STRENGTH CHARACTERISTICS OF SOIL-CEMENT MIXTURES

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SOIL-CEMENT MIXTURES

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To my teachers and to two of the best, my parents

who taught me to search for the truth.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

NOMENCLATURE

ϕ ----- inclination of strength envelope with respect to the horizontal "angle of internal friction"

ϕ_{sc} ----- ϕ value for soil-cement

ϕ_s ----- ϕ value for soil

c ----- interception of strength envelope with the shear stress axis "cohesion"

s ----- shear stress

σ ----- normal stress

σ_B ----- normal stress at which the break in the strength envelope occurs

σ_{ff} ----- normal stress on the failure plane at failure

σ_1 ----- total vertical stress

σ_3 ----- confining stress

$\sigma_1 - \sigma_3$ ----- deviator stress

γ_d ----- dry unit weight

w ----- water content

CHAPTER I

INTRODUCTION

When a soil is treated to improve its strength and durability it is said to be "stabilized." Cement stabilized soil consists of a pulverized soil and measured amount of Portland cement and water compacted and cured to a specified period.

Soil-cement was first employed in road construction in South Carolina in 1935, and since then has been used on an increasing scale, mainly for highway and airfield construction.

Mechanism of Stabilization with Cement

When Portland cement is added to a moist soil, the resulting cementation can be imagined as a combination of 1) mechanical bonding of the cement to rough grain surfaces plus 2) chemical bonds developing between the cement and the grain surface (1). The latter process becomes more important for fine-grained soils due to the hardening of soils by lime liberated as a result of the hydration of cement (2).

Effect of Molding Water and Cement Content on Strength

Compressive strength is the property most widely used to describe soil-cement mixtures; it serves to indicate the degree of reaction, relative "setting time" and rate of hardening of soil-cement-water mixtures.

Cotton (3) and Felt (4) showed that the compressive strength of soil-cement mixtures increased with cement content.

The effect of molding water content on unconfined compressive strength of soil-cement mixtures has been investigated by Cotton (3), Watson (5), Felt (4), and others (6,7). Their works indicate that the strength reaches a maximum and decreases in a manner somewhat like that of the moisture-density curve.

On the three soils tested (a sandy loam, a sandy clay loam, and a clay loam) Watson (5) concluded that "because of the wide difference in the amount of water which is necessary to bring about maximum density, the water-cement ratio is not a suitable control for soil-cement mixtures."

Effect of Cement Content on ϕ and c

Whitehurst (8) reported that cement-treated soil develop values of c and ϕ that are markedly higher than values for the raw soil. On Tennessee gravel c increased with increase in cement content to a maximum and then decreased; while ϕ increased with increase in cement content to a maximum and then remained about the same.

Balmer (9) showed that unconfined compressive strength and c increased with cement content and age. His work indicates that ϕ for the cemented soil was higher than ϕ for the raw soil, but an increase in cement content did not affect the ϕ values. The research of Paquette and McGee (10) supports Balmer's findings.

The results of triaxial testing on soil-cement mixtures reported in the literature were all limited to a low confining pressure (less than 100 psi). Means and Parcher (11) postulated that when sand grains are cemented, the bonds of cementation are likely to exist only at very small areas of contact between the grains; and a cemented material undergoes two failures, one when the cohesive resistance of cementation is broken and again when the internal shearing resistance of the granular component is exceeded. The strength envelope and the stress-strain characteristics presented by Means and Parcher are given in Fig 1.

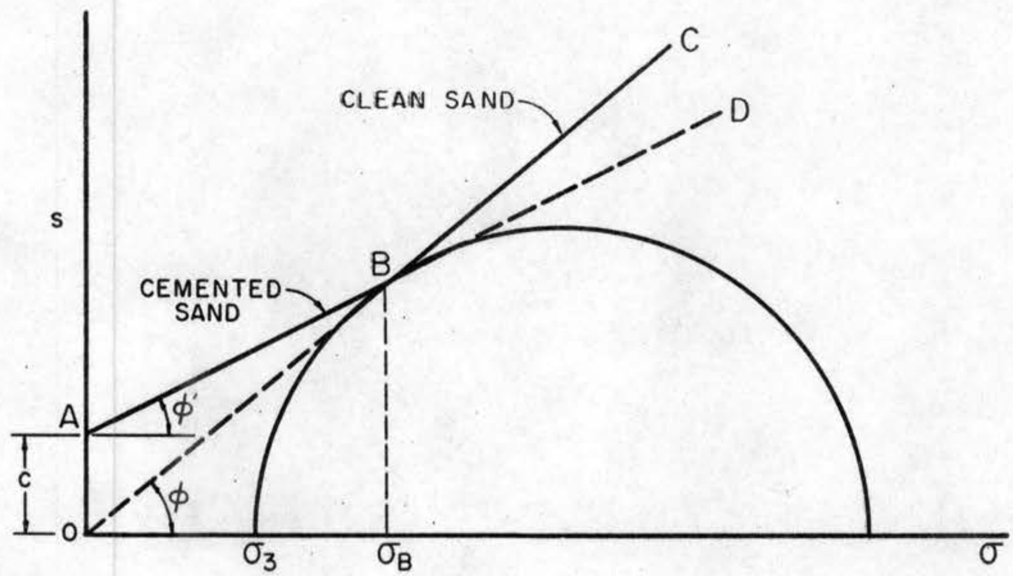
Effect of Method of Compaction

Effect of method of compaction on strength characteristics of soil-cement mixtures has not received the attention of researchers to date.

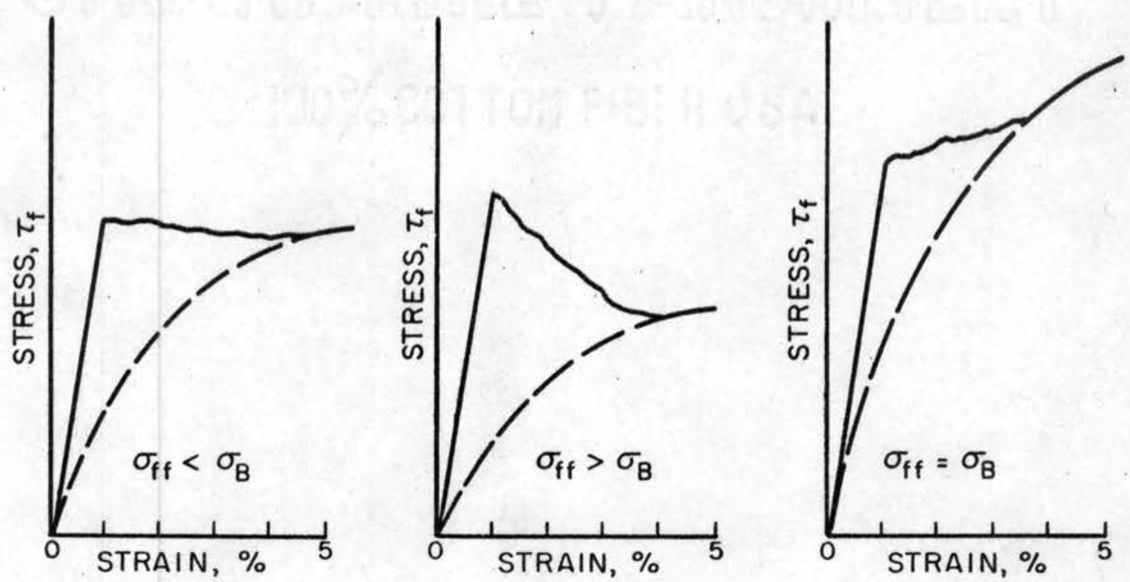
Seed and Chan (12) showed that the method of compaction has little effect on the strength of clay samples compacted dry of optimum, with kneading compaction yielding higher strengths than impact compaction. For samples compacted wet of optimum the influence of method of compaction is considerable at about 5% strain. Wet of optimum strength of samples of the same composition increases in the following order of compaction methods: Kneading, impact, vibratory, and static. In terms of the work of Lambe (13,14) on soil structure, this seems to indicate that the degree of clay particle orientation and/or the pore-water pressure decrease in the same order so that the more flocculated structure gives the highest strength.

Nature and Scope of the Investigation

Two methods of compaction, impact and kneading compaction were employed to investigate the effect of method of compaction on the



a) STRENGTH LINE FOR CEMENTED GRANULAR SOIL.



b) STRESS-DEFORMATION CHARACTERISTICS OF CEMENTED SOIL.

Figure 1. Strength Envelope and Stress-Strain Characteristics of Cemented Granular Soil. (After Means and Parcher)

strength of soil-cement mixtures.

The strength was evaluated by the results of two compression tests: unconfined and undrained triaxial test.

The strength envelope was investigated up to confining pressures of 1213 psi utilizing a high pressure triaxial cell.

CHAPTER II

MATERIALS AND PROCEDURES

Materials Used

Soils

Four soils were selected with a wide range of properties: a medium, clean, well-graded river sand, a clean, uniformly graded Ottawa sand, a gray silt, and a permian red clay.

The gradations of the four soils are shown in Fig 2. Some of the soil properties are shown in Table I.

The silt and clay were air dried, pulverized and passed through a U. S. No. 30 sieve.

Cement

Type I Portland cement was used throughout this investigation.

Specimen Preparation

Mixing

The required cement content as expressed by per cent of total soil-cement weight was hand mixed with the measured amount of soil.

The water required to give the desired dry density and water content was added and the mixture was hand mixed again. The mixture was then compacted to the required density.

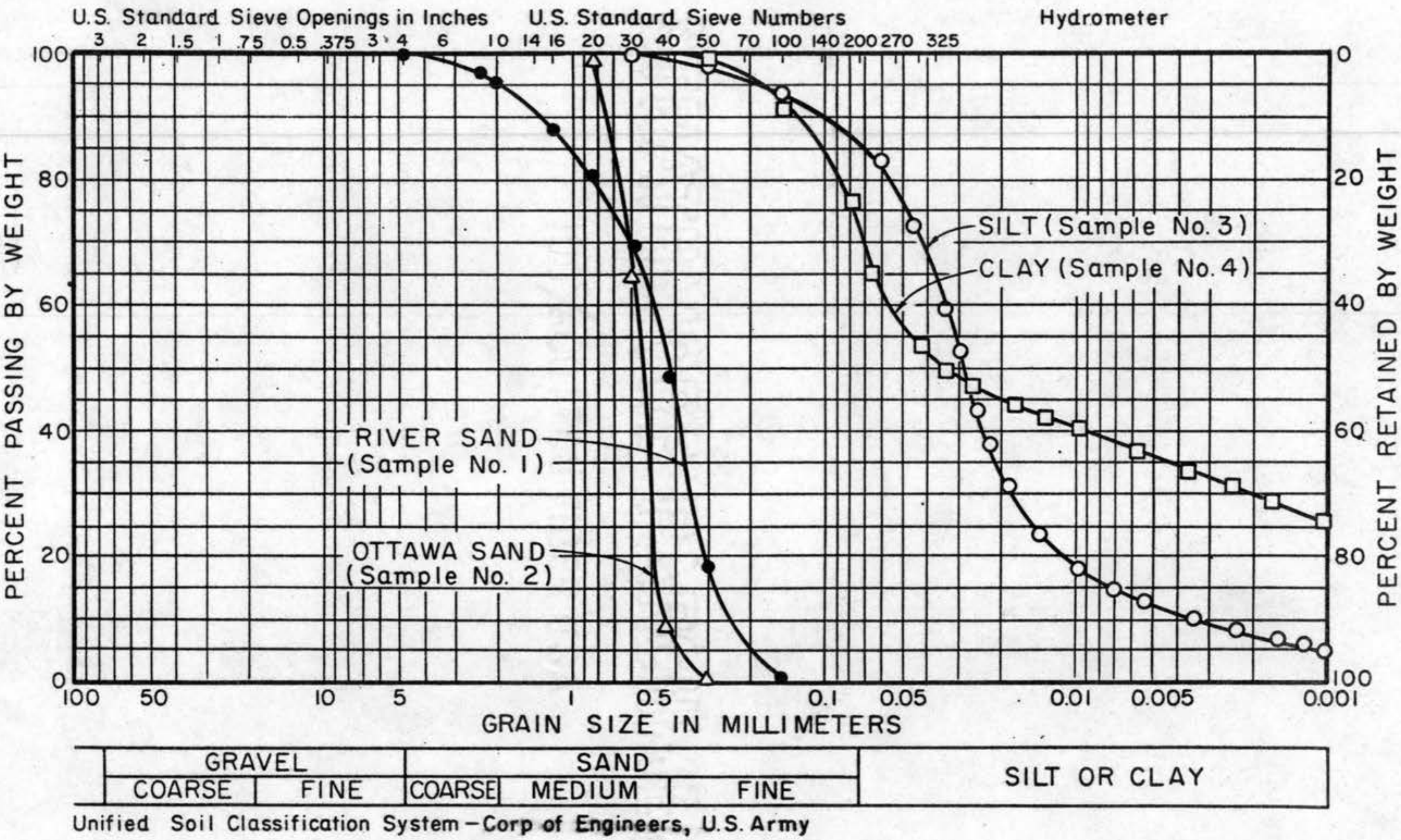


Figure 2. Grain Size Distribution.

TABLE I

SOIL PROPERTIES

Sample No.	1	2	3	4
Source of Sample	Ponca City Oklahoma	Ottawa Illinois	Nebraska	Stillwater Oklahoma
Specific Gravity G_s	2.62	2.64	2.69	2.72
Atterberg Limits				
Liquid Limit %			33	41
Plastic Limit %	NP	NP	26	19
Plasticity Index %			7	22
Description of Sample	medium well graded, river sand	uniformly graded, Ottawa sand	gray silt	permian red clay

Curing

After molding, the granular specimens were placed in a curing desiccator for about 12 hours, then wrapped in Saran Wrap, waxed, and stored in a moist room to cure.

The fine-grained samples were wrapped, waxed, and stored immediately after molding.

Three curing periods were used: two days, seven days, and twenty-eight days.

Compaction Equipment and Characteristics

Kneading Compaction

The Harvard Miniature compaction apparatus was used to produce 1.40 inch diameter by 2.80 inch high specimens. The mixture was compacted in five layers as suggested by Wilson (15). Unless otherwise stated, the 40 lb spring tamper was used.

Impact Compaction

A drop hammer of 0.825 lb weight, with a face diameter of 0.70 inch and a drop height of 6 inches was manufactured by the Research Apparatus Development Laboratory, Oklahoma State Uniersity, for use as a scale model of the Standard Proctor hammer.

This hammer was used to mold 1.40 inch diameter by 2.80 inch high specimens by the impact method. To get compaction effort equivalent to those of the Standard Proctor compaction test, 25 blows per layer were required when the mixture was compacted in three layers.

The model hammer and a split mold used in molding the granular soil specimens are shown in Fig 3.

Compaction Characteristics of the Mixtures

Dry density-water content relations for the four soils with different cement contents are shown in Fig 4.

Lower dry density was obtained using the model hammer compared to the Standard Proctor test for the granular soils, as illustrated in Fig 4a. However, it gave identical dry density-water content relations for the fine-grained soils as indicated in Fig 4d.

As shown in Figs 4a and 4b the two granular soils showed appreciable increase in density with increase in cement content. This is due to the lack of fines in the two granular soils used. Maximum density was reached only with 10% cement content. This might be due to the lack of fines and/or the bulking effect of the sand. The bulking effect of the sand is illustrated in Fig 5.

To determine the effect of cement content and method of compaction, comparative specimens were prepared at the same water content and dry density. For the granular soils, the correlation is shown in Figs 6 and 7.

As Figs 7b and 7c show, it was not possible to get the same density at different cement contents for sample No. 2 by the kneading compaction, since there was little change in density with increase in number of tamps per layer or the spring tamping force. All specimens for this sample were prepared by impact compaction.

Tables II and III contain the number of tamps per layer required by the Harvard Miniature Apparatus to give densities equivalent to those of the impact compaction (Standard Proctor) for silt and clay.

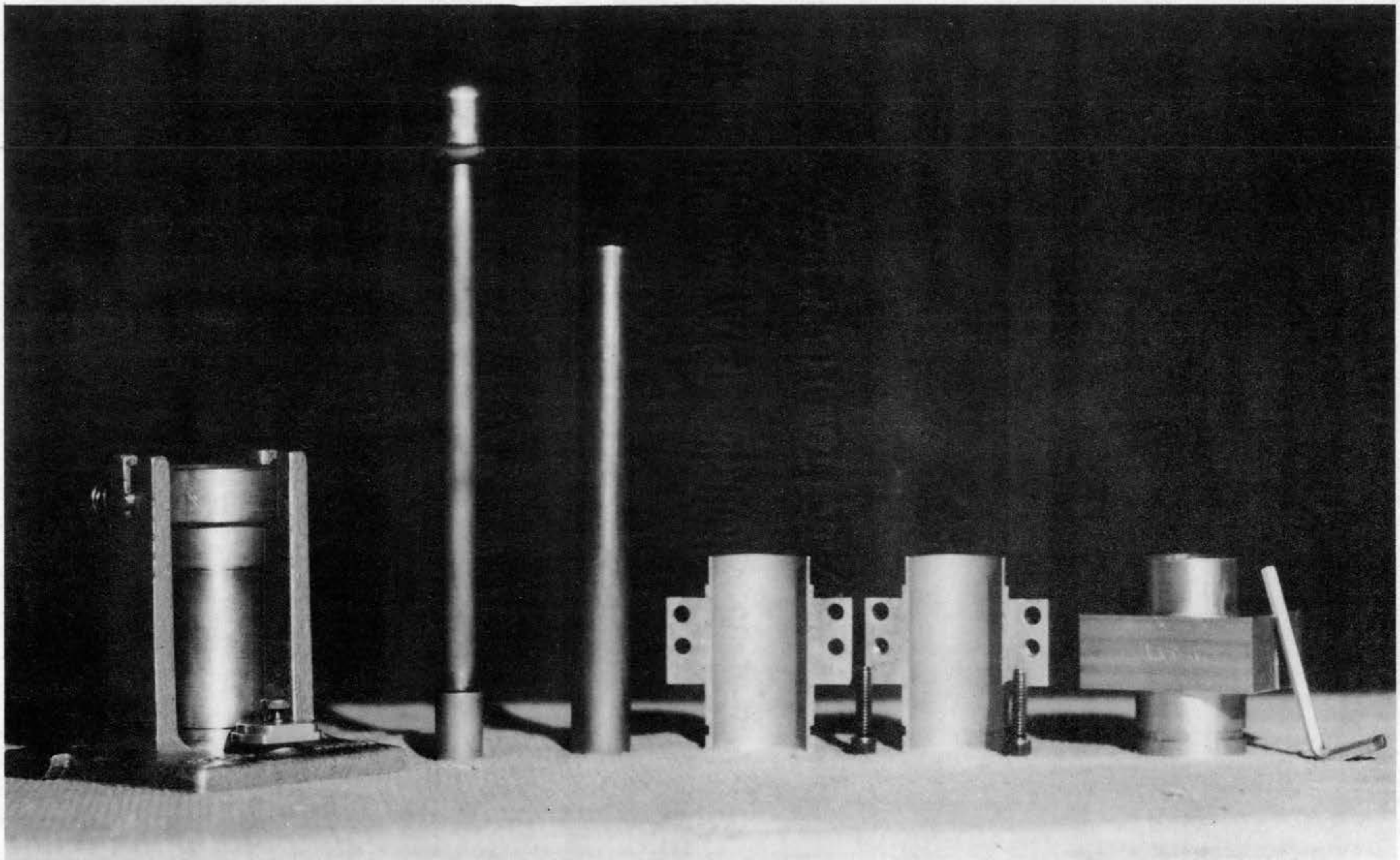


Fig. 3. Model Hammer and Molds used.

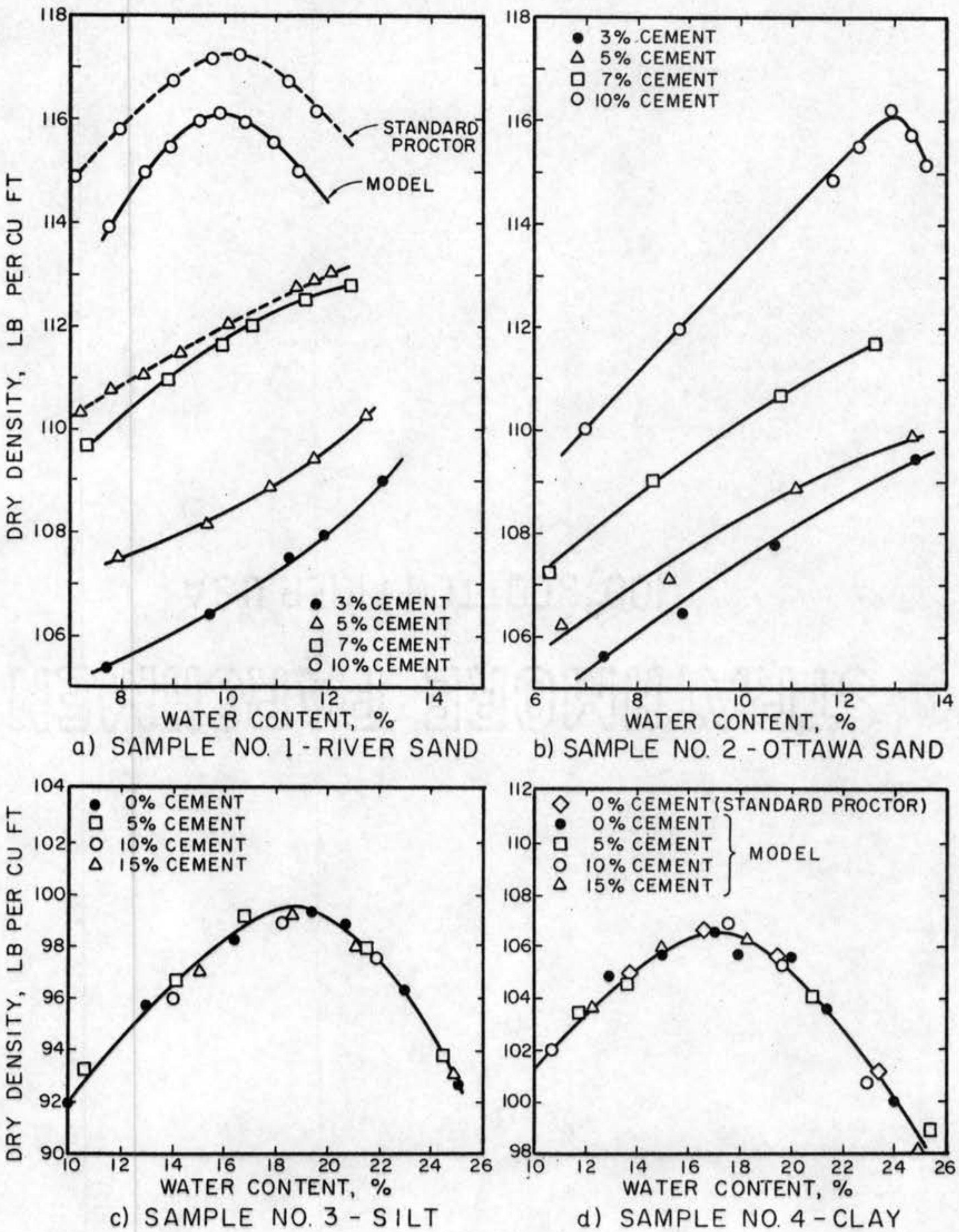


Figure 4. Dry Density-Water Content Relations, Impact Compaction.

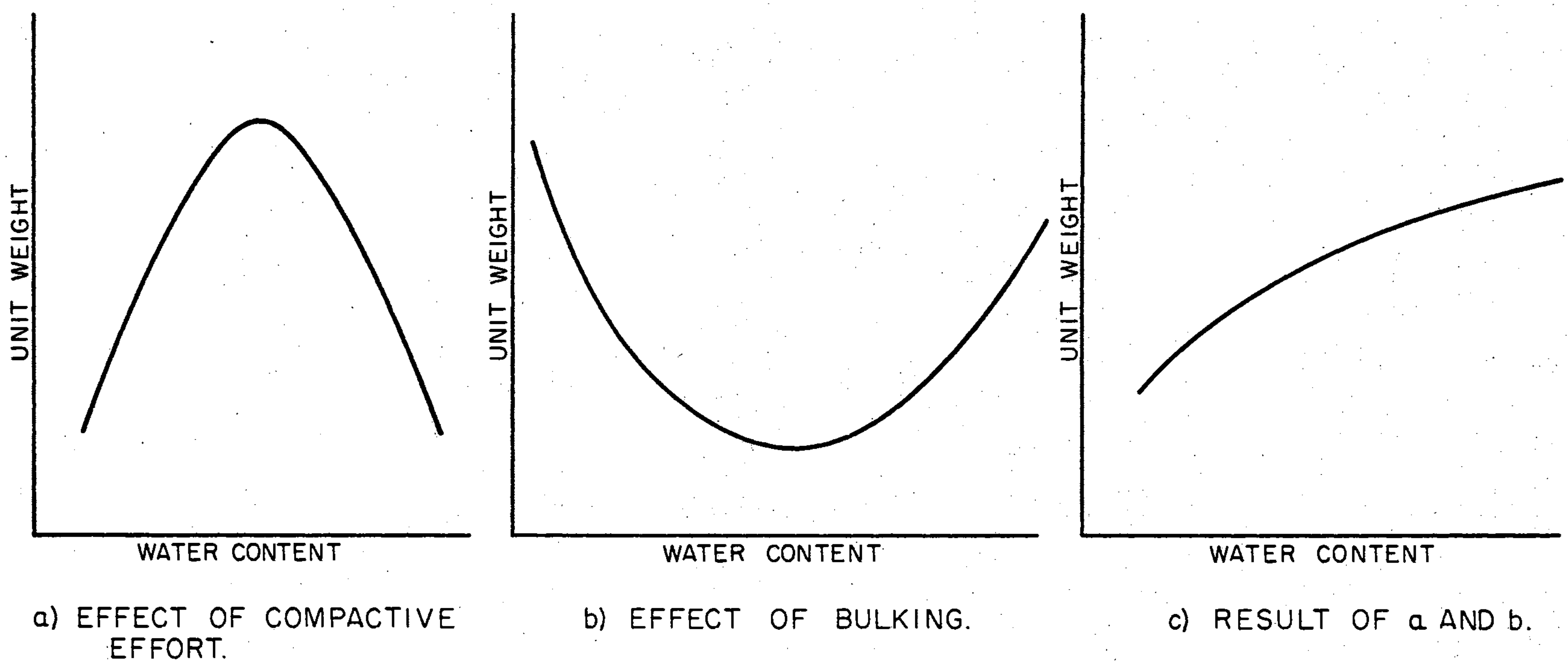


Figure 5. Compaction of Sand Lacking Fines.

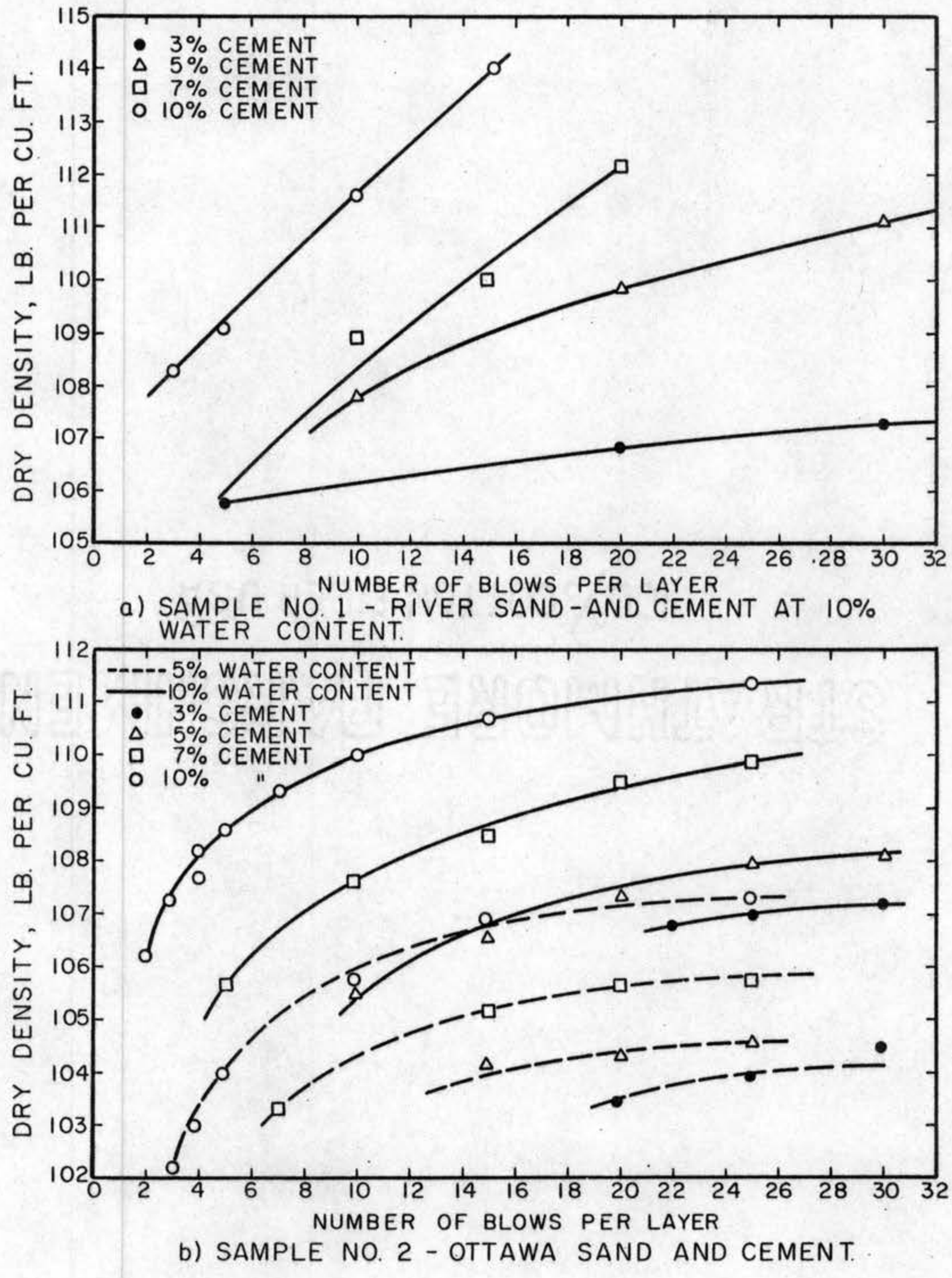


Figure 6. Influence of Number of Blows Per Layer on Dry Density (Impact Compaction, 3 Layers).

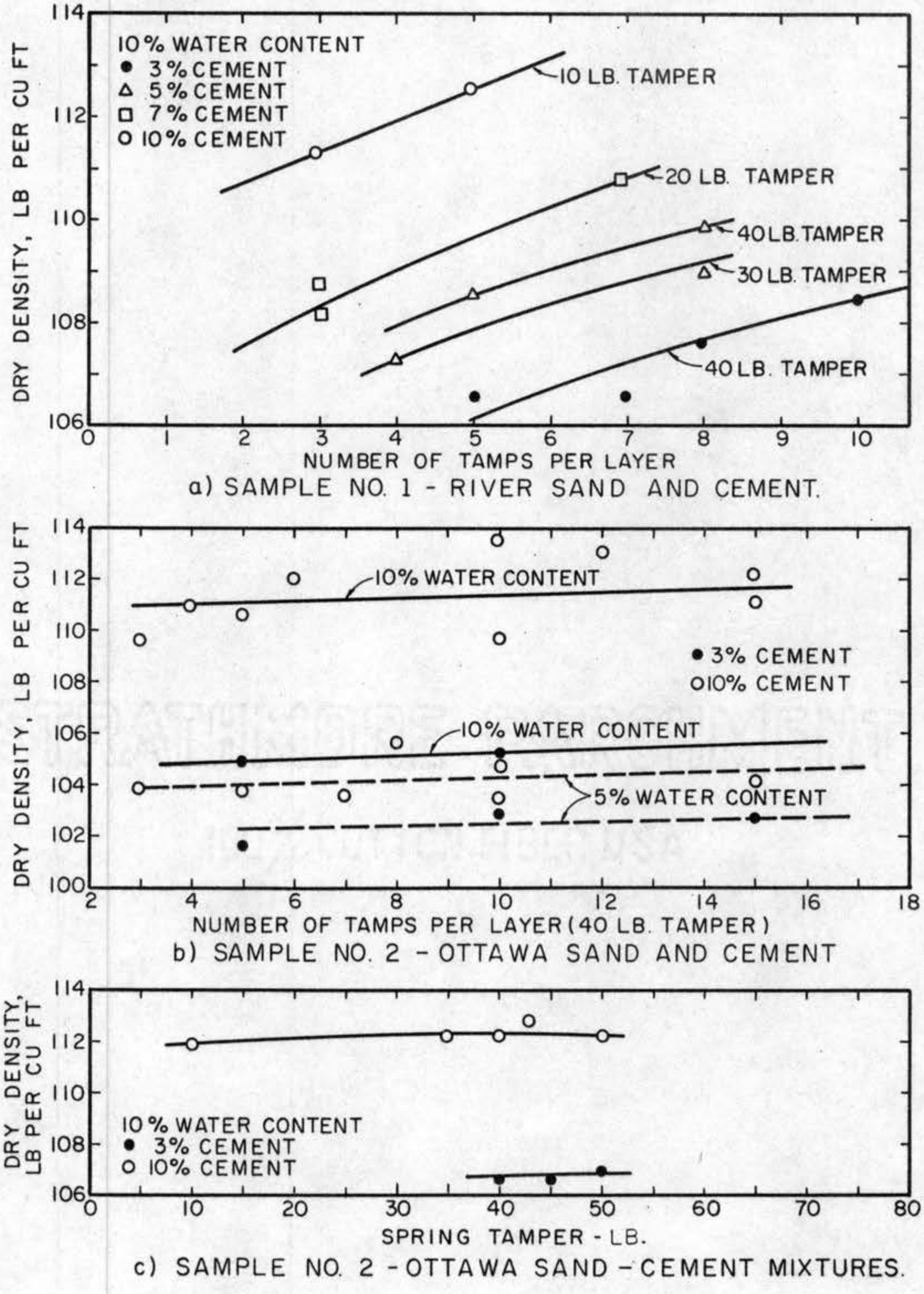


Figure 7. Influence of Spring Tamper and Number of Tamps Per Layer on Dry Density (Kneading Compaction, 5 Layers).

TABLE II

KNEADING COMPACTION FOR SAMPLE NO. 3-SILT

Per Cent Cement	No. of tamps per layer required to give the densities and water content equivalent to impact compaction (40 lb tamper, 5 layers). Dry of Optimum γ_d=97.5 lb per cu ft w = 15%	At Optimum γ_d=99.5 lb per cu ft w = 19%	Wet of Optimum γ_d=96.0 lb per cu ft w = 23%
0	-	4	-
5	5	5	5
10	8	5	5
15	-	6	-

TABLE III

KNEADING COMPACTION FOR SAMPLE NO. 4-CLAY

Per Cent Cement	No. of tamps per layer required to give densities and water contents equivalent to impact compaction (40 lb tamper, 5 layers). Dry of Optimum γ_d=104.2 lb per cu ft w = 13%	At Optimum γ_d=106.5 lb per cu ft w = 17.2%	Wet of Optimum γ_d=104.2 lb per cu ft w = 20.8%
0	3	3	-
5	5	5	7
10	5	5	8
15	5	5	-

Compression Tests

Unconfined Compression Tests

At the specified curing age, the wax was removed from the specimens and the unconfined compressive strength determined. The specimens were not immersed in water before testing (16); however, each value of unconfined compressive strength reported was the average of at least three tests.

The tests were carried out at a constant deformation rate of 0.02 inch per minute. A hydraulic testing machine was used for all cylinders except those having 0% and 3% cement contents, for which a screw-type compression machine was used.

Triaxial Compression Tests

A high pressure triaxial cell suitable for lateral working pressures up to 1500 psi was utilized. Rubber membranes of 1.40 inch ID and 0.025 inch wall thickness were used. The membrane was placed tightly around the base and held by O-rings. The sample was then placed inside the membrane with the aid of a triaxial membrane jacket. A cap was placed on top of the sample and O-rings were fixed tightly around the extended part of the membrane over the cap. After the cell was tightened the chamber around the sample was filled with hydraulic oil. The upper platen of the hydraulic compression machine was brought in contact with the triaxial load piston by adjusting the upper crosshead. The confining pressure σ_3 was applied by a hand operated hydraulic pump. A dead weight tester was used to measure the confining pressure. The initial reading of the axial strain dial gauge was recorded and the deviator stress (σ_1-σ_3) applied by means of a hydraulic compression machine at a deformation rate of 0.02 inch per minute. Deviator load, axial strain, and time were recorded at regular intervals. The arrangement used is shown in Fig 8.

The samples were tested at the specified curing age immediately after removal from the wax. The samples were not saturated. All triaxial tests carried out were undrained. No attempt was made to measure pore water pressure; therefore all values of stresses reported were total stresses. The peak stress was selected as the failure criterion.

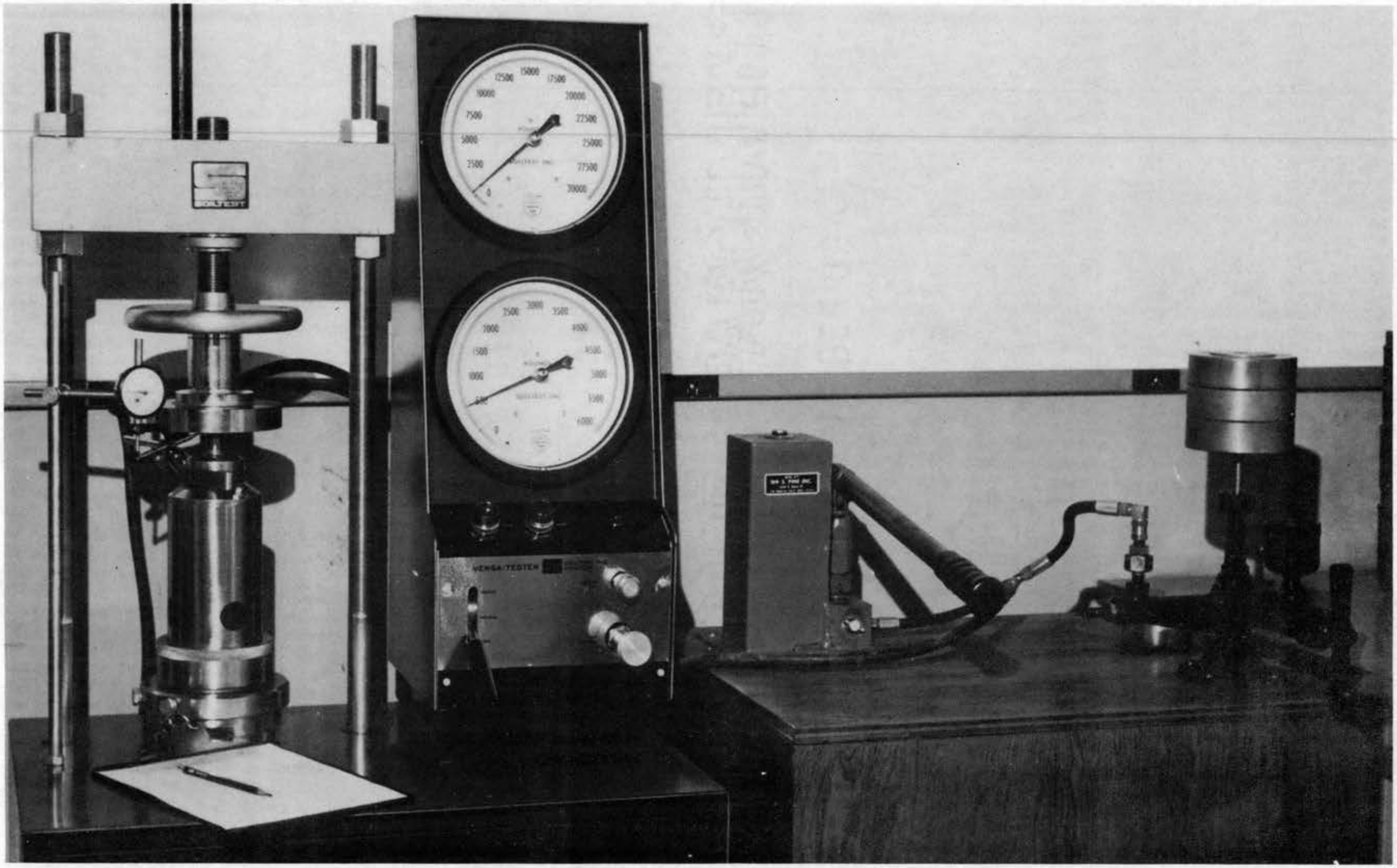


Fig. 8. Triaxial Testing utilizing hydraulic pump,
dead weight tester and hydraulic compression machine.

