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UKTRP-85-1

LABORATORY EVALUATIONS OF STABILIZED FLUE GAS DESULFURIZATION SLUDGE (SCRUBBER SLUDGE) AND AGGREGATE MIXTURES

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16. Abstract

The Kentucky Transportation Research Program has completed a laboratory study involving the use of flue gas desulfurization sludge (scrubber sludge) for potential application as a highway subbase and/or embankment material. Scrubber sludge is a waste product formed when fly ash (and other residue) is combined with a lime dust slurry filter cake and stabilized with quicklime (calcium oxide). Samples of stockpiled (field) sludge and dry sludge components were obtained from the Robert Reid Station (Big Rivers Electric Corporation) in Sebree, Kentucky. Dry sludge components (fly ash, filter cake, and quicklime) were used to prepare sludge samples in the laboratory, allowing a higher degree of quality control for comparison purposes. Mixtures for testing included scrubber sludge, scrubber sludge with pond ash (bottom ash), and scrubber sludge with dense graded limestone aggregate (DGA). One objective of laboratory analyses was the determination of optimum mixture proportions. A mixture of 20-percent scrubber sludge and 80-percent pond ash was determined to be the optimum design mix. That mixture showed significant strength gain with curing and had a static-chord modulus of elasticity approximately 118 times the compressive strength. Strength and modulus tests indicated that mixtures of scrubber sludge and pond ash were superior to mixtures of scrubber sludge and DGA. The scope of the study, however, did not permit complete explanation of these observations. An economic study showed that scrubber sludge with pond ash can be used economically as a highway subbase material, especially on low-fatigue roads, by partially replacing more expensive pavement layers. Triaxial tests and computer simulations indicated that scrubber sludge could be used as an embankment material in some applications. However, this would be economical only if suitable fill material was not available at or near the fill site.

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INTRODUCTION

In October 1982, the Kentucky Transportation Research Program (KTRP) was contacted by the Kentucky Transportation Cabinet, Department of Highways (KyDOH), concerning the use of scrubber sludge (flue gas desulfurization sludge) in highway construction An experimental project approximately 2.2 miles in length was proposed as a section of the Sebree Bypass, in Webster County. The experimental project is located on KY 494 between US 41 and KY 132. The experimental section is the 1.9 miles nearest US 41. A control section of 0.3 mile is located at the other end of the project at KY 132. In November 1982, an abbreviated work plan was submitted outlining procedures for investigating the material to determine how it could be used in the construction of the Sebree Bypass and for monitoring performance after construction.

The abbreviated work plan outlined three tasks: laboratory studies to determine potential uses and design parameters, monitoring the construction of an experimental project with one or more experimental features, and extended evaluation over a 5-year period to determine long-term characteristics of the materials and construction features. In January 1983, authorization was received to begin the study.

Laboratory analyses concentrated on two possible uses of scrubber sludge in highway construction. One application involved a mixture of scrubber sludge and aggregate as a subbase material in pavement construction. The second application involved use of scrubber sludge as embankment material.

In May 1983, an interim report was submitted to KyDOH. The report included interim findings on the engineering characteristics of scrubber sludge, thickness design criteria, and economics of scrubber sludge use for the Sebree Bypass. A copy of the interim report is included here as Appendix A.

Materials described in this report were tested only for engineering properties. No chemical tests were performed to evaluate environmental effects. It is recommended that approval of the Kentucky Environmental Protection Agency be obtained prior to any construction using either scrubber sludge or pond ash since the materials are waste products.

COMPONENTS OF SCRUBBER SLUDGE

The term scrubber sludge is used to describe stabilized flue gas desulfurization sludge. This is a waste material obtained from scrubbers used to remove fly ash and residue from the coal-burning processes of electric generating power plants such as the Robert Reid Station (Big Rivers Electric Corporation) located at Sebree, Kentucky. Major components of the unstabilized sludge are fly ash and a lime-dust slurry filter cake material consisting of calcium sulfate and calcium sulfite. Quicklime is added to stabilize the sludge, and the stabilization reactions begin almost immediately. The resulting stabilized compound is ettringite ($3CaO.Al_2O_3.3CaSO_4, 32H_2O$). The fly ash is silt-size and spherical, with particle diameters ranging from 0.015 to 0.050 mm. Typical properties of ash from this facility are shown in Table 1 (Poulson and Ruggiano, 1980). In this report, references are made to laboratory scrubber sludge and field scrubber sludge, which are described in the following paragraphs.

The term laboratory scrubber sludge is used to identify mixtures of sludge prepared in the laboratory from dewatered samples of filter cake, fly ash, and quicklime. That process allowed close control of mixture proportions. For all laboratory

scrubber sludge and aggregate mixtures, component proportions were chosen to be typical of materials at the Robert Reid Station, as indicated by Mr. Ed Chisholm of Big Rivers Electric Corporation. Those proportions were 2 percent lime, 25 percent fly ash, and 73 percent filter cake.

The term field scrubber sludge identifies sludge obtained from stockpiles at the Robert Reid Station. Two samples of field sludge were obtained (in an uncompacted state) in 6-inch diameter concrete cylinder molds during an on-site visit in January 1983. In addition, the Big Rivers Electric Corporation shipped to the KTRP approximately 100 pounds of field scrubber sludge in sealed containers. That field scrubber sludge was typical of sludge that would be supplied for the experimental project.

AGGREGATES

Two types of aggregate -- DGA (dense-graded limestone aggregate) and pond ash (also called bottom ash) -- were used to prepare sludge-aggregate mixtures. The DGA was obtained from an approved source (Lexington Quarry) and was assumed to meet KyDOH specifications. The pond ash was tested by the Division of Materials, KyDOH. A copy of the Aggregate Test Report is included as Appendix B. The pond ash passed all requirements for a compacted base material except the very coarse particles (plus 3/4 inch) did not meet gradation requirements. Four gradation tests were performed, and a typical gradation curve is shown in Figure 1. All gradation curves are shown in Appendix C. All curves show a disproportionate amount of plus 1-inch material. The large size of the coarse particles is an indication that the pond ash might be more suitable as a subbase material than as a base material. A slake-durability test (Kentucky Method No. KM-64-513) was performed on the pond ash samples. The slake-durability test indicated that pond ash is less durable (95 percent retained) than DGA (usually greater than 99 percent retained) but can still be considered a rock-like material. Durability results also would be an indication that pond ash might be more suitable as a subbase material than as a base material.

MOISTURE-DENSITY RELATIONSHIPS

Moisture-density relationships were developed for scrubber sludge and for sludge-aggregate mixtures. Specimens were compacted by the method described in ASTM C 593 - 76a, with two exceptions: aggregate larger than 3/4 inch but smaller than 1 inch was allowed to better simulate stockpiled aggregate and the small compaction hammer (5.5 pounds and 12-inch drop) was used to better simulate construction compaction efforts.

Moisture-density relationships were found for nine design mixtures. Maximum dry density and optimum moisture content were determined using a polynomial fitting program. A smoothing technique was used to eliminate localized changes in concavity. Mixture designs and results are summarized in Table 2. A typical moisture-density plot is shown in Figure 2. All moisture-density curves are shown in Appendix D. Three mixtures of 100 percent sludge were tested to determine if varying mix proportions would have a significant effect on the moisture-density relationship. There was not a significant difference, so all further testing was based on the typical proportions of 2 percent lime, 25 percent fly ash, and 73 percent filter cake.

SPECIMEN PREPARATION

Specimens were prepared for testing by the method described in ASTM C 593-67a, with exceptions previously noted. Laboratory sludge specimens for strength and modulus testing were

Table 1. Typical Ash Properties of Coals Used at Robert Reid Station, Big Rivers Electric Corporation.

CONSTITUENT	PERCENTAGE BY WEIGHT
Silica	39 - 44
Aluminum and Iron Oxide	40 - 61
Calcium Oxide	4.5 - 6.0
Magnesium Oxide	2 - 3
Sulfate	0.5 - 5.0
Sulfite	0.2 - 1.0

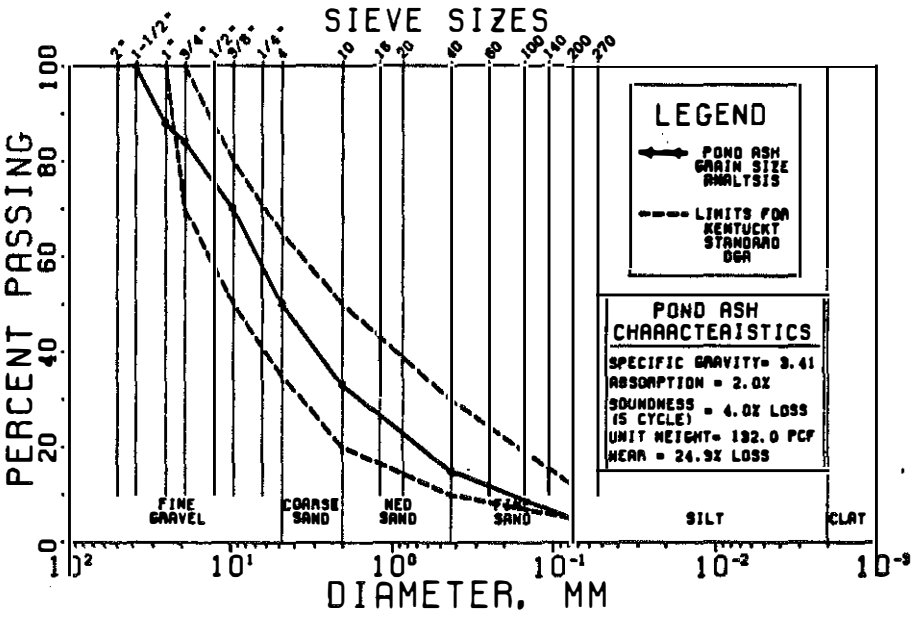


Figure 1. Typical Gradation for Pond Ash from Robert Reid Station and for Dense-Graded Aggregate.

Table 2. Summary of Moisture-Density Relationships.

MIX NO.	COMPOSITION OF SLUDGE* %LIME	%FA	%FC	PERCENT SLUDGE	PERCENT POND ASH	PERCENT DGA	OPTIMUM MOISTURE CONTENT (%)	MAXIMUM DRY DENSITY (pcf)
1	2	20	78	100	-	-	53.3	60.2
2	2	15	83	100	-	-	50.4	62.5
3	2	25	73	100	-	-	50.4	65.2
4	2	25	73	10	90	-	10.3	150.5
5	2	25	73	10	-	90	9.9	133.7
6	2	25	73	15	85	-	11.2	151.4
7	2	25	73	15	-	85	10.9	130.6
8	2	25	73	20	80	-	11.0	132.8
9	2	25	73	20	-	80	11.8	124.9

*FA -- Fly ash
FC -- Filter cake

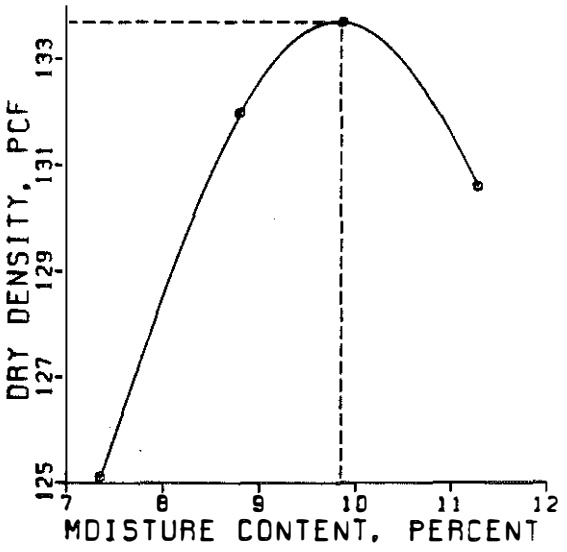


Figure 2. Typical Moisture-Density Relationship.

prepared for the mixes listed in Table 2 as Mixes 3 through 9. Mixes listed as Mixes 1 and 2 were not typical of scrubber sludge available at the Robert Reid Station and were not included in the strength testing phase. Specimens were compacted at the optimum moisture content, as listed in Table 2. All specimens were cured 7 days in sealed cans at 100 degrees Fahrenheit, as described in ASTM C 593 - 76a. Approximately half of the samples were cured at ambient temperatures in sealed containers for an additional 21 days. ASTM C 593 - 76a requires submerging samples for 4 hours prior to compressive strength testing. It was not possible to submerge the sludge specimens, because the specimens began to slake immediately upon submergence. Figure 3 shows a typical specimen of laboratory sludge and DGA after curing for 7 days and after being capped with sulfur mortar in accordance with ASTM C 617 - 76. Figure 4 shows the same specimen after submergence for 15 minutes; Figure 5 shows the specimen after 4 hours. The specimen disintegrated completely, with only material adhering to the capping compound remaining intact. The severe slaking also prevented vacuum saturation or freeze-thaw testing.

Field scrubber sludge from the stockpiles at the Robert Reid Station was delivered to the KTRP. Specimens were compacted with and without pond ash in the as-delivered condition. The specimens were not, therefore, compacted at optimum moisture content, but at the actual field moisture content. Curing conditions included oven curing (as in ASTM C 593 - 76a), ambient curing, and combinations of oven and ambient curing. When submerged, field sludge specimens exhibited much less slaking than laboratory sludge specimens. Although there was a reaction, it was considerably more passive than the reaction shown in Figure 4. Field sludge specimens were not submerged prior to testing in order to provide a better basis for comparisons with laboratory sludge specimens. Two uncompacted specimens also were submerged at the age of 56 days. The samples were 100-percent scrubber sludge and were obtained from the Robert Reid Station's stockpiles in 6-inch diameter concrete cylinder molds in January 1983. Figure 6 shows one of the specimens at an age of 56 days. Uncompacted sludge was not very cohesive, and some of the material crumbled when the specimen was extruded from the cylinder mold (see Figure 6). Figure 7 shows the sample after it had been submerged for 48 hours. There was no appreciable slaking during the 48-hour period.

SAMPLE TESTING

ASTM C 593 - 76a provides specifications for vacuum saturation and compressive strength testing. As previously mentioned, vacuum saturation was not possible due to slaking of specimens when submerged in water. Both compressive strength tests (ASTM C 39 - 72) and splitting tensile strength tests (ASTM C 496 - 71) were performed.

During compressive strength tests, additional information was obtained by measuring deformation with deflection dial gauges. Measurement of axial deformation provided for calculation of modulus of elasticity. A computer program was developed to calculate and plot the static-chord modulus of elasticity from axial load and axial deformation data. ASTM C 469 - 65 describes the static-chord modulus of elasticity and provides an equation for its calculation. To facilitate a computer solution, the modulus was calculated by a four point least-squares fitting technique. The fitted static-chord modulus of elasticity is shown on the stress-strain plots as a dashed line (see Figures 8 through 10). The static-chord modulus of elasticity is important for design considerations and for comparison purposes. The static-chord modulus of elasticity is

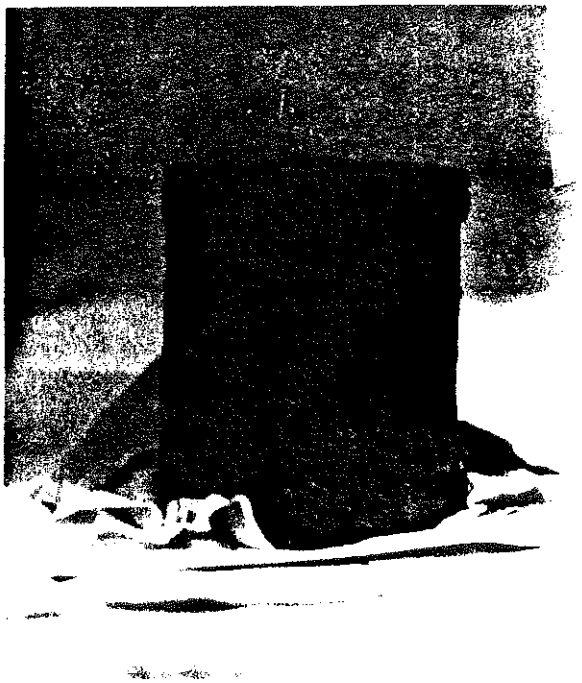


Figure 3. Typical Compressive Strength Specimen.

Figure 4. Specimen after Submergence for 15 Minutes.

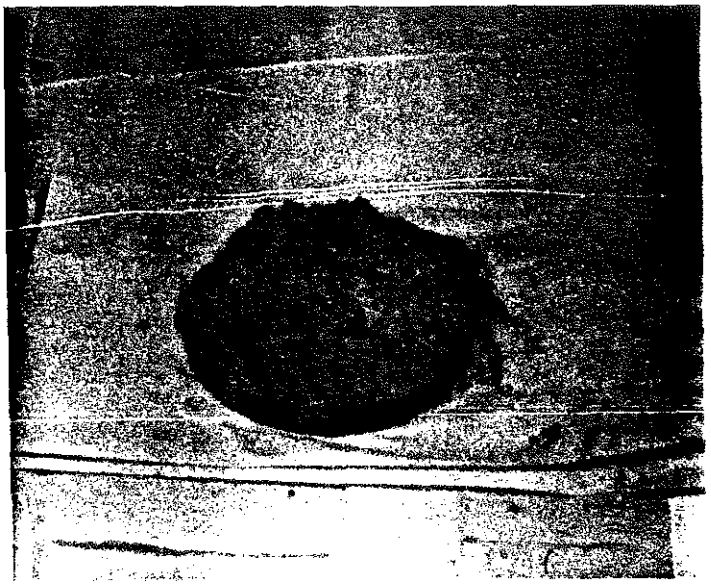


Figure 5. Disintegrated Specimen after 4 Hours (Material Held together by Capping Compound).

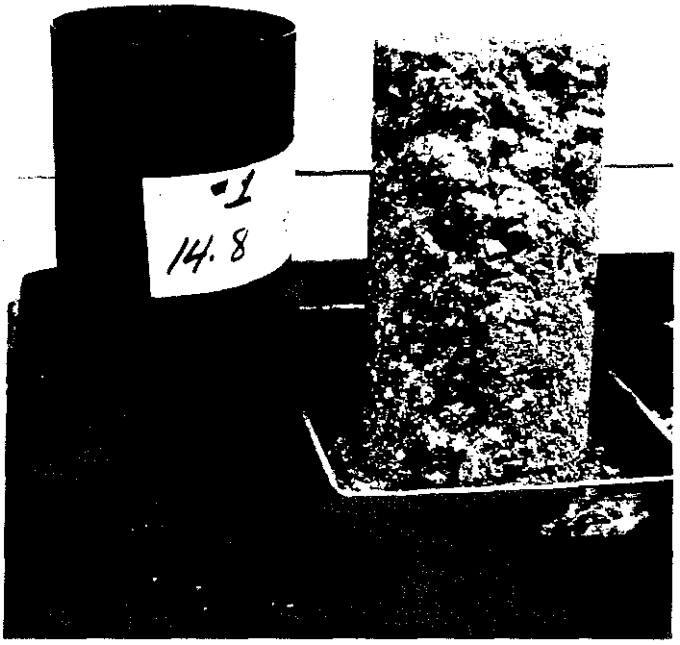


Figure 6. Uncompacted Field Sludge Specimen at 56 Days.

Figure 7. Uncompacted Field Sludge Specimen after Being Submerged for 48 Hours.

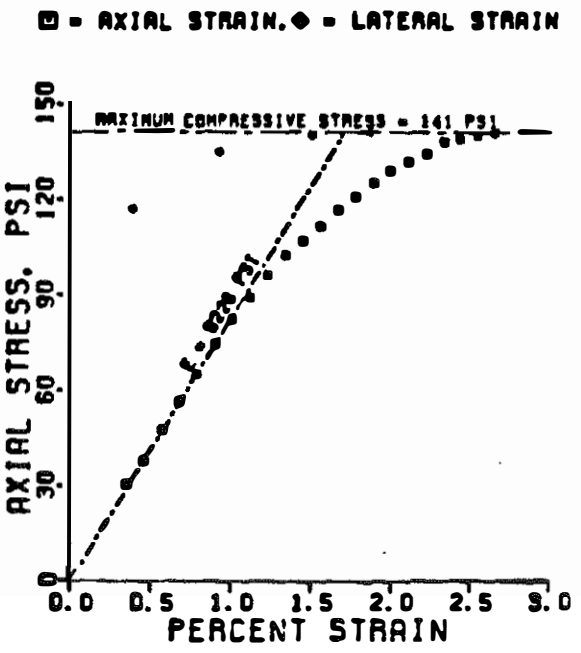


Figure 8. Example of Stress-Strain Plot with Lateral Strain Measured Only in Plastic Region.

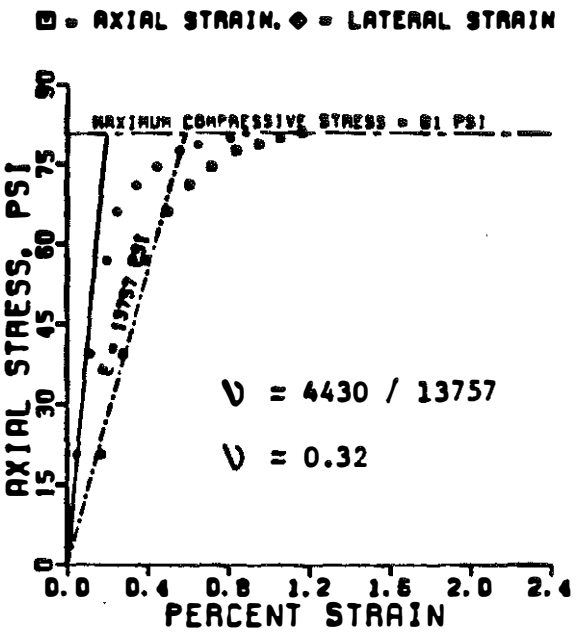


Figure 9. Example of Stress-Strain Curve Showing a Reasonable Approximation of Poisson's Ratio.

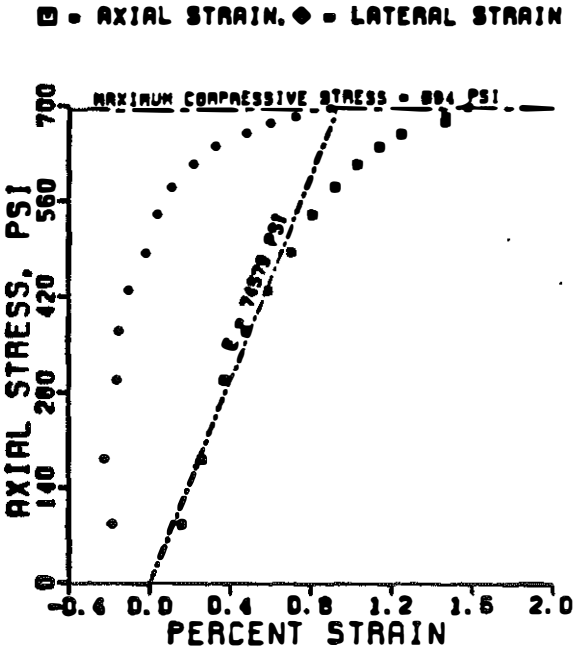


Figure 10. Example of Stress-Strain Curve Showing Incorrect Lateral Strain Data.

not the ultimate (initial tangent) modulus of elasticity. Results of compressive strength and static-chord modulus tests for all samples are presented in Appendix E.

Attempts were made to measure lateral deformation during compressive strength testing for the purpose of determining Poisson's ratio. (For a given stress interval, Poisson's ratio is by definition, the ratio of lateral strain to axial strain.) Poisson's ratio was estimated from the ratio of the slopes of the axial stress-axial strain curve and the axial stress-lateral strain curve. Two methods were used to measure lateral deformation. The first consisted of marking a strip of paper around the specimen; the strip was allowed to expand under loading. This provided reasonable results in the plastic strain region, but was not sufficiently accurate to provide data in the elastic strain region (as shown in Figure 8). A second method used three deflection dial gauges. The dial gauges were located about the mid-height circumference at third points, radiating outward from the centroid. This method produced very erratic results. Although some data appeared accurate, other data obviously were not reliable. An example of data that appeared accurate is shown in Figure 9, with the Poisson's ratio approximately equal to 0.32. Figure 9 also illustrates the method used to approximate Poisson's ratio: curves are drawn through the lateral strain and axial strain data, tangent lines are projected from the curves, the slopes of the lines are measured, and Poisson's ratio is calculated as the ratio of slopes from the axial and lateral stress-strain curves. An example of data that was not accurate is shown in Figure 10, with negative lateral strain values measured during compressive loading. Although this data was not accurate, estimates of Poisson's ratio were still made by considering the slopes between two levels of stress (as shown in Figure 10). A Poisson's ratio of 0.40 was selected for use with elastic layer theory to calculate stresses, strains, and deflections. A value of 0.40 is typically associated with granular bases in Kentucky.

ASTM C 469 - 65 describes a combined compressometer-extensometer that would provide better data for Poisson's ratio estimations. However, the cost of such a device was beyond the scope of this study. Although the reported values of Poisson's ratio must be regarded as crude estimates, they represent data obtained at practically no cost.

Results of testing of laboratory sludge mixtures are listed in Table 3. Results of testing of field sludge mixtures are summarized in Table 4.

OPTIMUM MIX DESIGN

Selection of the optimum mixture design should include both economic and structural considerations. To maximize the utilization of scrubber sludge, a waste product, the optimum mixture design is a one that has a high proportion of scrubber sludge but still produces a high strength and modulus of elasticity. The costs of retrieval and transportation of the sludge may, however, preclude its use on any given project.

Figures 11 through 14 show modulus of elasticity versus unconfined compressive strength for various mixtures. Table 5 summaries useful results from those plots. All mixture types showed a very linear relationship between strength and modulus of elasticity, but scrubber sludge with pond ash mixtures showed much higher strengths and moduli than scrubber sludge with DGA mixtures. In general, the static-chord modulus of elasticity is about 118 times the compressive strength for scrubber sludge-pond ash mixtures.

Figure 15 shows 7-day compressive strength versus percentage of sludge

Table 3. Results from Laboratory Testing of Scrubber Sludge-Aggregate Mixtures.

MIX NO.	AGGREGATE TYPE	AGGREGATE %	AGE (DAYS)	AVERAGE COMPRESSIVE STRENGTH (psi)	AVERAGE MODULUS OF ELASTICITY (psi)	AVERAGE TENSILE STRENGTH (psi)	AVERAGE POISSON'S RATIO	TENSILE TO COMPRESSIVE STRENGTH RATIO (%)	STRENGTH RATIO OF MODULUS TO COMPRESSIVE
3	-	0	7	107	9,508	-	0.28	-	89
			28	207	18,312	-	0.31	-	88
4	PA	90	7	118	11,899	13	0.41	11.0	101
			28	826	77,471	62	0.20	7.5	94
5	DGA	90	7	114	3,910	4	0.35	3.5	34
			28	286	26,124	10	0.37	3.5	91
6	PA	85	7	160	13,478	7	0.23	4.4	84
			28	646	76,632	68	0.33	10.6	119
7	DGA	85	7	189	9,115	6	0.17	3.1	48
			28	275	17,700	12	0.18	4.4	64
8	PA	80	7	196	23,190	12	0.12	6.1	118
			28	617	70,536	9	0.18	1.5	114
9	DGA	80	7	168	11,949	9	0.24	5.4	71
			28	254	19,883	-	0.22	-	78

Table 4. Results from Field Sludge Testing.

AGGR. TYPE	% AGGR.	AGE (DAYS)	AVERAGE COMPRESSIVE STRENGTH (psi)	AVERAGE MODULUS OF ELASTICITY (psi)	AVERAGE POISSON'S RATIO	RATIO OF MODULUS TO COMPRESSIVE STRENGTH (%)
-	0	7 *	71	9,564	0.36	135
-	0	7	98	12,517	0.35	128
PA**	70	7	211	21,321	0.41	101
PA	80	7	264	37,813	0.43	143
PA	85	7	309	40,152	0.37	130
PA	90	7	186	14,553	0.29	78
-	0	28 *	130	17,186	0.32	132
-	0	28	166	25,500	0.33	154
PA	70	28	393	58,306	0.36	148
PA	80	28	560	74,078	0.38	132
PA	85	28	670	77,046	0.25	115
PA	90	28	557	83,856	0.29	151
-	0	62 *	155	25,103	0.36	162

*Does not conform to ASTM C 593 - 76a
(cured in ambient environment only)
**PA -- Pond Ash

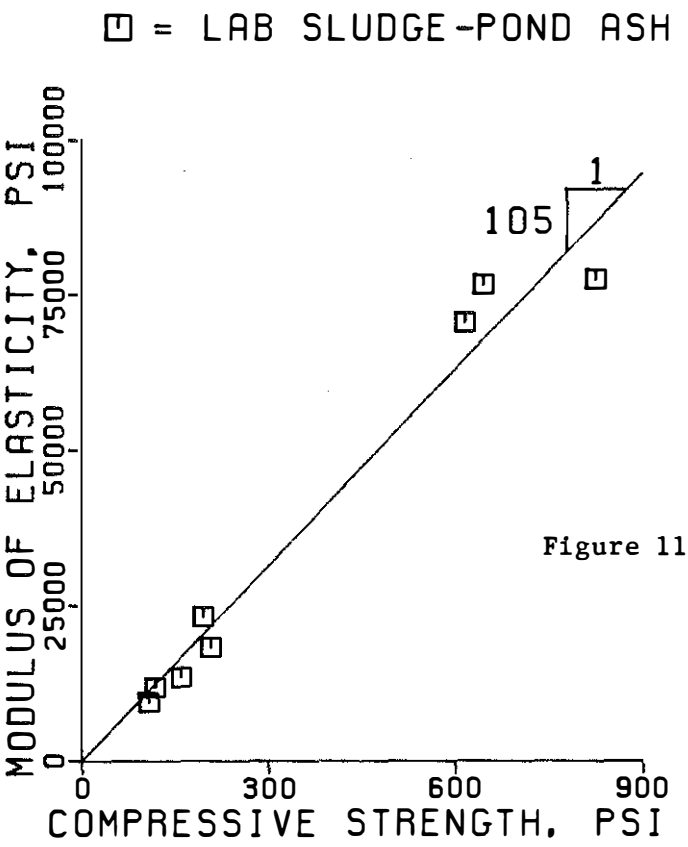


Figure 11. Modulus of Elasticity versus Compressive Strength for Laboratory Sludge with Pond Ash.

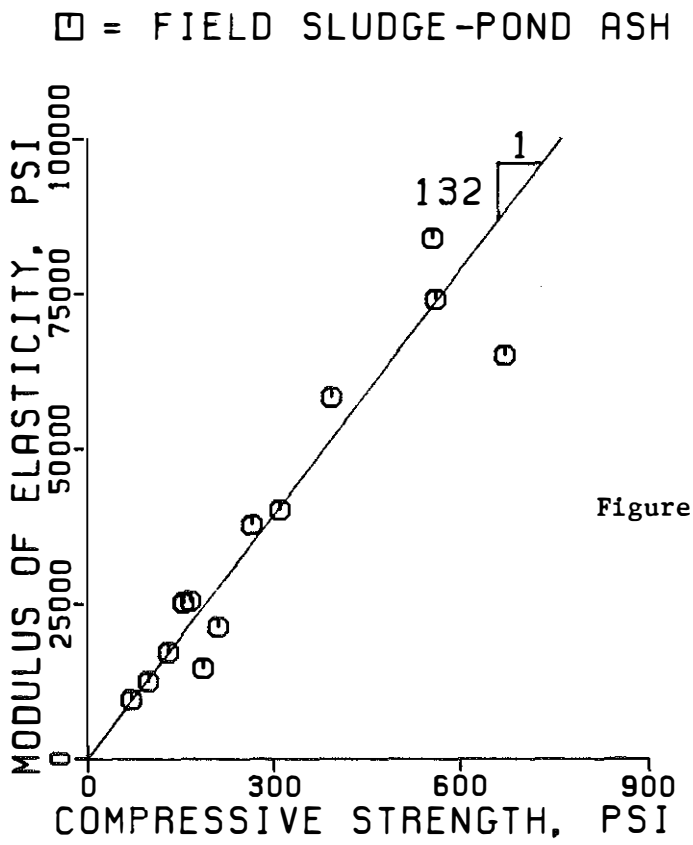


Figure 12. Modulus of Elasticity versus Compressive Strength for Field Sludge with Pond Ash.

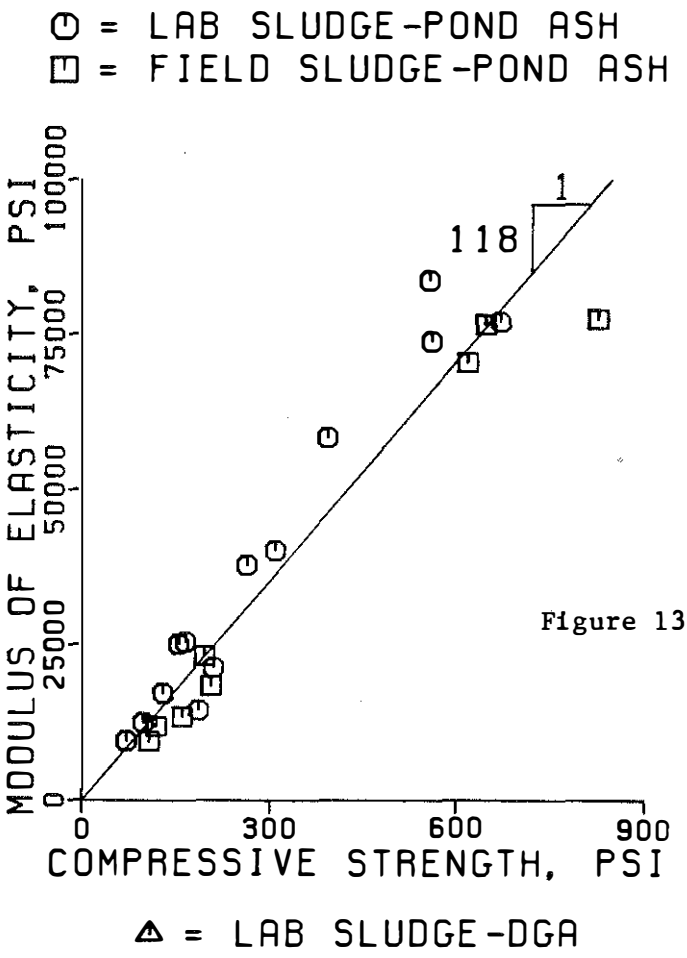


Figure 13. Modulus of Elasticity versus Compressive Strength for All Pond Ash Mixes.

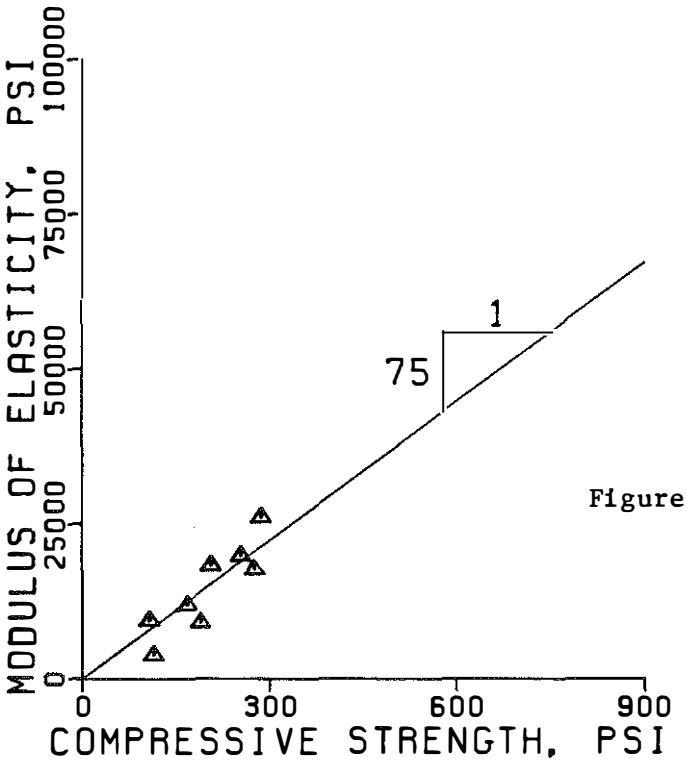


Figure 14. Modulus of Elasticity versus Compressive Strength for Laboratory Sludge with Dense-graded Aggregate.

Table 5. Fitting Data for Plots of Modulus of Elasticity versus Unconfined Compressive Strength.

TYPE OF SLUDGE	TYPE OF AGGREGATE	LEAST-SQUARES EQUATION*	CORRELATION COEFFICIENT
Lab	Pond Ash	E = 105.4 CS	0.987
Field	Pond Ash	E = 131.6 CS	0.983
Lab & Field (Combined)	Pond Ash	E = 118.3 CS	0.973
Lab	DGA	E = 74.7 CS	0.957

*Equations fitted by least-squares method, with equation forced through the origin, so that modulus of elasticity equals zero when unconfined compressive strength equals zero.

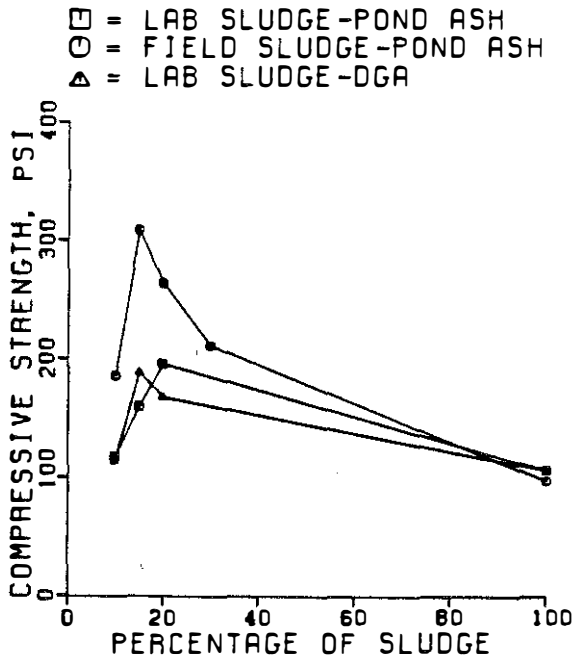


Figure 15. 7-Day Unconfined Compressive Strength versus Percentage Sludge.

for the three mixture types (laboratory sludge with pond ash, field sludge with pond ash, and laboratory sludge with DGA). The field sludge with pond ash produced much higher compressive strengths at 7 days than the other mixtures. All three types showed a decrease in compressive strength as the aggregate was increased from 80-percent to 90-percent. This indicates the sludge matrix is important for the development of early compressive strength.

Figure 16 shows 28-day unconfined compressive strength versus percentage of sludge for three mixture types. Both the laboratory sludge with pond ash and the field sludge with pond ash produced much higher compressive strengths at 28 days than the laboratory sludge with DGA. There was a general trend of increasing compressive strength at 28 days with increasing percentage of pond ash for both laboratory sludge and field sludge mixtures. In contrast, the addition of DGA to the laboratory sludge did not significantly improve the 28-day compressive strength.

Figure 17 shows 7-day static-chord modulus of elasticity versus percentage of sludge for the three mixture types. The sludge with pond ash showed higher modulus of elasticity at 7 days than the sludge with DGA. All three types showed a decrease in modulus as the aggregate was increased from 80 percent to 90 percent. That also indicates the sludge matrix is important for the development of early modulus of elasticity and is consistent with observed performance on the basis of compressive strength analyses.

Figure 18 shows 28-day modulus of elasticity versus percentage of sludge for the three mixture types. The sludge with pond ash showed higher modulus of elasticity at 28 days than the sludge with DGA. There was a general trend of increasing modulus of elasticity at 28 days with increasing percentage of pond ash for both laboratory sludge and field sludge. In contrast, there was little improvement in 28-day modulus of elasticity with increasing percentage of DGA.

Based on observations summarized by Figures 15 through 18, DGA does not appear to be as good an aggregate for use with scrubber sludge as Pond ash. The relative variations of performance containing DGA and scrubber sludge compared with mixtures containing pond ash and scrubber sludge cannot be explained at this time. Therefore, the optimum mixture design, based on this study, involves a mixture of scrubber sludge and pond ash. However, to completely define an optimum mixture design, it is necessary to assign optimum percentages of sludge and pond ash. As previously discussed, a high percentage of pond ash is necessary to produce high compressive strength and modulus of elasticity at 28 days. Also, a significant percentage of scrubber sludge is necessary to insure early gains in compressive strength and modulus of elasticity (important for construction considerations). To consider both effects, the data were normalized by setting the maximum point on each curve equal to 100 percent and expressing each data point as a percentage of the maximum.

Figure 19 is a plot for laboratory scrubber sludge with pond ash. It shows normalized values for 7-day and 28-day unconfined compressive strength and for 7-day and 28-day modulus of elasticity. Those curves illustrate the trends that have been discussed.

Figure 20 is a plot for field scrubber sludge with pond ash. It shows normalized values as in Figure 19. The field sludge and pond ash curves were not conclusive.

Figure 21 shows all the normalized data points for both laboratory sludge with pond ash and field sludge with pond ash. Average normalized values were

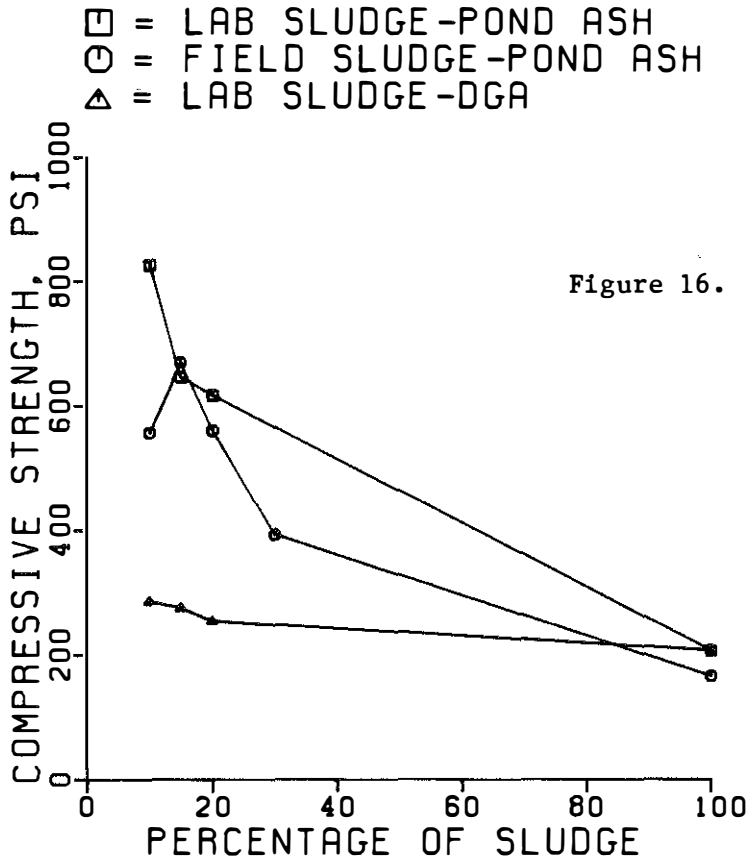


Figure 16. 28-Day Unconfined Compressive Strength versus Percentage Sludge.

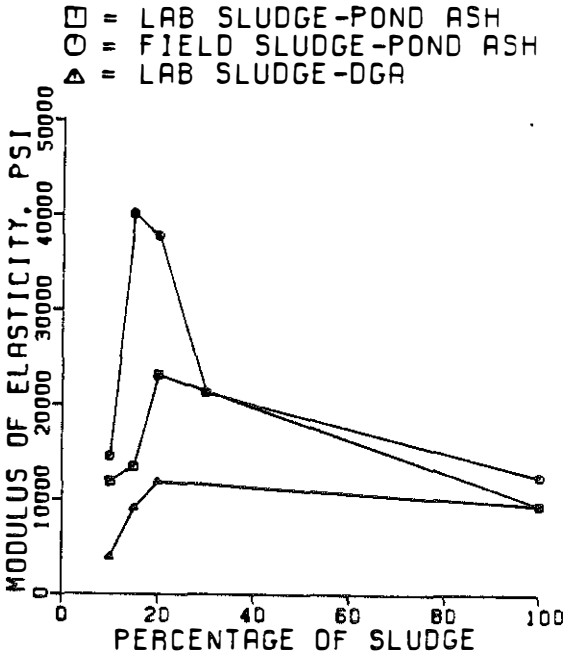


Figure 17. 7-Day Modulus of Elasticity versus Percentage Sludge.

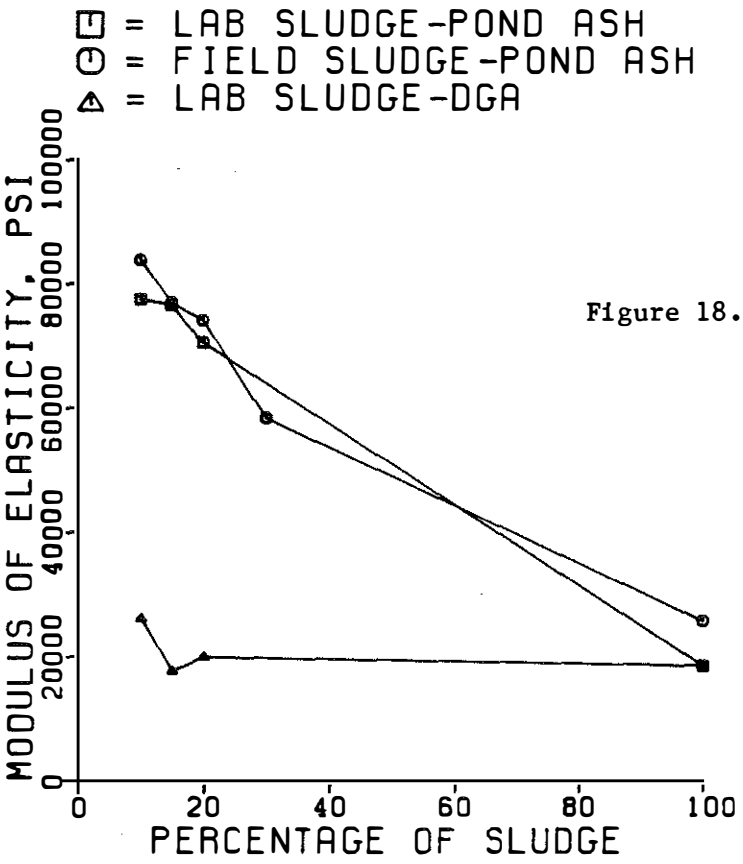


Figure 18. 28-Day Modulus of Elasticity versus Percentage Sludge.

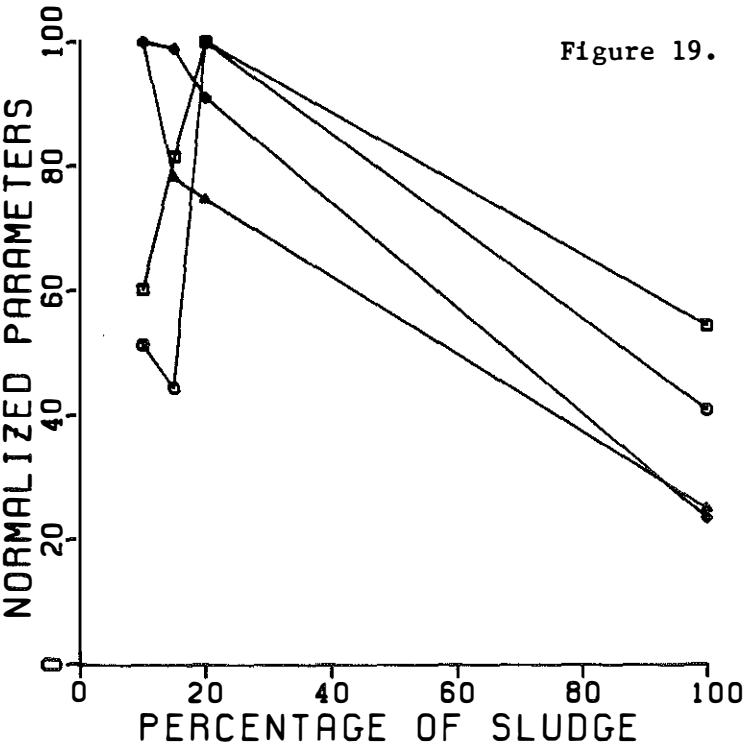


Figure 19. Normalized Parameters for Laboratory Scrubber Sludge with Pond Ash.

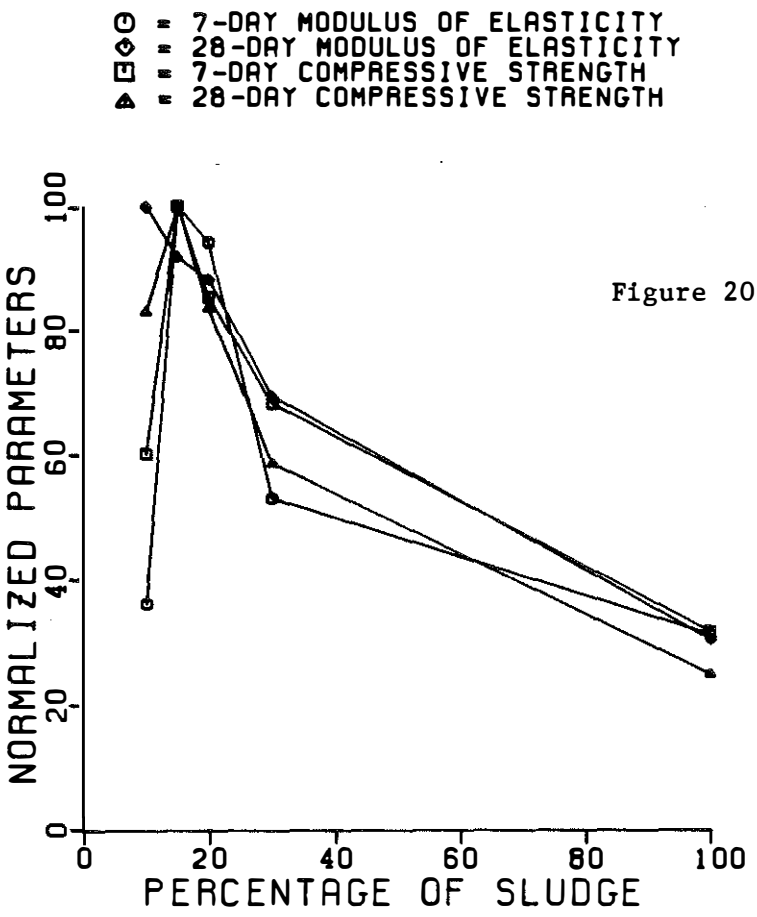


Figure 20. Normalized Parameters for Field Scrubber Sludge with Pond Ash.

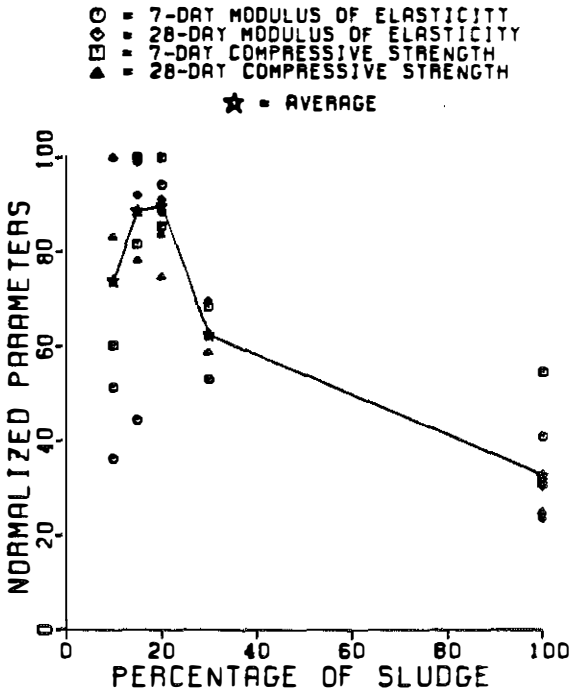


Figure 21. Normalized Parameters and Composite Curve for All Mixtures of Scrubber Sludge with Pond Ash.

plotted for 10, 15, 20, 30, and 100-percent sludge to form a composite curve. The composite curve gave equal weight to laboratory sludge and field sludge, compressive strength and modulus of elasticity, and 7-day and 28-day values. The composite curve peaks at 20-percent sludge. However, there is only a slight drop for the 15-percent sludge mixture. The decrease for 30 percent sludge is significant. Based on the composite curve, the mixture of 20-percent scrubber sludge with 80-percent pond ash was chosen as the optimum design mixture because it maximized the amount of scrubber sludge used without a significant loss of structural properties.

