,%

Figure 4. Unconfined compressive strength of sand-loess with 8 per cent cement. Six hour delay between mixing and compaction.

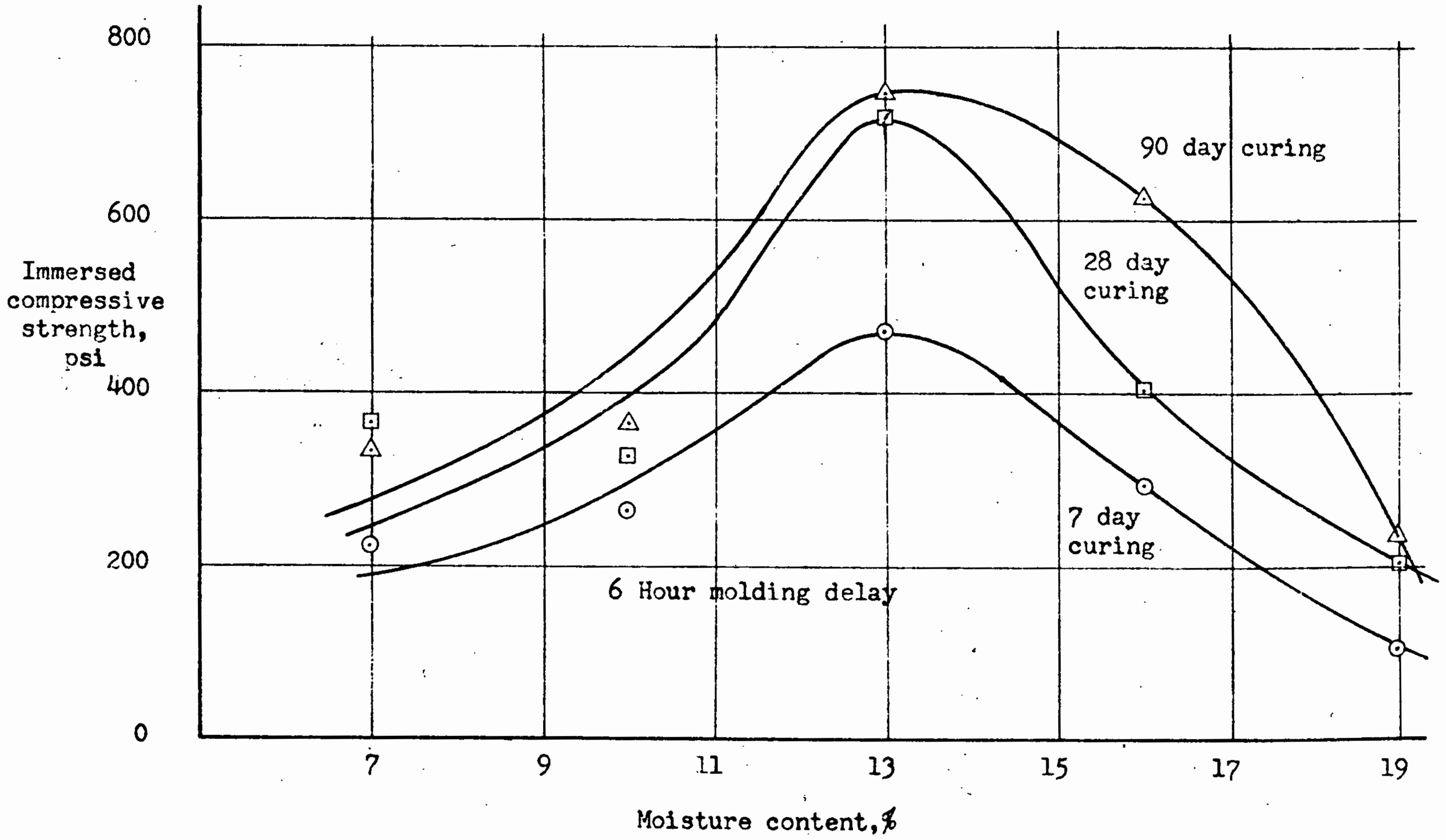

800
600
400
200
0
Immersed compressive strength, psi
7
9
11
13
15
17
19
Moisture content,%
90 day curing
28 day curing
7 day curing
6 Hour molding delay

Figure 5. Unconfined compressive strength of sand-loess with 8 per cent cement. Twenty-four hour delay between mixing and compaction.

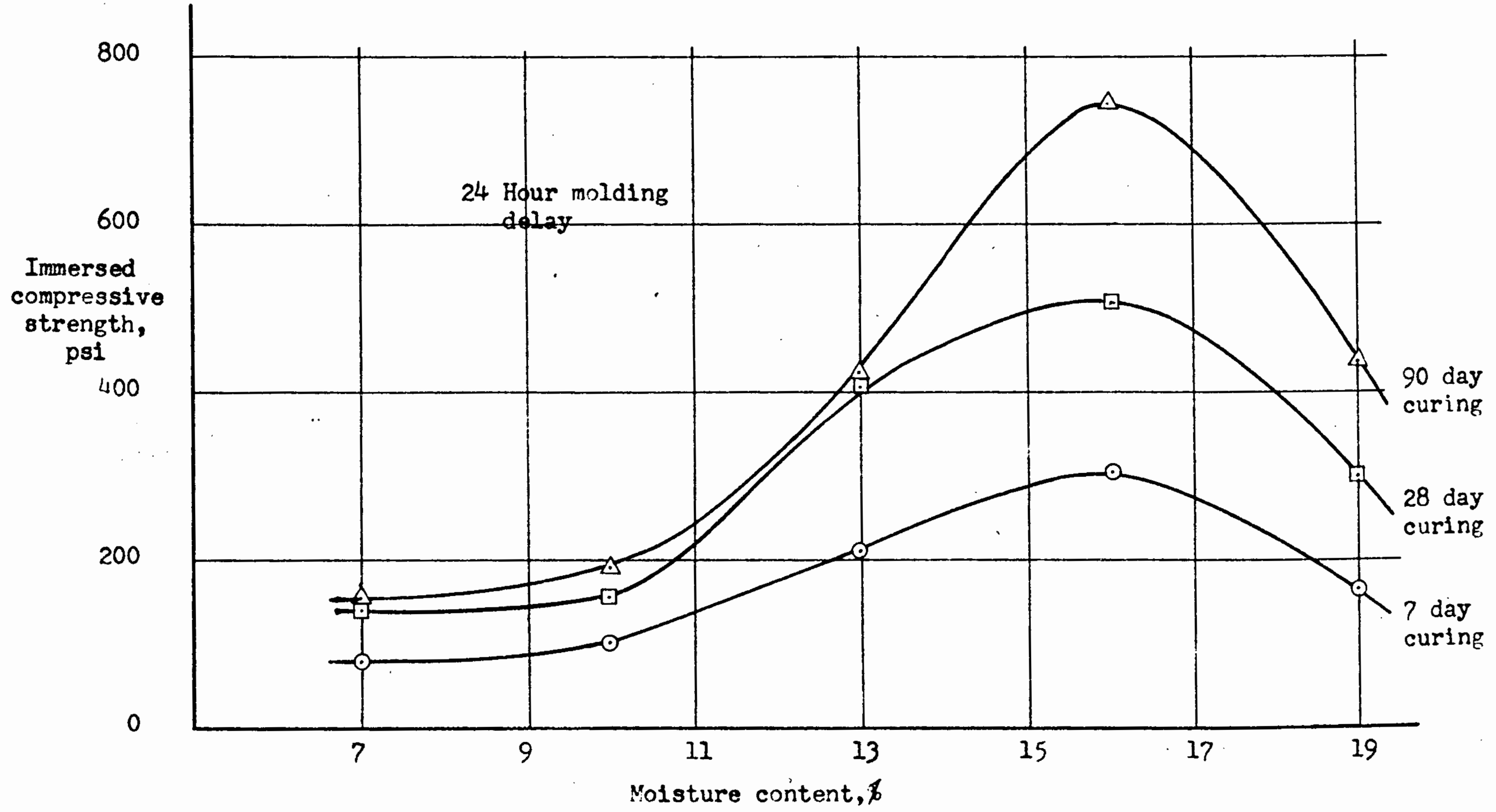
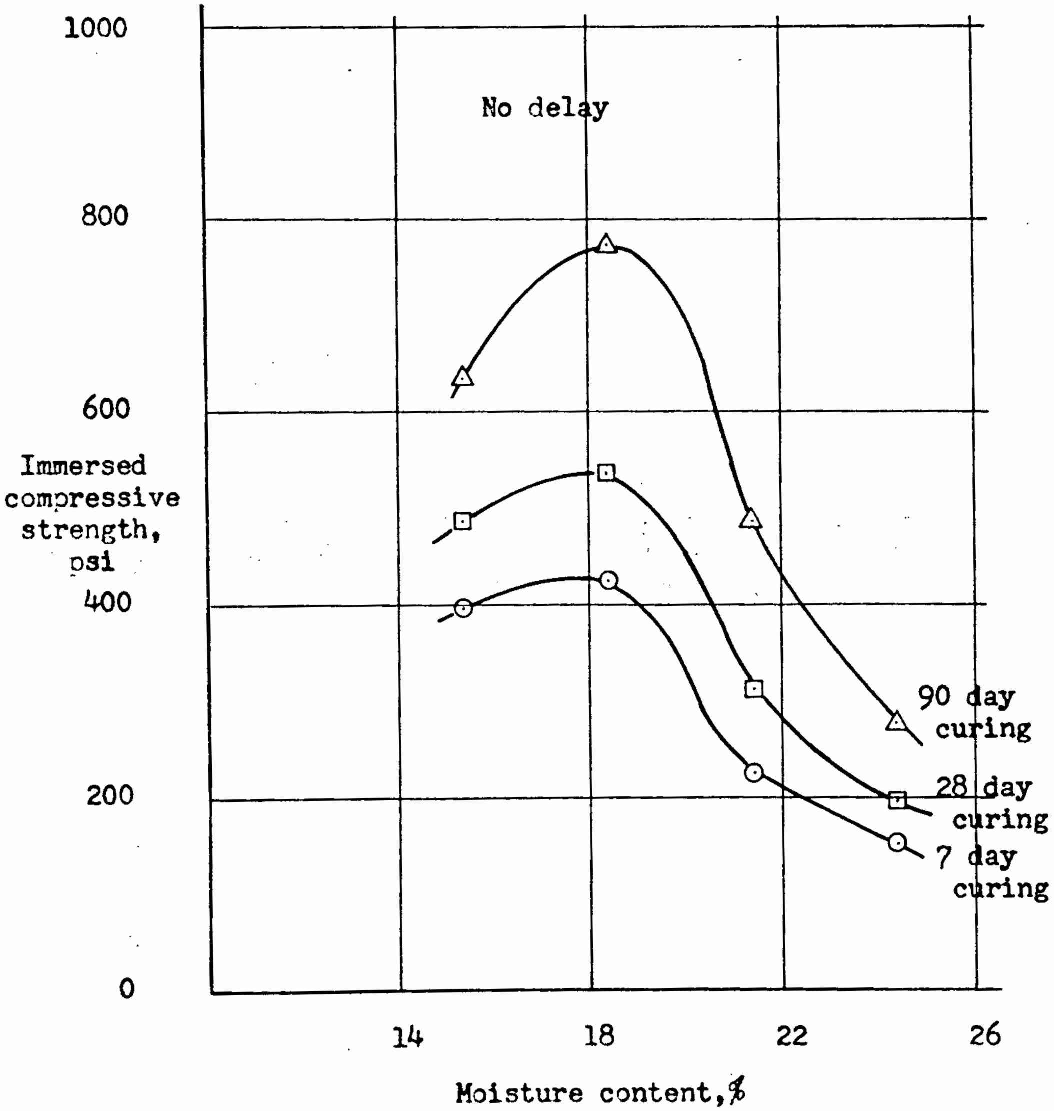

800
600
400
200
0
Immersed compressive strength, psi
24 Hour molding delay
90 day curing
28 day curing
7 day curing
7
9
11
13
15
17
19
Moisture content,%

Figure 6. Unconfined compressive strength of friable loess with 8 per cent cement. No delay between mixing and compaction.



No delay
1000
800
600
400
200
0
Immersed compressive strength, psi
14
18
22
26
Moisture content,%
90 day curing
28 day curing
7 day curing

Figure 7. Unconfined compressive strength of friable loess with 8 per cent cement. Two hour delay between mixing and compaction.

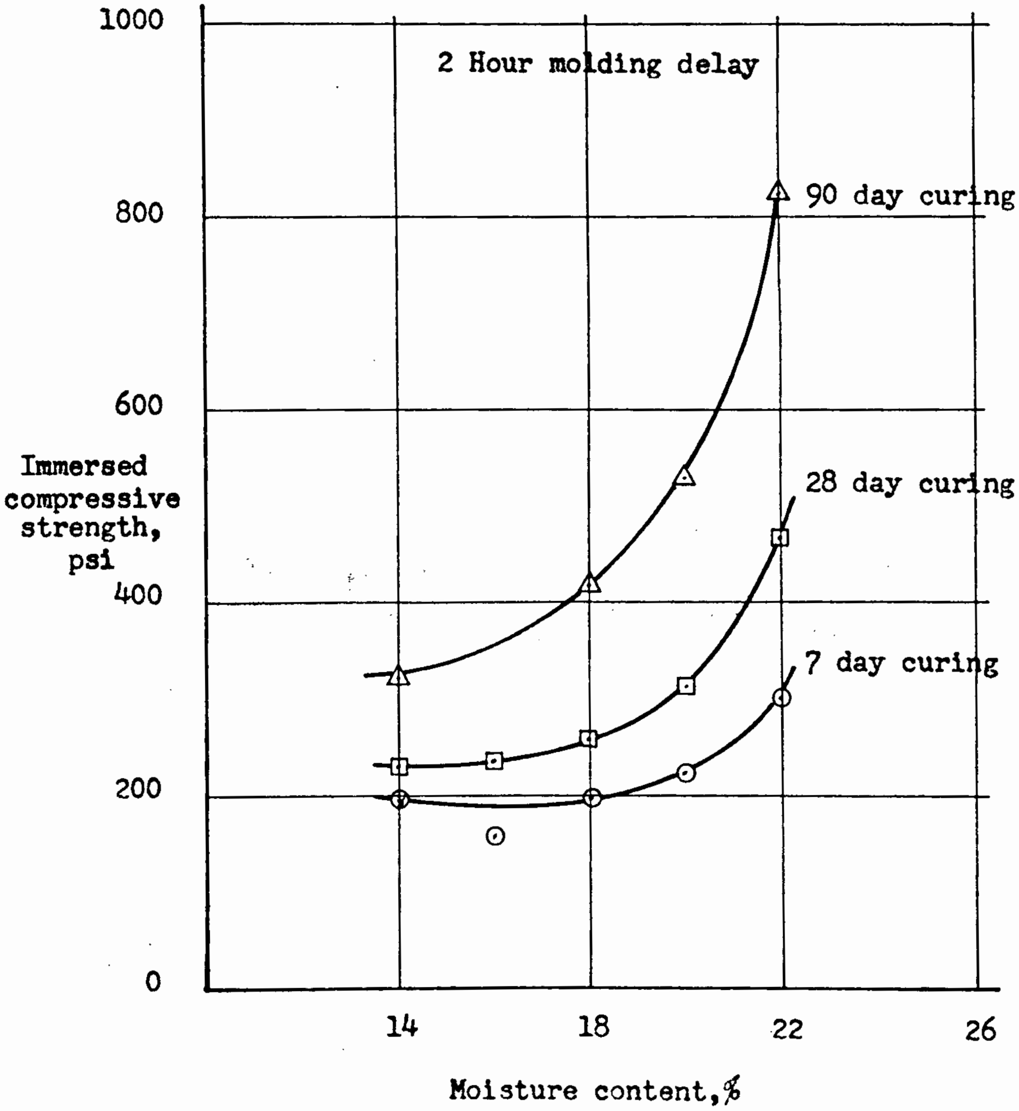

2 Hour molding delay
90 day curing
28 day curing
7 day curing
Immersed compressive strength, psi
1000
800
600
400
200
0
14
18
22
26
Moisture content,%

Figure 8. Unconfined compressive strength of friable loess with 8 per cent cement. Six hour delay between mixing and compaction.