CHAPTER III

RESULTS OF UNCONFINED COMPRESSION TESTS

Granular Soils

Sample No. 1 (River Sand)

The results of unconfined compression tests on river sand-cement mixtures indicate:

1. When the soil-cement mixtures were compacted to the same density of 109 lb per cu ft at a water content of 10%, the unconfined compressive strength increased with increase in cement content as shown in Fig 9.
2. After seven days curing, specimens prepared by impact compaction gave higher strengths than specimens prepared by kneading compaction. The same relation appears to hold at a water content of 5%, using the same compactive effort but obtaining a lower dry density of 107 lb per cu ft.
3. The results presented in Fig 9 also indicate that the strengths obtained with 5% water content were higher than the ones obtained with 10% water content, although the density of the latter specimens was higher. This result suggests that the effect of water-cement ratio is stronger than the effect of density. Since only a portion of the water added is required for hydration of cement, any additional water causes a

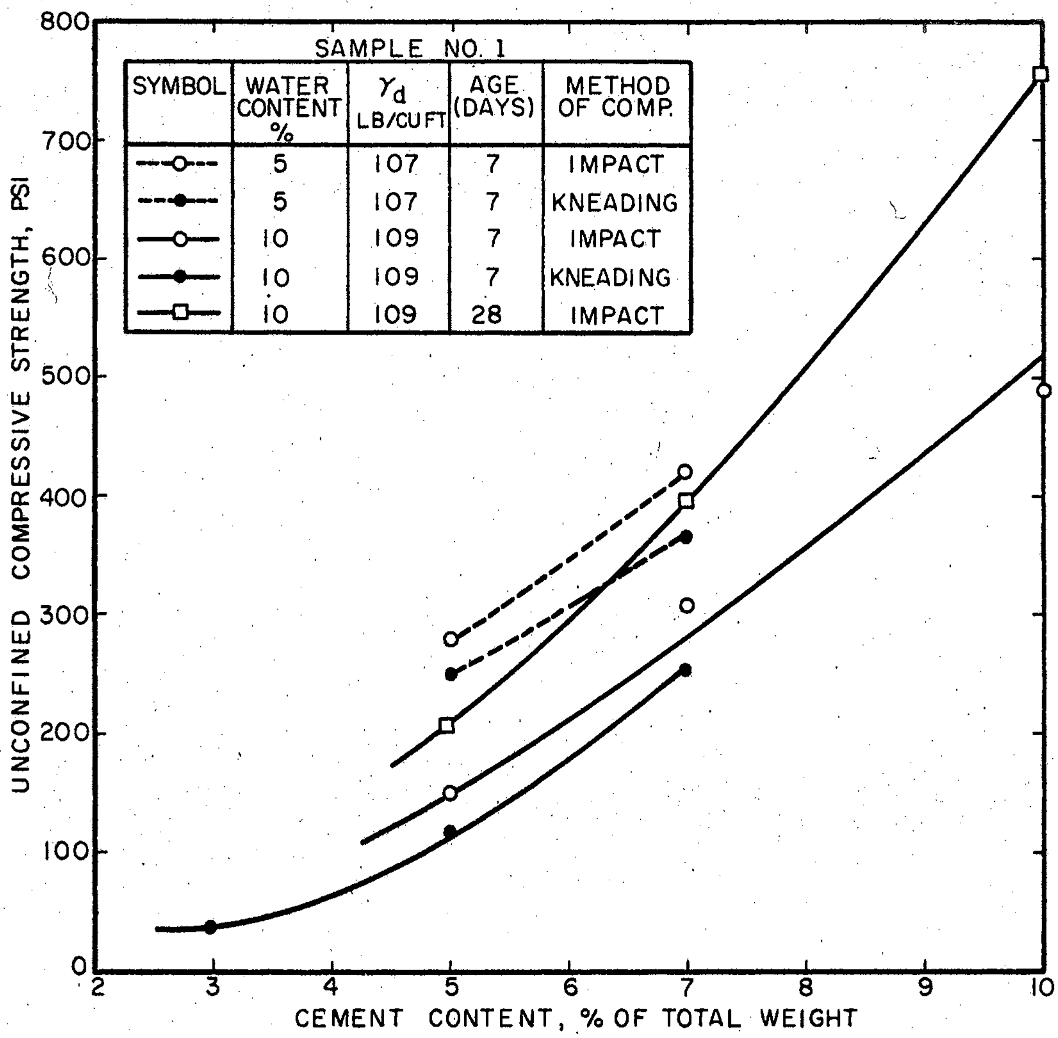


Figure 9. Effect of Cement Content, Age, Water Content, and Method of Compaction on Strength of River Sand-Cement Mixtures.

reduction in strength analogous to that found in concrete.

4. The difference in strength resulting from method of compaction seems to increase rather than decrease with curing age as might have been expected. This indicates that the method of compaction has an influence on the rate of cement hydration, impact compaction producing better hydration. The gain in strength with age is illustrated in Fig 10a.

Sample No. 2 (Ottawa Sand)

1. The results of unconfined compressive tests on the Ottawa sand-cement mixtures agreed well with those for the river sand: the lower the water-cement ratio, the higher the strength, despite the fact that density increases in the opposite direction. This result is shown in Fig 11.
2. The gain in strength resulting from the difference in water-cement ratio increases with curing age as shown in Fig. 10b.

Fine-Grained Soils

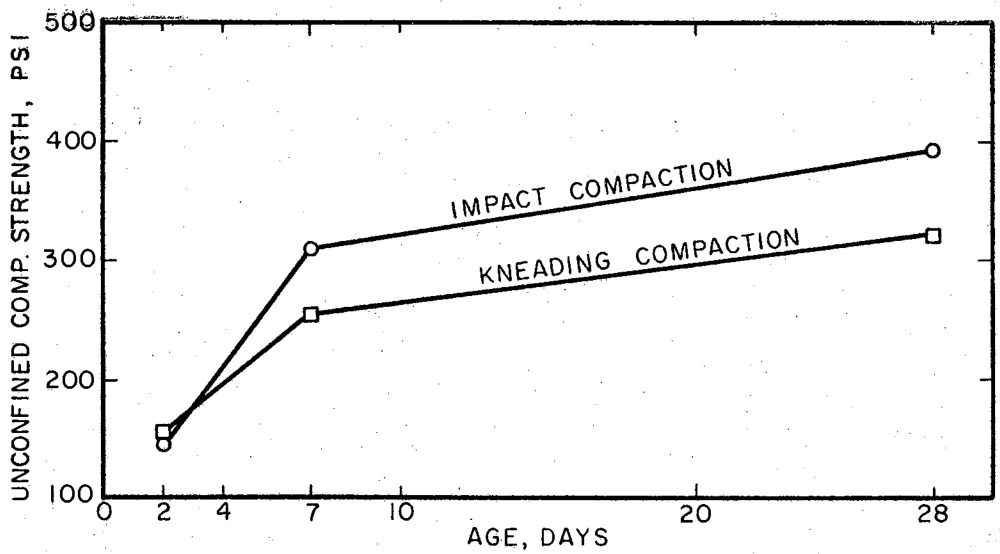
Two fine-grained soils were used in this investigation.

Sample No. 3 (Silt)

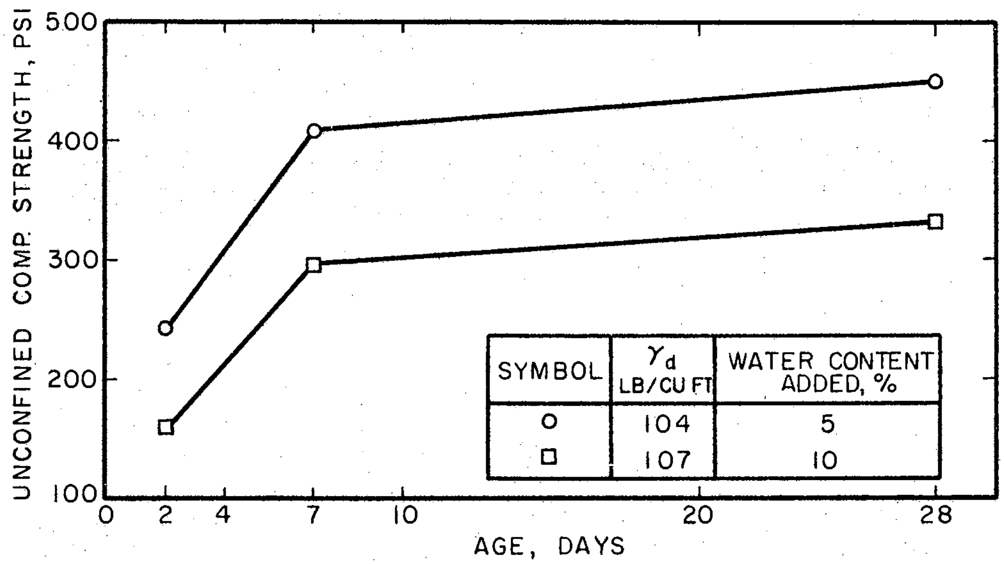
Three sets of specimens were prepared: dry of optimum (γ_d = 97.5 lb per cu ft, w = 15%), at optimum (γ_d = 99.5 lb per cu ft, w = 19%), and wet of optimum (γ_d = 96.0 lb per cu ft, w = 23%).

The following results were obtained:

1. The strength-water content relations followed patterns similar to the density-water content relations. The seven day



a) RIVER SAND + 7% CEMENT (γ_d = 109 LB/CU FT, WATER CONTENT = 10%)



b) OTTAWA SAND + 7% CEMENT–IMPACT COMPACTION.

Figure 10. Effect of Curing Age on Unconfined Compressive Strength of Granular Soils + 7% Cement.

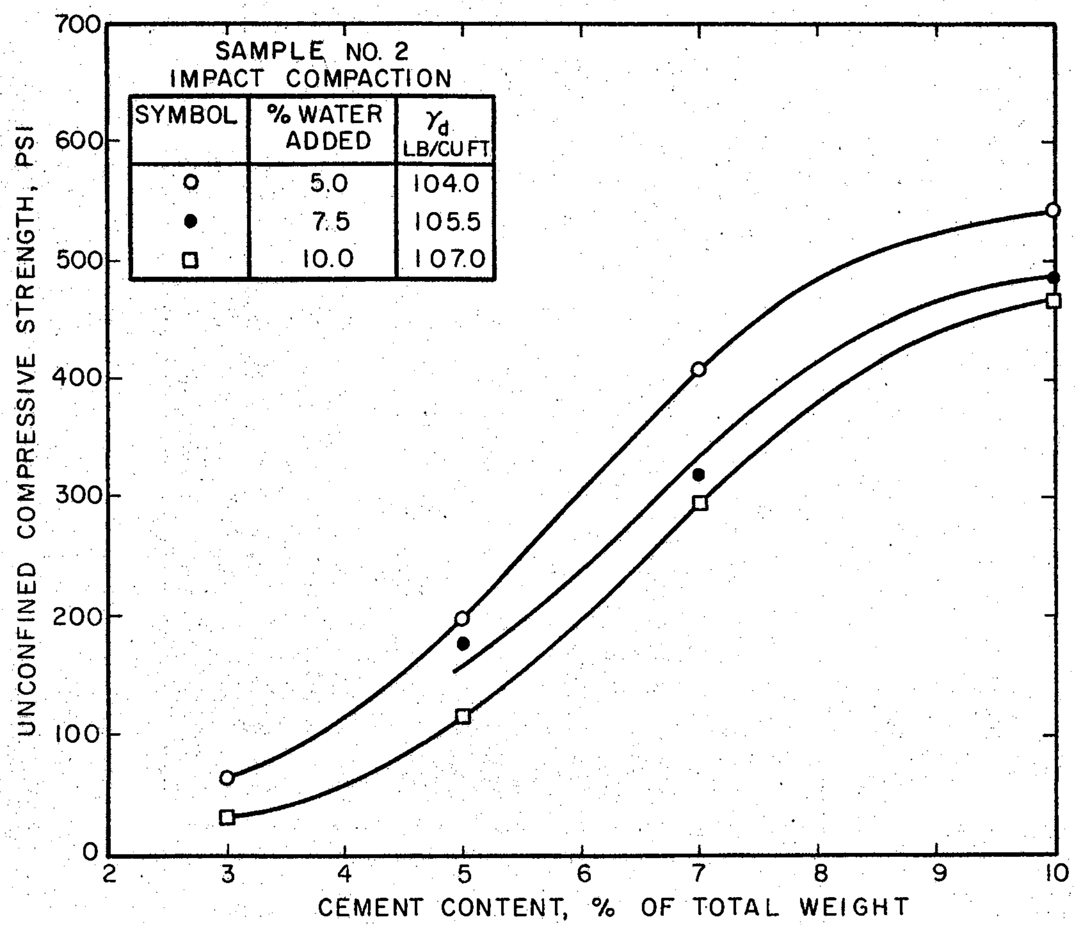


Figure 11. Effect of Cement and Molding Water Content on Strength of Ottawa Sand-Cement Mixtures Cured for 7 Days.

strength increased to a maximum and then decreased for all cement contents used as shown in Fig 12.

2. At seven days with 10% cement content, the specimens molded by kneading compaction gave higher strength than the corresponding specimens molded by impact compaction for the dry of optimum and at optimum cases. Wet of optimum impact compaction gave higher strength than kneading compaction. This result agrees with results presented by Seed and Chan (12) for a silty clay soil with no cement, suggesting that particle orientation remained unchanged during hydration of the cement.

3. The strength vs curing age relations for both methods of compaction with 10% cement, as presented in Fig 13a show that:

   a. The specimens prepared by kneading compaction gave higher strength than those prepared by impact compaction dry of optimum and at optimum for the three curing ages tried: two, seven, and twenty-eight days.

   b. Wet of optimum impact compaction gave higher strengths for all ages.

   c. The strength-curing age relations for impact compaction were almost linear. The results for the three water contents used were nearly parallel. The specimens prepared by kneading compaction showed a similar pattern as seen in Fig 13a.

   d. The specimens prepared by kneading compaction showed a higher gain in strength with age than those of impact compaction between two and seven days curing time. The samples prepared by impact compaction showed more gain in

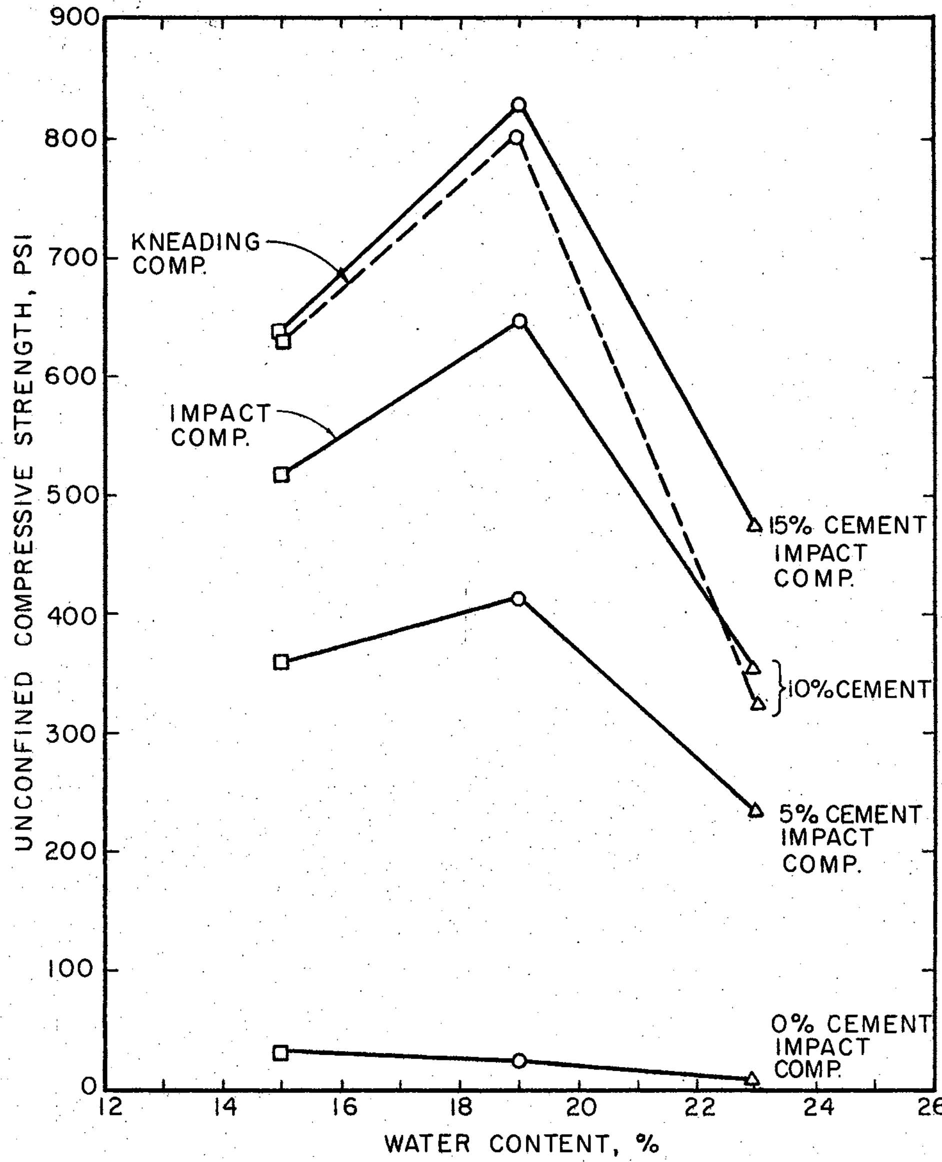


Figure 12. Effect of Molding Water Content, Method of Compaction, and Cement Content on Strength of Soil (Silt)-Cement Mixtures Cured for 7 Days.

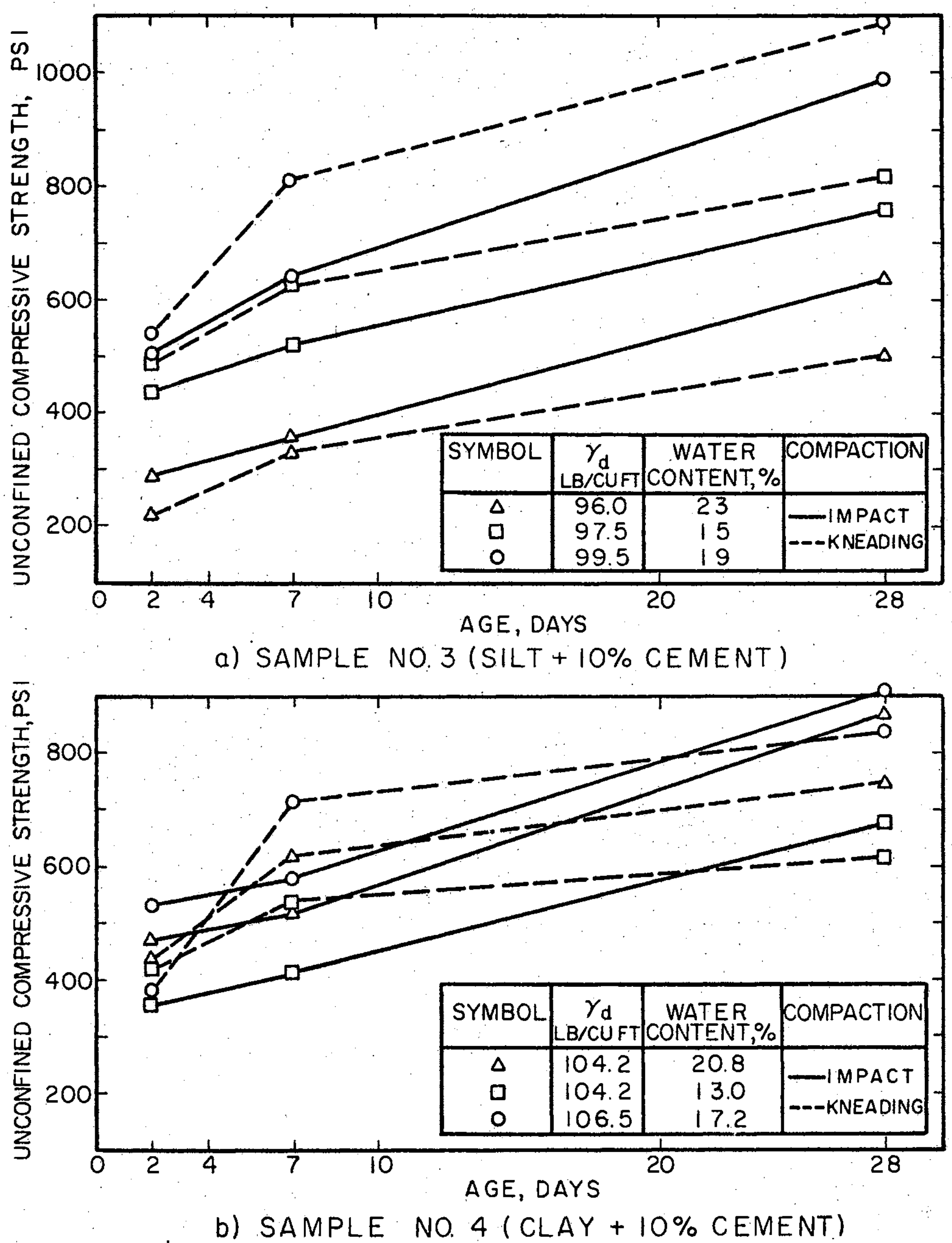


Figure 13. Effect of Method of Compaction, Molding Water Content, and Curing Time on Unconfined Compressive Strength of Fine-Grained Soil-Cement Mixture.

strength than those prepared by kneading compaction between the ages of seven and twenty-eight days. This is illustrated by the slope of the lines in Fig 13a.

4. The strength at optimum water content increased with increase in cement content for specimens cured seven days. These relationships are shown in Fig 14a.

Sample No. 4 (Clay)

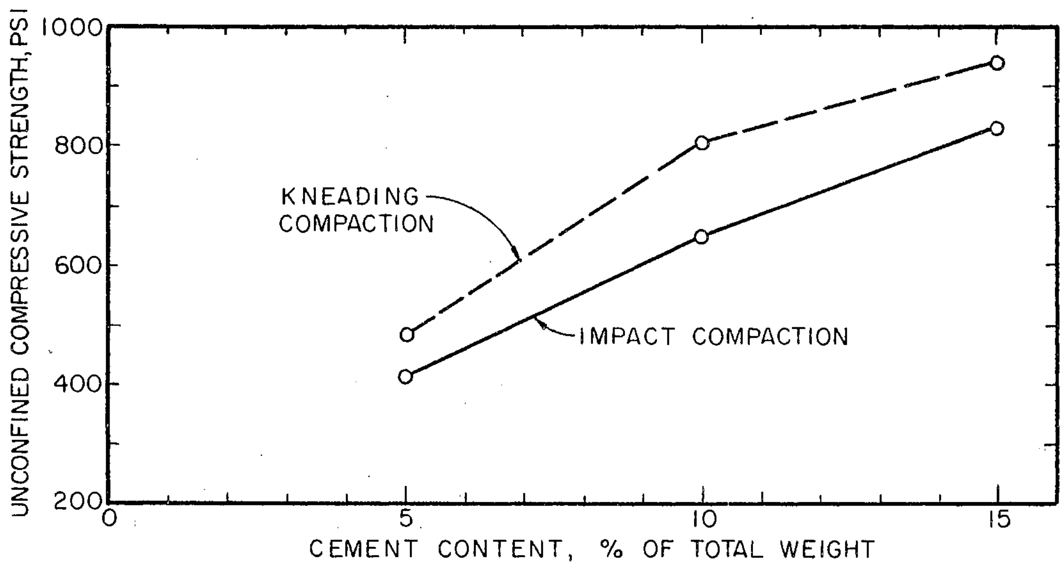
Three sets of specimens were prepared by the two methods of compaction and with different cement contents, they were: dry of optimum (γ_d = 104.2 lb per cu ft, w = 13.0%), at optimum (γ_d = 106.5 lb per cu ft, w = 17.2%), and wet of optimum (γ_d = 104.2 lb per cu ft, w = 20.8%).

The following results were observed:

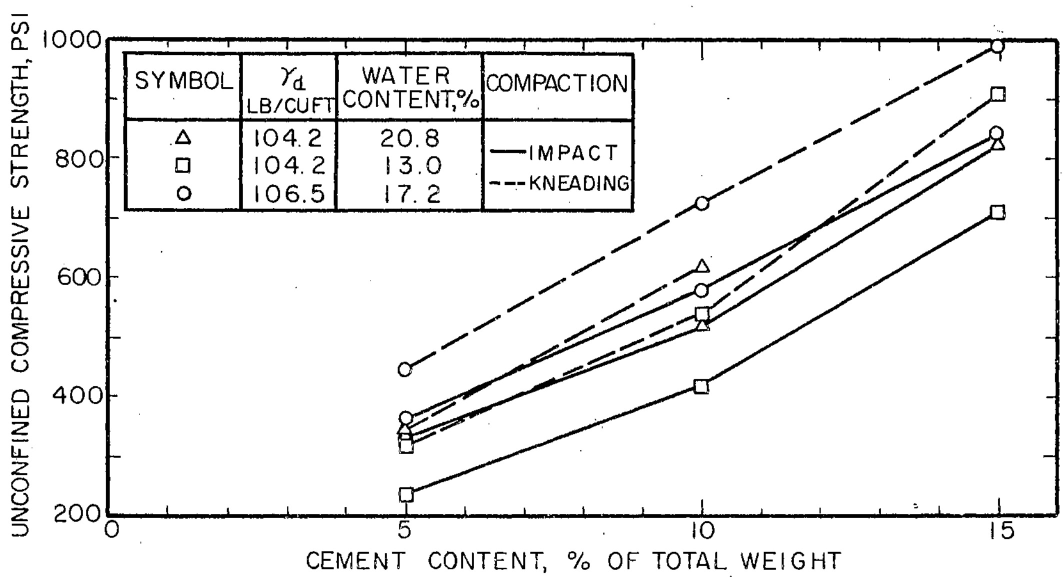
1. As shown in Fig 15, at seven and twenty-eight days, the strength-water content relations followed those of the density-water content for specimens prepared by the two methods. At two days, the specimens prepared by kneading compaction with 10% cement gave a lower strength at optimum. This result was questioned, but repeated tests gave the same result. The results of triaxial tests did not explain this phenomenon.

2. The strength-age relations shown in Fig 13b for the three water contents used illustrate that:

   a. The slope of the lines between two and seven days is higher for the specimens prepared by kneading compaction than those prepared by impact compaction.



a) SILT-CEMENT MIXTURE (γ_d = 99.5 LB/CU FT, WATER CONTENT = 19%), CURED FOR 7 DAYS.



b) CLAY-CEMENT MIXTURES CURED FOR 7 DAYS

Figure 14. Effect of Method of Compaction, Cement Content, and Molding Water Content on Strength of Fine-Grained Soil-Cement Mixtures at 7 Days.

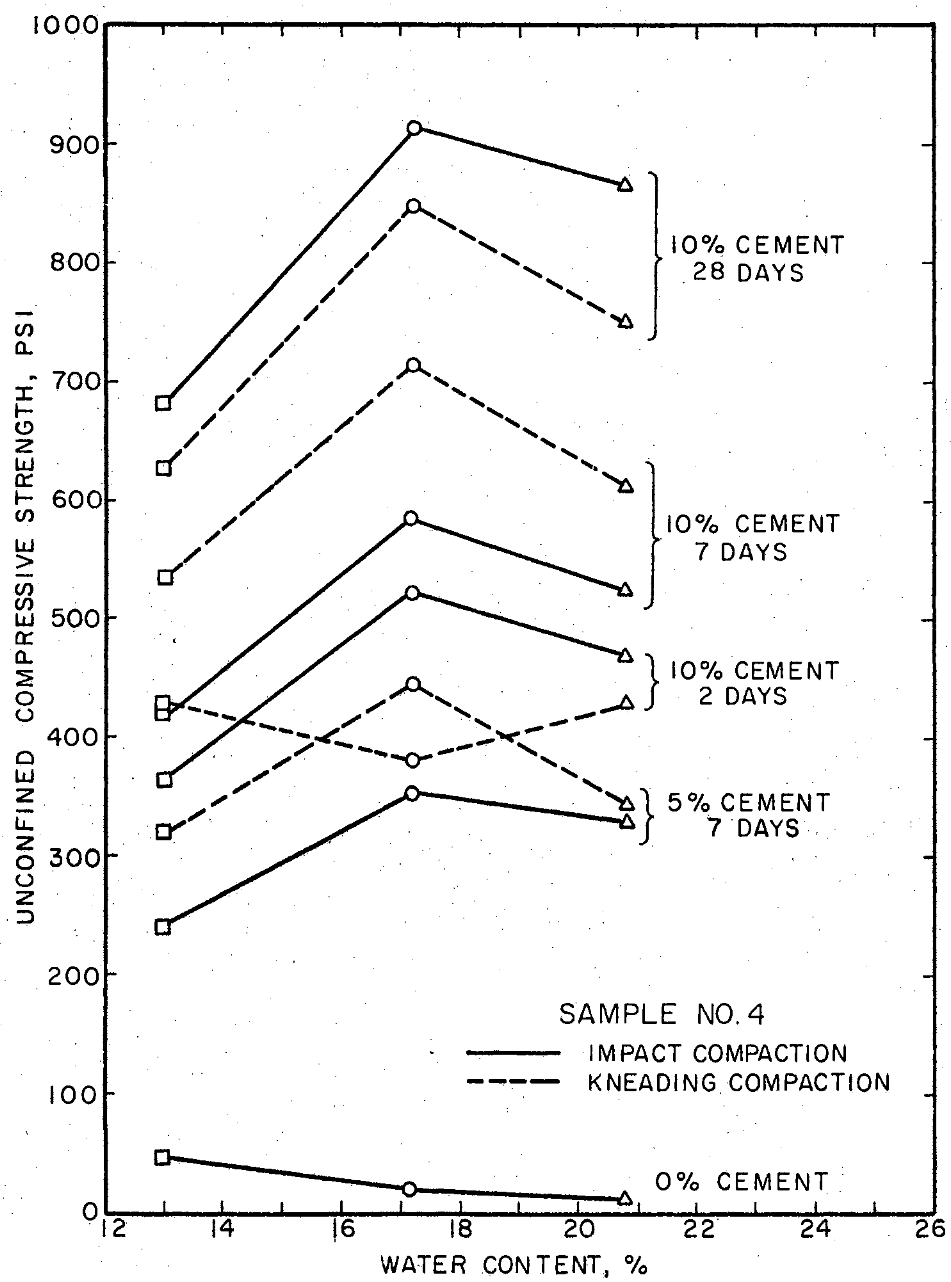


Figure 15. Effect of Molding Water Content, Method of Compaction, Cement Content, and Curing Age on Strength of Clay-Cement Mixtures.

b. From seven to twenty-eight days the slope is greater for the specimens prepared by impact compaction and therefore the rate of strength gain was higher than for those prepared by kneading compaction.

c. Within the range tested, the specimens prepared by impact compaction gave nearly linear strength-age relations.

d. At seven days the specimens prepared by kneading compaction gave higher strength than the corresponding specimens prepared by impact compaction for the three water contents used. At twenty-eight days the strength results reversed as shown in Fig 13b.

The results of Fig 13b show that a specimen prepared by kneading compaction attains most of its strength at seven days and does not gain appreciable strength after that time. This seems to agree with the results on Sample No. 3 (silt) shown in Fig 13a, although the silt showed (comparatively) more gain in strength between the ages of seven and twenty-eight days.

This phenomena indicate that the effect of compaction method on soil-cement mixtures does not only influence particle orientation and/or pore water pressure as in the case of soils with no cement; but in addition it influences the rate of cement hydration, with impact compaction yielding better hydration with age.

3. The unconfined compressive strength increases with increase in cement content. At optimum water content the relation was linear for both methods of compaction as shown in Fig 14b.

CHAPTER IV

RESULTS OF TRIAXIAL COMPRESSION TESTS

General

A typical result obtained from an undrained triaxial test is shown in Fig 16. In each case where a break in the strength envelope was observed at a normal stress σ_B , ϕ_{SC} was greater than ϕ_S.

From Fig 16 it is clear that for normal stresses smaller than σ_B Coulomb's law

$$s = c + \sigma \tan \phi_{SC} \tag{1}$$

can be applied. For normal stresses greater than σ_B , Coulomb's law for shear stress should be modified to

$$s = c + \sigma_B \tan \phi_{SC} + (\sigma - \sigma_B) \tan \phi_S \tag{2}$$

Typical stress-strain relations at different confining pressures are given in Fig 17 for granular soil, and in Fig 18 for fine-grained soil-cement mixtures.

Granular Soils

Stress-strain curves for the two granular soil-cement mixtures are given in Appendix A (Figs A-1 through A-4).

At the lower molding water content used, the stress-strain relations showed a sharp peak indicating more brittle behavior.

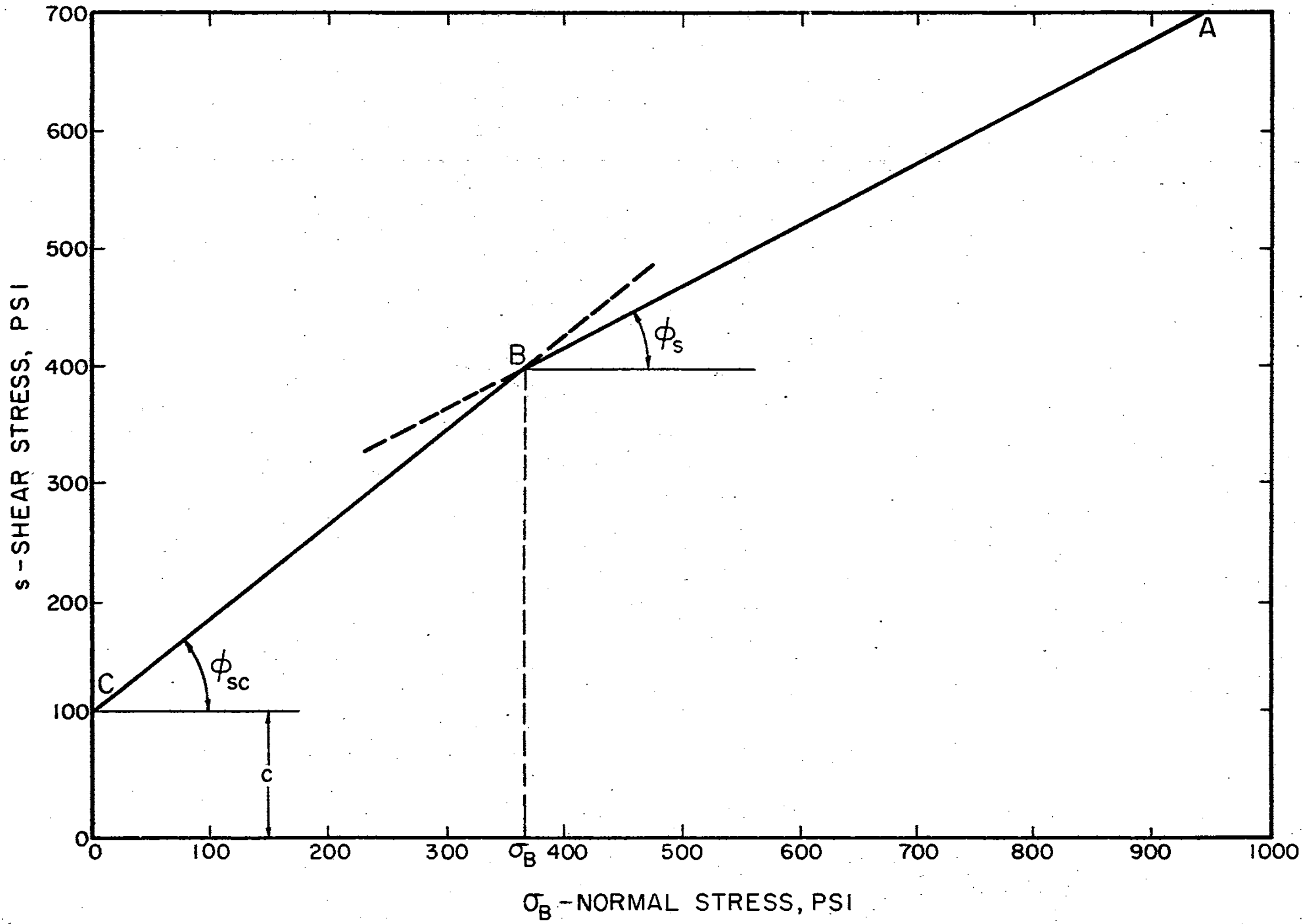


Figure 16. Typical Strength Envelope (Ottawa Sand + 7% Cement, γ_d = 104 pcf, w = 5%, Age = 7 days).

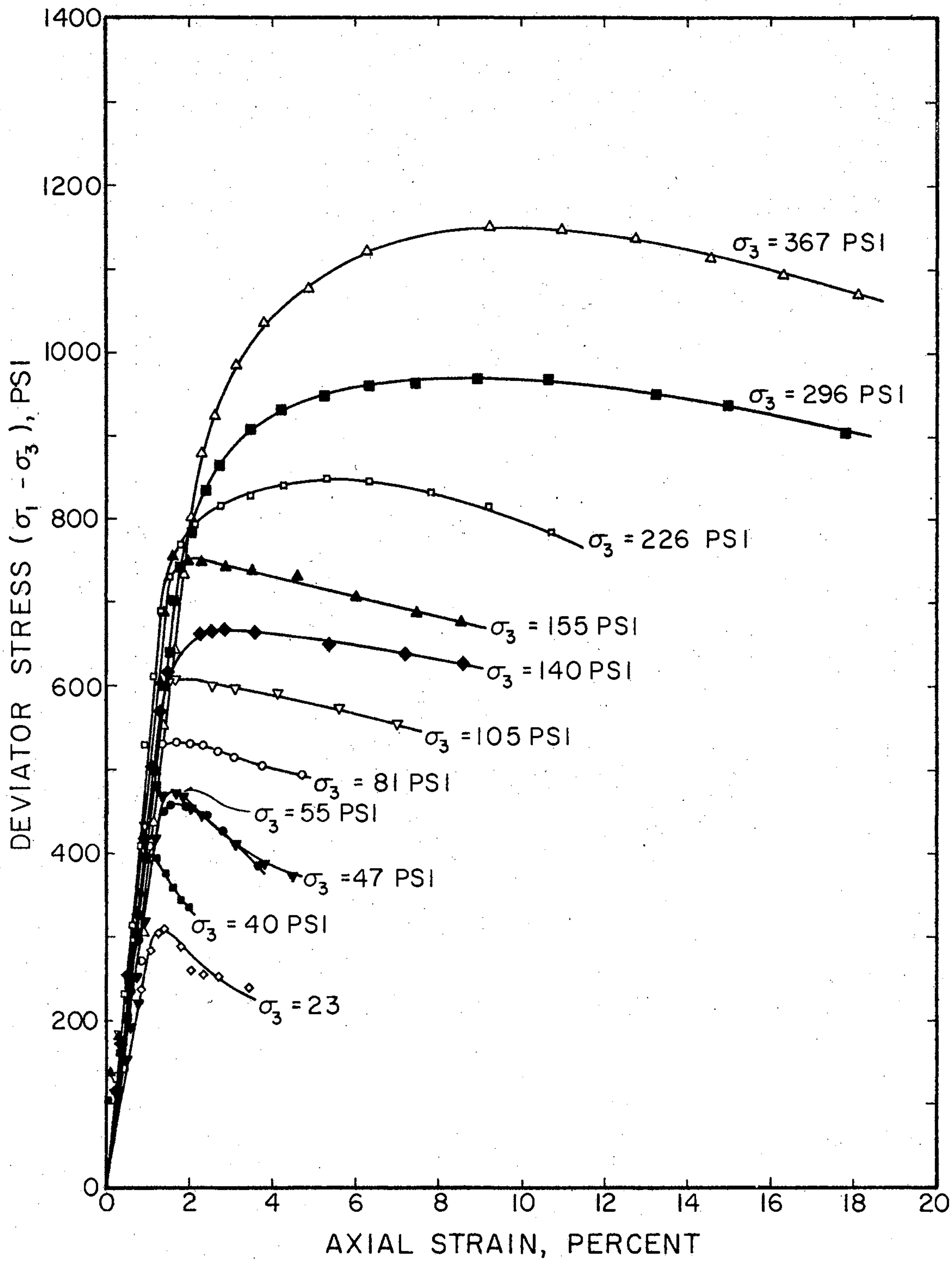


Figure 17. Typical Stress-Strain Relations for Granular Soil-Cement Mixtures (River Sand + 7% Cement, γ_d = 109 pcf, w = 10%, 7 Days, Kneading Compaction).

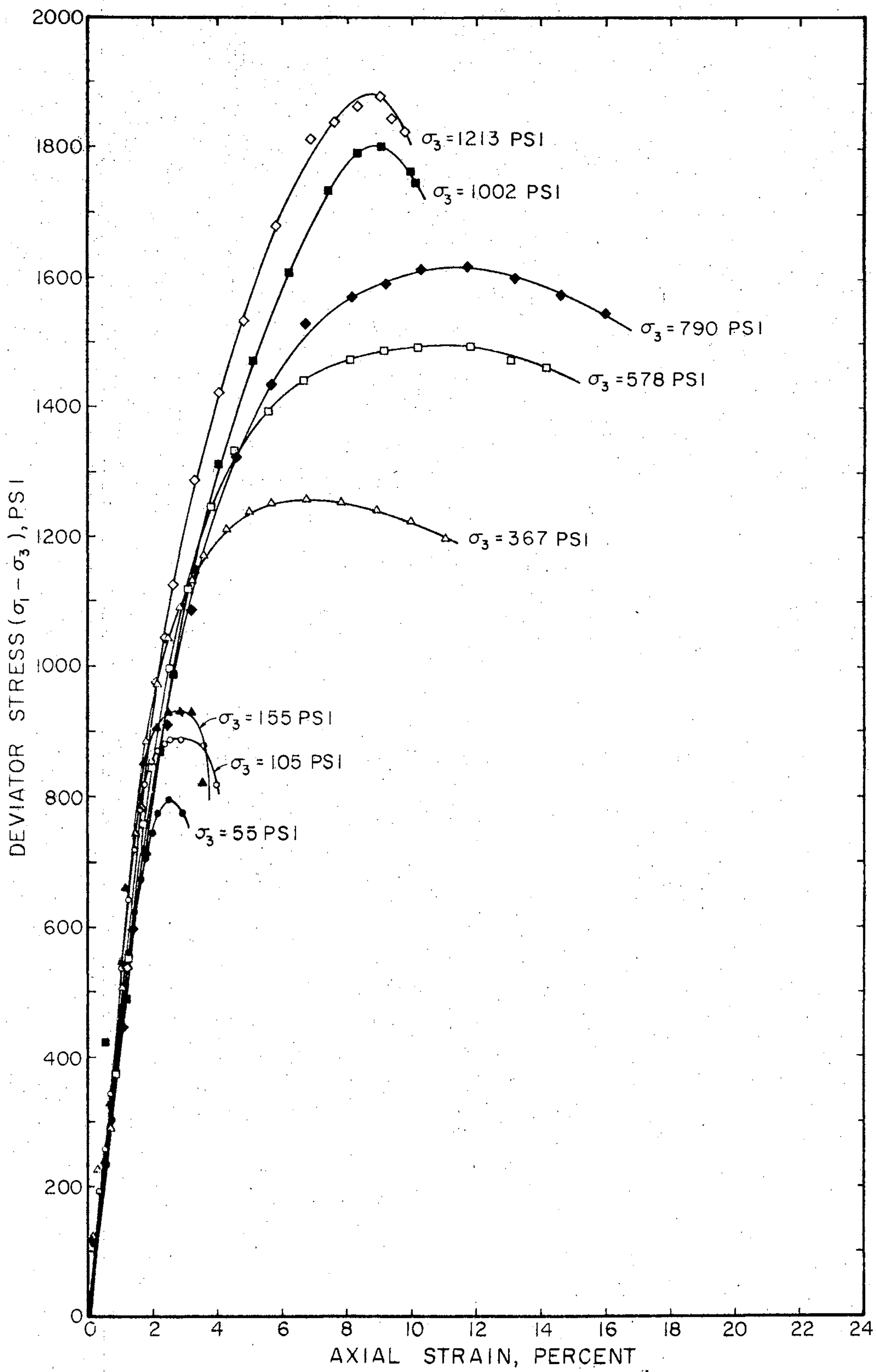


Figure 18. Typical Stress-Strain Relations for Fine-Grained Soil-Cement Mixtures (Clay + 10% Cement, γ_d = 106.5 pcf, w = 17.2%, 7 Days, Kneading Compaction).