OTHER DESIGN CONSIDERATIONS

MATERIAL PROPERTIES

The tensile strength of the mixtures was low (only about 5-percent) in comparison to the compressive strength. This is a strong indication that scrubber sludge mixtures would serve best as a subbase material.

The compacted laboratory sludge mixtures slaked badly when submerged at 7 days and at 28 days. Uncompacted field sludge specimens slaked very little when submerged at 56 days. It appears that resistance to slaking may be related to the lag time associated with stabilization of the sludge (filter cake, fly ash, and water) with lime. All specimens were more resistant to slaking as they aged. Therefore, slaking is probably a short-term problem. Special care should be taken to protect the material after placement until it develops sufficient cohesiveness to resist slaking.

The most serious implication of slaking is the possibility of leaching. Leaching could reduce the strength of sludge layers and could possibly cause some contamination of ground water. To minimize those effects, sludge mixtures should be used in a trench design with no daylighting. This is an even stronger reason for using these mixtures only as subbase material.

Another design consideration is the possible reactivity of the scrubber sludge materials. A number of laboratory scrubber sludge specimens were made without sieving components. Those specimens could not be tested because small lumps of lime were so reactive they caused pop-outs when cured at 100 degrees Fahrenheit. A typical specimen with pop-outs is shown in Figure 22. Subsequent samples of laboratory scrubber sludge had all components (except aggregate) passing a No. 16 sieve. Although this prevented violent reactions (as in Figure 22), all sludge mixtures gave off a strong odor during curing. It appeared that sulfur was being driven off. The fumes appeared to act as an irritant. This should be considered in field use, but might not be a problem, as the open air would permit rapid dissipation of fumes. The specimens also gave off heat during the mixing process, indicating rapid hydration of the lime. Field sludge samples did not react in the violent manner of the laboratory sludge, although lumps of lime were clearly visible. The excess quicklime (calcium oxide) in the scrubber sludge probably reacted in the stockpile to form hydrated lime (calcium hydroxide). This also may relate to the decomposition of samples when submerged in water, as previously discussed.

PAVEMENT THICKNESS DESIGN

Design procedures in Kentucky currently are based on elastic layer theory to determine pavement thickness requirements. Flexible pavement designs are based upon limiting strain criteria at the top of the subgrade and at the bottom of the asphaltic concrete (Havens et al., 1981; Southgate et al., 1981).

The Kentucky flexible pavement design

curves (Southgate et al., 1981) were used to determine thickness requirements for 7,600,000 equivalent axleloads (EAL) and California Bearing Ratio (CBR) 5 subgrade (modulus of 7.5 ksi). The resulting conventional design thickness was 8.5 inches asphaltic concrete over 17.0 inches dense-graded limestone aggregate. The Chevron N-layer computer program (Michelow, 1963) was used to compute critical strains for a matrix of combinations of layer thicknesses for asphaltic concrete, dense-graded limestone aggregate base, and scrubber sludge-aggregate base for the same "design" conditions. All strain calculations were determined for an 18,000-pound axleload. Details of such procedures are presented elsewhere (Sharpe et al., 1984).

The Chevron N-layer computer program requires layer thicknesses and modulus and Poisson's ratio for each layer as input in addition to load for calculation of stresses, strains, and deflections. A summary of input parameters is presented in Table 6.

Experience in Kentucky, has indicated a design modulus of elasticity of 480 ksi is appropriate for asphaltic concrete. Experience also has indicated the modulus of elasticity of a granular base is a function of the moduli of the confining layers. For this design situation, the confining layers are asphaltic concrete on top and scrubber sludge-aggregate mixture on the bottom. Estimation of the modulus for a crushed stone layer constructed on a conventional subgrade layer is determined as the product of the modulus of the subgrade and a proportionality constant; there is an inverse relationship between log of the proportionality constant and log of subgrade modulus. The ratio of the modulus of crushed stone to that of the subgrade is equal to 2.8 at a CBR of 7 and to 1 when the moduli of asphaltic concrete, crushed stone base, and subgrade are all equal (Havens et al., 1981; Sharpe et al., 1979), the case of a Boussimesq semi-infinite half space. Laboratory triaxial testing also has indicated variations in modulus as a function of confining pressure (Allen, 1978). Modulus of the subgrade (in psi) can be approximated by the product of CBR and 1500. The confining effect of a scrubber sludge-aggregate layer were not completely determined at the time of design; therefore, it was decided to use the same design modulus for the crushed stone layer when placed between asphaltic concrete and scrubber sludge-aggregate mixture as between asphaltic concrete and subgrade. This, however, is likely a conservative estimate.

The design modulus for the scrubber sludge-aggregate mixture was somewhat arbitrarily selected at 18 ksi and is representative of the weakest modulus determined for 7-day specimens for any of the mixtures containing 20 percent scrubber sludge. Specimens were prepared according to ASTM C 593. Estimates of elastic modulus were determined using the static-chord method in ASTM C 469.

The 7-day compressive strength associated with the design modulus of elasticity (18 ksi) is 150 psi (see Figure 13). A review of Figures 15 through 18 demonstrate the significant conservatism associated with the selection of the design modulus and associated compressive strength. In all examples, the design modulus and associated compressive strength are significantly less than observed moduli or compressive strengths for both laboratory and field mixtures containing 20 percent scrubber sludge and 80 percent pond ash aggregate. The values were selected because of uncertainties associated with long-term durability of the subbase. Favorable performance and serviceability of experimental pavement structures will provide more definitive information relating to selection of design strengths.

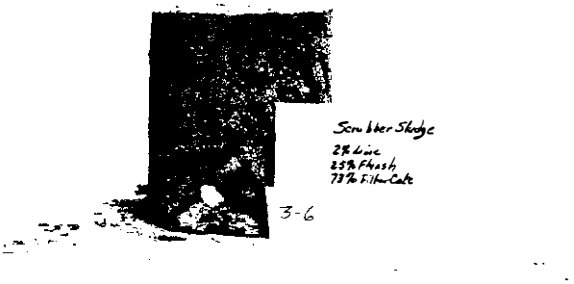


Figure 22. Pop-outs Caused by Reaction of Small Lumps of Lime.

Table 6. Summary of Design Moduli and Poisson's Ratios.

MATERIAL	MODULUS (psi)	POISSON'S RATIO
Asphaltic Concrete	480,000	0.40
Dense-Graded Limestone Aggregate	23,000	0.40
Scrubber Sludge - Aggregate Mixture	18,000	0.40
Subgrade	7,500	0.45

Critical strains determined from theoretical calculations using the Chevron N-layer program were used in combination with limiting strain criteria (Havens et al., 1981; Sharpe et al., 1984) and calculated critical strains for the conventional design (determined from Kentucky flexible design curves (Southgate et al., 1981)) were used to develop the relationship for structurally equivalent designs in Figure 23.

For this particular design situation, strains at the top of the subgrade were most critical. Therefore, Figure 23 was developed on the basis of equal vertical compressive strains at the top of the subgrade. Specifics relating to development of Figure 23 are presented elsewhere (Sharpe et al., 1984). The lines on Figure 23 represent structurally equivalent designs for various thicknesses of scrubber sludge-aggregate mixtures substituted for all or a portion of the dense-graded limestone aggregate base or a combination of dense-graded aggregate base and asphaltic concrete base.

Figure 23 was developed for a particular construction project and represents structurally equivalent designs for one fatigue value (EAL = 7,200,000) and one subgrade support (CBR = 5). However, similar relationships can be determined for other fatigue loading levels and for other subgrade supports.

ECONOMIC CONSIDERATIONS

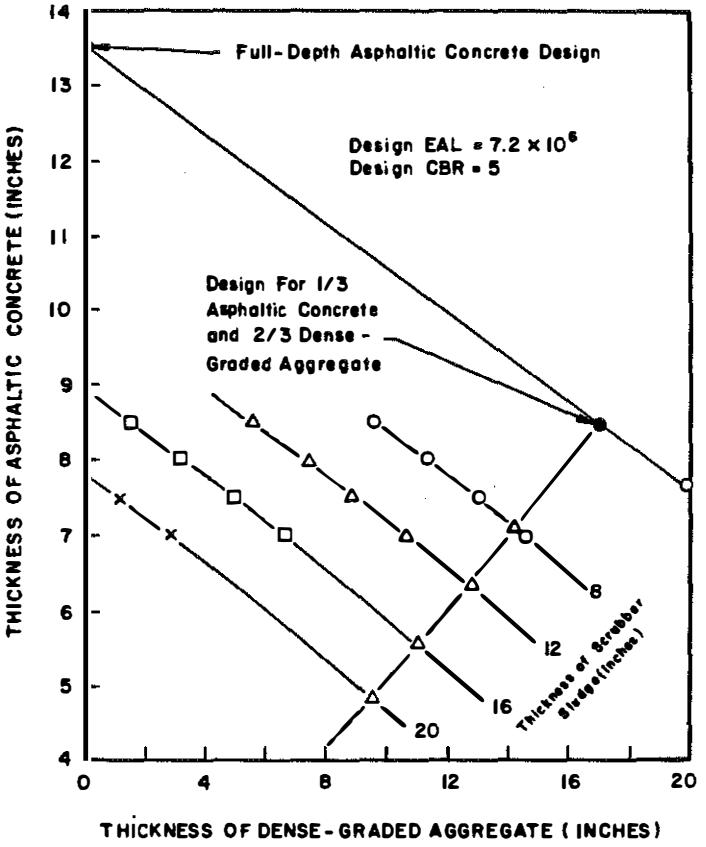
For economical utilization of scrubber sludge, it is essential to have a source of material near the project. Officials of the Robert Reid Station at Sebree, Kentucky, agreed to supply materials at no cost. The only costs to be incurred for the proposed project involve transportation and placement costs. Use of scrubber sludge would not be economical for areas where it is not available as a waste product.

Transportation and blending costs were estimated in the interim report for various experimental designs (see Appendix A). The cost was estimated at $1.75 per ton. On October 20, 1983, KTRP received a copy of a memorandum indicating that the actual unit bid was for $6.50 per ton. That represents a considerable increase in the cost per mile. For example, for Alternate Design 3 (6-1/2 inches of asphaltic concrete, 8 inches of DGA, 16 inches of scrubber sludge-pond ash, CBR 5) the cost (for paving materials only) would increase from $199,408 to $258,262 per mile. The savings per mile compared with conventional flexible pavement design would decrease from $85,558 per mile to $26,704 per mile; there also is an increase in cost of $17,811 per mile compared to the full-depth asphaltic concrete alternate. Even with a significant increase in the unit cost of sludge mixtures, the alternate designs are still competitive. There is a high probability that the unit bid is inflated by uncertainty about use of a new material. It is also probable that the unit price will decrease if the material is used successfully in an experimental project.

Cost savings from use of scrubber sludge mixtures result from reduction in thickness of more expensive base and surface courses. It is likely that the most economical use for scrubber sludge would be for a low-fatigue road. For low-fatigue situations, a larger percentage of the base and/or surface could be replaced by scrubber sludge without detrimental effects.

CONSTRUCTION OF EXPERIMENTAL SUBBASE

Construction of the experimental pavement system utilizing a scrubber sludge-aggregate mixture was begun July 1984 and completed October 1984. Construction procedures and research evaluations are summarized below.



Thickness design curves utilizing scrubber sludge and pond ash-type materials.

Figure 23. Thickness Design Curves (Scrubber Sludge and Pond Ash Mixture as a Subbase).

SOURCES OF MATERIAL

Scrubber sludge was obtained from stockpiles at the Robert Reid Station in Sebree, Kentucky. The scrubber sludge was not stockpiled for more than 3 days prior to blending with aggregate for placement on the roadway.

Pond ash from the Robert Reid Station was used as the aggregate. Prior to construction, the pond ash was removed from sedimentation ponds, stockpiled, and allowed to dewater naturally. A typical pond ash gradation curve and other properties are shown in Figure 1.

PRE-CONSTRUCTION TESTING

Prior to construction, samples were obtained from stockpiles of scrubber sludge and pond ash. The samples were tested for moisture content by ASTM D 2216 - 71. Target values of optimum moisture content and maximum dry density were obtained by compacting a mixture of 80 percent pond ash and 20 percent scrubber sludge. The compaction test was performed as described in ASTM D 698 - 78, with the exception that the materials were not oven dried prior to mixing. The natural moisture content of the materials was accounted for so the dry-weight equivalent mixture was an 80-20 blend.

BLENDING OF MATERIALS

It was originally planned to use belt feeders and a pug mill to blend the scrubber sludge-pond ash mixture to desired proportions. Laboratory proportioning was on the basis of equivalent dry weights. The design mixture proportion was 80 percent pond ash and 20 percent scrubber sludge by weight.

The scrubber sludge in its stabilized condition was so cohesive it would not feed properly with the available equipment. To facilitate blending, an alternate method was used. The materials were proportioned by volume and mixed on the ground by front-end loaders. The final mixture was obtained by feeding the blend into an unheated conventional asphalt plant mixer and adding water to obtain the optimum moisture content. Although this produced a more uniform mixture, it still did not seem to be completely homogeneous. Sludge seemed to form pockets in the mixture, although this was not readily verifiable. The blending process is illustrated by Figure 24.

PLACEMENT OF MATERIALS

The scrubber sludge-aggregate subbase was placed using conventional equipment normally used for the placement of dense-graded aggregate base. Scrubber sludge-aggregate material was placed in three lifts of 4 to 6 inches each for a total depth of 16 inches. Density and moisture content were monitored, and the moisture added at the plant was modified as necessary to provide the optimum moisture content. Material near the surface of each lift dried quickly, producing discontinuities in the homogeneity of the subbase course. There were pockets of almost pure scrubber sludge, which has a much higher water-holding capacity. Long after the majority of the surface had dried, those pockets of sludge were very moist and appeared very slick and workable. However, the material as a whole was workable and seemed to have the expected design characteristics when compacted. The placement process is illustrated by Figure 25.

DATA COLLECTED DURING CONSTRUCTION

Nuclear density meters were used routinely to determine in-place densities and moisture contents for comparison with laboratory-determined target values; field results compared favorably with laboratory target values. Samples were obtained from the field and returned to the laboratory for more extensive testing and analyses, which are not yet completed.

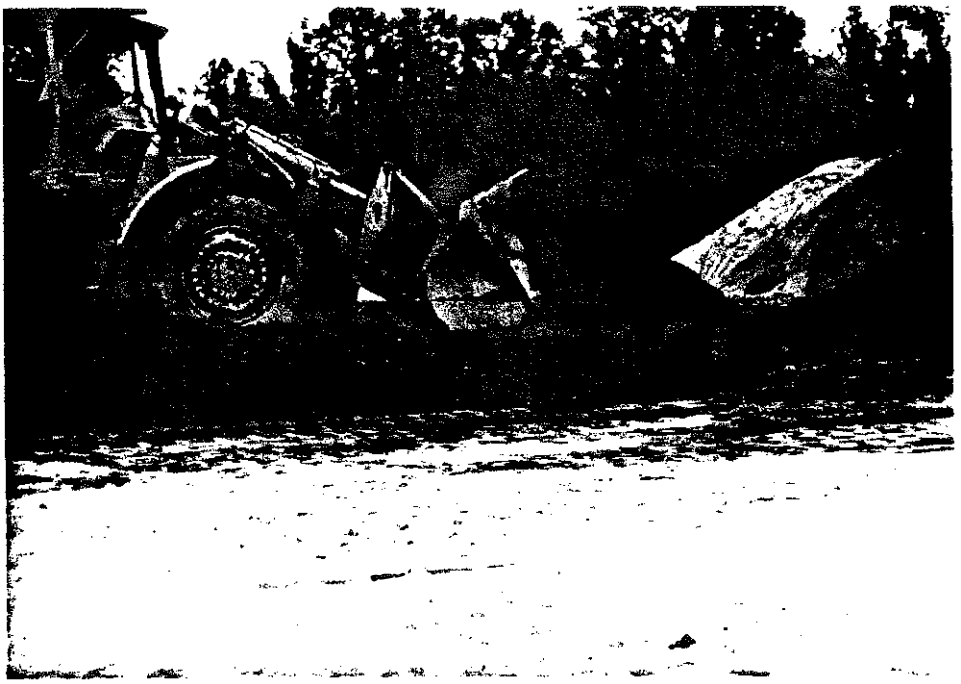


Figure 24. Blending of Scrubber Sludge and Pond Ash.

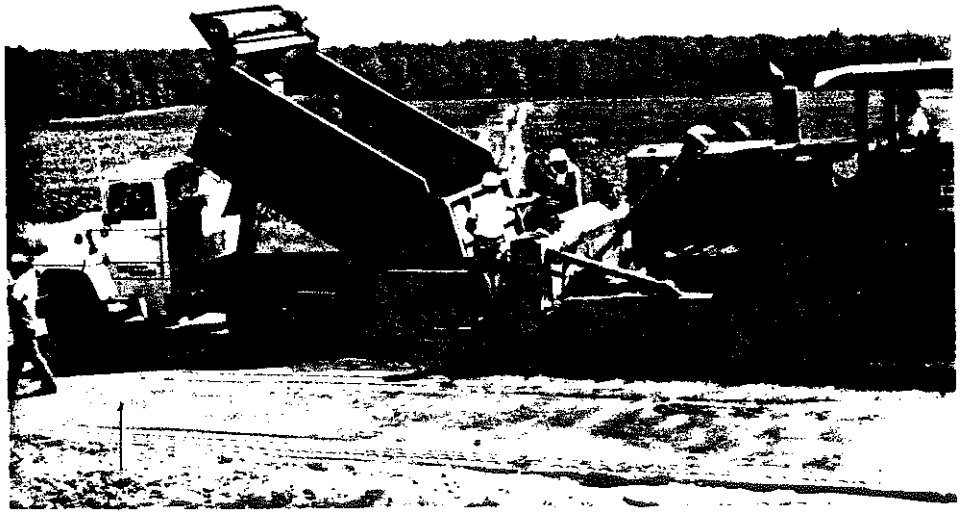


Figure 25. Placement of Scrubber Sludge-Pond Ash Mixture.

Photographs documenting all phases of the construction activities also were obtained. Additionally, deflection measurements were obtained directly on the subgrade, on the scrubber sludge-aggregate subbase, and on the compacted dense-graded limestone aggregate base. Deflection measurements on the completed asphaltic concrete pavement will be obtained in the spring of 1985. A summary of deflection measurements are presented in Table 7. Analyses of deflection data are not yet completed. Deflection data will be used to "back calculate" the effective modulus of elasticity for the various layers of the pavement structure using procedures presented elsewhere (Sharpe et al., 1979; Sharpe et al., 1981; Sharpe et al., 1984).

EMBANKMENT ANALYSES

Nine isotopically consolidated-undrained triaxial tests with pore-pressure measurements were run on scrubber sludge specimens (three tests on each of three mixtures) 4 inches in height and 2 inches in diameter. The specimens were compacted at optimum moisture using the compactive effort of ASTM D 698 - 78 and immediately placed in the test chamber without curing. The specimens were then consolidated overnight under the chosen confining pressure. After consolidation, the specimens were loaded to failure (time of test approximately 20 hours) at an average strain rate of 0.014 percent per minute.

Specimens apparently continued to hydrate while in the test chamber. Very little volume change occurred during consolidation, indicating a stiff specimen. Also, stress-strain curves were very "rough" after reaching a peak (failure), indicating a number of localized brittle failures and slips typical of stiff materials. A typical stress-strain curve is shown in Figure 26. All stress-strain curves are shown in Appendix F.

Figure 27 is an example of the effective stress paths. All effective stress path plots are shown in Appendix F. The internal friction angle may be calculated from $\phi' = \arcsin(\tan \alpha)$, in which α is defined as illustrated in Figure 28. Cohesion, c', is the y-intercept of the K_f-line, d, divided by the cosine of ϕ'. The ϕ' values were 41.8 degrees, 40.5 degrees, and 40.7 degrees for Mixtures 1, 2, and 3, respectively. Cohesion values were 0, 7.1, and 5.8 pounds per square inch, respectively. Others have demonstrated similar results for these analyses (Cowherd and Kazmi, 1982).

To determine the effect of moisture content on shear strength properties, three triaxial tests were run on specimens compacted approximately three percent wet of optimum (Mixture 3). It appeared that shear strength was not appreciably affected by moisture contents within two or three percent of optimum, when the material was compacted. Again, added strength from hydration may tend to negate any strength differences due to small changes in moisture content. However, this may not be true for large moisture variations from optimum.

Because strength parameters for all tests were very similar, the results were combined into one plot (Figure 28) to determine a "collective" internal friction angle to be used in stability analyses. The resulting internal angle of friction was 40.8 degrees and the cohesion was 6.1 pounds per square inch. Often, when a slide occurs in an over-consolidated clay or brittle material such as these mixtures, a tension crack will form on the active or "driving" side of the slide. When that occurs, the cohesion will be zero. Therefore, when making stability analyses for this study, cohesion was assumed to be zero.

Sludge material taken from the stockpile without laboratory processing (field sludge) also was tested.

Table 7. Summary of Deflection Measurements.

	DEFLECTIONS (10^{-5} inch)											
	ON TOP OF SUBGRADE SENSOR NO.				ON TOP OF SLUDGE SENSOR NO.				ON TOP OF DGA SENSOR NO.			
MP	1	2	3	4	1	2	3	4	1	2	3	4
127	281	170	102	68	338	302	272	229	124	74	46	36
122	234	62	36	24	324	293	263	231	94	43	25	14
117	255	112	48	56	329	300	230	194	162	78	42	24
112	103	38	17	11	254	232	218	212	---	---	---	---
107	154	48	26	20	263	238	221	207	110	70	45	24
102	195	112	72	44	255	242	224	205	87	39	23	16
97	116	51	33	24	251	236	222	204	88	47	15	5
92	409	140	47	24	260	236	217	203	116	36	13	4
87	272	143	57	45	260	249	228	206	101	52	34	16
82	270	132	106	79	263	243	225	206	71	28	18	R*
77	361	150	53	24	257	239	223	206	66	21	12	5
72	366	224	150	116	269	249	228	207	104	43	29	26
67	288	136	91	69	266	247	227	210	96	43	26	18
62	187	41	12	13	256	235	212	194	73	25	12	8
57	131	37	19	14	257	241	218	209	74	24	11	7
52	221	114	74	46	269	248	226	230	94	44	28	17
47	458	160	60	35	269	248	227	224	70	38	26	18
42	255	113	69	44	266	245	227	223	55	31	21	16
37	305	129	65	39	267	249	227	224	75	38	28	20
32	705	380	110	70	329	310	281	267	118	60	36	26
27	448	193	68	45	274	251	228	215	86	42	24	16
Mean	286	128	62	43	275	254	231	212	93	44	26	15

* Sensor in a resonant condition

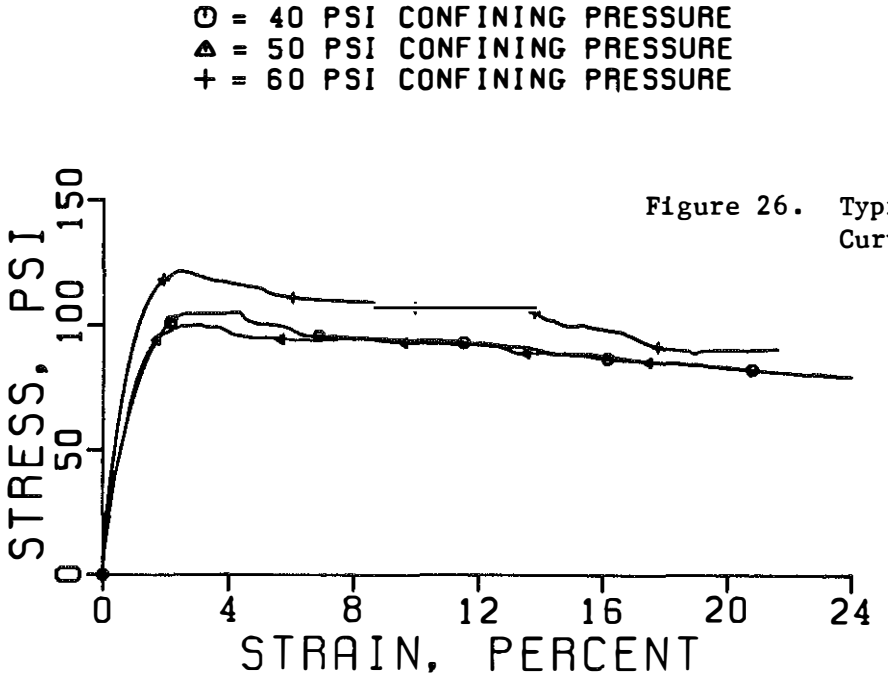


Figure 26. Typical Stress-Strain Curves from Triaxial Tests.

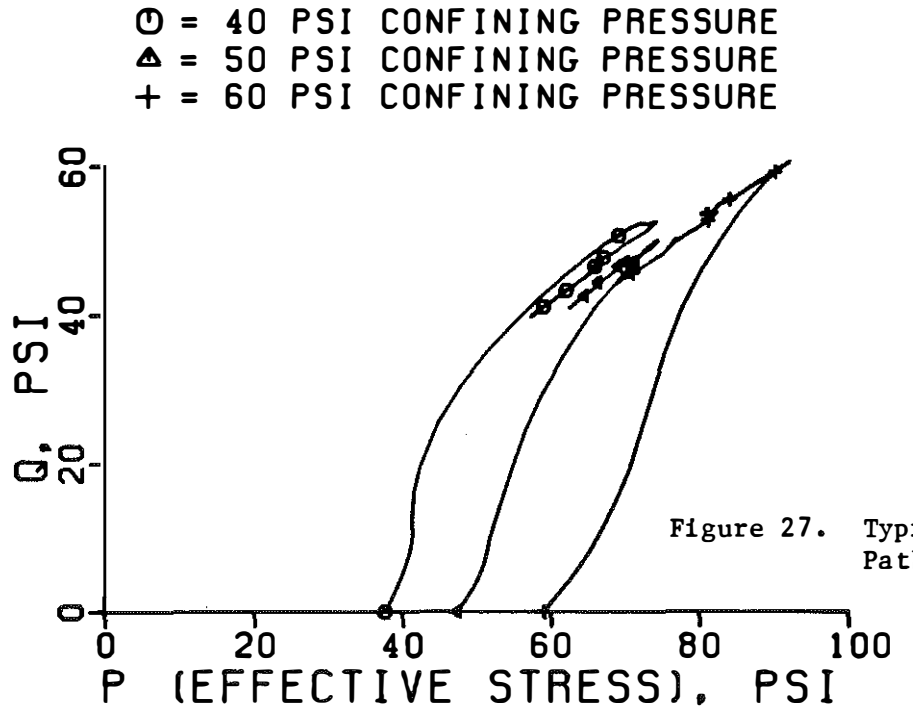


Figure 27. Typical Effective Stress Paths from Triaxial Tests.

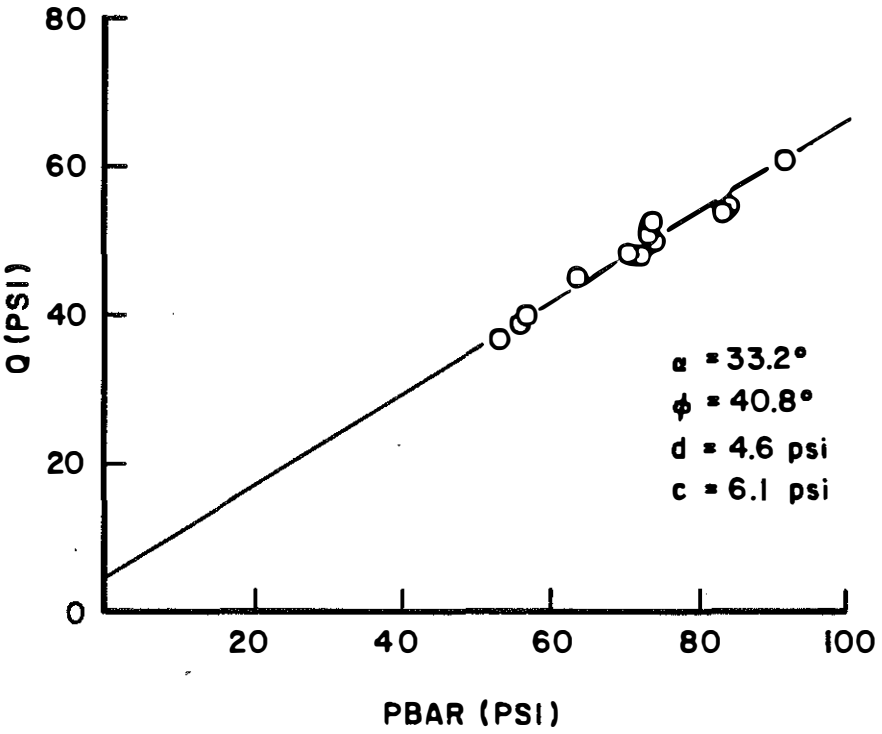


Figure 28. Combined Effective Stress Parameters for Three Mixtures Using the Peak Point from Each Stress Path.

Although the c' values for the three tests were different, the ϕ' values were approximately the same (average ϕ' = 39.9 degrees). That compared well with the combined ϕ' value of 40.8 degrees for the laboratory mixtures.

A typical embankment cross section is illustrated by Figure 29. Other cross sections analyzed for this study are presented in Appendix G. Table 8 summarizes input parameters and resulting safety factors. Slope stability analyses were completed using Bishop's simplified method of slices (Bishop, 1955). Each embankment consisted of scrubber sludge with 2 feet of soil cover. The side slopes of the soil cover were flatter than the side slopes of the scrubber sludge core. A soil cover is required by the Kentucky Natural Resources and Environmental Protection Cabinet. In all analyses, the soil cover was assumed to have an internal friction angle of 28 degrees and zero cohesion. The unit weight was assumed to be 115 pounds per cubic foot. For the scrubber sludge, an average value of 63 pounds per cubic foot was used as the unit weight. Analyses were performed for both high and low water tables and for both rigid and compressible foundations.

Case 1 was a scrubber sludge core 18 feet high, 60 feet wide at the top with side slopes that were 2 feet horizontal to 1 foot vertical (2:1). The side slopes of the soil cover were 3:1. It appeared from these analyses that an embankment having a soil cover on a 3:1 side slope would be marginal (factor of safety less than 1.5) under high water conditions with failure occurring within the soil cover. However, if the water table could be maintained below the embankment level, it appeared the embankment with 3:1 side slopes may be a viable design. If the water table rises slightly above the level used in Analysis 1A, the factor of safety falls to less than 1.0. Again, failure would occur in the soil cover.

Case 2 was a scrubber sludge core 18 feet high, 60 feet wide at the top, with side slopes that were 2.5:1. Side slopes of the soil cover was 3.5:1.

Case 3 was a scrubber sludge core with side slopes of 3:1 and a soil cover with side slopes of 4:1. As in Case 1, the embankment was 60 feet across the top and the scrubber sludge core was 18 feet in height.

Cases 4 and 5 were similar to Cases 1 and 3, respectively, except the height of the scrubber sludge core was 38 feet.

A summary of all analyses is given in Table 8. Most critical arcs were shallow slips through the earth cover. However, when using a compressible foundation and a high water table, the critical arcs passed through the sludge core and foundation. That occurred only when the side slopes of the earth cover was 3.5:1 or 4:1. When the earth cover side slopes were 3:1, shallow slips in the cover still prevailed.

It is recommended that embankments 20 feet or less in height be constructed with side slopes on the earth cover no steeper than 3.5:1. For embankments over 20 feet, side slopes should be 4:1 or flatter. This recommendation is based upon information shown in Figure 29. Analysis 5C had a factor of safety of 1.42, which is considered marginal (less than 1.5). Therefore, any side slope steeper than 4:1 will, undoubtedly, yield a factor of safety even lower, making the design unacceptable. These recommendations are based on the assumptions of a high water table and that the material will be placed with moisture contents near optimum and with unit weights near the laboratory maximum dry density.

It should be noted that use of scrubber sludge as an embankment material would only be economical when suitable fill material was not available at or near the fill site.

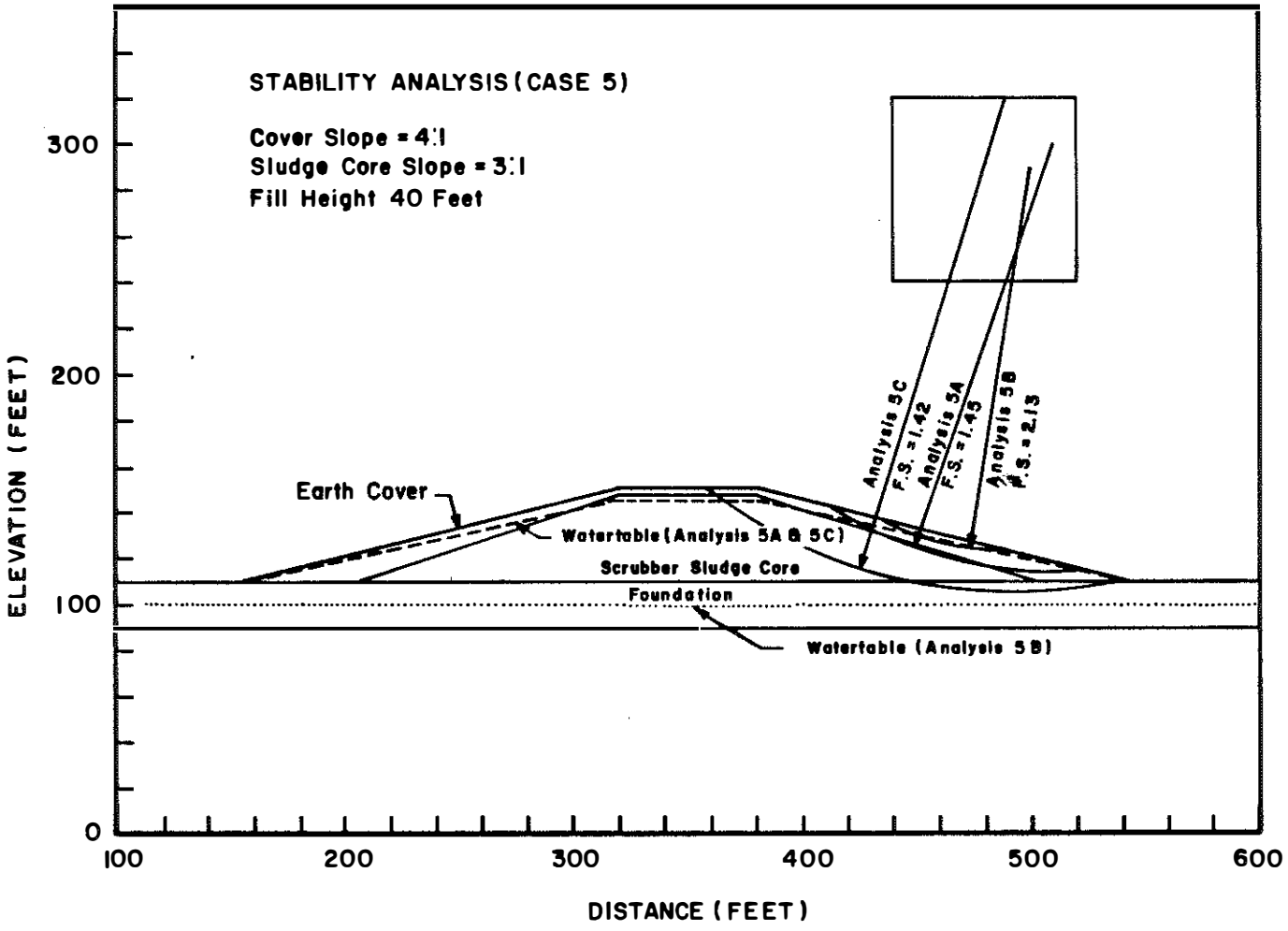


Figure 29. Typical Embankment Cross Section for Slope Stability Analyses.

Table 8. Summary of Slope Stability Analyses.

CASE NO.	ANALYSIS NO.	FILL HEIGHT (feet)	SIDE SLOPES		FOUNDATION TYPE	WATER TABLE	SHEAR STRENGTH PARAMETERS				MINIMUM SAFETY FACTOR
			CORE	COVER				CORE	COVER	FOUNDATION	
1	1A	20	2:1	3:1	Rigid	High	ϕ'	40.7	28.0	45.0*	1.21
							c'	0	0	4500*	
	1B	20	2:1	3:1	Rigid	Low	ϕ'	40.7	28.0	45.0	1.62
							c'	0	0	4500	
	1C	20	2:1	3:1	Compressible	High	ϕ'	40.7	28.0	28.0	1.17
							c'	0	0	0	
2	2A	20	2.5:1	3.5:1	Rigid	High	ϕ'	40.7	28.0	45.0	1.63
							c'	0	0	4500	
	2B	20	2.5:1	3.5:1	Rigid	Low	ϕ'	40.7	28.0	45.0	1.89
							c'	0	0	4500	
	2C	20	2.5:1	3.5:1	Compressible	High	ϕ'	40.7	28.0	28.0	1.55
							c'	0	0	0	
3	3A	20	3:1	4:1	Rigid	High	ϕ'	40.7	28.0	45.0	1.67
							c'	0	0	4500	
	3B	20	3:1	4:1	Rigid	Low	ϕ'	40.7	28.0	45.0	2.15
							c'	0	0	4500	
	3C	20	3:1	4:1	Compressible	High	ϕ'	40.7	28.0	28.0	2.08
							c'	0	0	0	
4	4A	40	2:1	3:1	Rigid	High	ϕ'	40.7	28.0	45.0	1.03
							c'	0	0	4500	
	4B	40	2:1	3:1	Rigid	Low	ϕ'	40.7	28.0	45.0	1.60
							c'	0	0	4500	
	4C	40	2:1	3:1	Compressible	High	ϕ'	40.7	28.0	28.0	1.03
							c'	0	0	0	
5	5A	40	3:1	4:1	Rigid	High	ϕ'	40.7	28.0	45.0	1.45
							c'	0	0	4500	
	5B	40	3:1	4:1	Rigid	Low	ϕ'	40.7	28.0	45.0	2.13
							c'	0	0	4500	
	5C	40	3:1	4:1	Compressible	High	ϕ'	40.7	28.0	28.0	1.42
							c'	0	0	0	

* ϕ' in degrees and c' in lb/sq in.

SUMMARY AND CONCLUSIONS

Laboratory analyses were used to evaluate potential engineering applications of scrubber sludge and scrubber sludge-aggregate mixtures. It was determined that a scrubber sludge-aggregate mixture could be used as a subbase in highway construction. Elastic layer theory was used to determine thickness requirements on the basis of elastic layer theory and laboratory-determined engineering properties. Analyses also were completed relating to the use of scrubber sludge as an embankment material. Laboratory-determined engineering properties were utilized in combination with slope stability analyses to determine maximum embankment heights and side slopes suitable for highway embankment applications.

Conclusions are incomplete at this time as the experimental field project was only completed in October 1984. Utilization of scrubber sludge-aggregate mixtures will be dependent upon demonstration of satisfactory long-term performance of the experimental pavement sections. Economic analyses have indicated that scrubber sludge-aggregate mixtures may be economically attractive initially, provided transportation costs from source to project site are not prohibitive. The same is true for scrubber sludge as an embankment material. Economic attractiveness as an embankment material is very much dependent upon the lack of available soil embankment material and the transportation costs associated with obtaining suitable material relative to that of scrubber sludge.

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APPENDIX A

INTERIM REPORT
May 1983

UNIVERSITY OF KENTUCKY

LEXINGTON, KENTUCKY 40506

COLLEGE OF ENGINEERING
KENTUCKY TRANSPORTATION RESEARCH PROGRAM
TRANSPORTATION RESEARCH BUILDING

TELEPHONE (606) 257-4513

May 3, 1983

Mr. R. A. Walsburger
Assistant State Highway Engineer
Kentucky Dept. of Highways
State Office Building
Frankfort, KY 40622

Dear Mr. Walsburger:

Subject: Interim Report - Use of Scrubber Sludge in Highway Construction

Enclosed for your review is a memorandum report concerning recent evaluations of scrubber sludge as a subbase material and/or an embankment material. The report also presents design proposals and associated economic projections concerning the use of this material as a subbase for the pavement structure of the Sebree By-Pass.

Please review this information and contact us relative to the next phase of our evaluations. If additional information and/or explanation is required, please contact this office at your convenience.

Sincerely,

Robert C. Deen
Director

RCD:neb
Enclosure

UNIVERSITY OF KENTUCKY

LEXINGTON, KENTUCKY 40506 - 0043

COLLEGE OF ENGINEERING
KENTUCKY TRANSPORTATION RESEARCH PROGRAM
TRANSPORTATION RESEARCH BUILDING

May 2, 1983

257-4513
TELEPHONE: (606) XXXXXXXX

MEMORANDUM

TO: Robert C. Deen, Director
Kentucky Transportation Research Program

FROM: Gary W. Sharpe, P. E.
Principal Research Engineer

SUBJECT: Interim Report and Recommendations
Concerning Use of Scrubber Sludge
in Highway Construction

On January 11, 1983, the Kentucky Transportation Research Program was requested to evaluate the feasibility of using "scrubber sludge" and other waste products in highway construction. This investigation was specifically related toward use of waste materials from the Big Rivers Power and Electric facility at Sebree for use in the construction of the Sebree By-Pass.

Two basic approaches were considered in this investigation. One involves the use of "scrubber sludge" or a mixture of scrubber sludge and aggregate as a subbase material. It was anticipated that use of this material would reduce the required thicknesses of higher quality paving materials. Two sources of aggregate were considered: (1) pond ash (bottom ash) from the Big River facility and (2) traditional dense graded aggregate. Dense-graded aggregate (DGA) from Central Rock in Lexington was used for laboratory mix evaluations. It was assumed that the quality of DGA would not vary significantly from available sources near Sebree. A second approach involves the use of scrubber sludge as an embankment material for low height embankments.

Components of scrubber sludge were obtained from Big Rivers Power and Electric Corporation for laboratory evaluations. Laboratory investigations involved evaluation of the engineering properties of the material and did not involve chemical analyses or analyses related to the effects of usage on the environment. It is highly recommended that approval of the Kentucky Environmental Protection Agency be obtained prior to any construction using either scrubber sludge or pond ash. All components were dewatered and converted to a dry state prior to remixing in the laboratory. Scrubber sludge was remixed according to proportions that approximately duplicated the field sludge produced at the Big Rivers facility. Other proportions were not studied due to time constraints, although it is recommend this be one aspect of continuing research. Mix proportions were supplied by Mr. Ed Chisholm of Big Rivers Power and Electric.

Three proportions of aggregate and scrubber sludge were evaluated: (1) 90% aggregate and 10% scrubber sludge, (2) 85% aggregate and 15% scrubber sludge, and

(3) 80% aggregate and 20% scrubber sludge. Two sources of aggregate were used: (1) pond ash from the Big Rivers facility and (2) dense graded aggregate from Central Rock in Lexington.

Evaluations for use as a subbase involved testing for unconfined compressive strength, tensile strength, axial strain, lateral strain, modulus of elasticity, and Poisson's ratio. Curing conditions also were varied from 100°F in a sealed container for seven days to curing at room temperature in air for seven days and 28 days. Other evaluations involved the determination of the gradation of the pond ash and saturation and slaking characteristics.

Extensive evaluations involved the use of labratory-mixed sludge. A smaller series of evaluations was conducted using processed sludge obtained from the Big Rivers facility. The testing of the processed sludge was conducted to verify or qualify the performance of the laboratory mixtures.

Both laboratory and field processed scrubber sludge were evaluated using tri-axial testing procedures to determine effective shear strength parameters. This information is required to determine the stability of an embankment. The effective shear strength parameters determined were the internal friction angle and the cohesion.

Detailed descriptions of procedures used to evaluate this material and more detailed findings will be presented in a research report at a later date. Confirmation of some of the research findings are also currently being completed. The following represents a very brief summary of current findings along with recommendations for use and design paramters.

Testing of unmixed "scrubber sludge" has involved undrained triaxial testing to determine the angle of internal friction and the cohesion of the material for slope stability analyses. Embankment geometry consisted of a scrubber sludge core 18 feet in height with 2 feet of earth cover. Embankment side slopes for the scrubber sludge and the earth cover varied from 2:1 to 4:1. The location of the watertable was also varied in the analyses. Result of the slope stability analyses indicated no failures occurred through the scrubber sludge core. Failures consisted of shallow slips through the earth cover. However, due to the detrimental effects of a high watertable on the required earth cover, it is recommended that embankments using a scrubber sludge core be designed with 3:1 side slopes on the core and 4:1 side slopes on the earth cover. These recommendations are based upon the assumption that the material will be placed with moisture contents near optimum and that densities are near the laboratory maximum dry density of 63 pounds per cubic foot. Factors of safety for these analyses were in the order of two.

Evaluation of the material as a base involved unconfined compression testing to determine ultimate compressive and tensile strengths, stress-strain characteristics, modulus of elasticity, and Poisson's ration. Testing involved laboratory prepared scrubber sludge as well as mixtures with pond ash or conventional dense graded aggregate. Testing is currently underway to verify test results using processed scrubber sludge from the Sebree facility.

Evaluation of the scrubber sludge indicated unconfined compressive strengths of 100 psi and a modulus of elasticity of 9,500 psi at 7 days when tested in an unsaturated condition. Attempts to saturate the material prior to compression testing were unsuccessful due to partial slaking of the sample. It was possible to saturate field compacted samples obtainedin December and cured in molds at room temperature for four months. No compression measurements were obtained due to the non-standard procedures used in preparing these samples. Since no slaking occurred with the field-compacted samples while slaking did occur with the laboratory-processed sludge, it was concluded that variations in behavior are either the result of (1) procedures used in preparing the laboratory sludge mixtures or (2) curing variations. Test results are still being evaluated to determine the reasons for this behavior. Preliminary testing with field sludge obtained from the Big Rivers facility apparently verify behavior observed with laboratory samples. Unconfined compressive strengths and moduli are similar. Also, slaking of samples of field sludge cured for seven days in air at room temperature occurred as did laboratory samples. This observation apparently supports the theory that the material is very slow curing and requires some time to develop strengths associated with other pozzalonic materials. Perhaps one aspect of future research should involve investigations relative to changing the proportions of the scrubber sludge. One possibility that has been considered involves increasing the amount of lime. This should provide for more rapid strength gains. An attempt was made to cure similar samples at 100°F in a sealed container for 7 days, but apparent tension cracking prevented evaluation of those samples.

Mixtures of laboratory prepared scrubber sludge and pond ash were evaluated for three different ratios of scrubber sludge and pond ash. Results of these tests for samples cured 7 dats at 100°F follow:

Mixture proportions	Average Compressive Strength (psi)	Average Modulus of Elasticity (psi)
90% Pond Ash; 10% Scrubber Sludge	94	8,112
85% Pond Ash; 15% Scrubber Sludge	160	10,285
80% Pond Ash; 20% Scrubber Sludge	196	15,512
90% DGA; 10% Scrubber Sludge	153	7,159
85% DGA; 15% Scrubber Sludge	189	7,782
80% DGA; 20% Scrubber Sludge	168	10,080

Twenty-eight day samples have been molded but evaluation of these samples have not been completed. However a summary of test results for mixtures of 10% scrubber sludge are presented below:

Mixture Proportions	Average Compressive Strength (psi)	Average Modulus of Elasticity (psi)
90% Pond Ash; 10% Scrubber Sludge	826	77,471
90% DGA; 10% Scrubber Sludge	286	26,124

Test data obtained to date have indicated that increased strengths and moduli may be obtained with increasing the proportion of scrubber sludge. Testing has not been completed relative to the determination of the optimum proporation of scrubber sludge. It is anticipated that the optimum proporation will be in the order of 20 to 30 percent scrubber sludge, but additional evaluations are required to determine the proportion more specifically. There are also some unexplained variations relative to the behavior of the DGA mixtures. Additional evaluations are underway to define these relationships.

The data do indicate the materials gain strength with time. The initial strengths were somewhat weaker than anticipated. As was previously stated, some variations between laboratory-prepared scrubber sludge and field-processed sludge were observed. Duplicate mixtures have been prepared using field scrubber sludge to more adequately define these variables. Evaluations are not yet completed.

Since mixtures of pond ash and scrubber sludge resulted in the highest early moduli and compressive strengths, pavement design calculations were developed for this material. Past research and literature have indicated the moduli of base and subbase materials to be dependent upon the strength of the confining layers. A relationship had been previously developed for conventional crushed stone bases. This same relationship was modified to convert static moduli presented above to moduli reflecting the effects of the confining layers. Test data indicated that moduli equal to or possibly exceeding the moduli for DGA might be anticipated if laboratory compaction and curing conditions could be duplicated in the field. Due to uncertainities associated with a lack of experience with this material, it was decided that scrubber sludge-pond ash mixtures would be assigned design moduli slightly weaker than moduli for conventional crushed stone bases.

Another reason for using conservative moduli for design purposes involves slow strength gain characteristics observed with the material. Given the proper amount of time, moduli for the scrubber sludge will likely reach and exceed the design moduli. However, modern construction schedules normally do not accomodate such long-term curing requirements.

Using the previously discussed relationship relative to moduli for DGA and an assumed relationship for the pond ash mixture, moduli of 23,000 and 18,000 psi were used for conventional DGA and the pond ash mixtures, respectively for a design CBR=5 (modulus = 7,500 psi). It is thought that the moduli used represent conservative estimates of anticipated field moduli and are not outside the limits of moduli defined by test data.

Limiting strain criteria used in Kentucky flexible pavement design procedures (480 ksi curves) were used to develop equivalent designs using scrubber sludge as a subbase material. The initial proposed design (8½" AC on 17¼" DGA or 13½" AC full-depth) were evaluated to determine design limiting strains. A matrix of thicknesses of asphaltic concrete (AC), dense-graded aggregate (DGA) and scrubber sludge using the moduli discussed above for DGA and 480 ksi for asphaltic concrete

was used to determine strain characteristics for these thicknesses. A number of equivalent designs were determined. Four proposed designs are presented below: The designs presented below are equivalent in terms of the design 18-kip equivalent axle loads (7.2 X 10^6 EAL's).

Initial Designs

1. 8 1/2" AC; 17 1/4" DGA
2. 13 1/2" AC (full depth)

Proposed Alternate Designs

1. 7 1/2" AC; 13" DGA; 8" Scrubber Sludge-Pond Ash
2. 7" AC; 10.5" DGA; 12" Scrubber Sludge-Pond Ash
3. 6.5" AC; 8" DGA; 16" Scrubber Sludge-Pond Ash
4. 6.0" AC; 6" DGA; 20" Scrubber Sludge-Pond Ash

An economic analysis and comparisons with the proposed conventional designs were also conducted. The following assumptions were used.