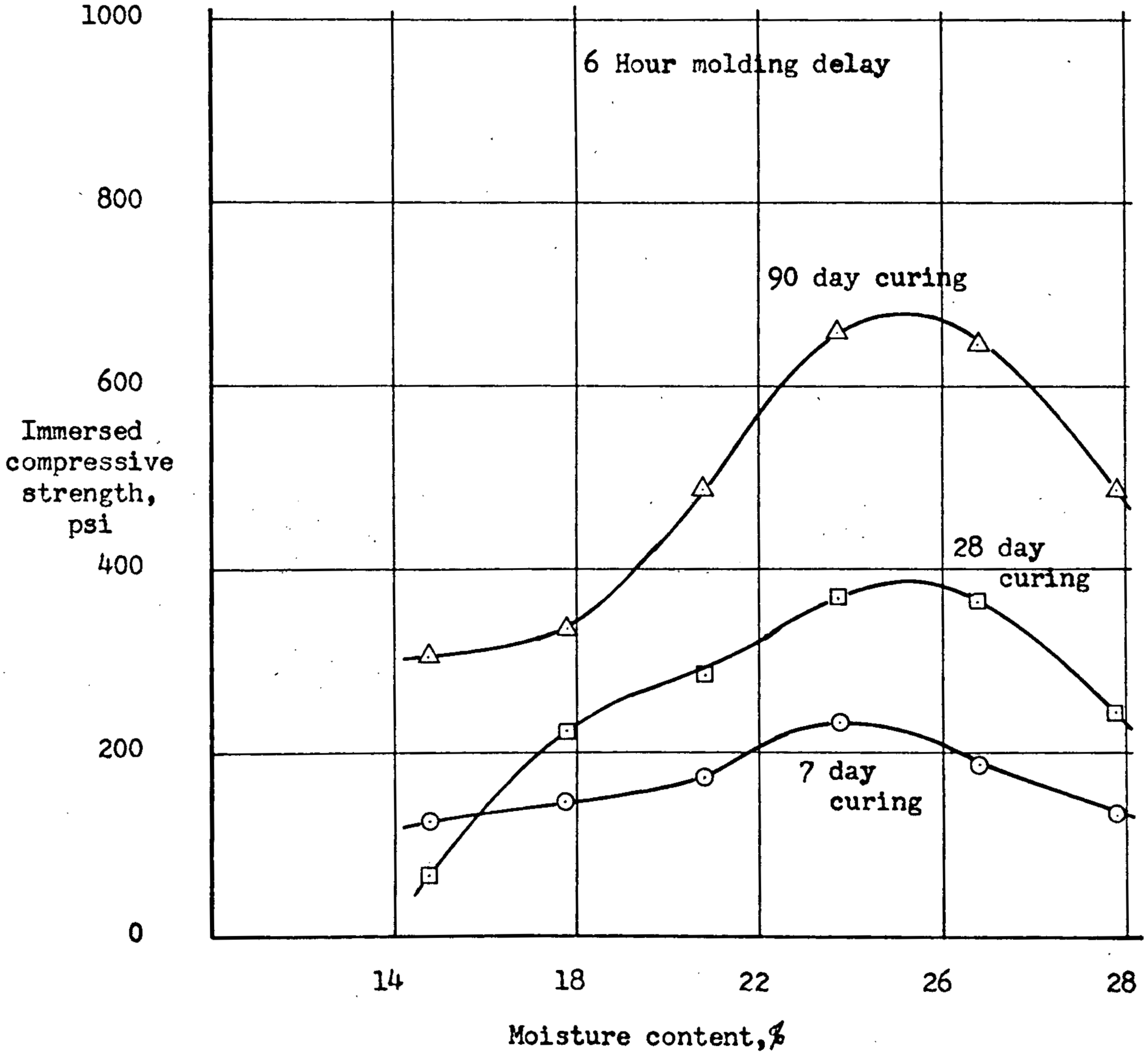

1000
800
600
400
200
0
Immersed compressive strength, psi
6 Hour molding delay
90 day curing
28 day curing
7 day curing
14
18
22
26
28
Moisture content,%

Figure 9. Unconfined compressive strength of friable loess with 8 per cent cement. Twenty-four hour delay between mixing and compaction.

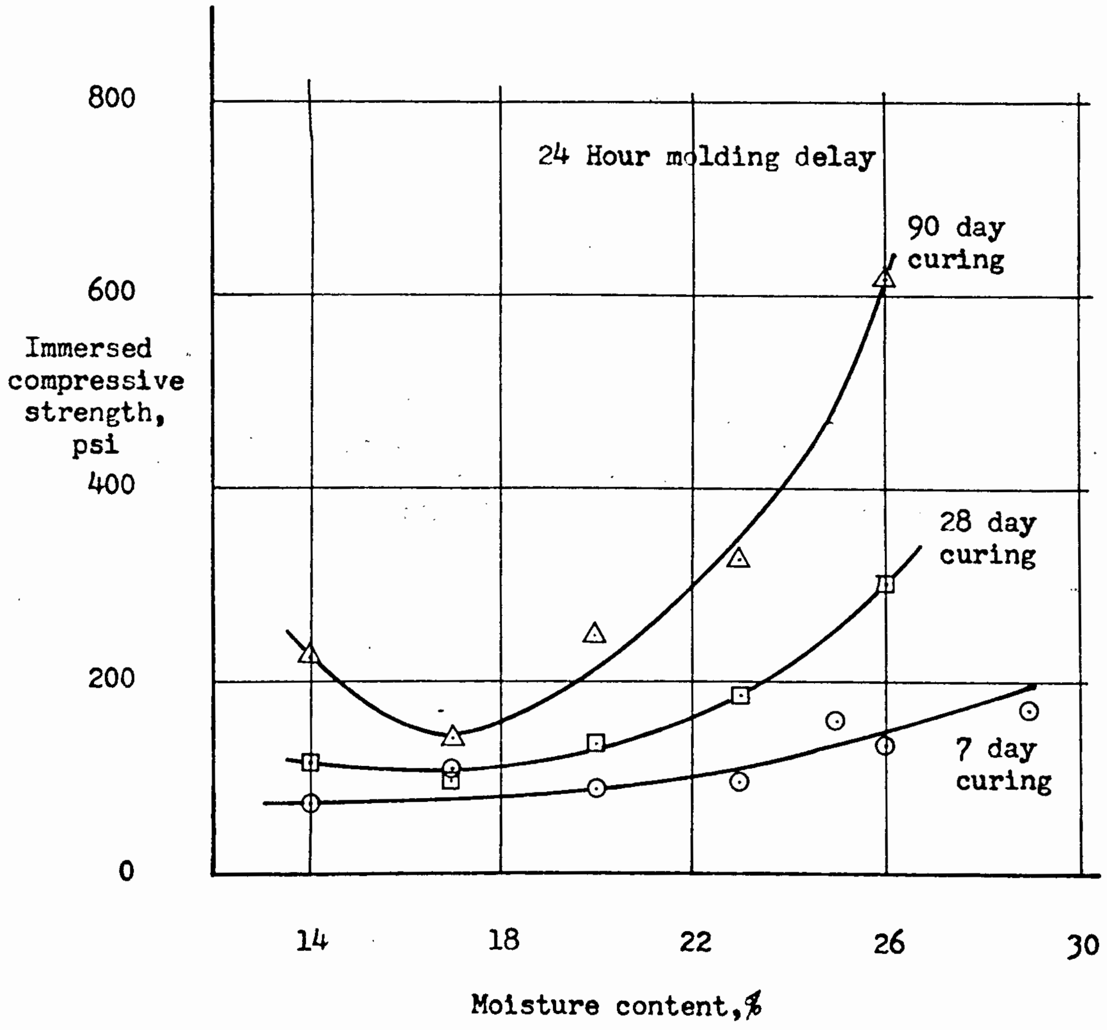

800
600
400
200
0
Immersed compressive strength, psi
24 Hour molding delay
90 day curing
28 day curing
7 day curing
14
18
22
26
30
Moisture content,%

Figure 10. Unconfined compressive strength of dune sand with 8 per cent cement. No delay between mixing and compaction.

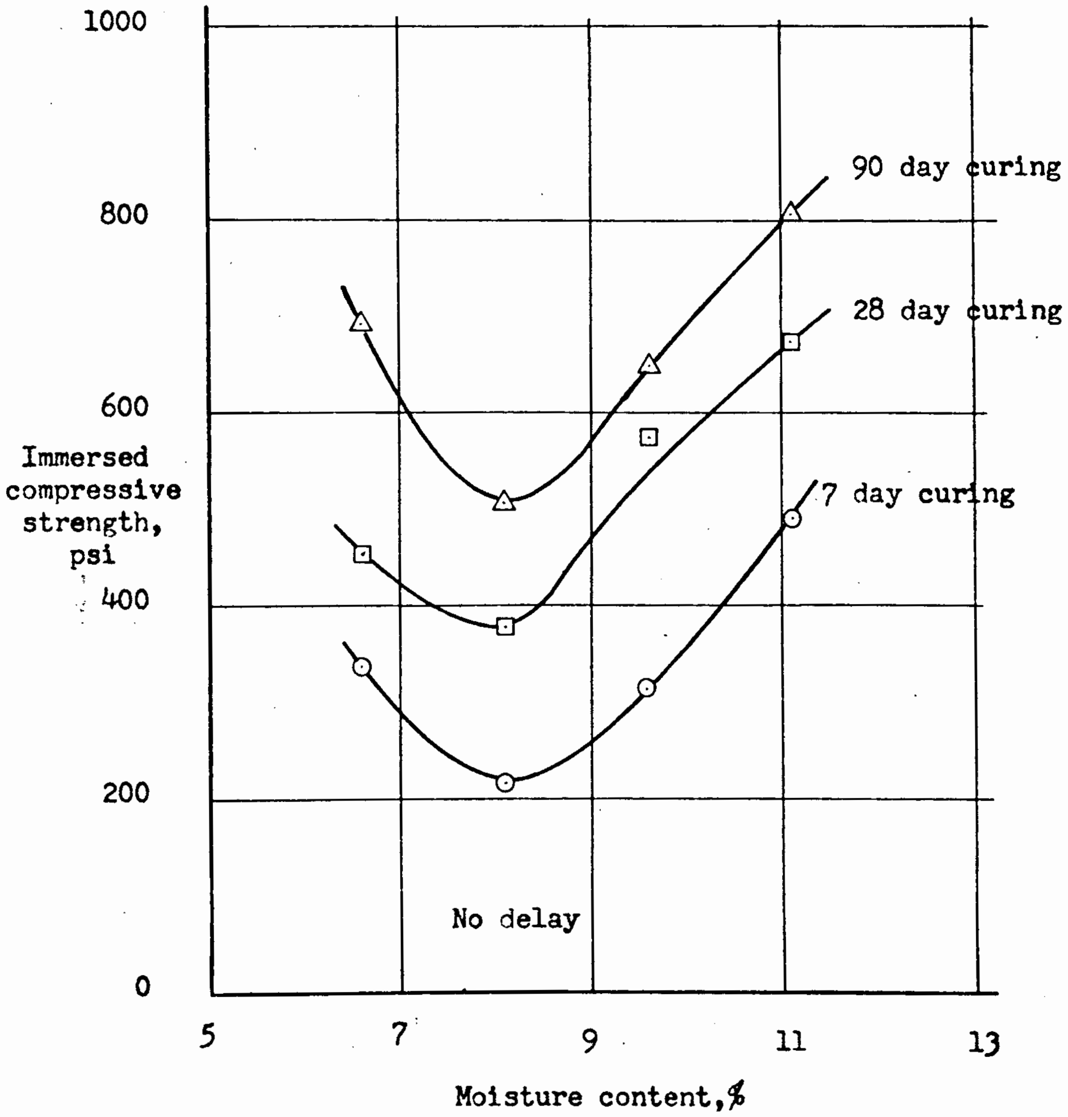

1000
800
600
400
200
0
Immersed compressive strength, psi
5
7
9
11
13
Moisture content,%
90 day curing
28 day curing
7 day curing
No delay

Figure 11. Unconfined compressive strength of dune sand with 8 per cent cement. Two hour delay between mixing and compaction.