Sample No. 1 (River Sand)

The Mohr circles for Sample No. 1 are shown in Appendix B (Figs B-1 through B-13). Fig 19 shows the effect of cement content on strength envelopes for the two methods of compaction employed. The effect of age on the strength envelopes is shown in Fig 20. The effect of molding water content, density, and method of compaction on the strength envelopes is illustrated by Fig 21. From the strength envelopes the following results were observed:

1. Both c and σ_B increased with curing age for specimens prepared by the two compaction methods used as shown in Fig 22.
2. Values of c and σ_B increased with cement content as illustrated in Fig 23.
3. At all ages and cement contents investigated, specimens prepared by impact compaction gave higher c and σ_B than corresponding specimens prepared by kneading compaction. This seems to agree well with the results of unconfined compressive strength reported in Chapter III.

The effect of method of compaction on values of c and unconfined strength seems to be due to an influence on the rate of cement hydration, with impact compaction yielding better hydration opportunities than kneading compaction, as particle orientation is not a factor in granular soils.

Sample No. 2 (Ottawa Sand)

Mohr circles for Sample No. 2 are shown in Appendix B (Figs B-14, B-15, and B-16). The strength envelopes shown in Fig 24 illustrate that:

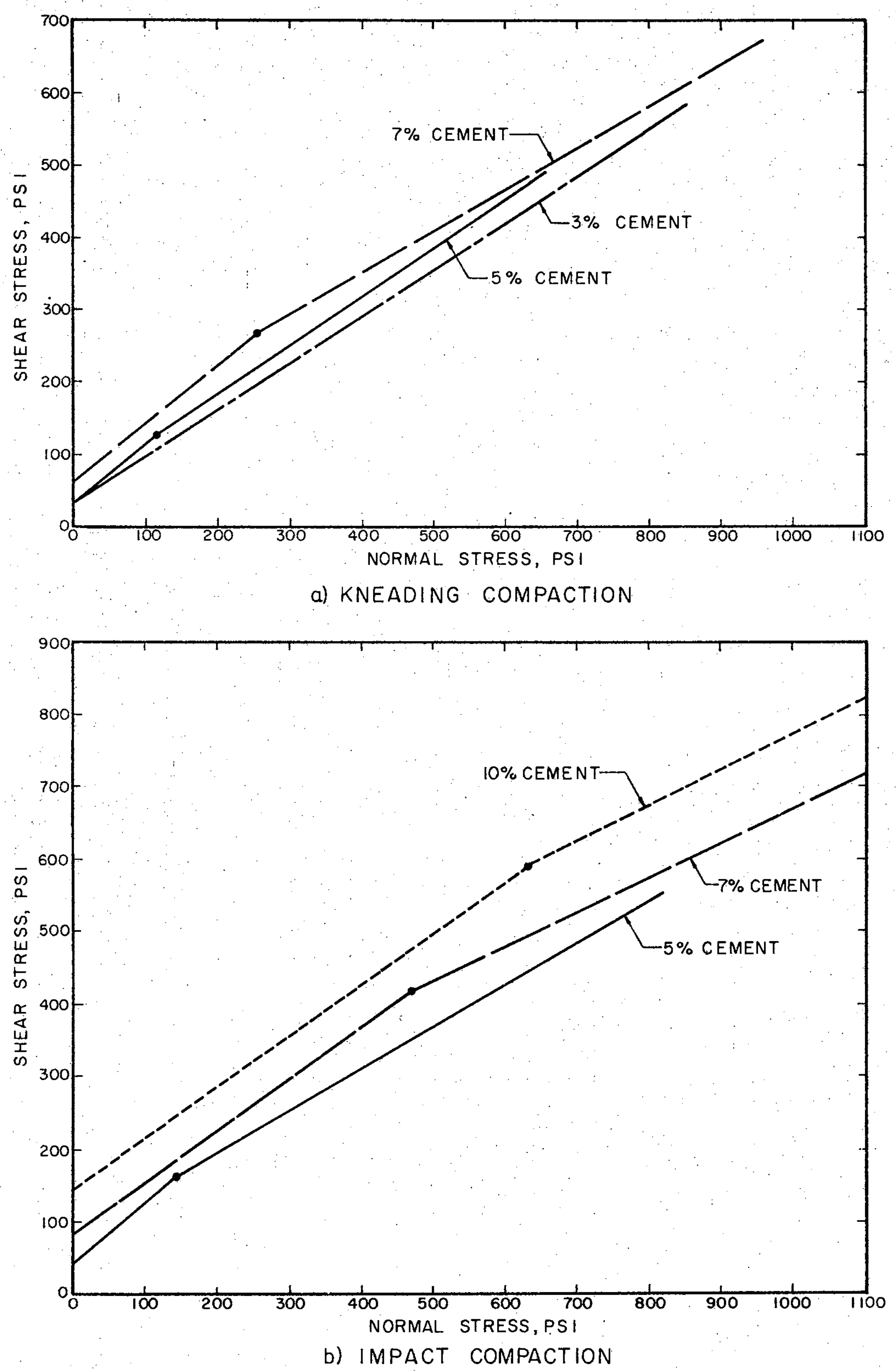
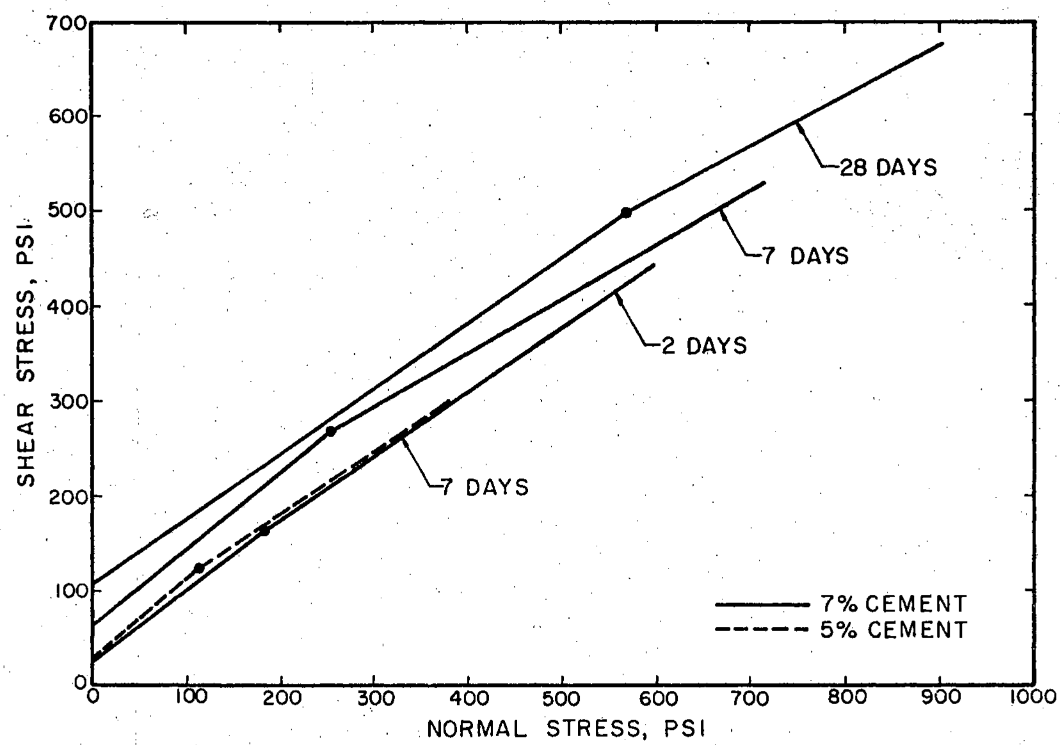
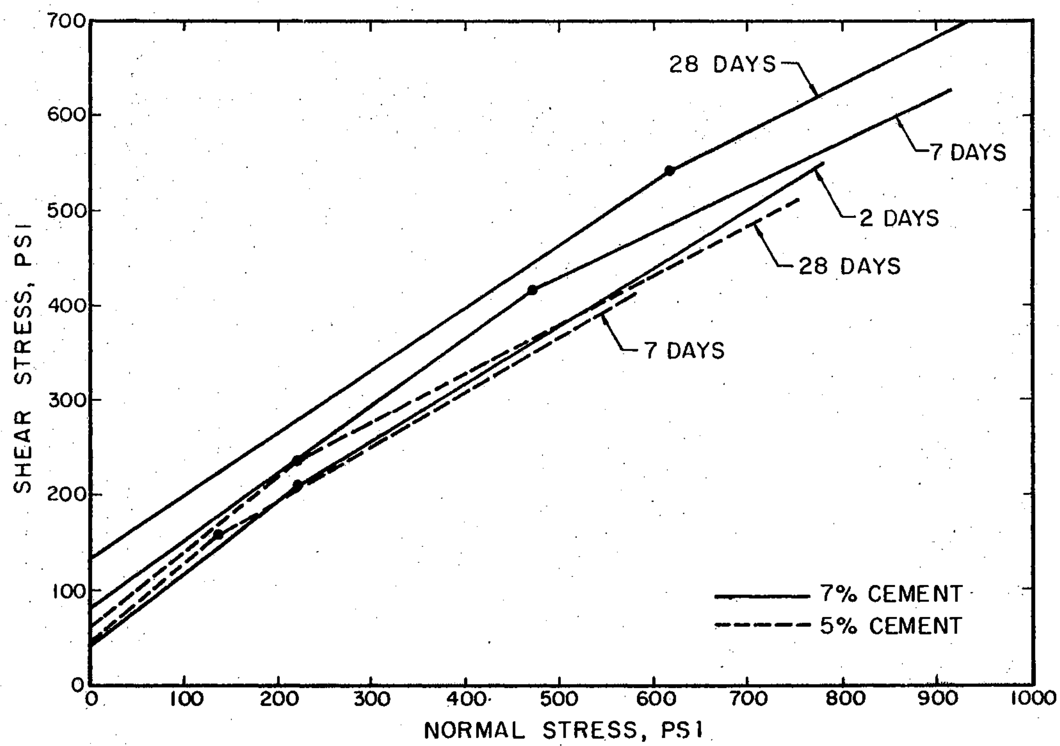


Figure 19. Effect of Cement Content and Method of Compaction on Strength Envelope (River Sand, γ_d = 109 pcf, w = 10%, 7 Days).



a) KNEADING COMPACTION



b) IMPACT COMPACTION

Figure 20. Effect of Age, Cement Content, and Method of Compaction on Strength Envelope (River Sand, γ_d = 109 pcf, w = 10%).

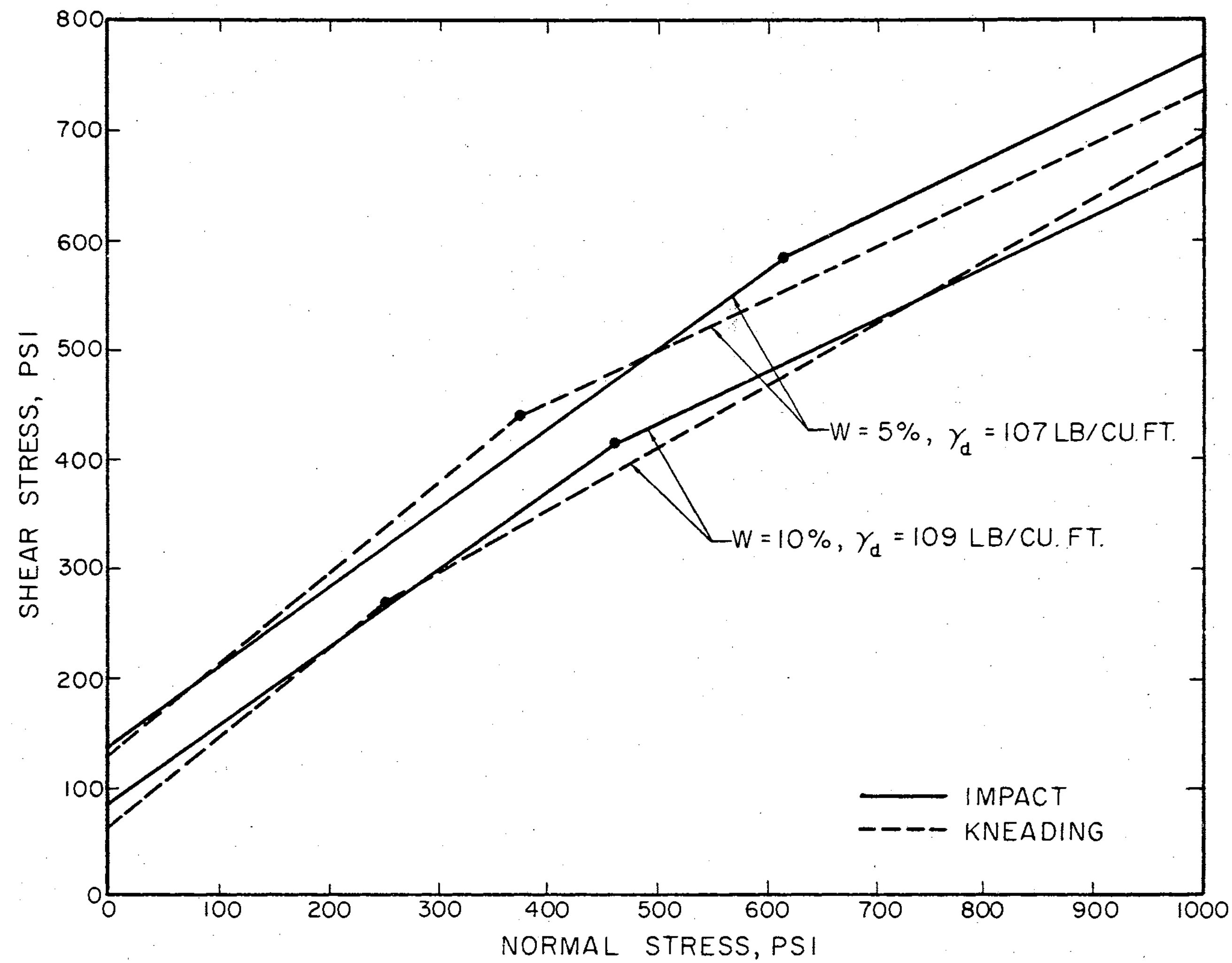
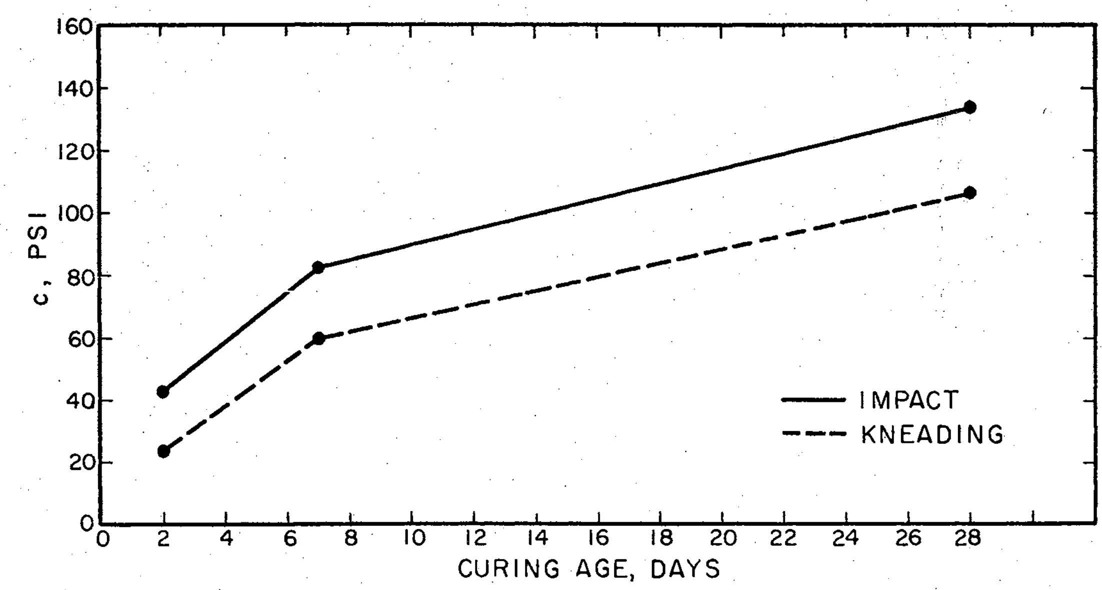
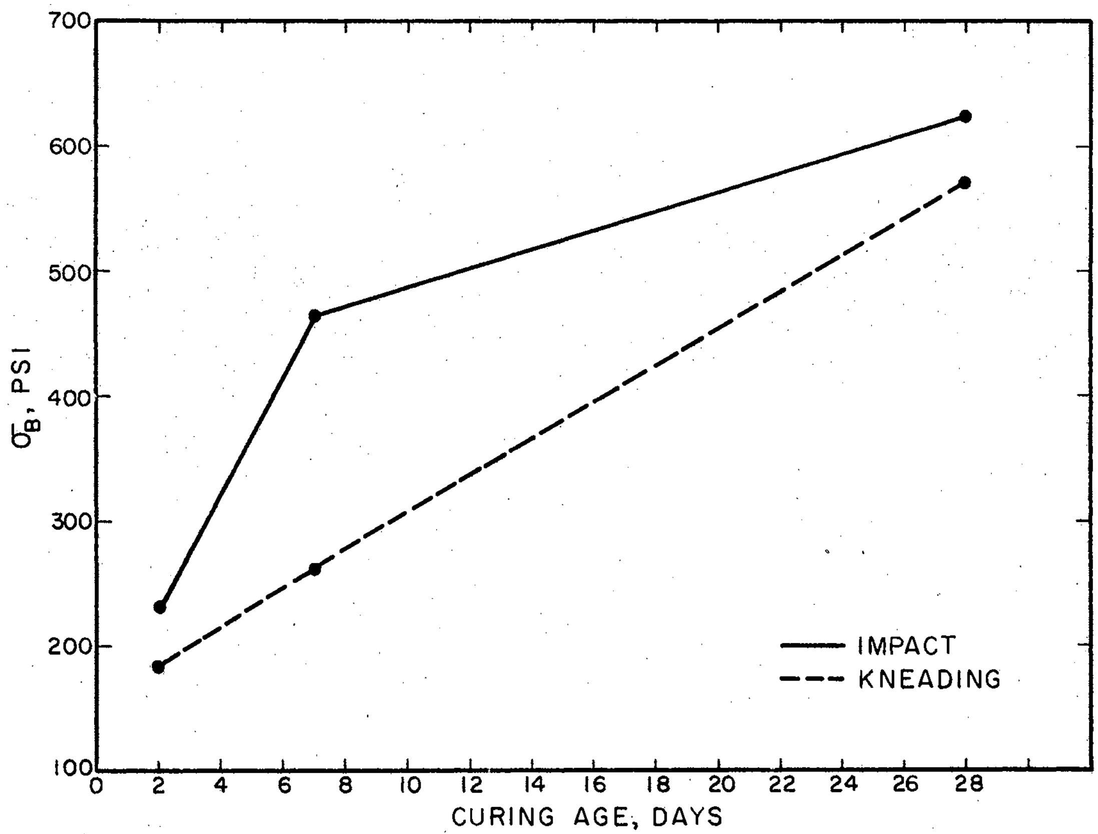


Figure 21. Effect of Method of Compaction, Density, and Molding Water Content on Strength Envelope (River Sand, 7 Days).

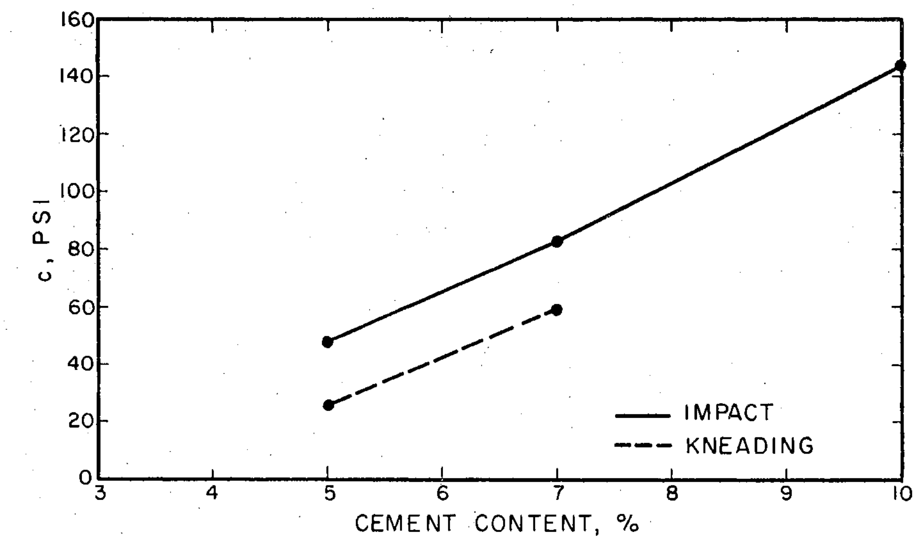


a) EFFECT OF CURING AGE ON c.

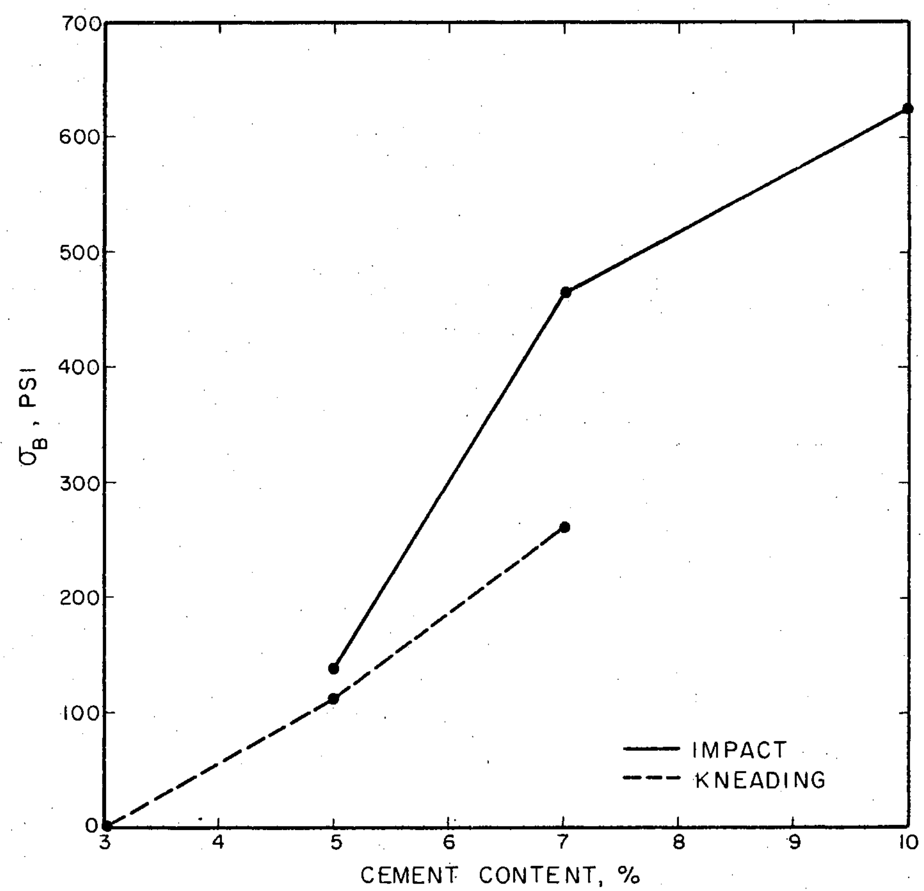


b) EFFECT OF CURING AGE ON σ_B.

Figure 22. Effect of Age and Method of Compaction on c and σ_B (River Sand + 7% Cement, γ_d = 109 pcf, w = 10%).



a) EFFECT OF CEMENT CONTENT ON c.



b) EFFECT OF CEMENT CONTENT ON σ_B.

Figure 23. Effect of Cement Content and Method of Compaction on c and σ_B (River Sand, γ_d = 109 pcf, w = 10%, 7 Days).

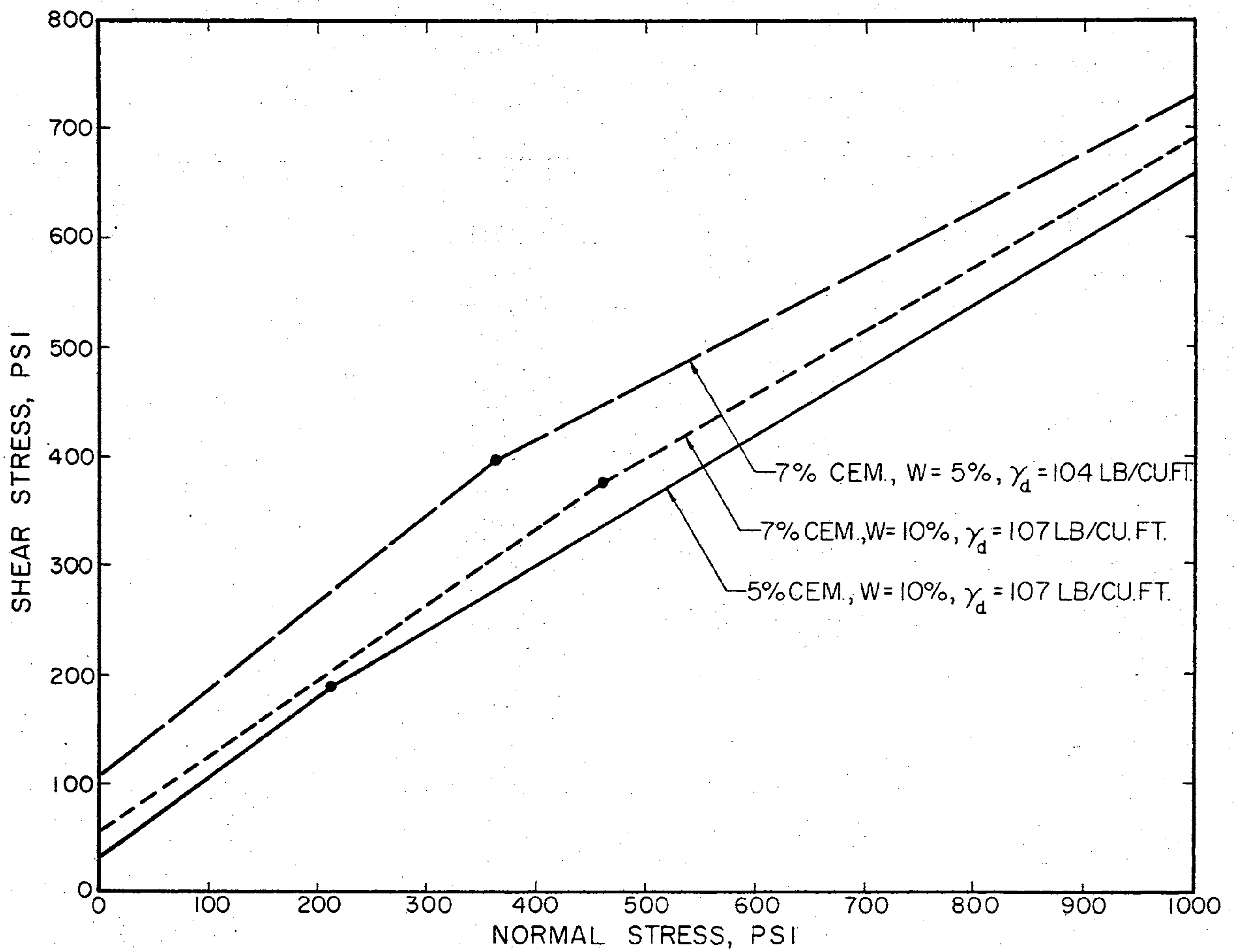


Figure 24. Influence of Cement, Water Content, and Density on Strength Envelope (Ottawa Sand, 7 Days).

1. ϕ_{SC} is greater than ϕ_S in all cases. The difference becomes greater at lower molding water content (hence lower density).

2. At the same molding water content, density, and age the following results were observed:

   a. Values of ϕ_S and ϕ_{SC} were not influenced by cement content, as seen in Table IV.

   b. Both c and σ_B increased with cement content and hence with an increase in unconfined compressive strength.

3. The lower the molding water content, the higher the c value.

Fine-Grained Soils

Stress-strain characteristics for the two fine-grained soils used are shown in Appendix A (Figs A-5 through A-11). For optimum water content these curves indicate that at low confining pressures sharp peaks develope at low strains. At an intermediate confining pressure, the stress levels off. As the confining pressure increases further the stress-strain curves show a peak again, although not as sharp as the one at low confining pressure. This phenomenon is clearly demonstrated wet of optimum. For specimens prepared dry of optimum no clear peak developed at high confining pressures. This might be due to a higher pore water pressure developed at higher water contents.

In general the strain at which failures occur increased with an increase in confining pressure up to a point and then start to decrease with increase in confining pressure.

The two methods of compaction used gave similar stress-strain relations.

TABLE IV

RESULTS OF COMPRESSION TESTS ON GRANULAR SOIL-CEMENT MIXTURES

Sample Number	Specimen Properties					Unconfined Compressive Strength psi	Results of Triaxial Tests			
	Cement Content %	w %	γ_d pcf	Age Days	Method of Compaction		c psi	σ_B psi	ϕ^o_{sc}	ϕ^o_s
1	3	10	109	7	kneading	37	-	-*	-	33
	5	10	109	7	impact	150	48	136	39	30
	5	10	107	7	kneading	119	26	110	40	34
	5	10	109	28	impact	207	60	224	38	28
	7	5	107	7	impact	422	134	621	36	26
	7	5	107	7	kneading	369	127	377	39	26
	7	10	109	2	kneading	153	24	185	37	34
	7	10	109	2	impact	145	43	230	37	32
	7	10	109	7	impact	310	83	465	36	26
	7	10	109	7	kneading	255	60	260	39	30
	7	10	109	28	impact	296	134	620	34	27
	7	10	109	28	kneading	320	107	570	35	28
	10	10	109	7	impact	491	145	625	36	27
2	5	10	107	7	impact	115	30	216	36	30
	7	5	104	7	impact	408	103	365	38	28
	7	10	107	7	impact	295	58	460	35	30

*At the confining pressure range investigated, no break in strength envelope was observed.

Sample No. 3 (Silt)

Water contents and densities used were as given in Chapter III for the unconfined tests. The Mohr circles for Sample No. 3 are given in Appendix B (Figs B-17 through B-27). Strength envelopes for slit molded at optimum water content with different cement contents and curing ages are shown in Fig 25. Figure 26 shows the strength envelope with 10% cement dry and wet of optimum, when specimens were cured for 7 days. While no break in the strength envelope was observed dry of optimum, the break was very clear wet of optimum.

From the strength envelopes at optimum water content the following results were deduced:

1. With 10% cement, ϕ_{SC} and ϕ_{S} were not affected by curing age.
2. Values of c increased with age as shown in Fig 27a.
3. The rate of gain in c between the ages of 2 to 7 days was higher for specimens prepared by kneading compaction, while the rate of gain in c was higher for specimens molded by impact compaction between the ages of 7 to 28 days. The values of c were higher for specimens prepared by kneading compaction than the corresponding specimens prepared by impact compaction at all ages. This agrees with higher unconfined strength of specimens molded by kneading compaction at optimum water content.
4. As shown in Fig 28 values of c increased with increase in cement content while σ_B remained about the same.
5. Values of ϕ_{SC} and ϕ_{S} were not influenced by method of

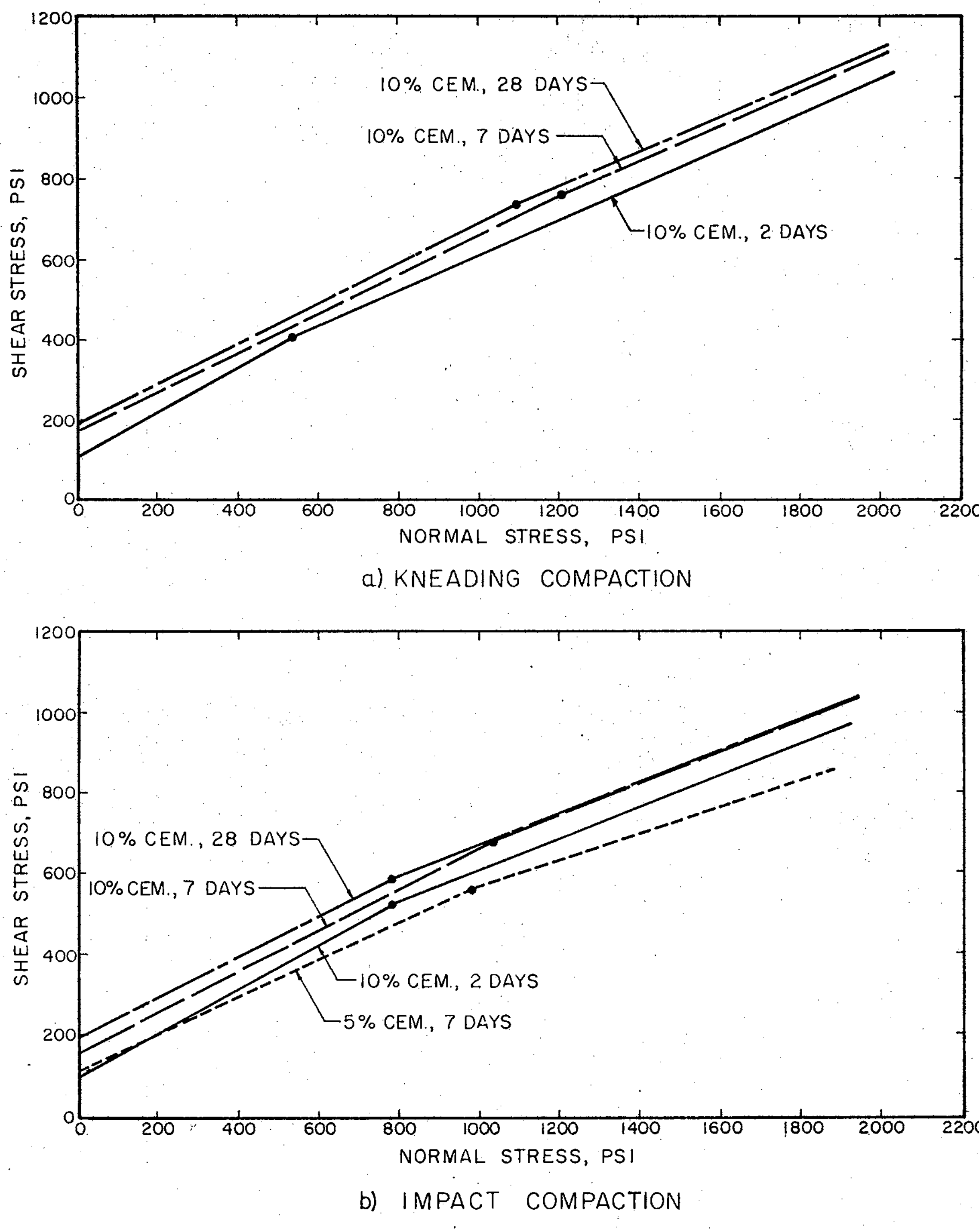
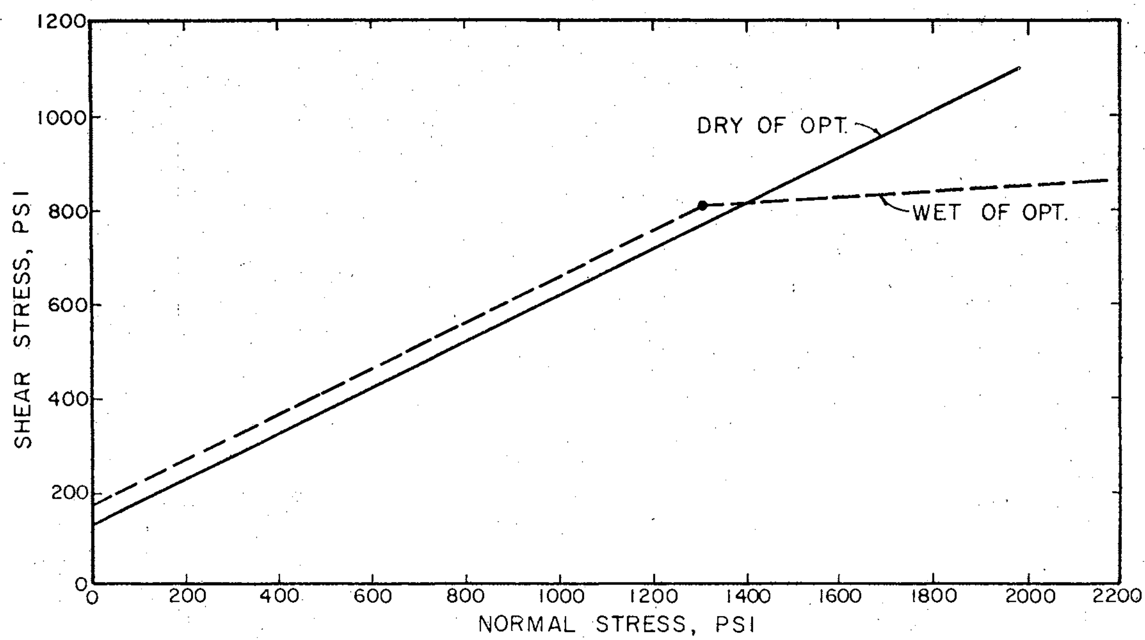
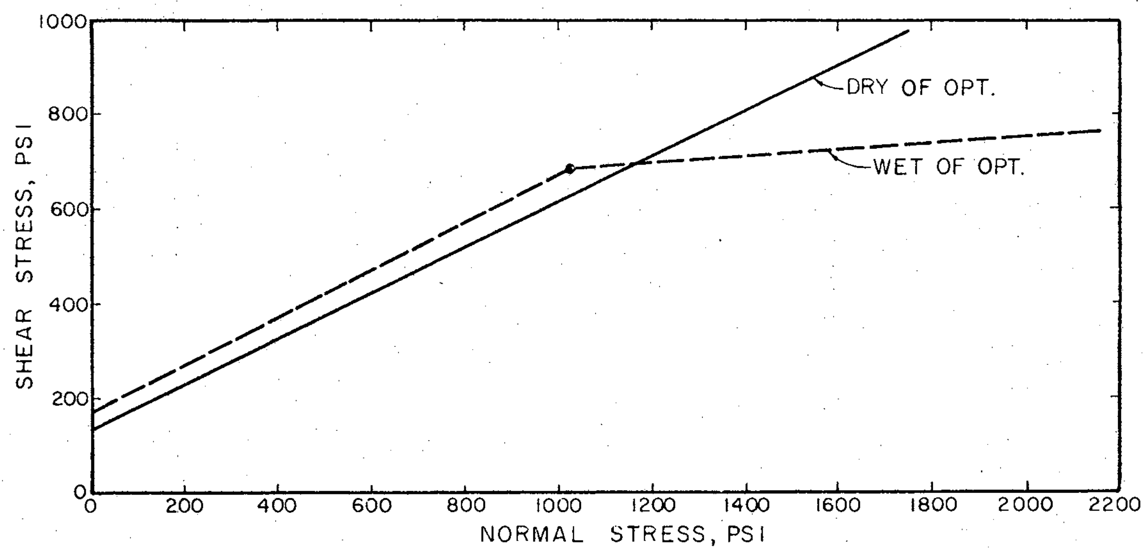


Figure 25. Influence of Age, and Method of Compaction on Strength Envelope (Silt, γ_d = 99.5 pcf, w = 19%).