Cost of Asphaltic Concrete	--	$23.00 per ton
Cost of Dense-Graded Aggregate	--	$10.00 per ton
Cost of Transportation of Scrubber Sludge-Pond Ash Mixtures	--	$ 1.75 per ton

Results of the analyses are presented below:

1. Conventional Pavement Design -- 8 1/2" AC, 17 1/4" DGA; CBR 5 - Cost Per Mile = $284,966

2. Full Depth Asphaltic Concrete Alternate 13 1/2" AC, CBR 5 - Cost Per Mile = $240,451

Experimental Designs using Scrubber Sludge-Pond Ash as a Subbase Material:

1. Alternate Design 7 1/2" AC; 13" DGA; 8" SS-PA; CBR 5
   Cost Per Mile = $245,098
   Anticipated Savings Per Mile $39,868 for Conventional Design
   $-4,647 for Full-Depth Design

2. Alternate Design 7" AC; 10 1/2" DGA; 12" SS-PA; CBR 5
   Cost Per Mile = $222,252
   Anticipated Savings Per Mile $ 62,714 for Conventional Design
   $ 18,199 for Full-Depth Design

3. Alternate Design 6 1/2" AC; 8" DGA; 16" SS-PA; CBR 5
   Cost Per Mile = $199,408
   Anticipated Savings Per Mile: $85,558 for Conventional Design
   $41,043 for Full-Depth Design

4. Alternate Design 6" AC; 6" DGA; 20" SS-PA; CBR 5

Cost Per Mile	=	$180,435
Anticipated Savings Per Mile		$104,531 for Conventional Design
		$ 60,019 for Full-Depth Design

The above estimates are based upon a one-mile pavement section having a 24-foot width. Costs associated with shoulders were not included in the analysis. No costs were estimated for blending of the pond ash and scrubber sludge. The feasibility of blending pond ash and scrubber sludge should be determined before proceeding with design activities. Conversations between KTRP staff and Big Rivers staff (Mr. Ed Chisholm) have indicated that blending is possible, but this was the extent of the conversation. No cost estimates were developed relative to the use of scrubber sludge as an alternate embankment material. Such analyses would be dependent upon costs of barrow material versus transportation costs of the scrubber sludge.

It is apparent from the information presented above that as the thickness of scrubber sludge and pond ash is increased, the required thickness of higher-type paving materials decreases. However, risks associated with the usage of an unproven material such as the scrubber sludge-pond ash mixture increase. An analysis was conducted to determine the overlay thickness required at some future date in the unlikely event the scrubber sludge layer completely failed. The analysis involved using the Kentucky 480 ksi flexible design curves and the assumption that the subbase layer (scrubber sludge-pond ash) deteriorated to zero structural worth. This assumption is especially punitive and next to impossible since the worst that could be expected is deterioration to a very low quality granular base. However, calculations were completed to provide some information relative to a complete material failure.

1. Proposed Alternate 7 1/2" AC; 13" DGA; 8" SS PA; CBR 5
   Future Overlay required if subbase fails -- 2" AC
   Cost at $30 per ton, $46,464 per mile

2. Proposed Alternate 7" AC; 10 1/2" DGA; 12" SS-PA, CBR 5
   Future Overlay required if subbase fails -- 3 1/2" AC
   Cost at $30 per ton, $81,312 per mile

3. Proposed Alternate 6 1/2" AC, 8" DGA; 16" SS-PA; CBR 5
   Future Overlay required if subbase failes -- 4 1/2" AC
   Cost at $30 per ton, $ 104,544 per mile

4. Proposed Alternate 6" AC; 6" DGA; 20" SS-PA; CBR 5
   Future Overlay required if subbase failes -- 5 3/4" AC
   Cost at $30 per ton, $133,584 per mile

As was previously stated, the above analysis is especially conservative, and it is highly unlikely the subbase will fail completely. Therefore, risks are not likely to result in the above costs but do provide a means for comparison.

Another means of comparing the experimental designs involves expressing the effects of the subbase as an improved CBR. The Kentucky 480 ksi flexible design curves were used to make this determination.

Initial Conventional Designs

(a)	8 1/2" AC; 17 1/4" DGA	Design CBR 5
(b)	13 1/2" AC	Design CBR 5

Proposed Experimental Designs

(a)	7 1/2" AC; 13" DGA; 8" SS-PA; Design CBR 5;	Effective CBR 10.0
(b)	7"AC; 10 1/2" DGA; 12" SS-PA; Design CBR 5;	Effective CBR 14.7
(c)	6 1/2" AC; 8" DGA; 16" SS-PA; Design CBR 5;	Effective CBR 22.2
(d)	6" AC; 6" DGA; 20" SS-PA; Design CBR 5;	Effective CBR 33.5

All designs presented are theoretically equivalent. Certainly greater risks are associated with greater quantities of scrubber sludge and pond ash. Selection of the design to be constructed should be ultimately decided in conjunction with Department of Highways officials. However, it is our recommendation that one of the intermediate designs be constructed. Therefore, it is our recommendation that the construction design be one of the following:

7" AC; 10 1/2" DGA; 12" SS-PA; or
6 1/2" AG, 8" DGA; 16" SS-PA

This recommendation represents a "middle ground" approach relative to the use of this material at this time.

One consideration in selecting the design using 7" AC as opposed to the 6.5" AC may involve vehicles anticipated to use the pavement. If high proportion of heavily loaded (possibly overloaded) vehicles are anticipated, thicker layers of asphaltic concrete will provide for greater protection of the lower layers of the structure. Initial traffic estimates (March 1, 1983) included anticipated traffic to be generated from a new coal mining site. Later estimates (March 16, 1983) did not include traffic generated from a possible new mining site. Final selection of the design should depend upon the traffic using the facility. From a research perspective, it is recommended that both designs be constructed and evaluated.

In summary, evaluations have indicated that a mixture of scrubber sludge and pond ash may be feasible for use as a subbase material in pavements. Specific economics are dependent upon exact material costs, transportation costs, and blending costs. It is recommended that usage of these materials be approved by the Kentucky Environmental Protection Agency before construction begins. It is also our understanding that current EPA regulations require this material to be covered. A final report will be prepared at a later date that will provide detailed presentations relative to testing and evaluation, and design analyses.

Special appreciation is extended to Mr. Herbert Southgate for his contributions relative to pavement thickness design requirements and to Mr. David Allen for his contributions relative to slope stability analysis and tri-axial analyses. Both will be co-authors of the final report and have been available for consultation relative to overall study activities.

GWS:jfh

APPENDIX B

AGGREGATE TEST REPORT ON POND ASH (BOTTOM ASH) FROM ROBERT REID STATION

TC64-102
(715)

AGGREGATE TEST RESULTS

Rev.
2-14-84

ID.No. _____
INSPECTOR SSN
DATE SAMPLED
TYPE OF INSPECTION: INF
PRODUCER NO./SUPPLIER NO.
MATERIALCODE
INSPECTED QUANTITY
LOT NO.
Sampled From: SOURCE STOCKPILE
RESPONSIBLE LOC ___ LAB ___ Name _____ Detail Test ☐ Distribution ☐☐

County: WEBSTER
Name: G. SHARPE Crew: UKTRP
Sample Sequence No.: 14347
Original Ident: 8-8-A
Name _____ Loc _____
Description: POND ASH SUBBASE
Units _____ SEBREE POWER PLANT

Proj Code	Project Number	QUANTITY	DATE ASSIGNED
	SSP-121-CO-103	0.0	
		0.0	
		0.0	
		0.0	

DATEREC.: 2-8-83
DATE COM.: 2-18-83
PASS/FAIL
Reason
Costs: 666 1501 02 03 06 09 01

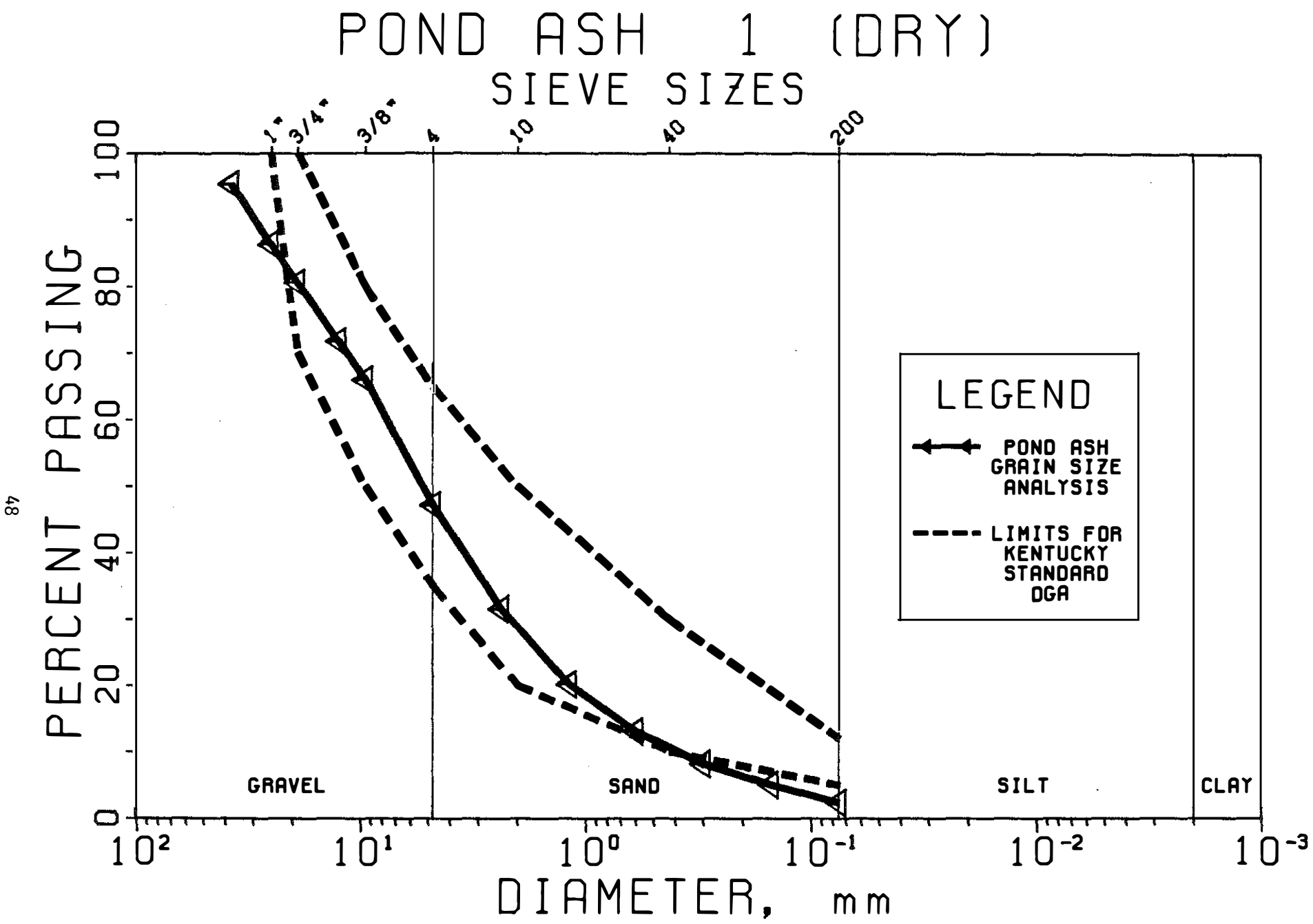
PHYSICAL		CHEMICAL					SIEVE ANALYSIS	
				Size	GRMS. RET.	% RET.	% Pass.	IN/OUT
Sp. Gravity	3.41 S S D	$CaCO_3$						
	3.34 B O D	$MgCO_3$						
	.00 A P P	R203						
		Insol		2				
Absorption %	2.0	SI02		1 1/2			100	
Soundness %	4	Insol Residue		1			88	- 12
Wear % (200)	(500) 24			3/4			84	+ 4
Unit Weight	132			1/2				
Clay Lumps %	0.0			3/8			70	
Shale%	0.0			No. 4			50	
Light Weight Particles %	.0			No. 8				
Coal %	0.0			No. 16			33	
Soft or Friable %	0.0			No. 30				
% Crushed 1 or More		2 or More		No. 40			15	
Str. Ratio %				No. 50				
Color Test				No. 200			5	
SE. Value	66			PAN				
Minus 200 Wash %	4.5	Lignite %	.0	TOTAL				
Metallic %	9.3	Pore Index	21					
% Voids	.0	Plas. Index	NP	FM .0				

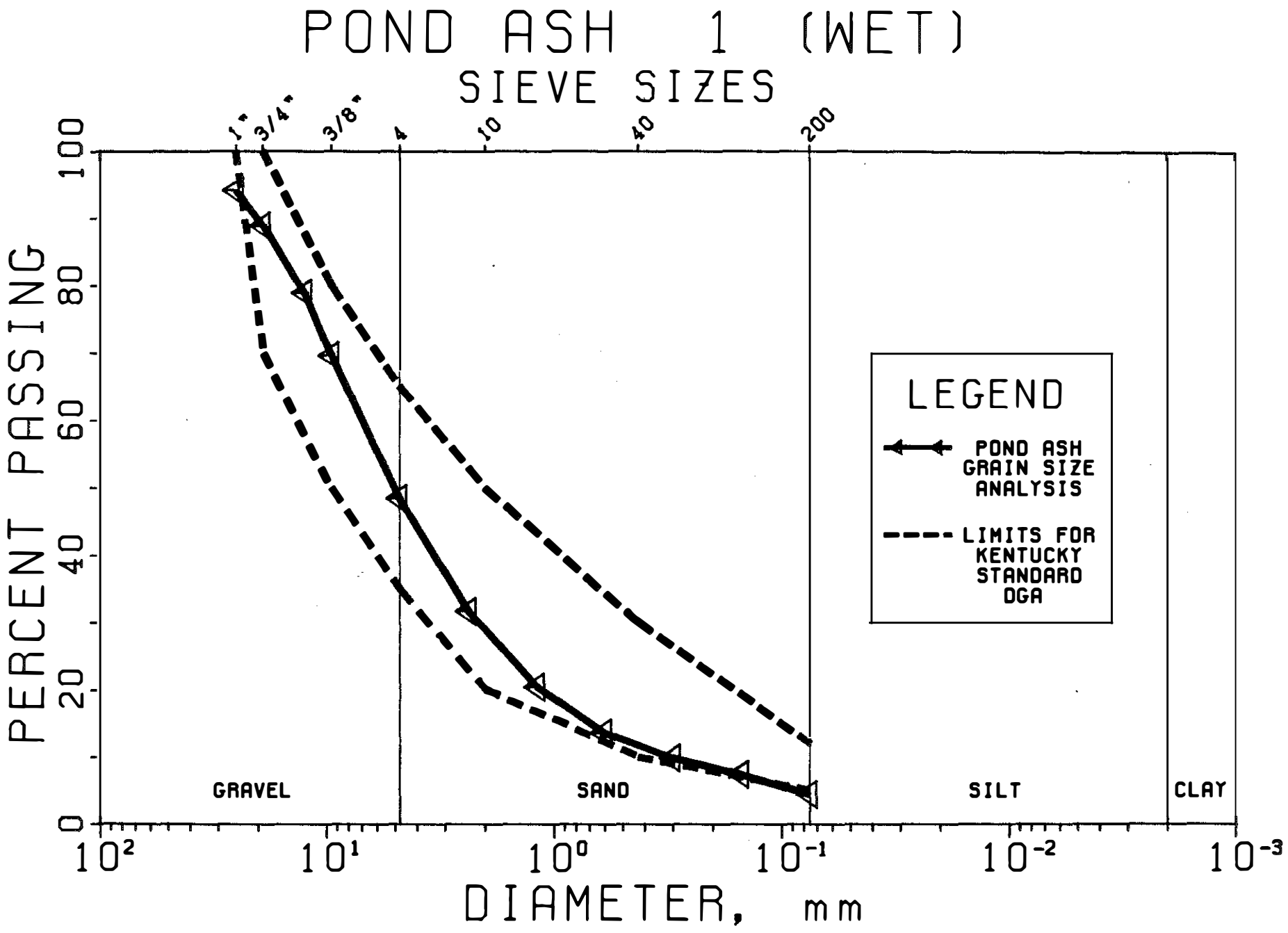
Remarks:

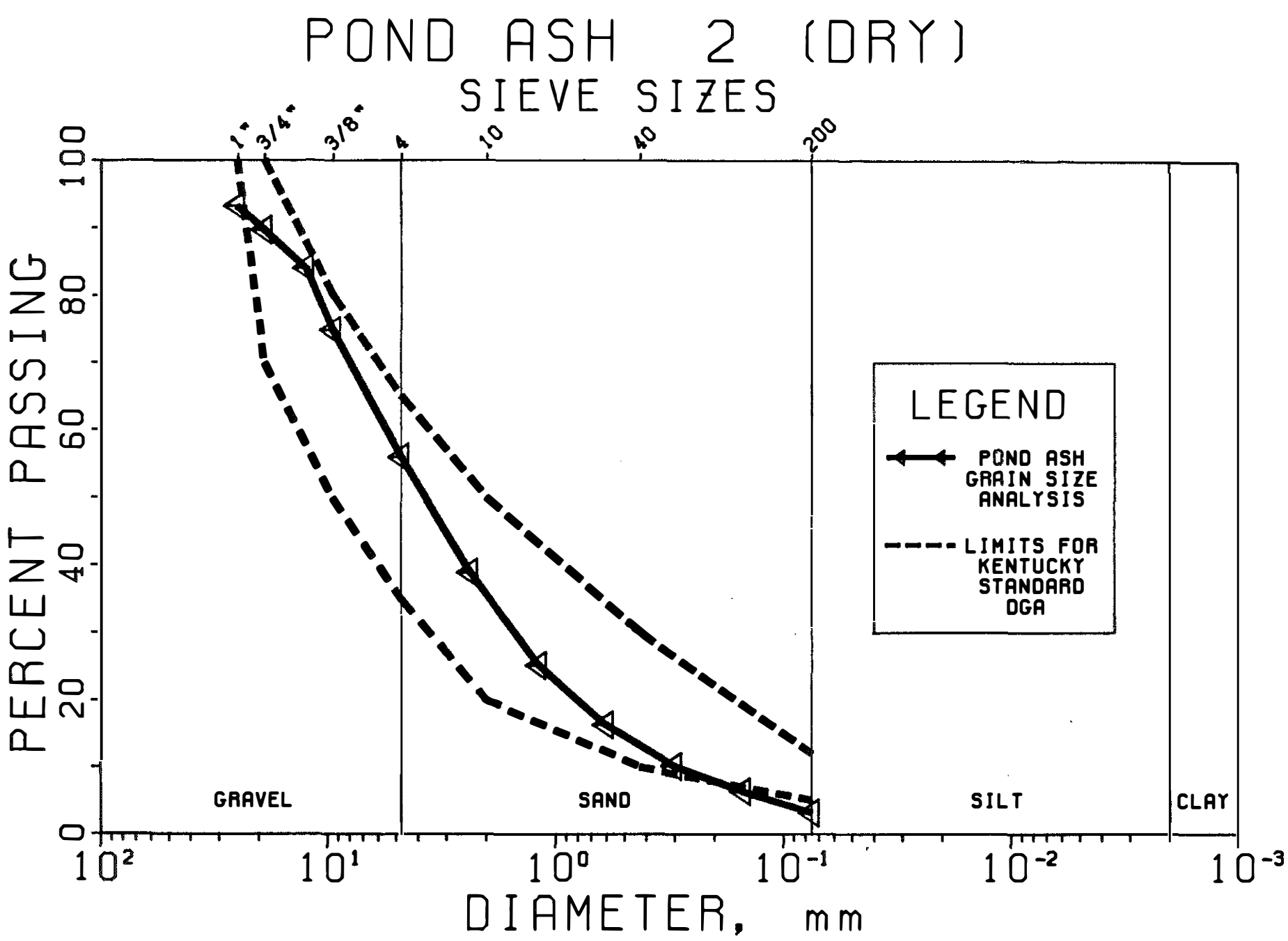
Copies: McCHORD, EPLEY, SHARP
DME, AGGREGATE FILE

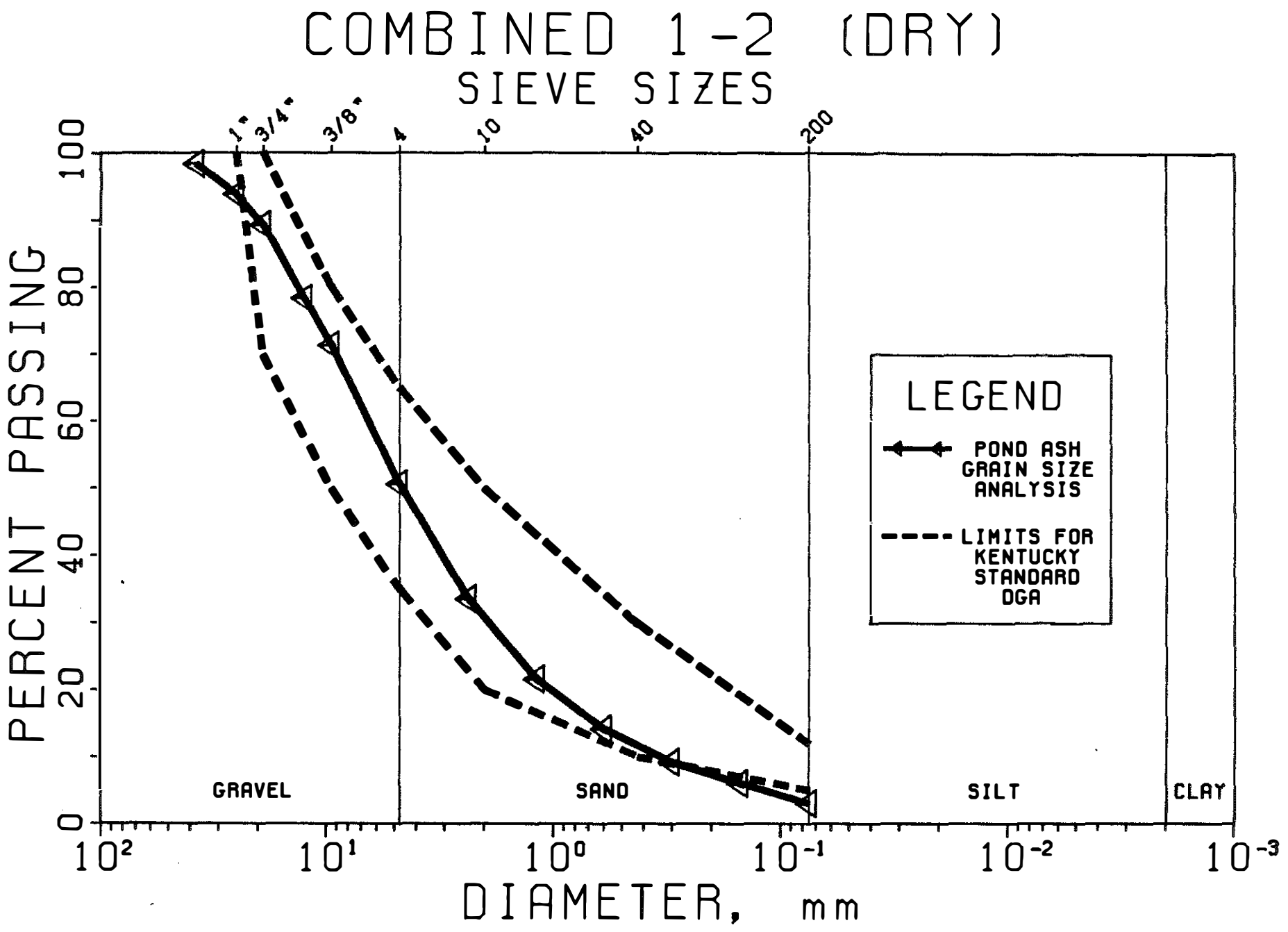
APPENDIX C

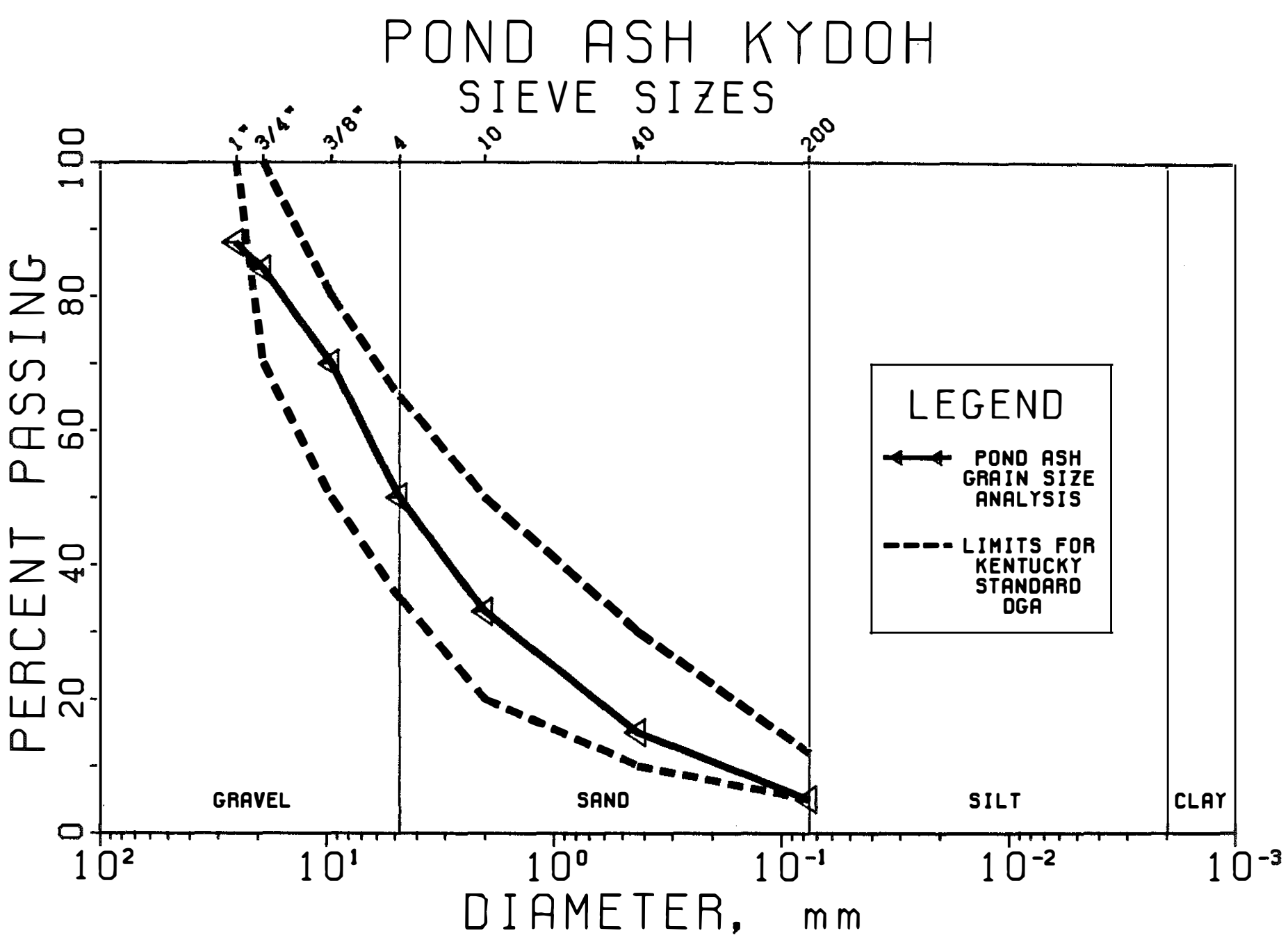
GRADATION CURVES FOR POND ASH (BOTTOM ASH) FROM ROBERT REID STATION


POND ASH 1 (DRY)
SIEVE SIZES
1"
3/4"
3/8"
4
10
40
200
PERCENT PASSING
100
80
60
40
20
0
GRAVEL
SAND
SILT
CLAY
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
DIAMETER, mm
LEGEND
POND ASH GRAIN SIZE ANALYSIS
LIMITS FOR KENTUCKY STANDARD DGA


POND ASH 1 (WET)
SIEVE SIZES
1"
3/4"
3/8"
4
10
40
200
PERCENT PASSING
100
80
60
40
20
0
LEGEND
POND ASH GRAIN SIZE ANALYSIS
LIMITS FOR KENTUCKY STANDARD DGA
GRAVEL
SAND
SILT
CLAY
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
DIAMETER, mm


POND ASH 2 (DRY)
SIEVE SIZES
1"
3/4"
3/8"
4
10
40
200
PERCENT PASSING
100
80
60
40
20
0
GRAVEL
SAND
SILT
CLAY
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
DIAMETER, mm
LEGEND
POND ASH GRAIN SIZE ANALYSIS
LIMITS FOR KENTUCKY STANDARD DGA


COMBINED 1-2 (DRY)
SIEVE SIZES
1"
3/4"
3/8"
4
10
40
200
PERCENT PASSING
100
80
60
40
20
0
GRAVEL
SAND
SILT
CLAY
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
DIAMETER, mm
LEGEND
POND ASH GRAIN SIZE ANALYSIS
LIMITS FOR KENTUCKY STANDARD DGA


POND ASH KYDOH
SIEVE SIZES
1"
3/4"
3/8"
4
10
40
200
PERCENT PASSING
100
80
60
40
20
0
LEGEND
POND ASH GRAIN SIZE ANALYSIS
LIMITS FOR KENTUCKY STANDARD DGA
GRAVEL
SAND
SILT
CLAY
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
DIAMETER, mm

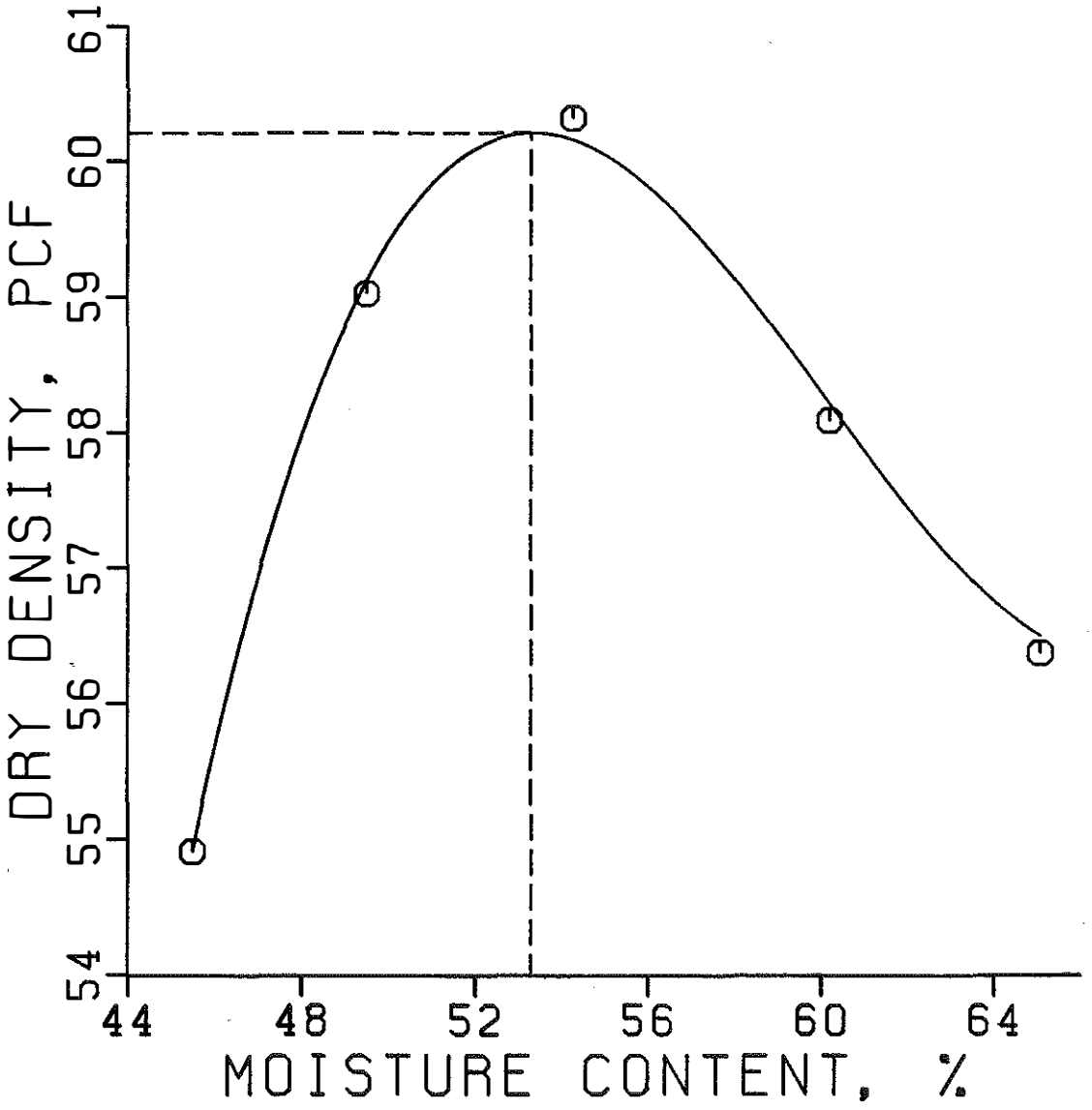
APPENDIX D

MOISTURE-DENSITY RELATIONSHIPS

SCRUBBER SLUDGE MIX 1

0 % AGGREGATE
100 % SLUDGE, CONSISTING OF:
2 % LIME
20 % FLY ASH
78 % FILTER CAKE

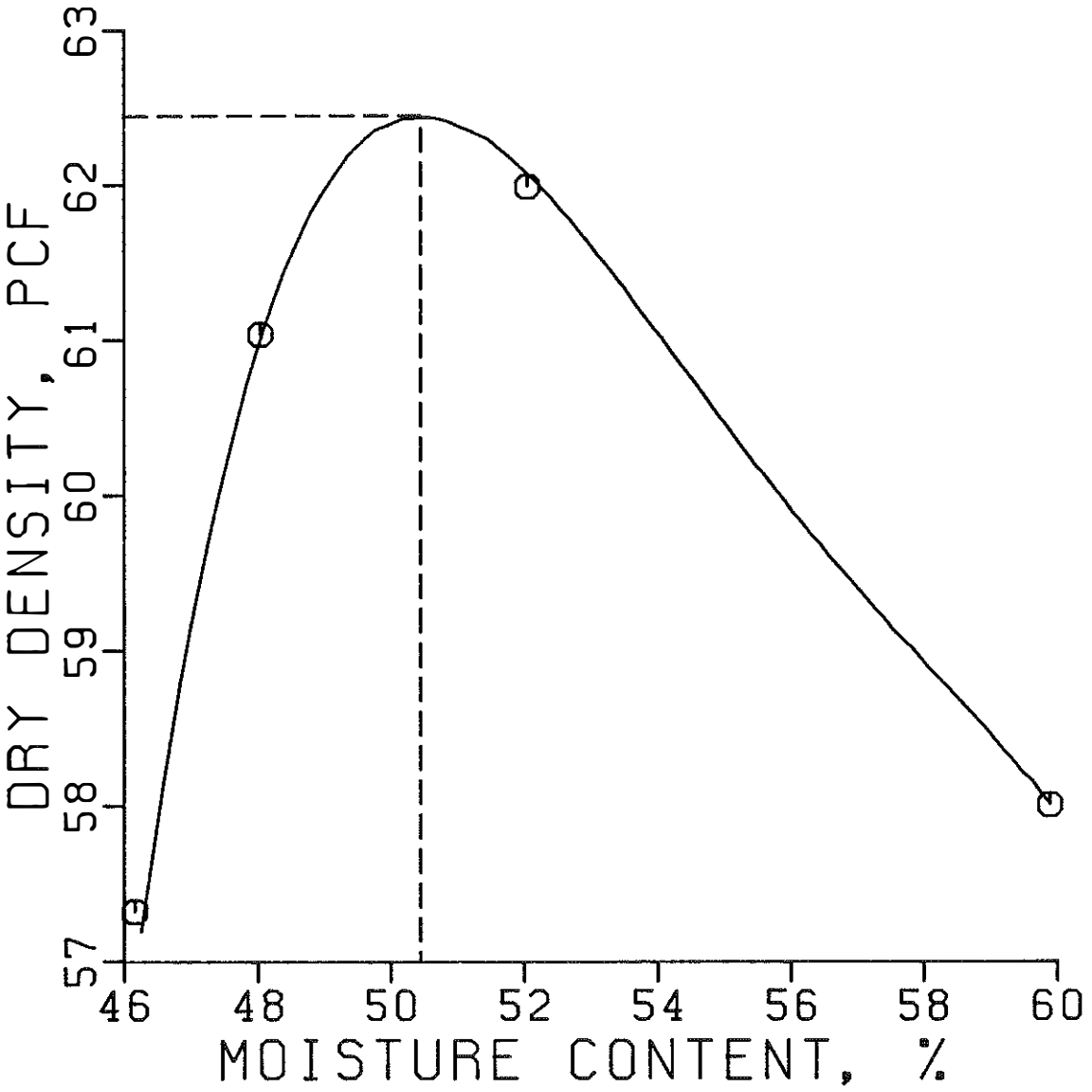
OPTIMUM MOISTURE CONTENT = 53.3 %
MAXIMUM DRY DENSITY = 60.2 PCF



SCRUBBER SLUDGE MIX 2

0 % AGGREGATE
100 % SLUDGE, CONSISTING OF:
2 % LIME
15 % FLY ASH
83 % FILTER CAKE

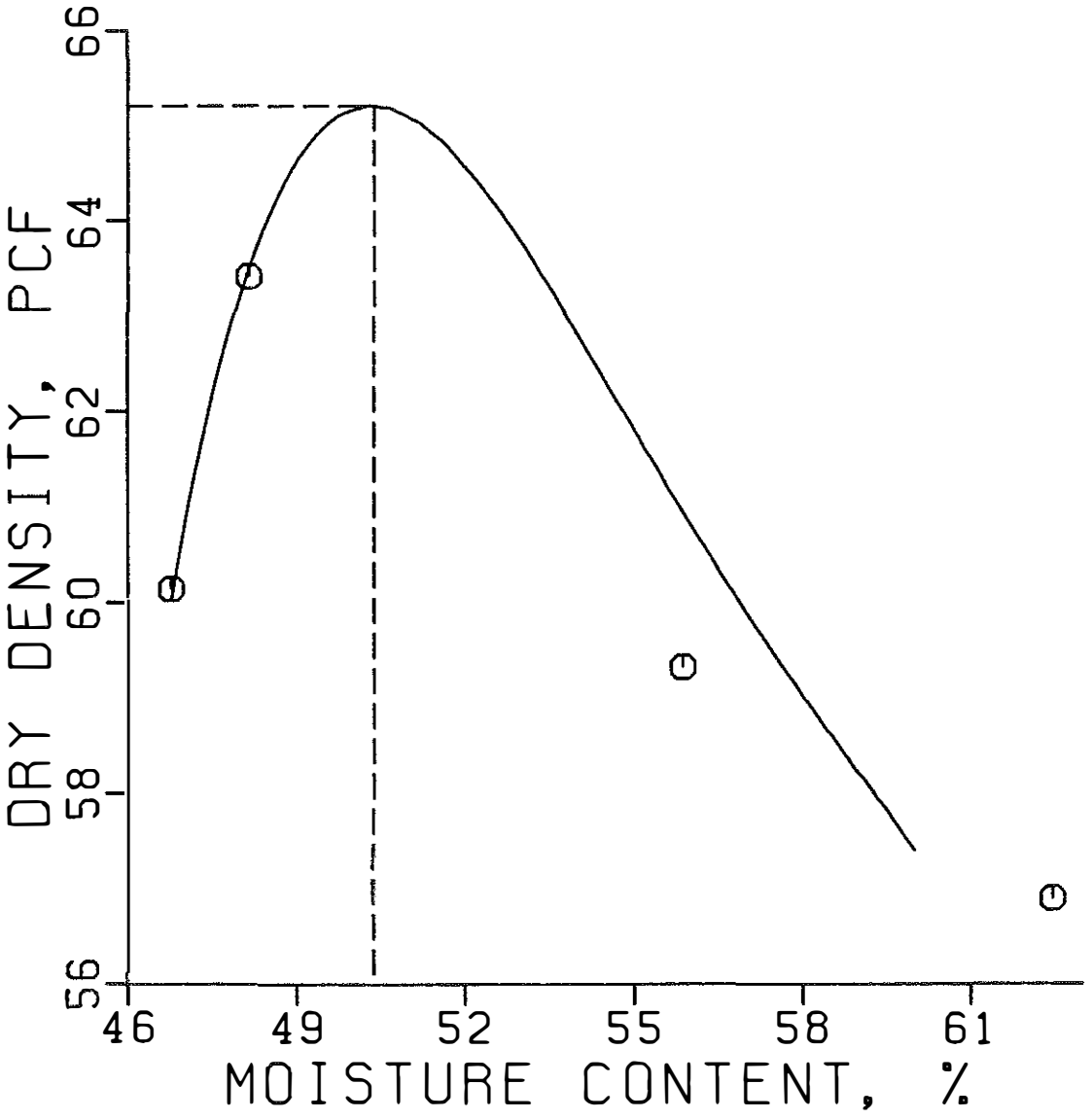
OPTIMUM MOISTURE CONTENT = 50.4 %
MAXIMUM DRY DENSITY = 62.5 PCF



SCRUBBER SLUDGE MIX 3

0 % AGGREGATE
100 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

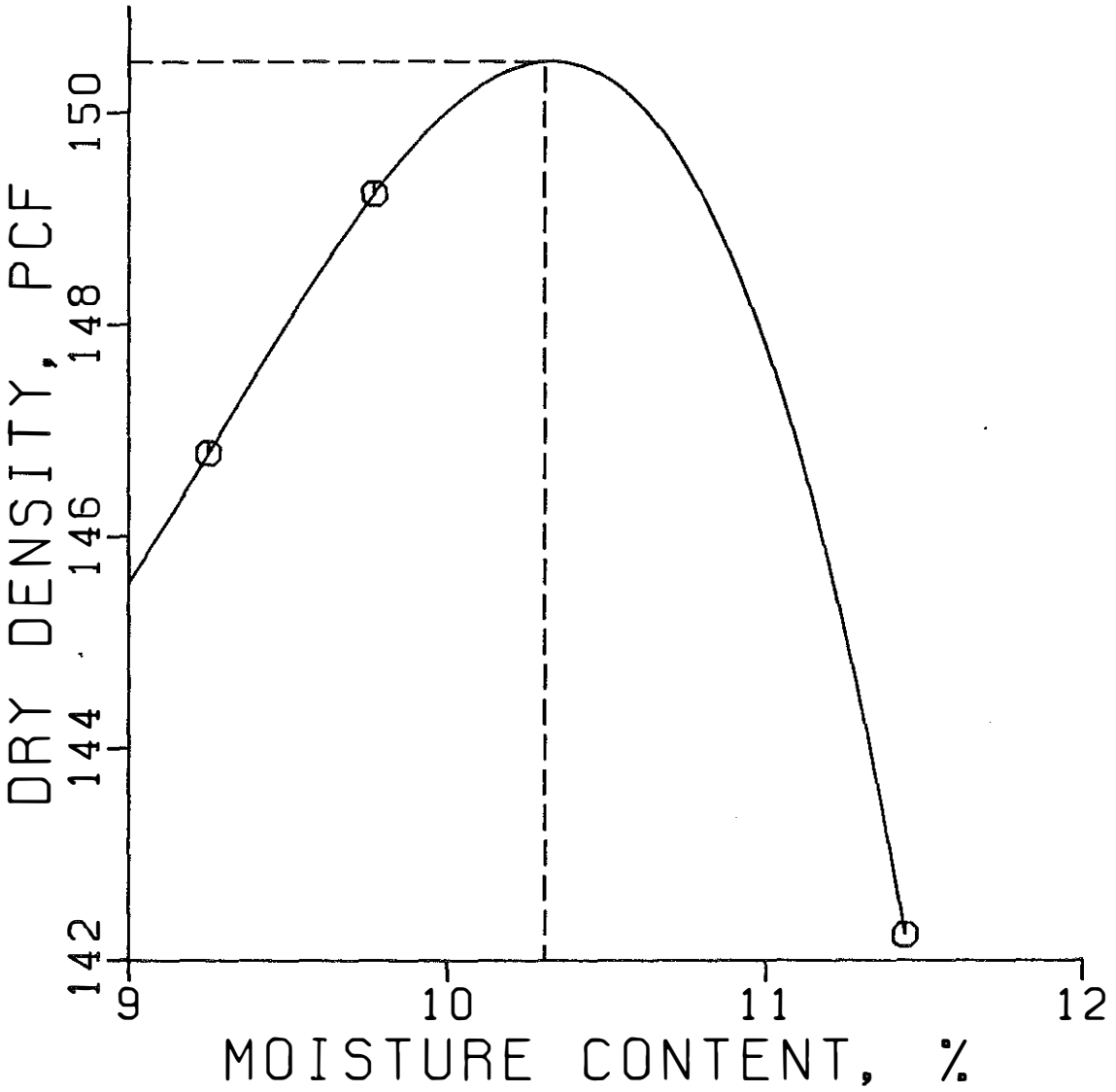
OPTIMUM MOISTURE CONTENT = 50.4 %
MAXIMUM DRY DENSITY = 65.2 PCF



SCRUBBER SLUDGE MIX 4

90 % POND ASH
10 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

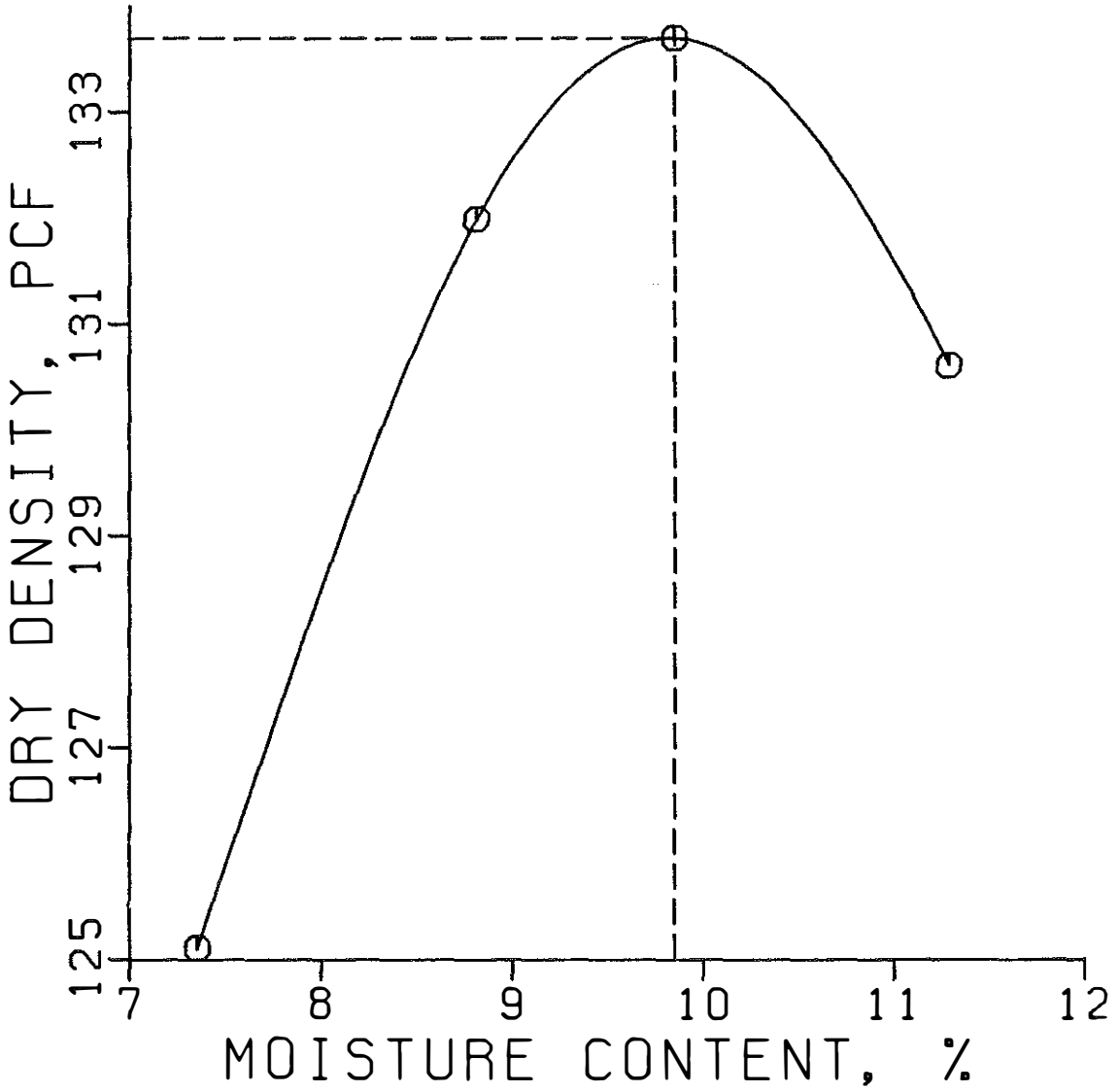
OPTIMUM MOISTURE CONTENT = 10.3 %
MAXIMUM DRY DENSITY = 150.5 PCF



SCRUBBER SLUDGE MIX 5

90 % DENSE GRADED AGGREGATE
10 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