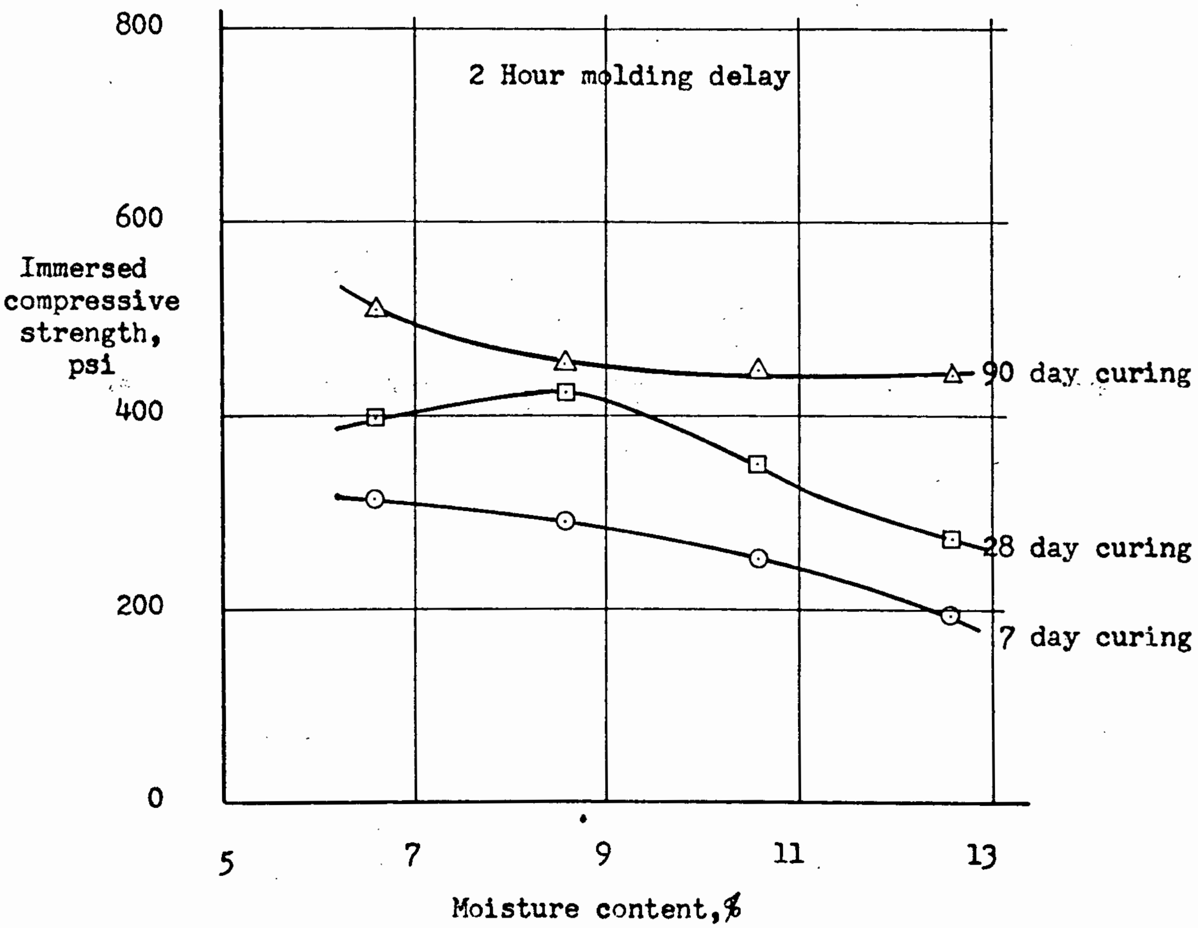

2 Hour molding delay
Immersed compressive strength, psi
800
600
400
200
0
5
7
9
11
13
Moisture content,%
90 day curing
28 day curing
7 day curing

Figure 12. Unconfined compressive strength of dune sand with 8 per cent cement. Six hour delay between mixing and compaction.

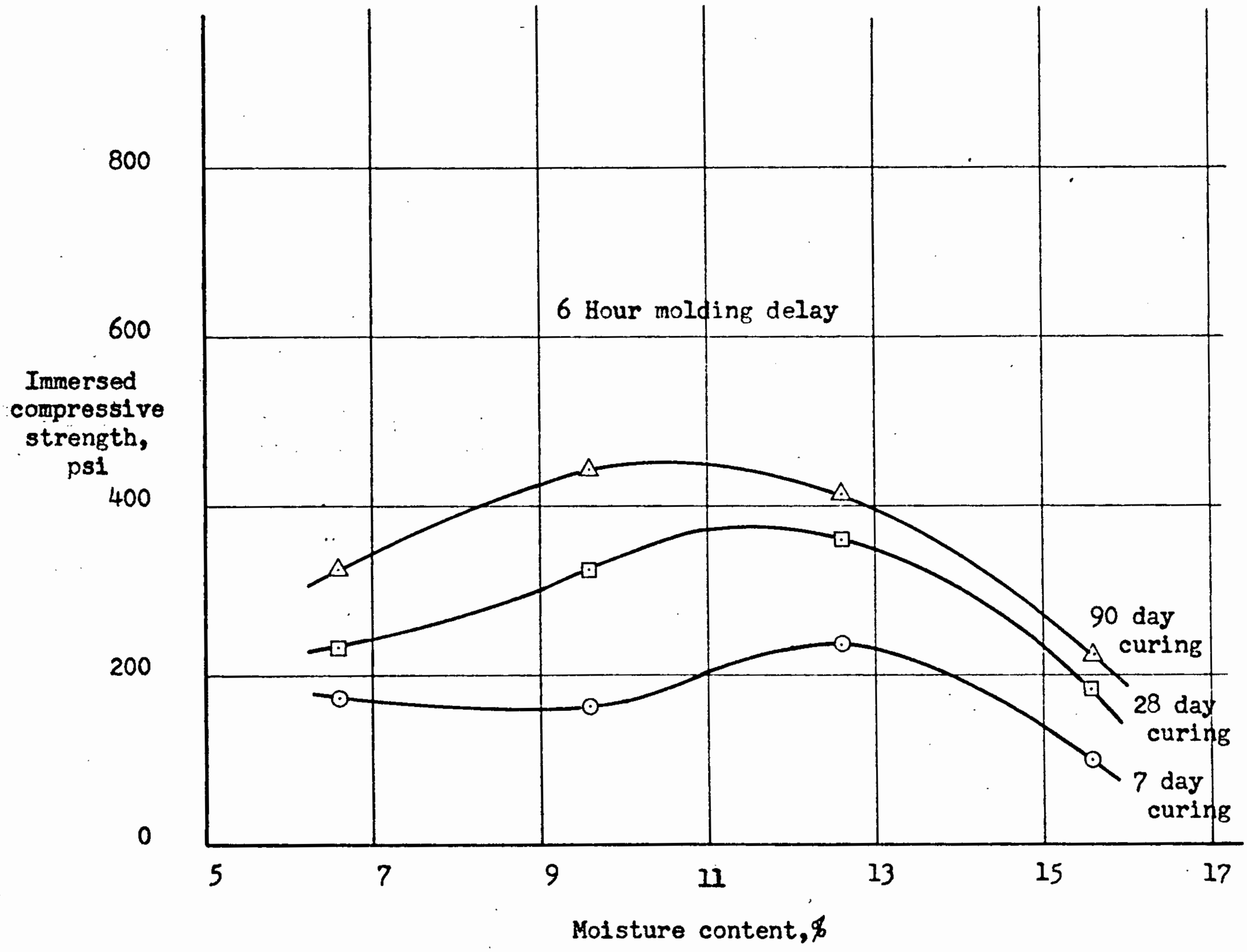

6 Hour molding delay
Immersed compressive strength, psi
800
600
400
200
0
5
7
9
11
13
15
17
Moisture content,%
90 day curing
28 day curing
7 day curing

Figure 13. Unconfined compressive strength of dune sand with 8 per cent cement. Twenty-four hour delay between mixing and compaction.

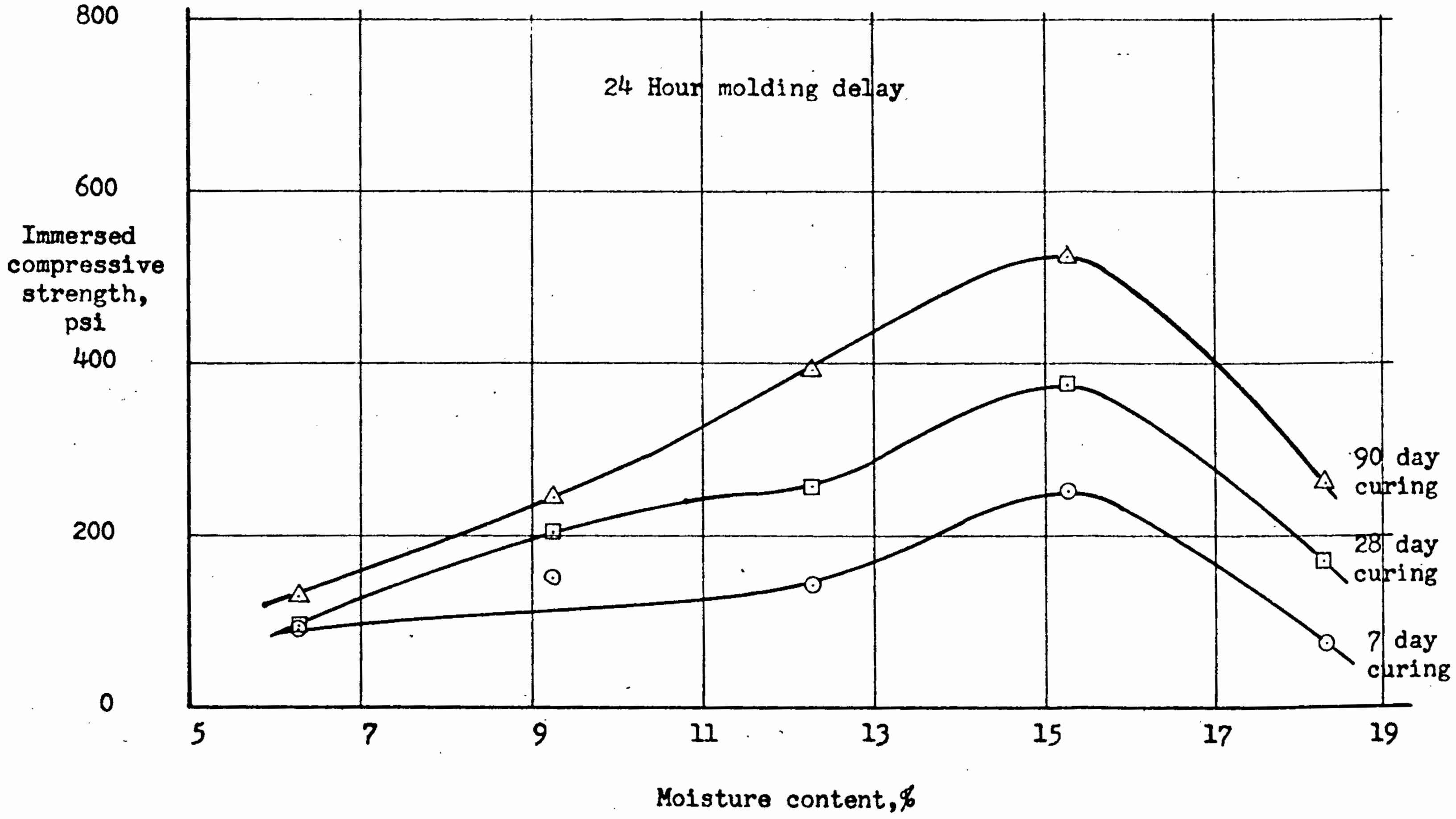

800
600
400
200
0
Immersed compressive strength, psi
24 Hour molding delay
90 day curing
28 day curing
7 day curing
5
7
9
11
13
15
17
19
Moisture content,%

Figure 14. Unconfined compressive strength of sand-loess with 2 per cent lime and 6 per cent cement. No delay between mixing and compaction.

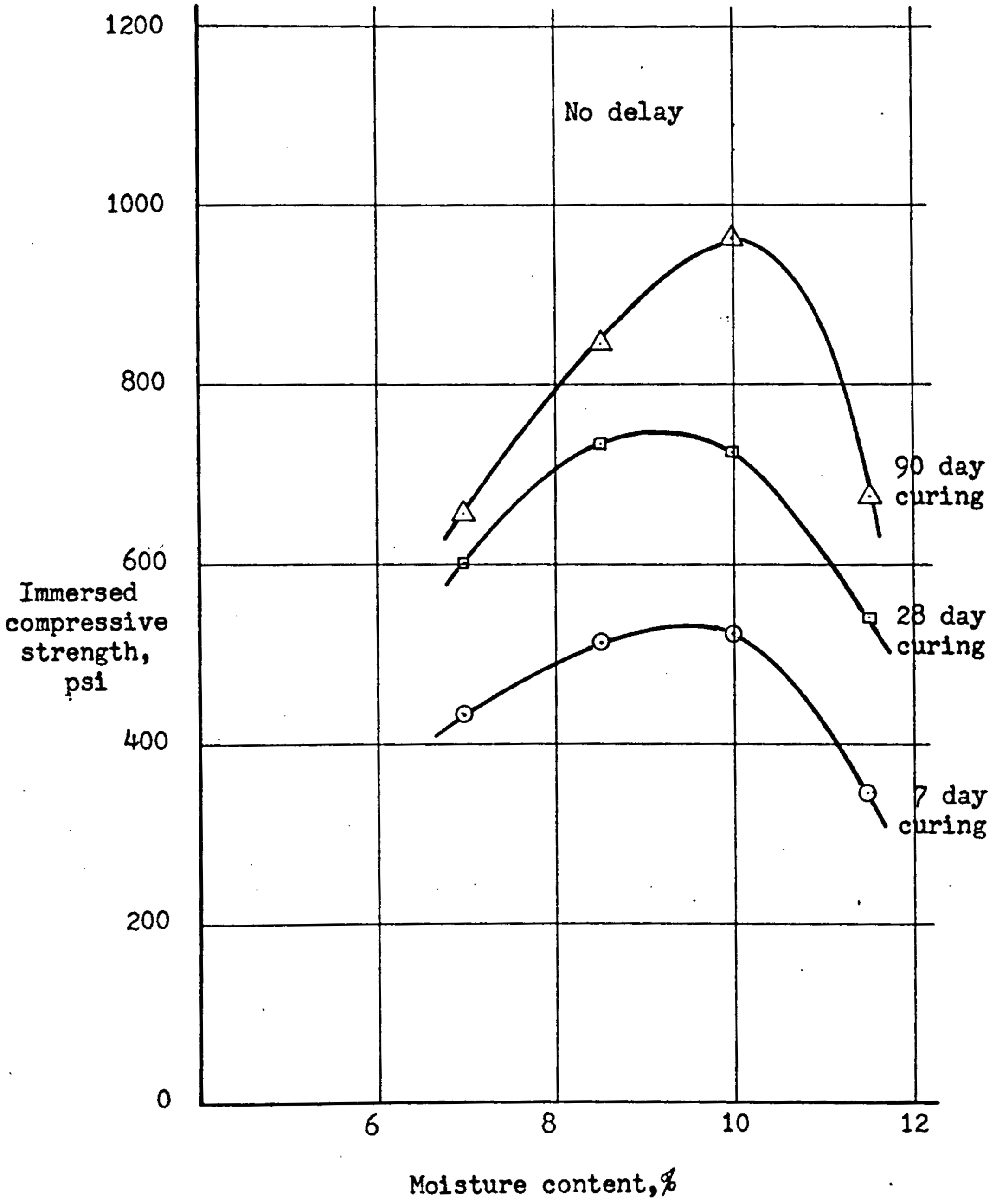

No delay
90 day curing
28 day curing
7 day curing
Immersed compressive strength, psi
0
200
400
600
800
1000
1200
6
8
10
12
Moisture content,%

Figure 15. Unconfined compressive strength of sand-loess with 2 per cent lime and 6 per cent cement. Two hour delay between mixing and compaction.