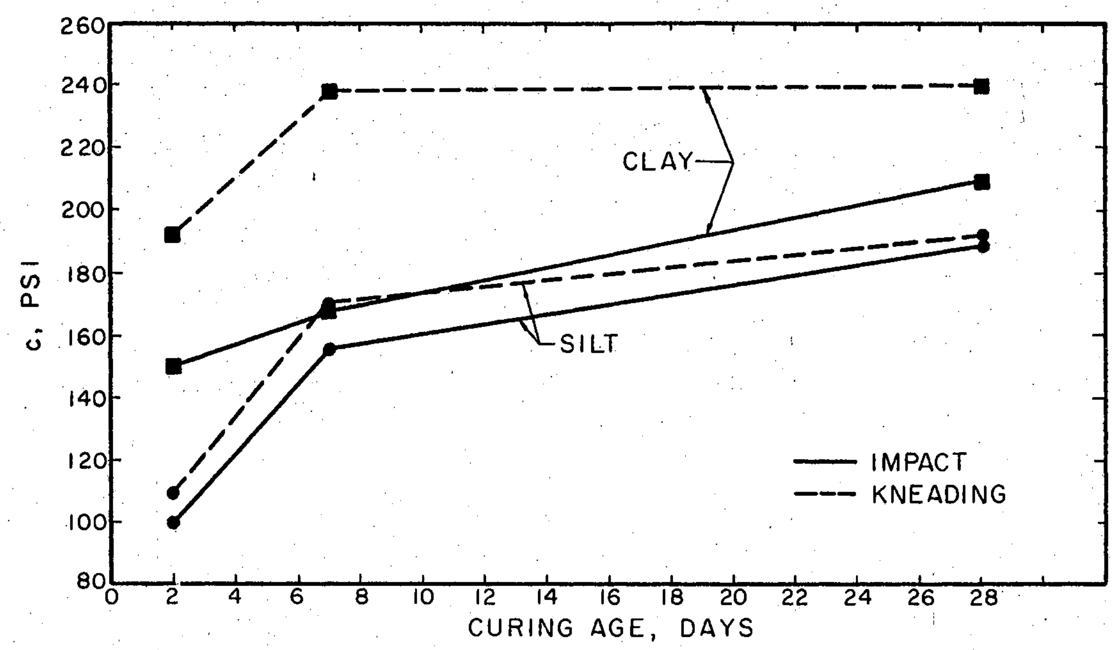


a) IMPACT COMPACTION

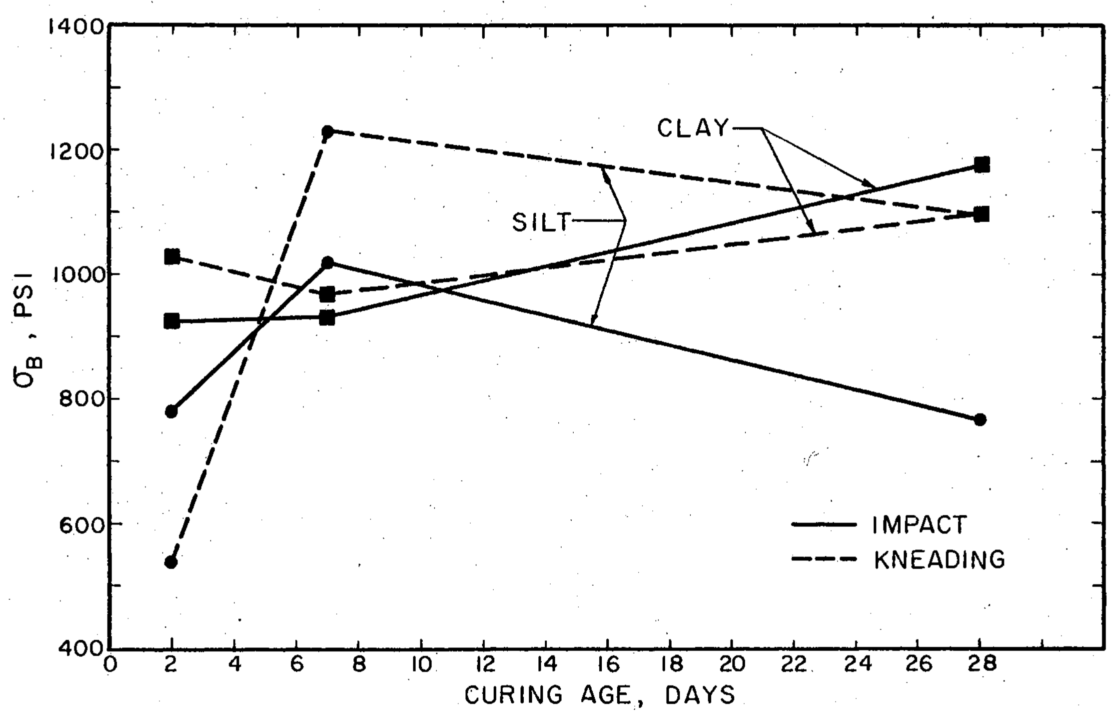


b) KNEADING COMPACTION

Figure 26. Influence of Molding Water Content on Strength Envelope (Silt + 10% Cement, 7 Days).

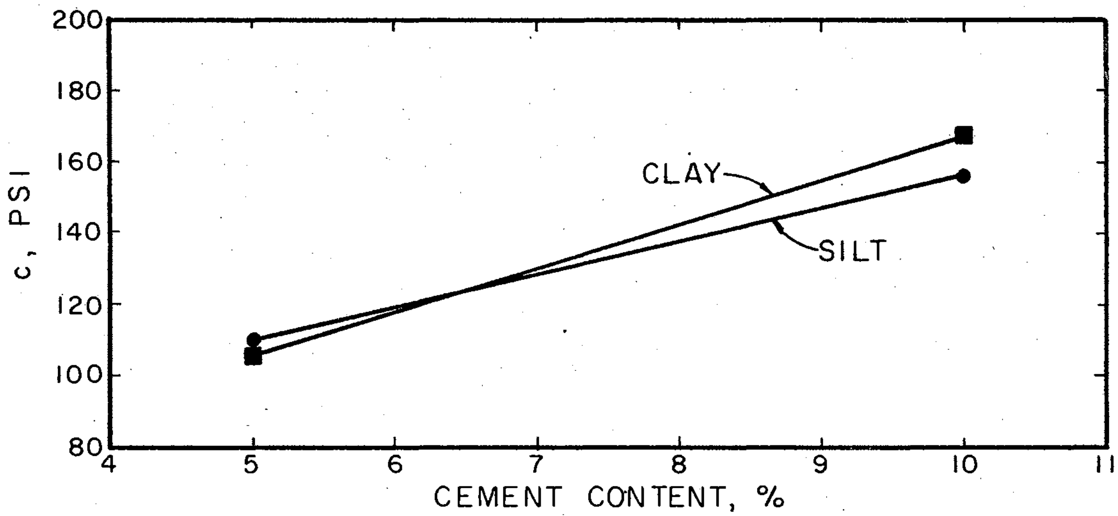


a) EFFECT OF CURING AGE ON c.

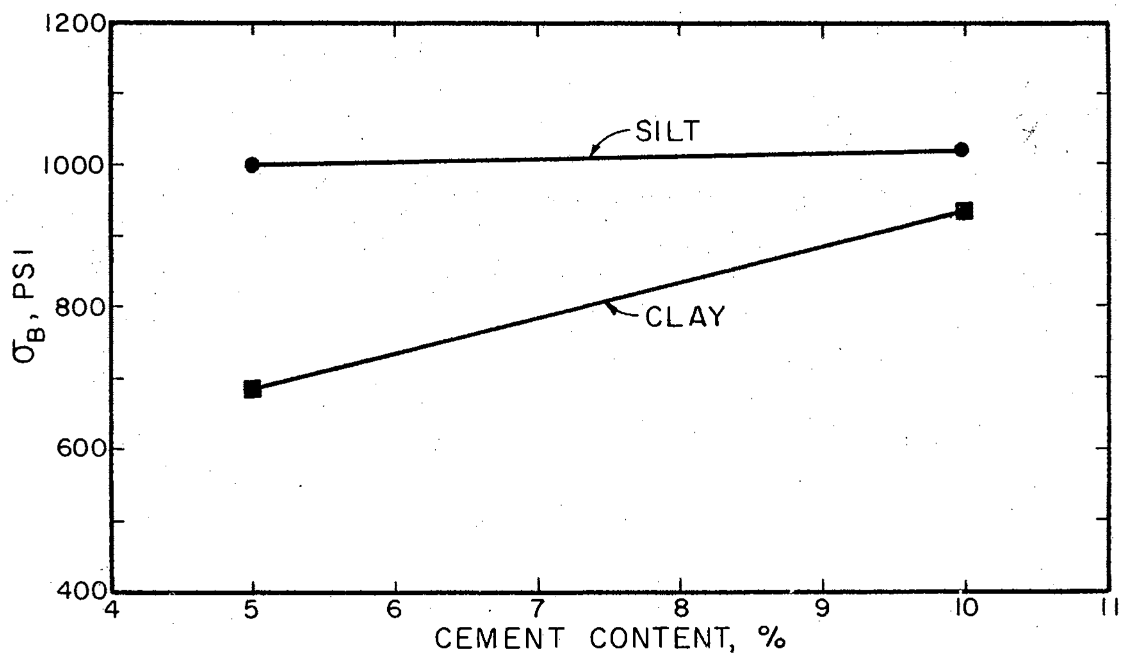


b) EFFECT OF CURING AGE ON σ_B.

Figure 27. Effect of Age and Method of Compaction on c and σ_B (Fine Grained Soil + 10% Cement, Optimum Water Content).



a) EFFECT OF CEMENT CONTENT ON c.



b) EFFECT OF CEMENT CONTENT ON σ_B.

Figure 28. Effect of Cement Content on c and σ_B (Fine-Grained Soils, Optimum Water Content, 7 Days, Impact Compaction).

compaction as shown in Table V.

The effect of molding water content on c is shown in Fig 29. Specimens molded by kneading compaction at optimum water content possess higher c and σ_B than specimens molded dry or wet of optimum. For specimens molded by impact compaction both σ_B and c increased with water content at 7 days.

Wet of optimum specimens prepared by impact compaction showed higher c and σ_B values than the corresponding specimens prepared by kneading compaction. Higher c values by impact compaction agrees well with higher unconfined compressive strength obtained; since kneading compaction produced less flocculant structure than impact compaction at wet of optimum.

Sample No. 4 (Clay)

Mohr circles for Sample No. 4 are given in Appendix B (Figs B-28 through B-37). The specimens were prepared at the water contents and densities given in Chapter III for the unconfined tests.

Figure 30 shows the strength envelopes for clay specimens with 10% cement, molded at different water content and cured for 7 days.

Strength envelopes for clay at optimum water content with different cement contents and ages are given in Fig 31. From the strength envelopes at optimum water contnet, the following results were obtained:

1. As shown in Table V, both ϕ_{SC} and ϕ_S increased with age between 7 and 28 days for specimens molded by kneading compaction. For impact compaction ϕ_{SC} increased between 2 and 7 days and remained roughly constant to 28 days.
2. Both values of ϕ_{SC} and ϕ_S increased with increase in

TABLE V

RESULTS OF COMPRESSION TESTS ON FINE-GRAINED SOIL-CEMENT MIXTURES

Sample Number	Specimen Properties					Unconfined Compressive Strength psi	Results of Triaxial Tests			
	Cement Content %	w %	γ_d pcf	Age Days	Method of Compaction		c psi	σ_B psi	ϕ^o_{sc}	ϕ^o_s
3	5	19.0	99.5	7	impact	416	110	1000	25	18
	10	19.0	99.5	2	impact	506	100	780	29	21
	10	19.0	99.5	2	kneading	536	109	540	29	23
	10	19.0	99.5	7	impact	648	156	1020	27	22
	10	19.0	99.5	7	kneading	807	170	1230	26	23
	10	19.0	99.5	28	impact	993	190	770	27	22
	10	19.0	99.5	28	kneading	1100	192	1100	26	23
	10	15.0	97.5	7	impact	518	130	-*	26	26
	10	15.0	97.5	7	kneading	637	120	-*	26	26
	10	23.0	96.0	7	impact	354	168	1305	26	4
	10	23.0	96.0	7	kneading	322	163	1022	27	4
4	0	17.2	106.5	7	impact	20	36	-*	-*	9
	5	17.2	106.5	7	impact	353	106	685	21	13
	10	17.2	106.5	2	impact	523	150	926	23	16
	10	17.2	106.5	2	kneading	380	192	1030	22	14
	10	17.2	106.5	7	impact	582	168	935	25	18
	10	17.2	106.5	7	kneading	718	238	970	25	13
	10	17.2	106.5	28	impact	916	210	1175	25	20
	10	17.2	106.5	28	kneading	850	240	1100	27	18
	10	13.0	104.2	2	kneading	425	67	**	25	**
	10	13.0	104.2	7	impact	419	95	650	29	22
	10	20.8	104.2	2	kneading	430	130	**	23	**
	10	20.8	104.2	7	impact	538	162	850	23	8

*No break in strength envelope **Investigated at low confining pressures only

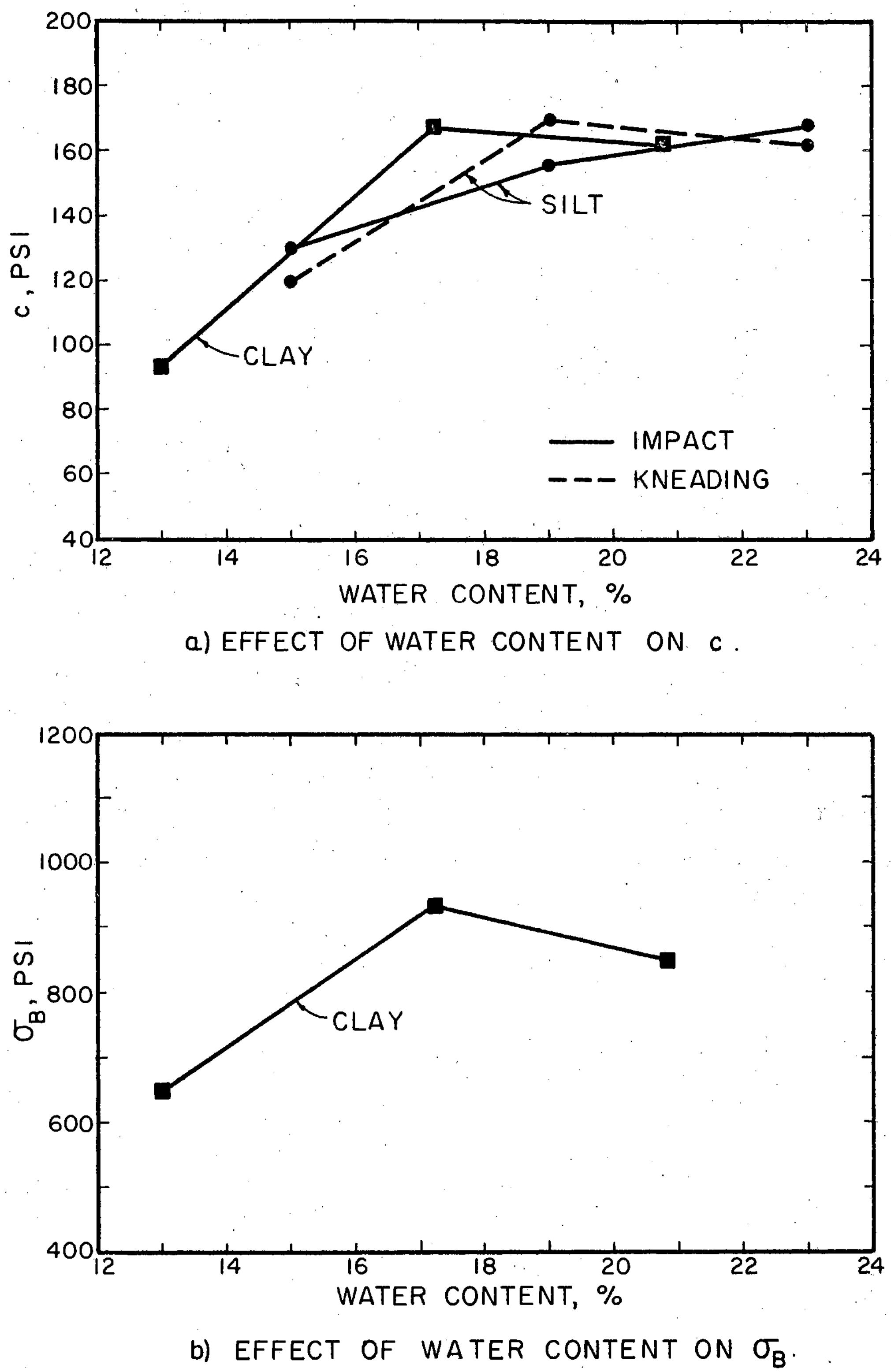


Figure 29. Effect of Molding Water Content on c and σ_B (Fine-Grained Soils + 10% Cement, 7 Days).

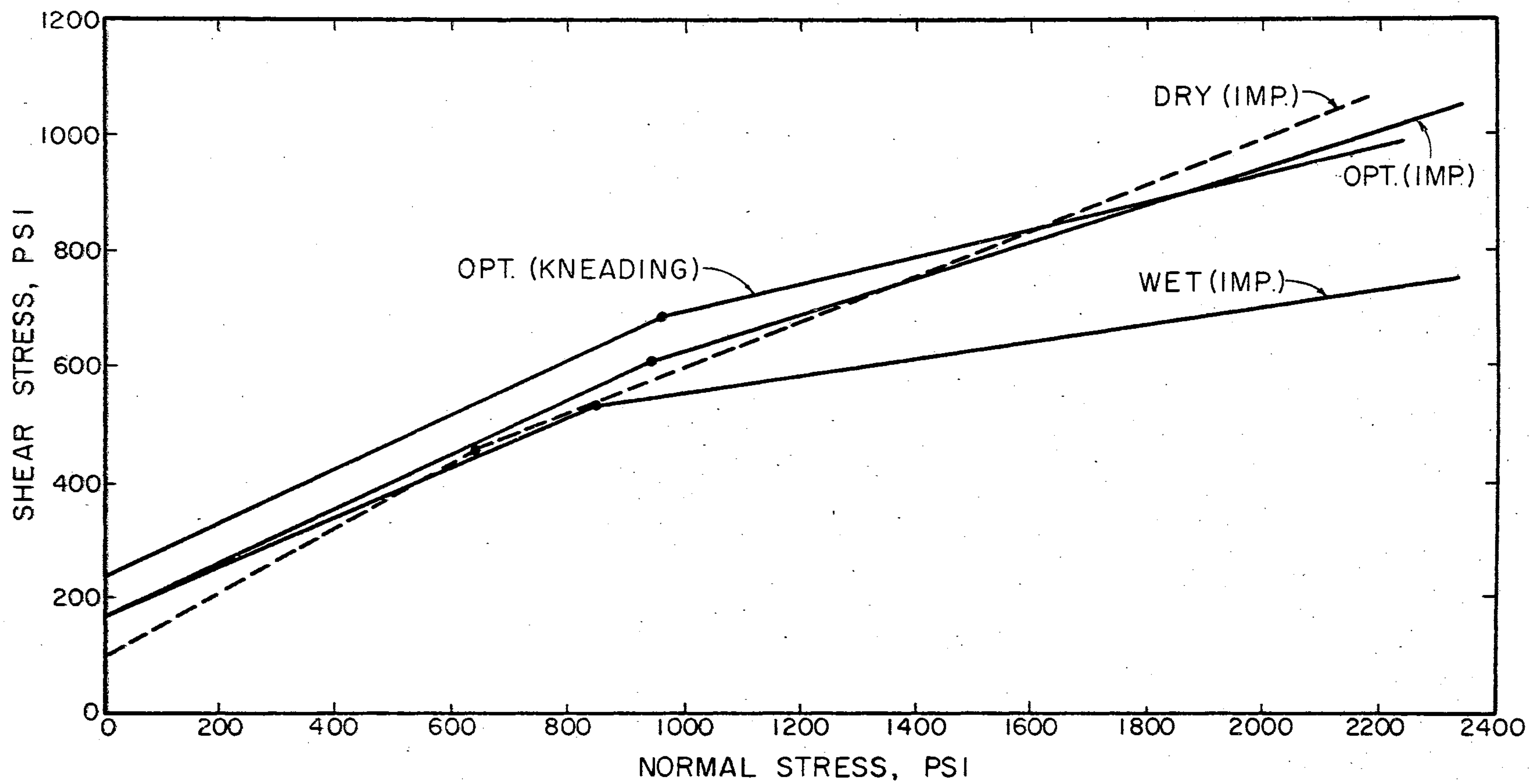
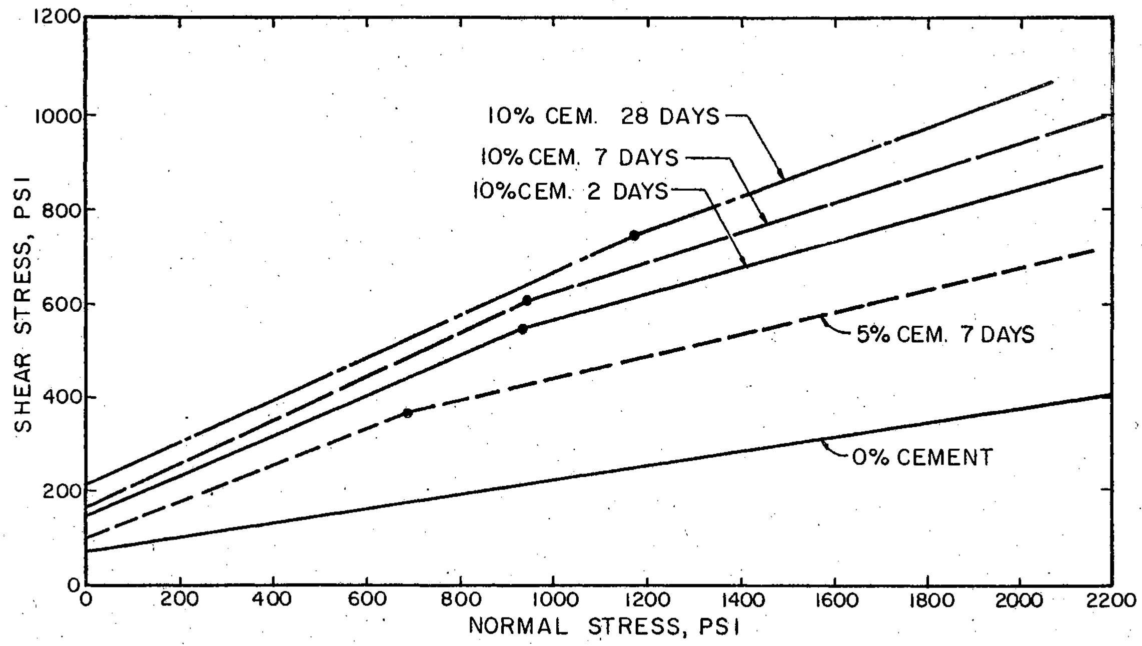
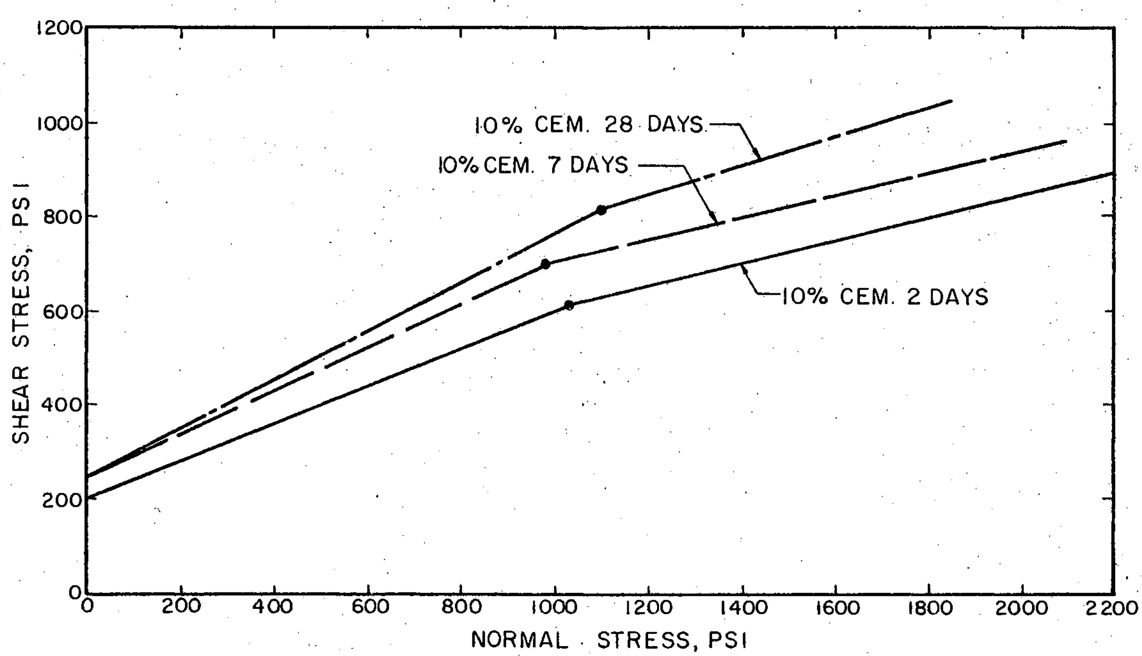


Figure 30. Influence of Molding Water Content on Strength Envelope (Clay + 10% Cement, 7 Days).



a) IMPACT COMPACTION



b) KNEADING COMPACTION

Figure 31. Influence of Age, Cement Content and Method of Compaction on Strength Envelope (Clay, γ_d = 106.5 pcf, w = 17.2%).

cement content.

3. The values of ϕ_S for specimens of soil-cement mixtures were higher than the ϕ value for clay with no cement. This might indicate that for fine-grained soils, although the mechanical bonds between the grains were broken at high pressures, the chemical bonds were not; hence the particles had rougher surfaces than clay with no cement, resulting in higher ϕ values.

4. The value of c increased with age and cement content as shown in Figs 27 and 28 respectively. The rate of gain in c between 2 and 7 days was higher for specimens prepared by kneading compaction. Between the ages of 7 to 28 days, the rate of gain in c was higher for specimens prepared by impact compaction. Specimens prepared by kneading compaction showed no appreciable increase in c between 7 to 28 days. This supports the findings of Chapter III for clay-cement mixtures.

5. For specimens prepared by impact compaction, σ_B increased with age and cement content as shown in Figs 27 and 28. For specimens prepared by kneading compaction, σ_B increased between the ages of 7 and 28 days.

The effect of molding water content on c and σ_B is shown in Fig 29 for specimens prepared by impact compaction. Specimens molded at optimum water content possess higher c and σ_B than specimens molded dry or wet of optimum.

Evaluation of Triaxial Results

Considering the Mohr circles and the strength envelopes presented in Appendix B, one might argue that there is no break in the strength envelope since a smooth curve could be fitted in most cases. However, the following results indicate that the break in the strength envelope is due to properties of soil-cement mixtures rather than to the curved nature of the strength envelope as presented by the Mohr theory:

1. The values of σ_B increase with cement content and age.
2. The molding water content influences the values of σ_B.
3. With Sample No. 3 (Silt) no break in the envelope was observed at dry of optimum while a break was observed for specimens prepared at optimum. The break becomes more pronounced at wet of optimum.
4. With Sample No. 4 (Clay) no break was observed when the soil was molded with no cement. The break becomes very clear at wet of optimum since ϕ_S obtained by undrained triaxial tests becomes small at wet of optimum.
5. Since specimens prepared in this investigation had comparatively low densities, the strength envelopes could be estimated by straight lines.

Since the confining pressures in this investigation were relatively high, a test was carried out to see the effect of σ_3 on Sample No. 1 (River Sand) with 7% cement molded with 10% water content. The specimen was cured for 28 days. A confining pressure of 578 psi (about double its unconfined compressive strength) was applied for a duration of 30 minutes without applying any deviator stress. When the pressure was removed the sample was examined. There was no apparent disturbance in the sample due to the application of the confining stress alone.

CHAPTER V

CONCLUSIONS

From the results presented in Chapters III and IV, the following conclusions may be drawn, limited to the soils and test conditions investigated:

1. For soil-cement mixtures the strength envelope consists of two segments, one representing the properties of soil-cement, the other nearly representing that of the raw soil. At normal stresses higher than σ_B, Coulomb's equation (Eq 1) for shear stress has to be modified as suggested in Eq 2.
2. For clean granular soils, the water-cement ratio law is applicable for soil-cement mixtures in a way analogous to that of concrete. The lower the molding water content, the higher the c values obtained, the higher the unconfined compressive strength and the more brittle the specimens become.
3. For granular soil-cement mixtures, the method of compaction seems to influence the rate of hydration of the cement. Specimens prepared by impact compaction gave higher c and unconfined compressive strengths than the corresponding specimens prepared by kneading compaction. σ_B was also greater for specimens molded by impact compaction.
4. For silt, specimens prepared by kneading compaction gave greater c values and unconfined compressive strength than

the corresponding specimens molded by impact compaction at optimum water content. Wet of optimum, specimens prepared by kneading compaction gave lower unconfined strength and lower c values than those prepared by impact compaction. Since impact compaction tends to produce more flocculant structure wet of optimum, it is clear that soil structure could partially explain the strength properties obtained from fine-grained soil-cement mixtures.

5. For both fine-grained soils, the rate of gain in c and unconfined compressive strength between 2 and 7 days was higher for specimens prepared by kneading compaction. The rate of gain in c and unconfined compressive strength between 7 and 28 days was higher for specimens prepared by impact compaction. This phenomena was more pronounced in the case of clay than with silt, which indicates that method of compaction influences the rate of hydration of the soil-cement mixture, with impact compaction yielding better hydration between 7 to 28 days.

Recommended Research

The following are suggestions for further research:

1. To investigate the effect of other methods of compaction, namely vibration and static, on strength properties of soil-cement mixtures. The effect of method of compaction will probably be more pronounced by static and vibration compaction as compared to impact and kneading compaction particularly wet of optimum.

2. To see how immersion of specimens will affect results obtained in this investigation.
3. To investigate the strength envelope with pore water pressure measurements, and hence to see whether a break in the strength envelope occurs when effective stresses rather than total stresses are plotted.
4. To investigate the effect of method of compaction on the resistance to freezing and thawing of soil-cement mixtures.
5. To investigate the effect of method of compaction on shrinkage of soil-cement mixtures.
6. To investigate the effect of method of compaction on strength of soil-cement mixtures using other types of soils.

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APPENDIX A

STRESS-STRAIN RELATIONS

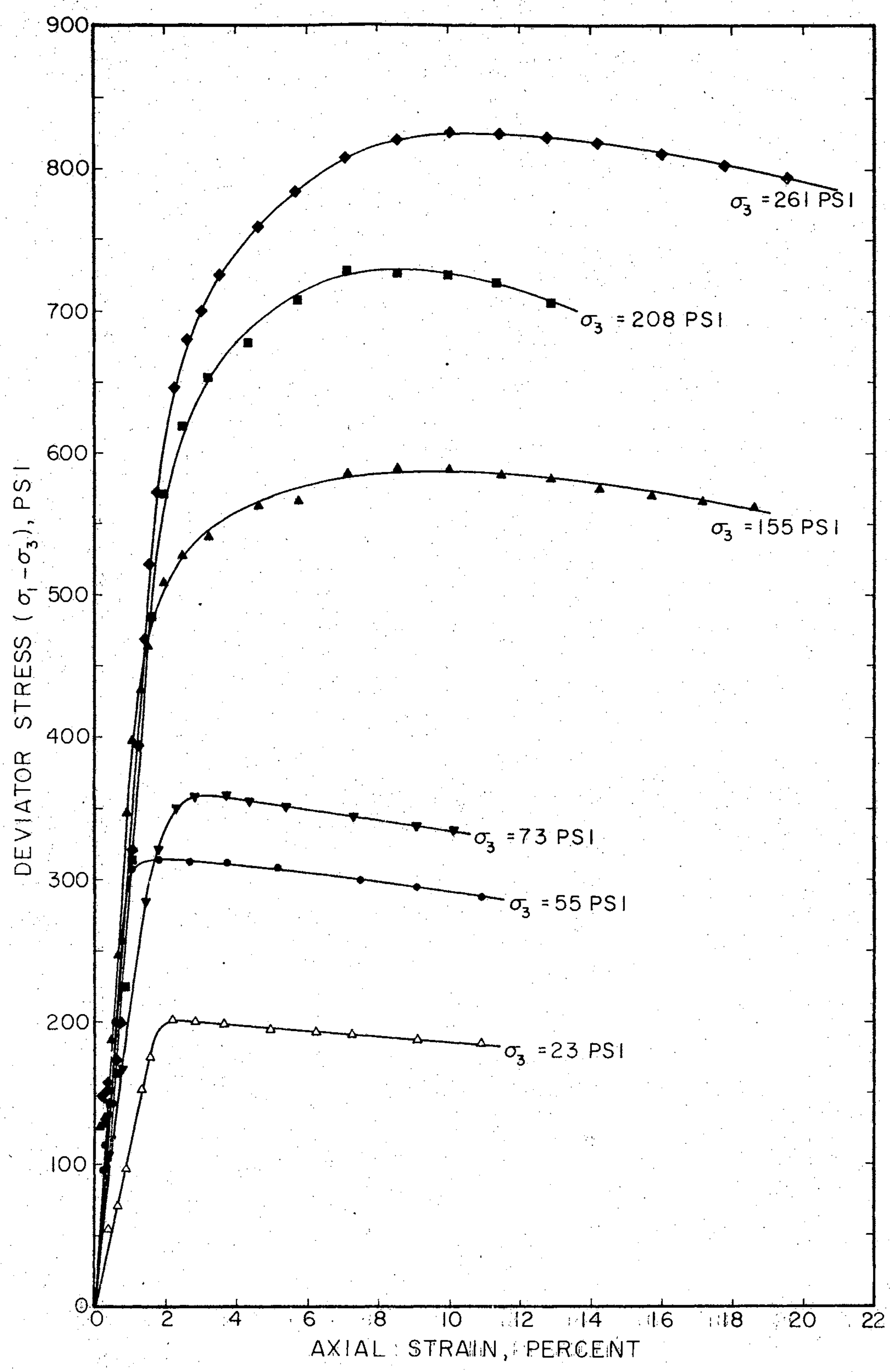

Figure A-1. Stress-Strain Characteristics (River Sand + 5% Cement, w = 10%, γ_d = 109 pcf, 7 Days, Kneading Compaction).

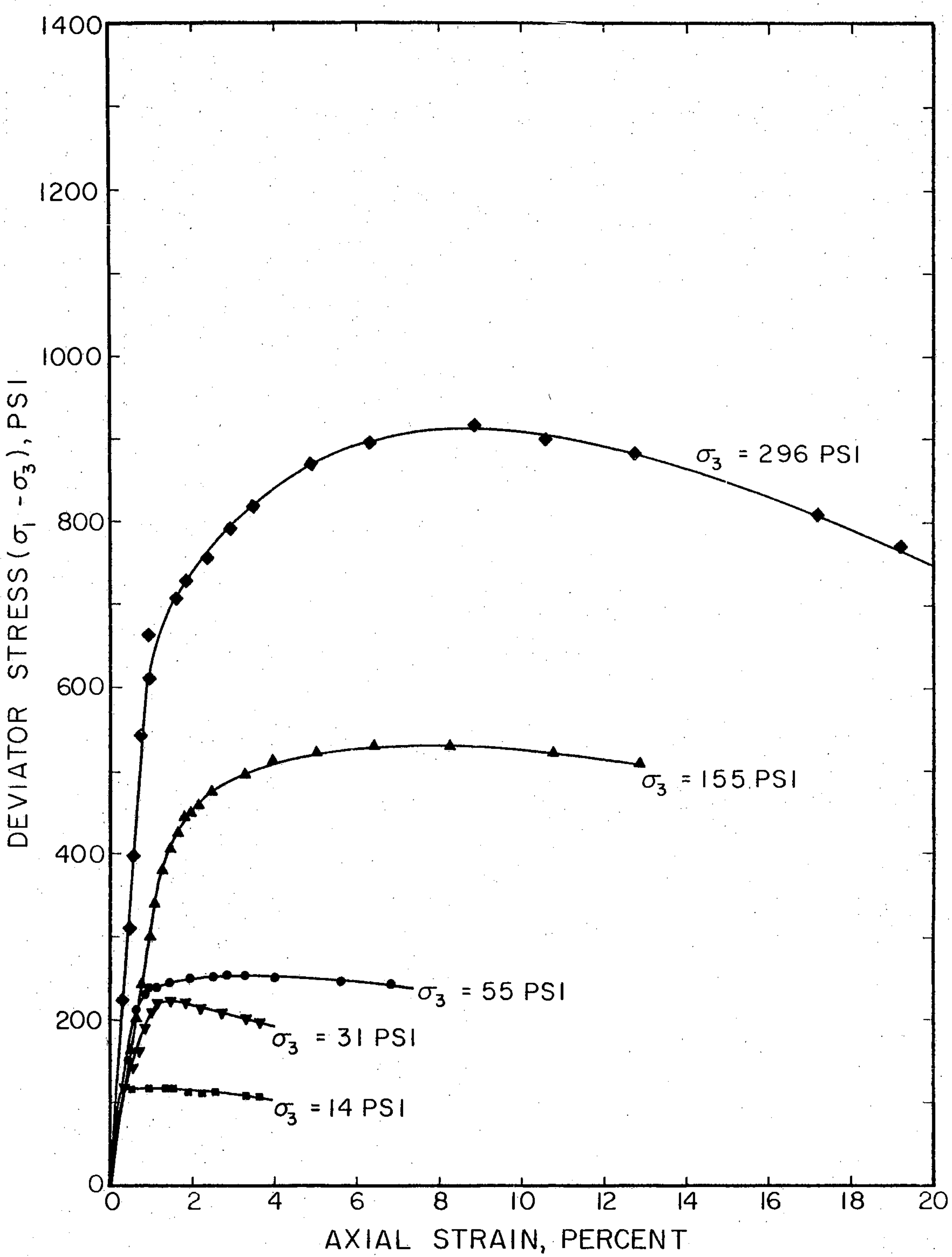

Figure A-2. Stress-Strain Characteristics (River Sand + 7% Cement, w = 10%, γ_d = 109 pcf, 2 Days, Kneading Compaction).

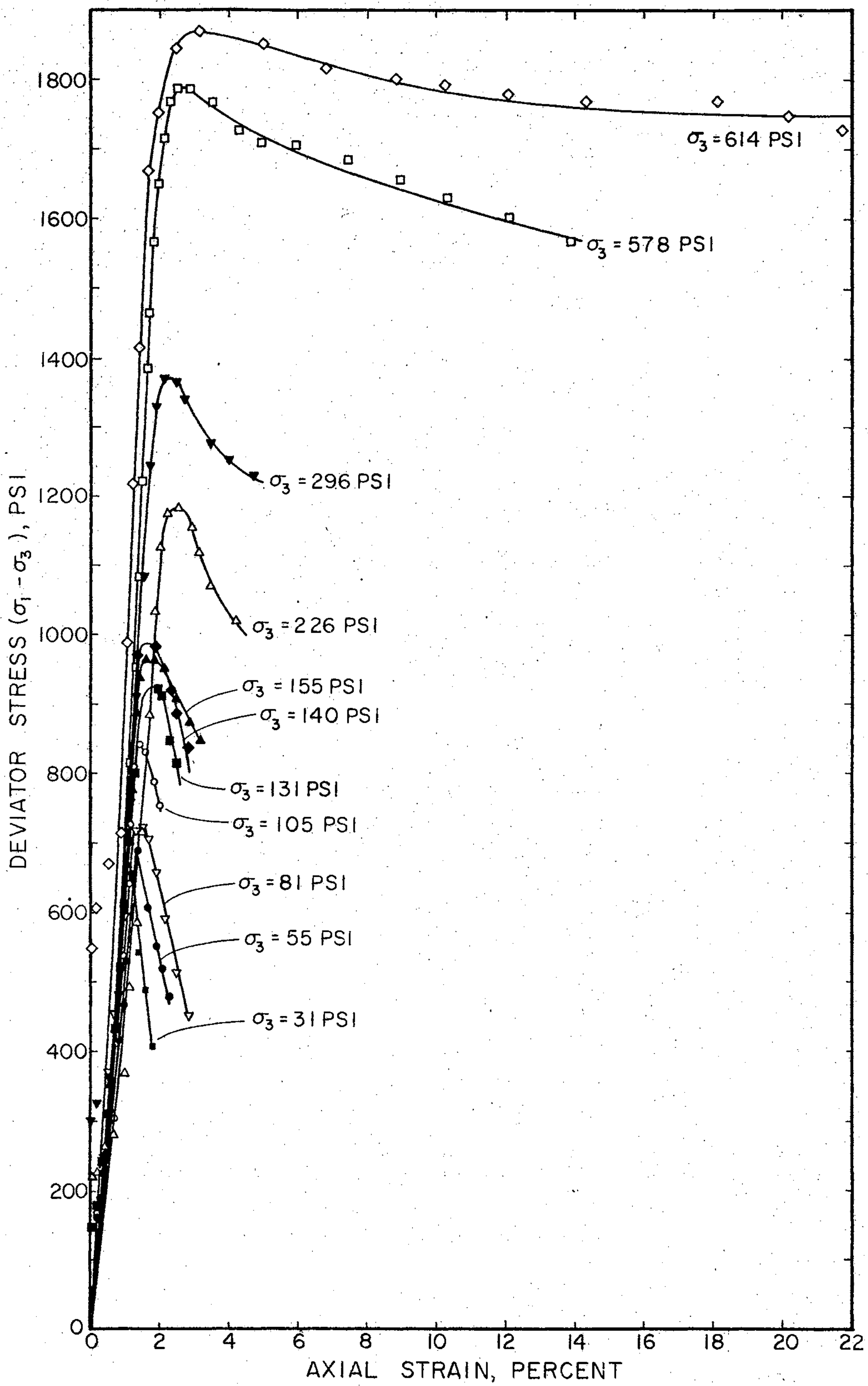

Figure A-3. Stress-Strain Characteristics (River Sand + 7% cement, w = 5%, γ_d = 107 pcf, 7 Days, Impact Compaction).

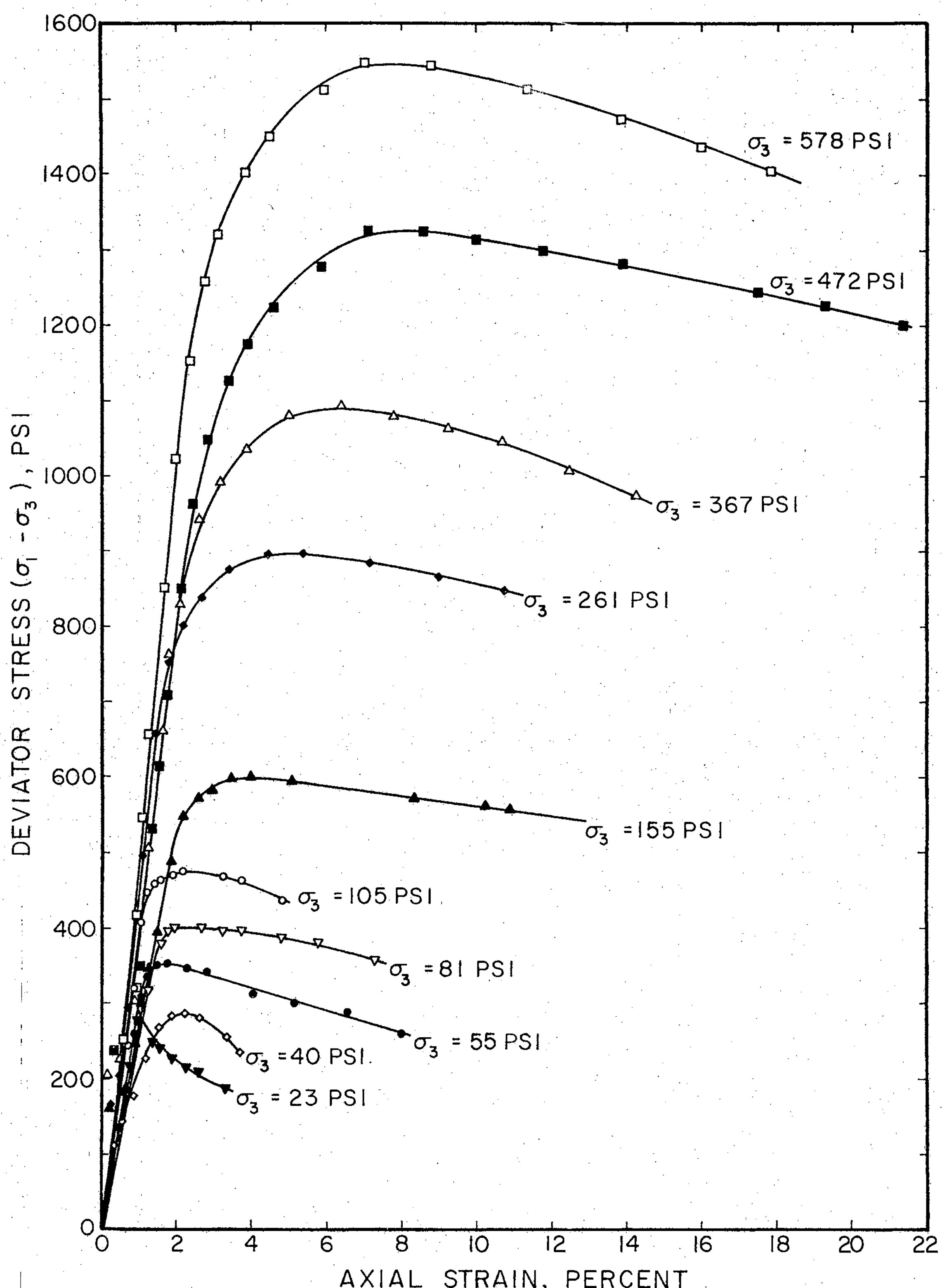

Figure A-4. Stress-Strain Characteristics (Ottawa Sand + 7% Cement, w = 10%, γ_d = 107 pcf, 7 Days, Impact Compaction).