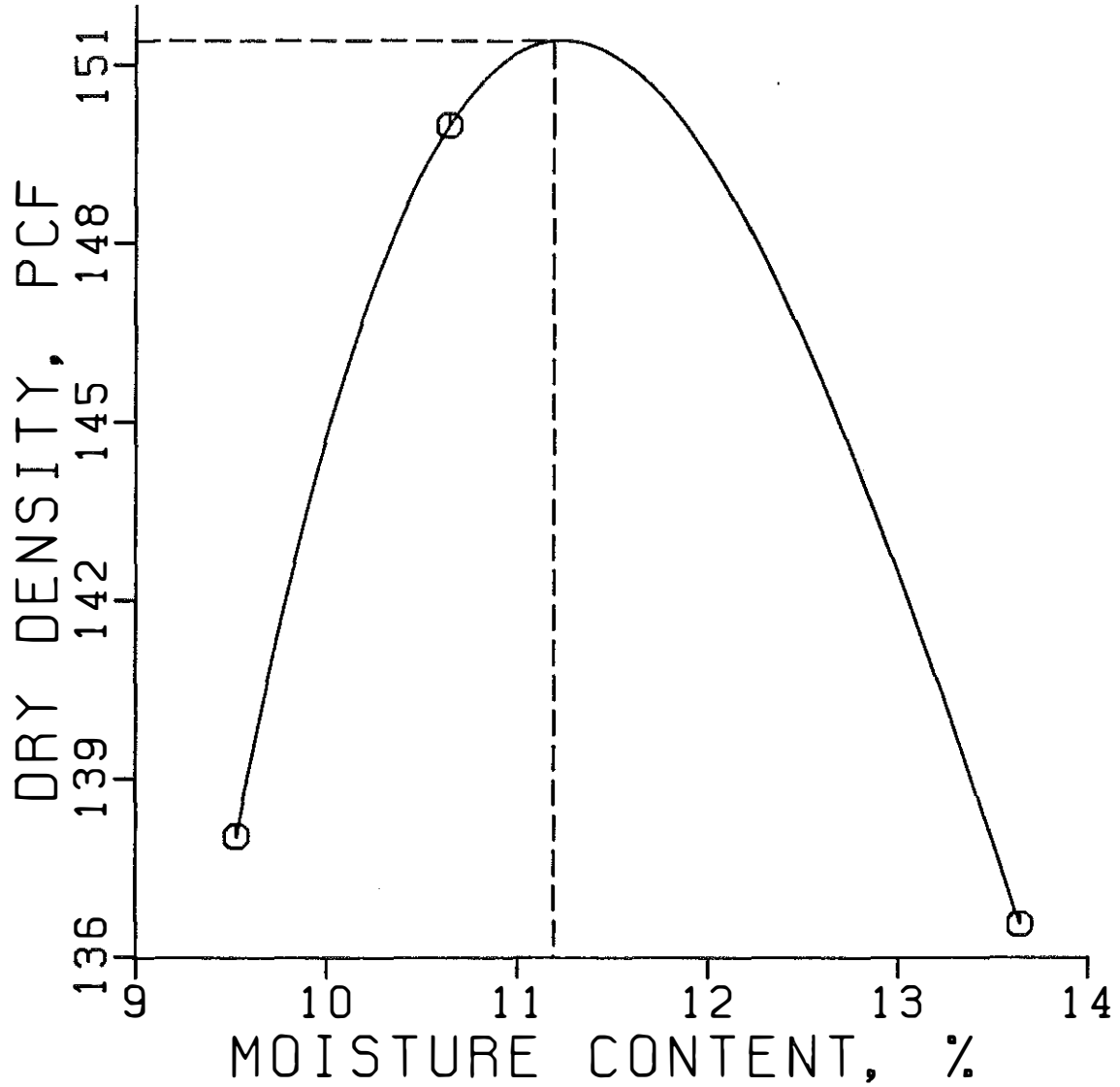
OPTIMUM MOISTURE CONTENT = 9.9 %
MAXIMUM DRY DENSITY = 133.7 PCF



SCRUBBER SLUDGE MIX 6

85 % POND ASH
15 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

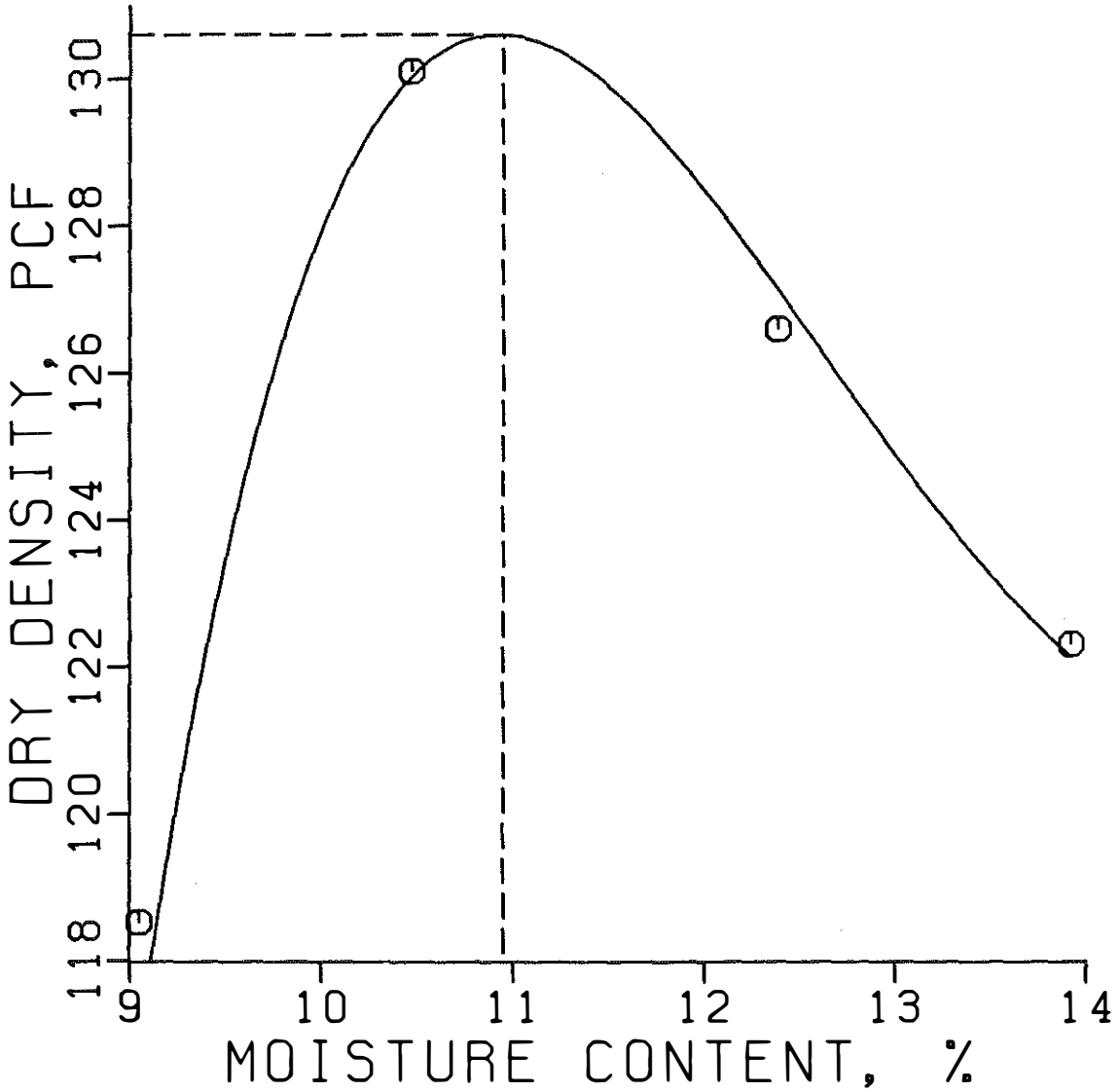
OPTIMUM MOISTURE CONTENT = 11.2 %
MAXIMUM DRY DENSITY = 151.4 PCF



SCRUBBER SLUDGE MIX 7

85 % DENSE GRADED AGGREGATE
15 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

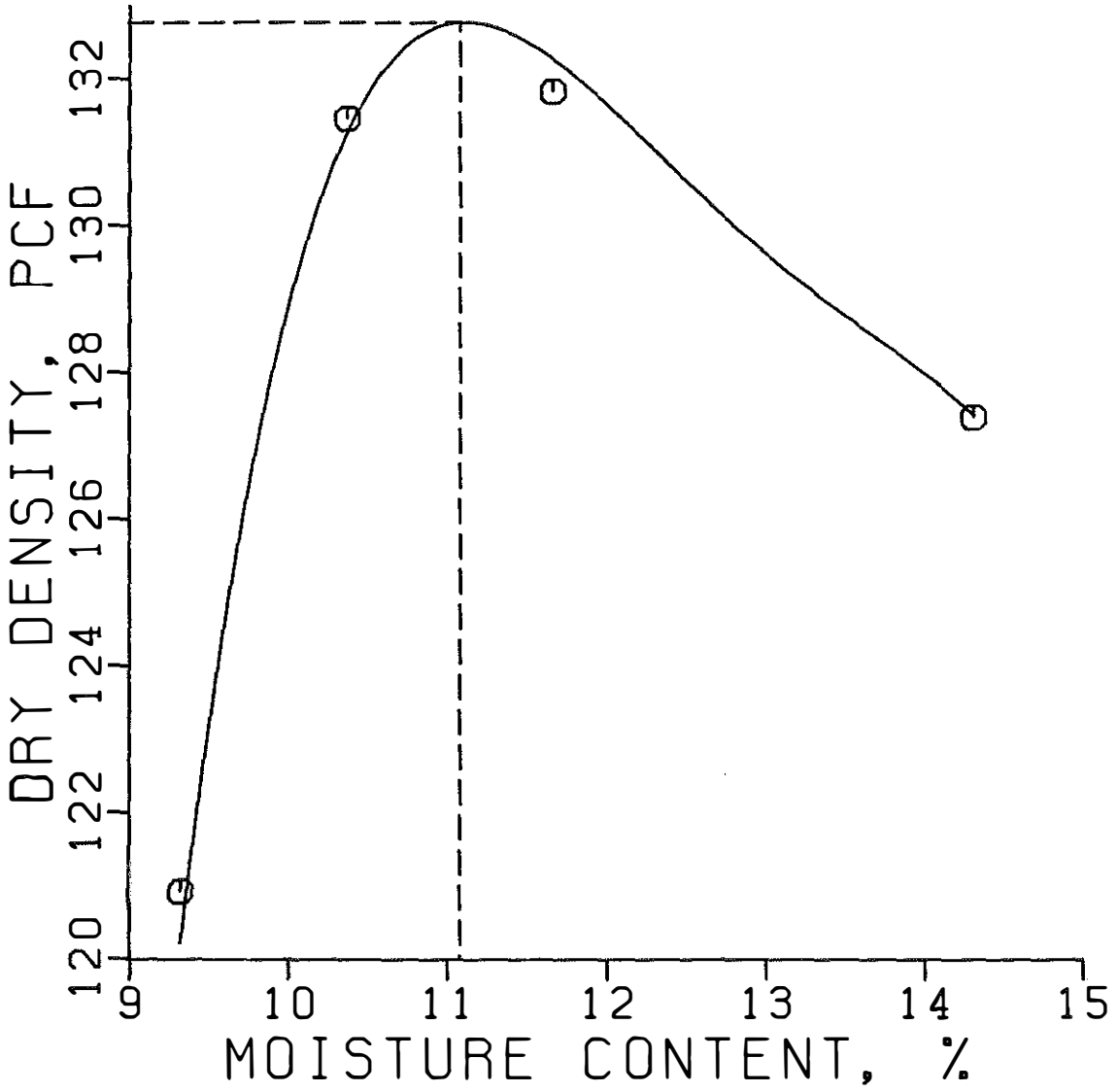
OPTIMUM MOISTURE CONTENT = 10.9 %
MAXIMUM DRY DENSITY = 130.6 PCF



SCRUBBER SLUDGE MIX 8

80 % POND ASH
20 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

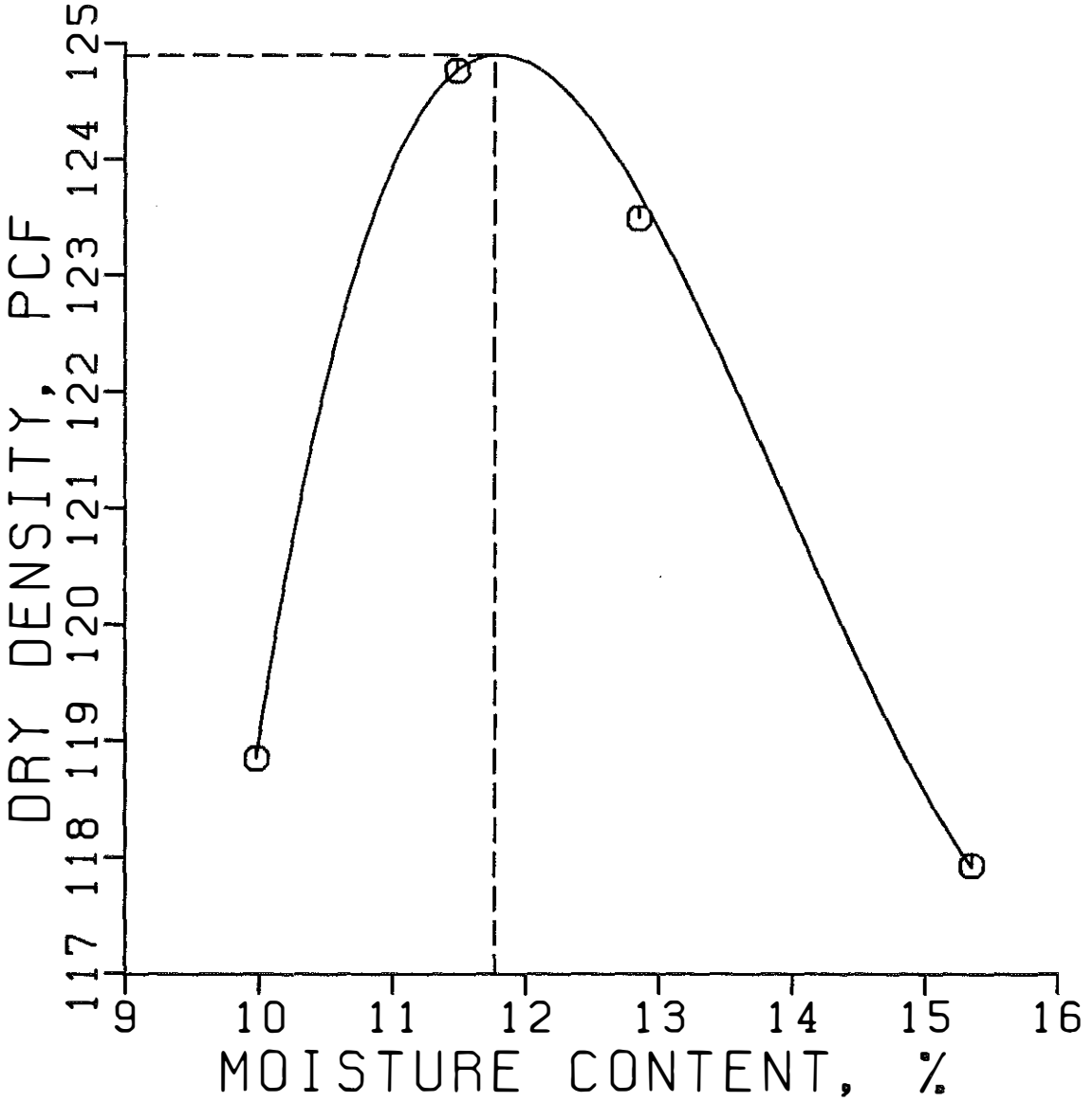
OPTIMUM MOISTURE CONTENT = 11.0 %
MAXIMUM DRY DENSITY = 132.8 PCF



SCRUBBER SLUDGE MIX 9

80 % DENSE GRADED AGGREGATE
20 % SLUDGE, CONSISTING OF:
2 % LIME
25 % FLY ASH
73 % FILTER CAKE

OPTIMUM MOISTURE CONTENT = 11.8 %
MAXIMUM DRY DENSITY = 124.9 PCF



APPENDIX E

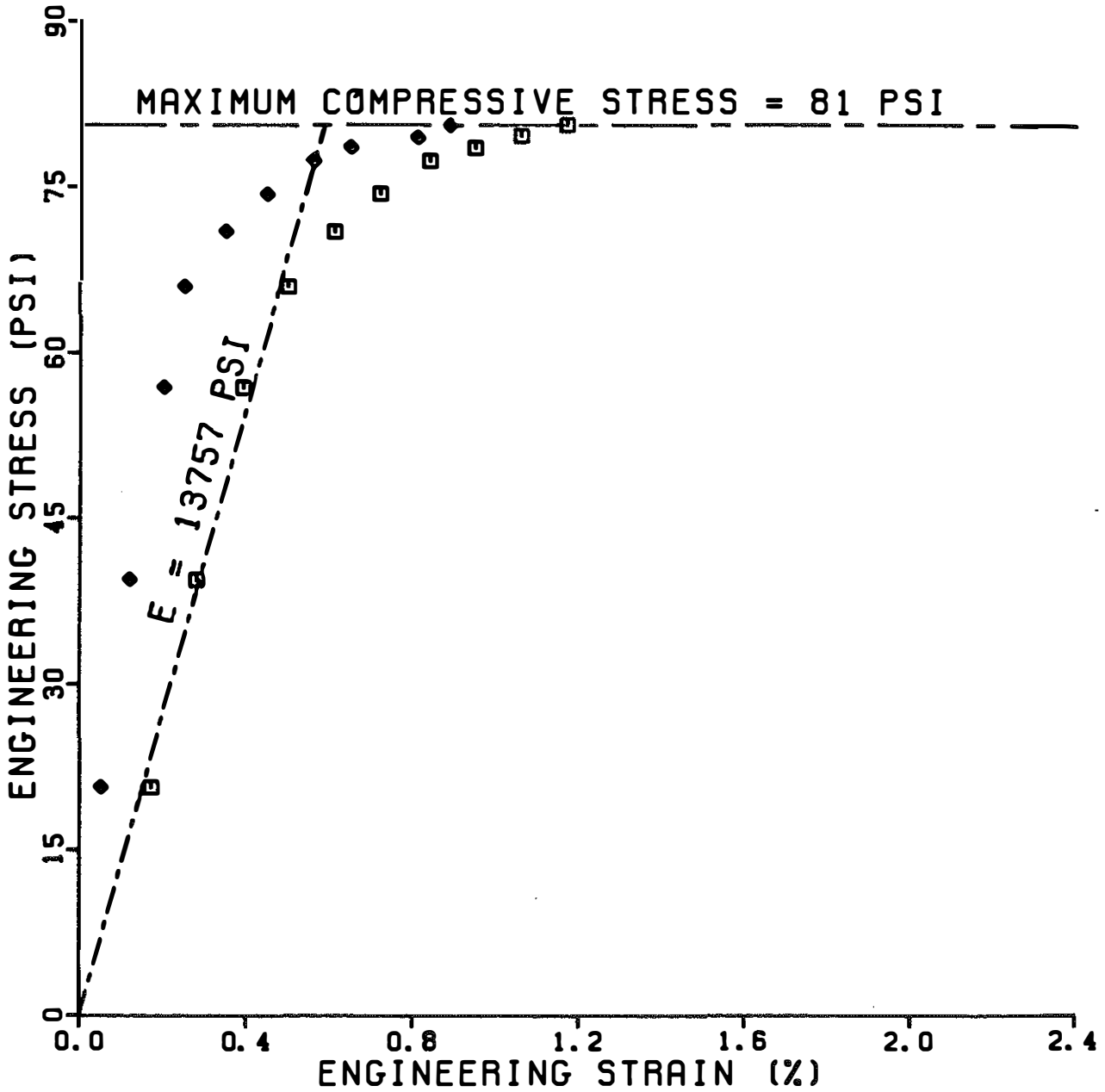
ANALYSES OF COMPRESSIVE STRENGTH AND STATIC-CHORD MODULUS OF ELASTICITY TESTS

SAMPLE NUMBER : F-1
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS



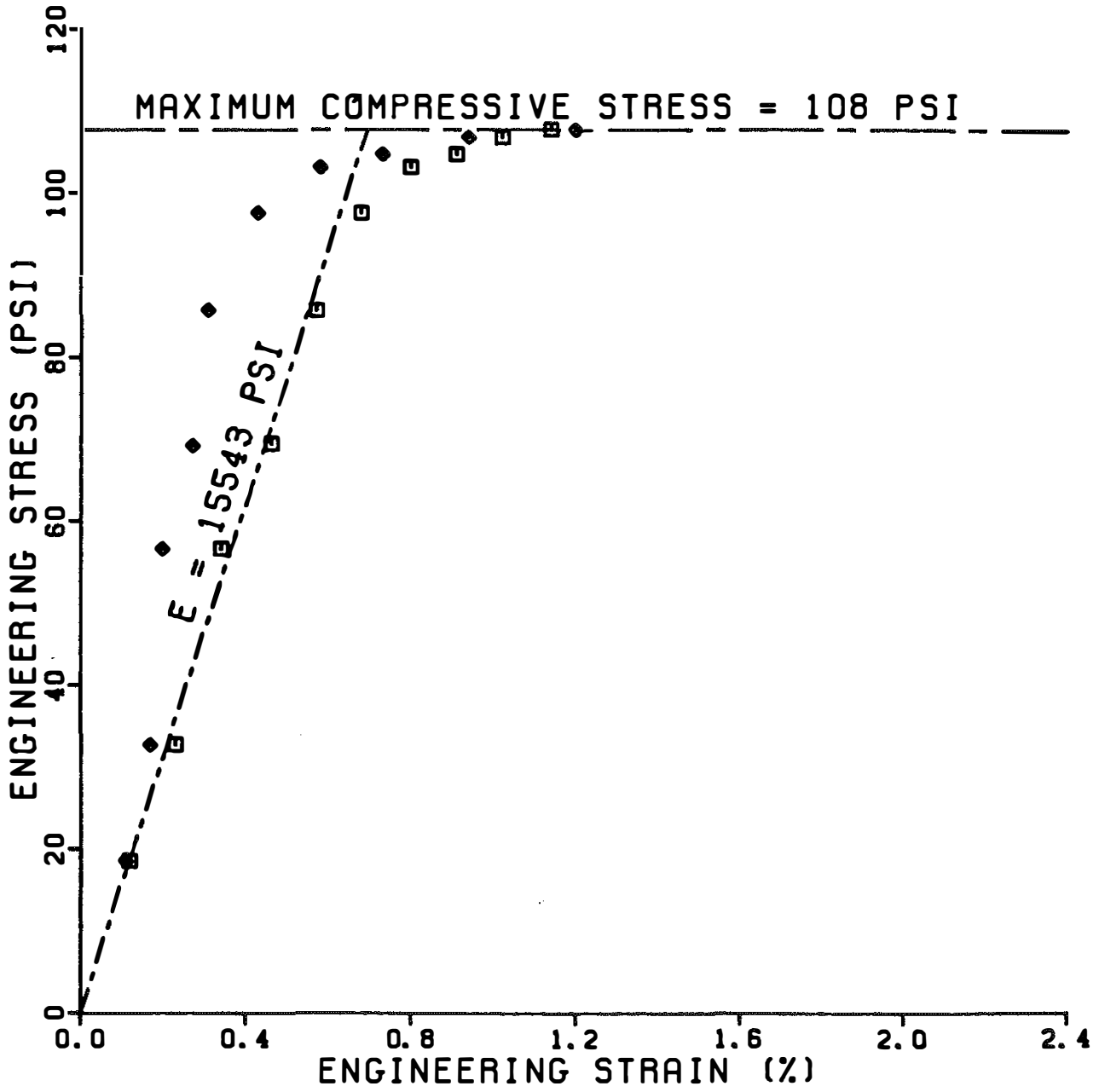
SAMPLE NUMBER : F-2
FIELD SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS

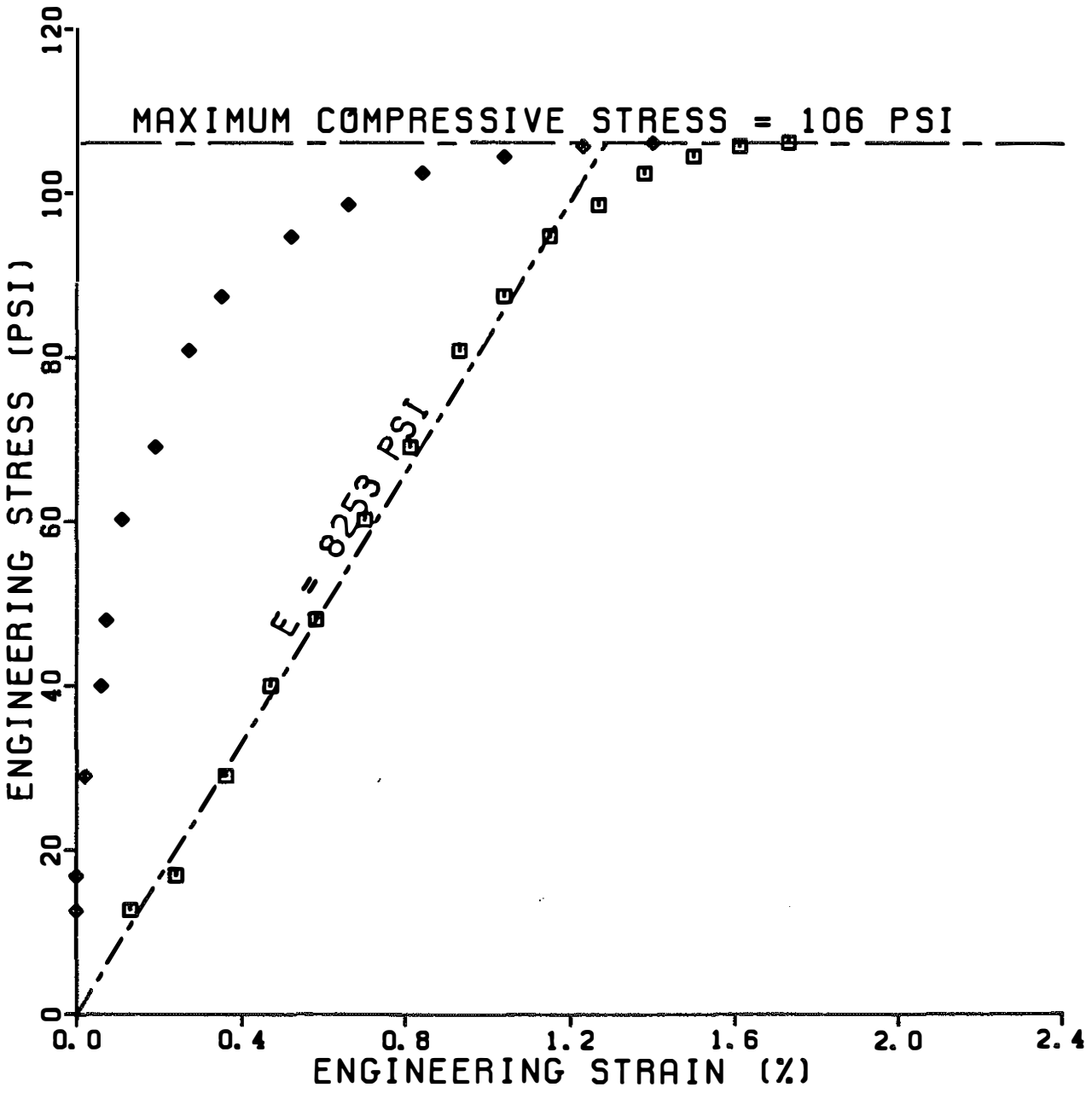


SAMPLE NUMBER : F-3
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS



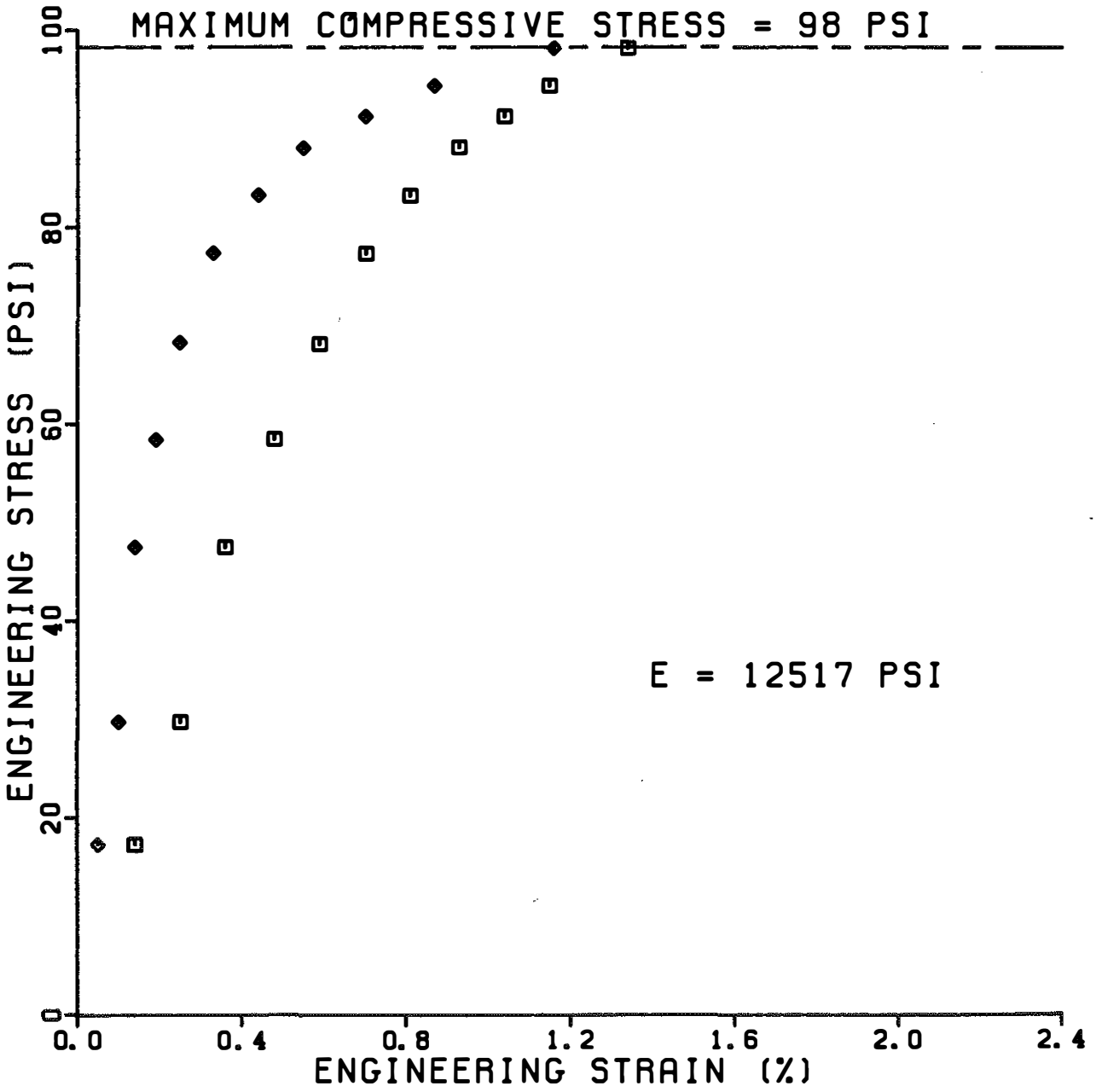
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS

MAXIMUM COMPRESSIVE STRESS = 98 PSI



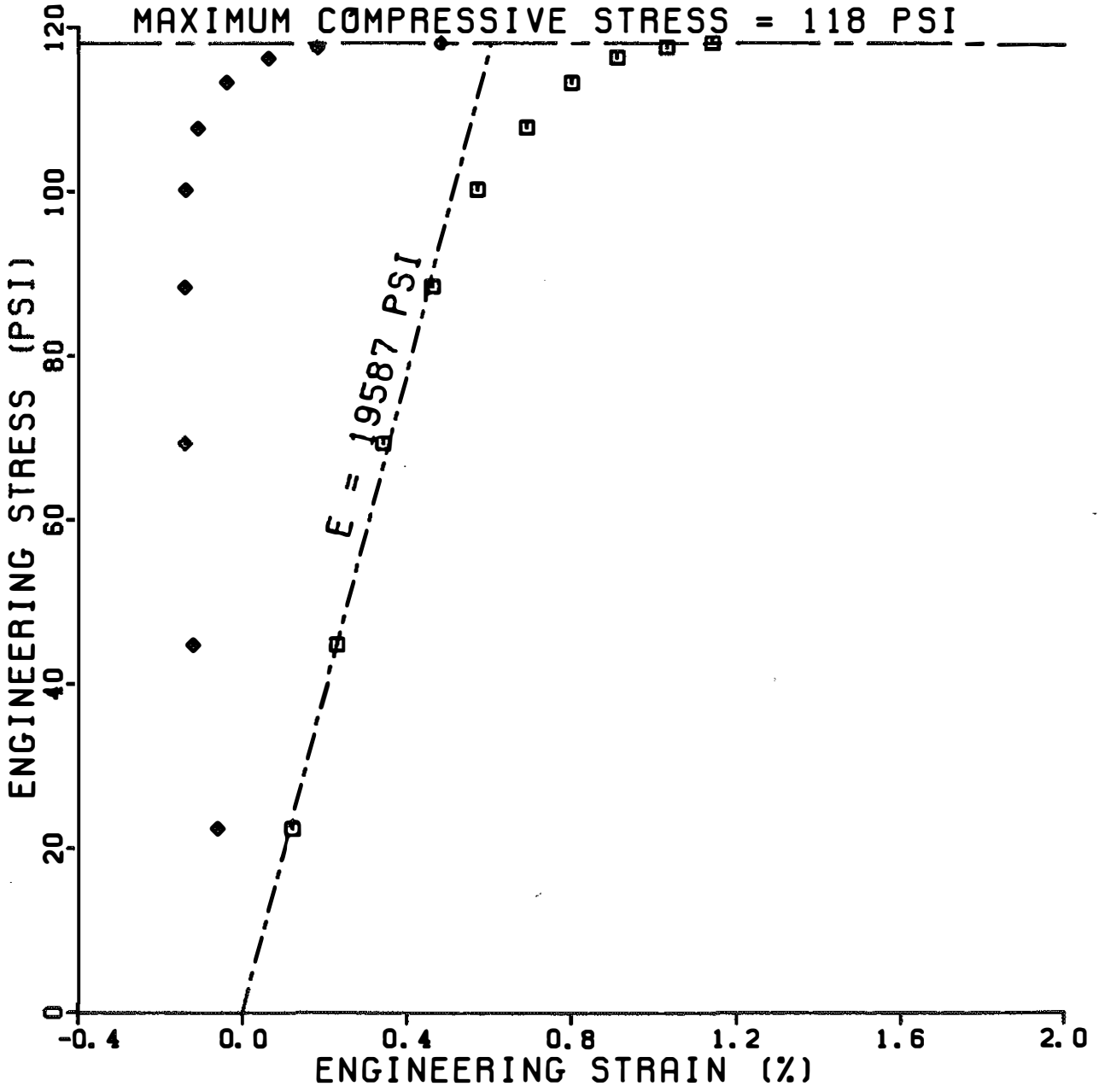
SAMPLE NUMBER : F-5
FIELD SLUDGE, 28-DAY AMBIENT CURING
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 118 PSI

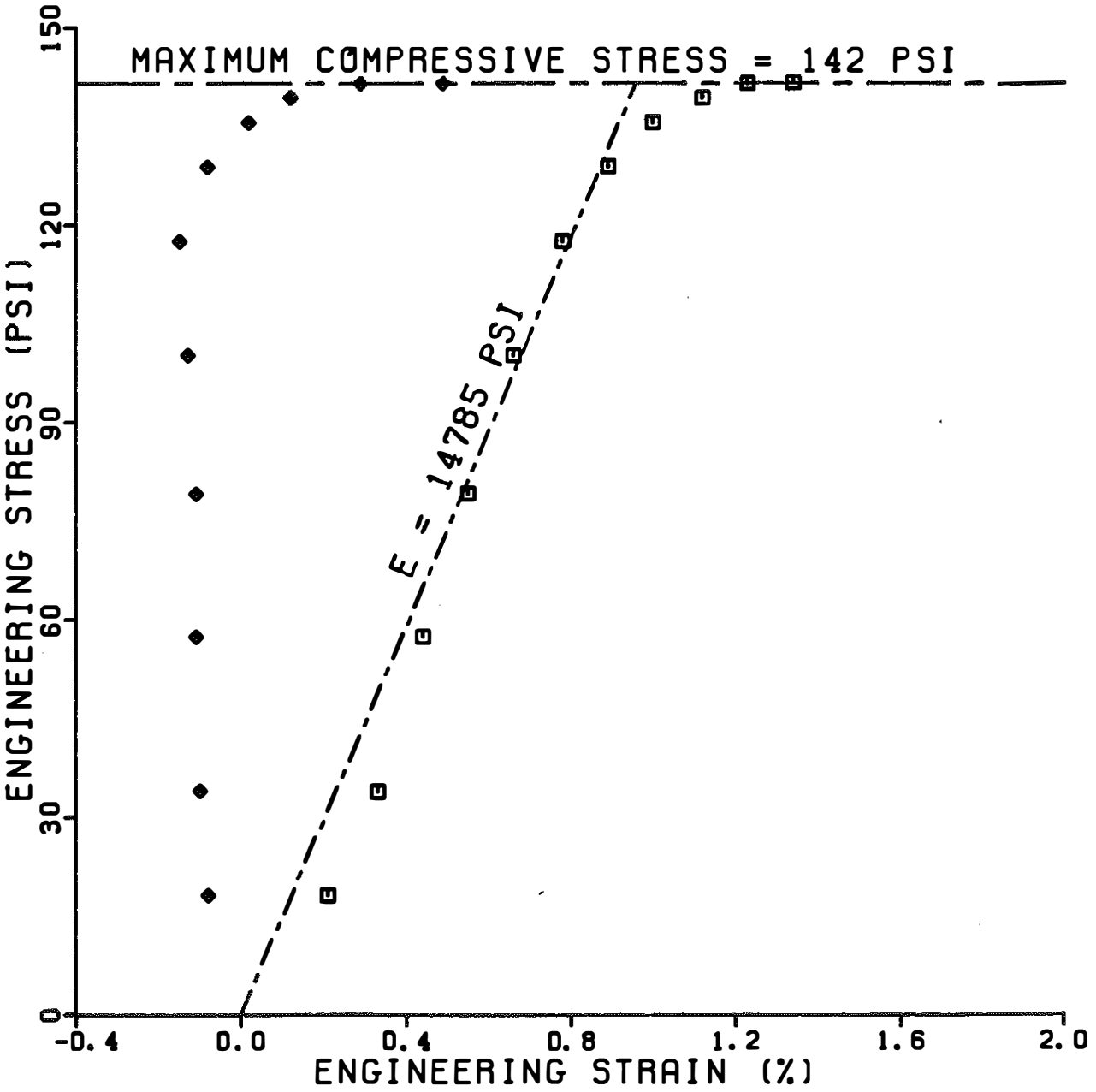


SAMPLE NUMBER : F-6
FIELD SLUDGE, 28-DAY AMBIENT CURING
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS



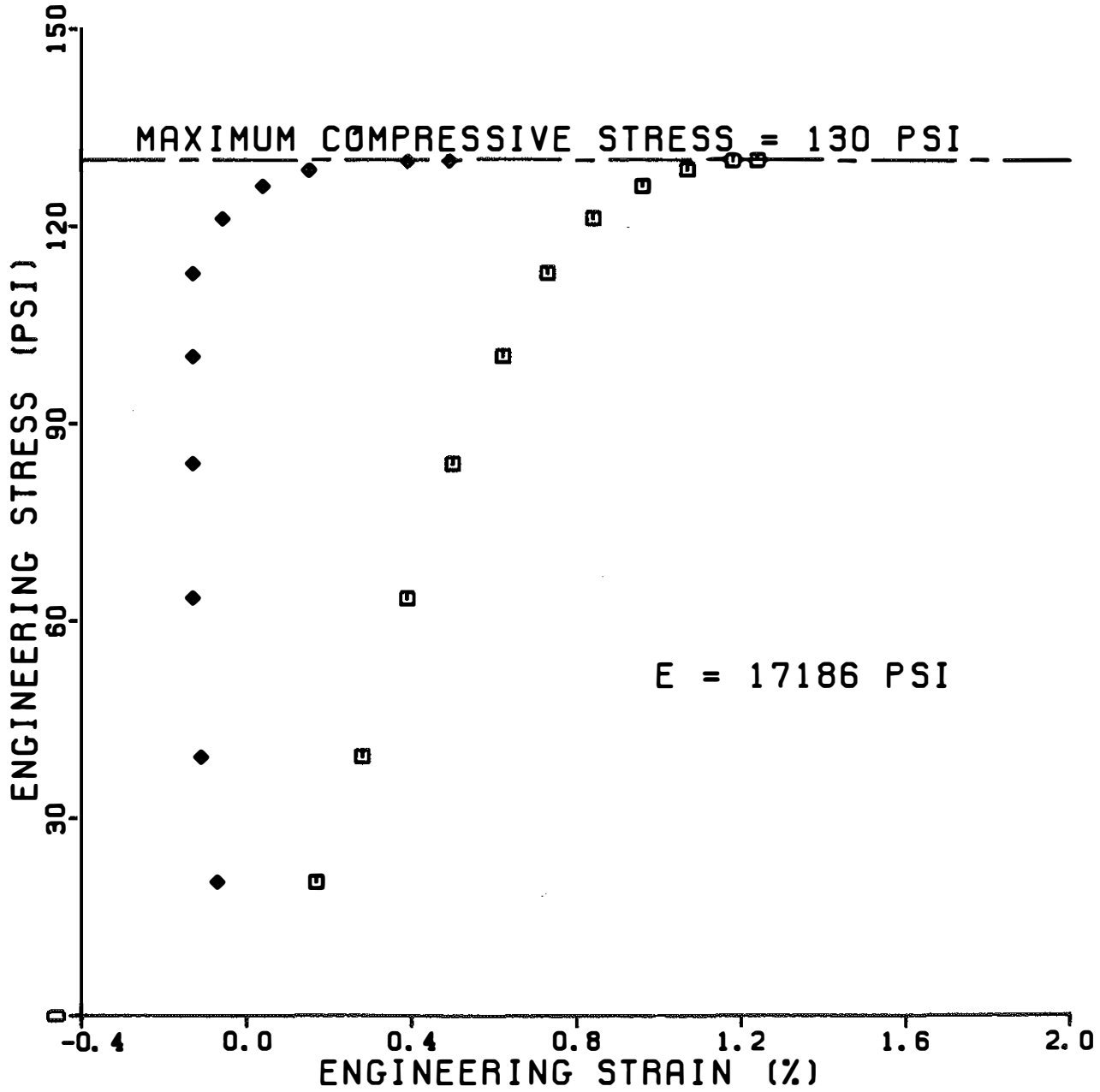
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 28-DAY AMBIENT CURING

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS

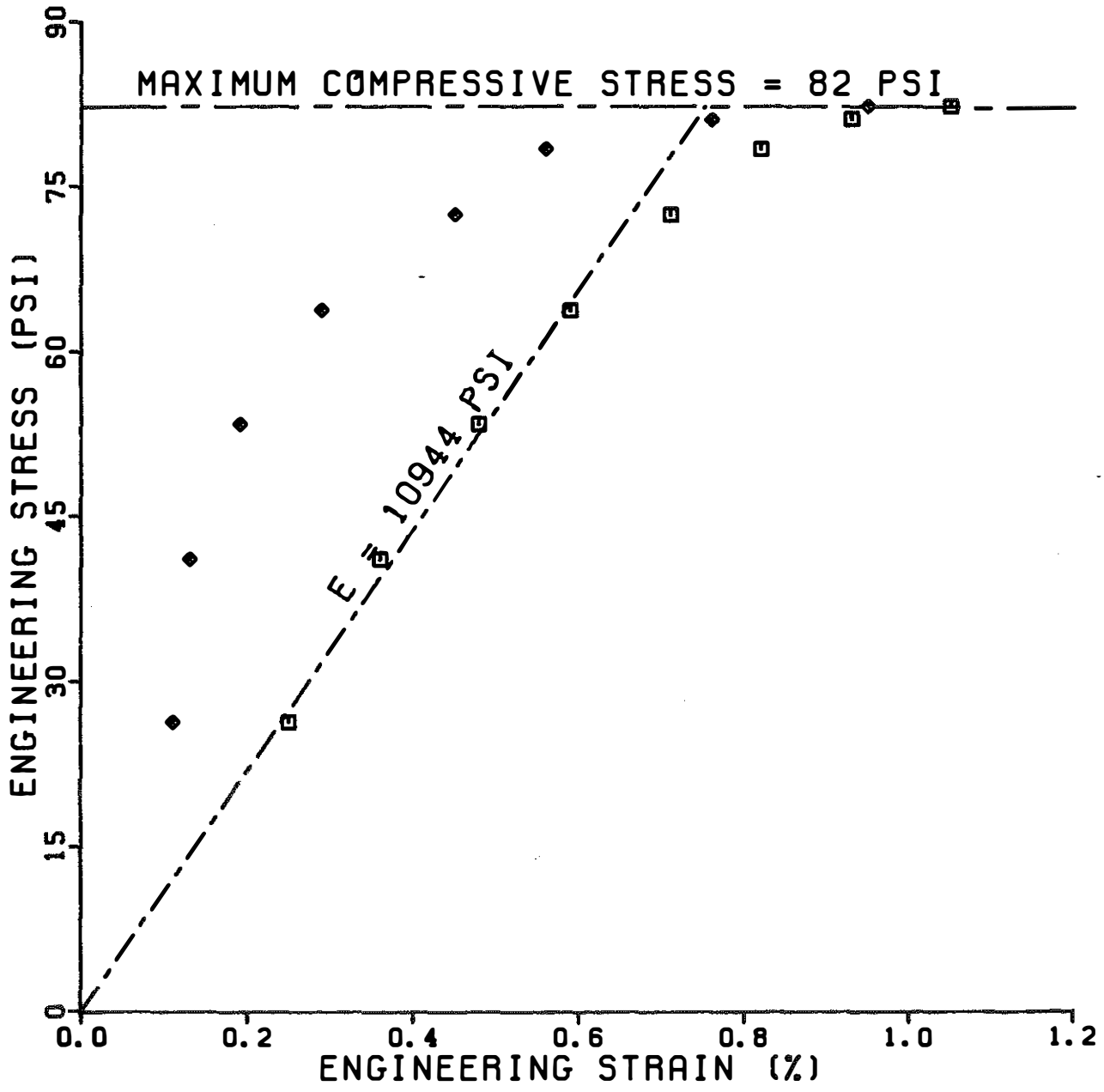


SAMPLE NUMBER : F-9
FIELD SLUDGE, 7-DAY AMBIENT CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS

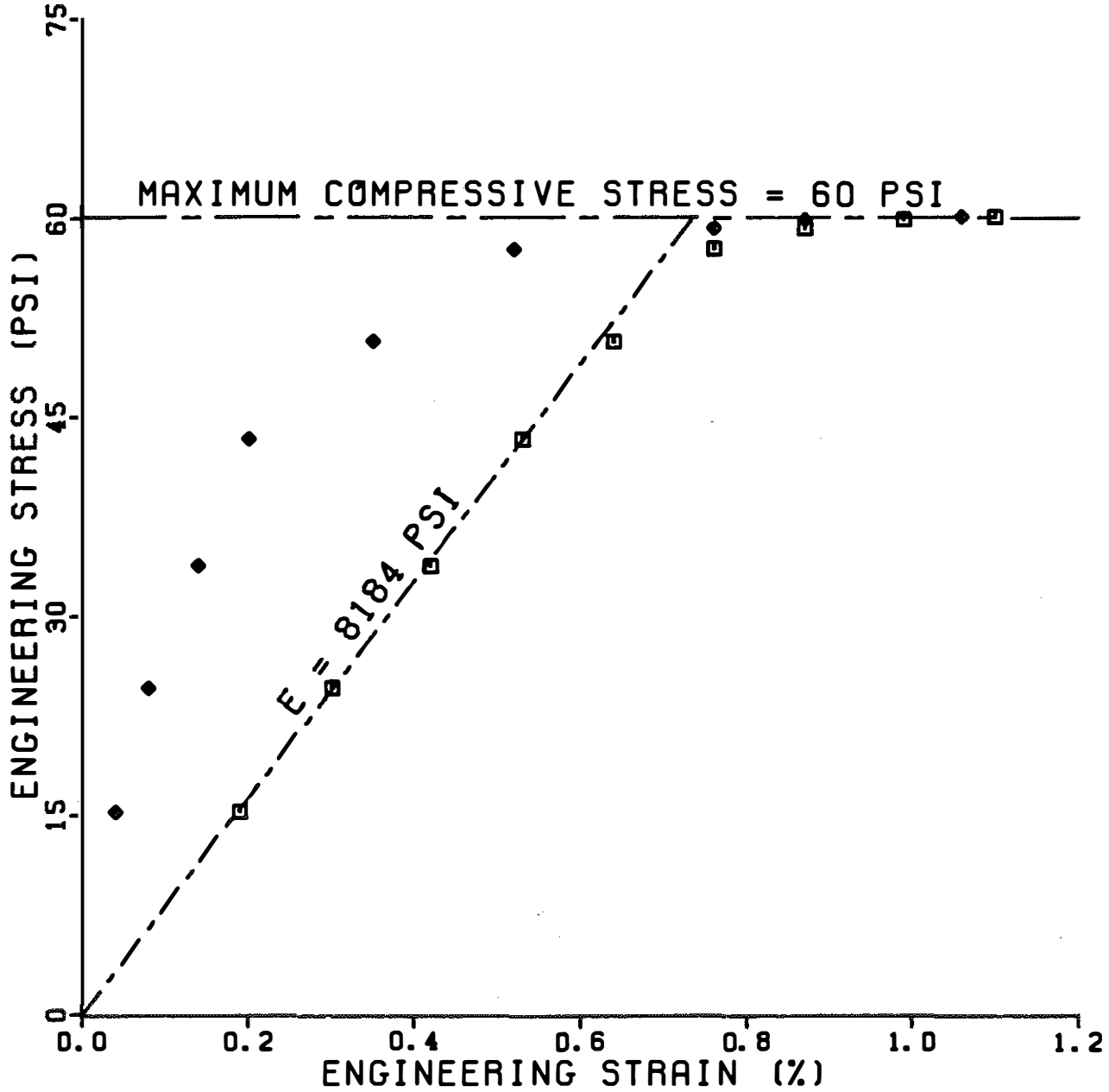


SAMPLE NUMBER : F-10
FIELD SLUDGE, 7-DAY AMBIENT CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS



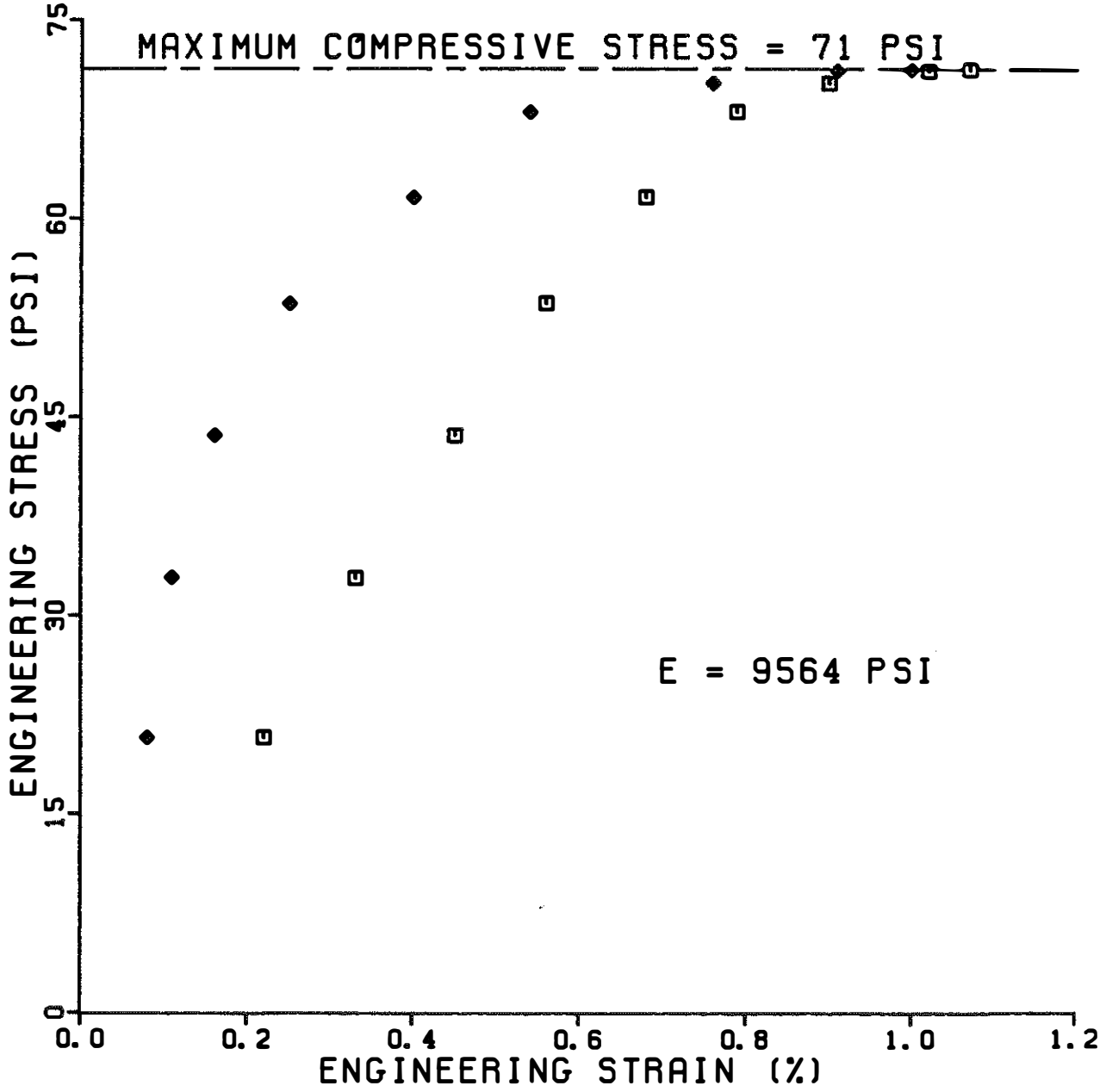
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY AMBIENT CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % COARSE
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 7 DAYS