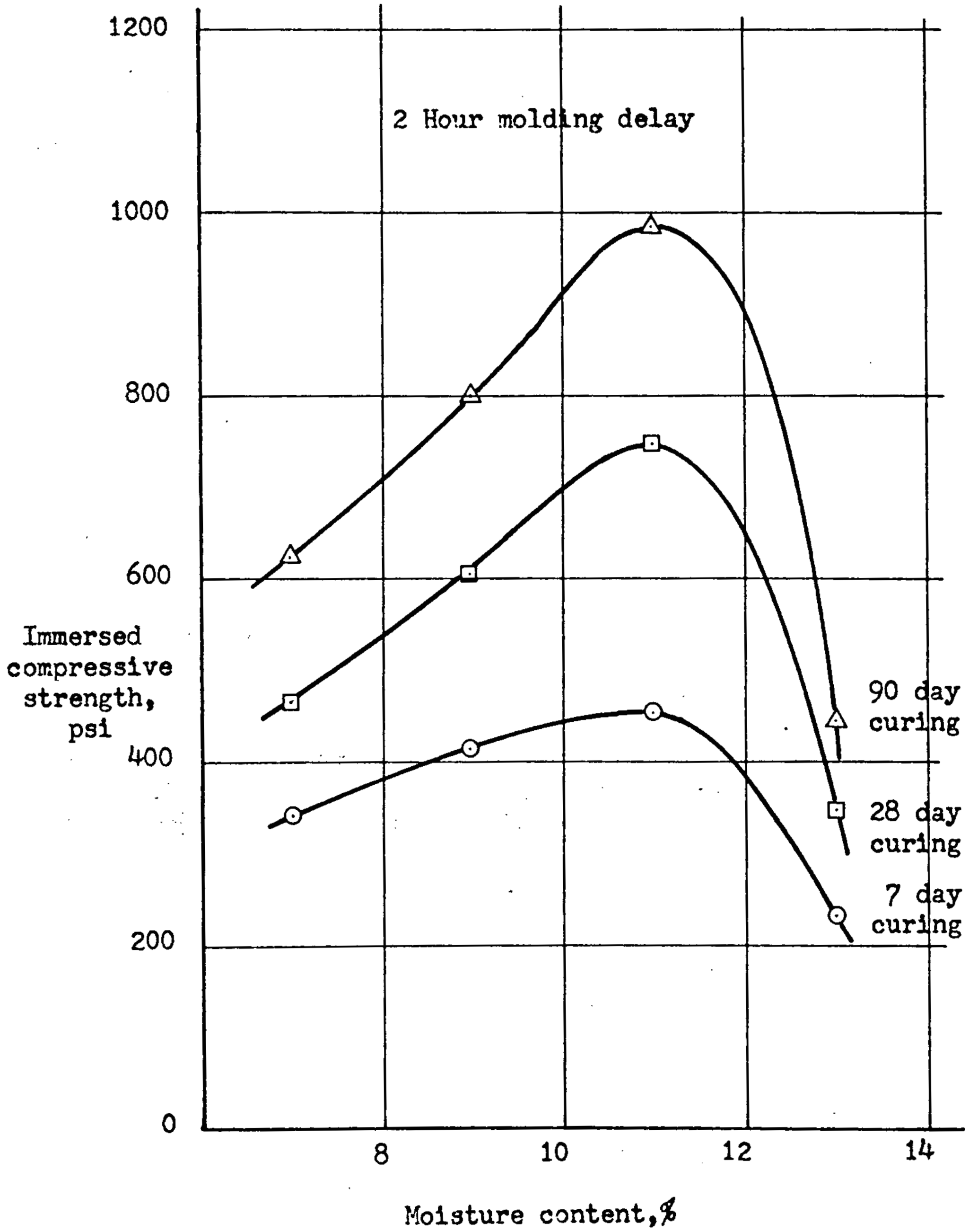

1200
1000
800
600
400
200
0
Immersed compressive strength, psi
2 Hour molding delay
90 day curing
28 day curing
7 day curing
8
10
12
14
Moisture content,%

Figure 16. Unconfined compressive strength of sand-loess with 2 per cent lime and 6 per cent cement. Twenty-four hour delay between mixing and compaction.

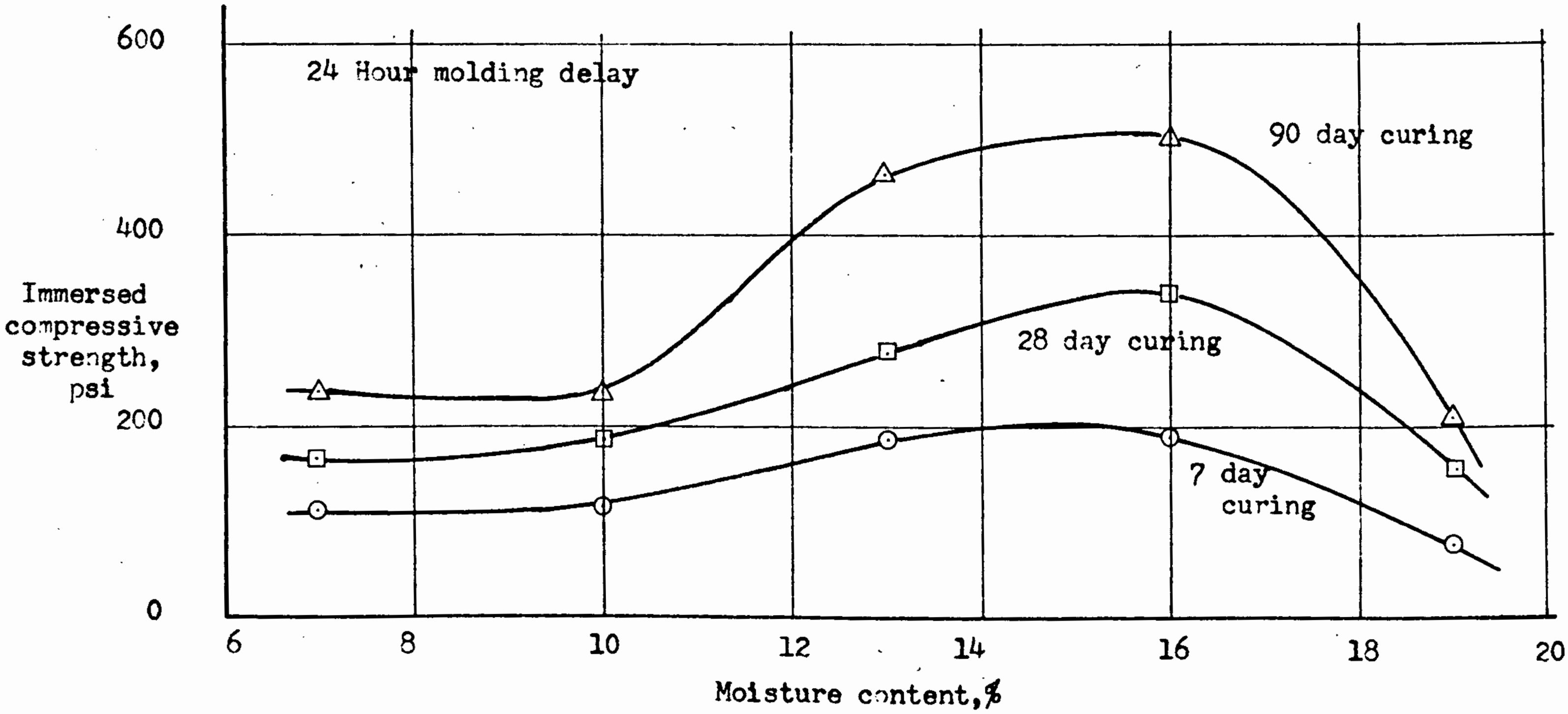

24 Hour molding delay
90 day curing
28 day curing
7 day curing
Immersed compressive strength, psi
600
400
200
0
6
8
10
12
14
16
18
20
Moisture content,%

Figure 17. Unconfined compressive strength of sand-loess with 2 per cent lime and 6 per cent cement. Cement added twenty-four hours after lime. No delay between mixing and compaction.

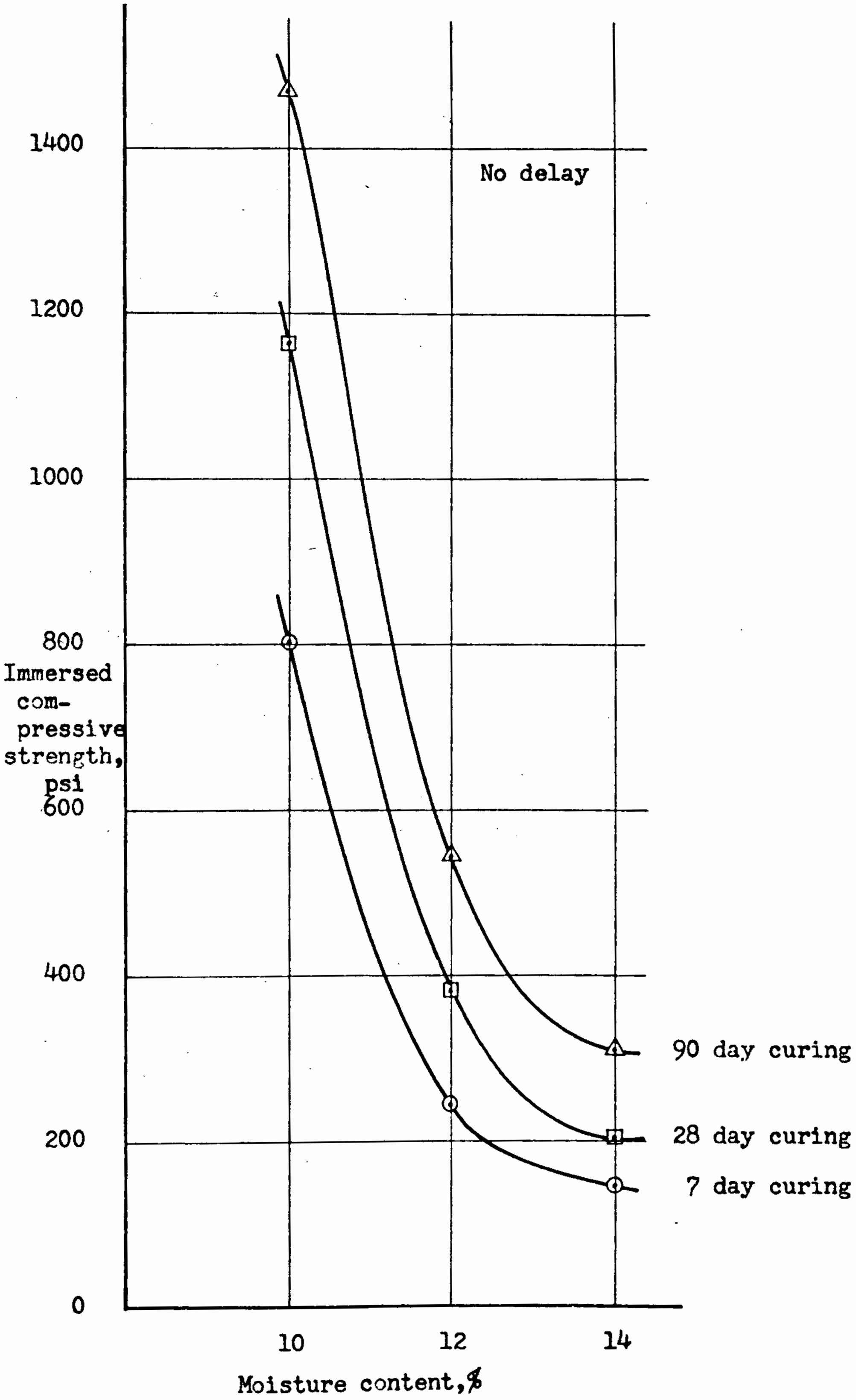

1400
1200
1000
800
600
400
200
0
Immersed com-pressive strength, psi
10
12
14
Moisture content,%
No delay
90 day curing
28 day curing
7 day curing

Figure 18. Unconfined compressive strength of sand-loess with 2 per cent lime and 6 per cent cement. Cement added twenty-four hours after lime. Two hour delay between mixing and compaction.