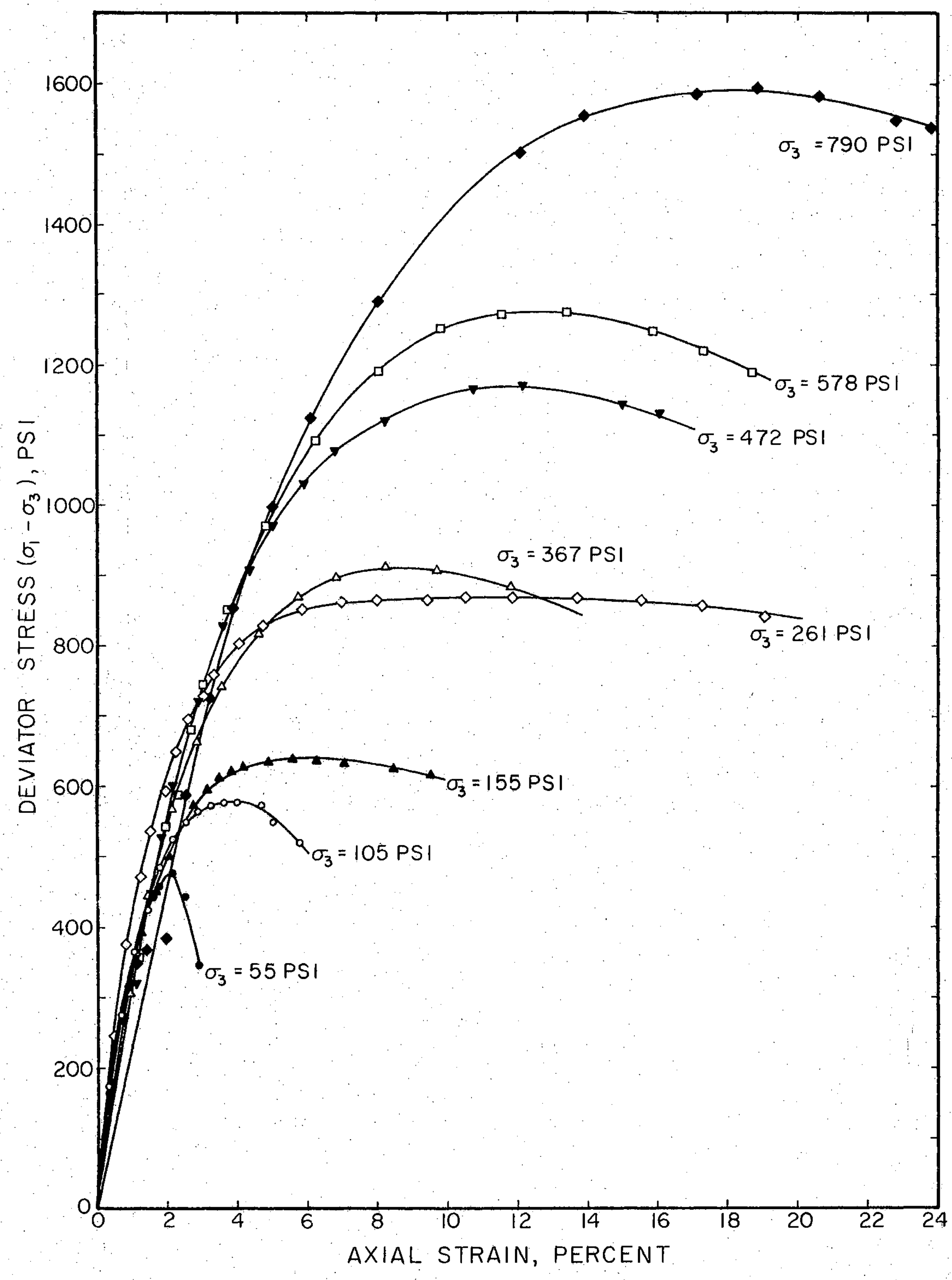

Figure A-5. Stress-Strain Characteristics (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 2 Days, Kneading Compaction).

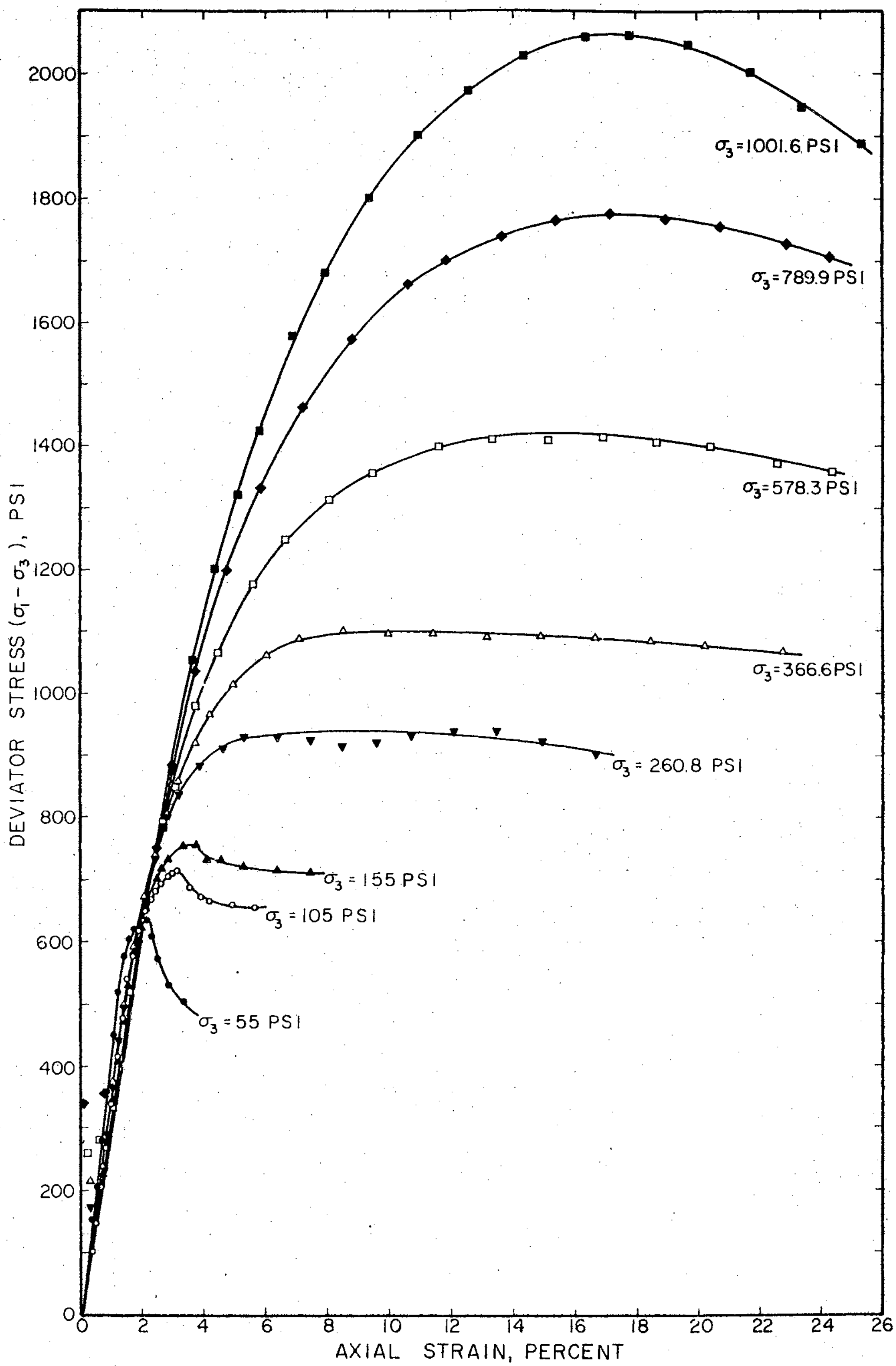

Figure A-6. Stress-Strain Characteristics (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 7 Days, Kneading Compaction).

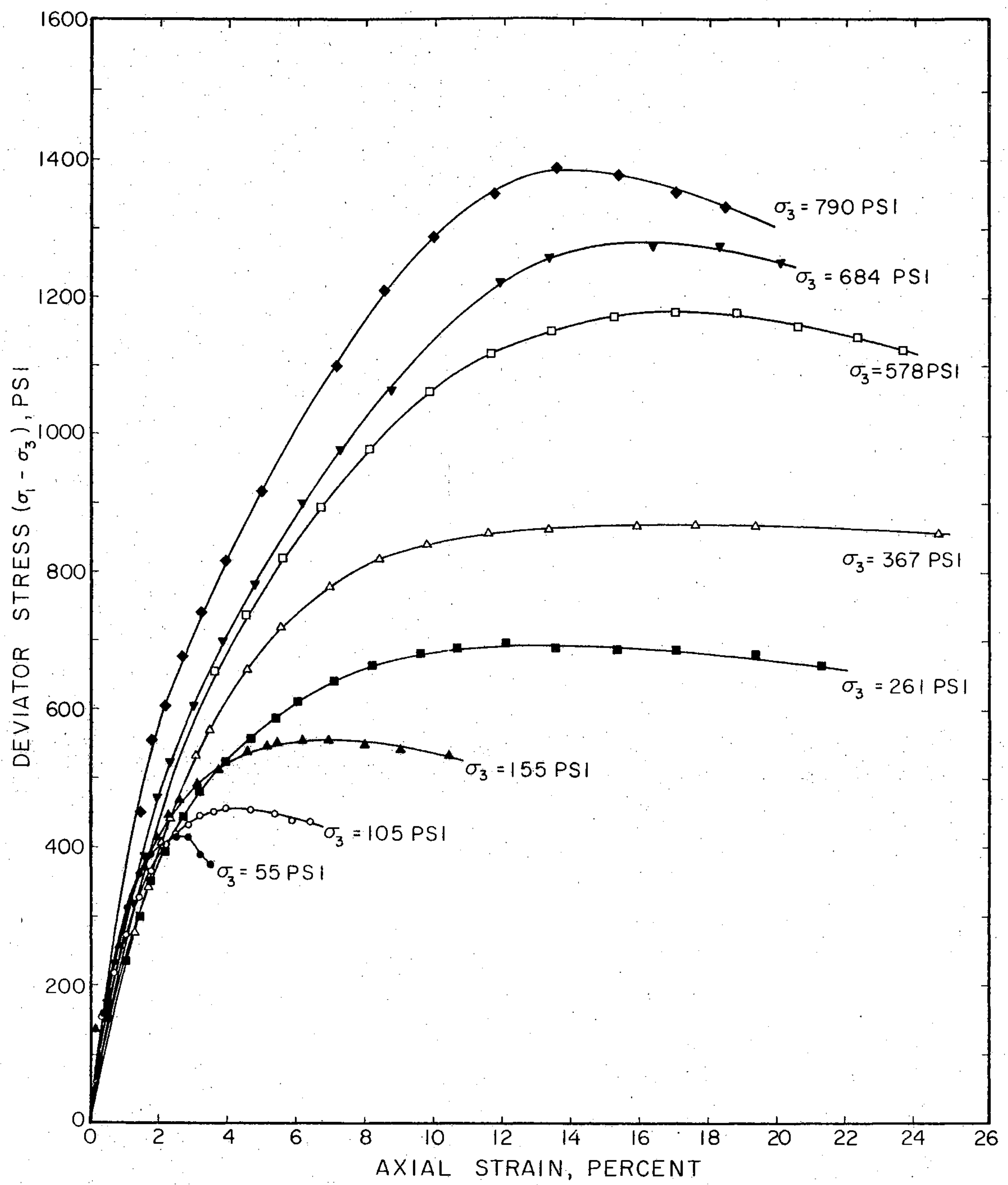

Figure A-7. Stress-Strain Characteristics (Silt + 5% Cement, w = 19.0%, γ_d = 99.5 pcf, 7 Days, Impact Compaction).

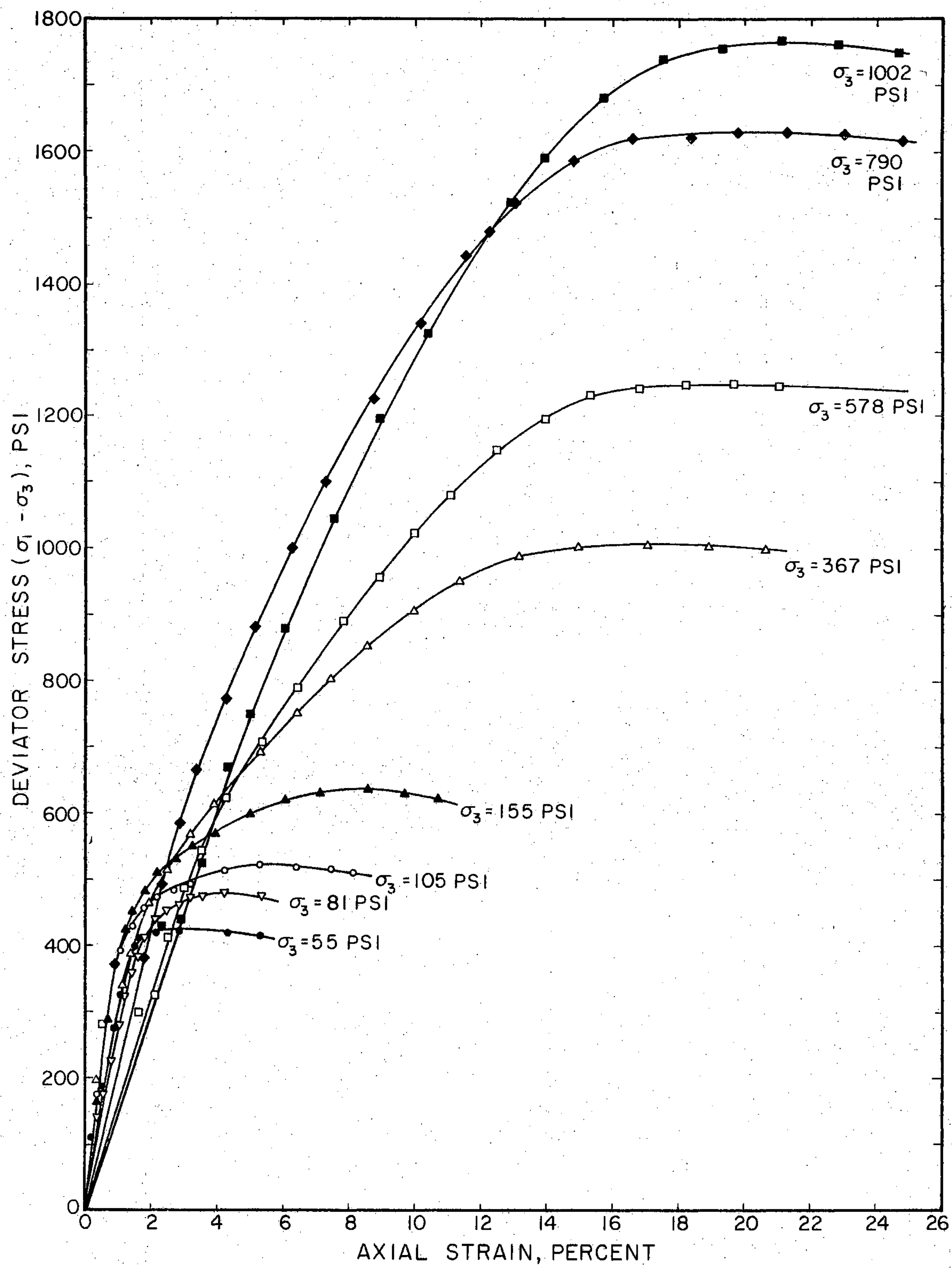

Figure A-8. Stress-Strain Characteristics (Clay + 10% Cement, $w = 13.0\%$, $\gamma_d = 104.2$ pcf, 7 Days, Impact Compaction).

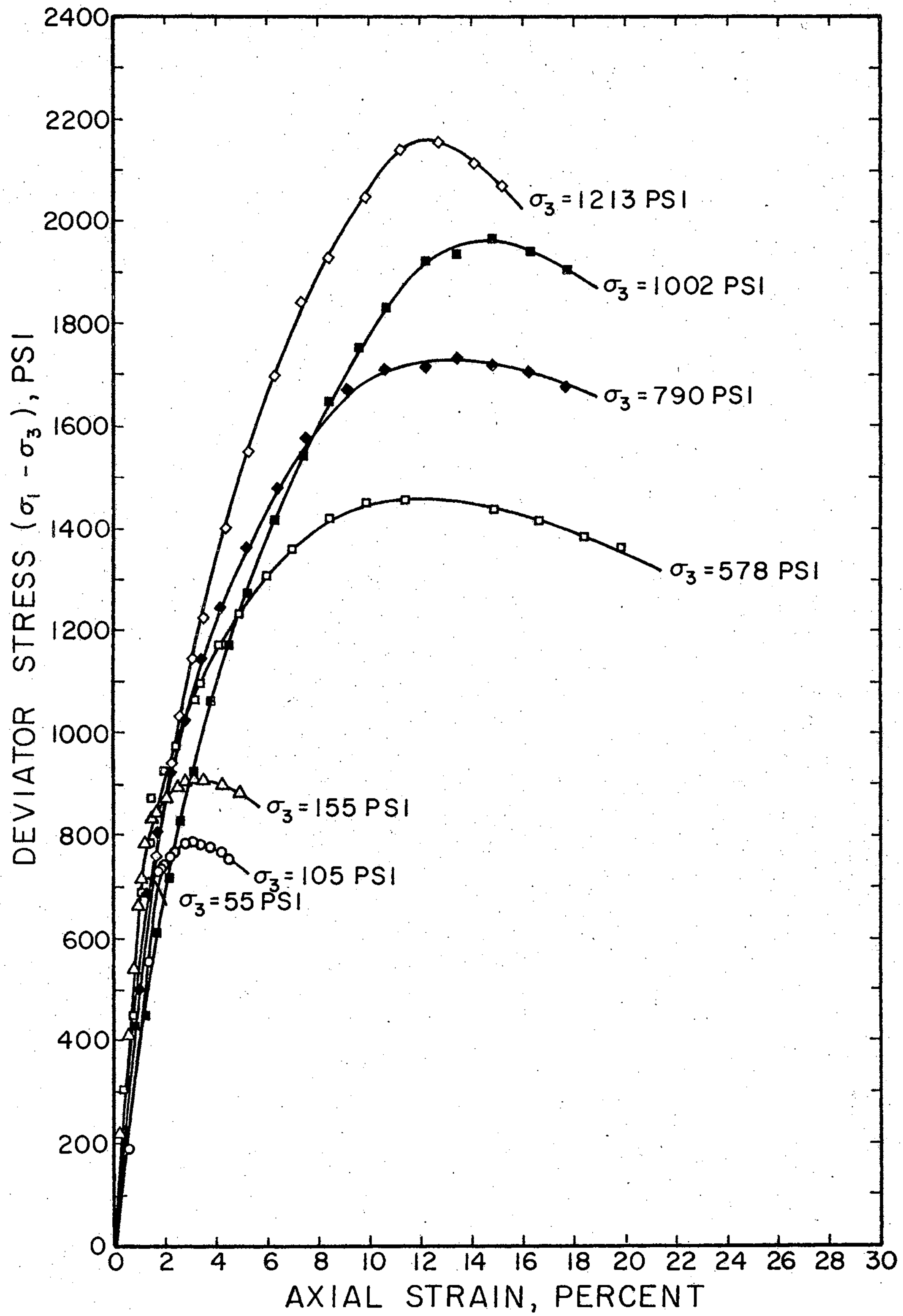

Figure A-9. Stress-Strain Characteristics (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 28 Days, Impact Compaction).

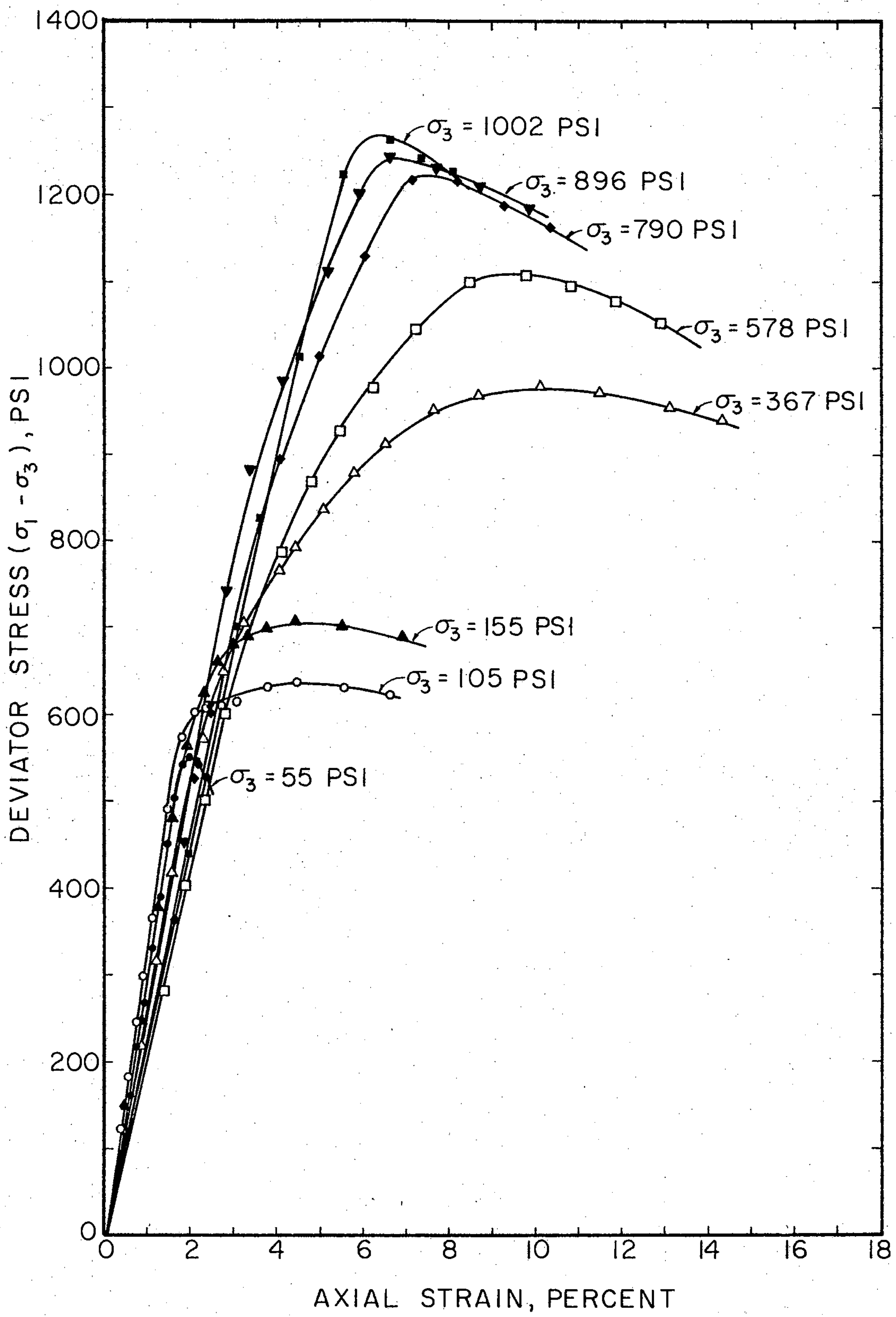

Figure A-10. Stress-Strain Characteristics (Clay + 10% Cement, w = 20.8%, γ_d = 104.2 pcf, 7 Days, Impact Compaction).

APPENDIX B

MOHR DIAGRAMS

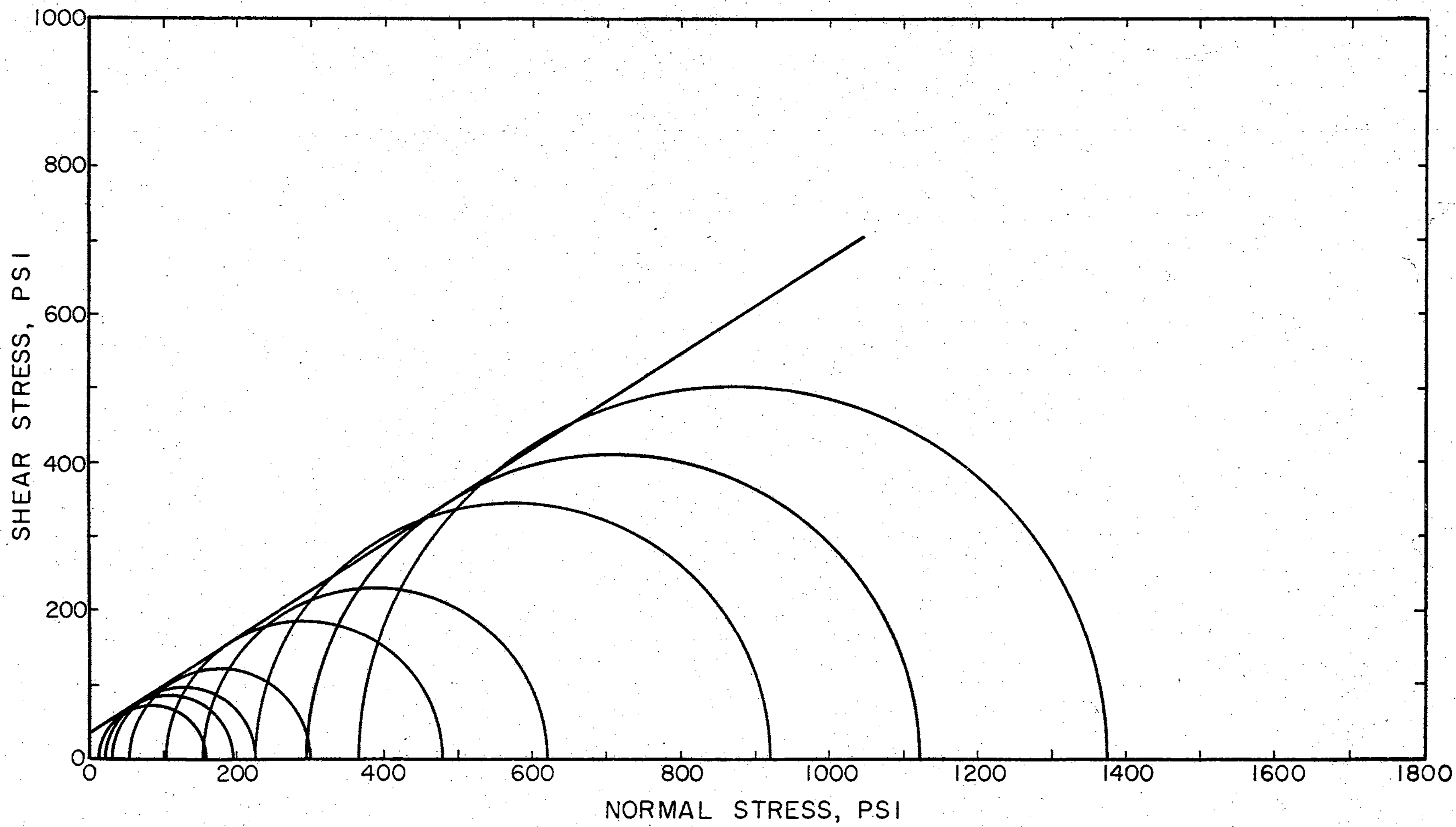

Figure B-1. Mohr Diagram (River Sand + 3% Cement, w = 10%, γ_d = 109 pcf, 7 Days, Kneading Compaction).

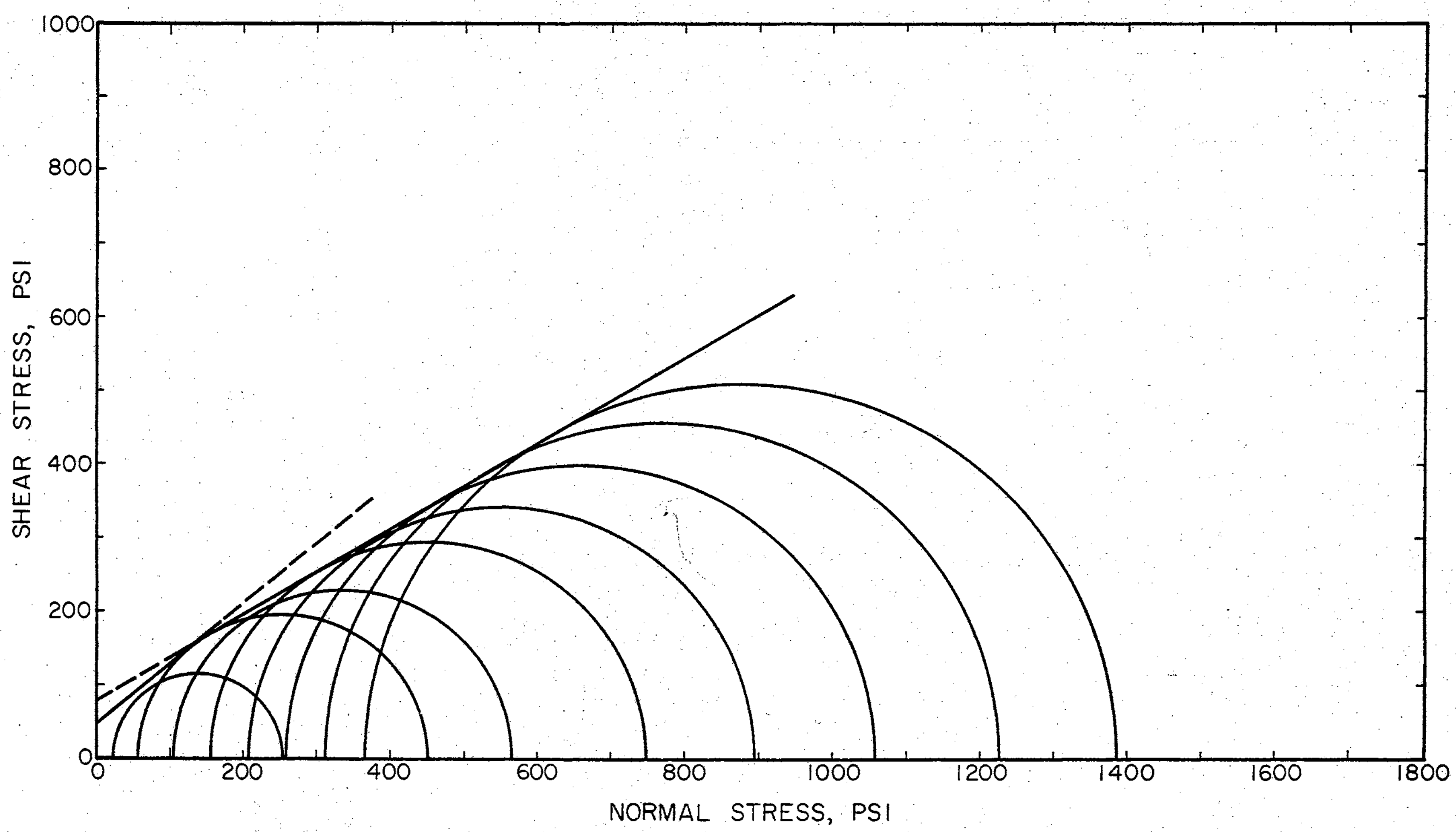

Figure B-2. Mohr Diagram (River Sand + 5% Cement, w = 10%, γ_d = 109 pcf, 7 Days, Impact Compaction).

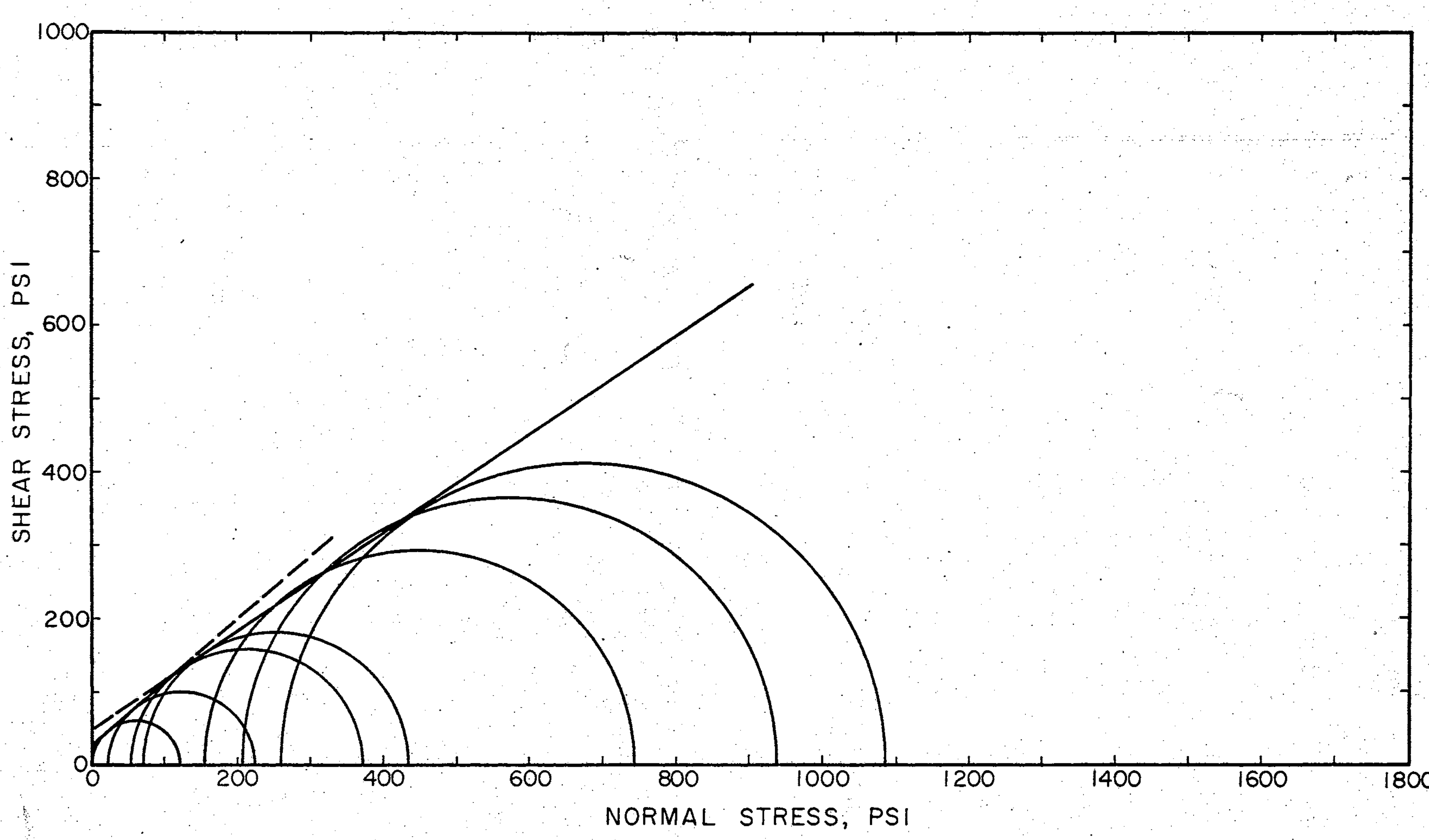

Figure B-3. Mohr Diagram (River Sand + 5% Cement, w = 10%, γ_d = 109 pcf, 7 Days, Kneading Compaction).

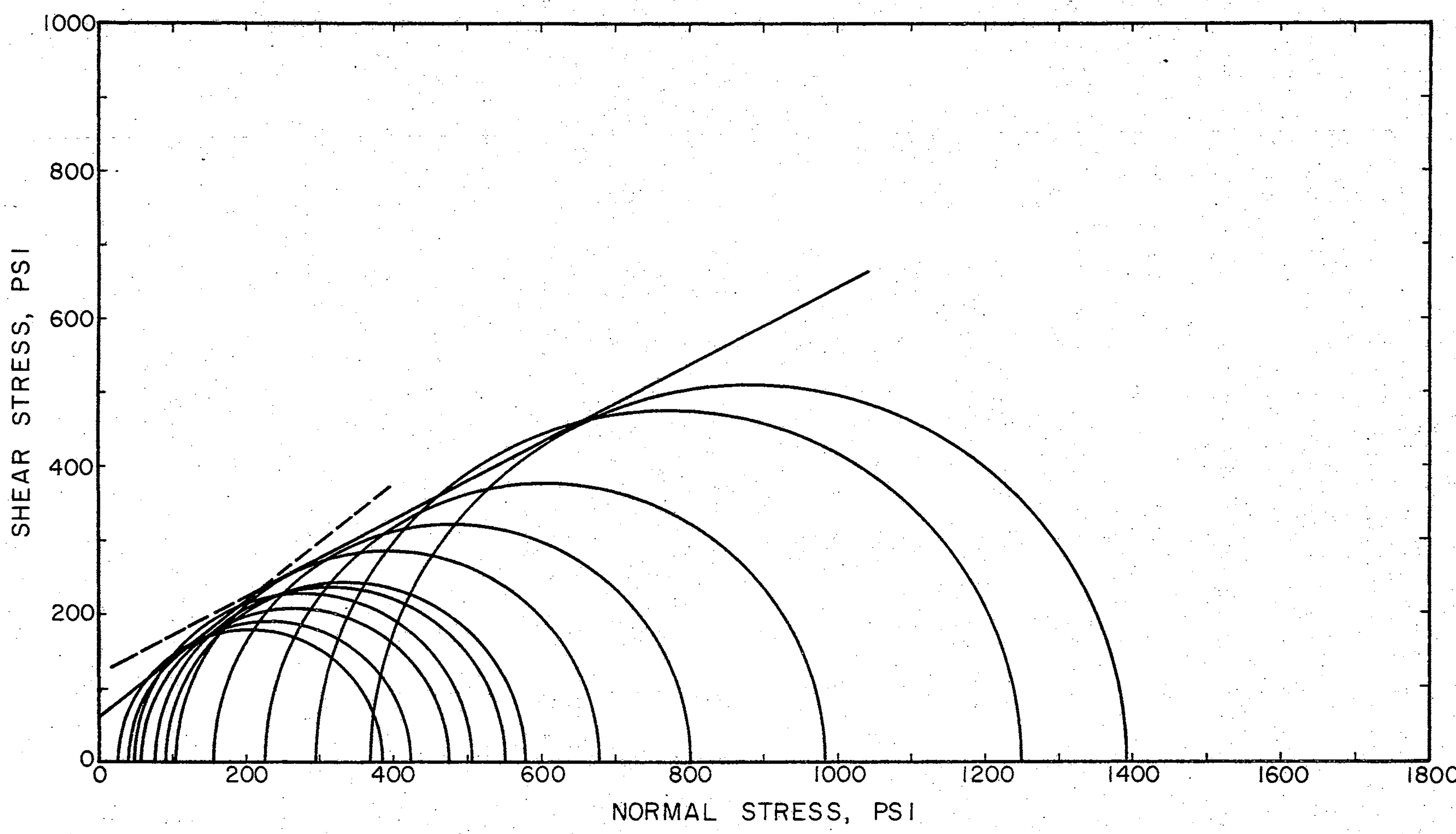

Figure B-4. Mohr Diagram (River Sand + 5% Cement, w = 10%, γ_d = 109 pcf, 28 Days, Impact Compaction).