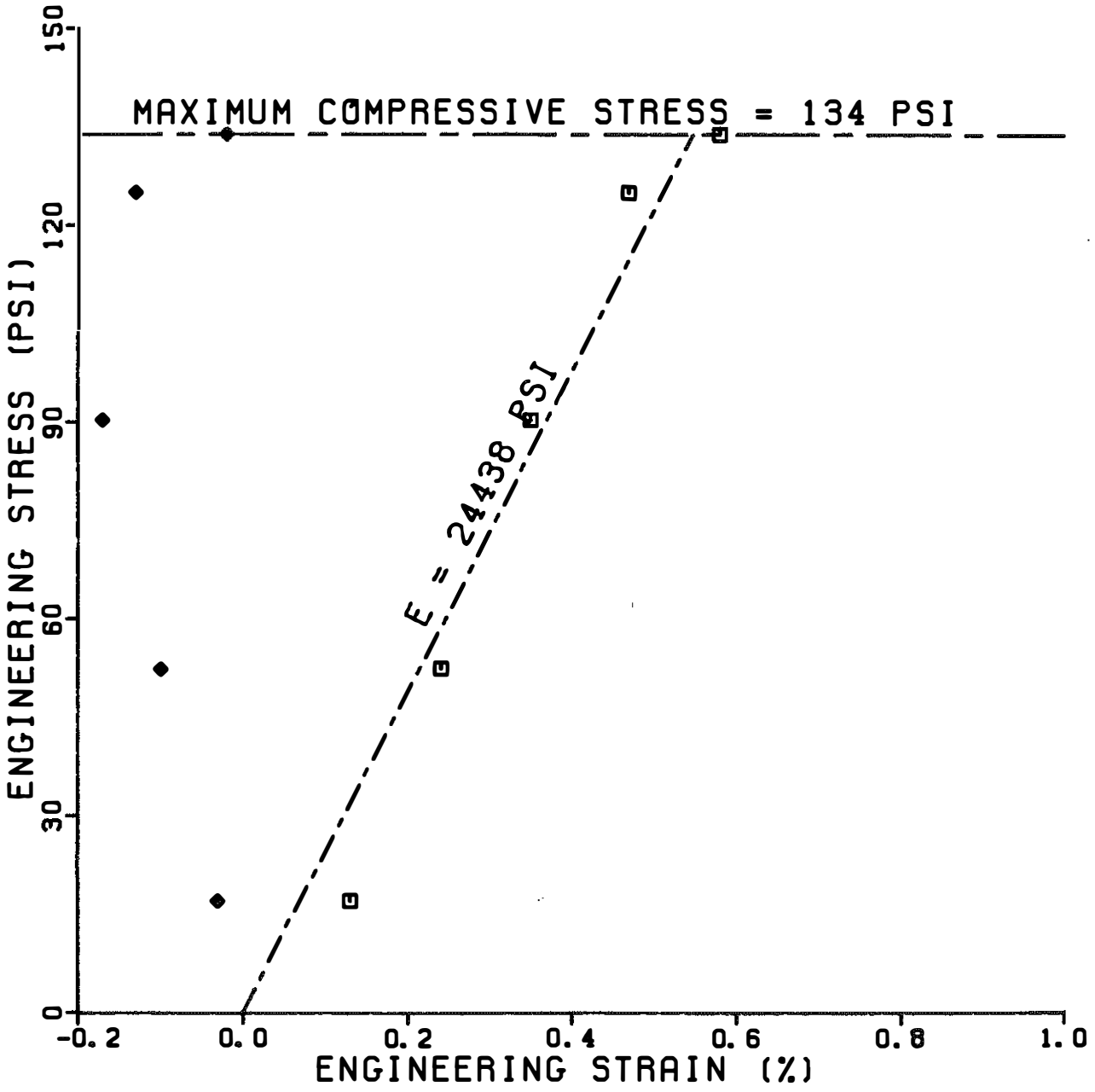


SAMPLE NUMBER : F-11
FIELD SLUDGE, 62-DAY AMBIENT CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 62 DAYS

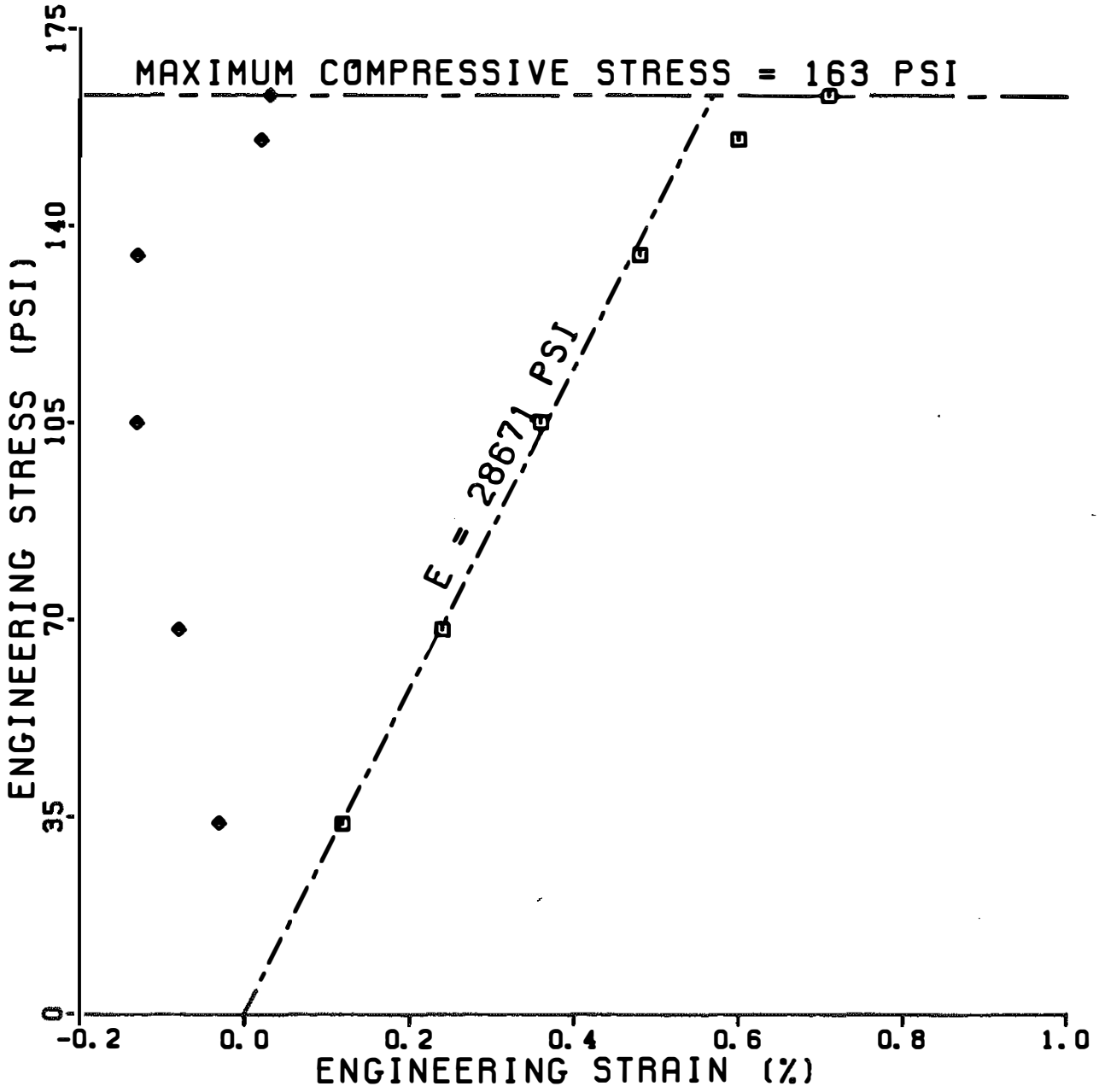


SAMPLE NUMBER : F-13
FIELD SLUDGE, 62-DAY AMBIENT CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 62 DAYS



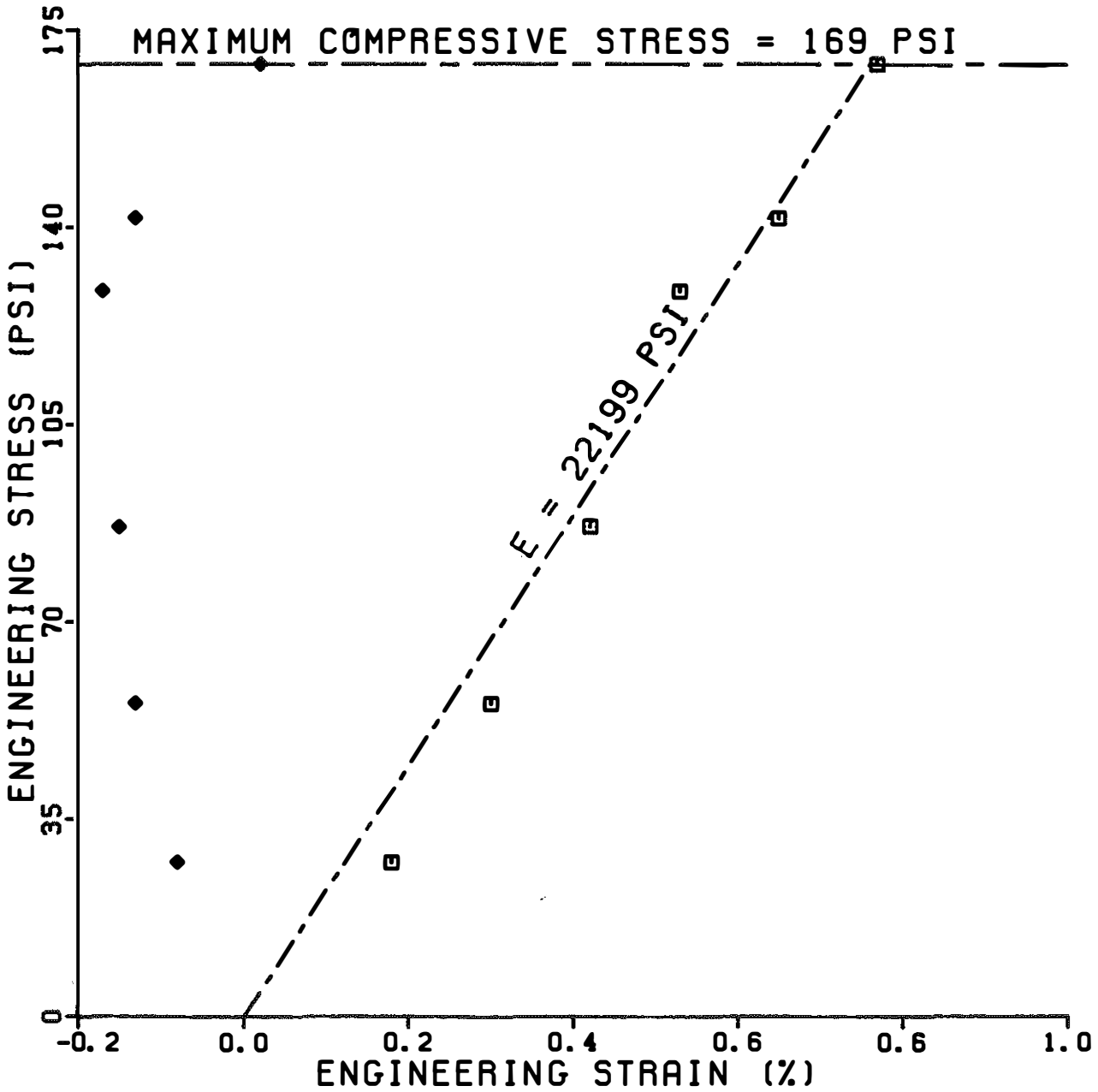
SAMPLE NUMBER : F-14
FIELD SLUDGE, 62-DAY AMBIENT CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 62 DAYS



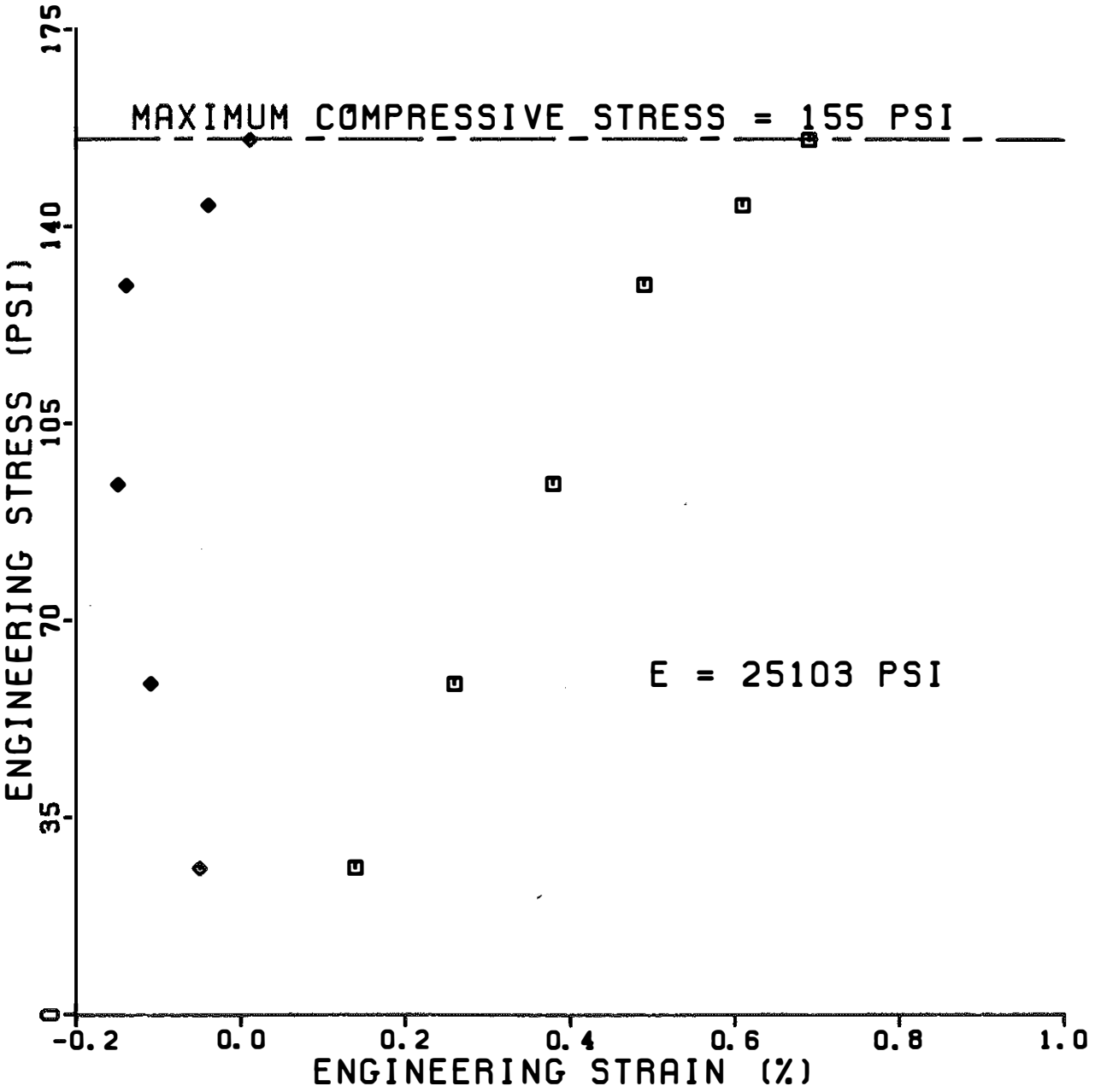
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 62-DAY AMBIENT CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 62 DAYS

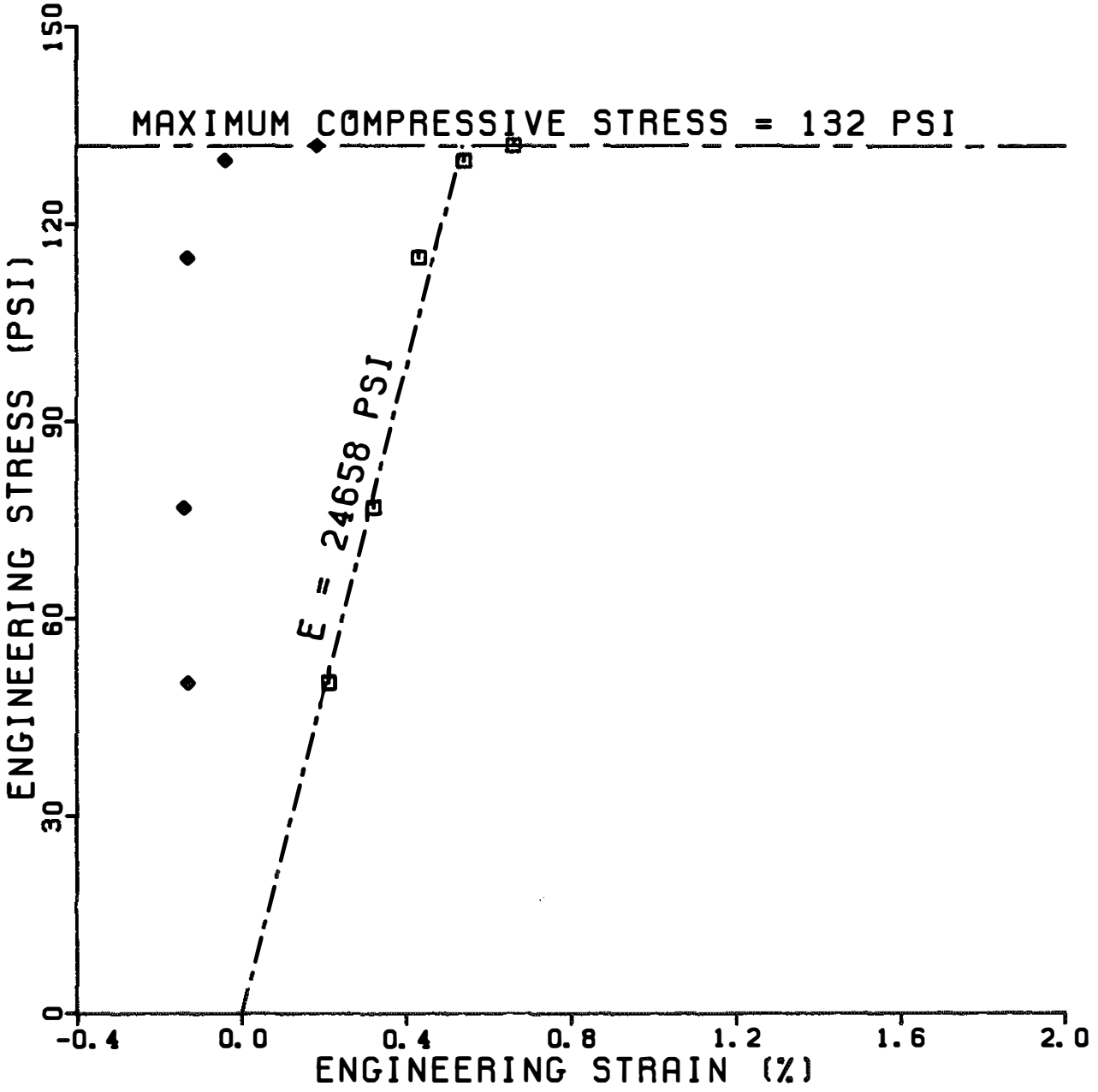


SAMPLE NUMBER : F-18
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS

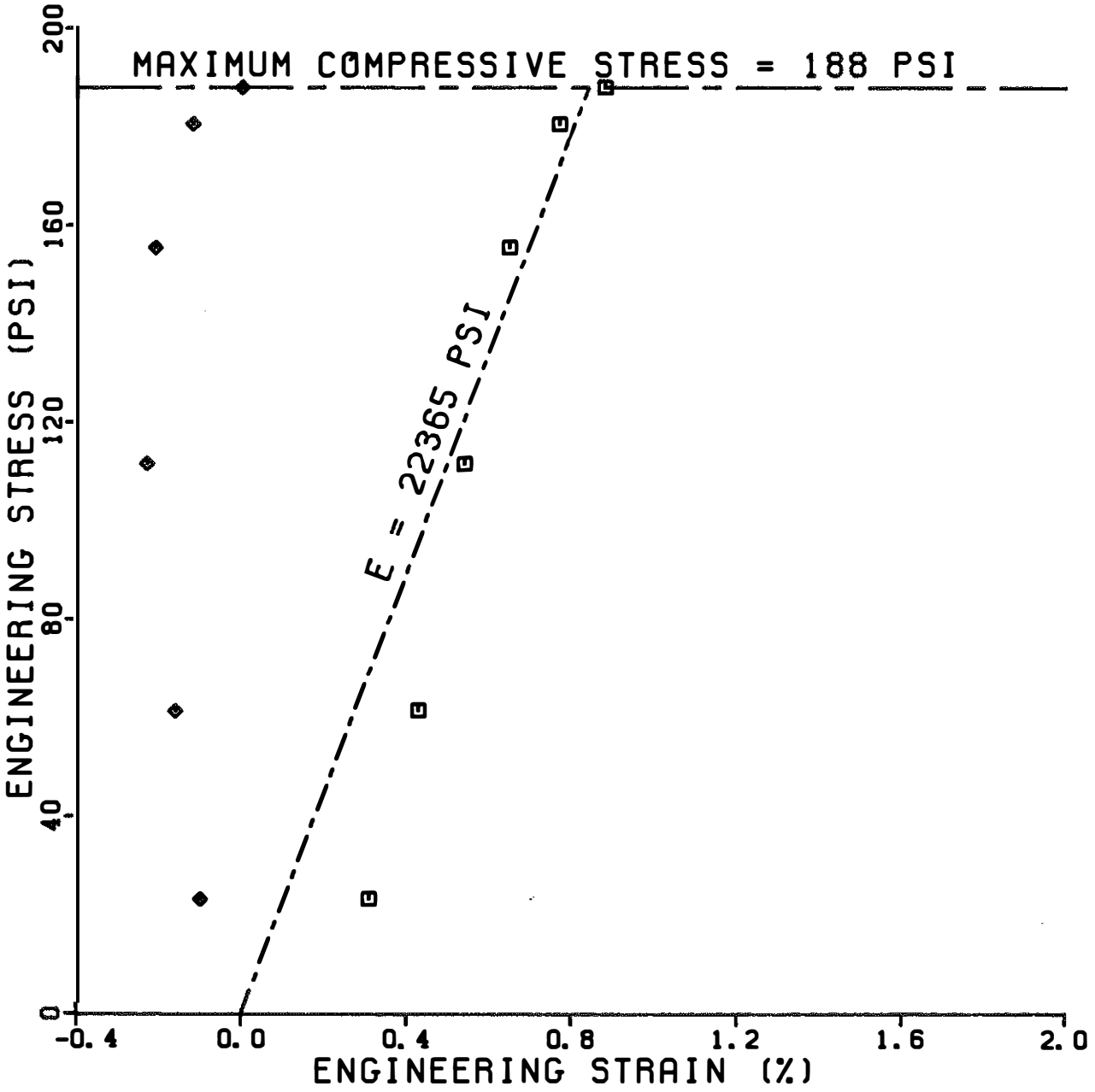


SAMPLE NUMBER : F-19
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS

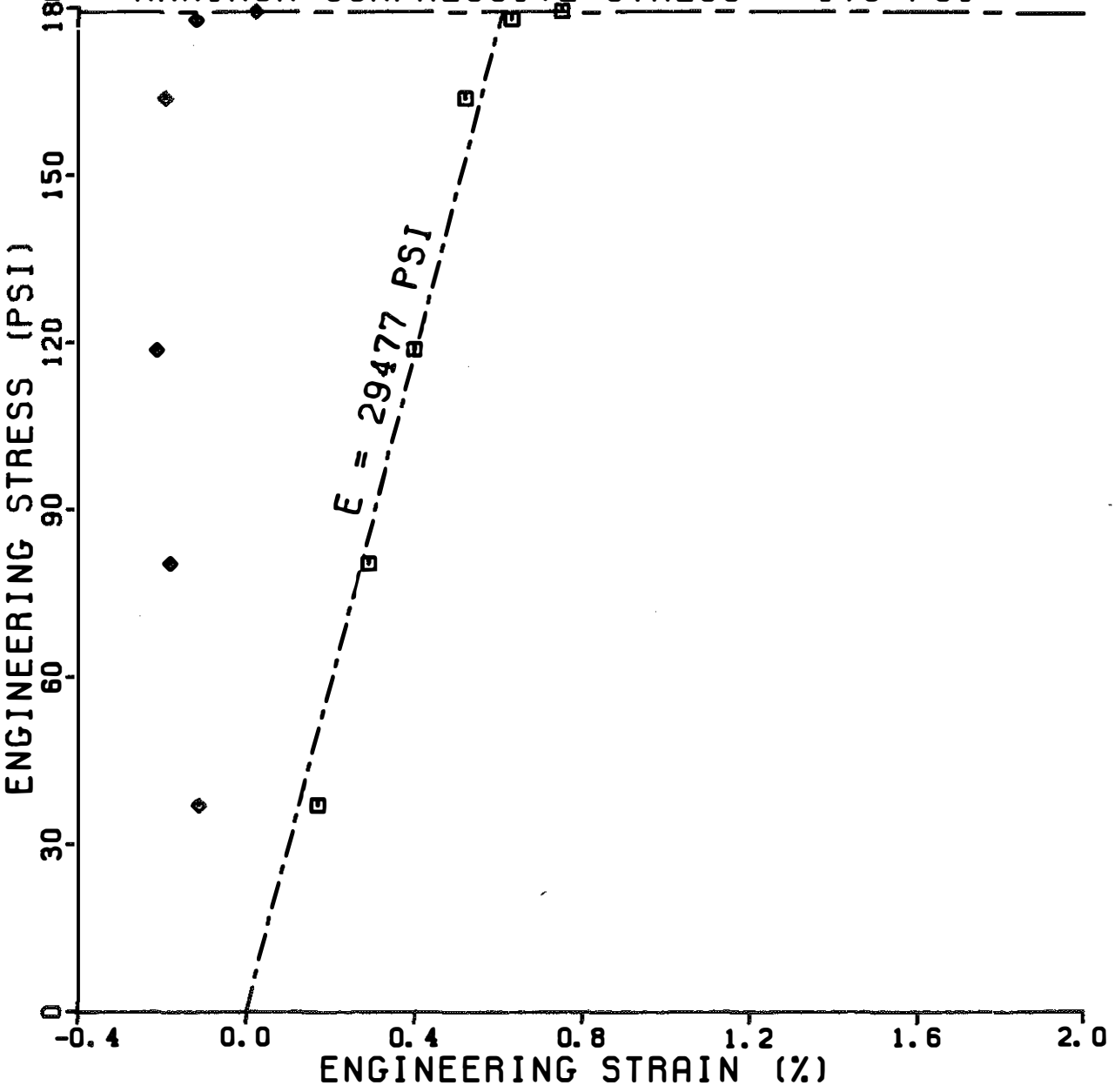


SAMPLE NUMBER : F-20
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 179 PSI



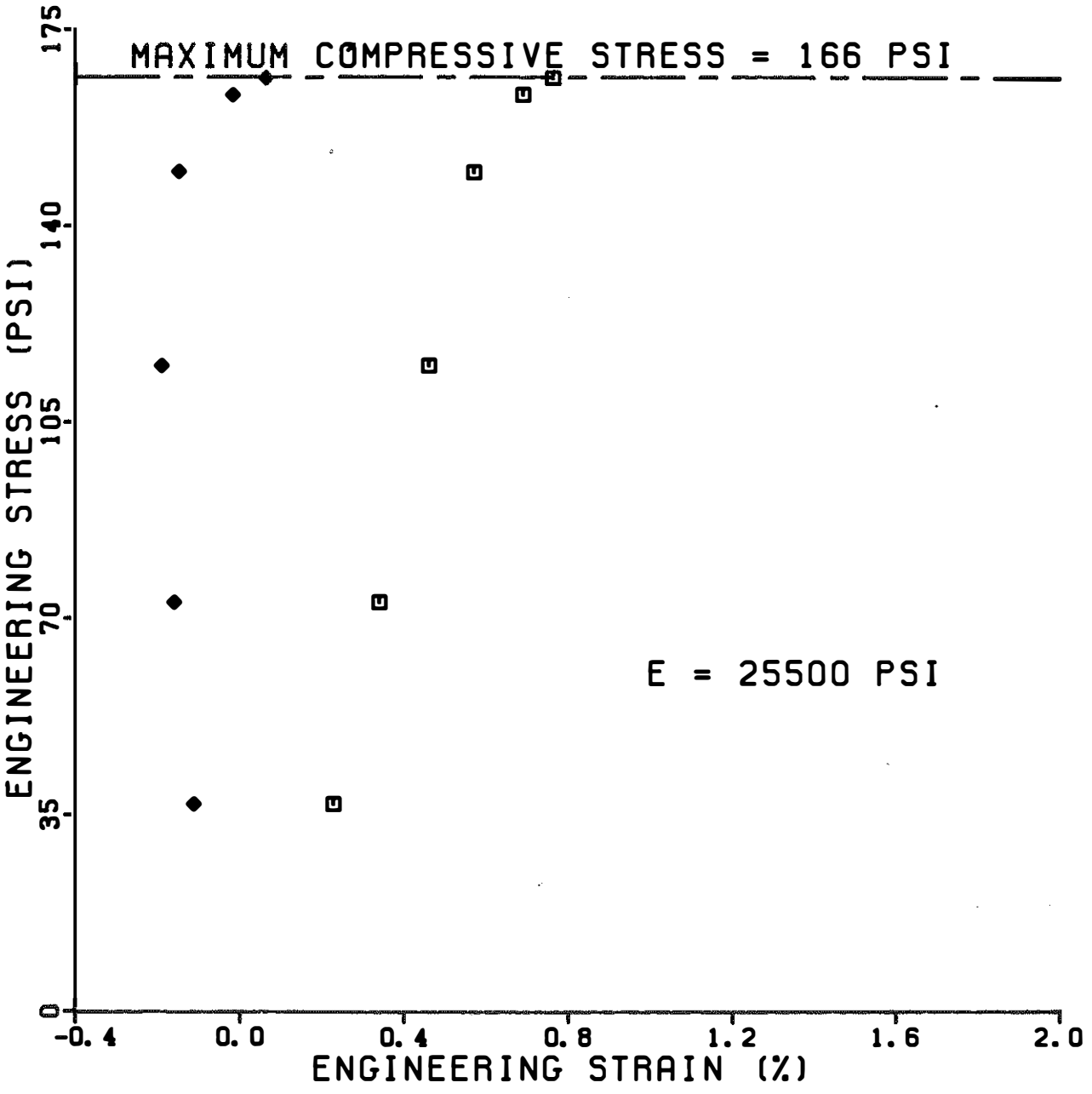
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 72 PCF
OPTIMUM MOISTURE = 43.7 %

MADE 4/21/83 -- CURED 28 DAYS

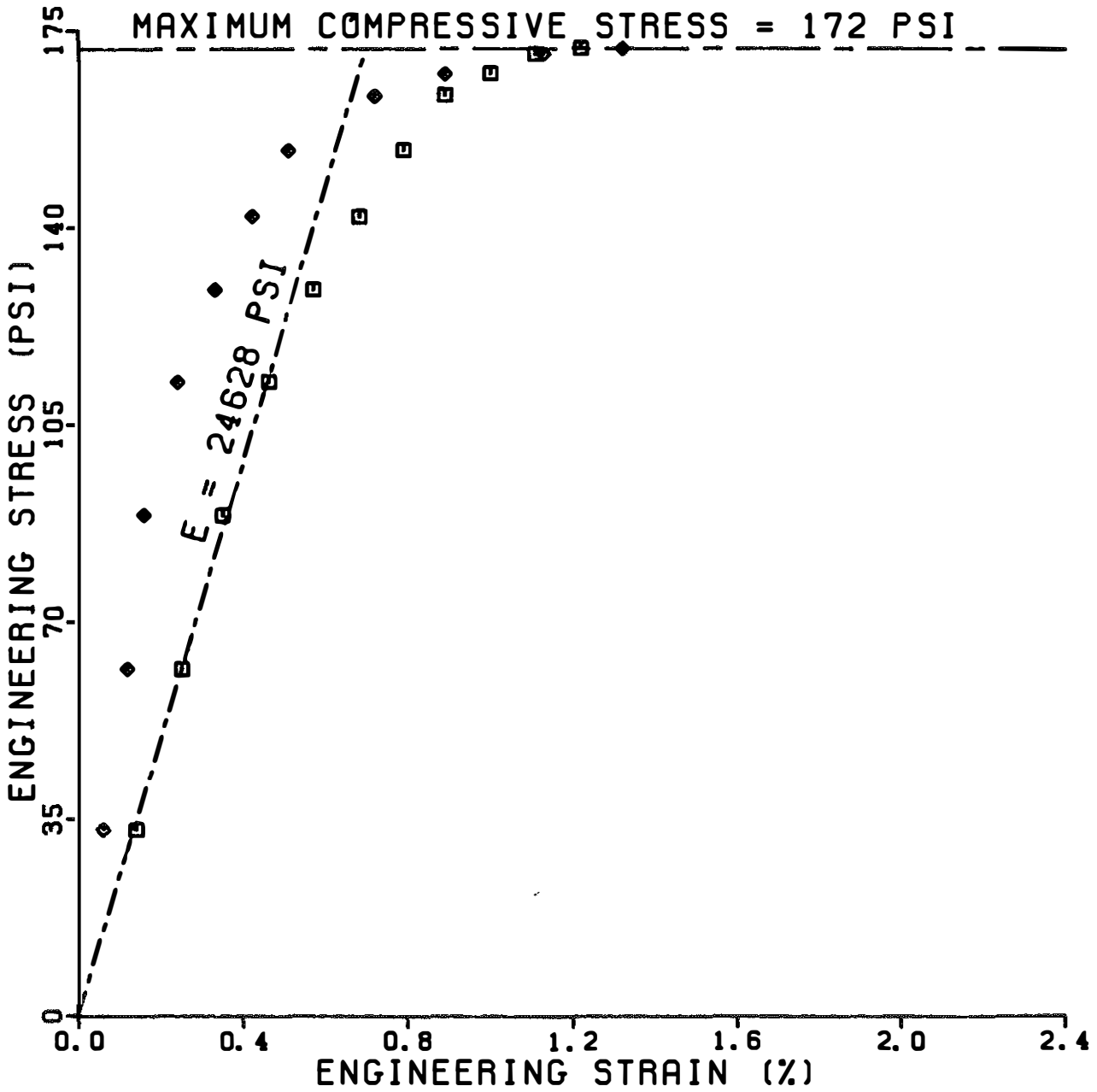


SAMPLE NUMBER : F-21
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
30 % POND ASH
70 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 128 PCF
OPTIMUM MOISTURE = 12.4 %

MADE 4/21/83 -- CURED 7 DAYS



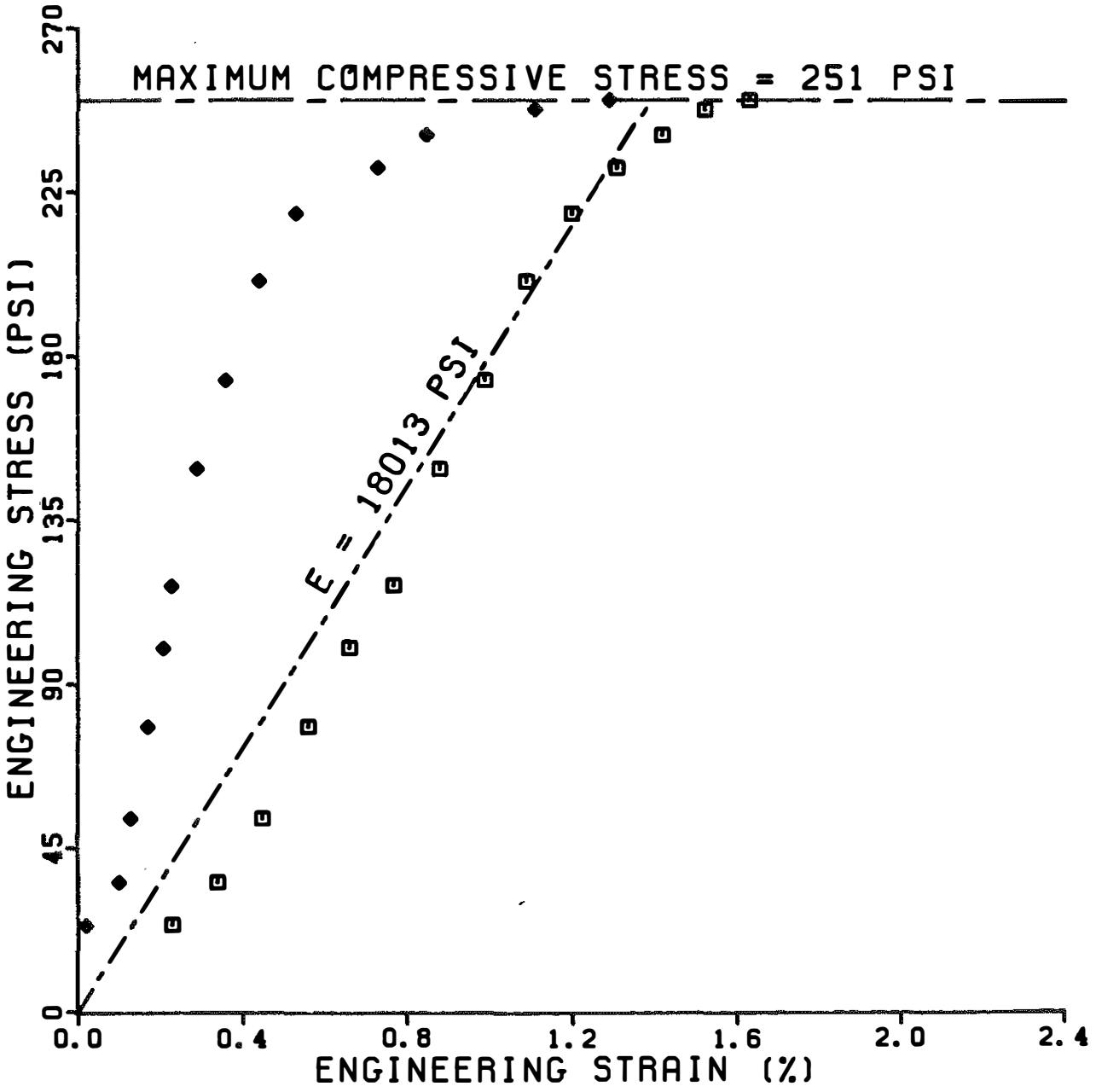
SAMPLE NUMBER : F-22
FIELD SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
30 % POND ASH
70 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 128 PCF
OPTIMUM MOISTURE = 12.4 %

MADE 4/21/83 -- CURED 7 DAYS



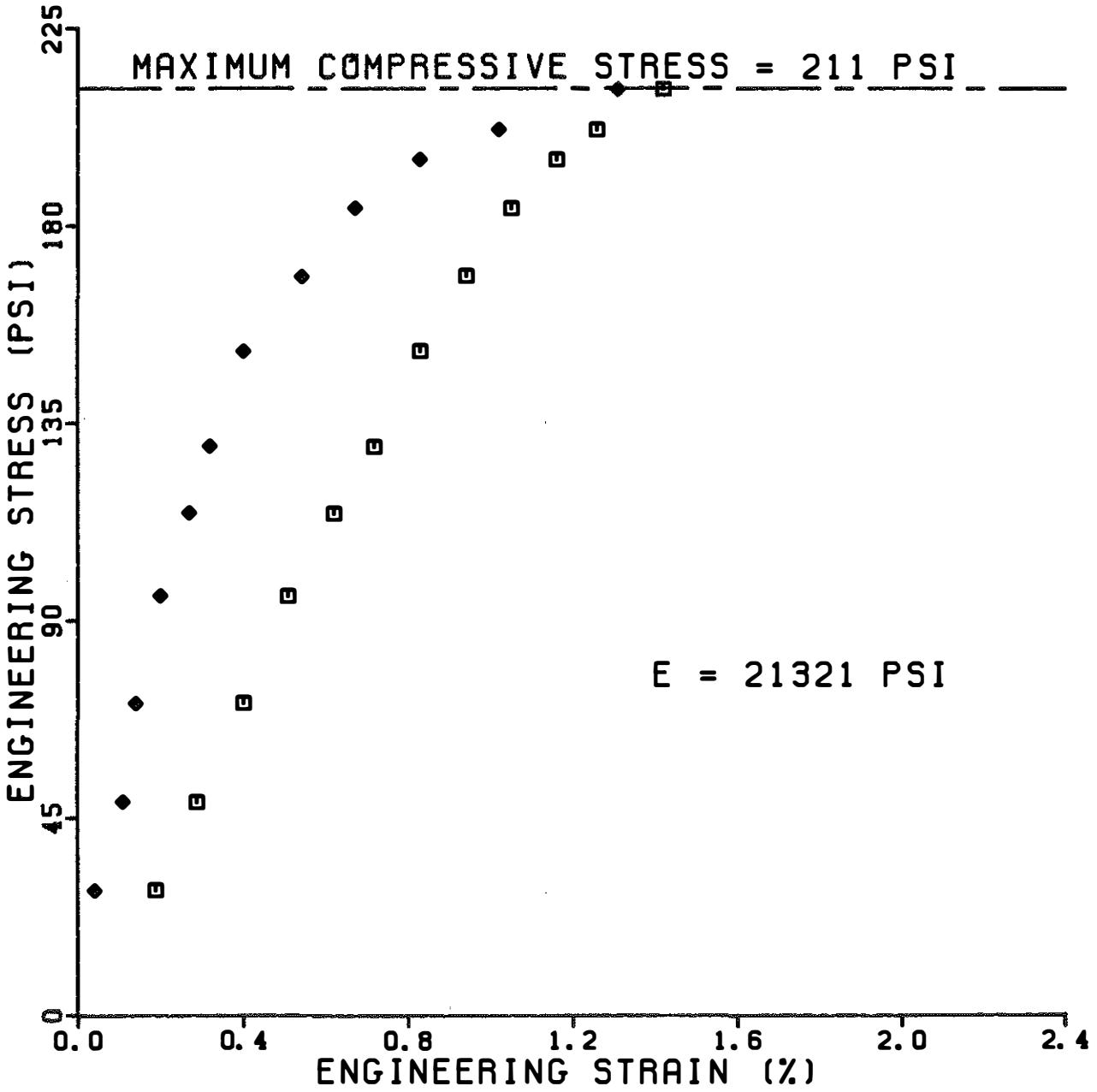
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
30 % POND ASH
70 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 128 PCF
OPTIMUM MOISTURE = 12.4 %

MADE 4/21/83 -- CURED 7 DAYS



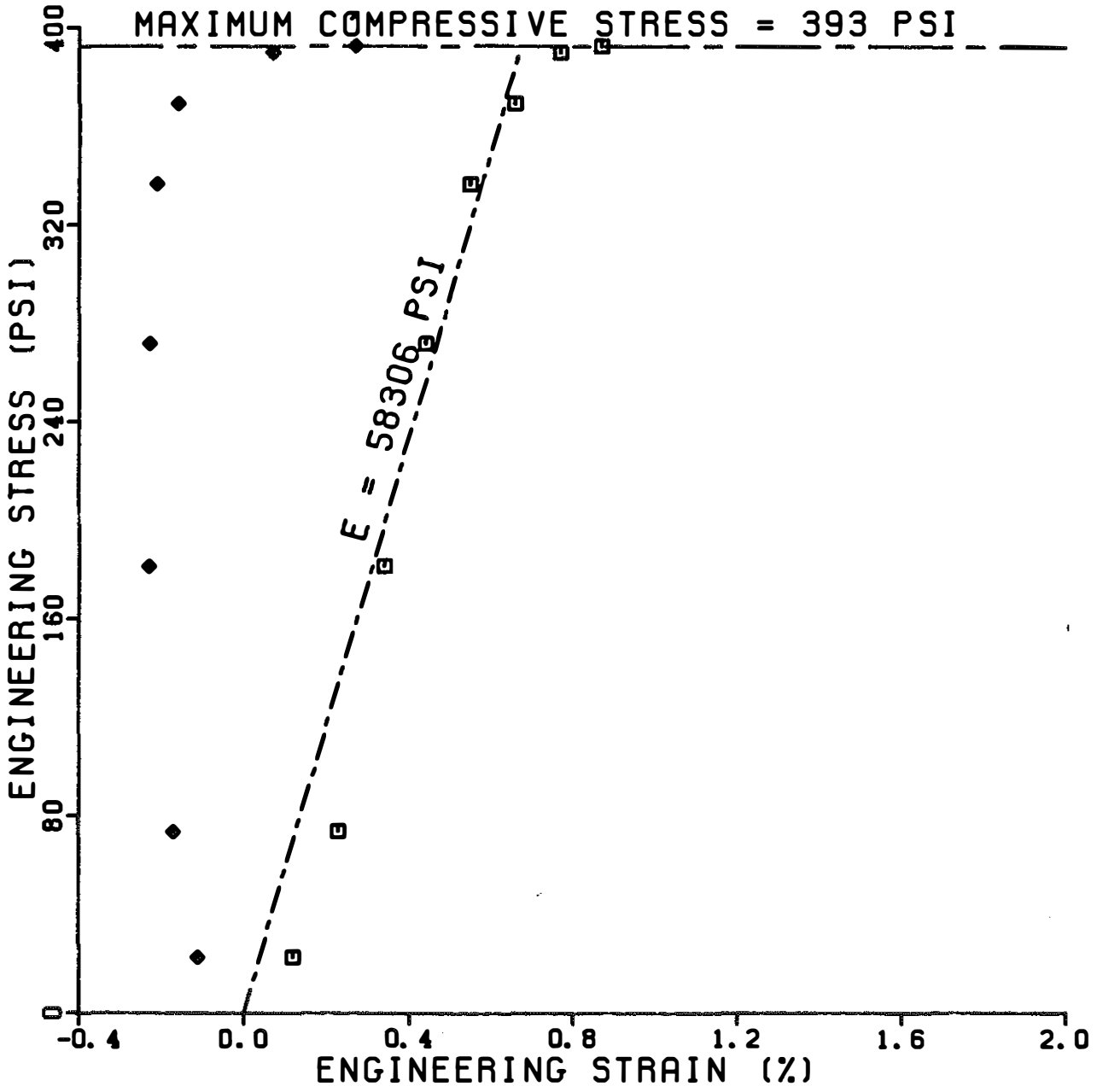
SAMPLE NUMBER : F-23
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
70 % POND ASH
30 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 128 PCF
OPTIMUM MOISTURE = 12.4 %

MADE 4/21/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 393 PSI

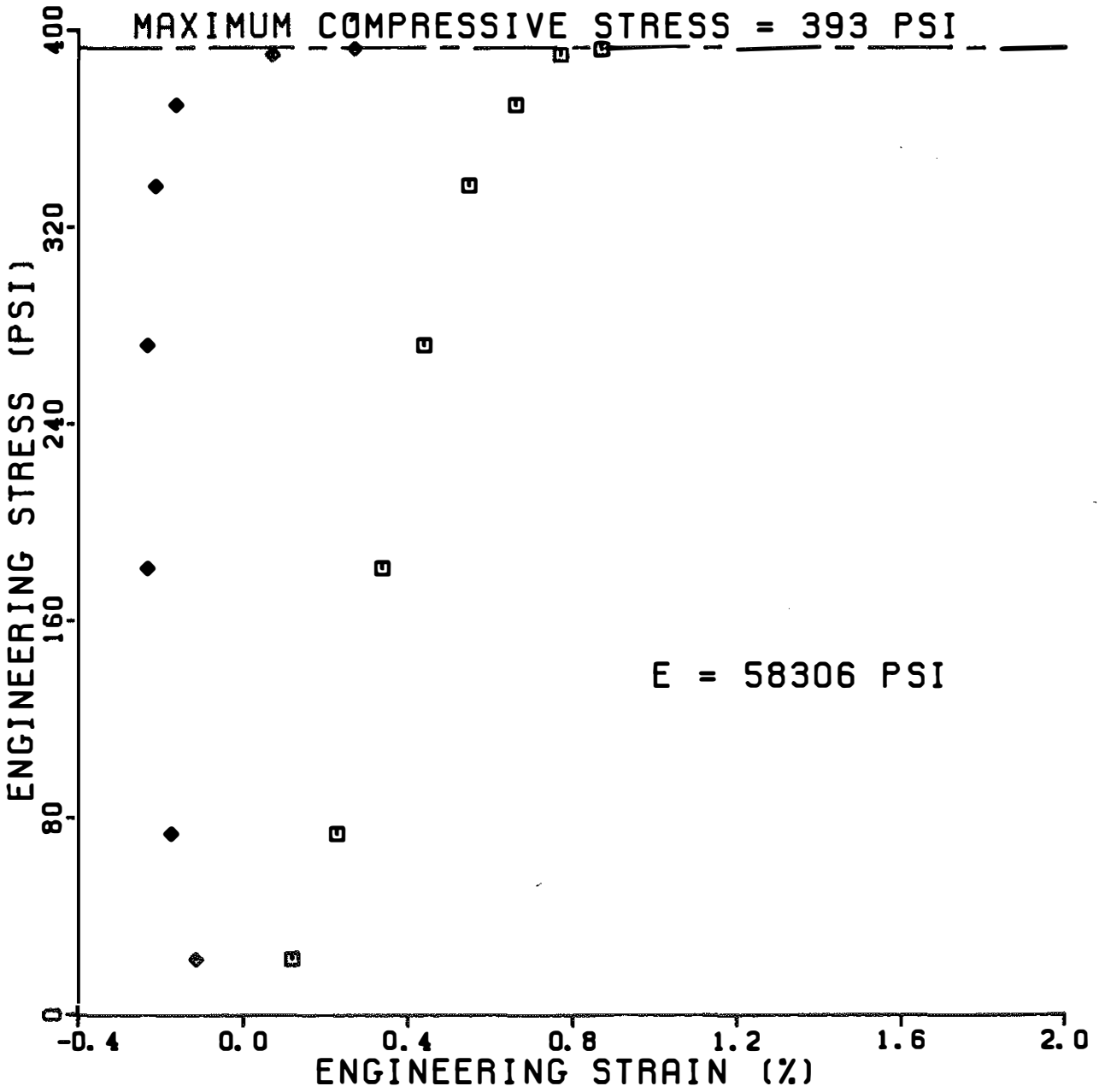


SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
70 % POND ASH
30 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 128 PCF
OPTIMUM MOISTURE = 12.4 %

MADE 4/21/83 -- CURED 28 DAYS

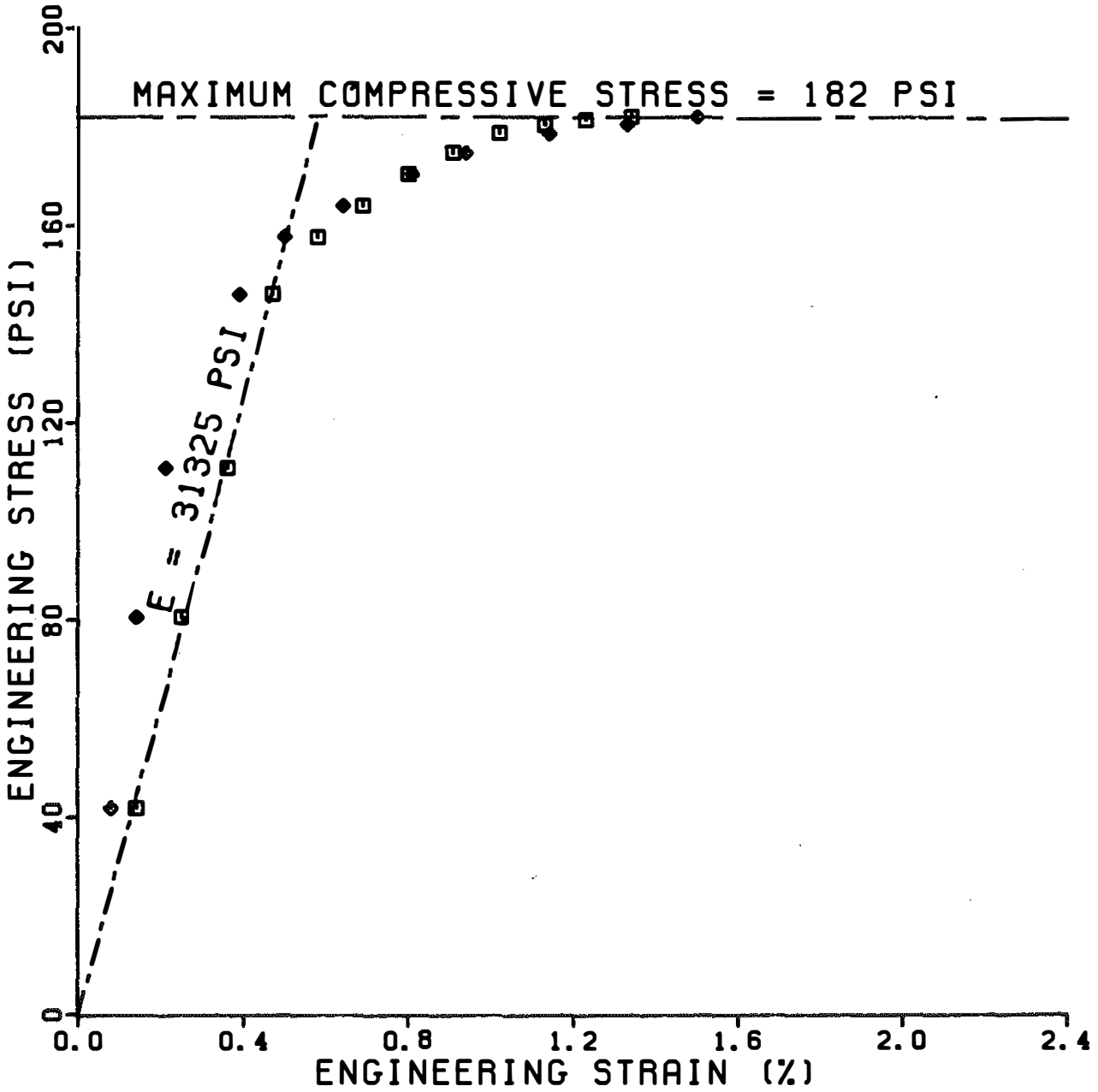


SAMPLE NUMBER : F-25
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 157 PCF
OPTIMUM MOISTURE = 9.5 %