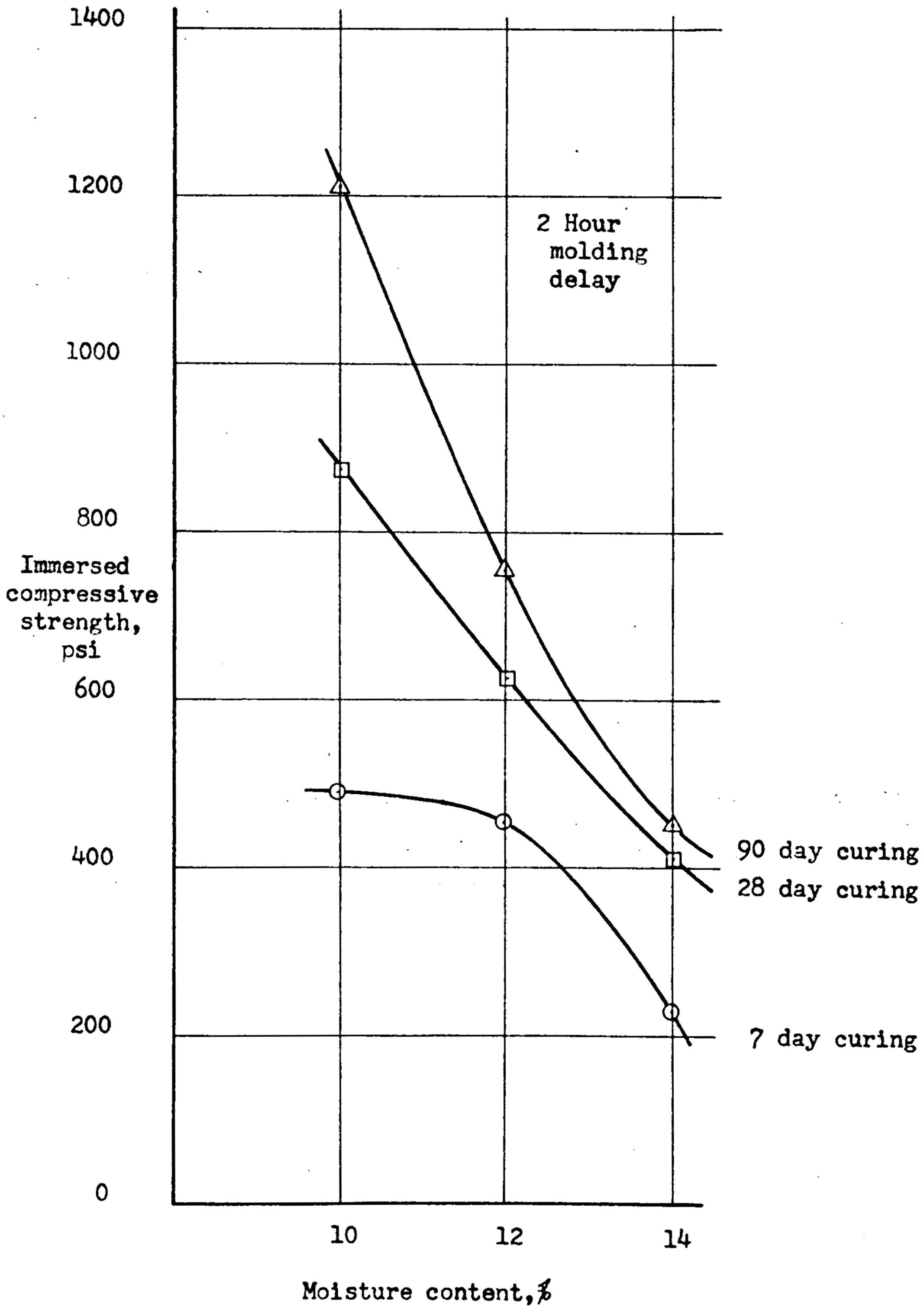
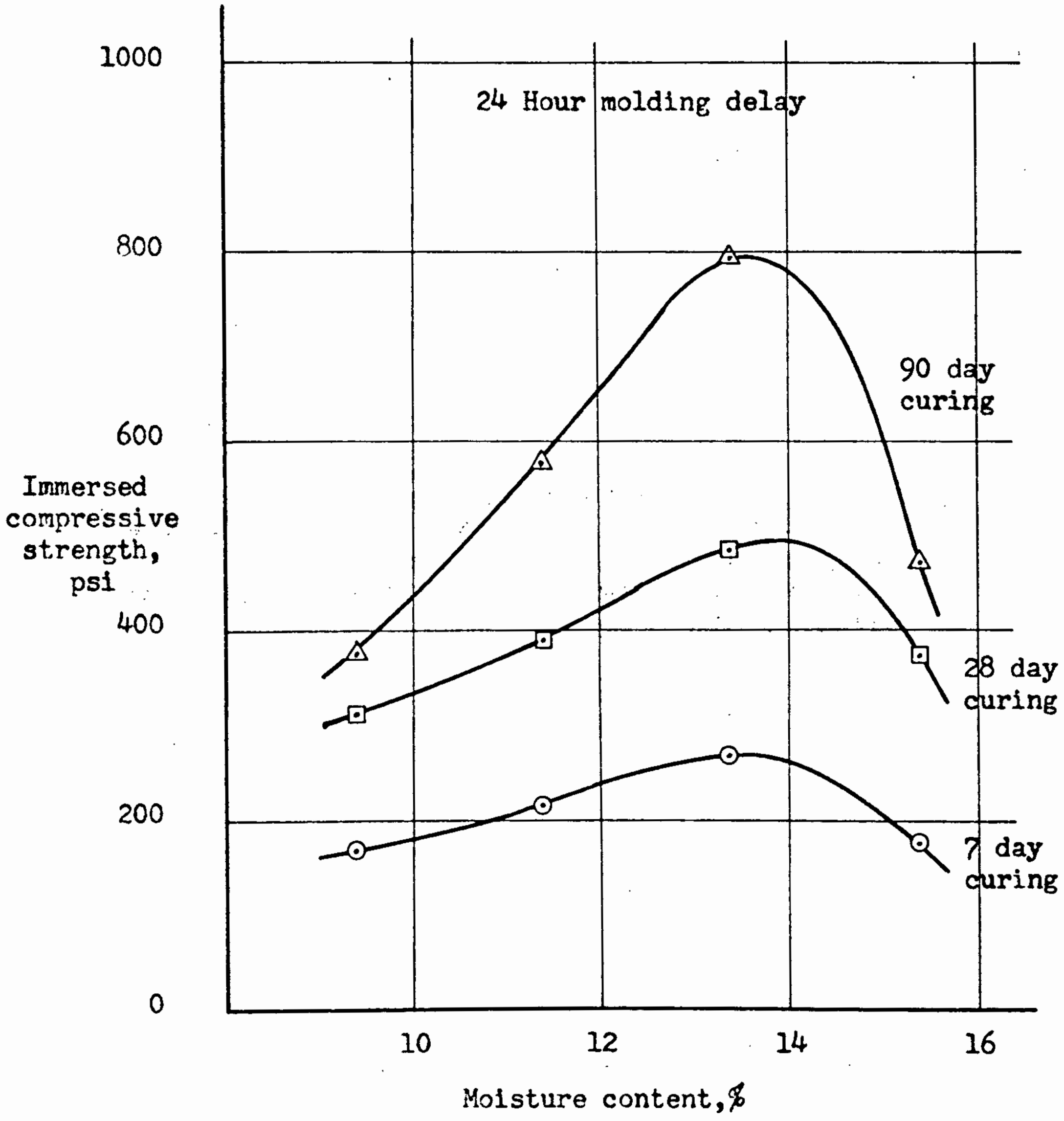

1400
1200
1000
800
Immersed compressive strength, psi
600
400
200
0
10
12
14
Moisture content,%
2 Hour molding delay
90 day curing
28 day curing
7 day curing

Figure 19. Unconfined compressive strength of sand-loess with 2 per cent lime and 6 per cent cement. Cement added twenty-four hours after lime. Twenty-four hour delay between mixing and compaction.


24 Hour molding delay
Immersed compressive strength, psi
1000
800
600
400
200
0
10
12
14
16
Moisture content,%
90 day curing
28 day curing
7 day curing

Density

The computed densities of the soil-cement and soil-lime-cement mixtures at various moisture contents are shown in Figures 20 through 24 for a compaction delay of 24 hours. Detailed data for all delay periods are presented in Tables 5 through 9 in the Appendix.

In general, the data indicate that the optimum moisture content for maximum density increases with increasing lengths of delay. Also, the maximum density for any delay period was less than the maximum density for the case of no delay.

The amount of increase in optimum moisture contents after various delay periods is summarized in Table 4. The greatest increase in moisture, for the 24 hour delay, varied from 3.7 per cent for dune sand-cement to 7.6 per cent for friable loess-cement. The amount of the increase for sand-loess for a given delay time was about equal regardless of the additive used, i.e., cement or lime plus cement, about 1 per cent increase being needed after a 2 hour delay, and 6 per cent after a 24 hour delay.

The effect of delay time on density which gave maximum 28 day strength is shown in Figure 25. In all mixtures tested, the decrease in density was more pronounced between no delay and 6 hours of delay, than in the interval between 6 hours and 24 hours delay. At the 6 hour delay, sand-loess exhibited the largest density loss (11 pcf), and the dune sand the least (5 pcf).

Table 4. Increase in optimum moisture content for maximum density after various delay periods between mixing and compaction

Soil	Additive	2 hour delay	6 hour delay	24 hour delay
Dune sand	8% cement	0%	0%	3.7%
Sand-loess	8% cement	1	3	6.4
Friable loess	8% cement	4	6.6	7.6
Sand-loess	2% lime + 6% cement	1	--	6
Sand-loess	2% lime + 6% cement (added 24 hours after lime)	1	---	6

The maximum 28 day compressive strength of soil-cement and soil-lime-cement mixtures after varying delays between mixing and compaction is shown in Figure 26. As in the density versus time delay curves, a 6 hour delay caused a sharp decrease in strength followed by a less pronounced decrease upon further delay. A 6 hour delay in compaction of dune sand-cement mixture resulted in a 50 per cent decrease in compressive strength from the no delay case. The sand-loess-cement mixture also exhibited a high loss (approximately 40 per cent) with a 6 hour delay, whereas the decrease in strength of the friable loess-cement was about

Figure 20. Dry density of sand-loess with 8 per cent cement. Twenty-four hour delay between mixing and compaction.

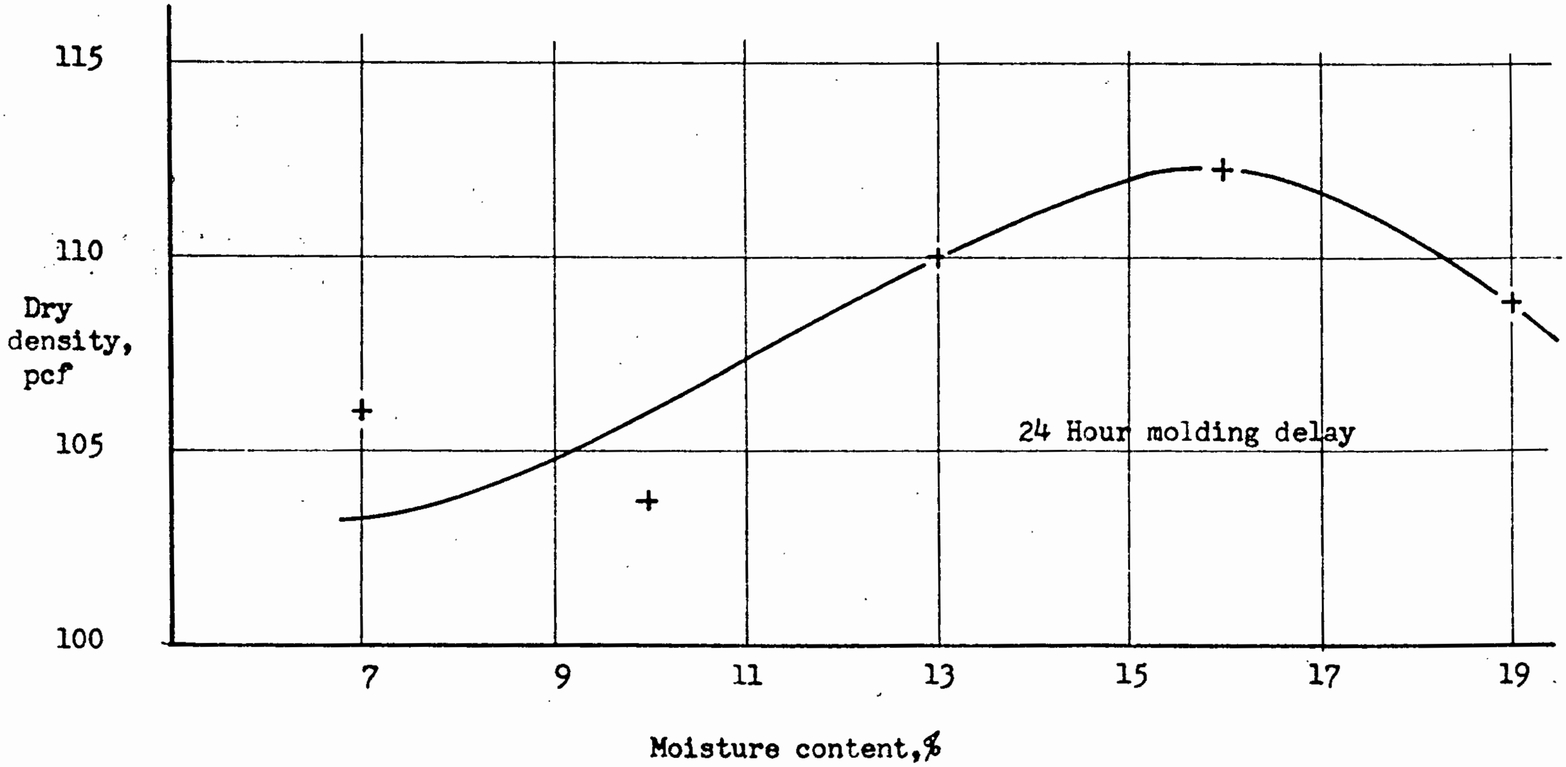

115
110
105
100
Dry density, pcf
7
9
11
13
15
17
19
Moisture content,%
24 Hour molding delay

Figure 21. Dry density of friable loess with 8 per cent cement. Twenty-four hour delay between mixing and compaction.