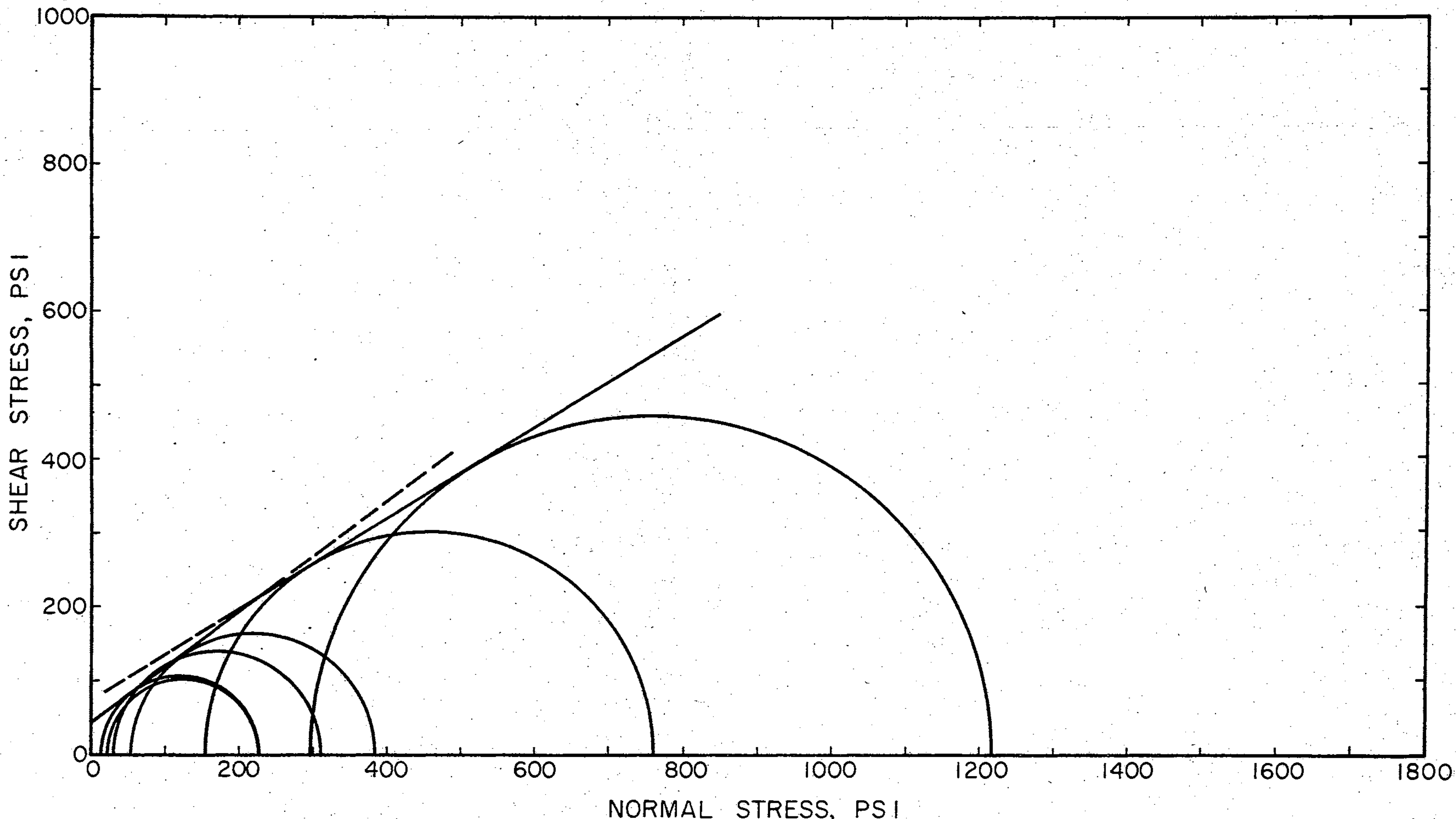

Figure B-5. Mohr Diagram (River Sand + 7% Cement, w = 10%, γ_d = 109 pcf, 2 Days, Impact Compaction).

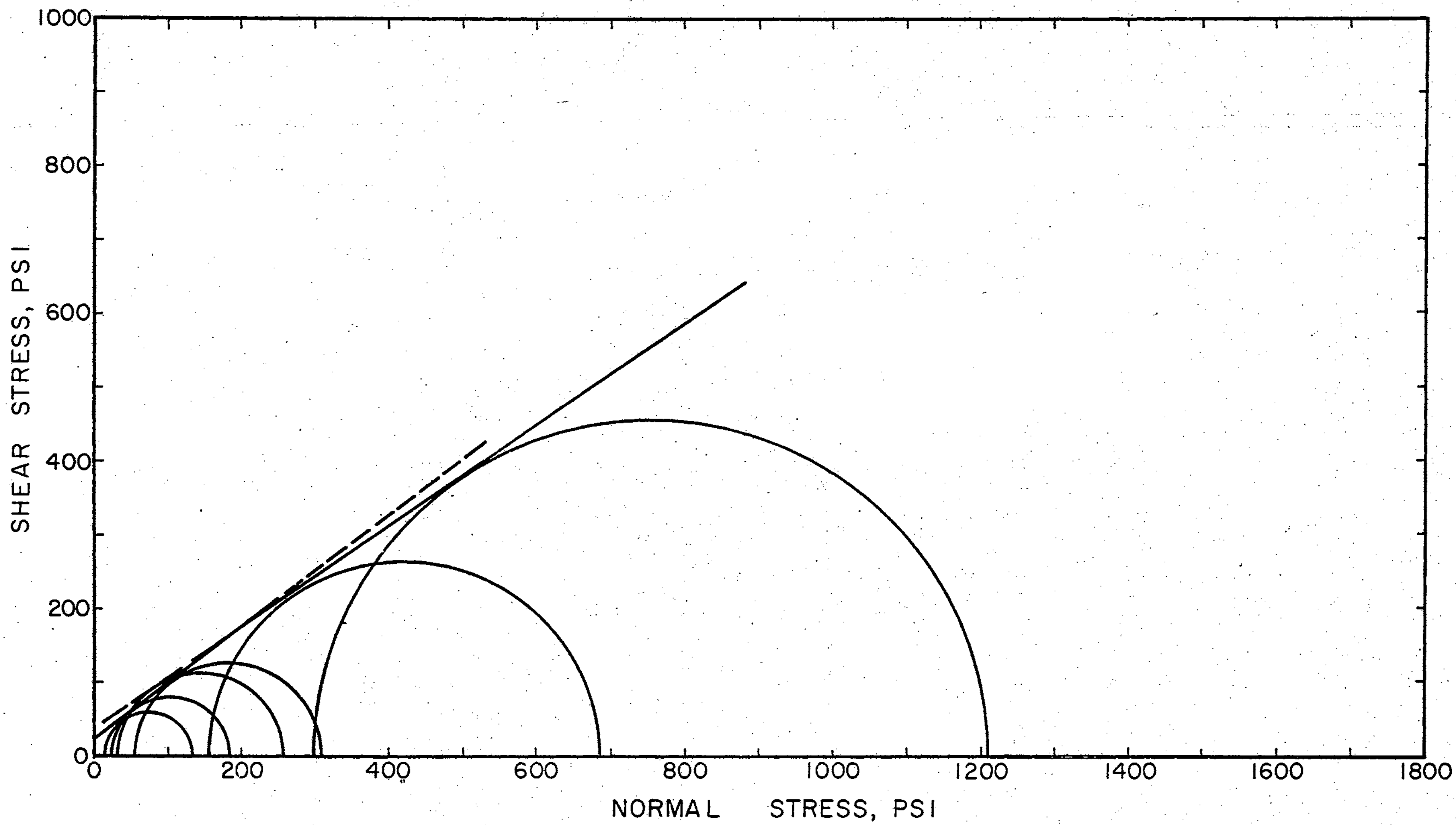

Figure B-6. Mohr Diagram (River Sand + 7% Cement, w = 10%, γ_d = 109 pcf, 2 Days, Kneading Compaction).

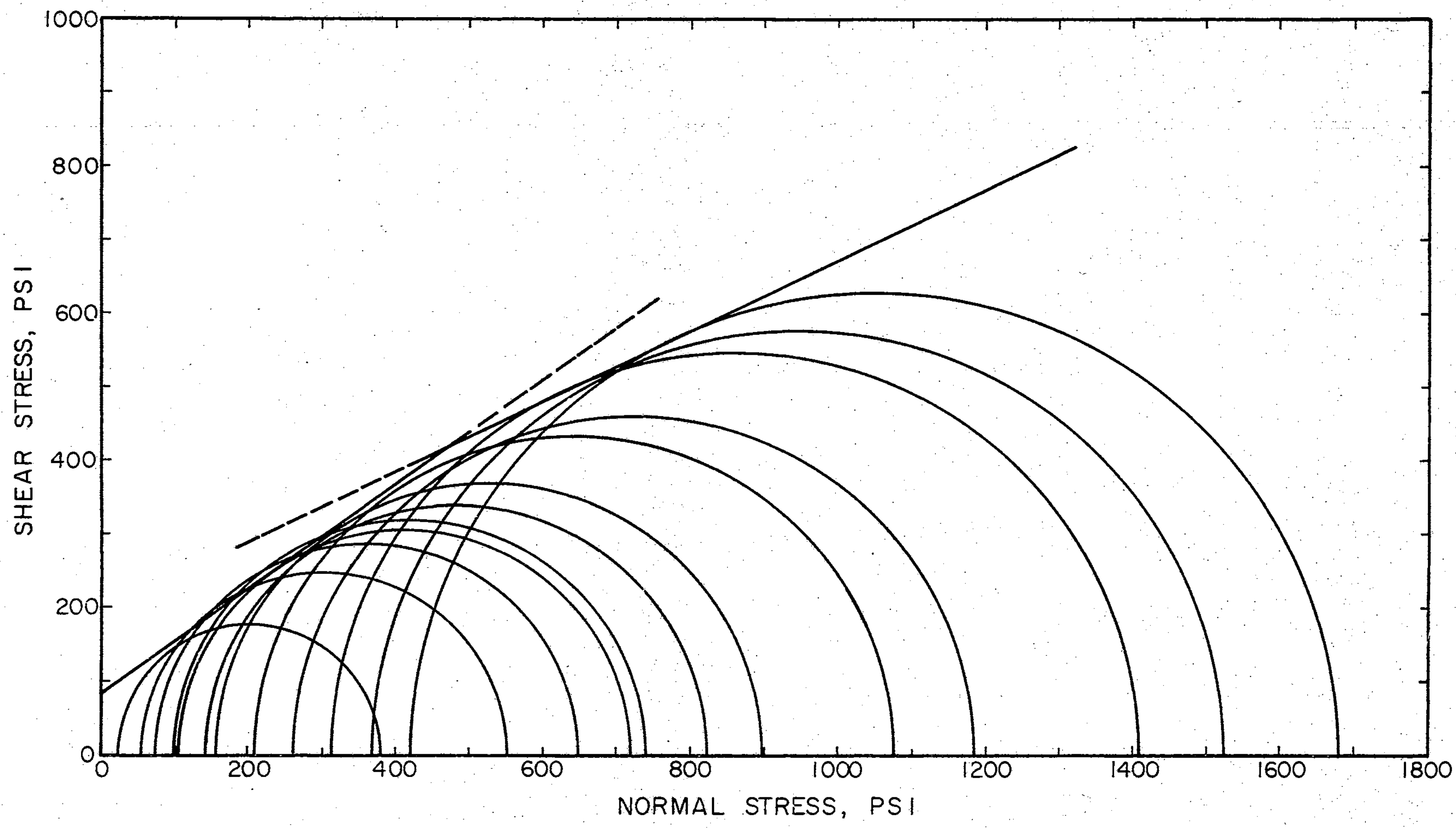

Figure B-7. Mohr Diagram (River Sand + 7 % Cement, w = 10%, γ_d = 109 pcf, 7 Days, Impact Compaction).

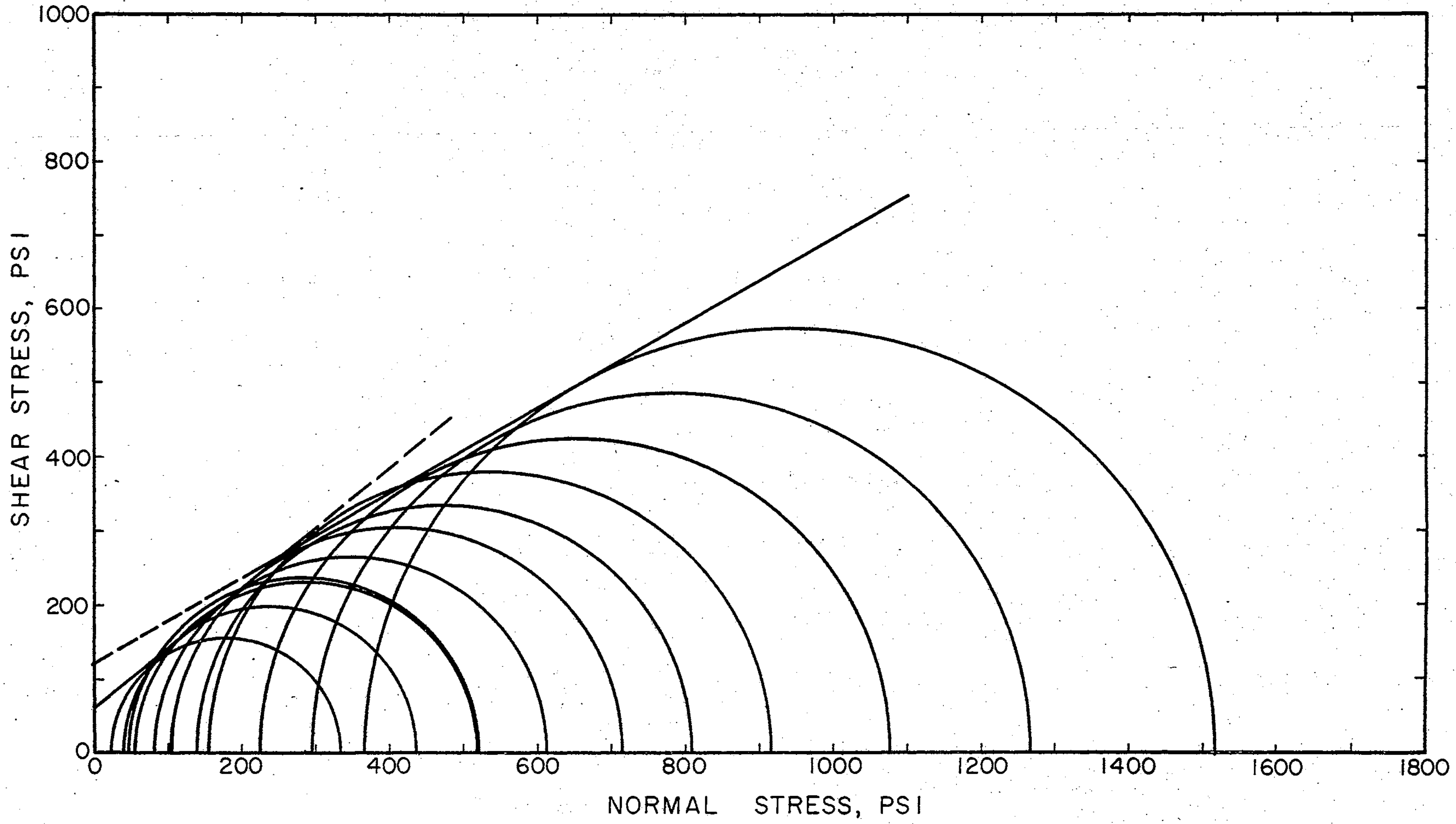

Figure B-8. Mohr Diagram (River Sand + 7% Cement, w = 10%, γ_d = 109 pcf, 7 Days, Kneading Compaction).

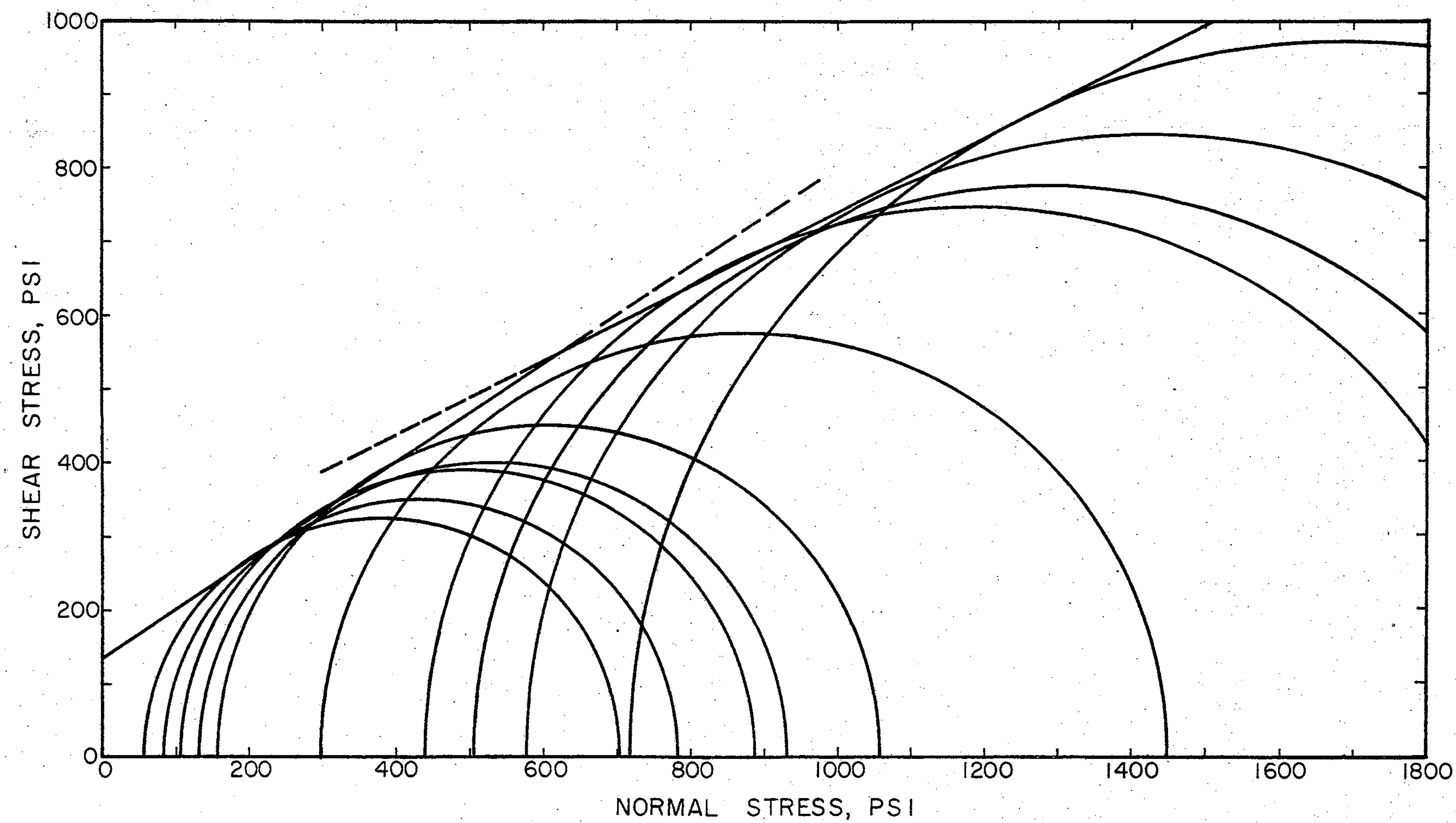

Figure B-9. Mohr Diagram (River Sand + 7% Cement, w = 10%, γ_d = 109 pcf, 28 Days, Impact Compaction).

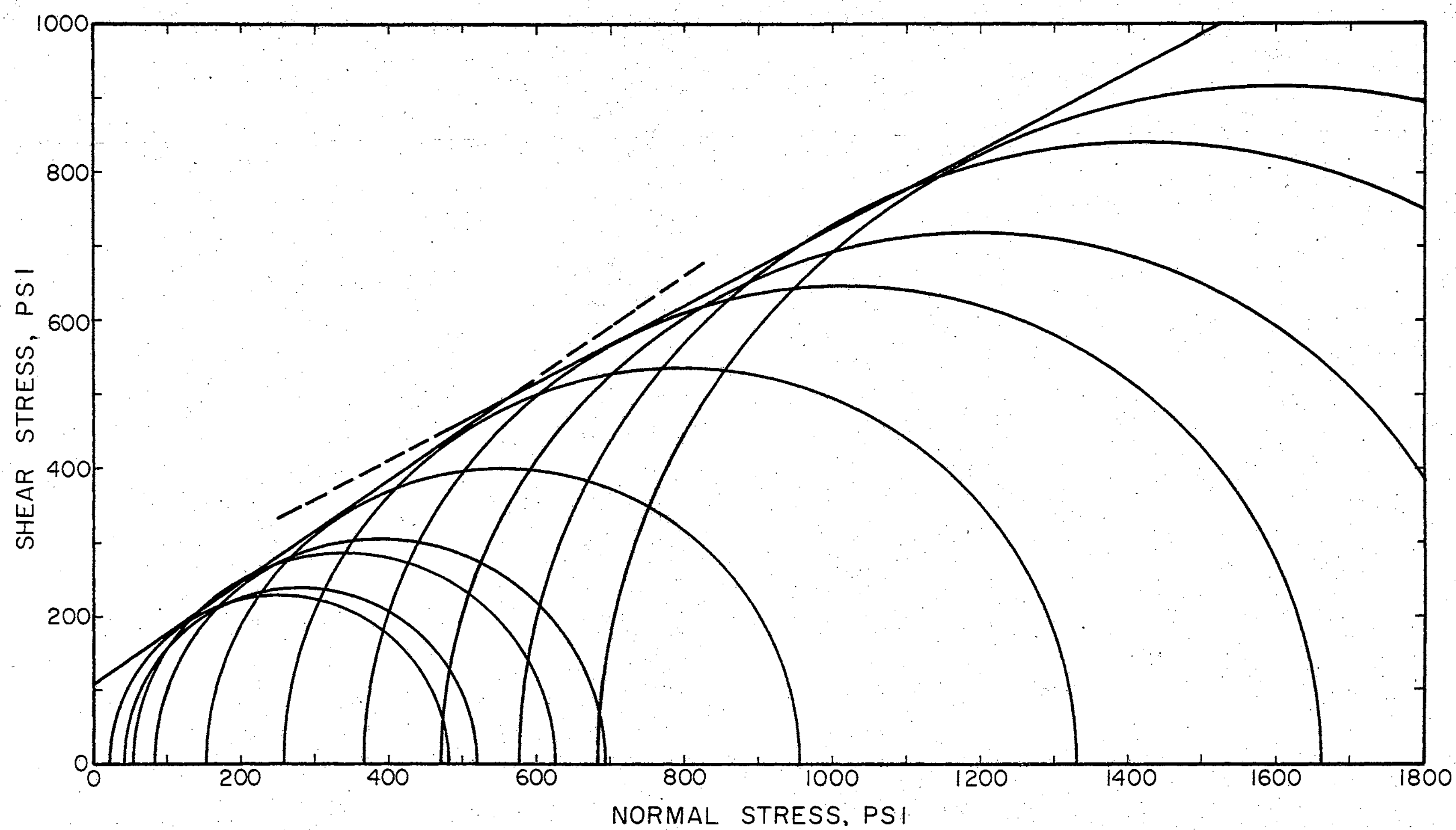

Figure B-10. Mohr Diagram (River Sand + 7% Cement, w = 10%, γ_d = 109 pcf, 28 Days, Kneading Compaction).

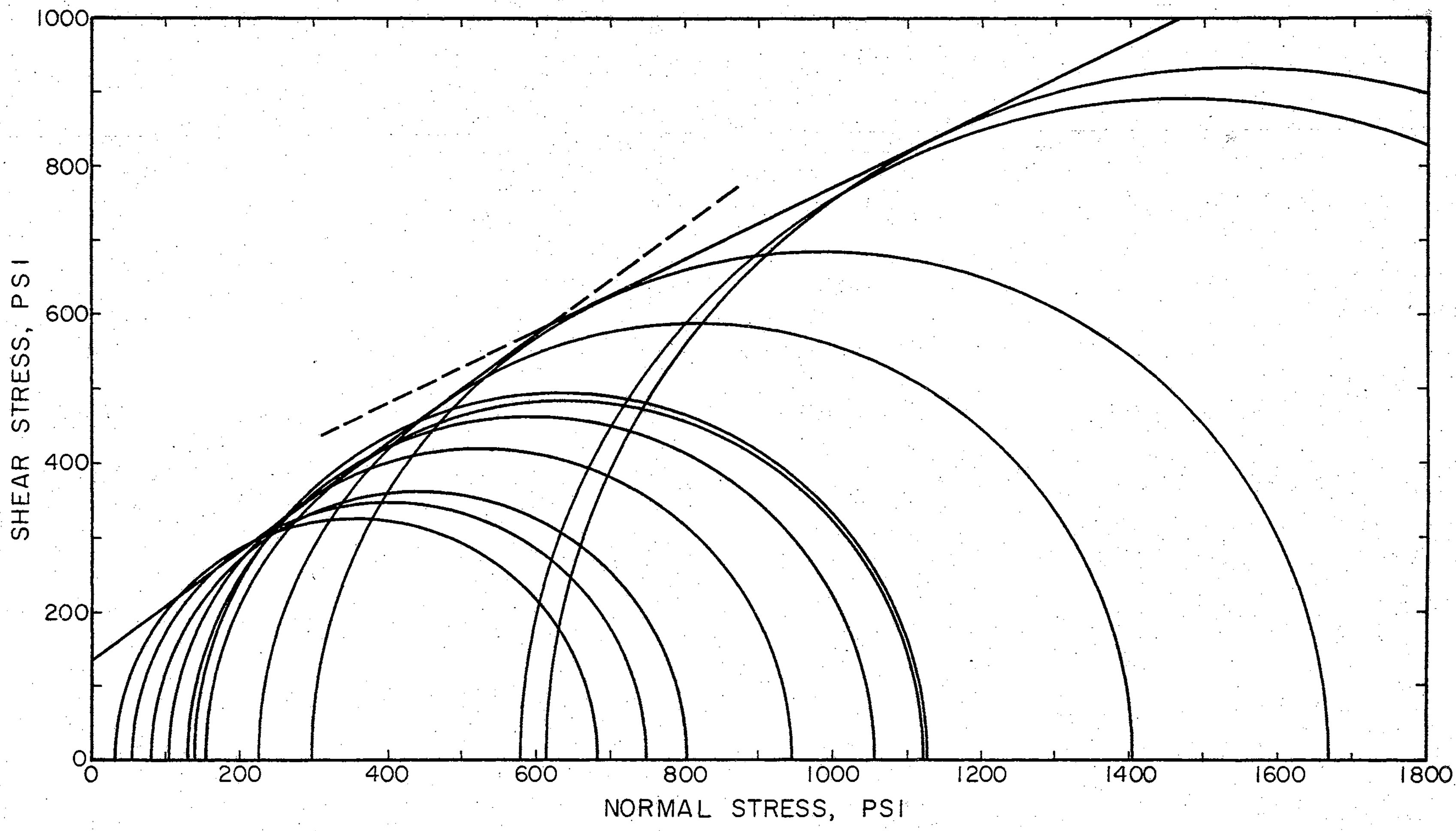

Figure B-11. Mohr Diagram (River Sand + 7% Cement, w = 5%, γ_d = 107 pcf, 7 Days, Impact Compaction).

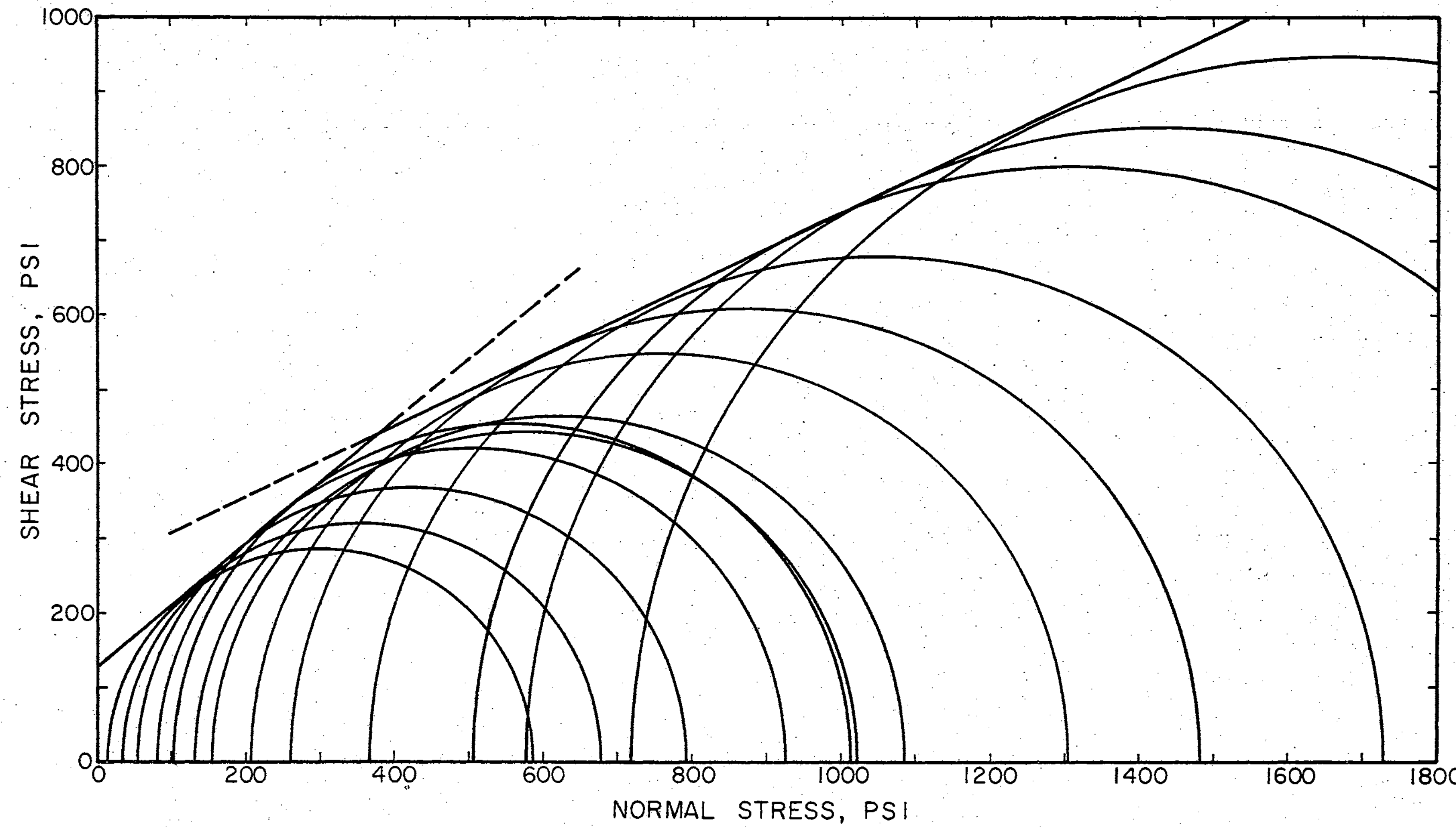

Figure B-12. Mohr Diagram (River Sand + 7% Cement, w = 5%, γ_d = 107 pcf, 7 Days, Kneading Compaction).

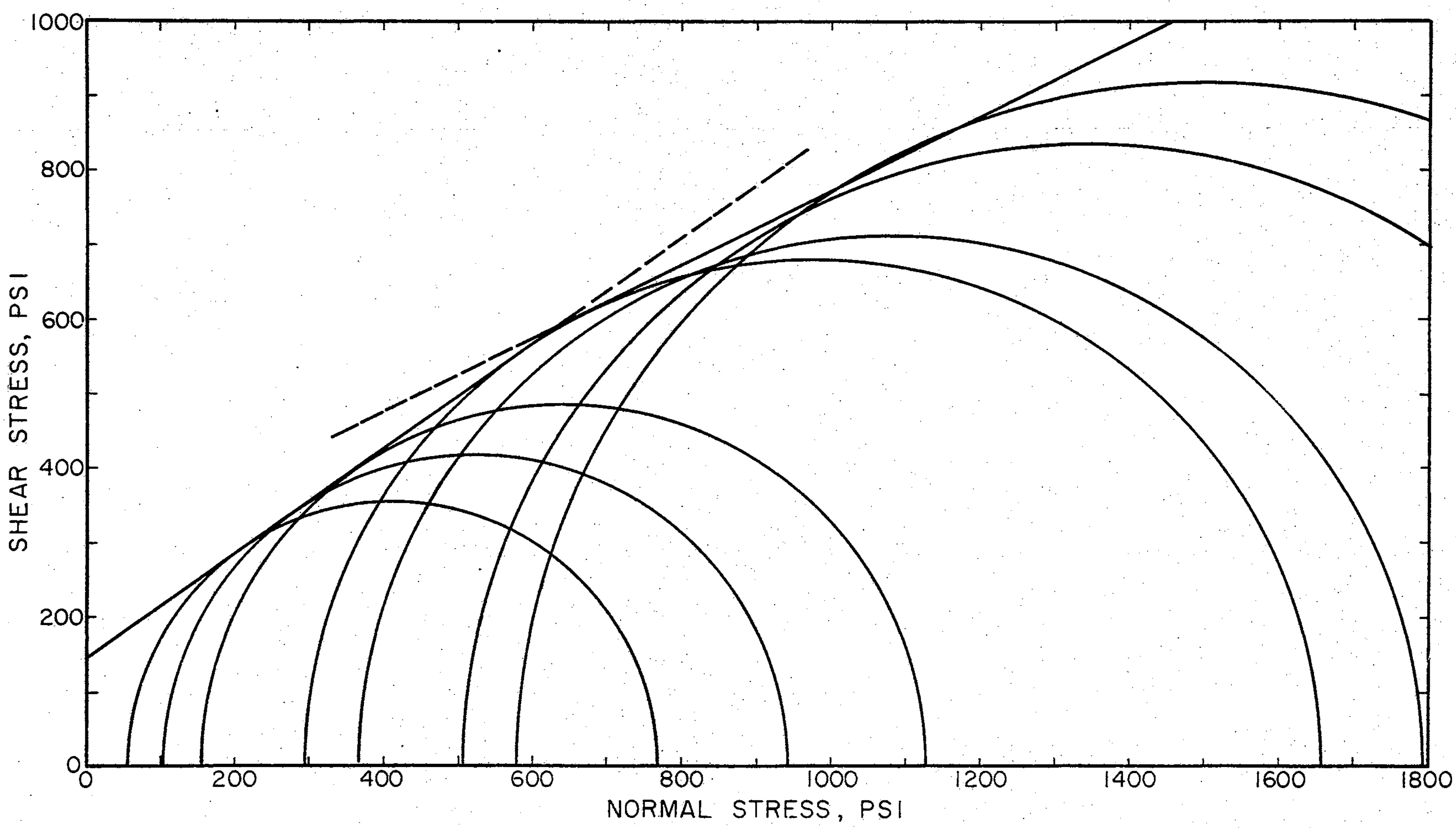

Figure B-13. Mohr Diagram (River Sand + 10% Cement, w = 10%, γ_d = 109 pcf, 7 Days, Impact Compaction).

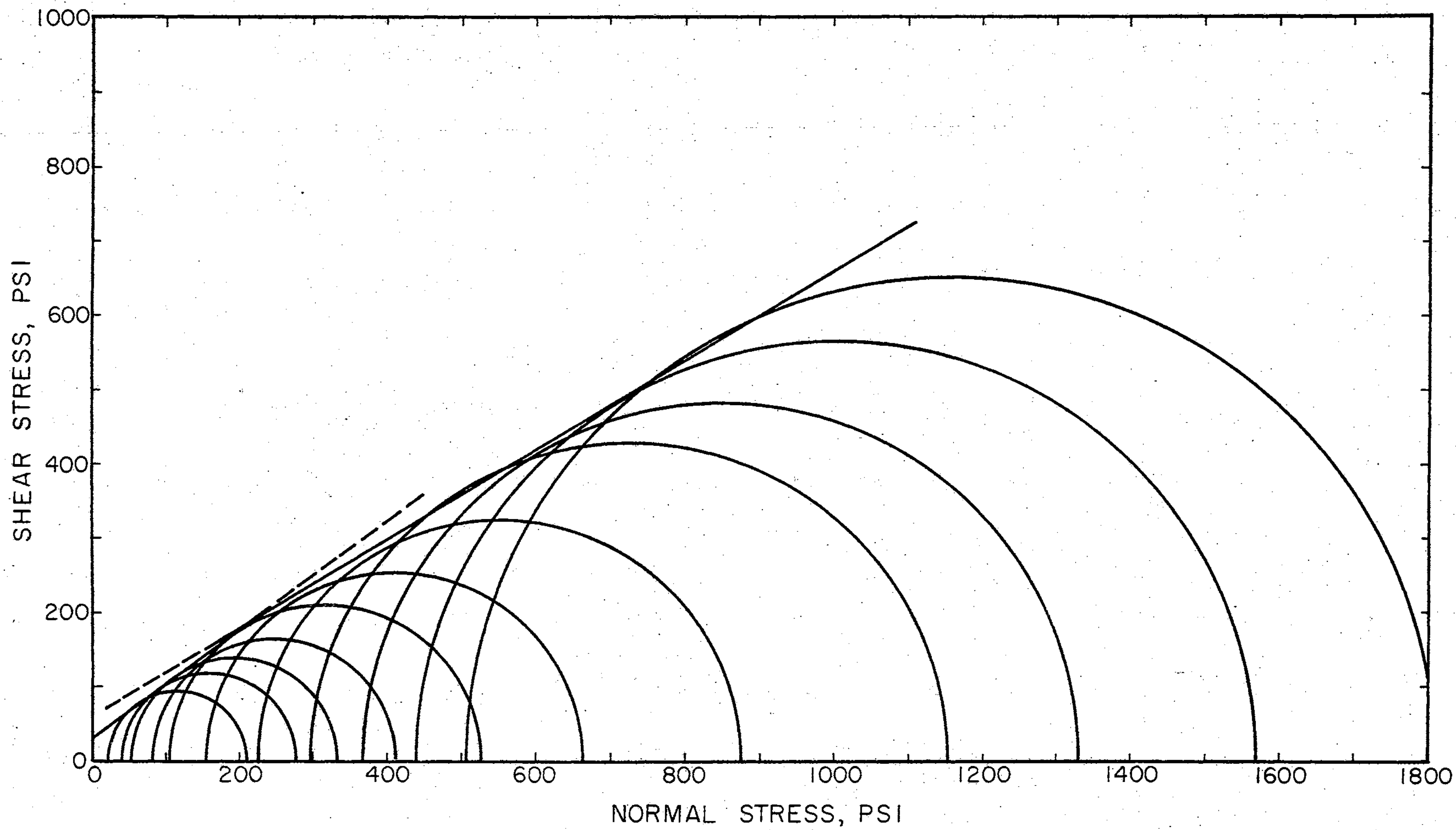

Figure B-14. Mohr Diagram (Ottawa Sand + 5% Cement, w = 10%, γ_d = 107 pcf, 7 Days, Impact Compaction).

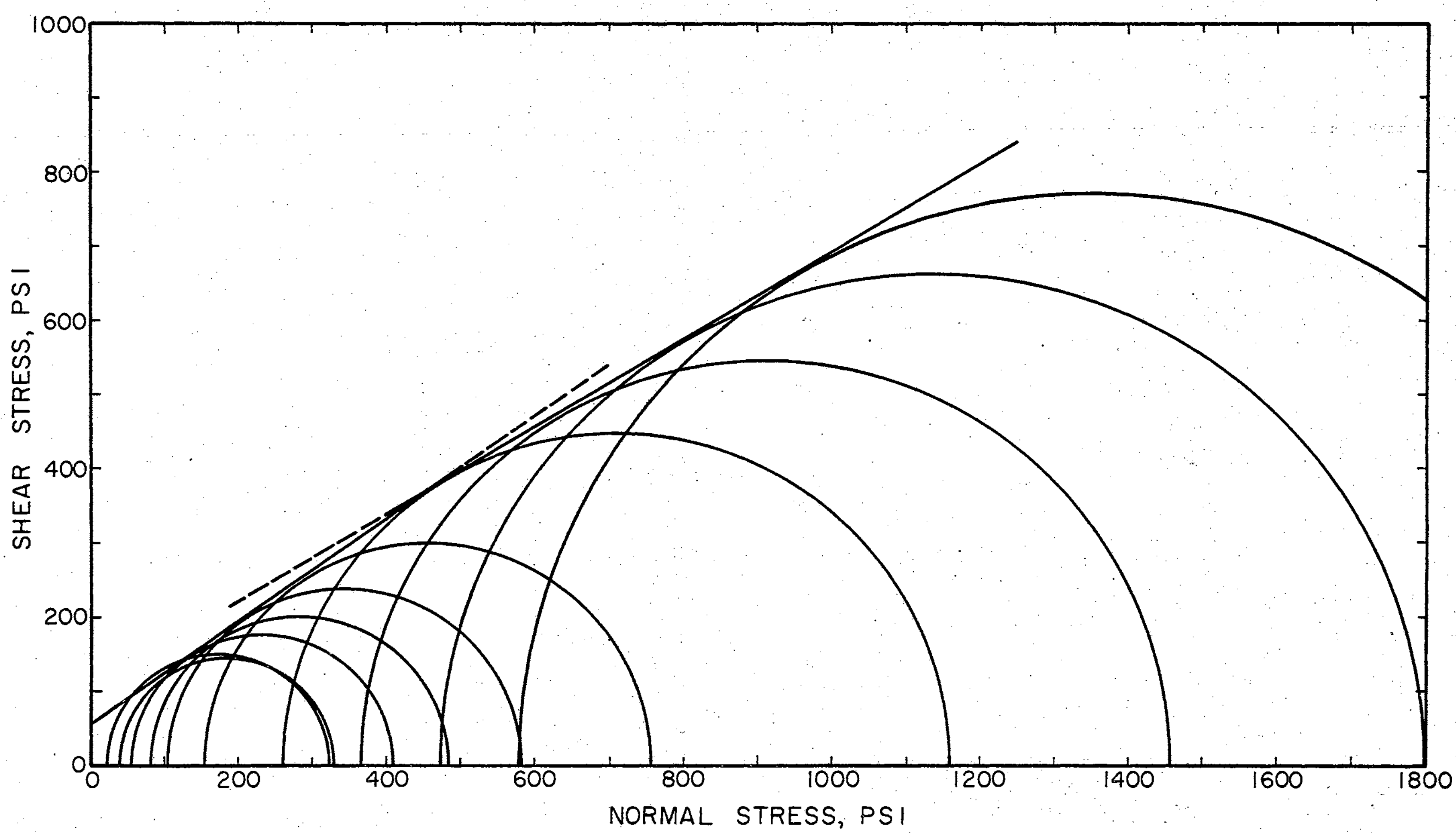

Figure B-15. Mohr Diagram (Ottawa Sand + 7% Cement, w = 10%, γ_d = 107 pcf, 7 Days, Impact Compaction).