MADE 4/21/83 -- CURED 7 DAYS

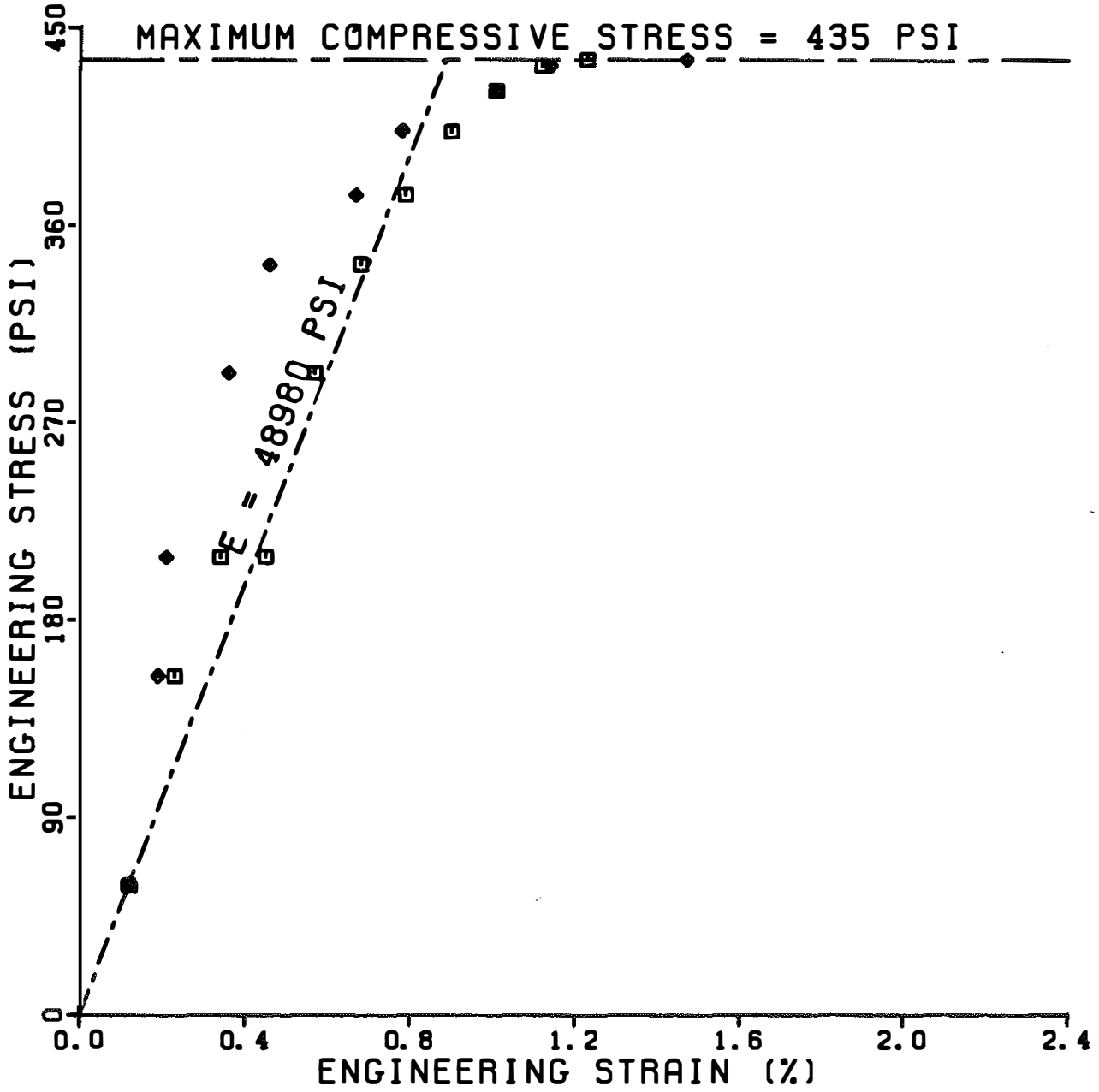


SAMPLE NUMBER : F-26
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 157 PCF
OPTIMUM MOISTURE = 9.5 %

MADE 4/21/83 -- CURED 7 DAYS



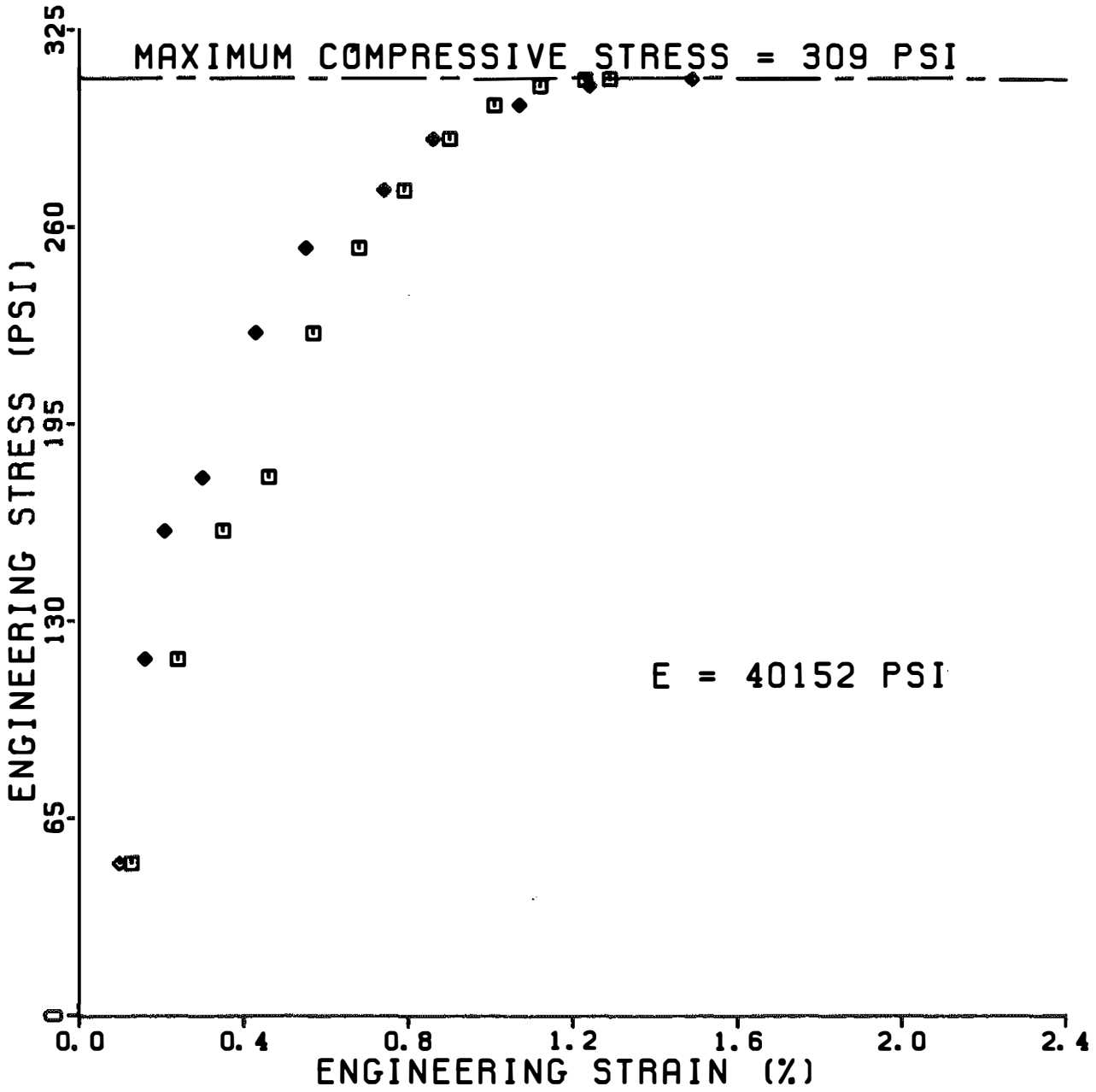
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 157 PCF
OPTIMUM MOISTURE = 9.5 %

MADE 4/21/83 -- CURED 7 DAYS

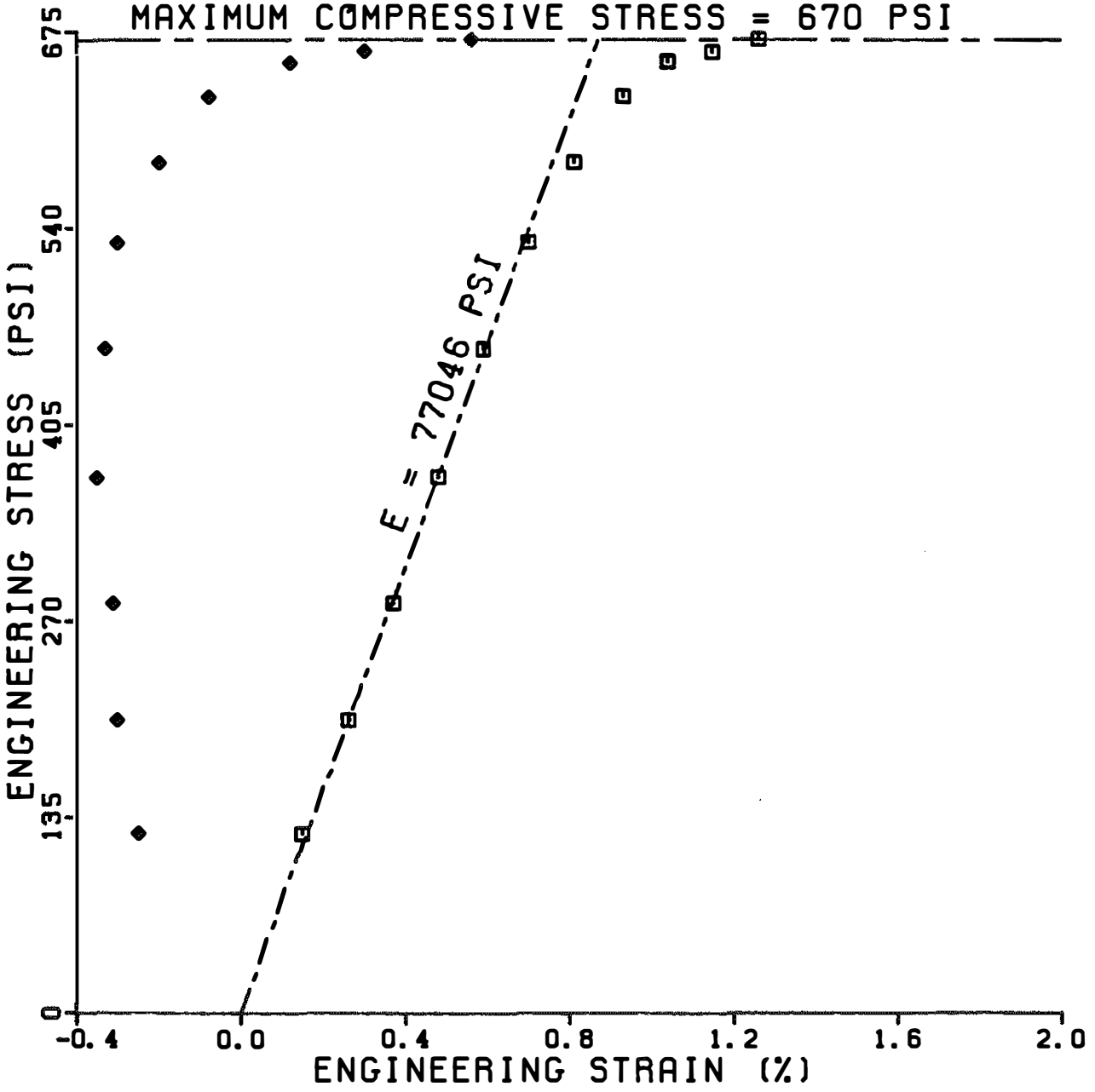


SAMPLE NUMBER : F-27
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
15 % POND ASH
85 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 157 PCF
OPTIMUM MOISTURE = 9.5 %

MADE 4/21/83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 670 PSI



SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

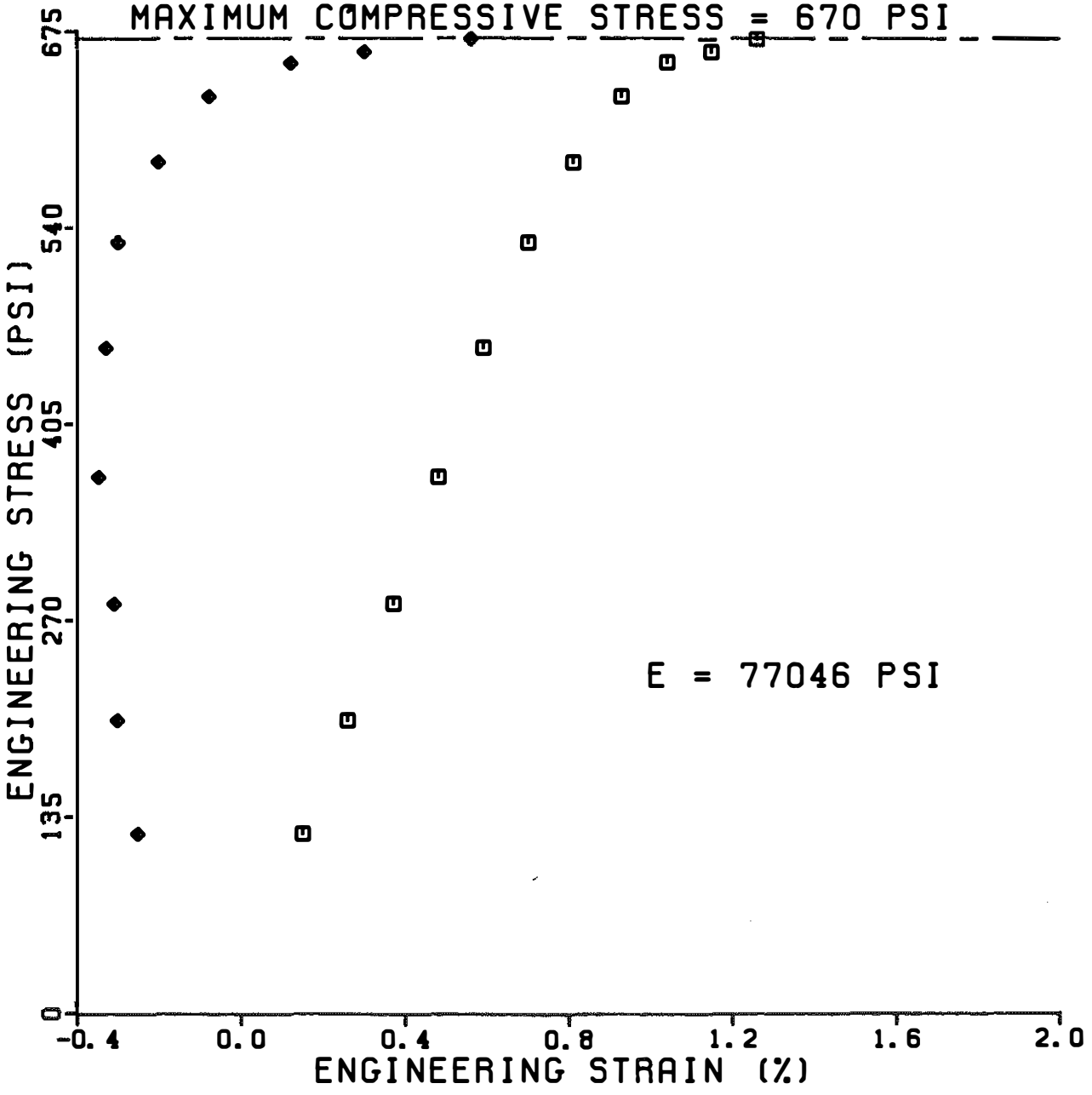
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
15 % POND ASH
85 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 157 PCF
OPTIMUM MOISTURE = 9.5 %

MADE 4/21/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 670 PSI

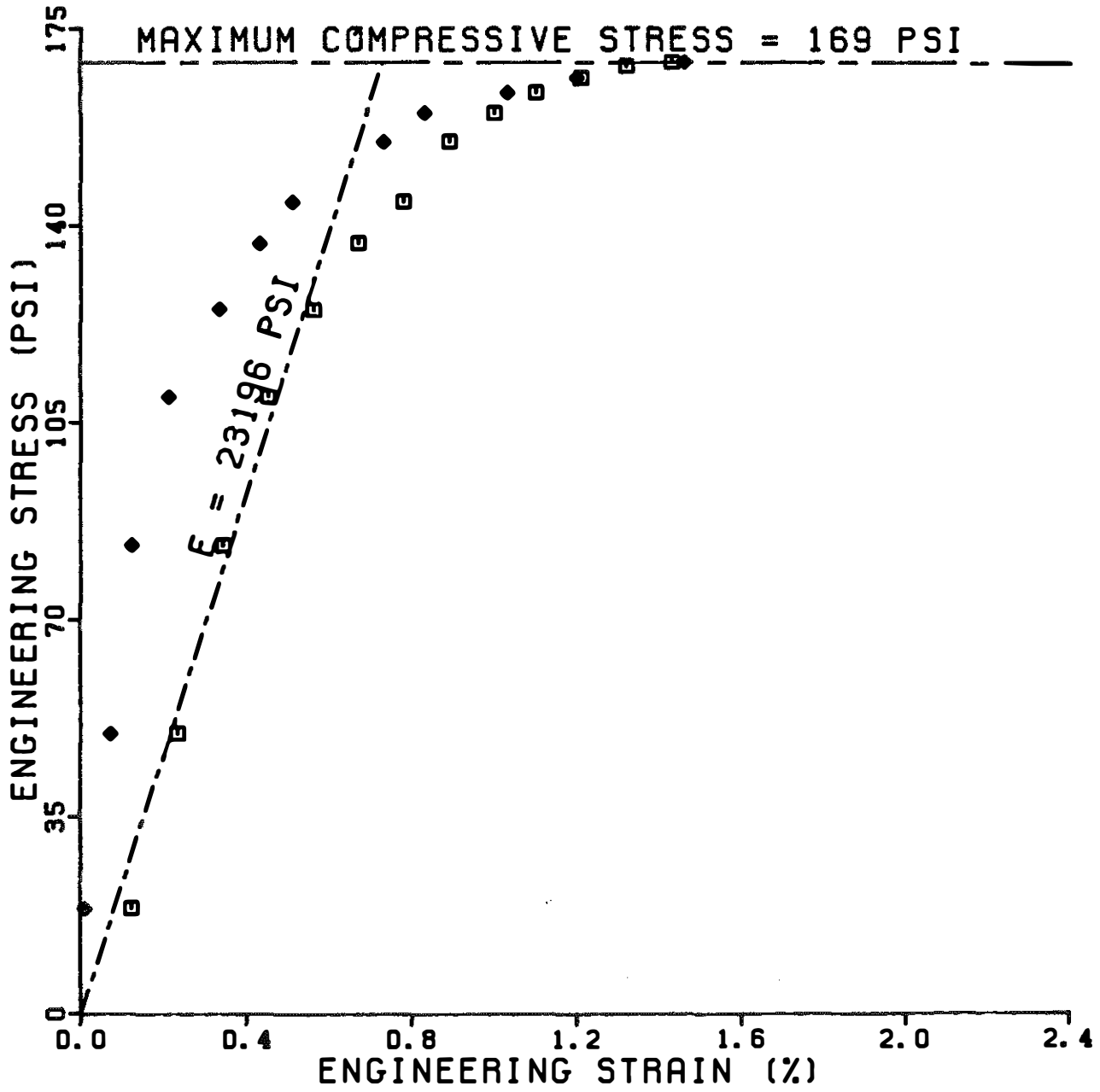


SAMPLE NUMBER : F-29
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 11.7 %

MADE 4/21/83 -- CURED 7 DAYS

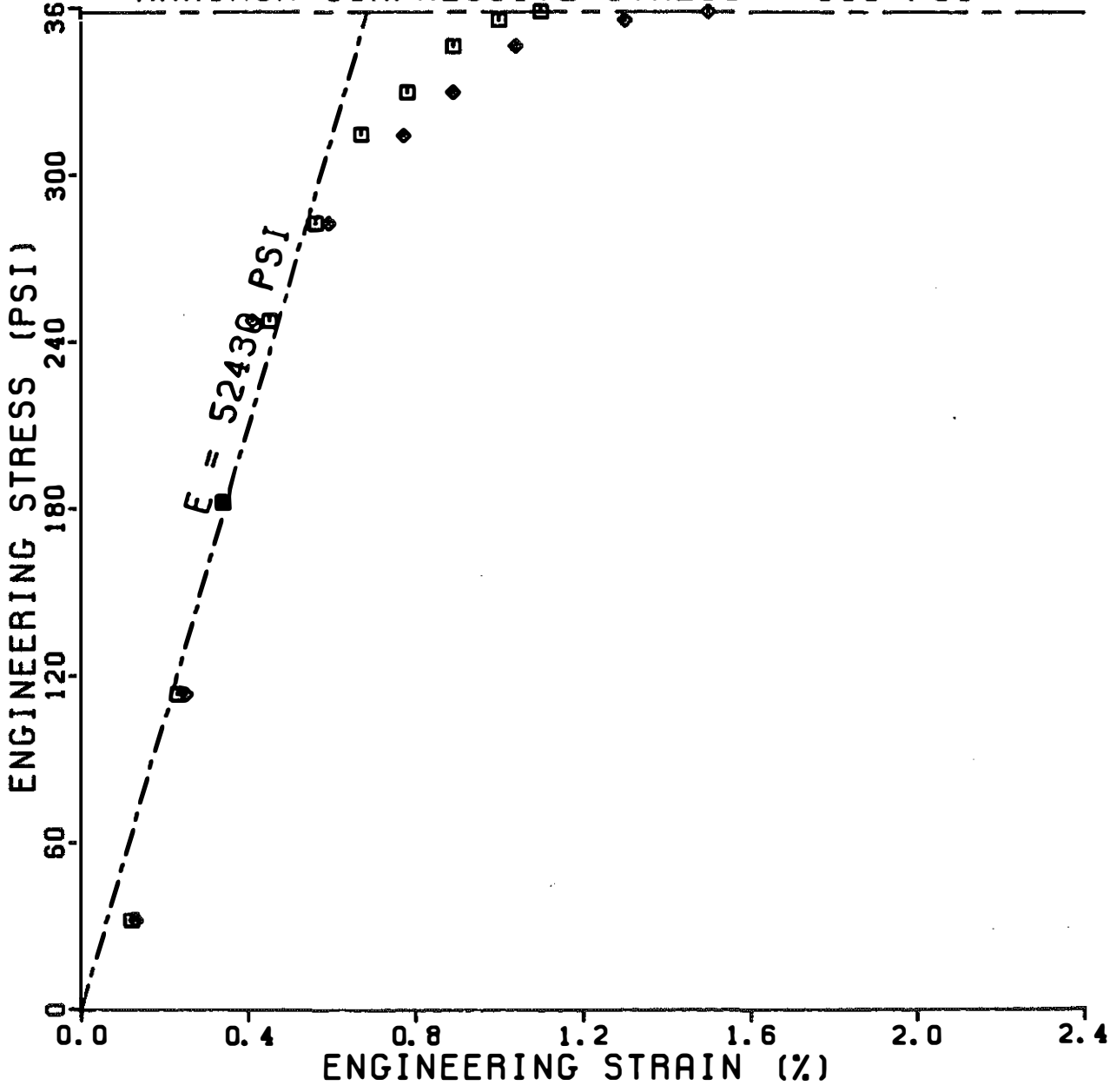


SAMPLE NUMBER : F-30
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 11.7 %

MADE 4/21/83 -- CURED 7 DAYS
MAXIMUM COMPRESSIVE STRESS = 359 PSI



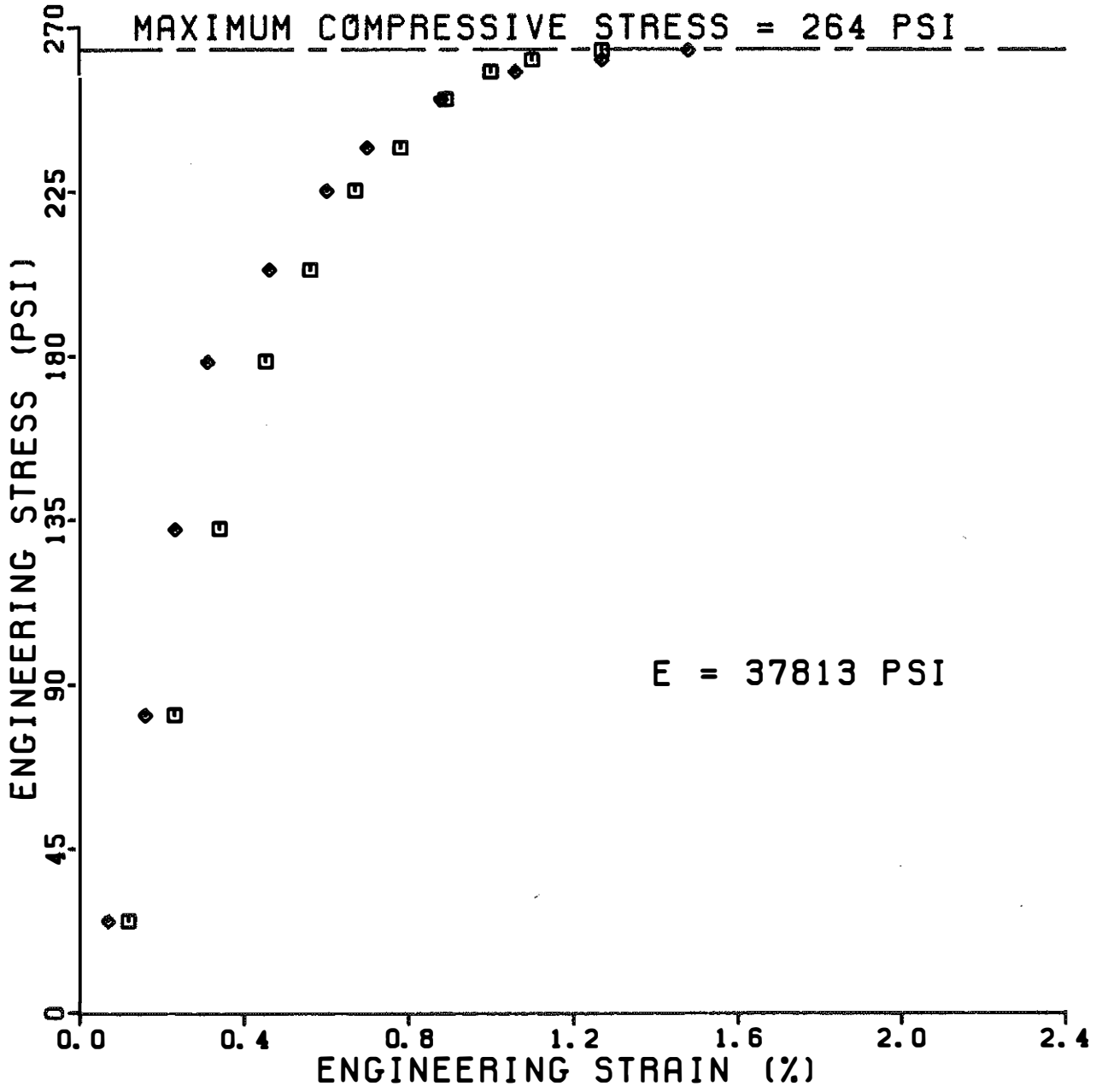
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 11.7 %

MADE 4/21/83 -- CURED 7 DAYS



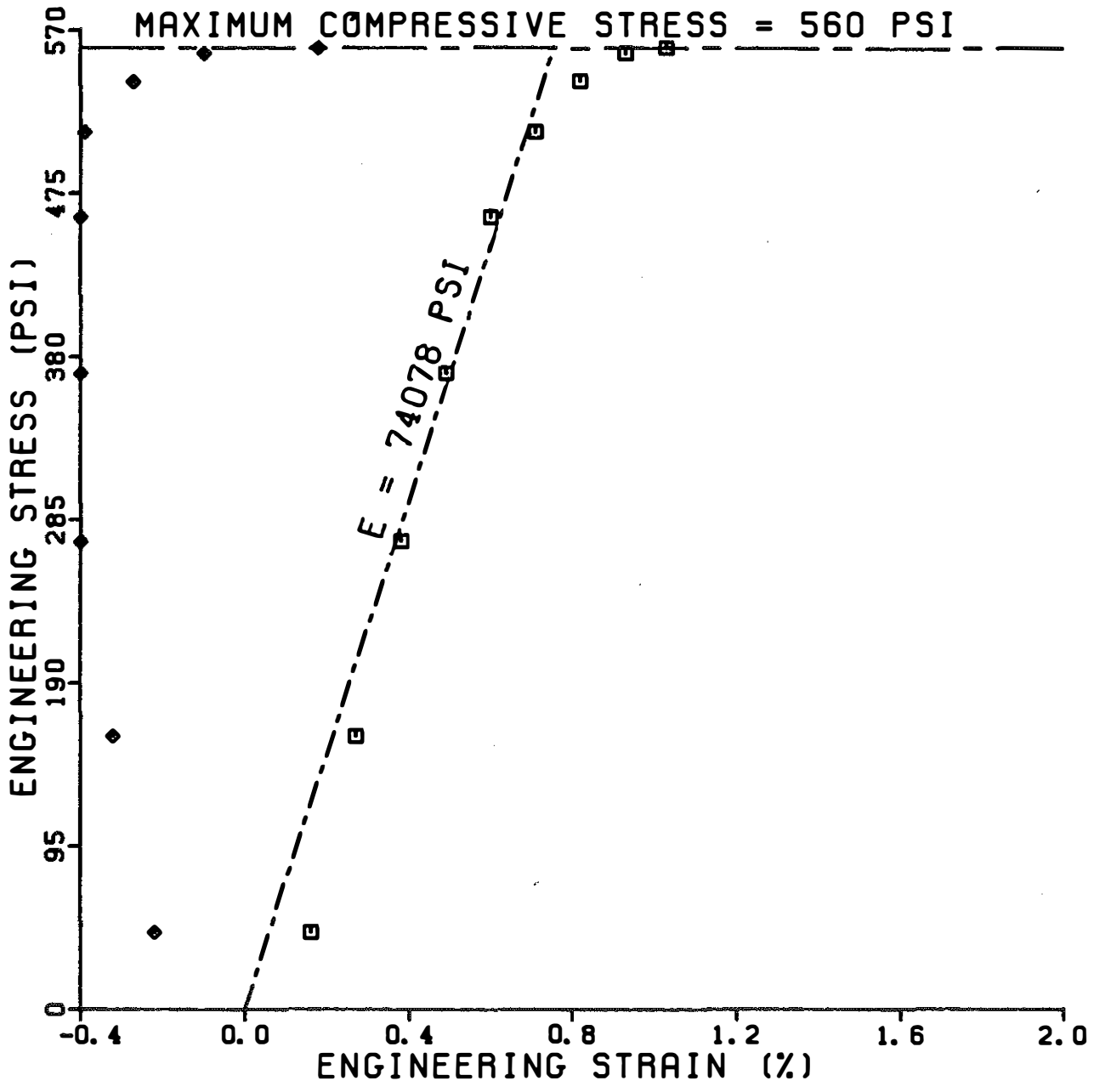
SAMPLE NUMBER : F-31
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 11.7 %

MADE 4/21/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 560 PSI



SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

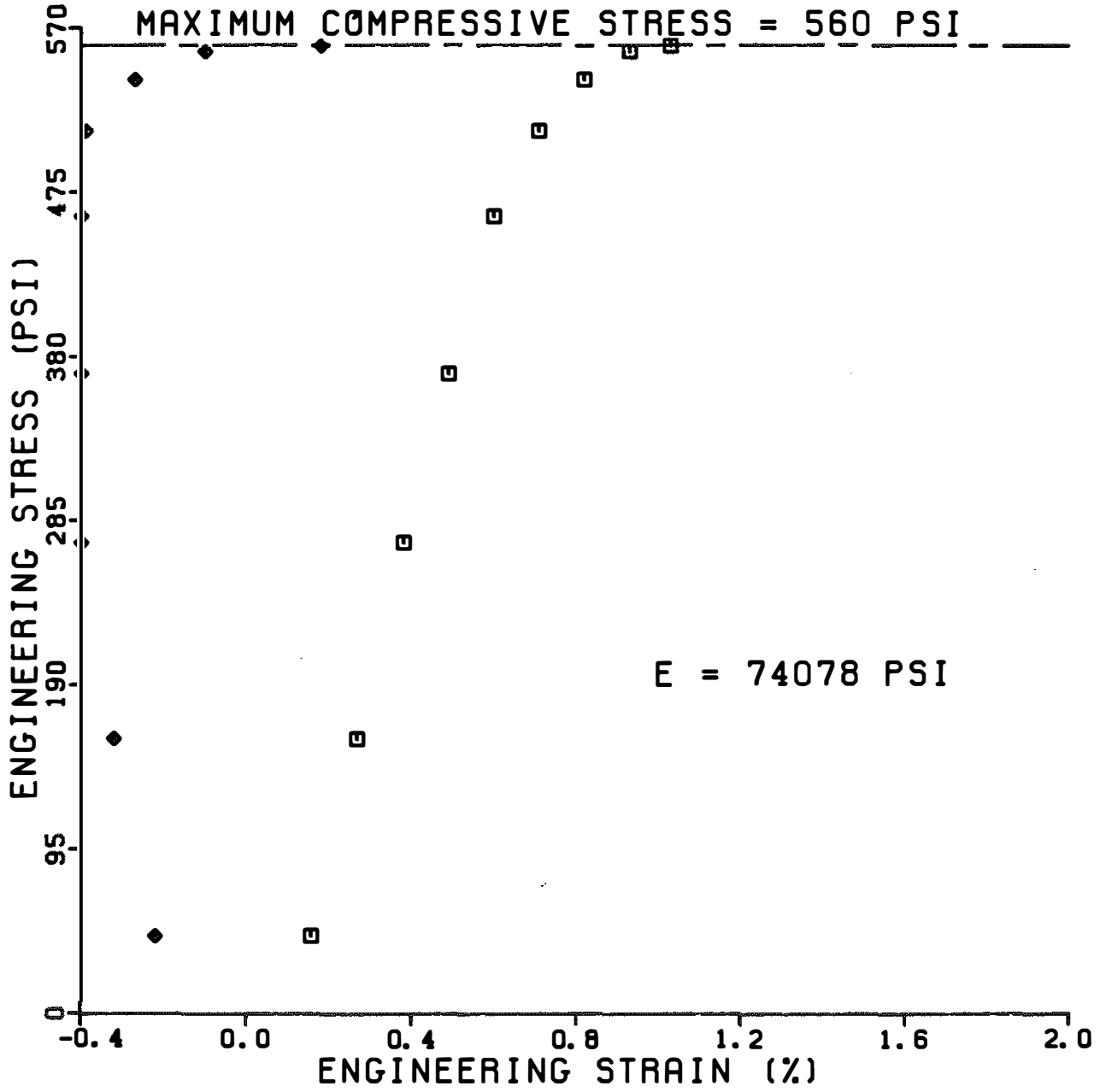
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 11.7 %

MADE 4/21/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 560 PSI

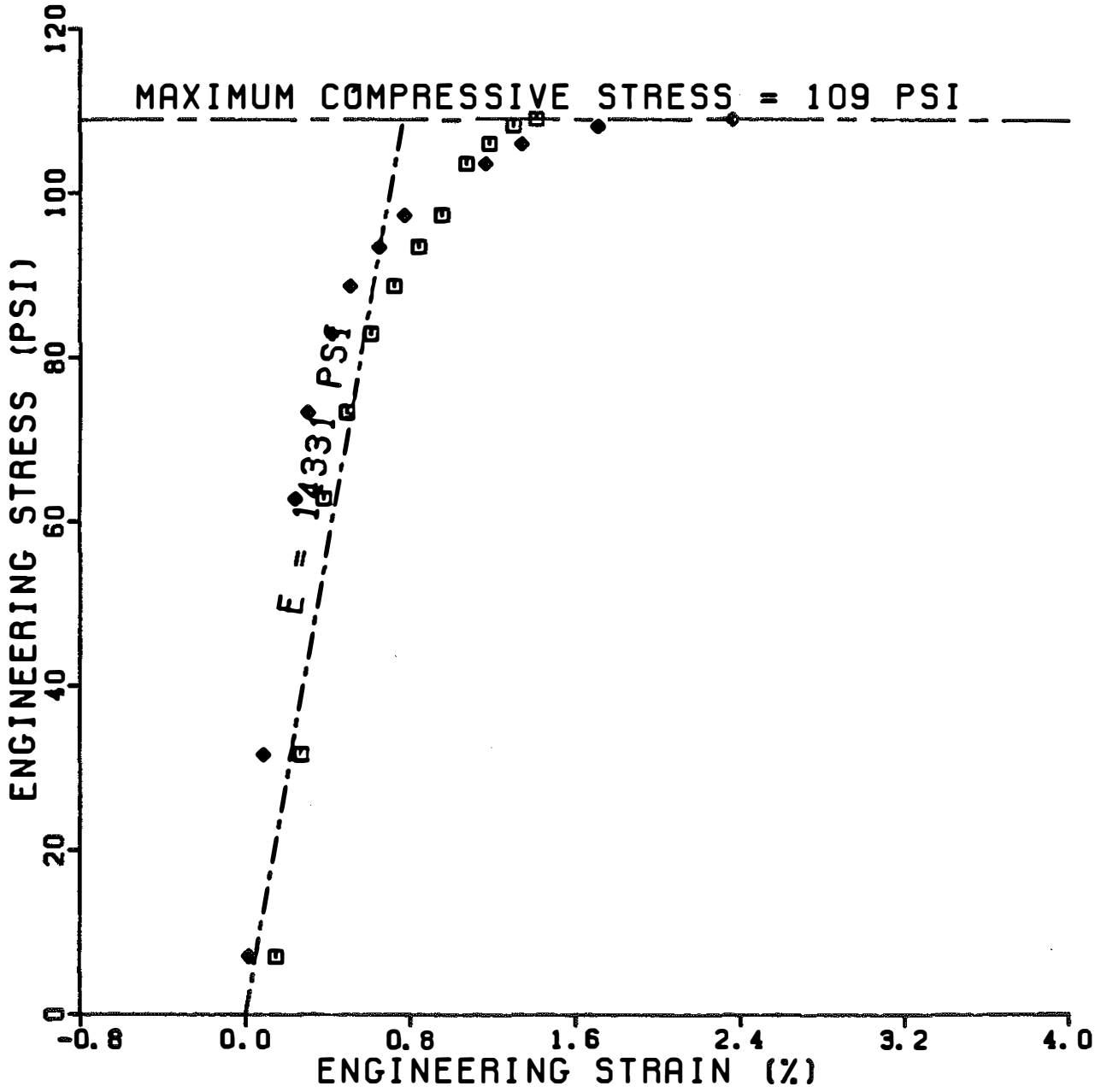


SAMPLE NUMBER : F-33
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 141 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4/21/83 -- CURED 7 DAYS

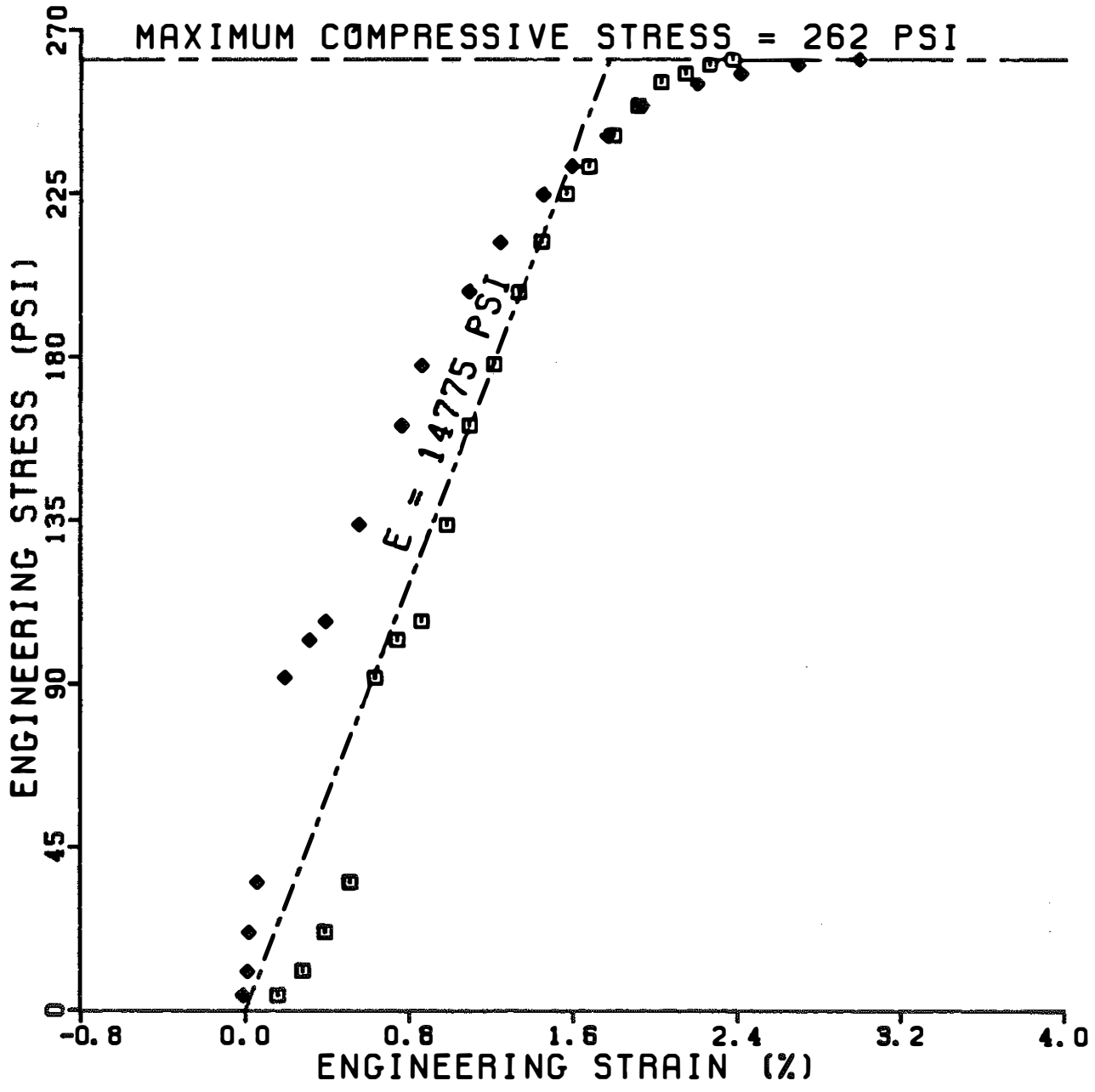


SAMPLE NUMBER : F-34
FIELD SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 141 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4/21/83 -- CURED 7 DAYS



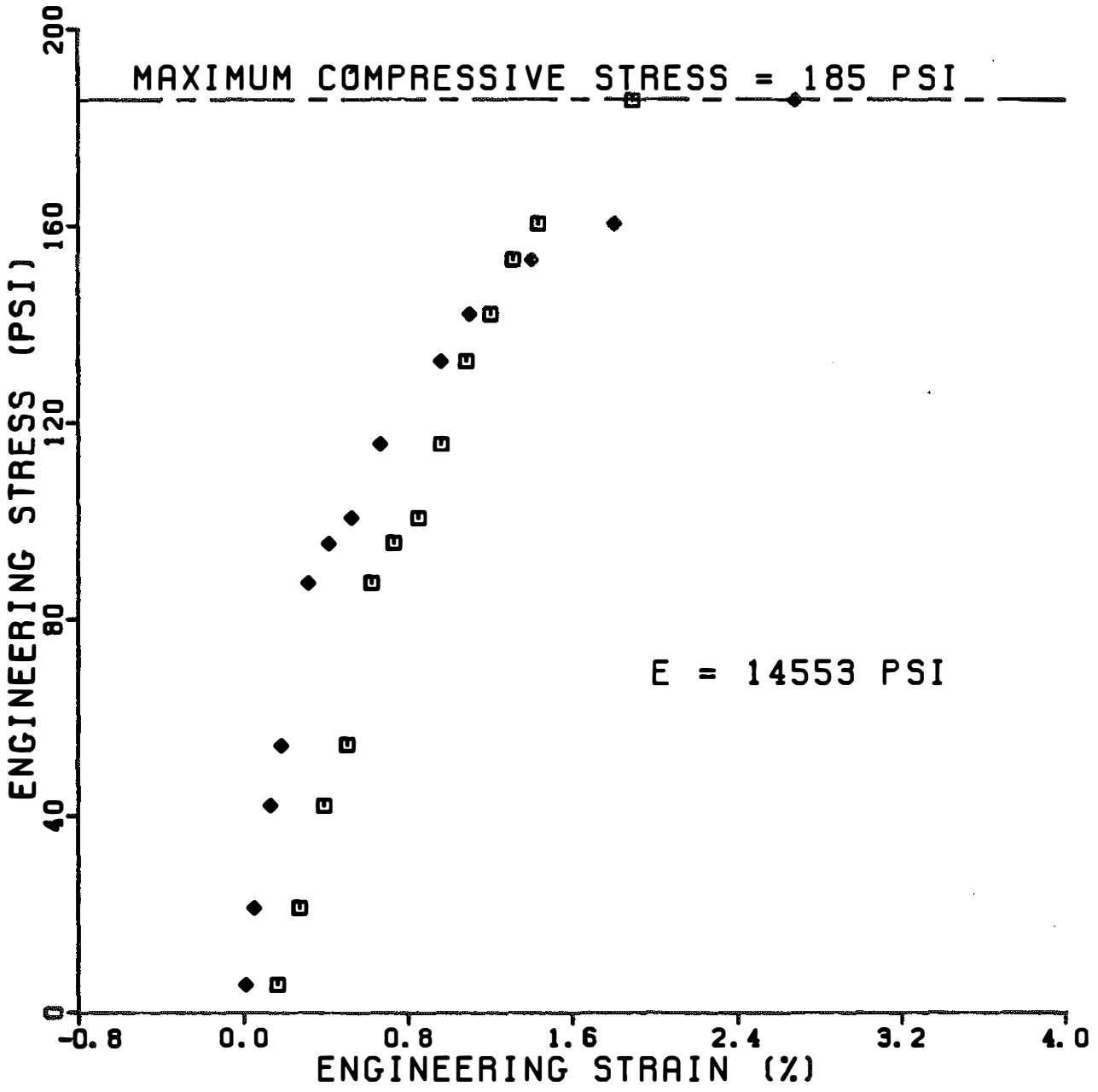
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 141 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4/21/83 -- CURED 7 DAYS



SAMPLE NUMBER : F-35
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

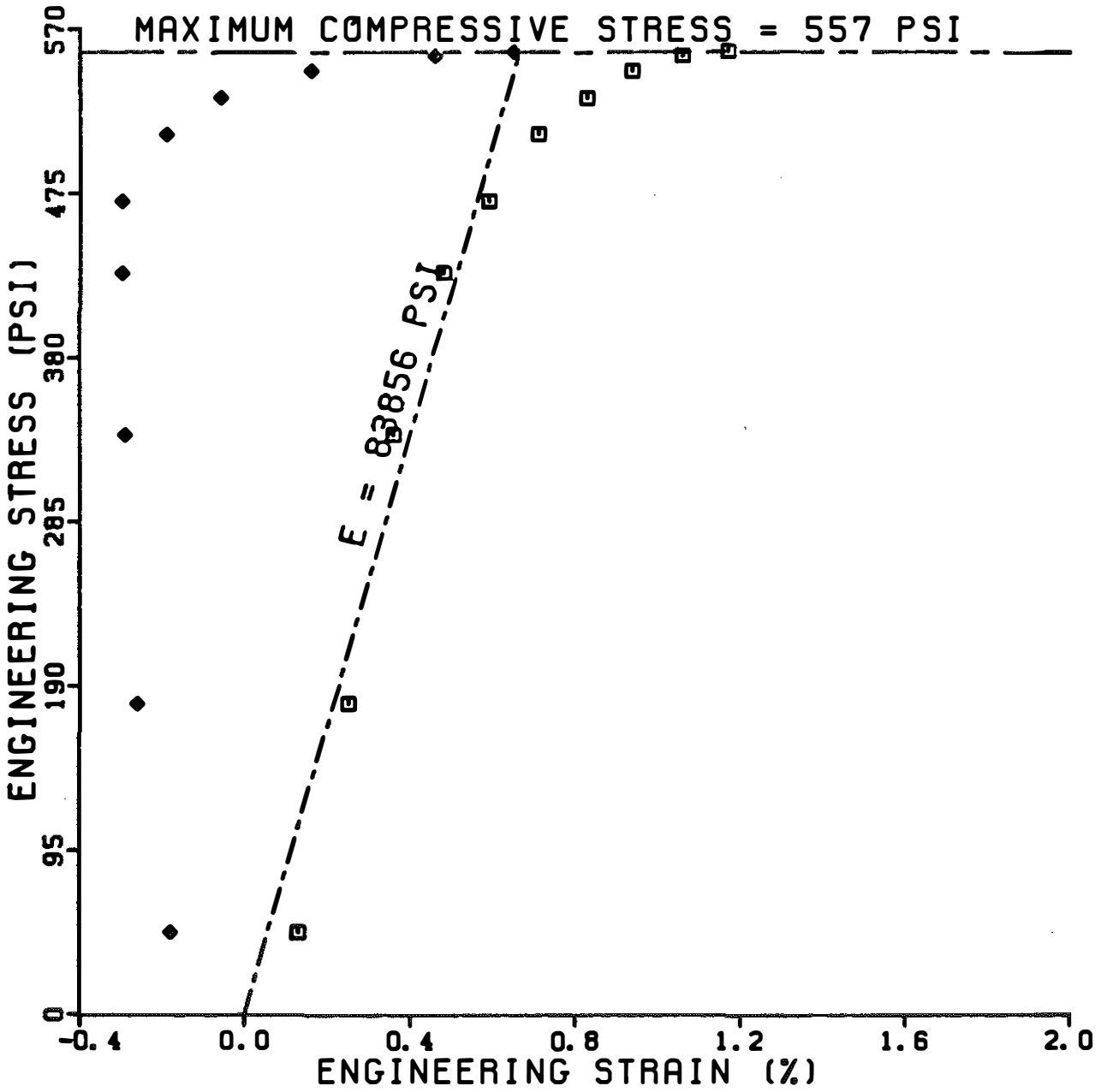
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 141 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4/21/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 557 PSI