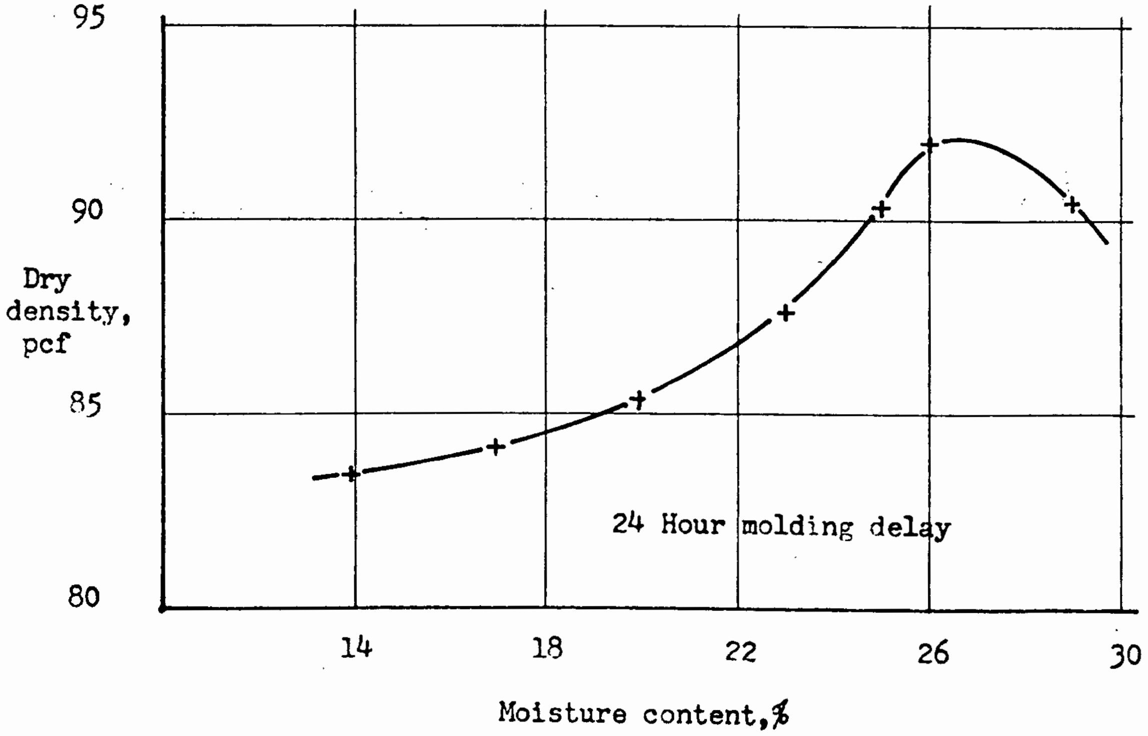

95
90
85
80
Dry density, pcf
14
18
22
26
30
Moisture content,%
24 Hour molding delay

Figure 22. Dry density of dune sand with 8 per cent cement. Twenty-four hour delay between mixing and compaction.

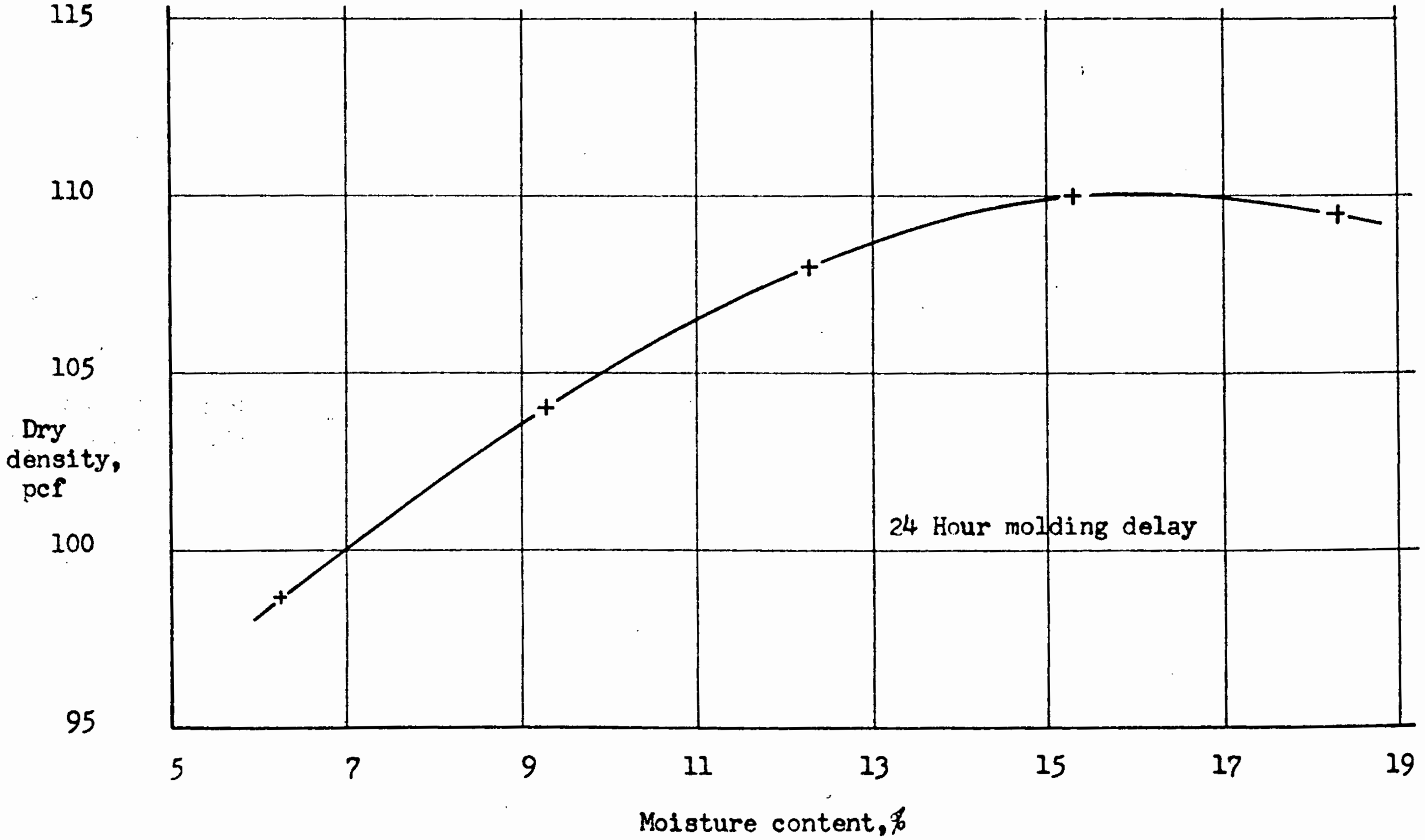

115
110
105
100
95
Dry density, pcf
5
7
9
11
13
15
17
19
Moisture content,%
24 Hour molding delay

Figure 23. Dry density of sand-loess with 2 per cent lime and 6 per cent cement. No delay between mixing and compaction.

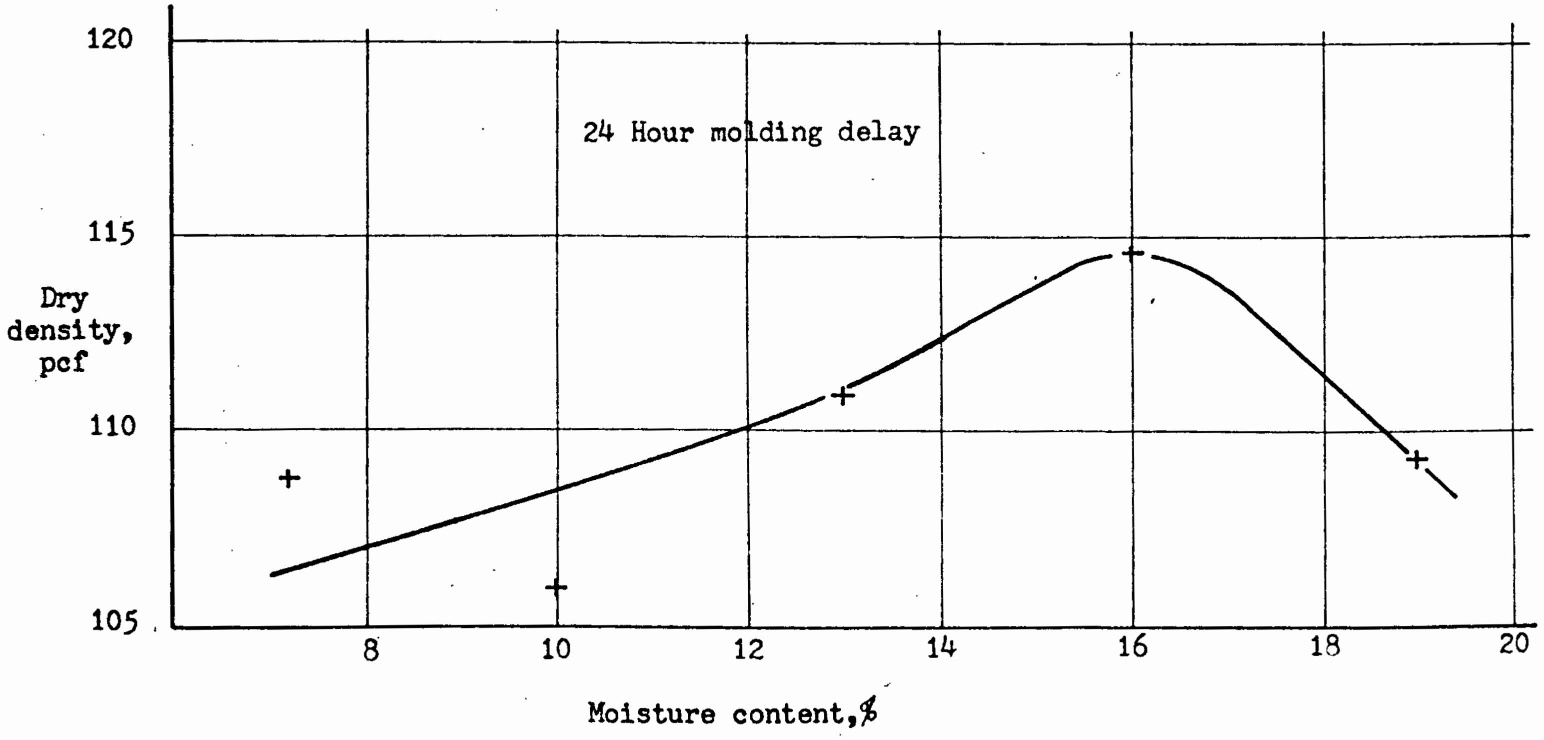

120
115
110
105
Dry density, pcf
24 Hour molding delay
8
10
12
14
16
18
20
Moisture content,%

Figure 24. Dry density of sand-loess with 2 per cent lime and 6 per cent cement. Cement added twenty-four hours after lime. Twenty-four hour delay between mixing and compaction.

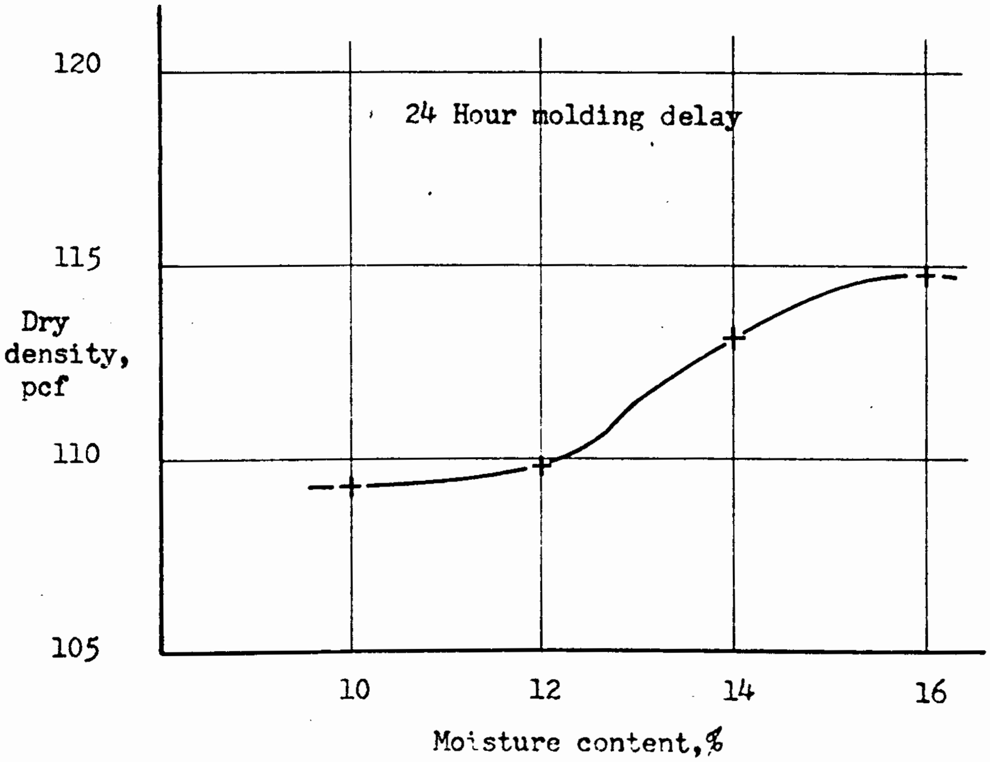

24 Hour molding delay
120
115
110
105
Dry density, pcf
10
12
14
16
Moisture content,%

Figure 25. Dry density at optimum moisture content for maximum 28 day strength of soil-cement and soil-lime cement mixtures at varying delays between mixing and compaction.