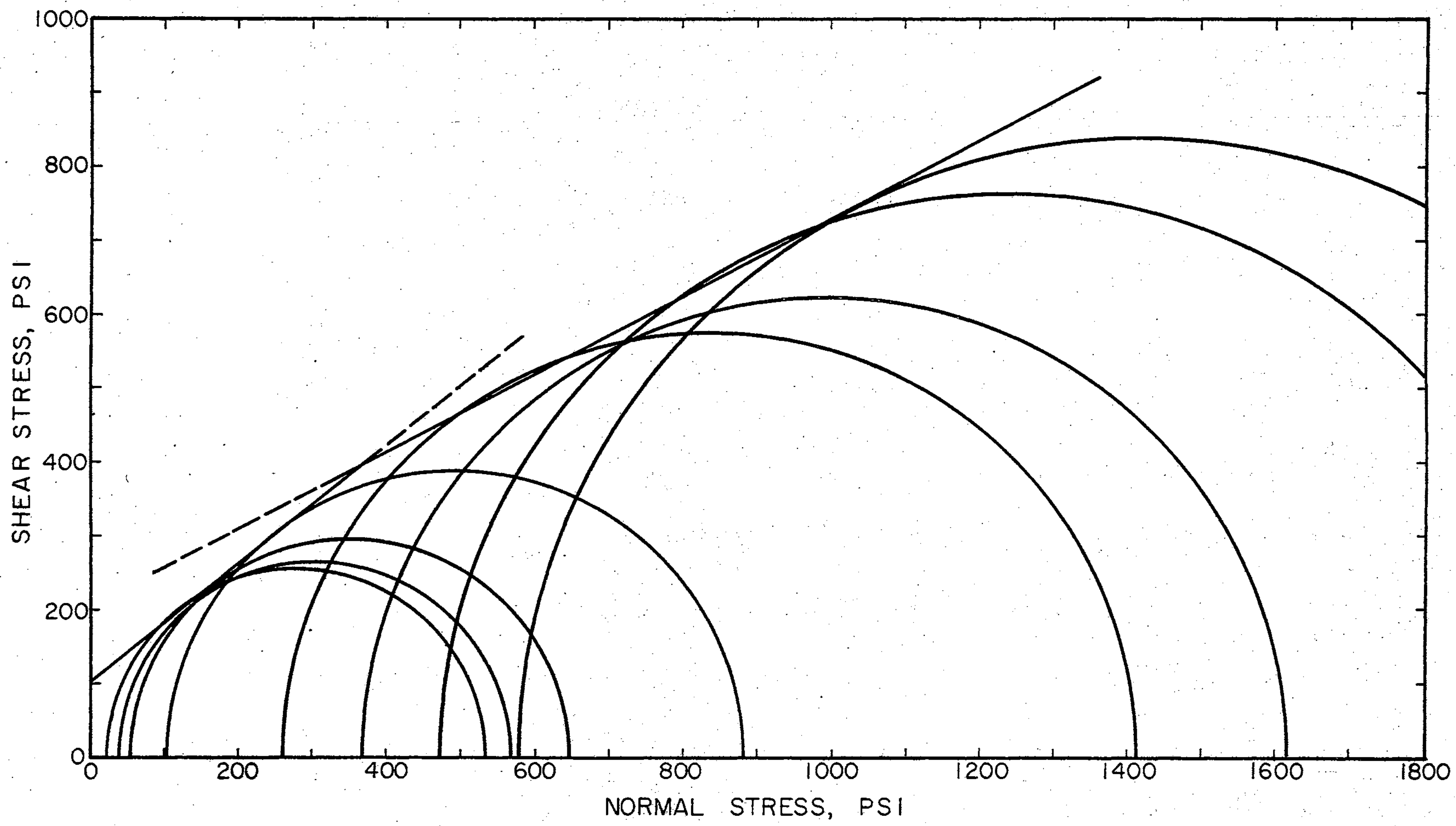

Figure B-16. Mohr Diagram (Ottawa Sand + 7% Cement, w = 5%, γ_d = 104 pcf, 7 Days, Impact Compaction).

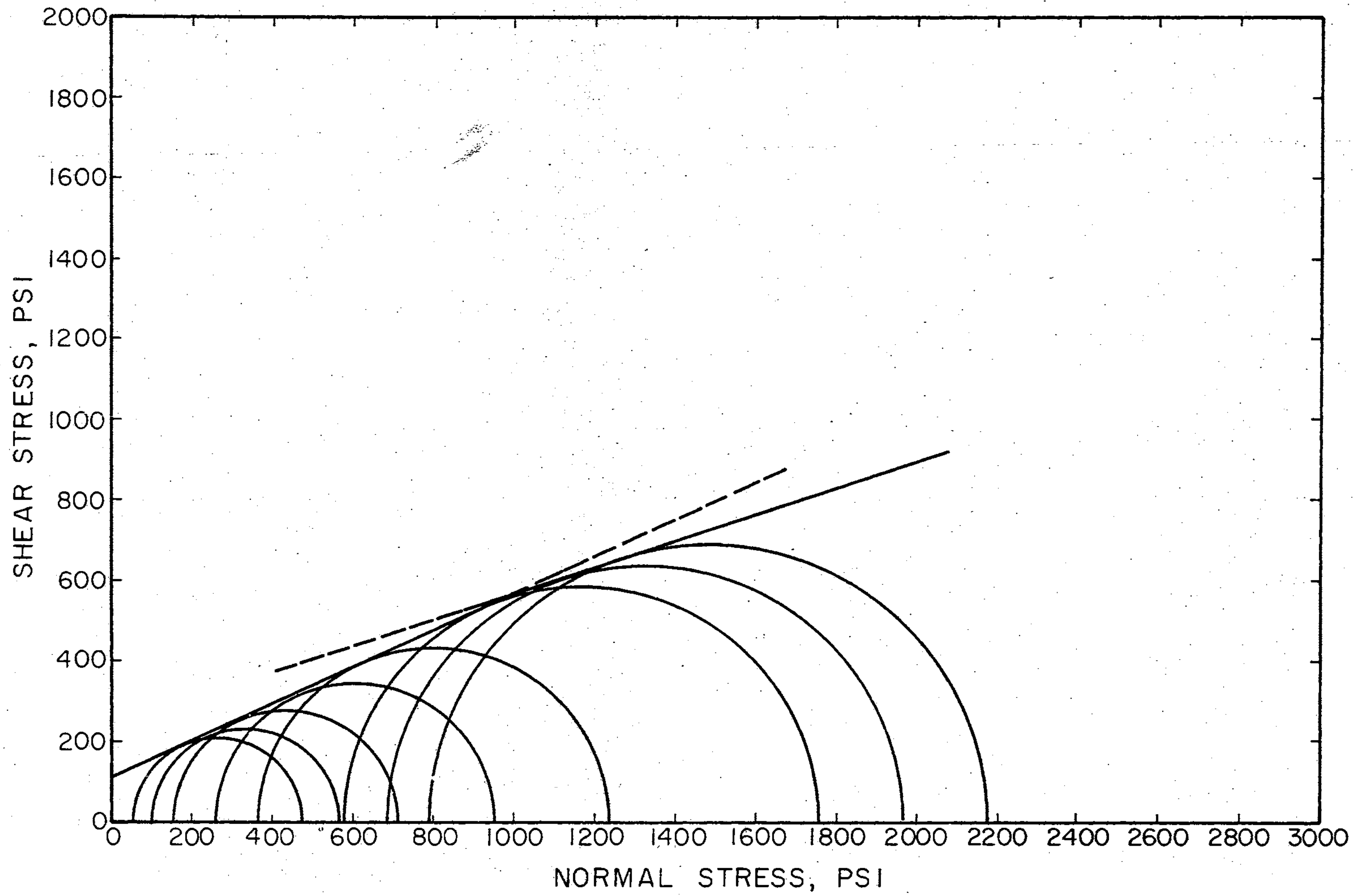

Figure B-17. Mohr Diagram (Silt + 5% Cement, w = 19.0%, γ_d = 99.5 pcf, 7 Days, Impact Compaction).

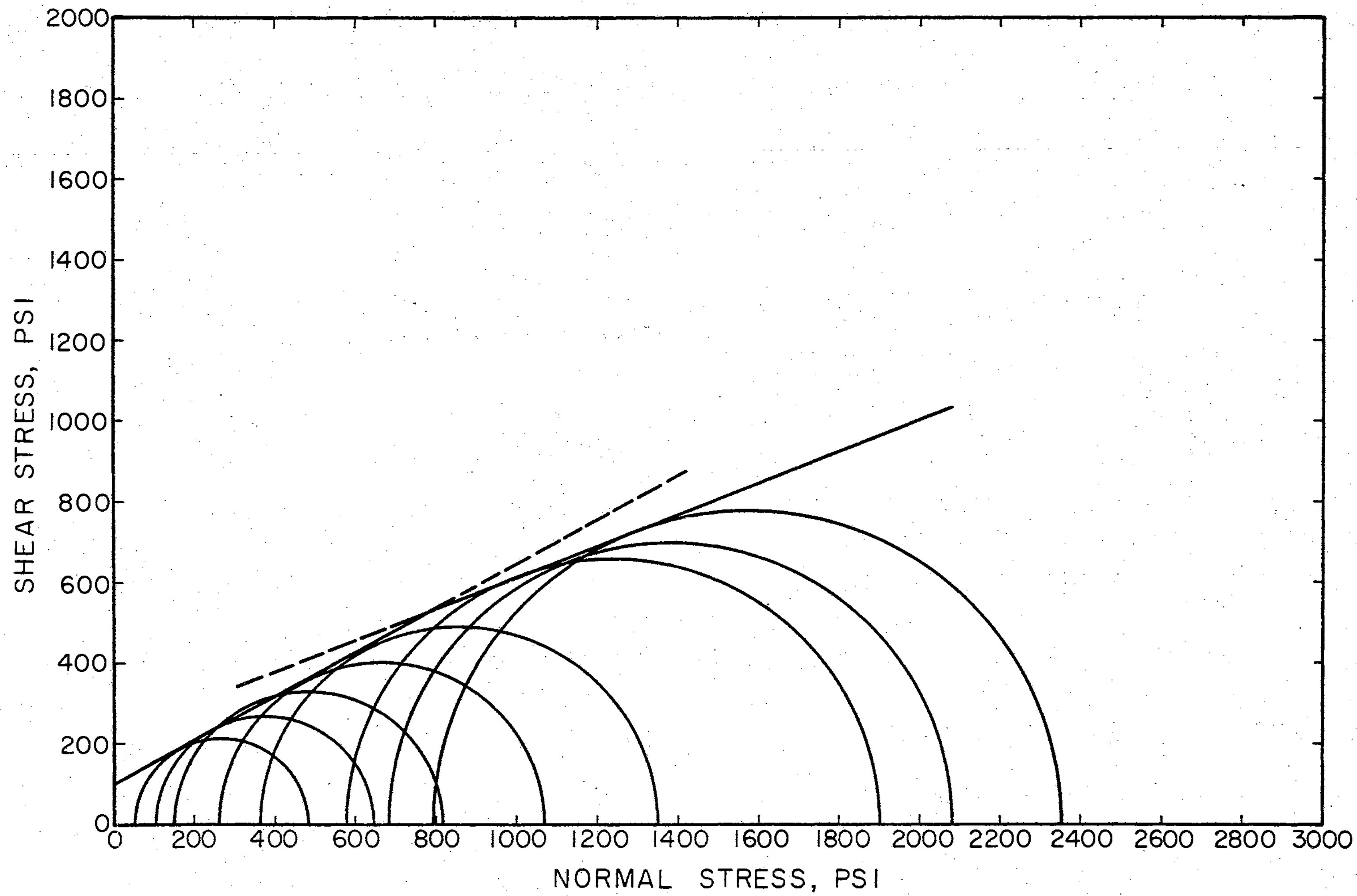

Figure B-18. Mohr Diagram (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 2 Days, Impact Compaction).

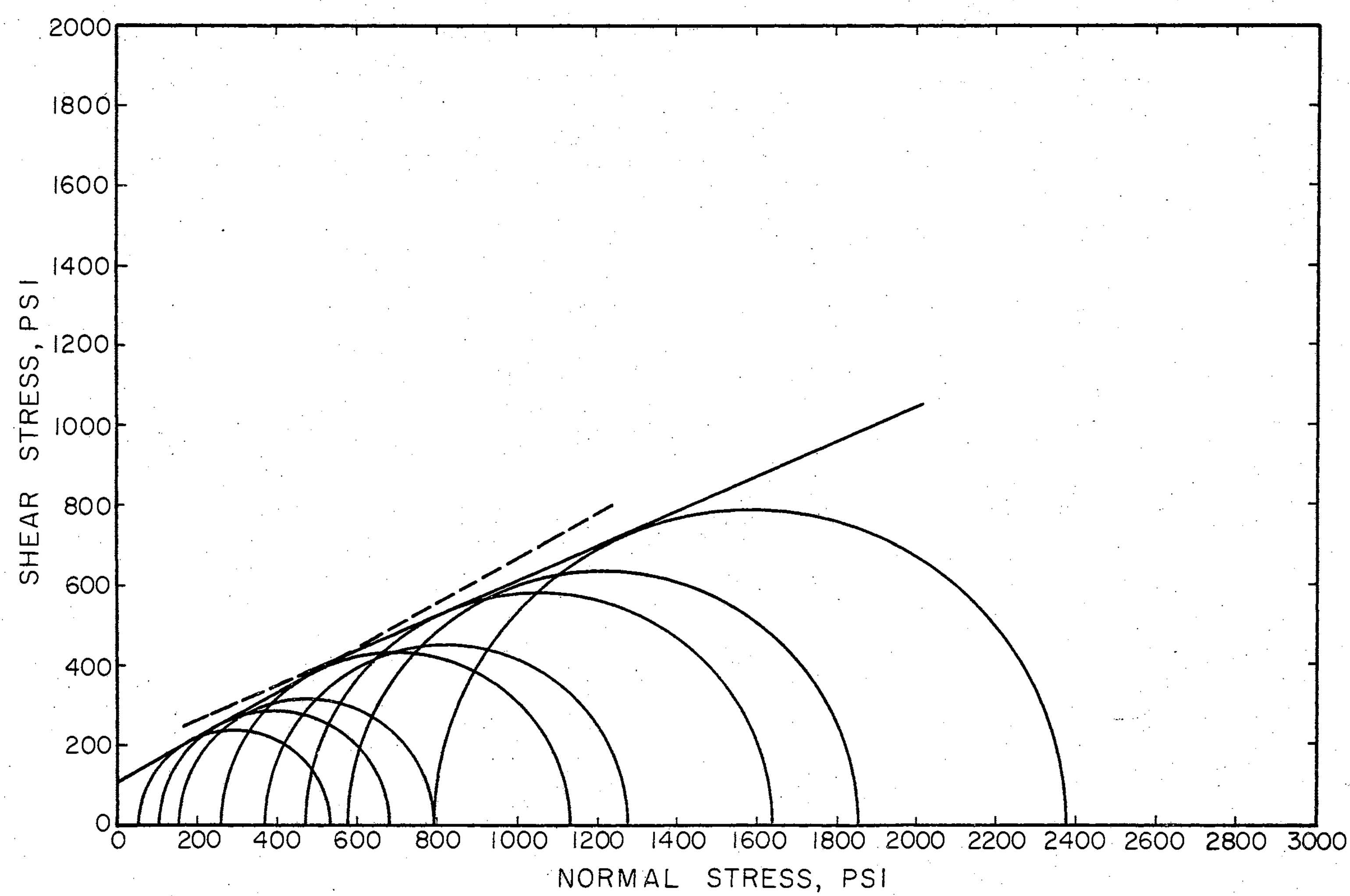

Figure B-19. Mohr Diagram (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 2 Days, Kneading Compaction).

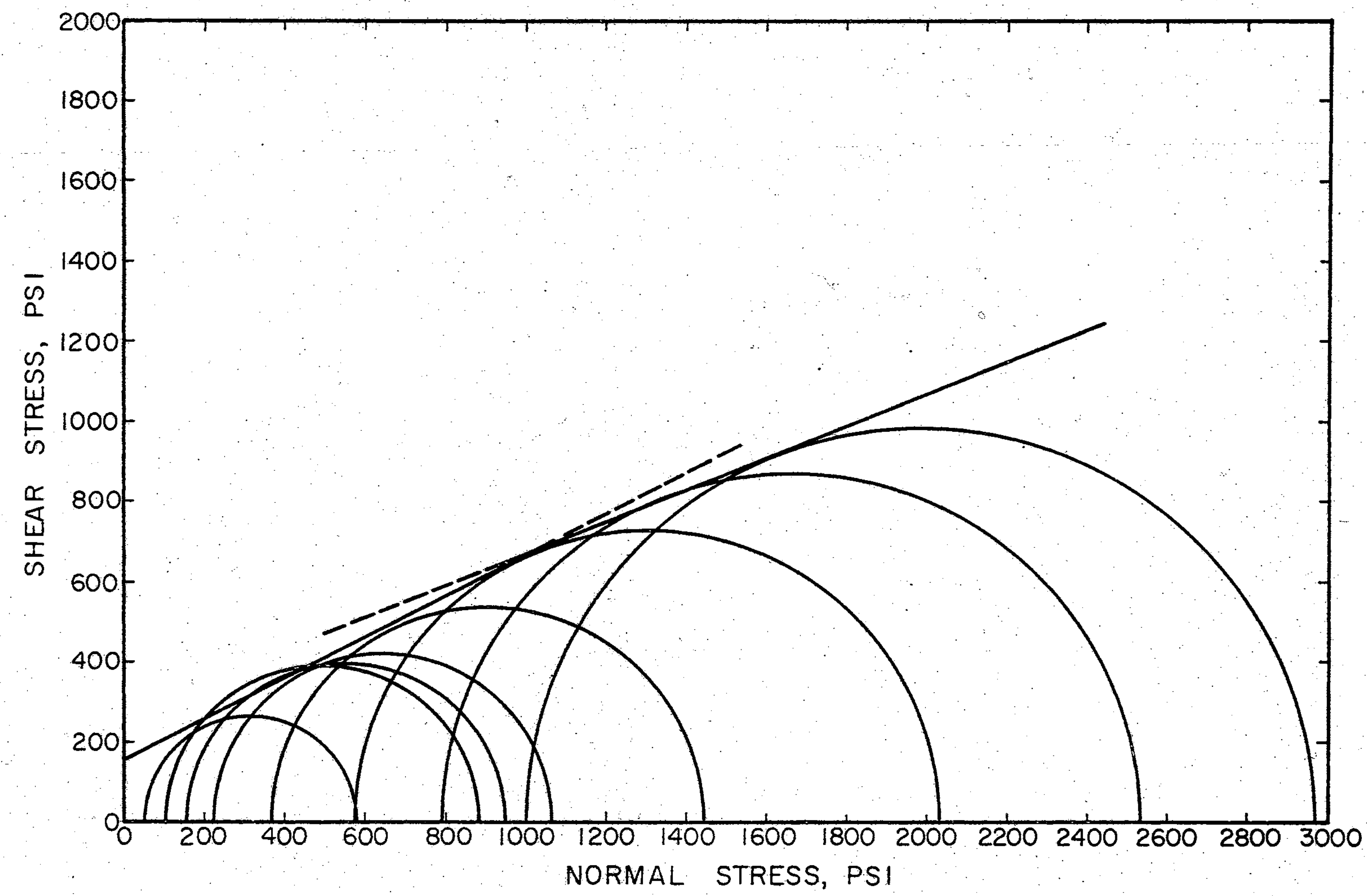

Figure B-20. Mohr Diagram (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 7 Days, Impact Compaction).

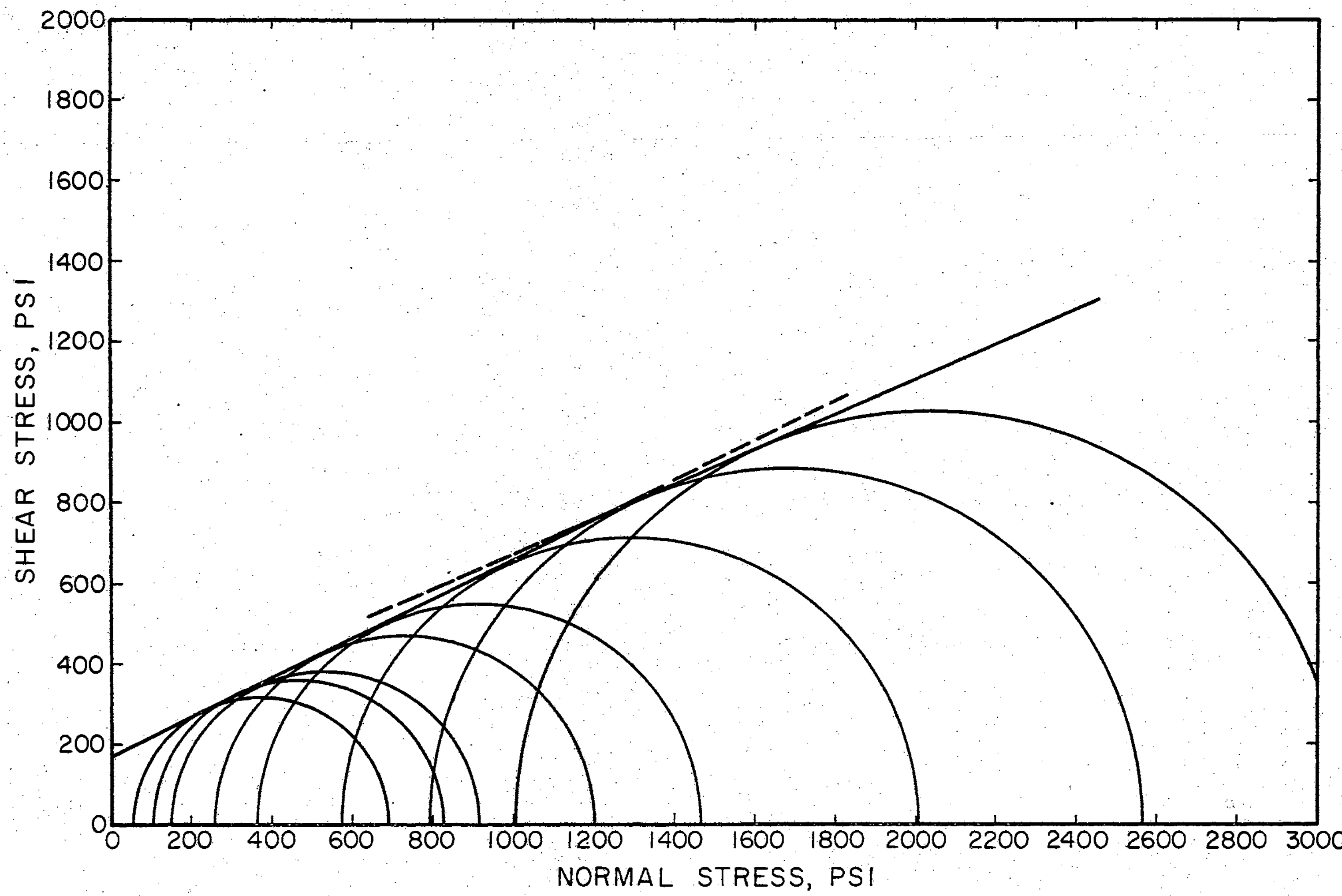

Figure B-21. Mohr Diagram (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 7 Days, Kneading Compaction).

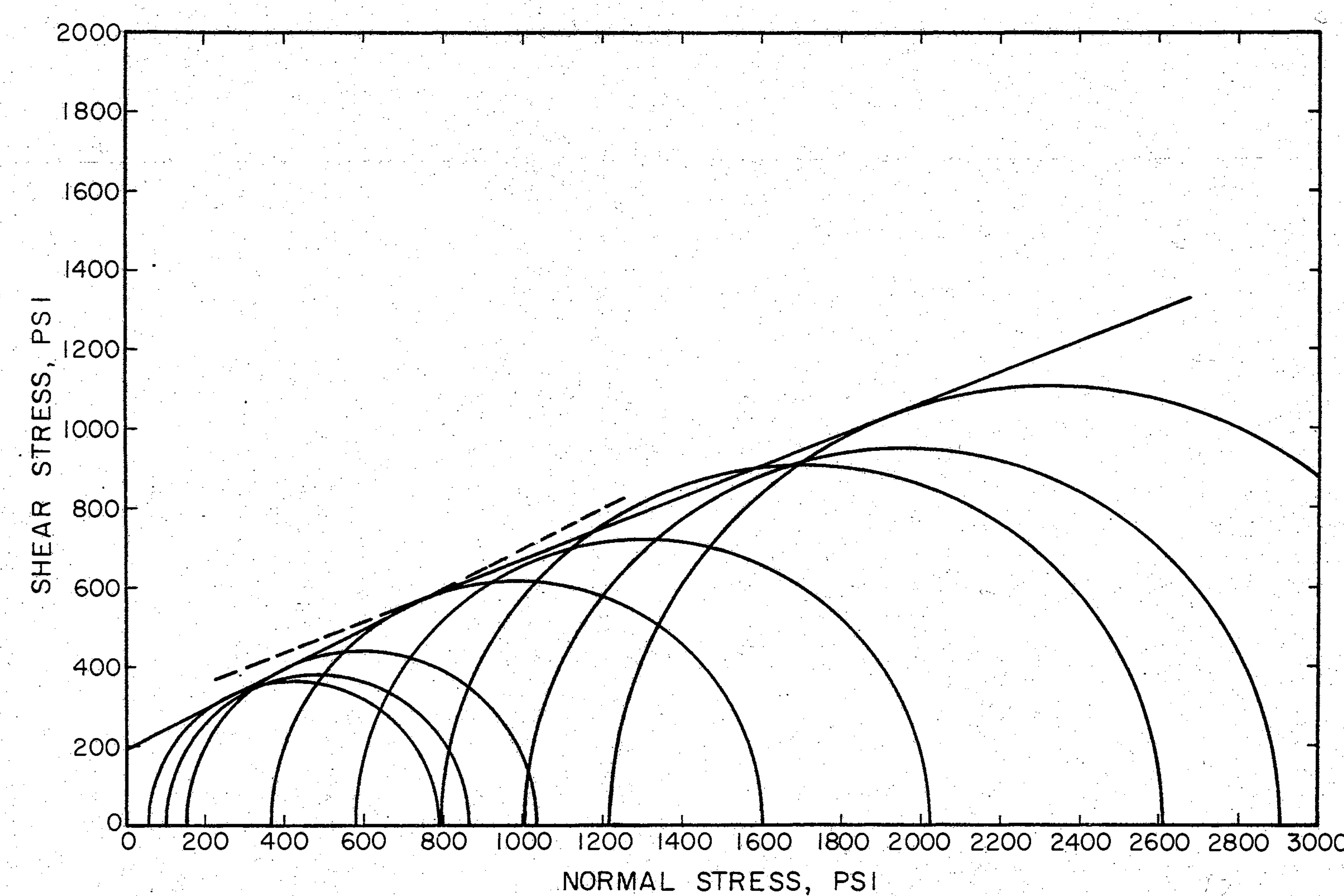

Figure B-22. Mohr Diagram (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 28 Days, Impact Compaction).

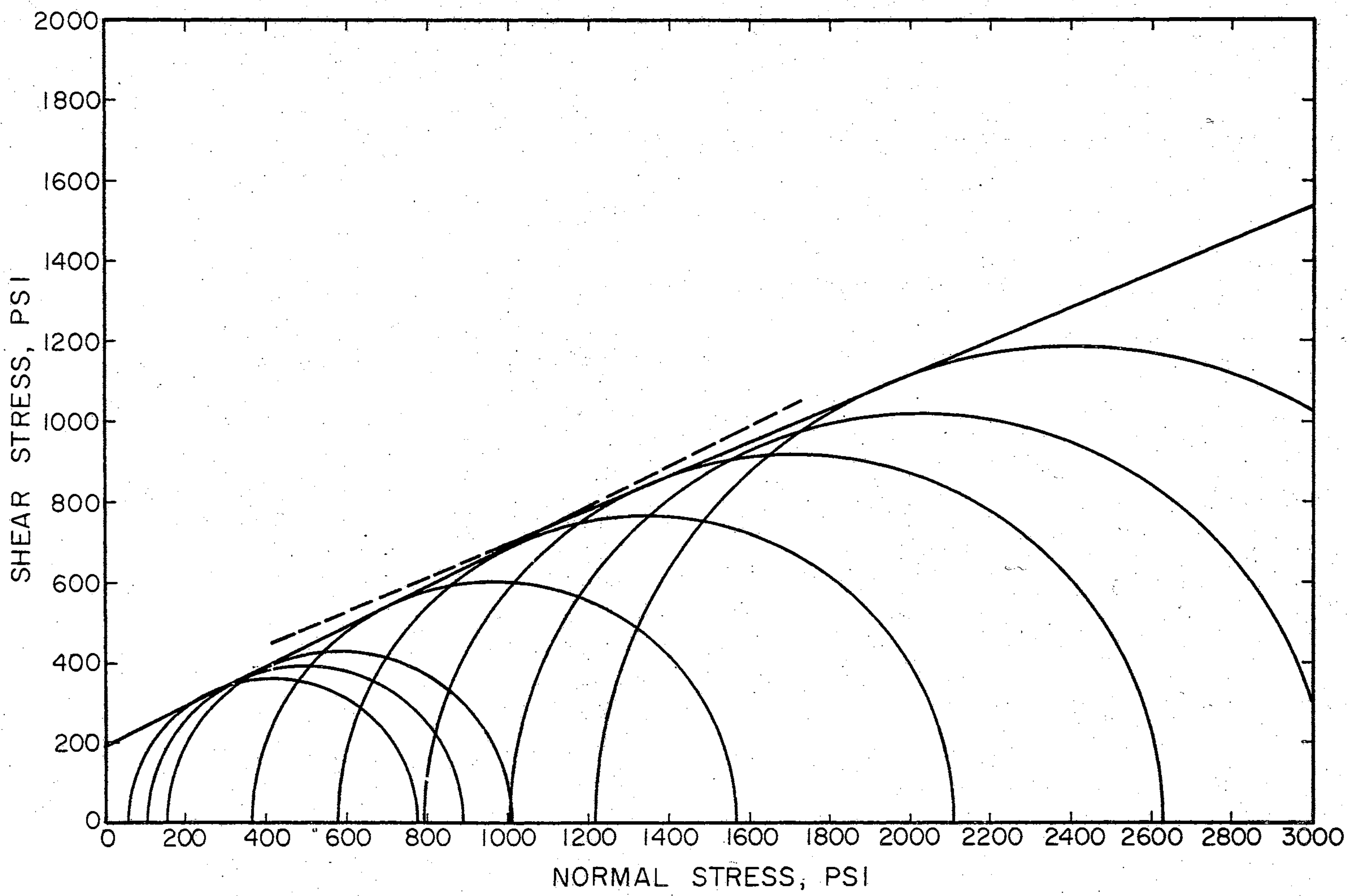

Figure B-23. Mohr Diagram (Silt + 10% Cement, w = 19.0%, γ_d = 99.5 pcf, 28 Days, Kneading Compaction).

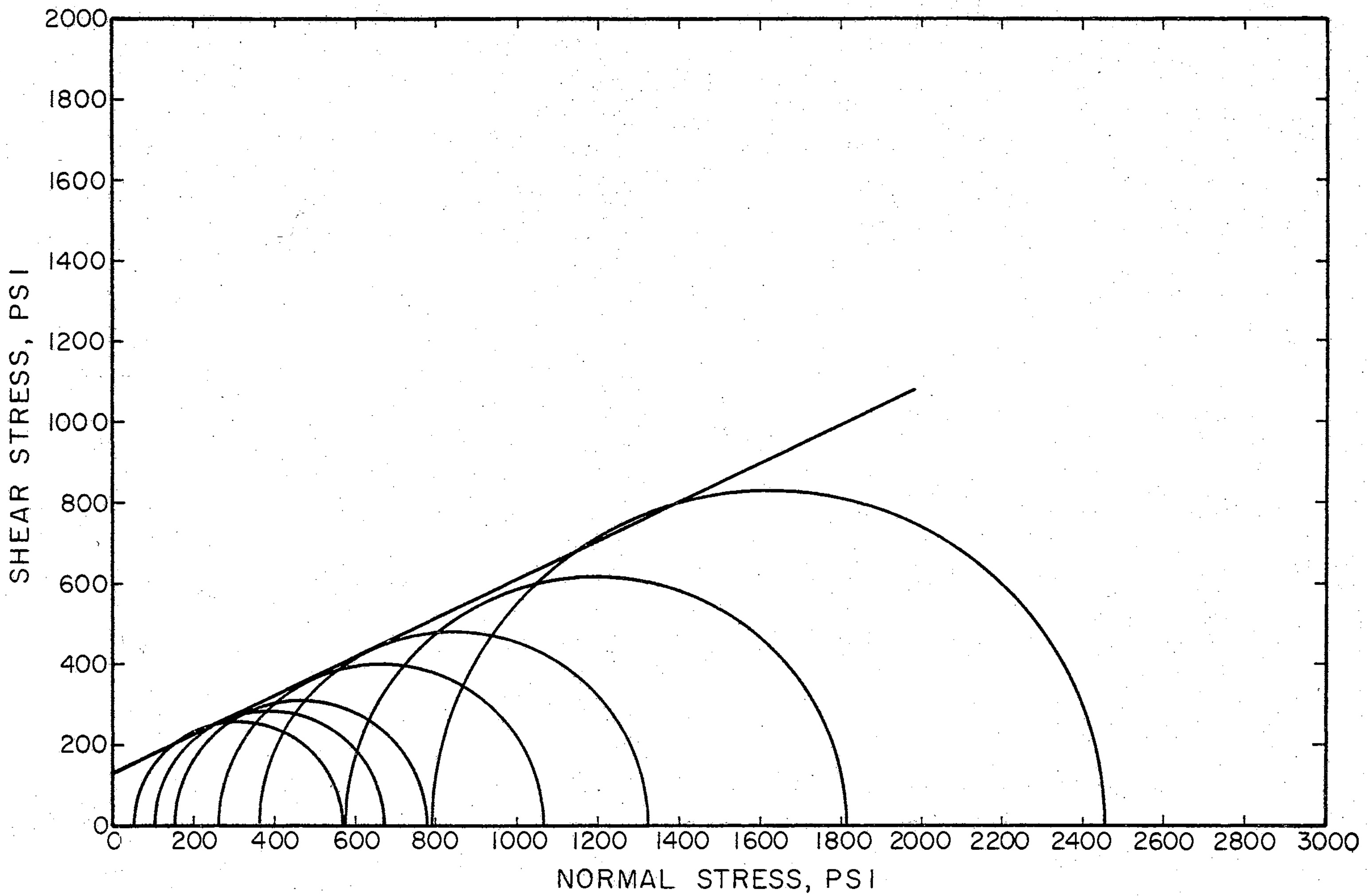

Figure B-24. Mohr Diagram (Silt + 10% Cement, w = 15.0%, γ_d = 97.5 pcf, 7 Days, Impact Compaction).

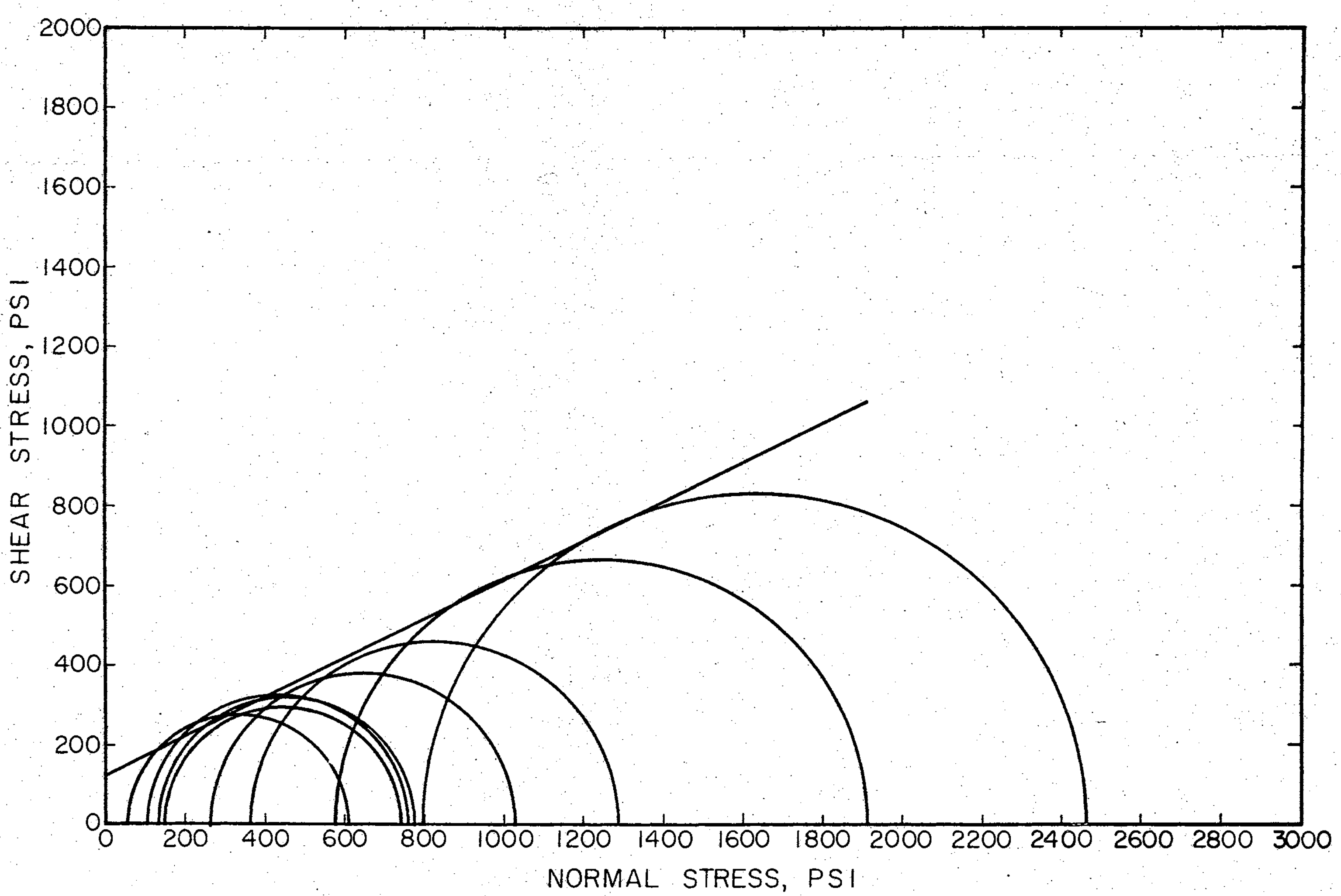

Figure B-25. Mohr Diagram (Silt + 10% Cement, w = 15.0%, γ_d = 97.5 pcf, 7 Days, Kneading Compaction).

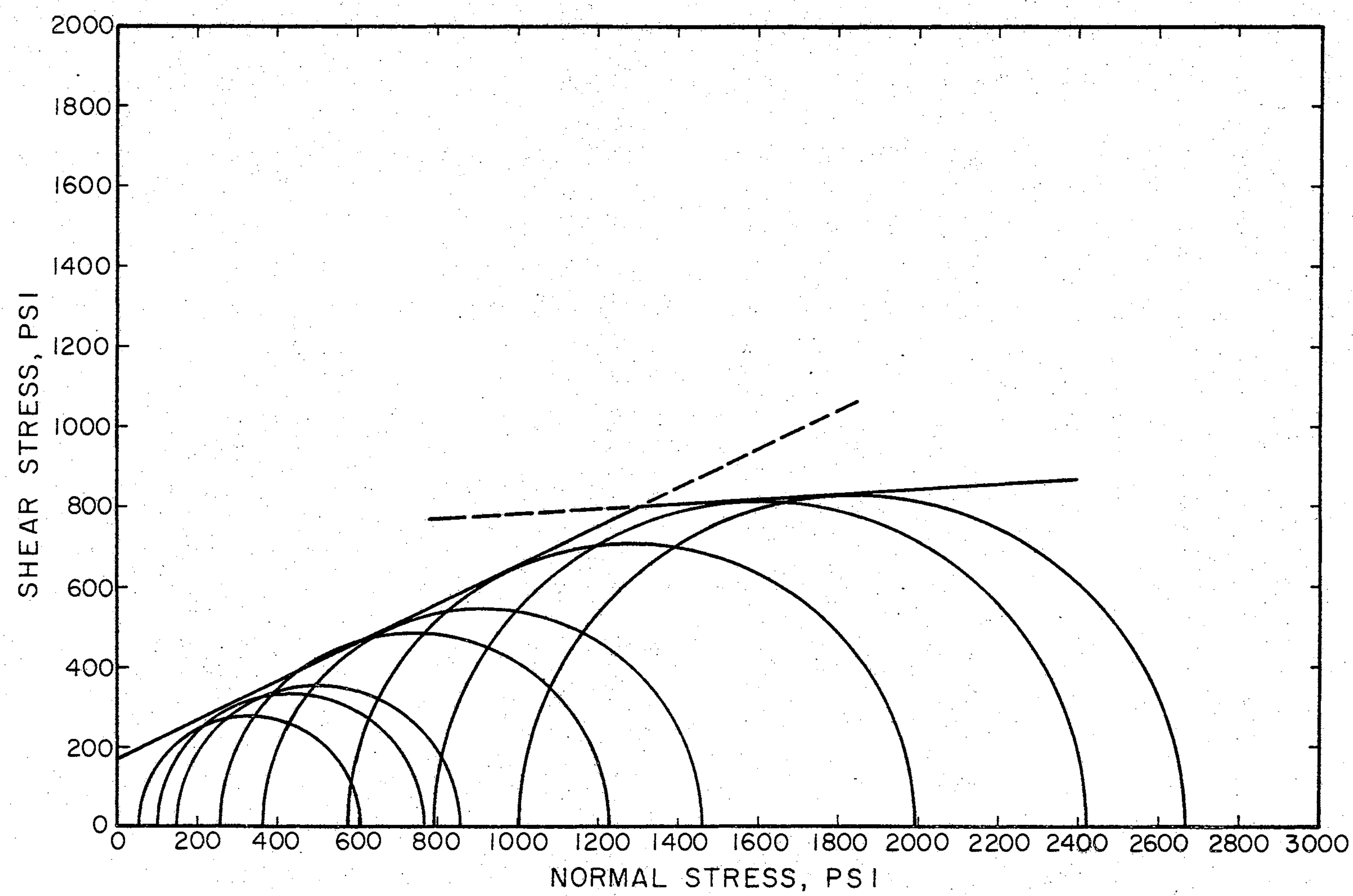

Figure B-26. Mohr Diagram (Silt + 10% Cement, w = 23.0%, γ_d = 96.0 pcf, 7 Days, Impact Compaction).