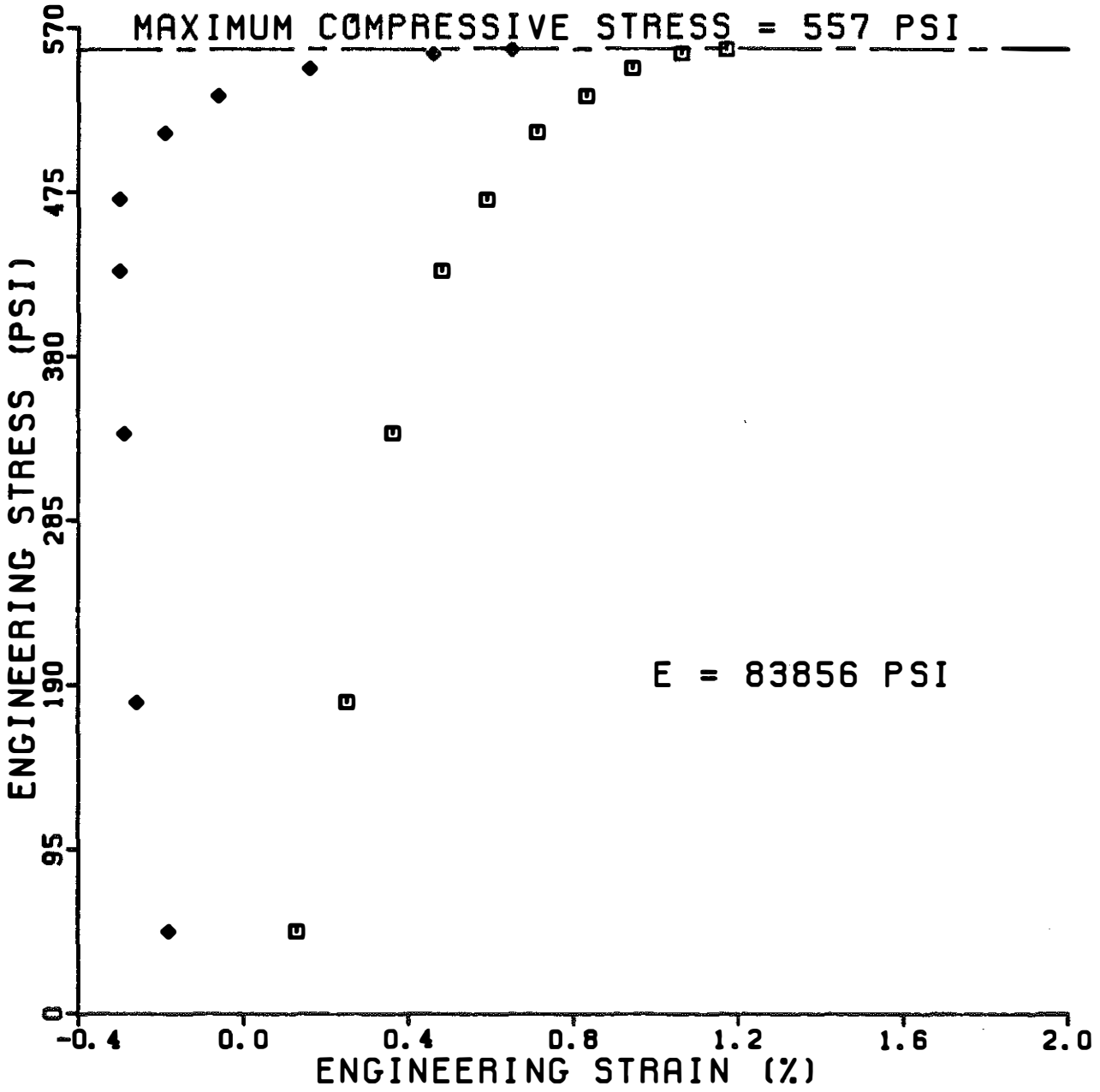
SAMPLE NUMBER : AVG.
FIELD SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 141 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4/21/83 -- CURED 28 DAYS

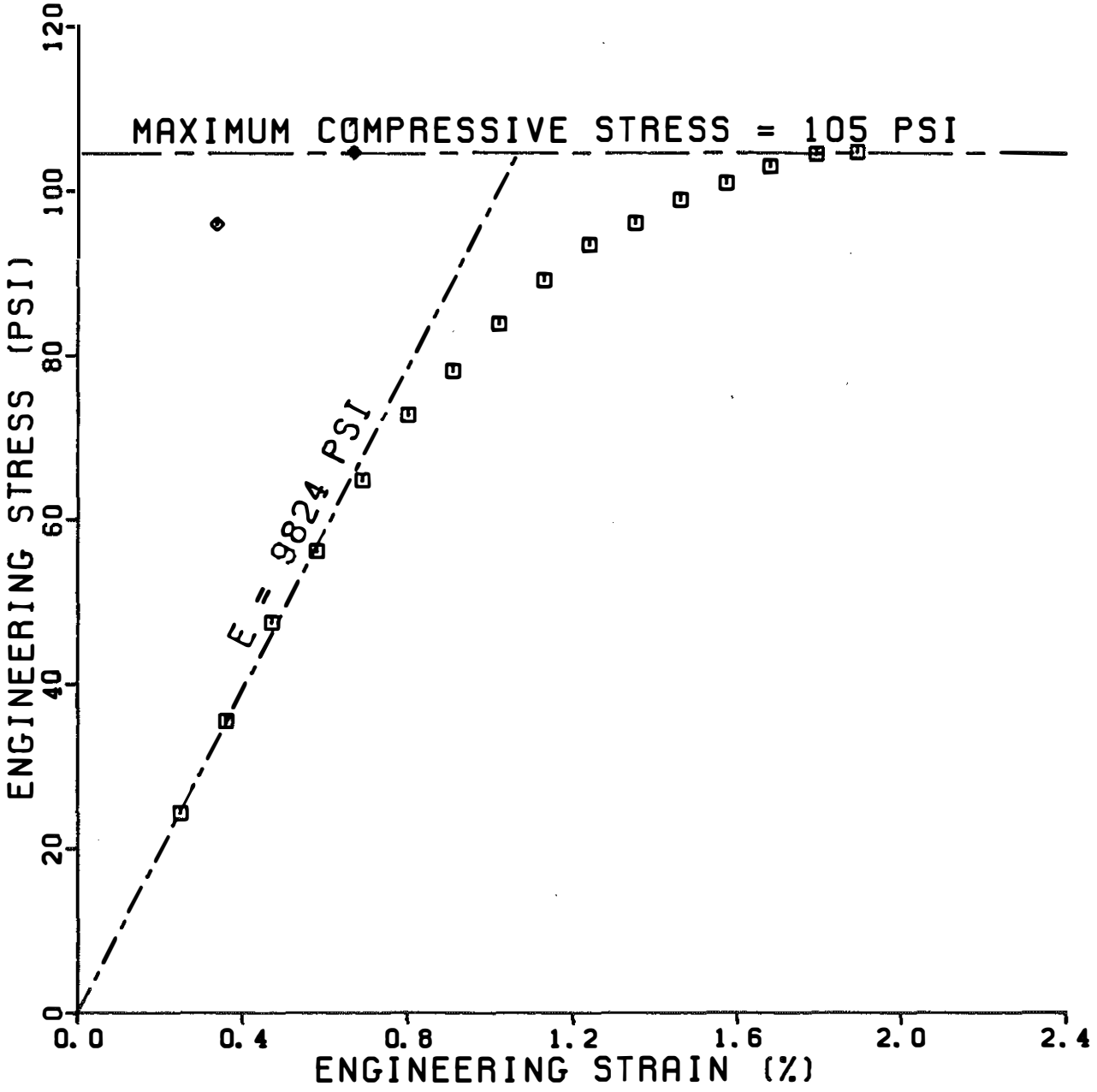


SAMPLE NUMBER : 3-2
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 65 PCF
OPTIMUM MOISTURE = 50.4 %

MADE 4-18-83 -- CURED 7 DAYS

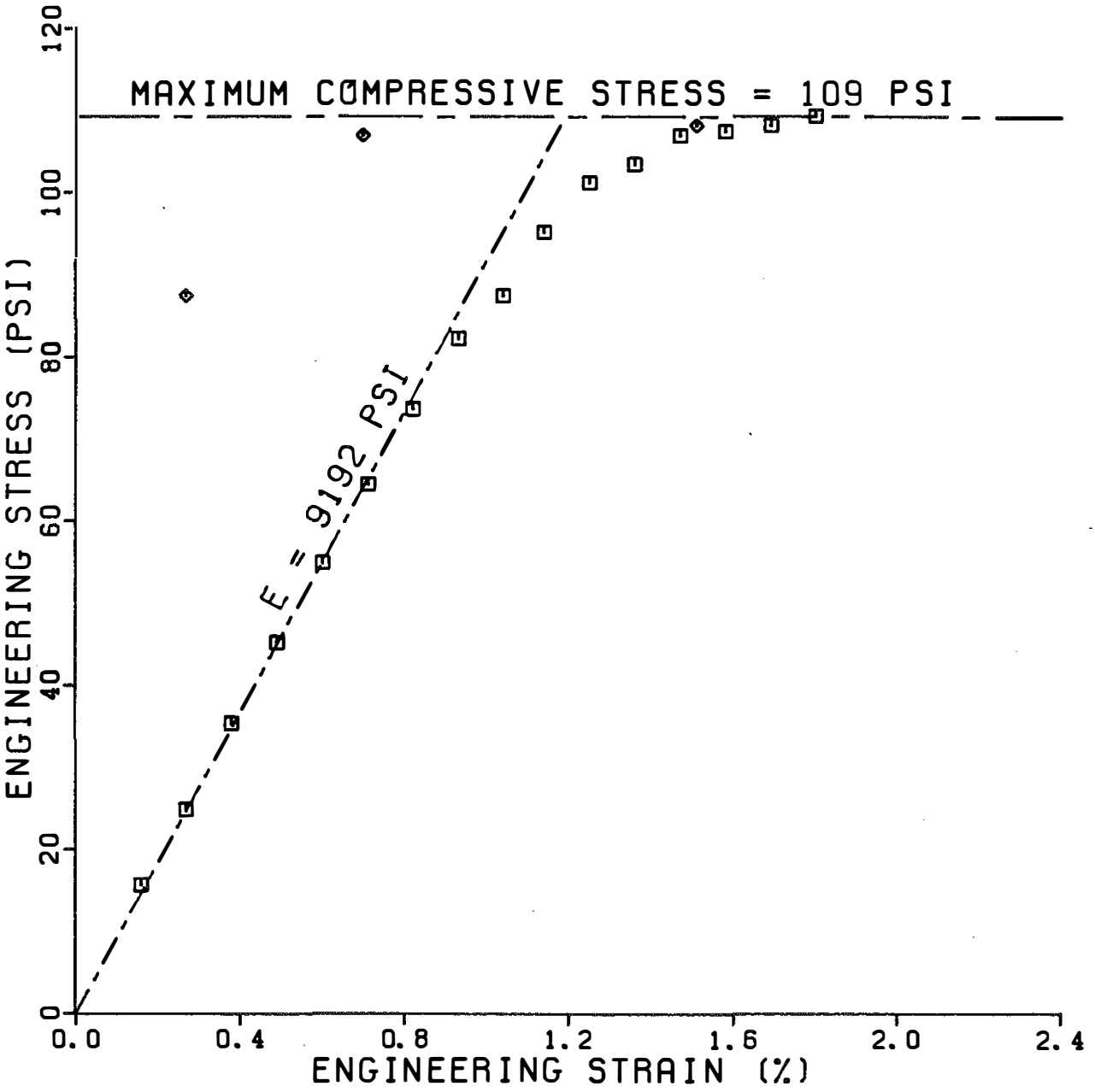


SAMPLE NUMBER : 3-3
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 65 PCF
OPTIMUM MOISTURE = 50.4 %

MADE 4-18-83 -- CURED 7 DAYS

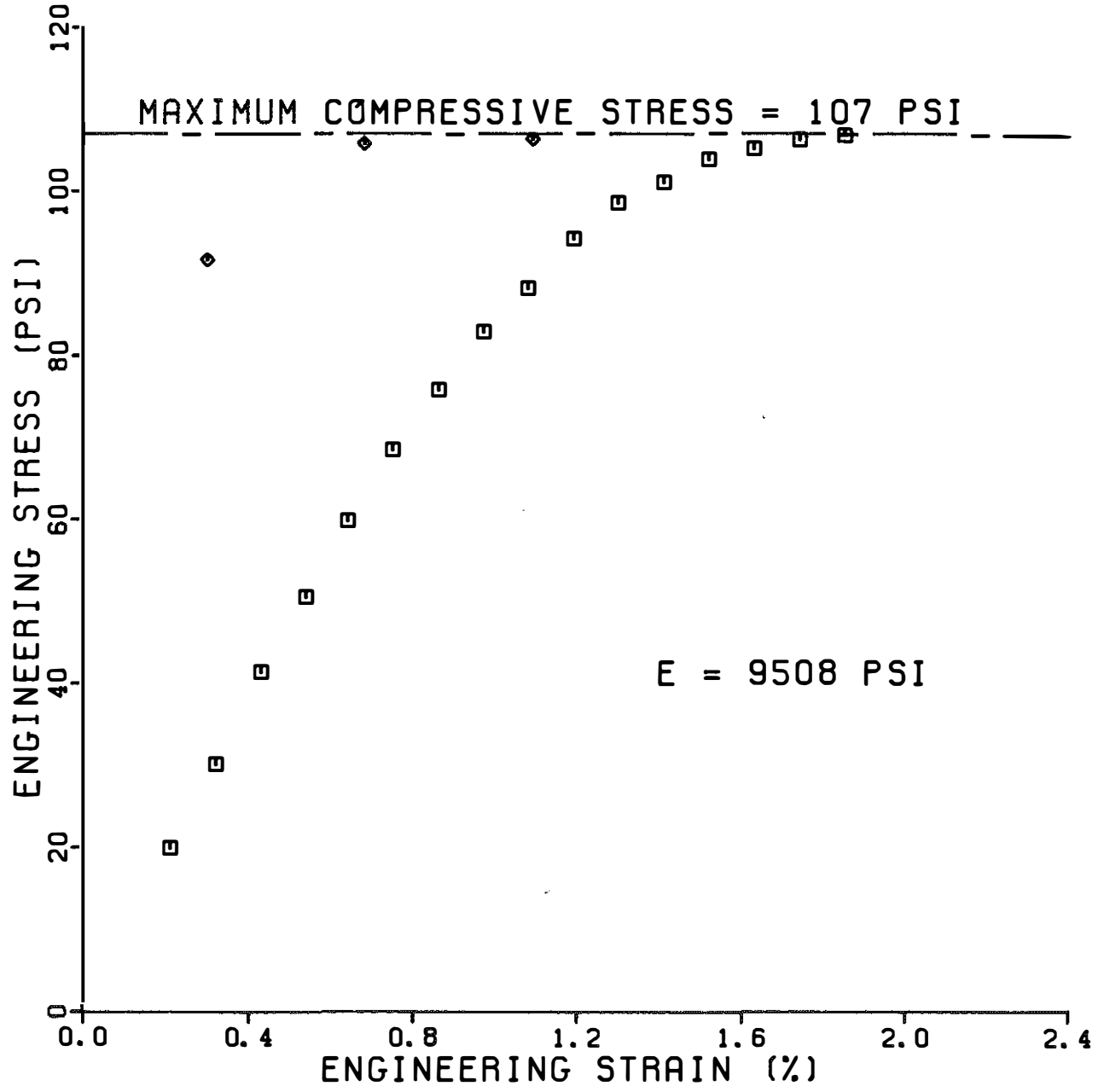


SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 65 PCF
OPTIMUM MOISTURE = 50.4 %

MADE 4-18-83 -- CURED 7 DAYS

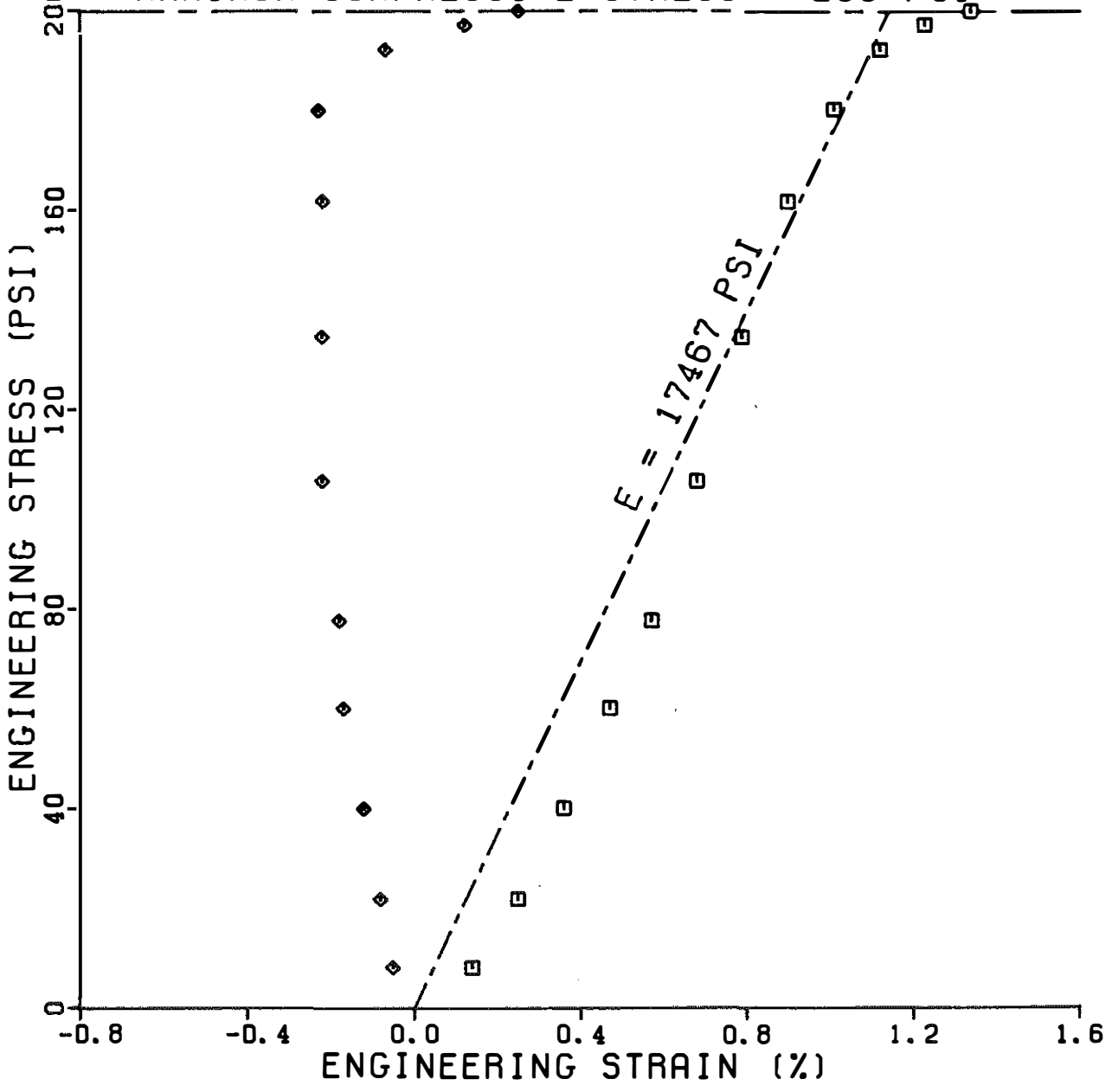


SAMPLE NUMBER : 3-5
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 65 PCF
OPTIMUM MOISTURE = 50.4 %

MADE 4-18-83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 200 PSI



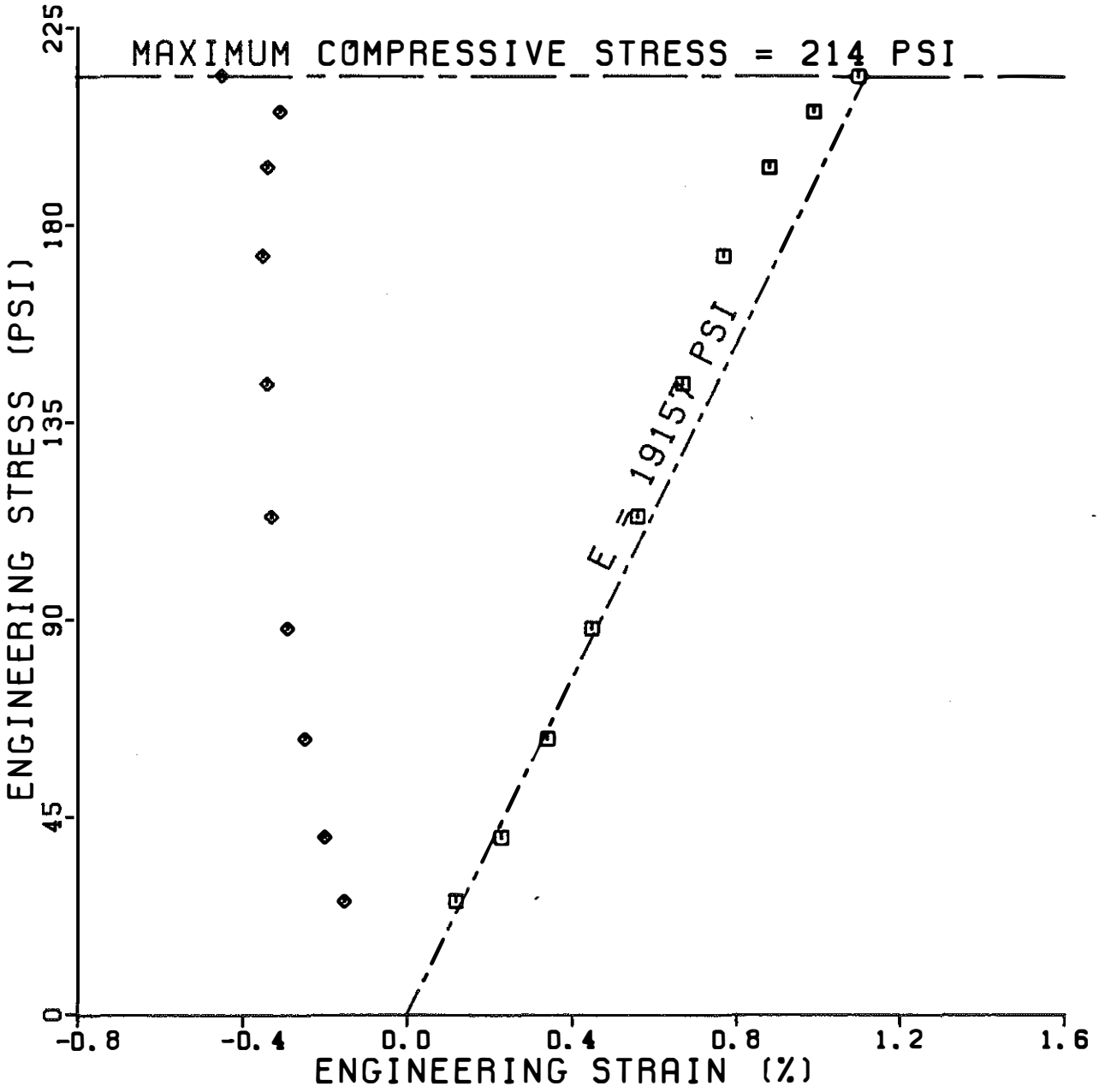
SAMPLE NUMBER : 3-6
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 65 PCF
OPTIMUM MOISTURE = 50.4 %

MADE 4-18-83 -- CURED 28 DAYS



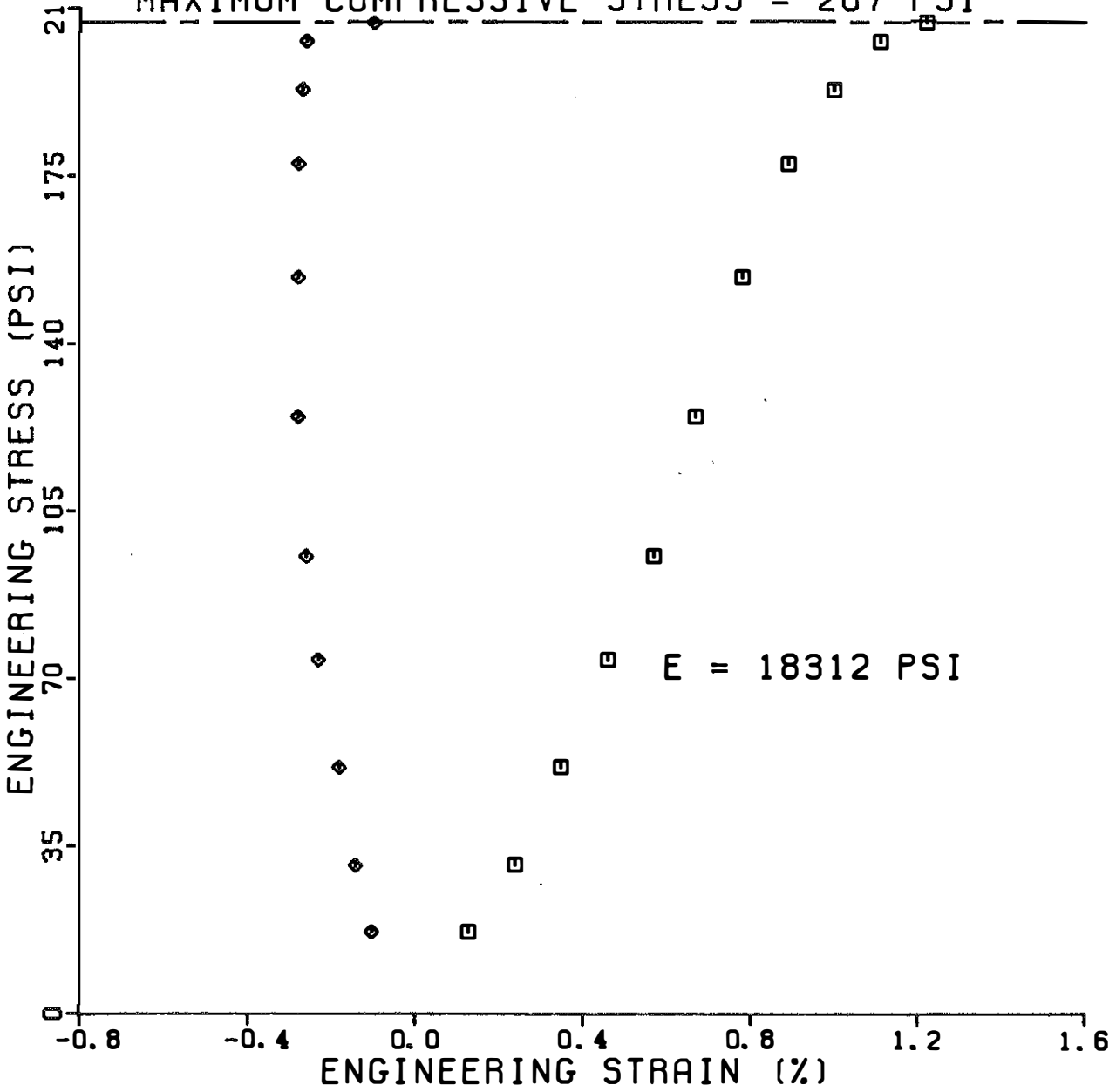
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
0 % NO AGGR.
100 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 65 PCF
OPTIMUM MOISTURE = 50.4 %

MADE 4-18-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 207 PSI

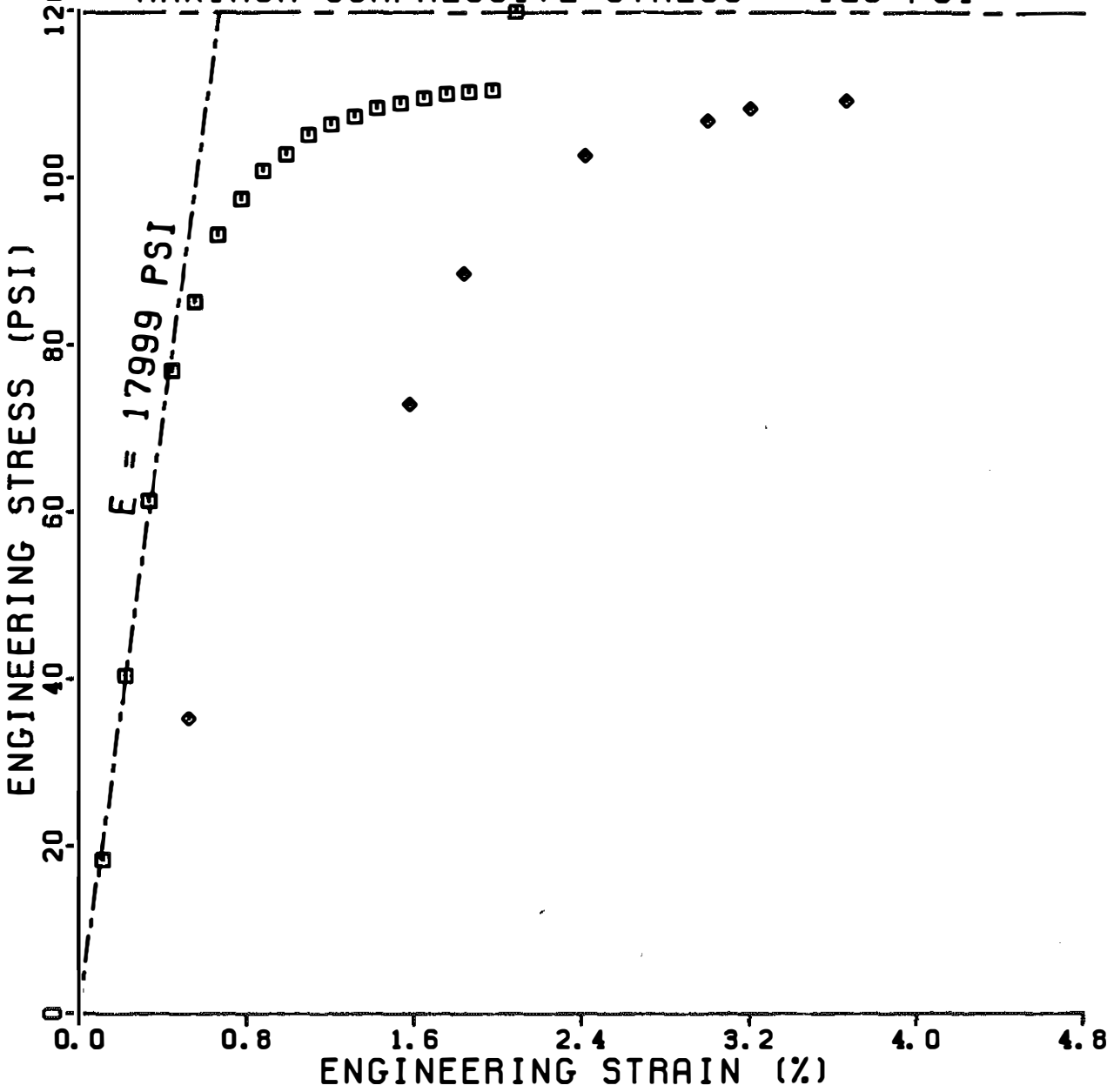


SAMPLE NUMBER : 4-1
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 7 DAYS
MAXIMUM COMPRESSIVE STRESS = 120 PSI

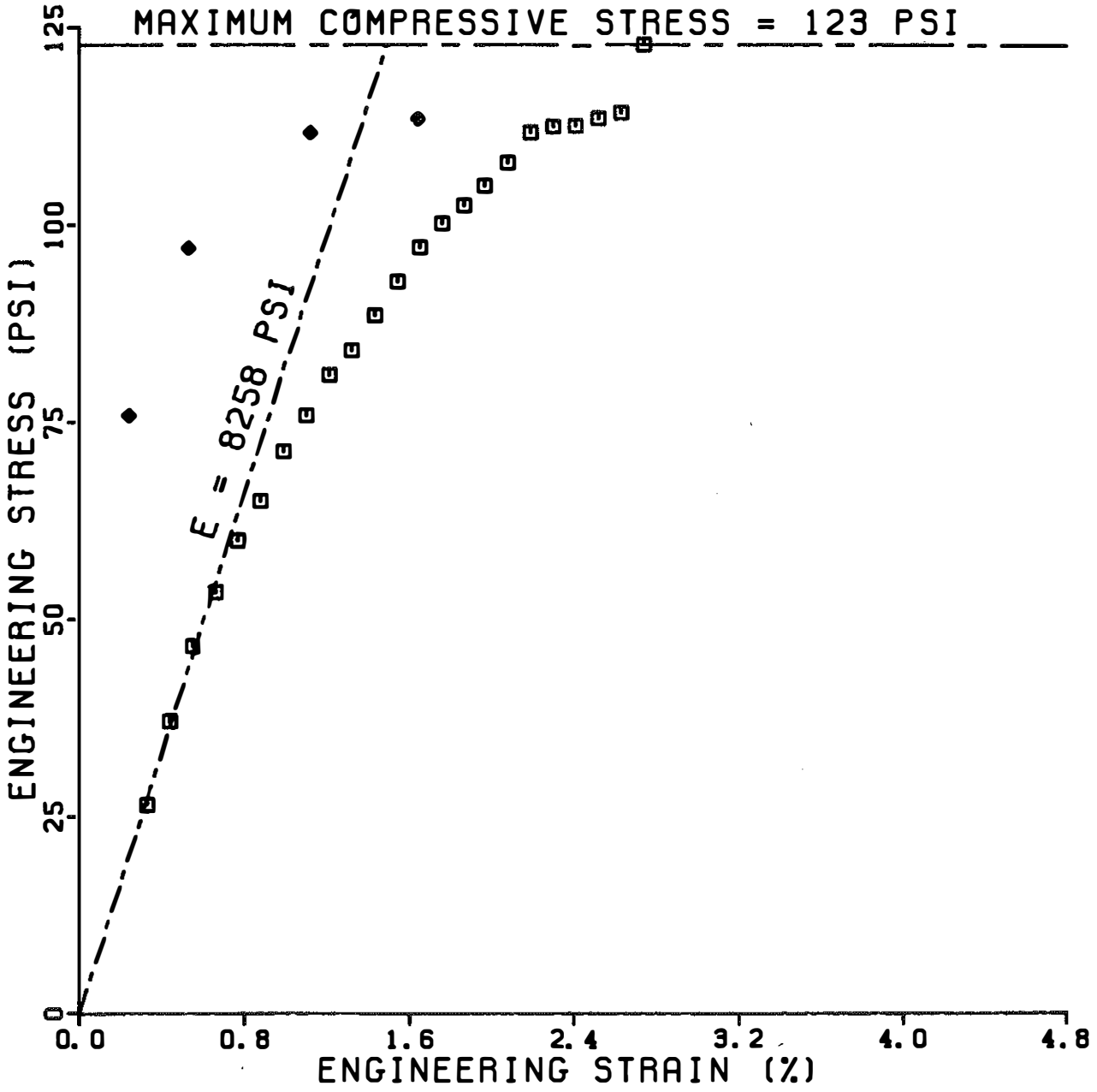


SAMPLE NUMBER : 4-2
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 7 DAYS



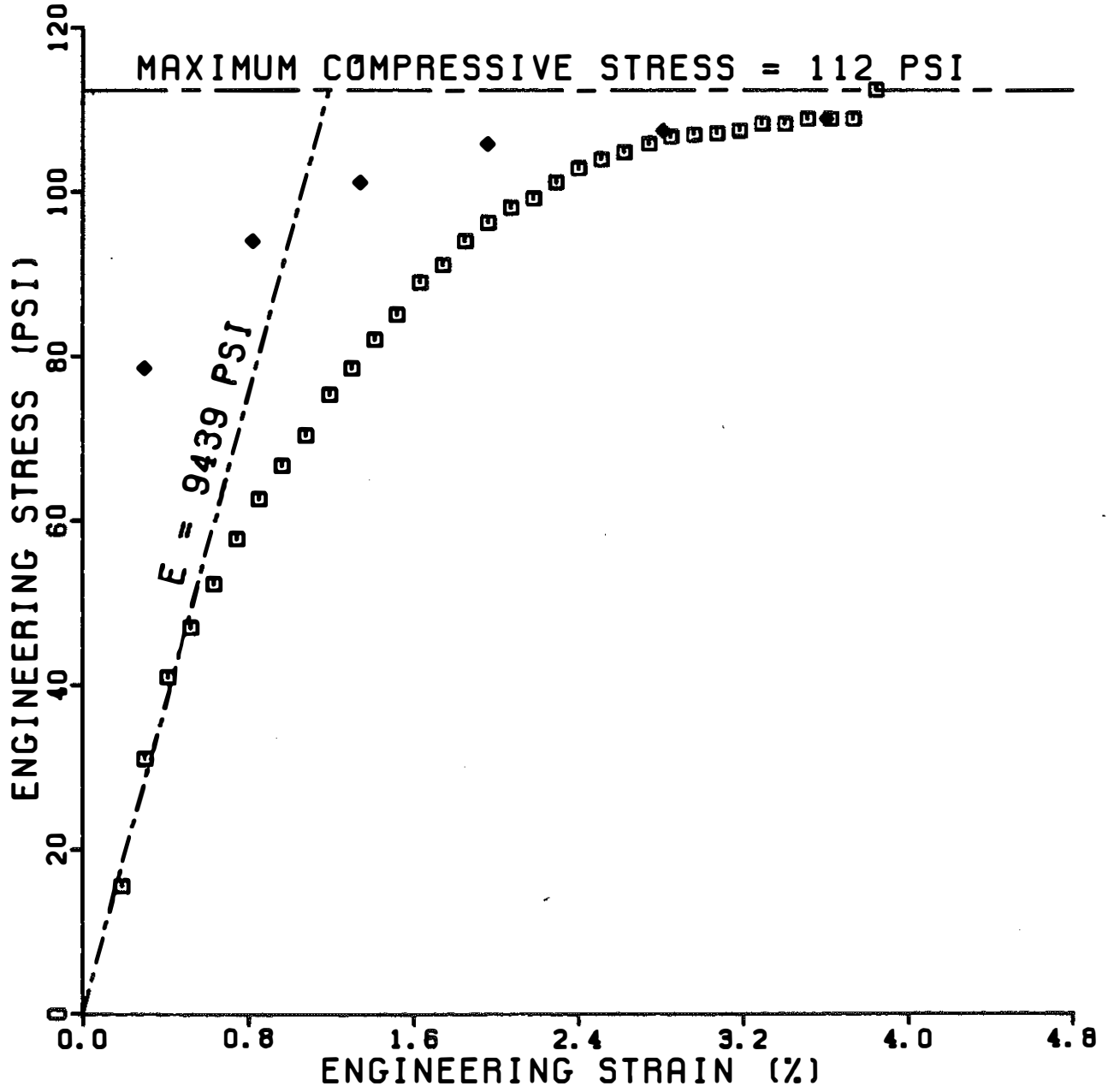
SAMPLE NUMBER : 4-3
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 7 DAYS



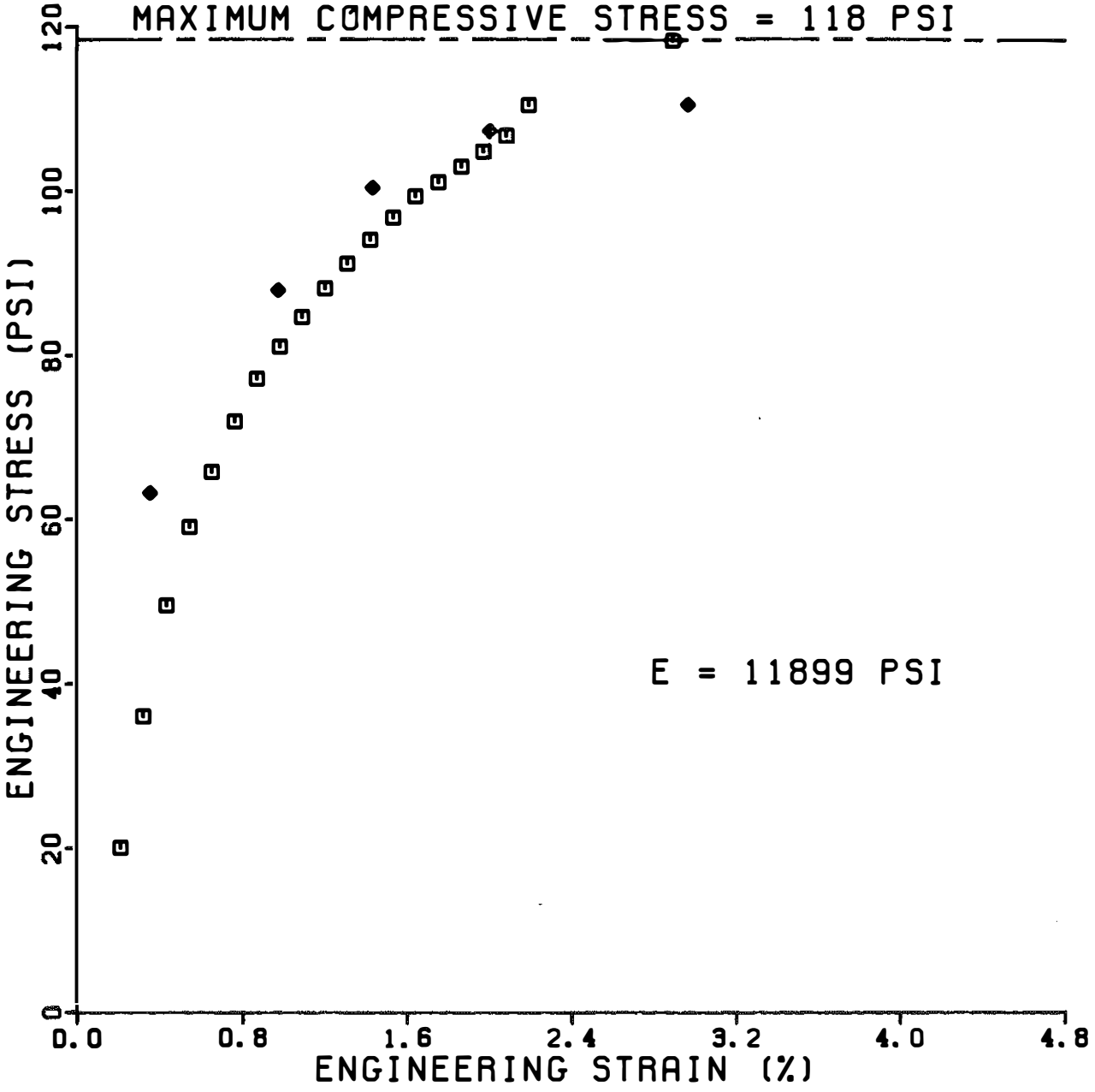
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY ØVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 7 DAYS

MAXIMUM COMPRESSIVE STRESS = 118 PSI

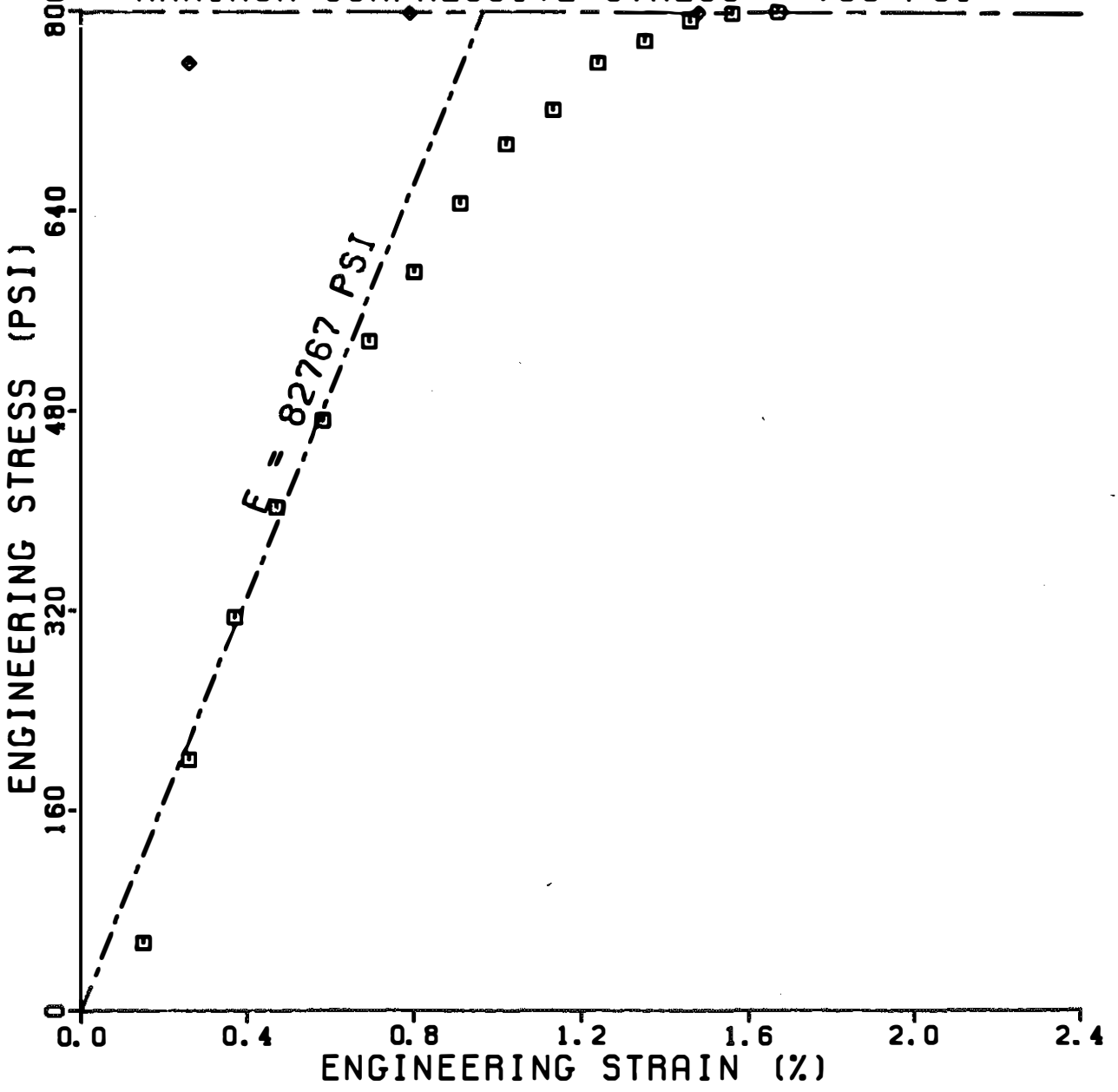


SAMPLE NUMBER : 4-7
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 799 PSI



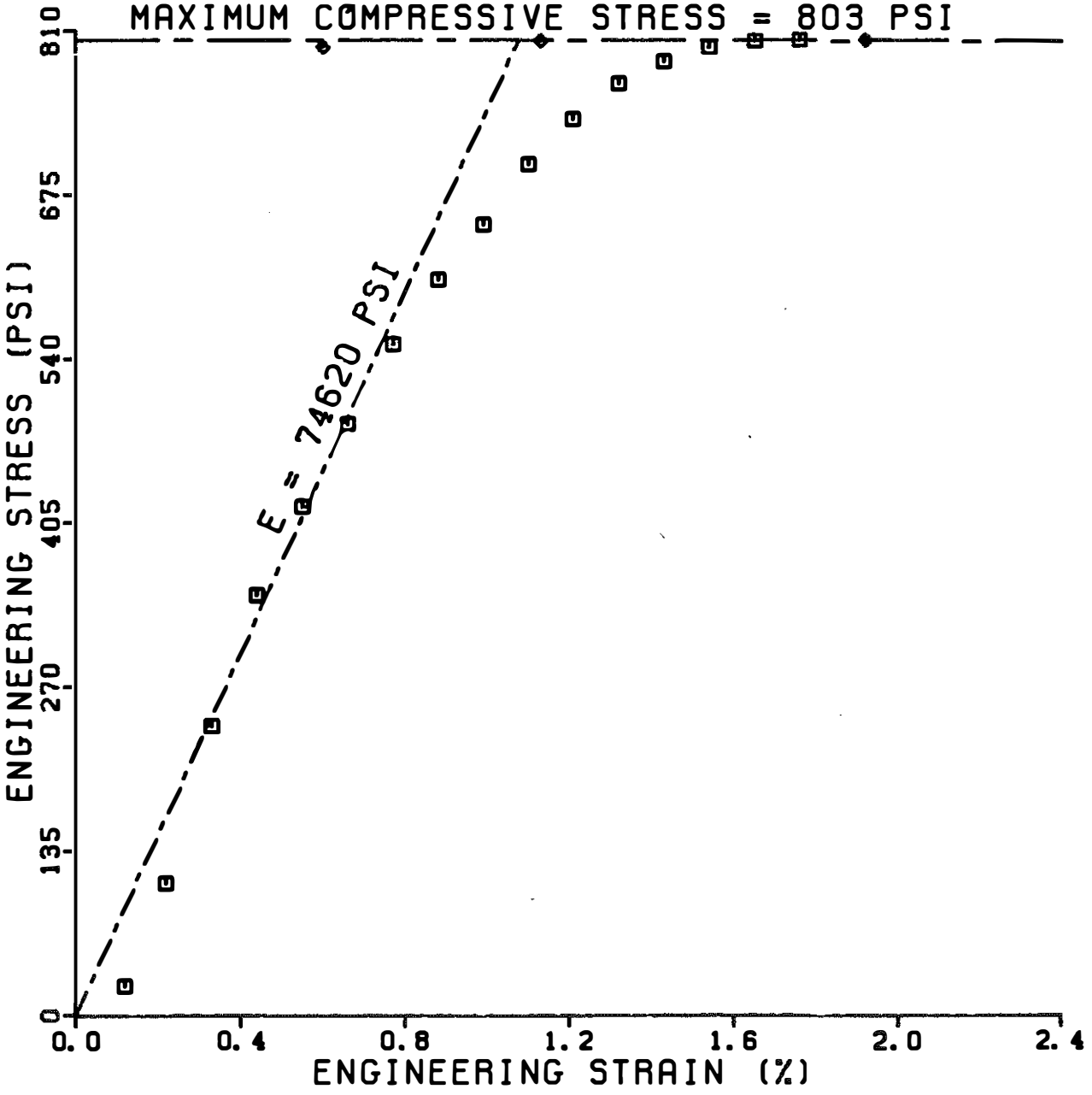
SAMPLE NUMBER : 4-9
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 803 PSI