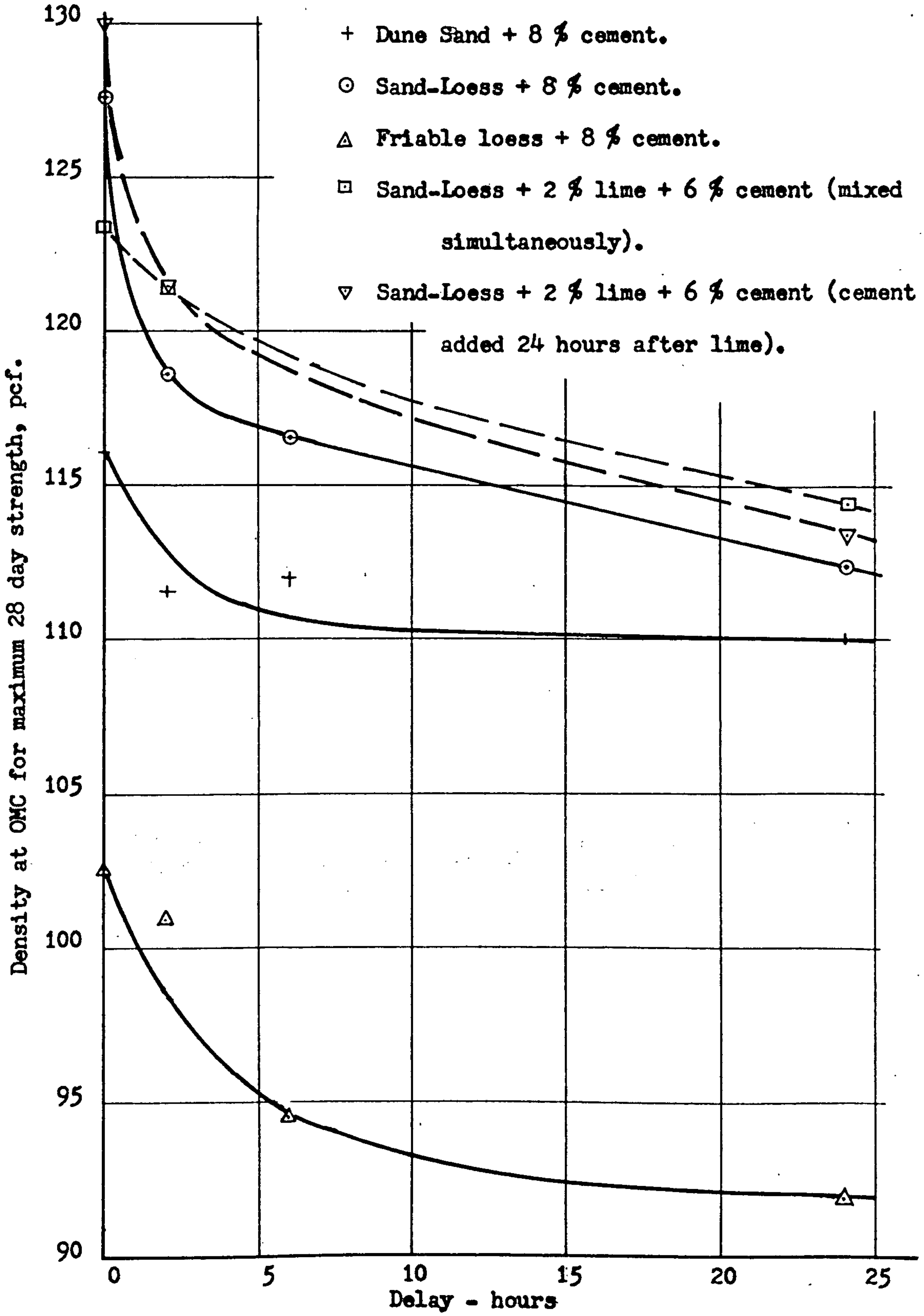
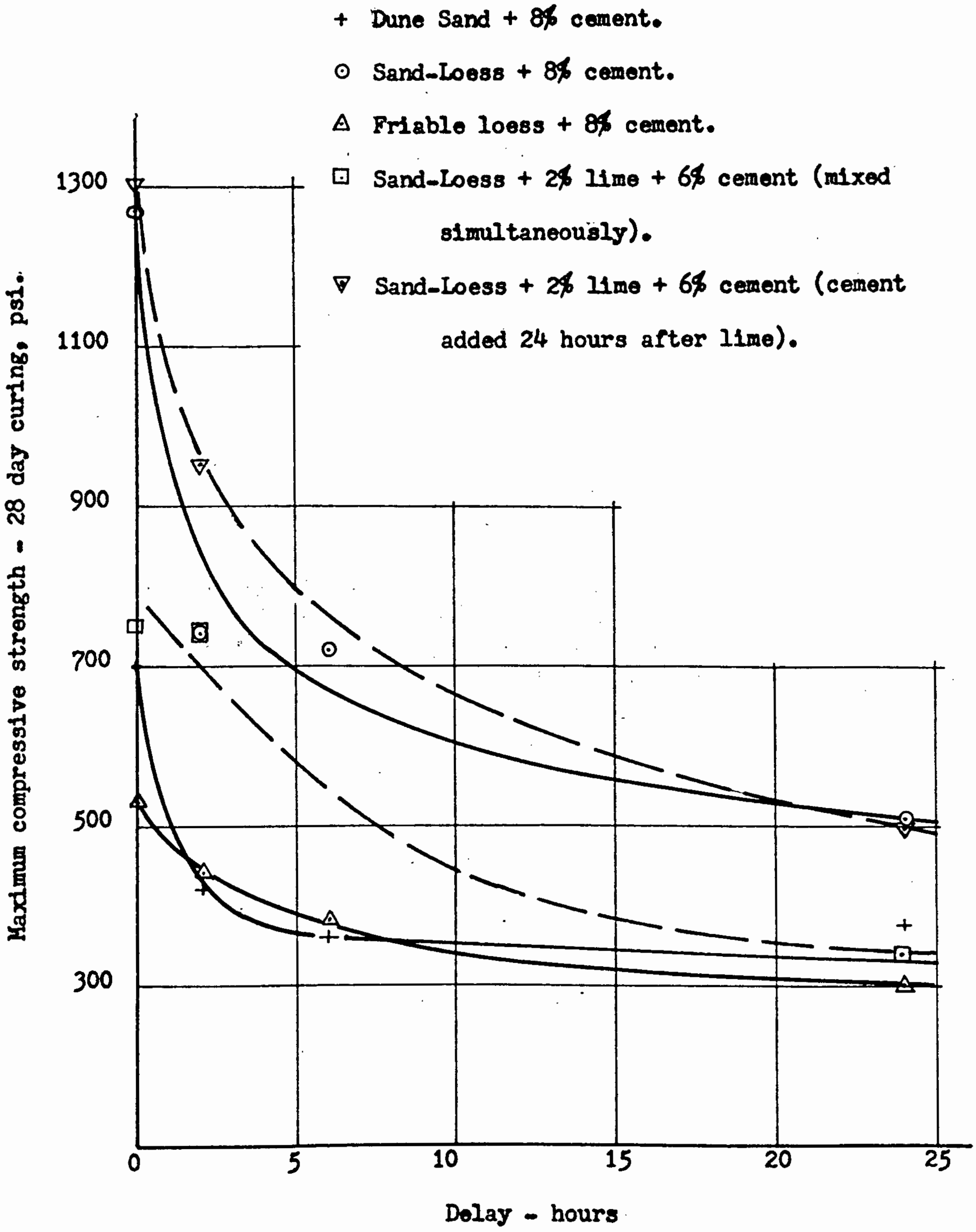

+ Dune Sand + 8 % cement.
⊙ Sand-Loess + 8 % cement.
△ Friable loess + 8 % cement.
⊡ Sand-Loess + 2 % lime + 6 % cement (mixed simultaneously).
▽ Sand-Loess + 2 % lime + 6 % cement (cement added 24 hours after lime).
Density at OMC for maximum 28 day strength, pcf.
130
125
120
115
110
105
100
95
90
0
5
10
15
20
25
Delay - hours

Figure 26. Maximum compressive strength after 28 day curing of soil-cement and soil-lime-cement mixtures at varying delays between mixing and compaction.


+ Dune Sand + 8% cement.
⊙ Sand-Loess + 8% cement.
△ Friable loess + 8% cement.
⊡ Sand-Loess + 2% lime + 6% cement (mixed simultaneously).
▽ Sand-Loess + 2% lime + 6% cement (cement added 24 hours after lime).
Maximum compressive strength - 28 day curing, psi.
1300
1100
900
700
500
300
0
5
10
15
20
25
Delay - hours

30 per cent. After a 24 hour delay the losses for dune sand, sand-loess, and friable loess were 53, 60, and 43 per cent respectively.

The relation between maximum 28 day compressive strength and computed density is shown in Figure 27. In all mixtures tested there was an increase in strength with increasing density, and the highest density occurred when there was no delay between mixing and compaction (Figure 25).

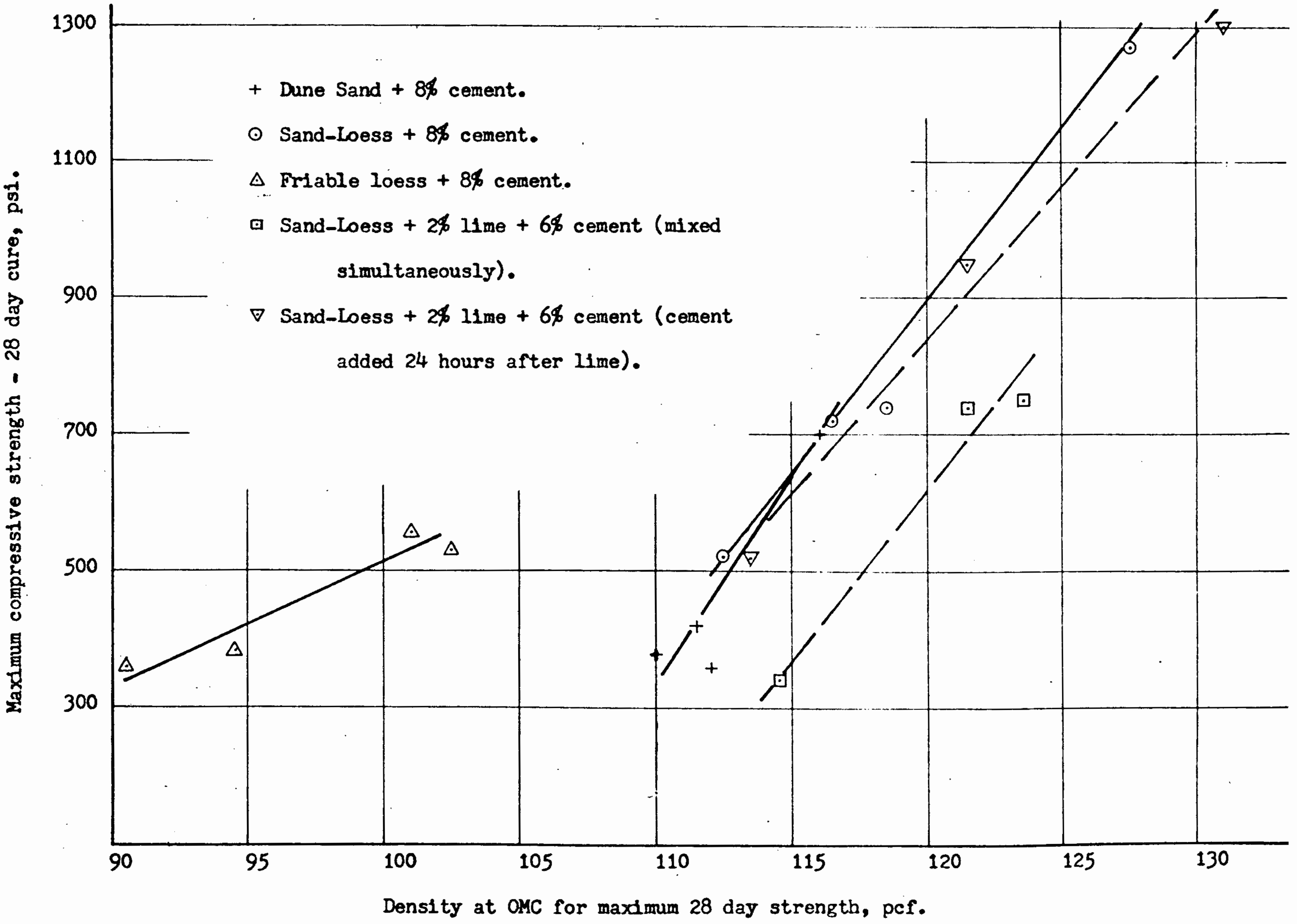
As indicated by the slopes of the strength-density curves in Figure 27, the friable loess-cement mixture was less sensitive to strength loss with decreasing density than were the other mixtures. It is seen that the strength-density relationship for the sand-loess soil was not affected by the type of additive, the three curves involving this soil all having equal slope. The strength of dune sand-cement was slightly more sensitive to change indensity than the sand-loess mixtures.

Discussion

Previous investigations have verified that the optimum moisture content varies when a certain time elapses between mixing and compaction (8). Other studies on montmorillinitic soils bear this out, even when remixing is done periodically within a relatively short delay time (6) (10).

The large reduction in maximum strength of the dune sand

Figure 27. Maximum compressive strength after 28 day curing of soil-cement and soil-lime-cement mixtures versus density at optimum moisture content for maximum 28 day strength.


+ Dune Sand + 8% cement.
⊙ Sand-Loess + 8% cement.
△ Friable loess + 8% cement.
⊡ Sand-Loess + 2% lime + 6% cement (mixed simultaneously).
▽ Sand-Loess + 2% lime + 6% cement (cement added 24 hours after lime).
1300
1100
900
700
500
300
Maximum compressive strength - 28 day cure, psi.
90
95
100
105
110
115
120
125
130
Density at OMC for maximum 28 day strength, pcf.

between the no delay and 2 hour delay cases and subsequent leveling off at longer delay periods could relate to a lack of secondary pozzolanic reactions between the soil clay and the lime released by the cement hydration, since the dune sand contains only 2 per cent clay, the remaining constituents being sand and silt. That is, the initial reaction of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) with moisture results in formation of calcium silicate hydrate (CSH) and lime. The lime can combine with clay to yield additional CSH, but the latter is a relatively slow process, and there is not much clay for the lime to react with in this soil. When the early cement bonding is broken by compaction, some period of time after mixing, it would seem reasonable that a loss in strength would occur. Although cement hydration continues after compaction is completed, the hydration that took place during the delay cannot be replaced. The fact that the strength gains between 28 and 90 day curing are about the same as those between the 7 and 28 day curing may also indicate a lack of pozzolanic reaction.

This same hypothesis may be tested by referring to the delay effects on other soils. The 7 per cent clay content of the sand-loess soil is relatively low, but higher than in the dune sand. The strength gains between the 28 and 90 day curing are, in general, slightly greater than those between 7 and 28 day curing, suggesting somewhat larger secondary pozzolanic reactions. The friable loess soil has a significant clay content (19.6 per cent), and apparent effects of secondary pozzolanic reactions are quite evident. The 7 day maximum strength after a 6 hour delay in compaction is less than 60 per cent of the 7 day maximum strength when there is no delay. However, the maximum 90 day strengths are nearly equal for all delays. This would seem to indicate that secondary pozzolanic reactions have not had time to become established by the end of the 7 day curing, and the loss of strength is mainly due to the breaking of some of the bonds that had been established by initial cement hydration during the 6 hour delay. The decrease in density may also have had some effect, but the decrease was only 8 pcf, or 8 per cent, and as shown in Figure 27, density was less important for strength with this soil than with the other soils. The nearly equal 90 day maximum strengths for all delays indicates the beneficial contribution to strength by the slower secondary pozzolanic reactions.

Several factors appeared to operate in regard to the apparent increase in optimum moisture content upon delay. First, when mixtures employing sand-loess and friable loess with moisture contents above the optimum were compacted with no delay after mixing, horizontal cracks appeared in the specimens as a result of the high compactive effort for that particular moisture condition. These local shear failures apparently were responsible for the low strengths at moisture contents even slightly above the optimum with no delay. With a delay in compaction, the reactions of the soil-cement-water system caused an apparent drying out of the mixture probably relating to an increase in plastic limit, and crack-free specimens were obtained even though the moisture content was not changed.