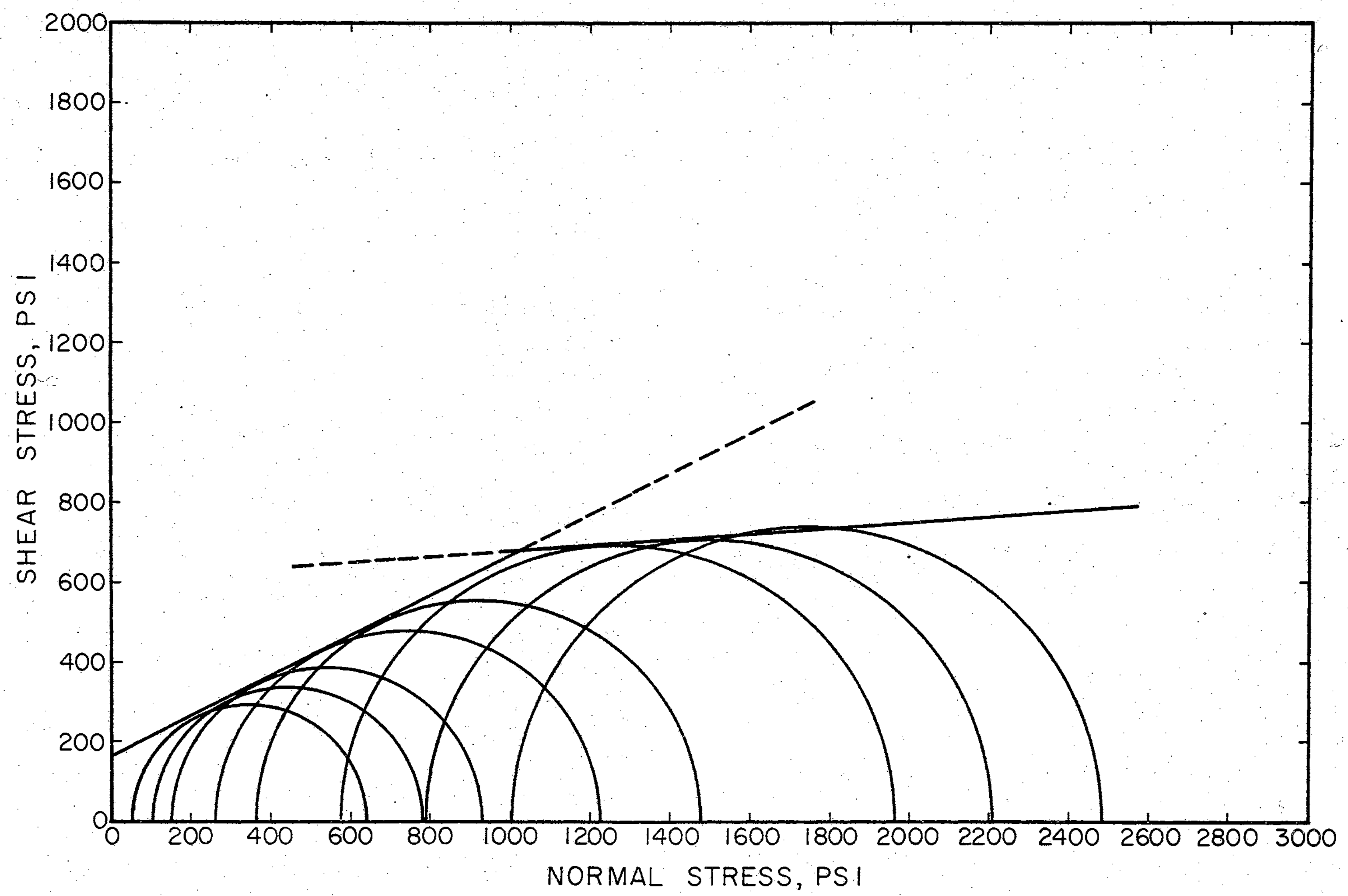

Figure B-27. Mohr Diagram (Silt + 10% Cement, w = 23.0%, γ_d = 96.0 pcf, 7 Days, Kneading Compaction).

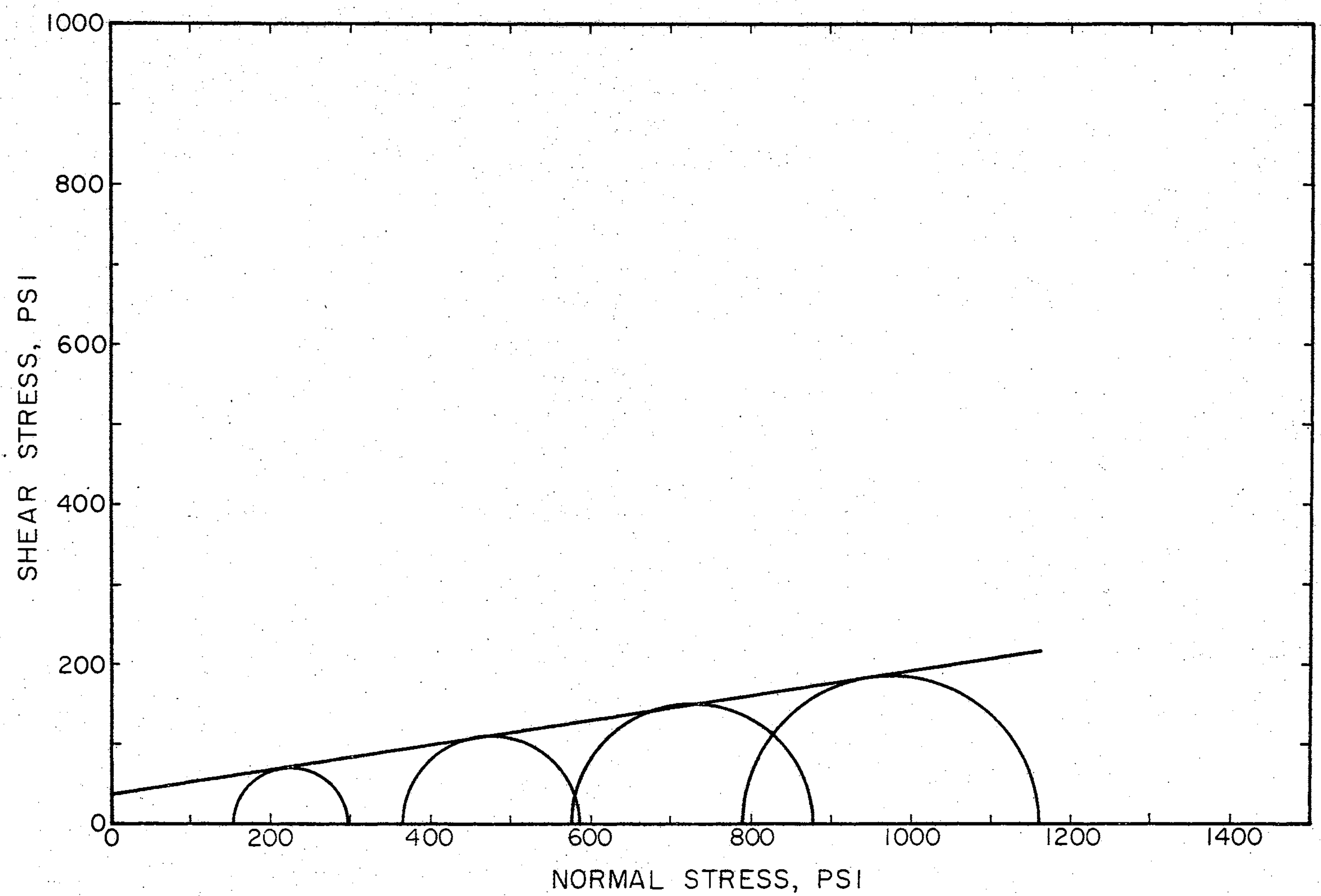

Figure B-28. Mohr Diagram (Clay + 0% Cement, w = 17.2%, γ_d = 106.5 pcf, 7 Days, Impact Compaction).

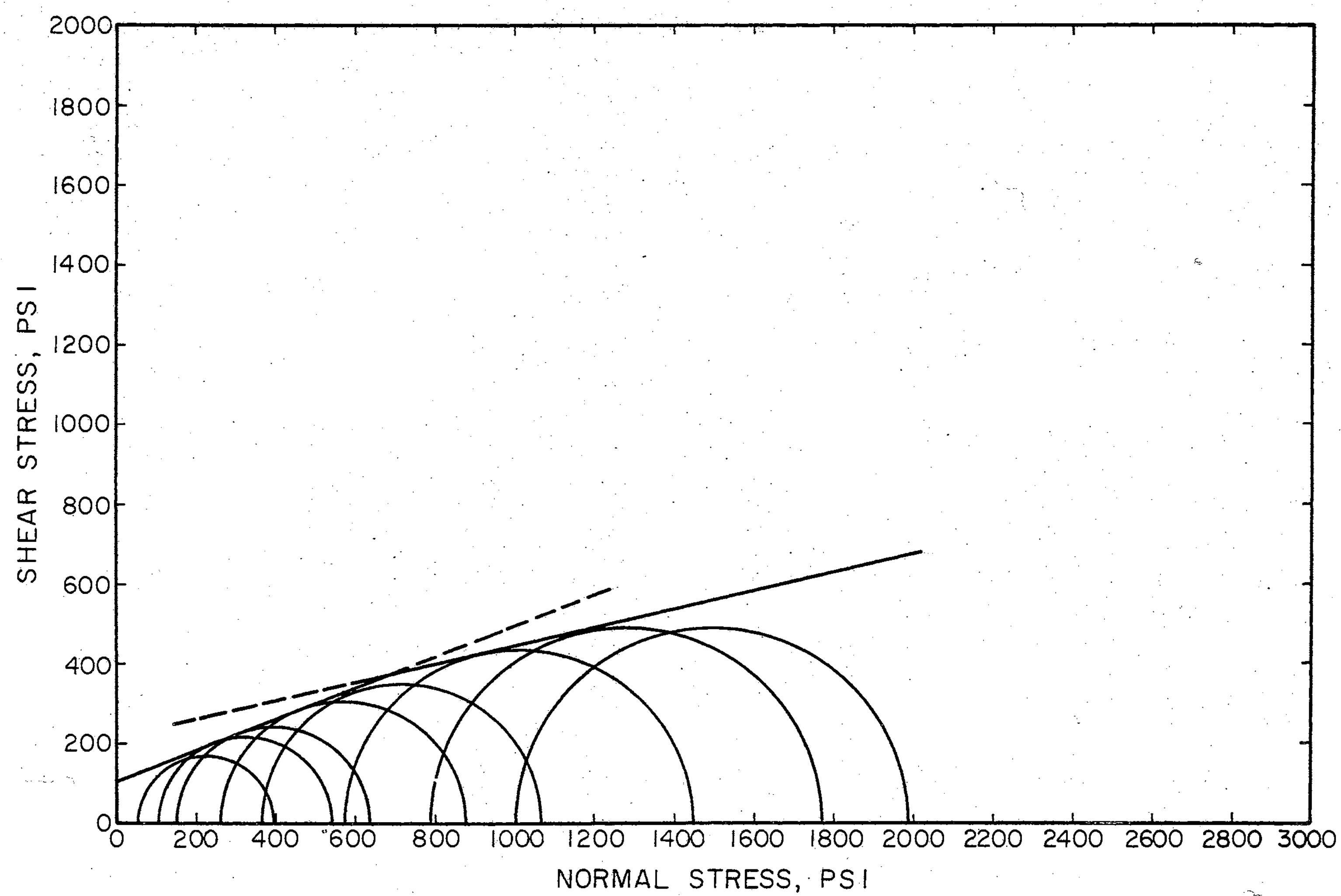

Figure B-29. Mohr Diagram (Clay + 5% Cement, w = 17.2%, γ_d = 106.5 pcf, 7 Days, Impact Compaction).

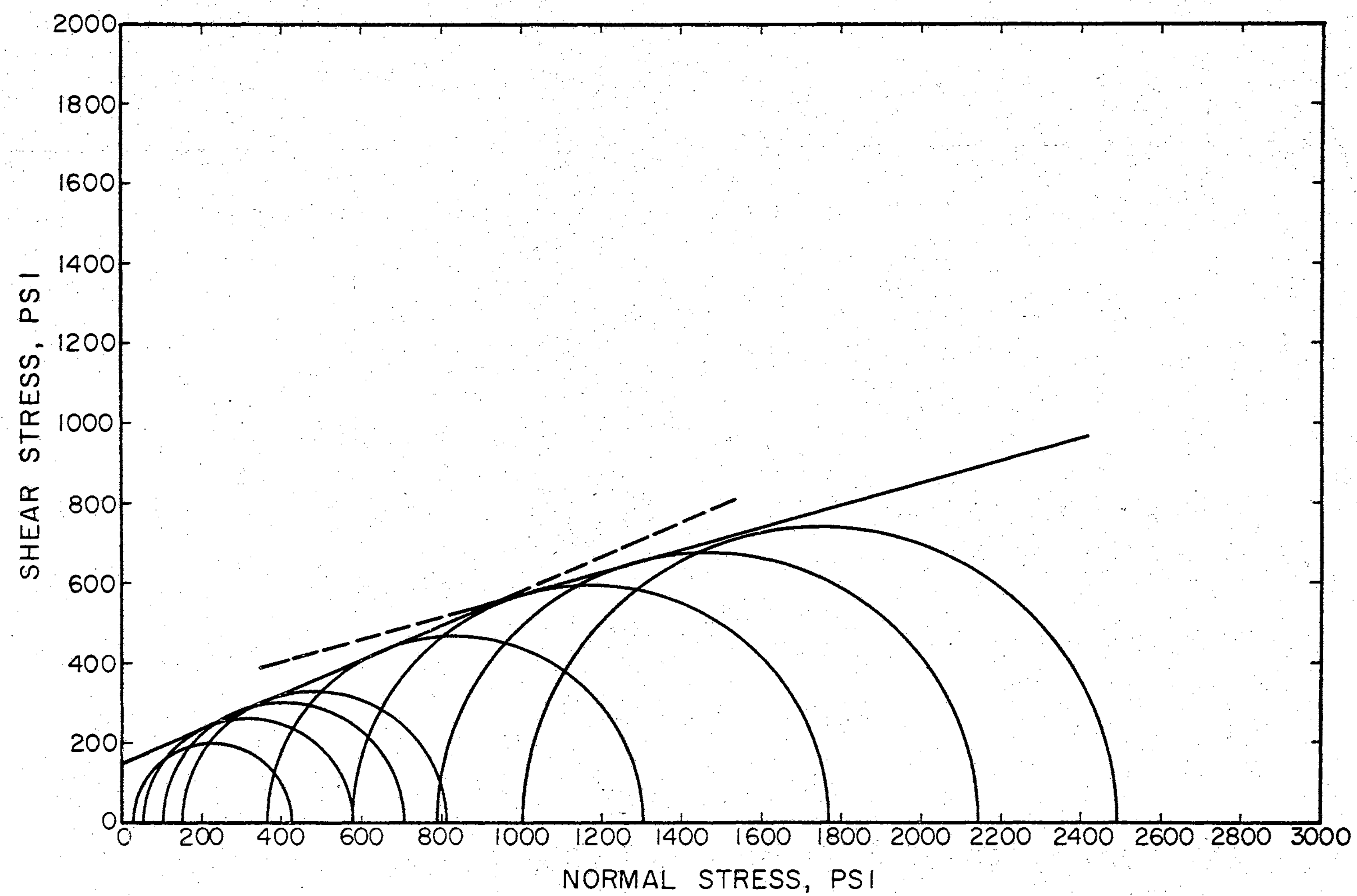

Figure B-30. Mohr Diagram (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 2 Days, Impact Compaction).

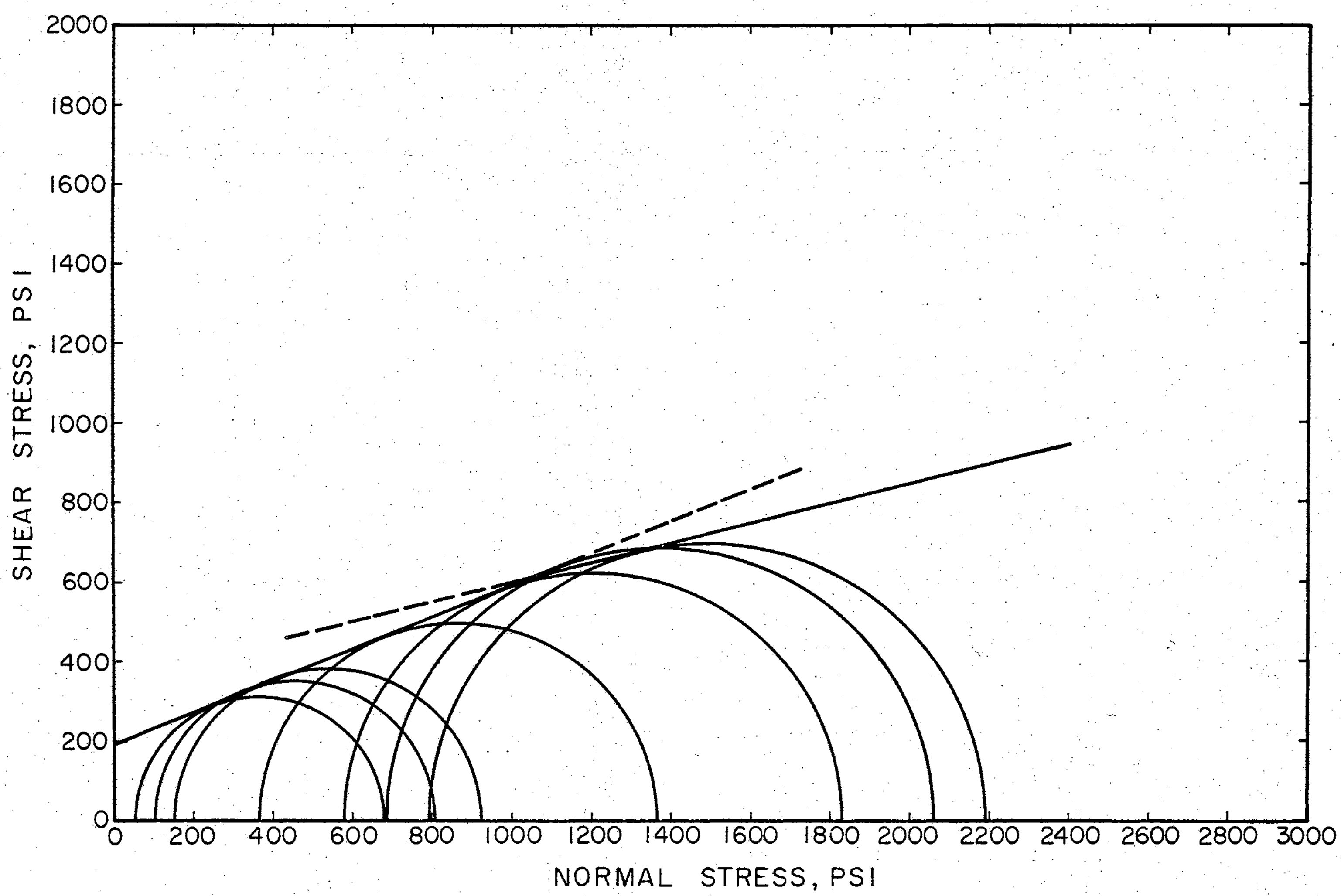

Figure B-31. Mohr Diagram (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 2 Days, Kneading Compaction).

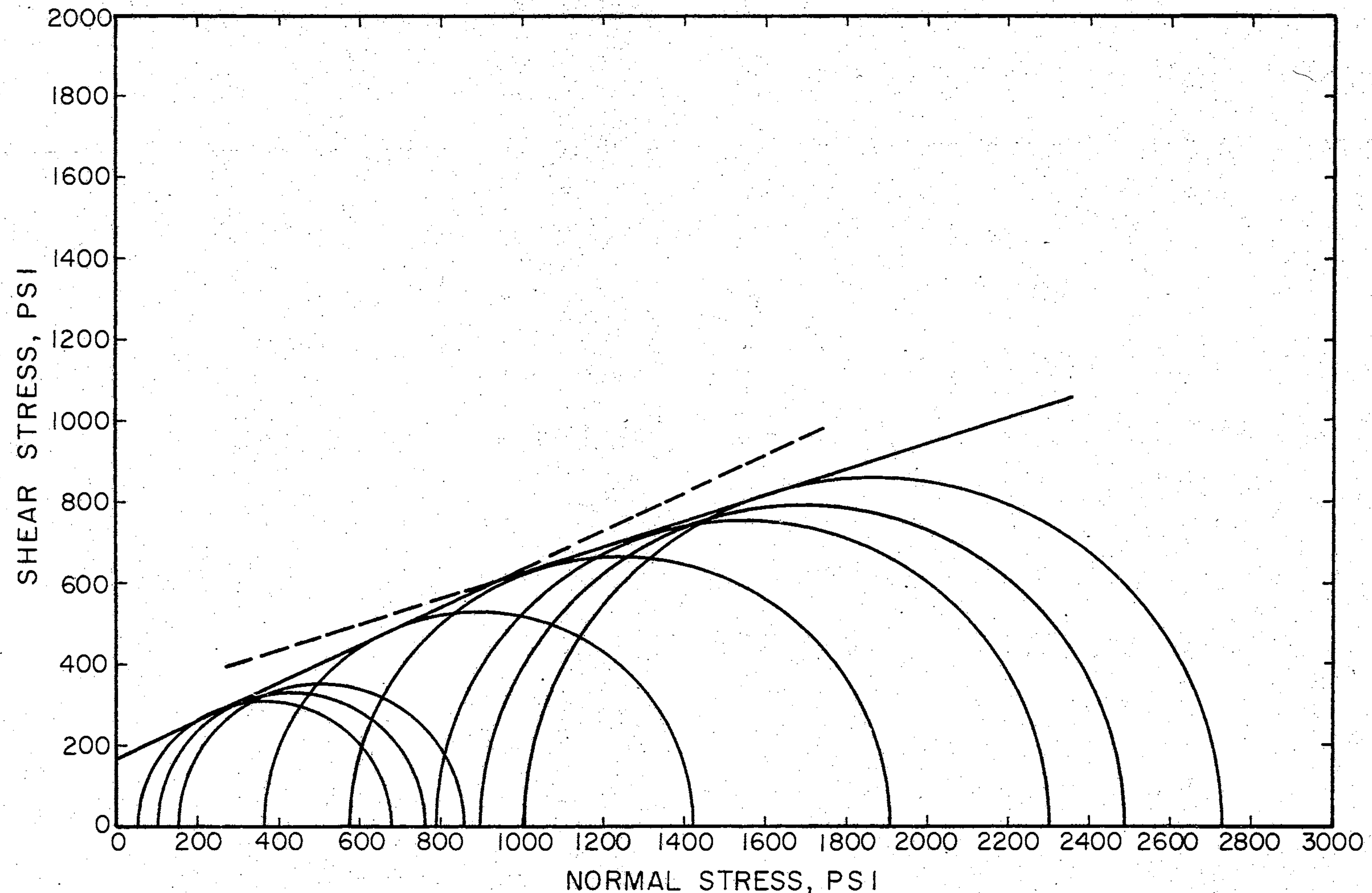

Figure B-32. Mohr Diagram (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 7 Days, Impact Compaction).

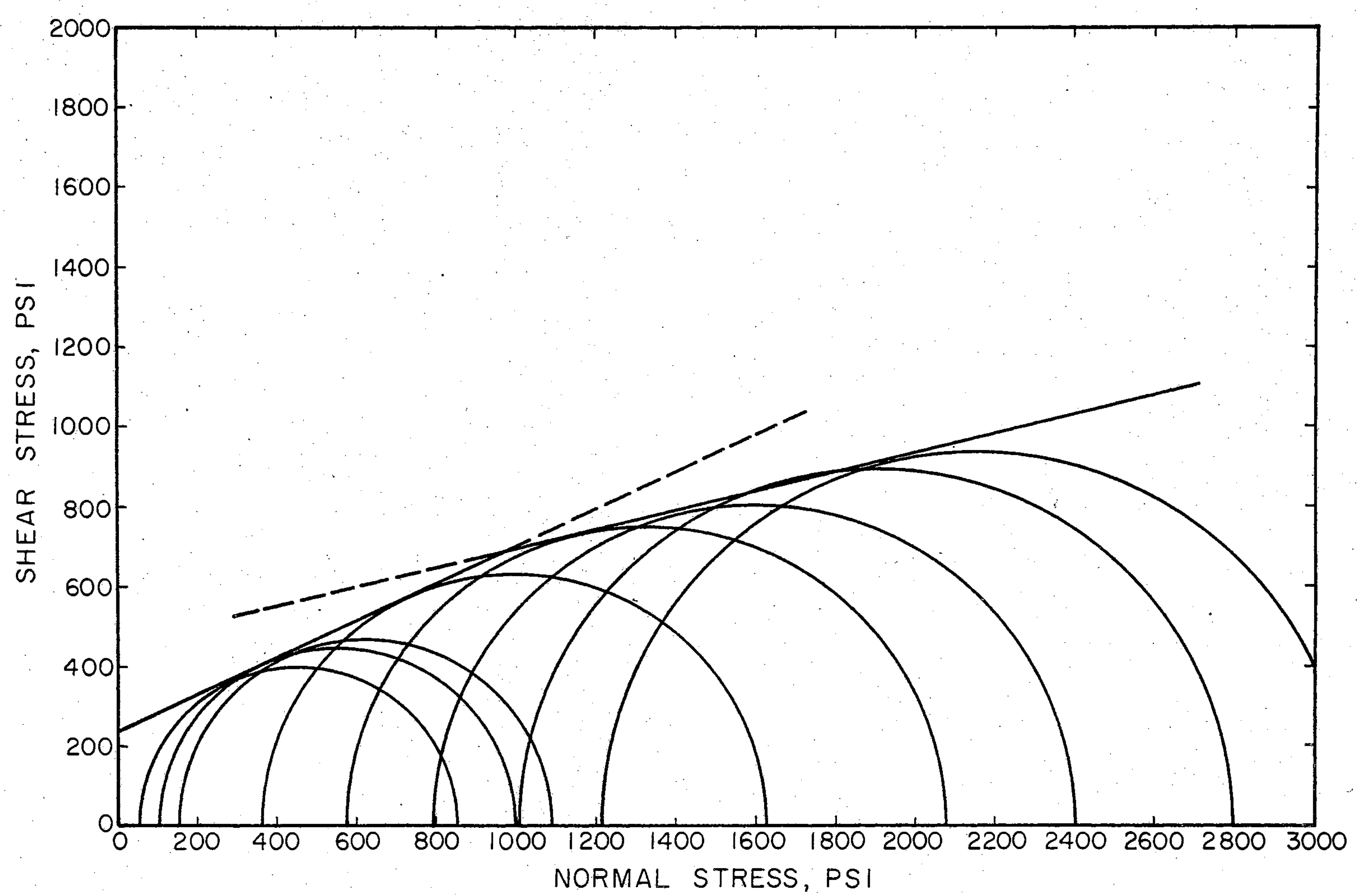

Figure B-33. Mohr Diagram (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 7 Days, Kneading Compaction).

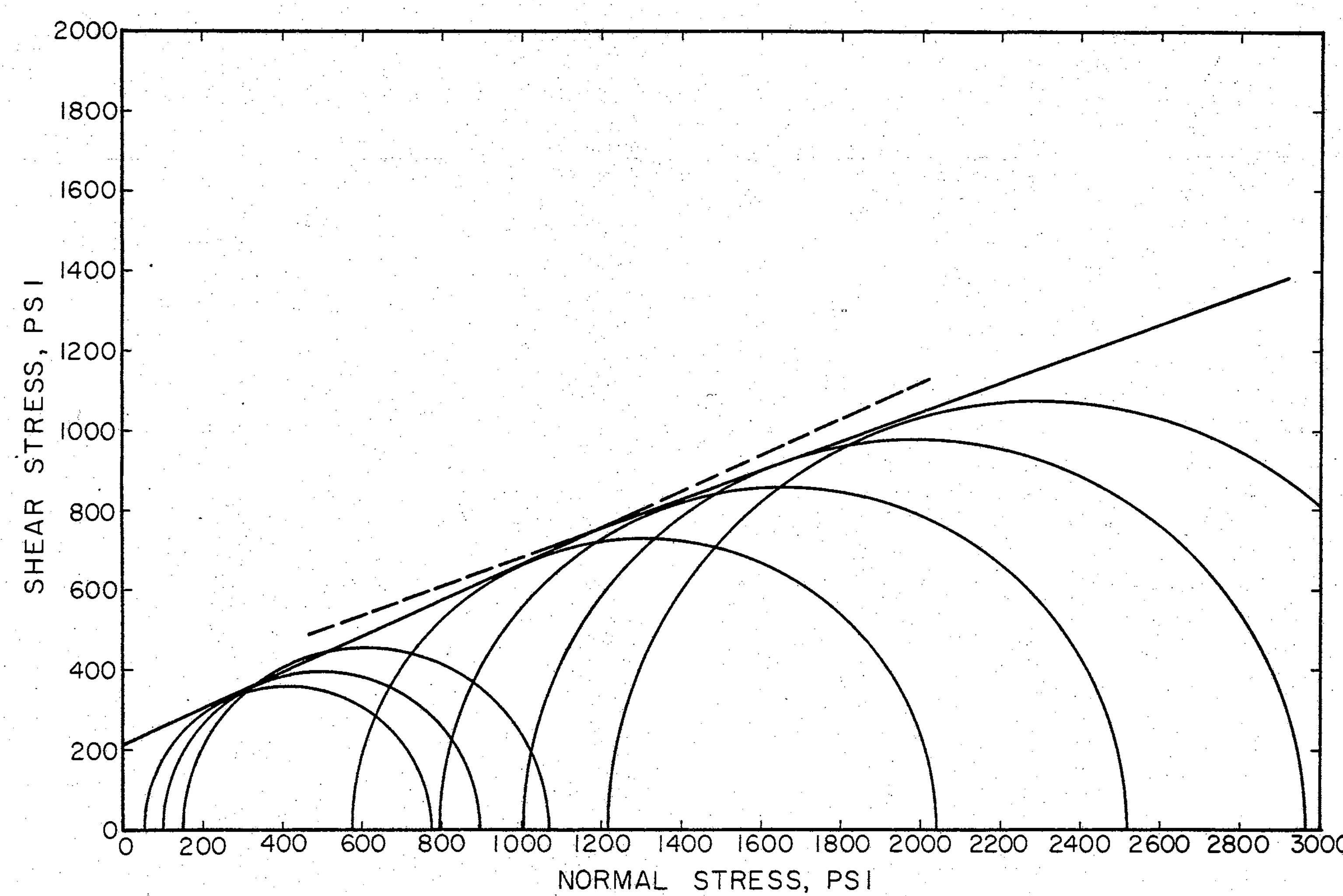

Figure B-34. Mohr Diagram (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 28 Days, Impact Compaction).

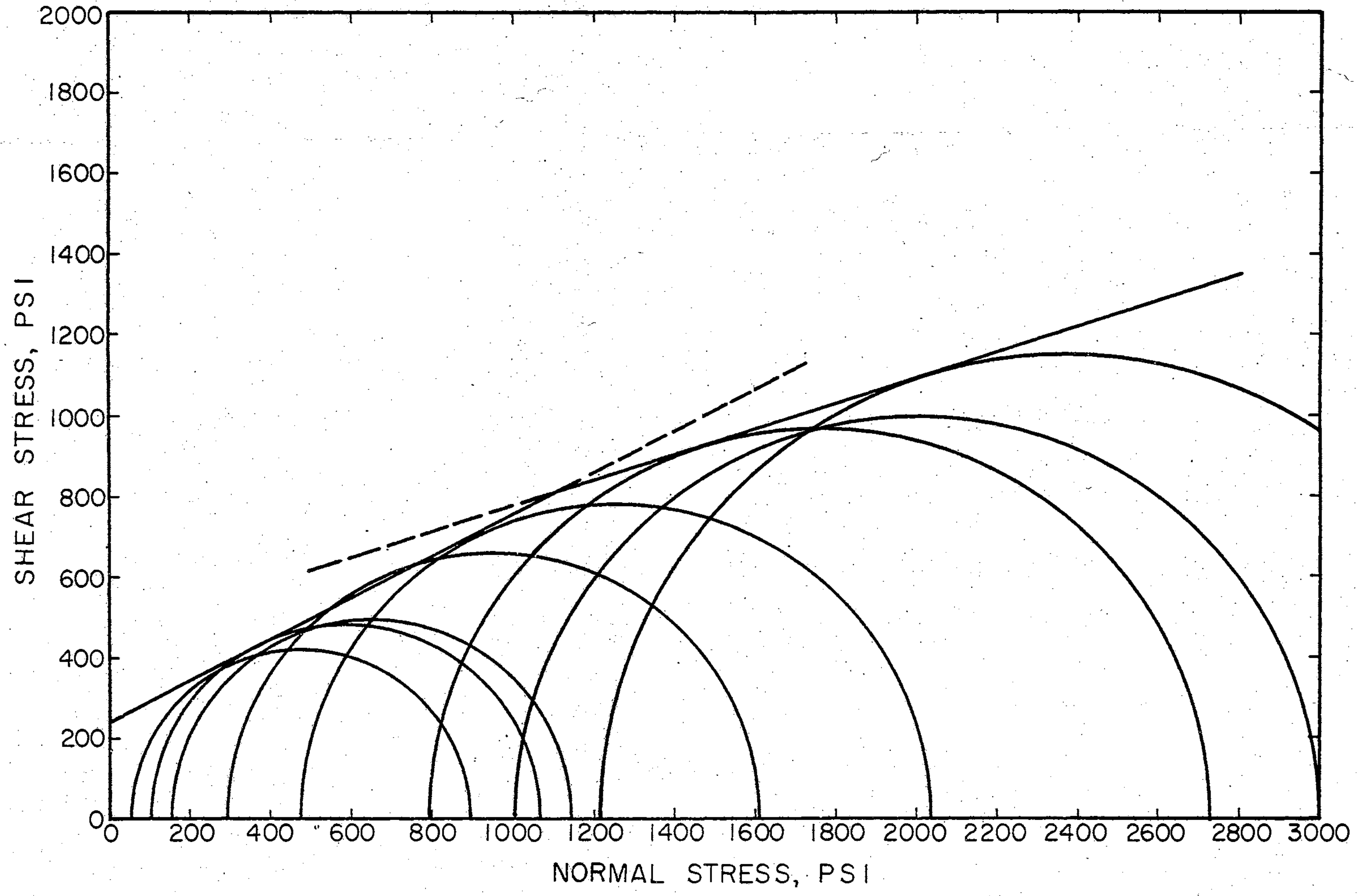

Figure B-35. Mohr Diagram (Clay + 10% Cement, w = 17.2%, γ_d = 106.5 pcf, 28 Days, Kneading Compaction).

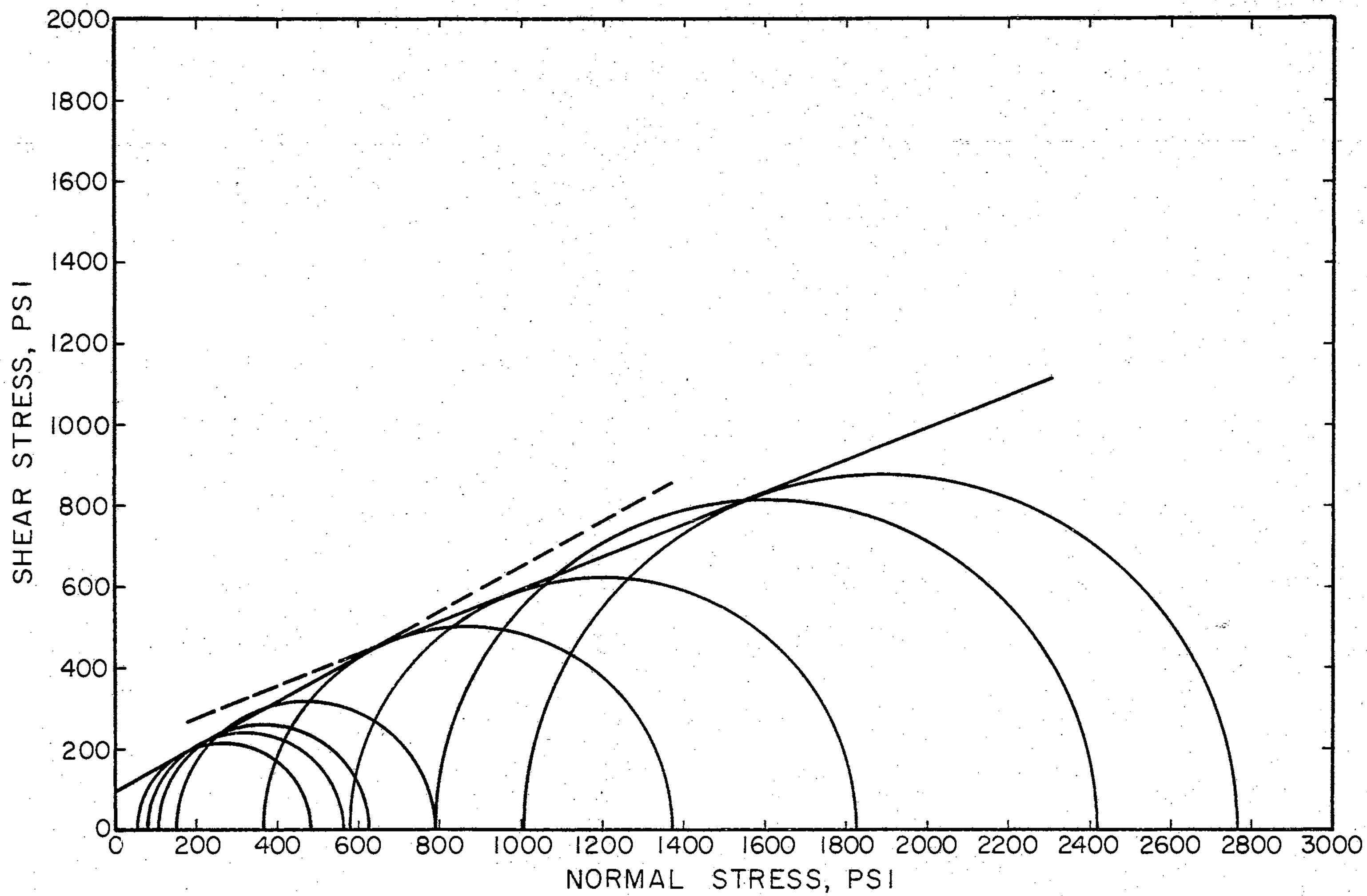

Figure B-36. Mohr Diagram (Clay + 10% Cement, w = 13.0%, γ_d = 104.2 pcf, 7 Days, Impact Compaction).

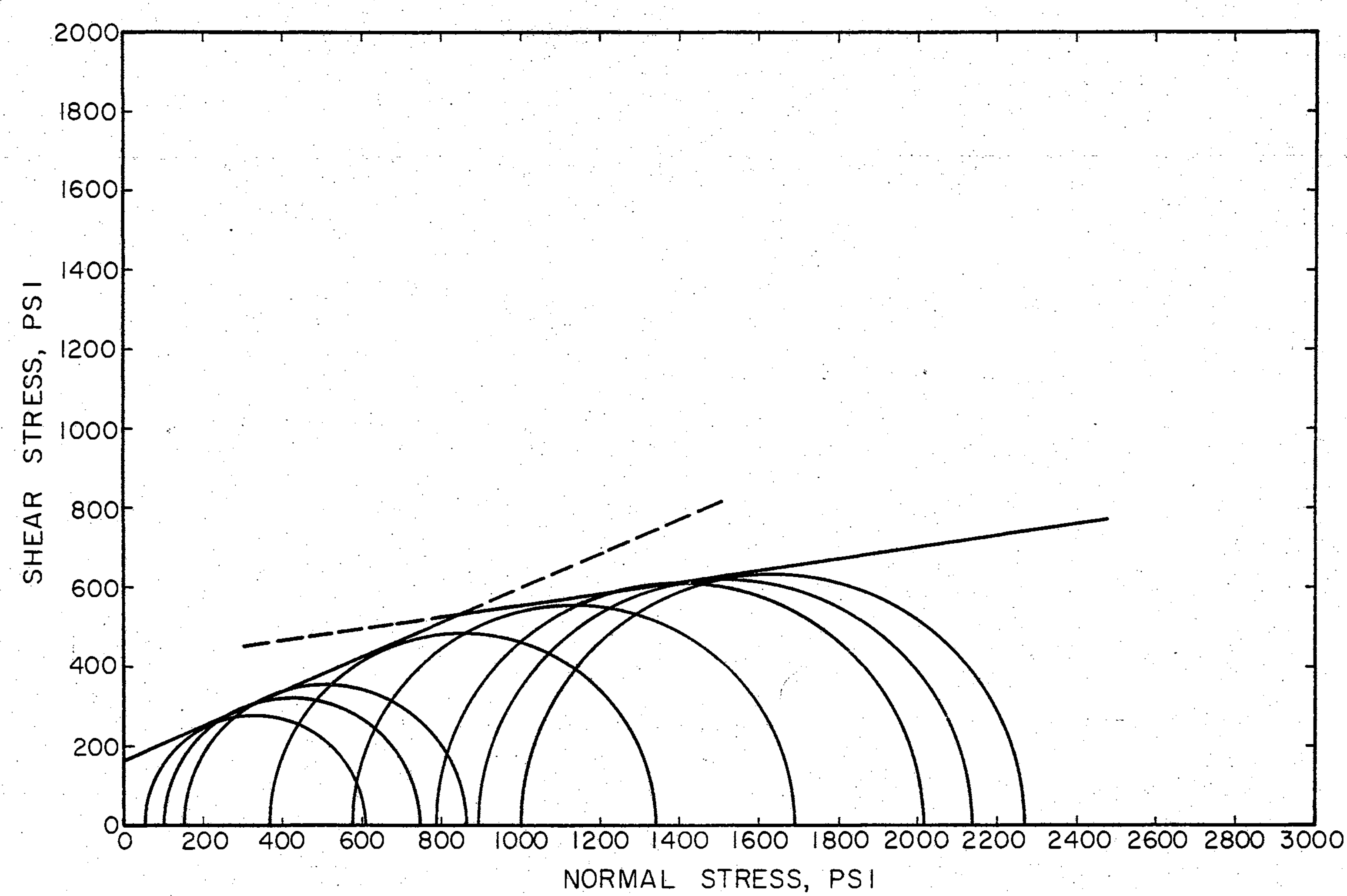

Figure B-37. Mohr Diagram (Clay + 10% Cement, w = 20.8%, γ_d = 104.2 pcf, 7 Days, Impact Compaction).

VITA

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