Secondly, it was visually observed during the delay periods that small aggregates were formed and that they became harder with increasing time. Compaction after high delay times did not completely deform these aggregates, and small air voids were visible in the specimens. The hardness of the aggregates decreased with increasing moisture contents; thus for higher moisture contents at the longer delays the aggregates were deformed more during compaction, decreasing the air voids and increasing the density and strength.

When both lime and cement were added to the sand-loess soil, the aggregation was not as pronounced, and the soil-lime-cement mixture, being more workable than the soil-cement mixture, compacted crack-free at lower moisture contents and yielded about the same strengths even at long delay times.

When curves of maximum 28 day compressive strength versus density (Figure 27) are compared, it is seen that the strength of the sand-loess with 2 percent lime and 6 per cent cement added simultaneously was less than sand-loess with 8 per cent cement or with 2 per cent lime and 5 per cent cement added 24 hours after the lime. The latter two mixtures had nearly equal strengths, about 250 psi above the former. One possible explanation is as follows: When lime and cement are added simultaneously to the soil, the cement, being the more active additive, probably reacts more rapidly than the lime and would tend to coat the individual soil particles to cause binding. When only lime is added and allowed to react for 24 hours, some small aggregations probably form. Subsequent addition of cement would then react to bind these aggregations. The cement could coat these aggregations more effectively than it could the individual soil particles, because of the decrease in surface area presented. Therefore, the 6 per cent cement was as effective for strength when added 24 hours after the lime as 8 per cent cement was with no lime, and lower strength resulted when lime and cement were added simultaneously.

In general, the strength loss from delay in compaction appears to be due to two factors: decrease in compacted density, and lower effective cement content due to hydration. These two effects are interrelated, because the cement hydration process results in fixing part of the mix water, which would result in lower compacted density; also any bonds formed by the hydrating cement will tend to be broken during compaction, using up part of the compaction energy. In the case of loess, the strength loss can in part be recovered by addition of 4 to 8 per cent more water (Table 4). If after 24 hours the cement is about 30 per cent hydrated, 8% x 0.30 = 2.4% hydrated cement. This will fix about 0.4 times its weight of water, or 2.4% x 0.4 = 1.0% water. This is relatively small compared to the 4 to 8 per cent additional water needed for maximum strength after delay; therefore the need for additional water may be more for lubrication of the clay-aggregate soil grains than to replace the water lost to the cement. With the clean sand, additional water was of relatively little benefit, reinforcing the hypothesis that the water is needed mainly as a lubricant.

In low-clay content soils, the strength loss due to lowering of the effective cement content by hydration cannot be made up except by addition of more cement. The loss relating to lowering of the density could presumably be recovered by use of higher compactive effort, although this was not investigated. As previously mentioned, when clay is present the situation is not so critical because the part of the strength relating to a long-term pozzolanic reaction is not adversely affected.

When the maximum 28 day compressive strength versus delay in compaction after mixing is plotted on a logarithmic grid (Figure 28) the relationship tended to result in straight lines indicating that decrease in strength due to delay in compaction is a power function of the form $y = a\ x^{-n}$ where y is compressive strength and x is delay time. Further investigation in this area would perhaps yield additional supporting evidence for this relationship.

Figure 28. Maximum 28 day compressive strength of soil-cement and soil-lime-cement mixtures at varying delays between mixing and compaction plotted on a log grid.

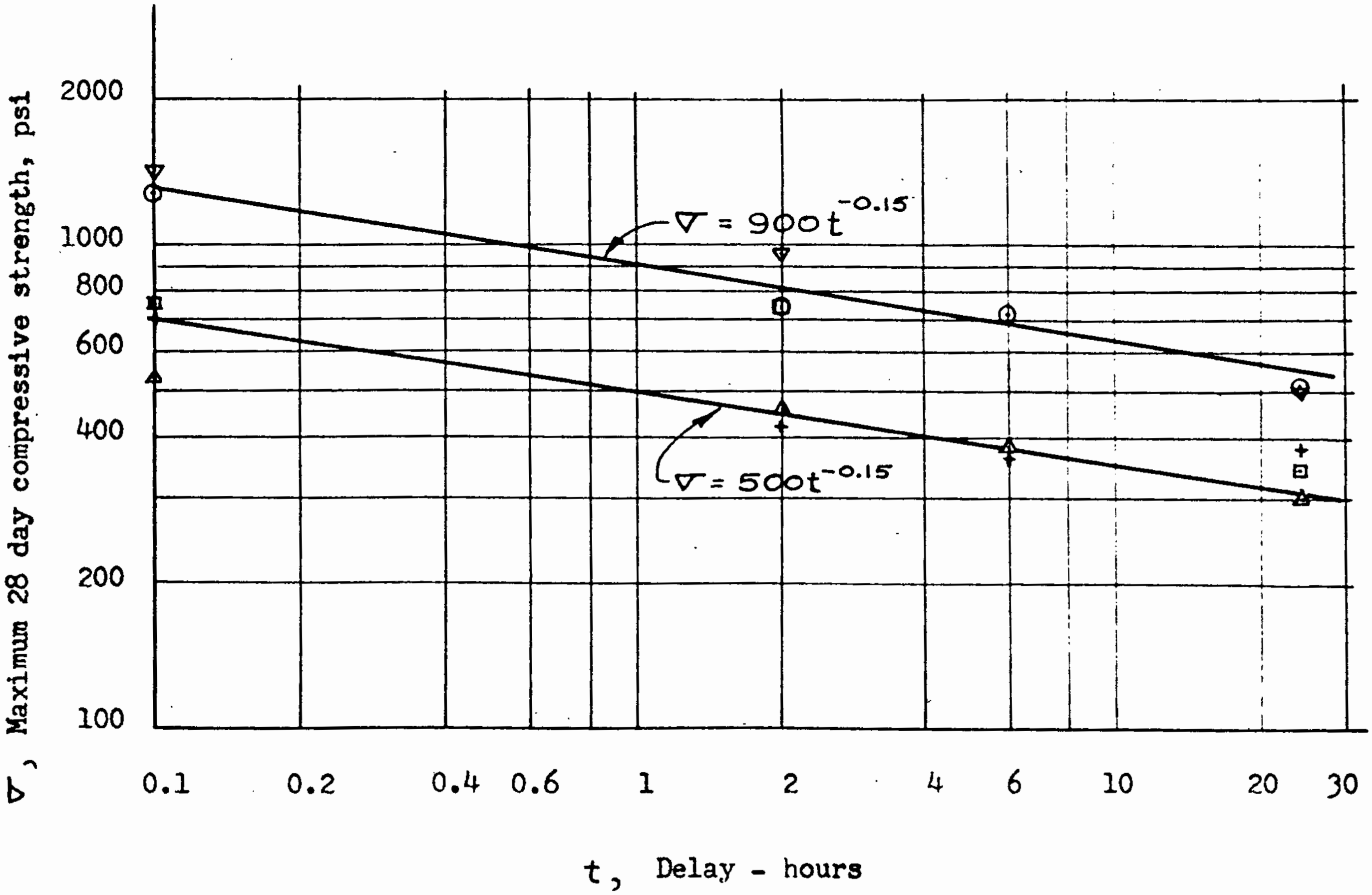
+ Dune Sand + 8% cement.

⊙ Sand-Loess + 8% cement.

△ Friable loess + 8% cement.

⊡ Sand-Loess + 2% lime + 6% cement (mixed simultaneously).

▽ Sand-Loess + 2% lime + 6% cement (cement added 24 hours after lime).



CONCLUSIONS

1. The compressive strength of soil-cement and soil-lime-cement mixtures is decreased by delays in compaction after mixing with water.

2. The amount of decrease in strength relates to the time of delay, the kind of soil, the molding moisture content, and in the case of soil-lime-cement, the sequence of mixing operations. In particular:

   a. The 28-day strength decreased as a power function of delay time. That is, considerable strength loss was caused by a delay in compaction of 2 hours, and most loss occurred during the first 6 hours. The loss from 6 to 24 hours was much less.

   b. Soils with low clay content were most susceptible to strength loss from delayed compaction. Soils containing clay tended to recover strength, apparently by pozzolanic reaction, and the 90 day strengths of loess-cement containing 20 per cent clay were about the same regardless of the delay.

   c. The optimum moisture content for maximum strength increases with increasing delay. The 24 hour delay caused nearly a 4 per cent increase in moisture requirement for dune sand-cement, and nearly an 8 per cent increase for friable loess-cement mixtures. Only a small part of the extra water is needed for cement hydration.

d. When lime was added 24 hours before cement to soils containing clay, strengths are higher than when lime and cement were added simultaneously.

3. Compressive strength of the various soil-cement mixtures related to the compacted density, the higher the density the higher the strength. Therefore with zero delay the moisture content for maximum density was also very close to the moisture content for maximum strength. An exception was the clean sand-cement, which showed an increase in strength with a moisture content below that for maximum density, apparently due to the lower water-cement ratio.

4. The density of soil-cement and soil-lime-cement mixtures decreases with increasing delays in compaction after mixing with water and is a major contributing factor to the decrease in strength. However, the decrease in density is not as deleterious for strength in soils with higher clay content, apparently because of pozzolanic reaction.

5. From a practical standpoint, in the construction of soil-cement and soil-lime-cement stabilized bases:

a. The delay between compaction and mixing should be minimized, especially for clean sandy soils, where a delay of 2 hours resulted in almost a 50 per cent decrease in 28-day compressive strength. Most of this loss may be attributed to a lower compacted density, and presumably could be counteracted by increasing the compactive effort. Unfortunately the latter is frequently costly or ineffective.

b. Delay is not so critical with soils containing clay, but additional water must be added. As a rule of thumb, based on the cement content used in this study, for a 2 hour delay about 1% extra water is needed for every 5 per cent montmorillinitic clay.

6. Since short delay times are the most critical, laboratory tests of soil-cement mixtures should incorporate delay times which duplicate normal or expected delays in the field. The difference in delay time may be the major factor contributing to the generally recognized disparity between field and laboratory data.

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APPENDIX

Table 5. Moisture-density-strength relationships[a]
(Soil: Dune sand (S-62) 92% soil, 8% cement)

Delay in compaction	Moisture content %	Dry density, pcf	Immersed compressive strength, psi		
			7 day	28 day	90 day
No delay	6.6	112.4	337	755	691
	8.1	113.2	218	379	504
	9.6	110.5	313	577	649
	11.1	116.0	791	674	806
2 hours	6.6	110.0	317	399	508
	8.6	111.8	290	425	452
	10.6	113.2	254	350	448
	12.6	115.6	192	271	445
6 hours	6.6	107.0	172	231	323
	9.6	109.5	162	233	442
	12.6	112.1	238	360	415
	15.6	113.1	100	182	221
24 hours	6.3	98.7	93	96	129
	9.3	104.0	152	205	244
	12.3	108.0	146	258	392
	15.3	110.0	254	379	524
	18.3	109.5	77		261

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[a] Percentages are based on dry weight of soil-cement mixture

Table 6. Moisture-density-strength relationships[a] (Soil: Sand-loess (Colfax mix) 92% soil, 8% cement)

Delay in compaction	Moisture content %	Dry density, pcf	Immersed compressive strength, psi 7 day	28 day	90 day
No delay	6.6	124.0	938	753	929
	8.1	124.0	756	1240	1432
	9.6	128.0	836	1174	1560
	11.1	127.0	478	793	1001
2 hour	6.9	118.5	389	554	590
	8.9	117.7	435	485	648
	10.9	118.5	586	740	981
	12.9	120.5	412	606	806
6 hour	7.0	113.0	221	366	333
	10.0	112.2	264	327	366
	13.0	116.7	471	720	746
	16.0	115.1	294	406	626
	19.0	111.0	106	205	238
24 hour	7.0	106	80	142	156
	10.0	103.7	103	159	192
	13.0	110.0	212	406	422
	16.0	112.3	304	508	743
	19.0	108.9	165	300	438

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[a] Percentages are based on dry weight of soil-cement mixture

Table 7. Moisture-density-strength relationships[a] (Soil: Friable loess (20-2) 92% soil, 8% cement)

Delay in compaction	Moisture content %	Dry density, pcf	Immersed compressive strength, psi		
			7 day	28 day	90 day
No delay	15.4	100.3	396	485	633
	18.4	102.7	422	534	773
	21.4	99.7	225	310	485
	24.4	97.1	152	195	277
2 hour	14.0	91.0	192	228	320
	16.0	89.7	156	231	287
	18.0	91.0	198	254	415
	20.0	92.6	221	307	527
	22.0	98.6	294	465	822
6 hour	14.8	88.1	123	64	307
	17.8	88.2	146	225	333
	20.8	90.7	175	281	488
	23.8	94.2	231	369	659
	26.8	94.1	188	366	646
	29.8	90.4	133	244	485
24 hour	14.0	83.4	70	113	221
	17.0	84.2	106	96	139
	20.0	85.3	87	133	244
	23.0	87.6	96	182	320
	25.0	90.3	160	-	-
	26.0	92.0	133	300	616
	29.0	90.5	170	-	-

[a] Percentages are based on dry weight of soil-cement mixture

Table 8. Moisture-density-strength relationships[a] (Soil: Sand-loess (Colfax mix) 92% soil, 2% lime, 6% cement)

Delay in compaction	Moisture content %	Dry density, pcf	Immersed compressive strength, psi		
			7 day	28 day	90 day
No delay	7.0	121.6	432	600	656
	8.5	123.0	511	733	846
	10.0	124.2	521	727	965
	11.5	124.7	346	537	674
2 hour	7.0	119.1	343	468	626
	9.0	120.7	412	603	789
	11.0	121.7	455	750	988
	13.0	121.4	231	346	442
24 hour	7.0	108.8	110	165	235
	10.0	106.0	116	182	235
	13.0	110.9	185	277	461
	16.0	114.6	188	340	501
	19.0	109.3	77	156	208

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[a] Percentages are based on dry weight of the soil-lime-cement mixture

Table 9. Moisture-density-strength relationships[a] (Soil: Sand-loess (Colfax mix) 92% soil, 2% lime, 6% cement), (cement added 24 hours after lime and water)

Delay in compaction	Moisture content %	Dry density, pcf	Immersed compressive strength, psi 7 day	28 day	90 day
No delay	10.0	127.8	803	1165	1471
	12.0	122.9	244	383	544
	14.0	117.7	149	205	313
2 hour	10.0	122.5	494	873	1215
	12.0	123.4	458	629	756
	14.0	118.7	231	412	452
24 hour	9.4	109.3	169	310	379
	11.4	109.8	218	392	580
	13.4	113.1	271	488	799
	15.4	114.7	179	277	475

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[a] Percentages are based on dry weight of the soil-lime-cement mixture