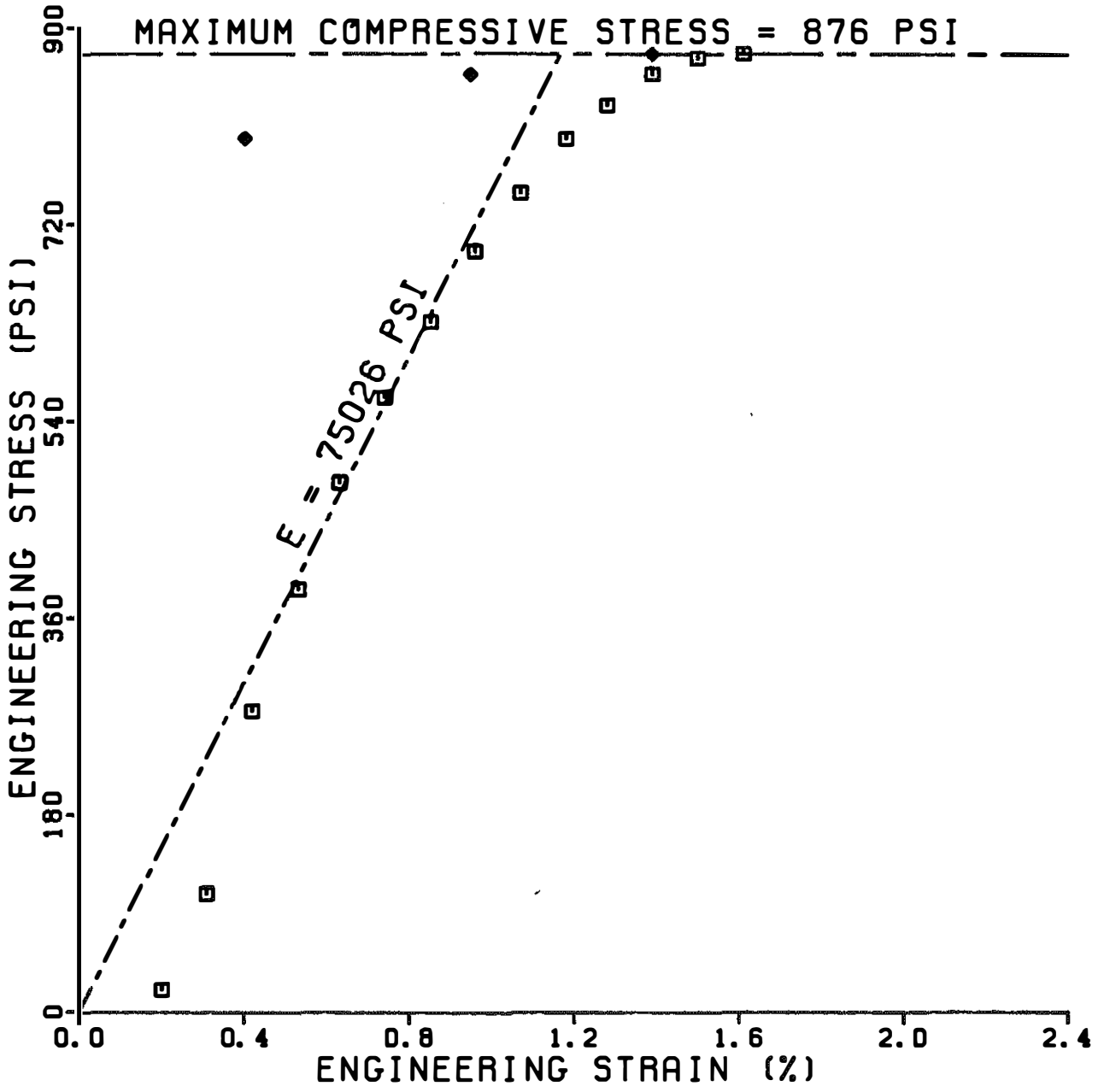


SAMPLE NUMBER : 4-10
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 28 DAYS



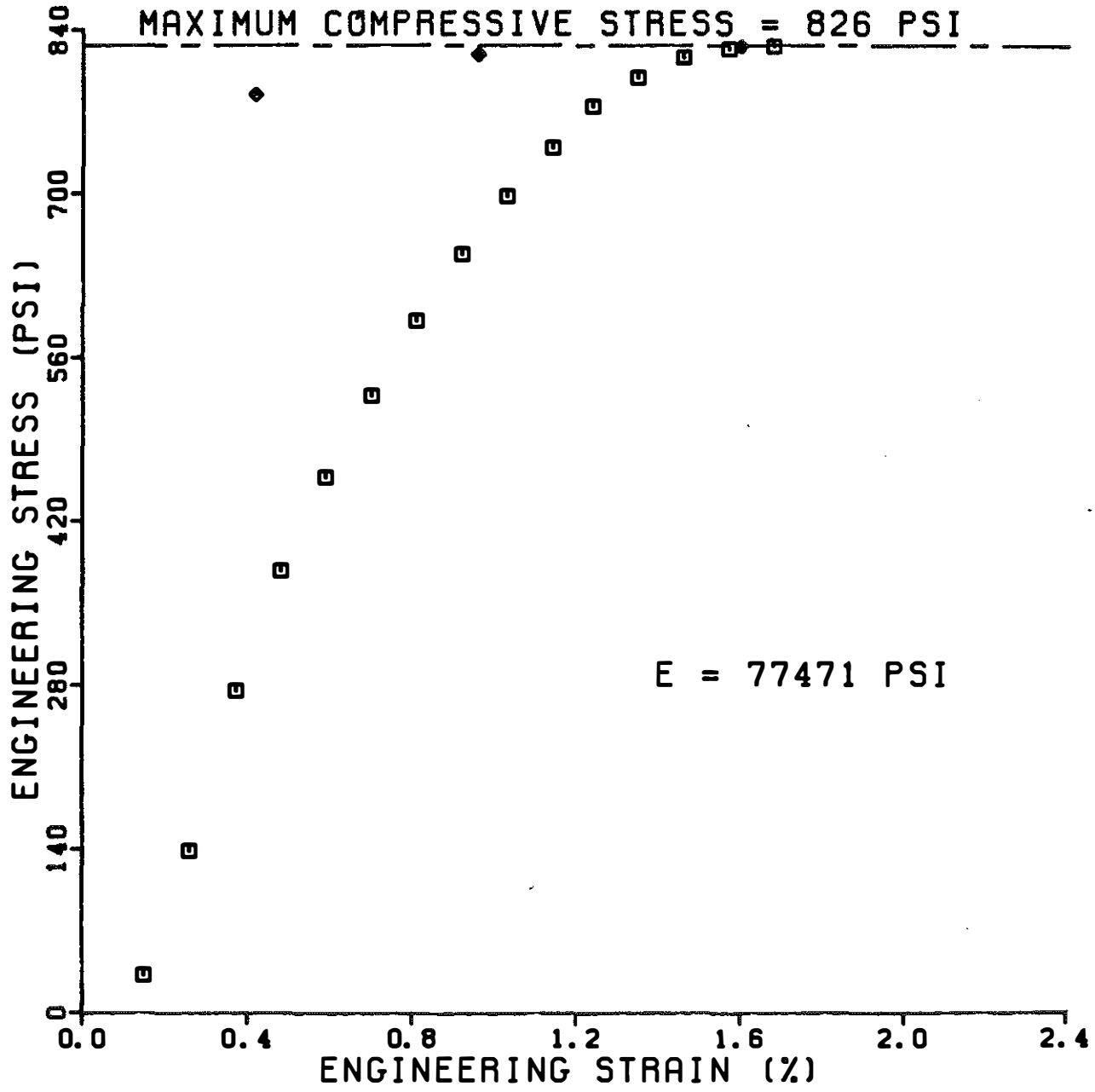
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % POND ASH
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 10.3 %

MADE 3/22/83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 826 PSI

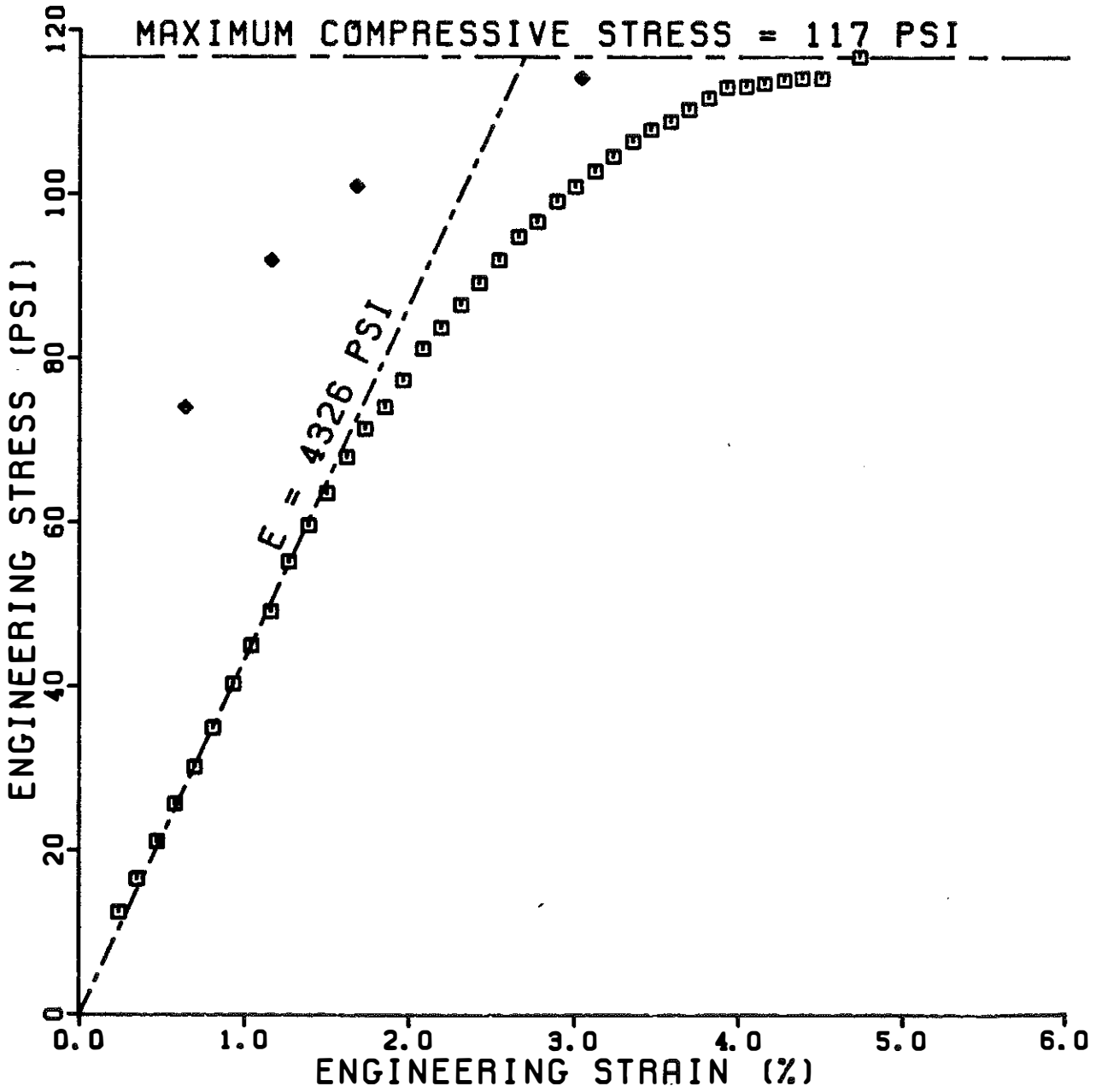


SAMPLE NUMBER : 5-1
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3/22/83 -- CURED 7 DAYS



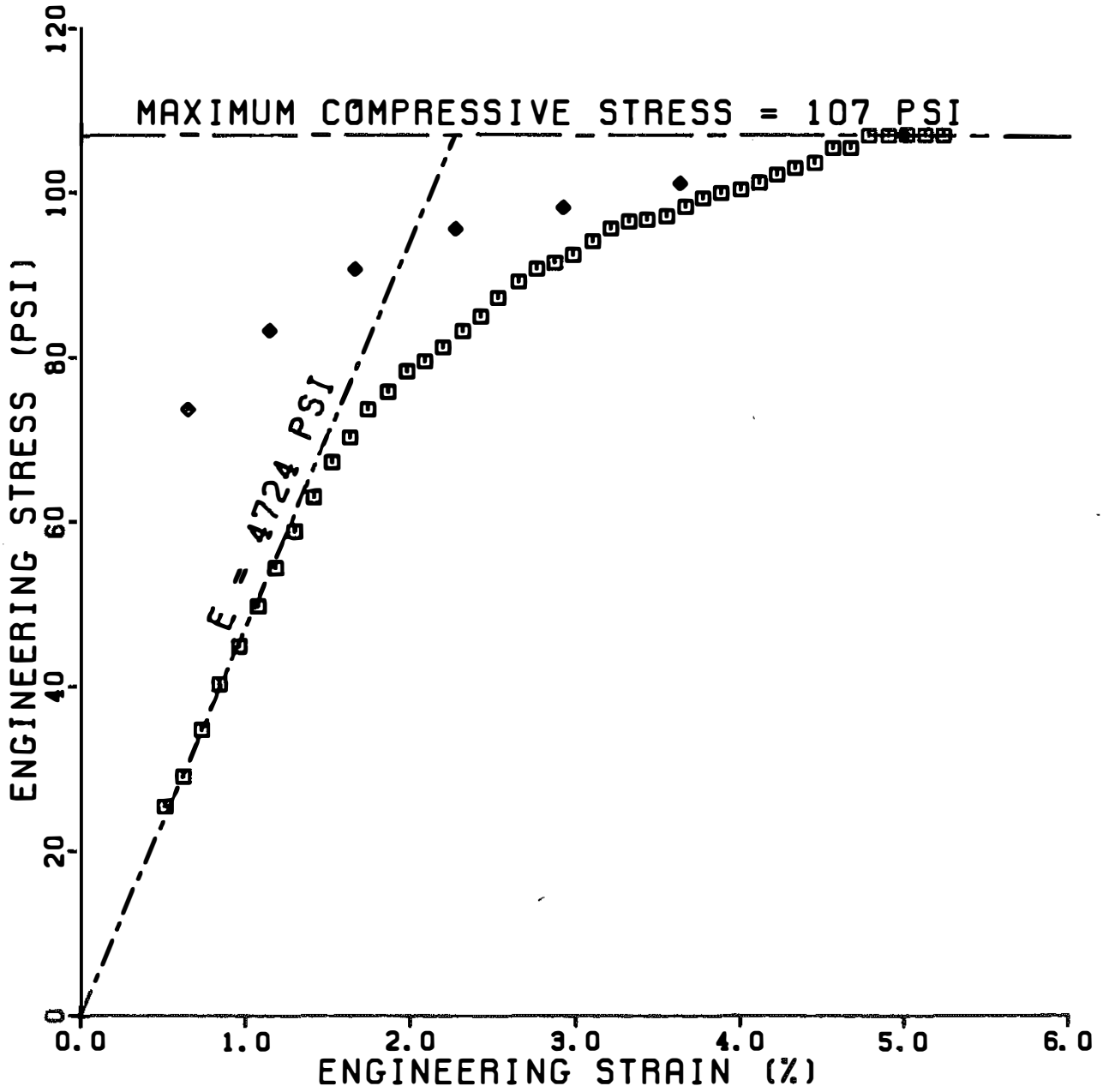
SAMPLE NUMBER : 5-2
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3/22/83 -- CURED 7 DAYS

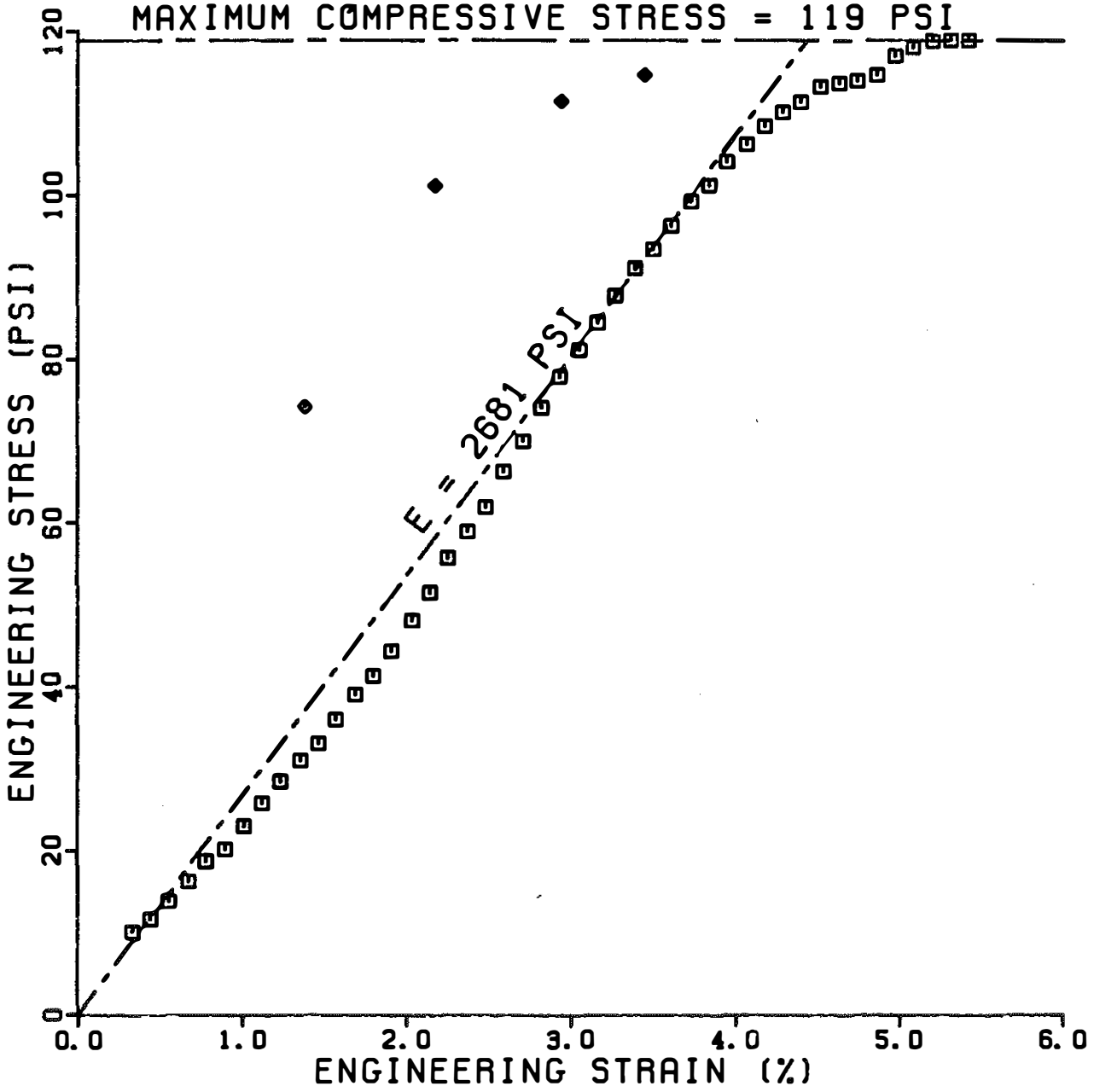


SAMPLE NUMBER : 5-3
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3/22/83 -- CURED 7 DAYS
MAXIMUM COMPRESSIVE STRESS = 119 PSI



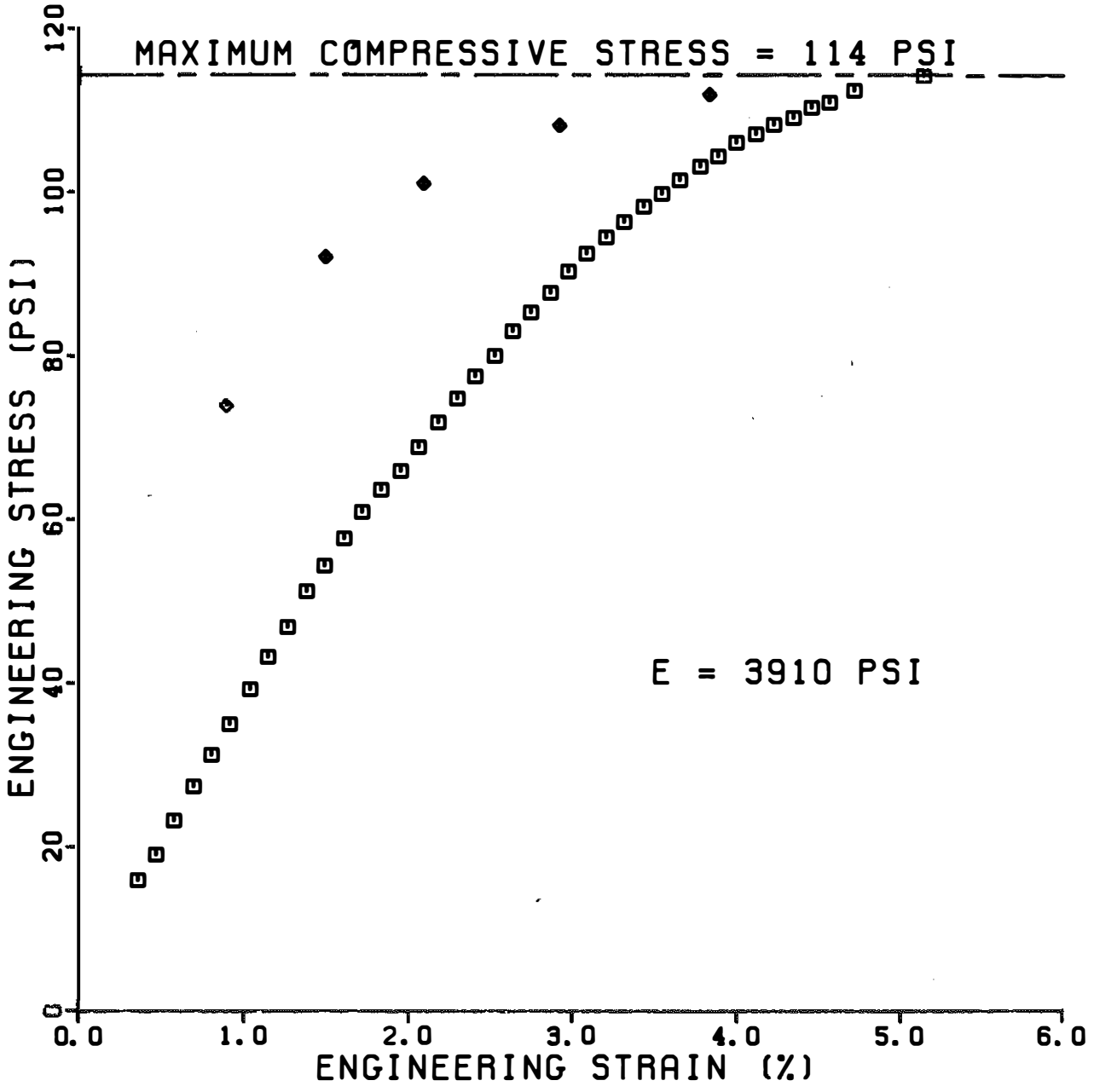
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3/22/83 -- CURED 7 DAYS



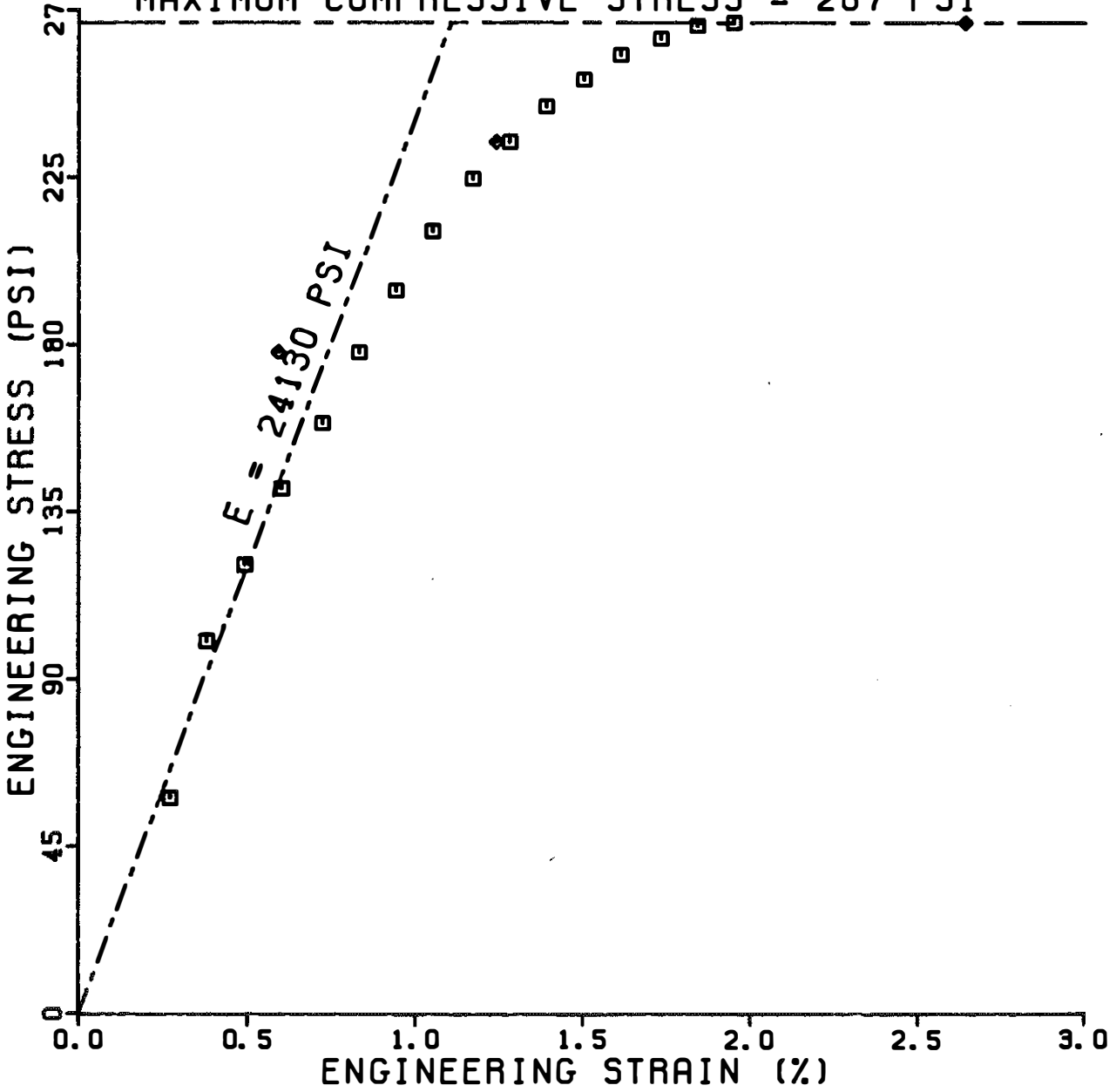
SAMPLE NUMBER : 5-9
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3-22-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 267 PSI

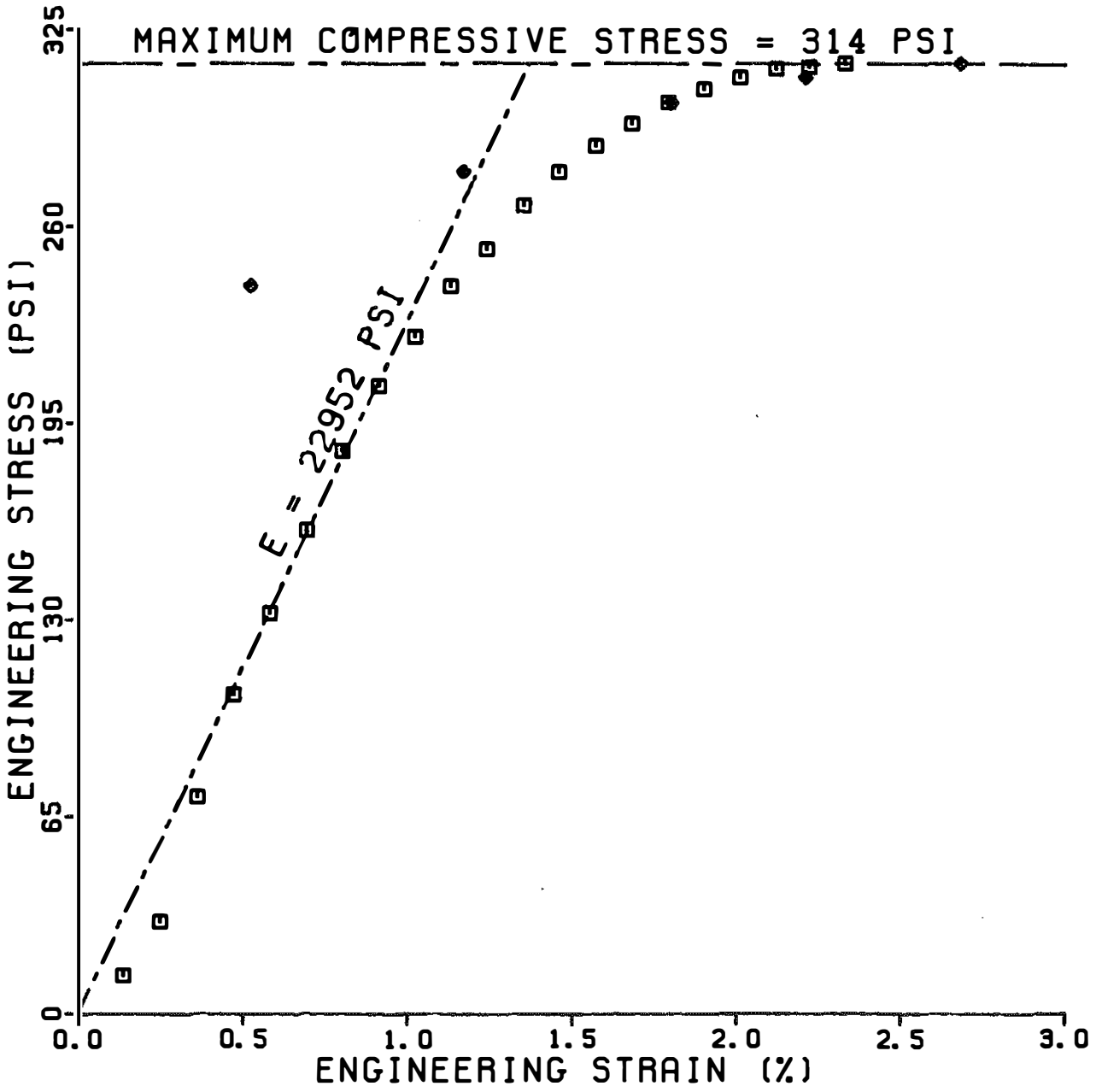


SAMPLE NUMBER : 5-11
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3-22-83 -- CURED 28 DAYS

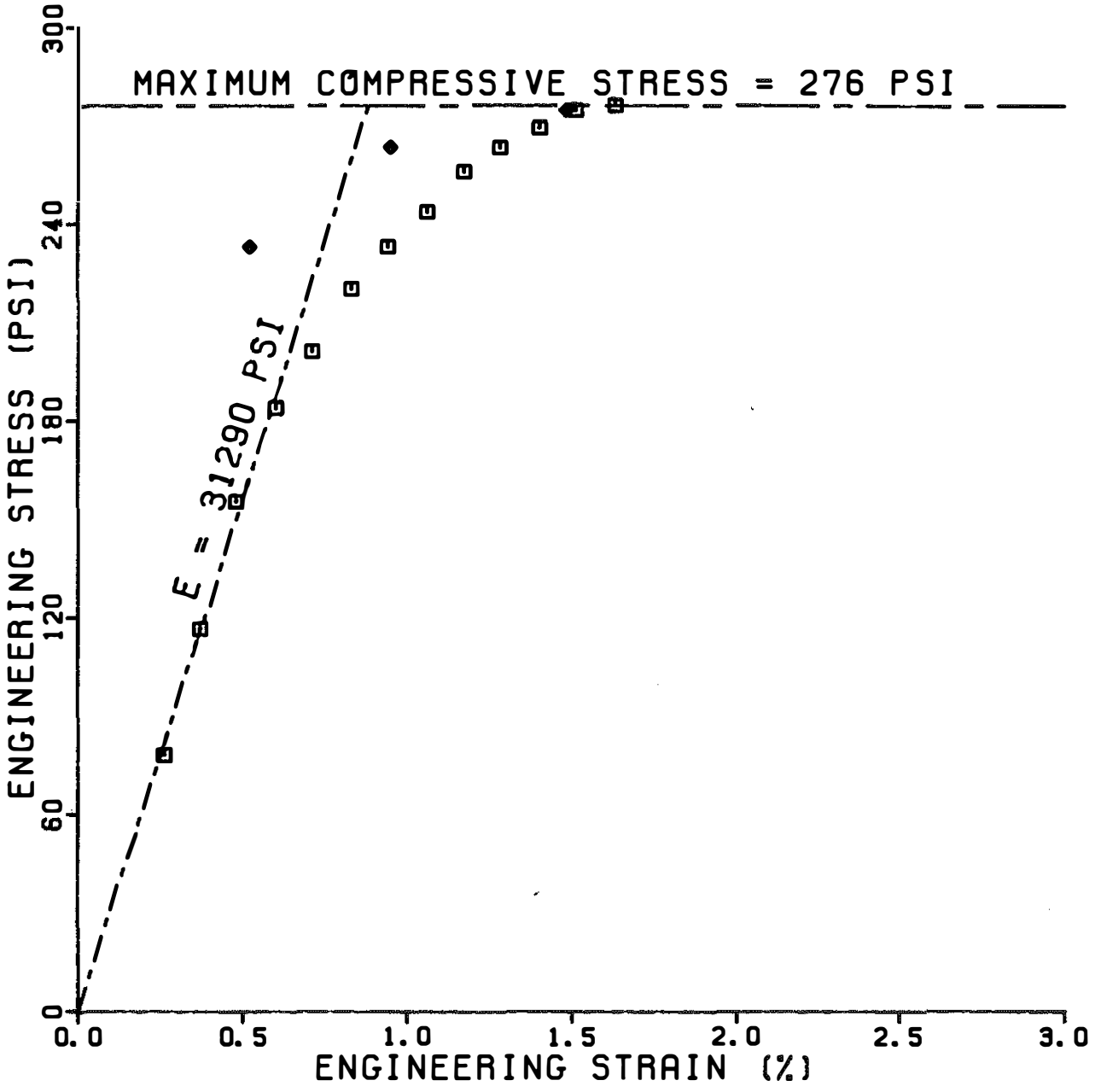


SAMPLE NUMBER : 5-12
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3-22-83 -- CURED 28 DAYS

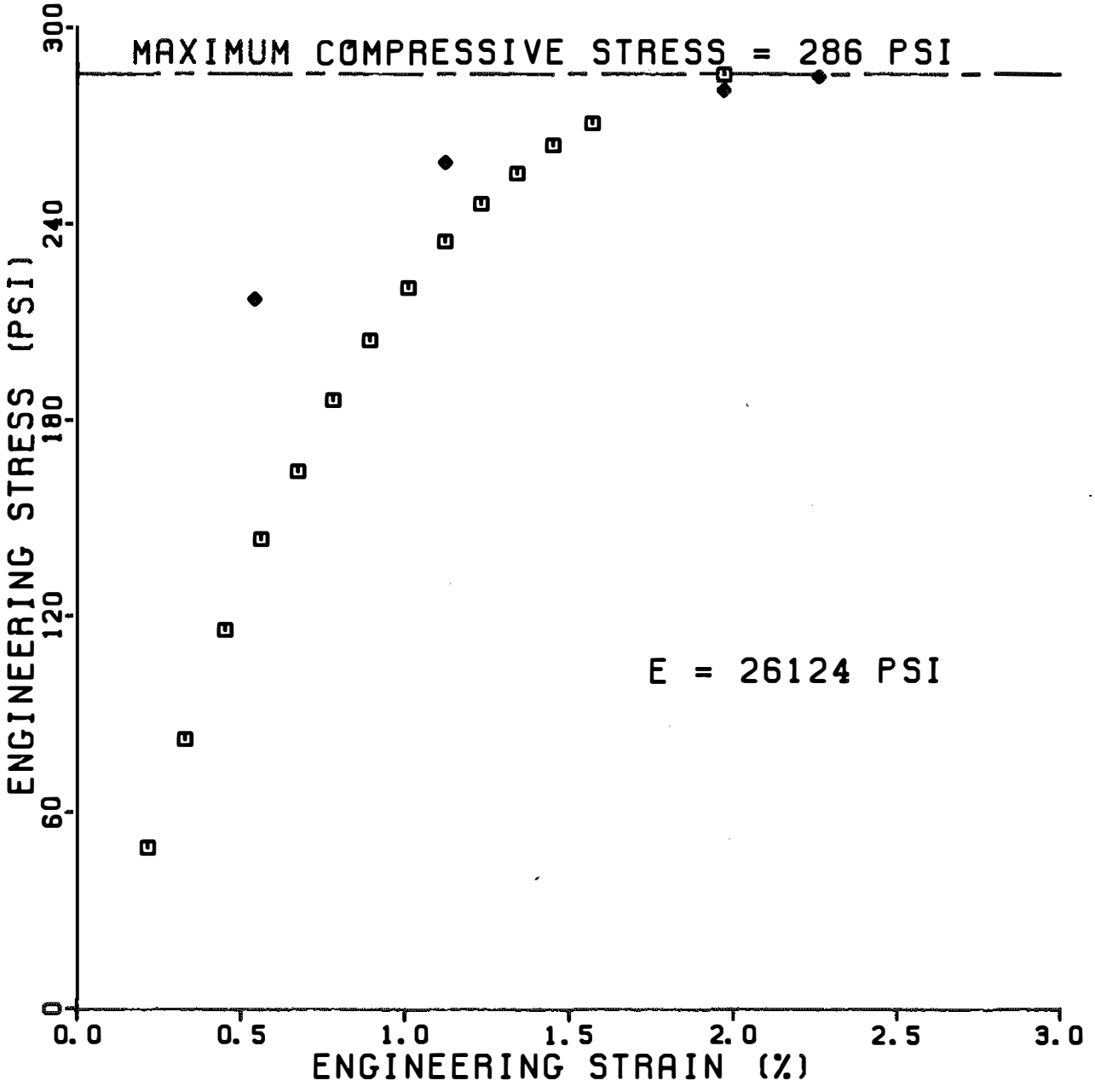


SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
90 % DGA
10 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 134 PCF
OPTIMUM MOISTURE = 9.9 %

MADE 3-22-83 -- CURED 28 DAYS

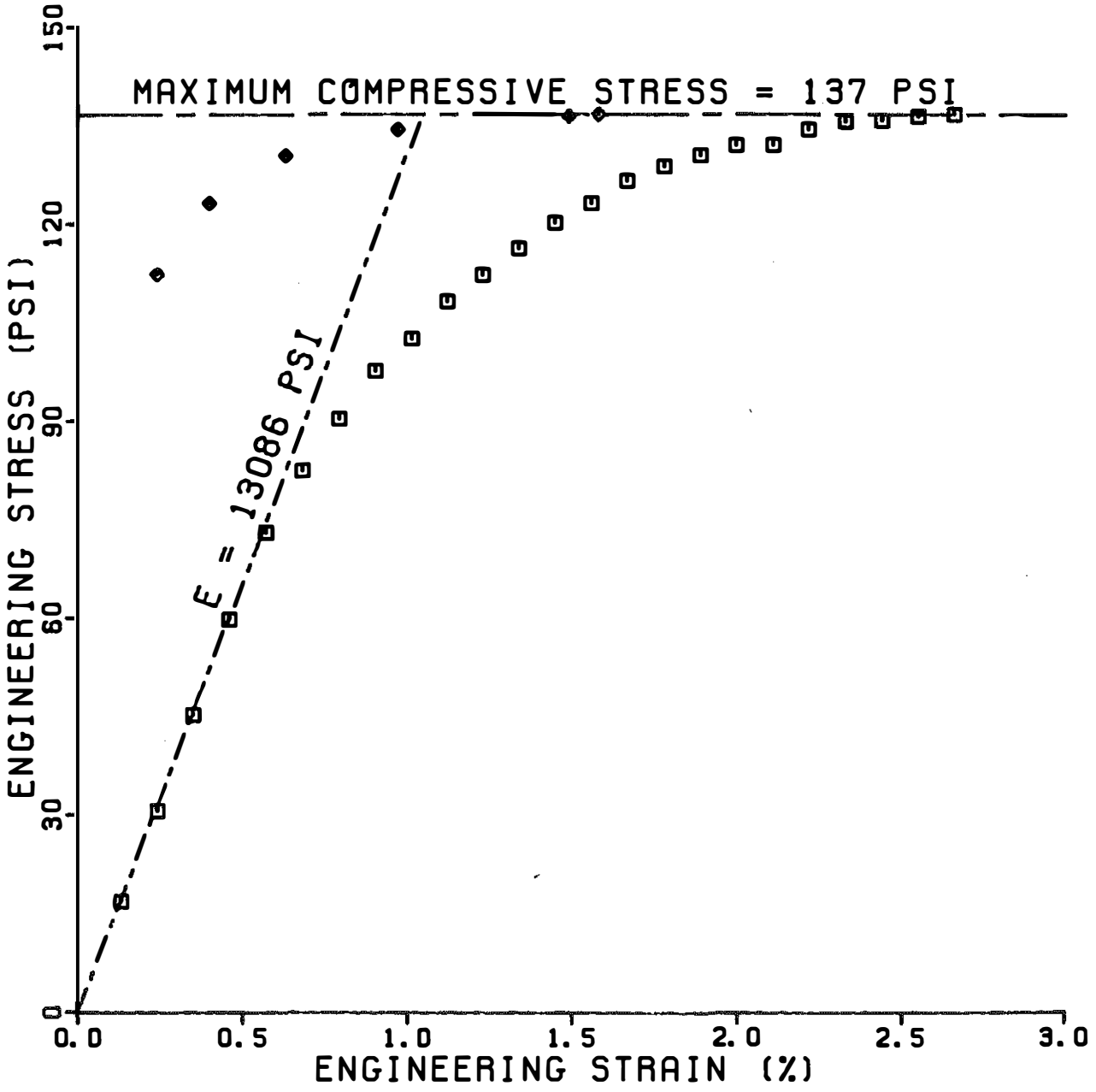


SAMPLE NUMBER : 6-1
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 7 DAYS

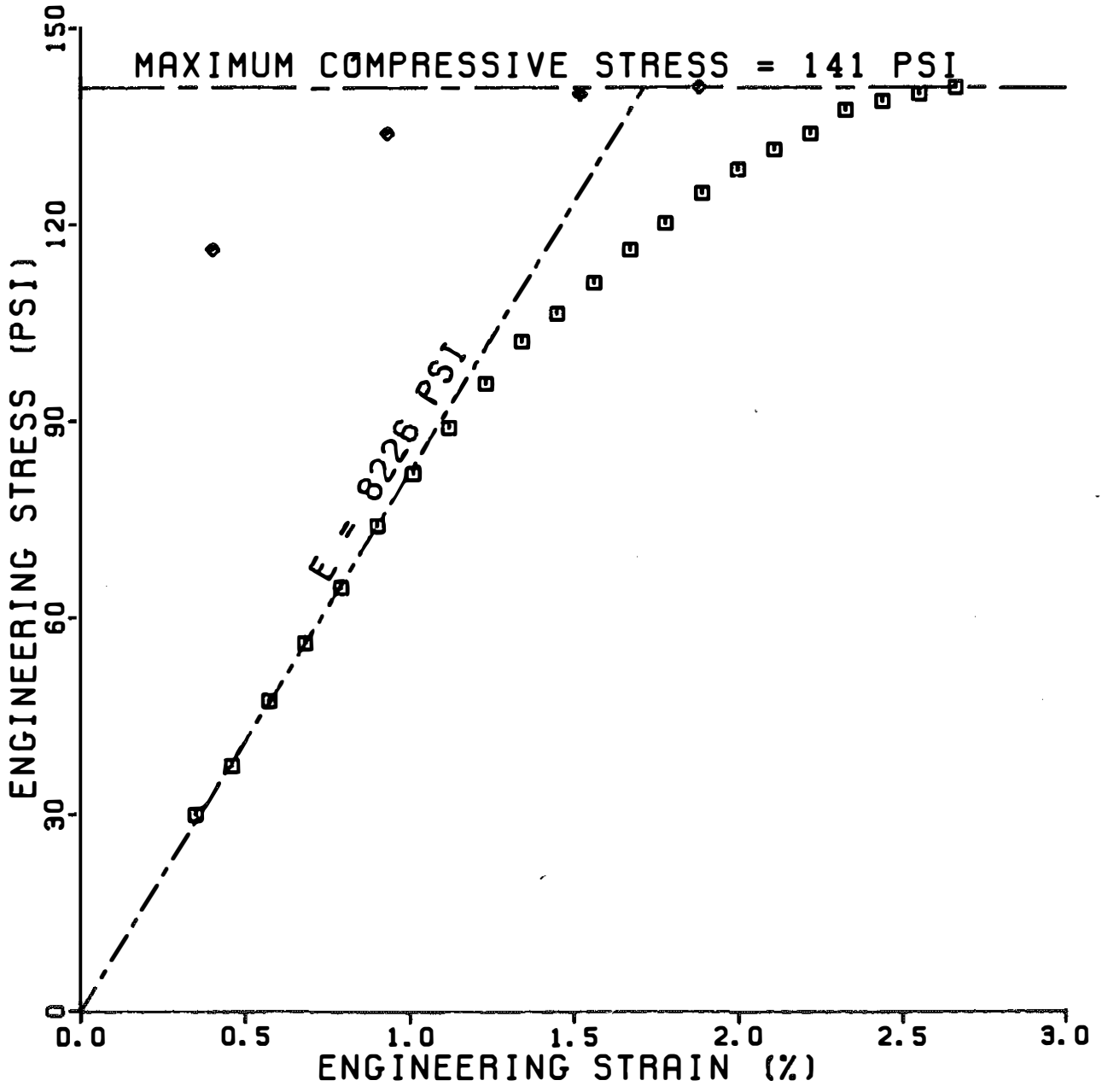


SAMPLE NUMBER : 6-2
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 7 DAYS

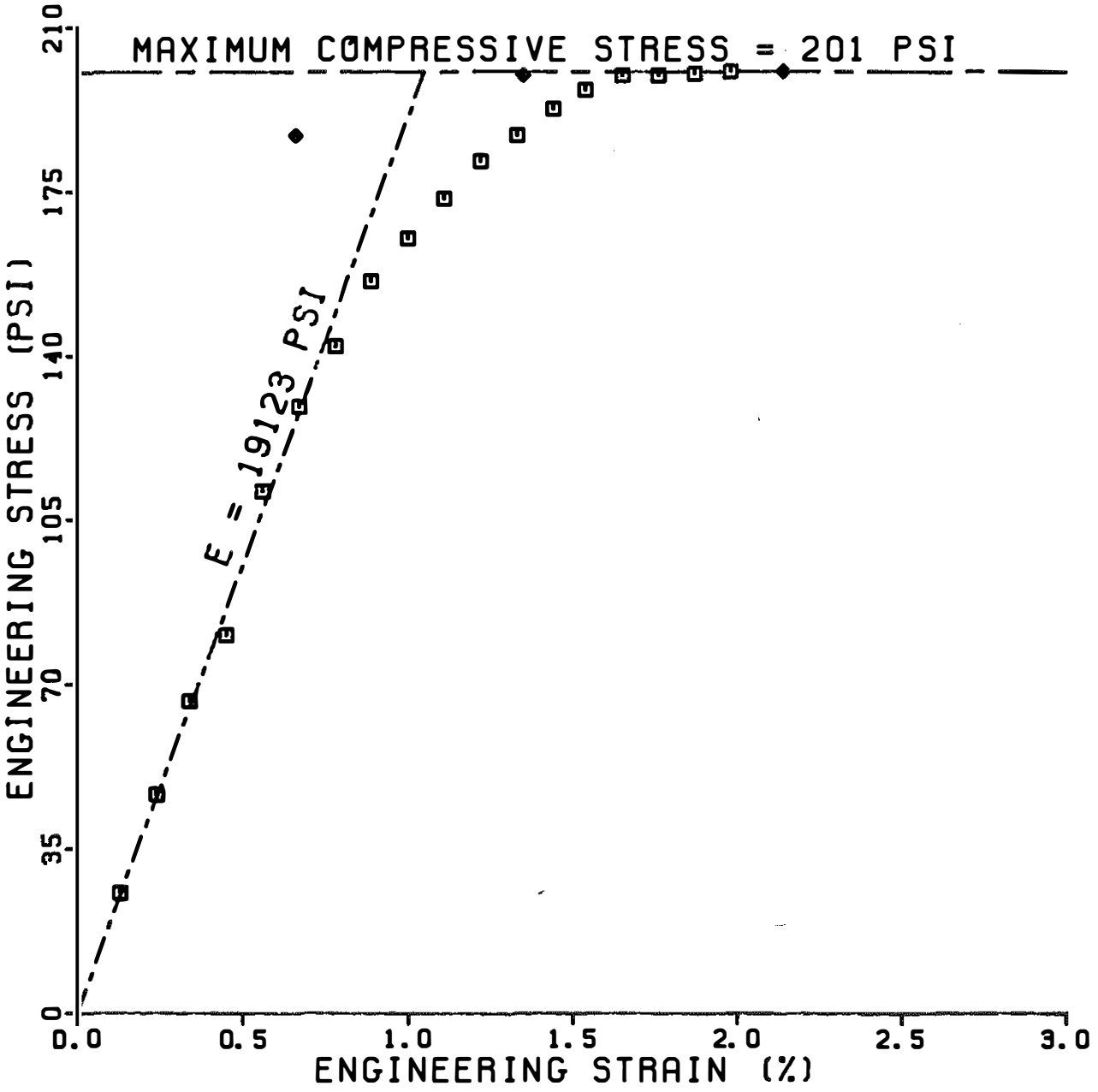


SAMPLE NUMBER : 6-3
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 7 DAYS



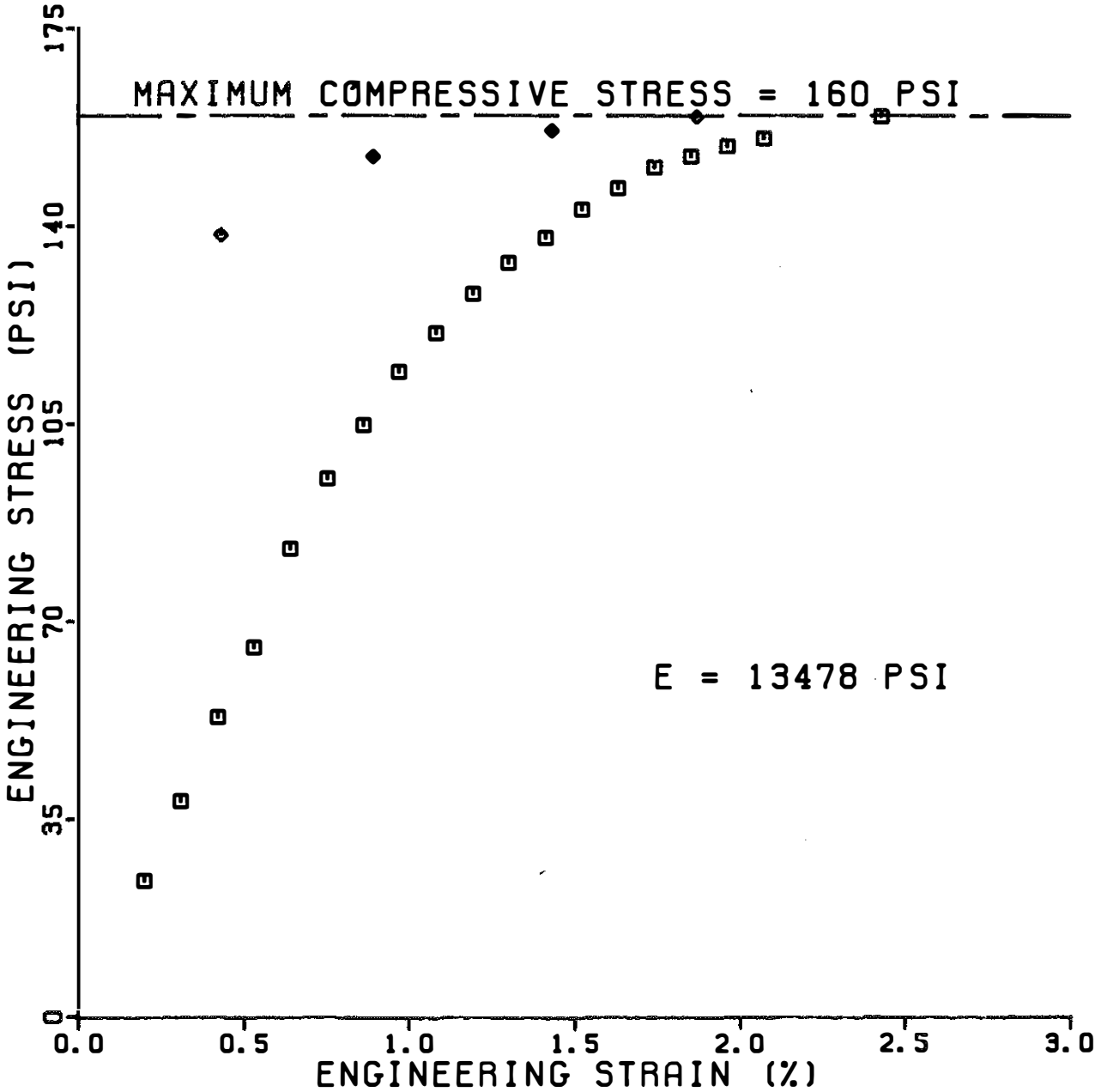
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 7 DAYS

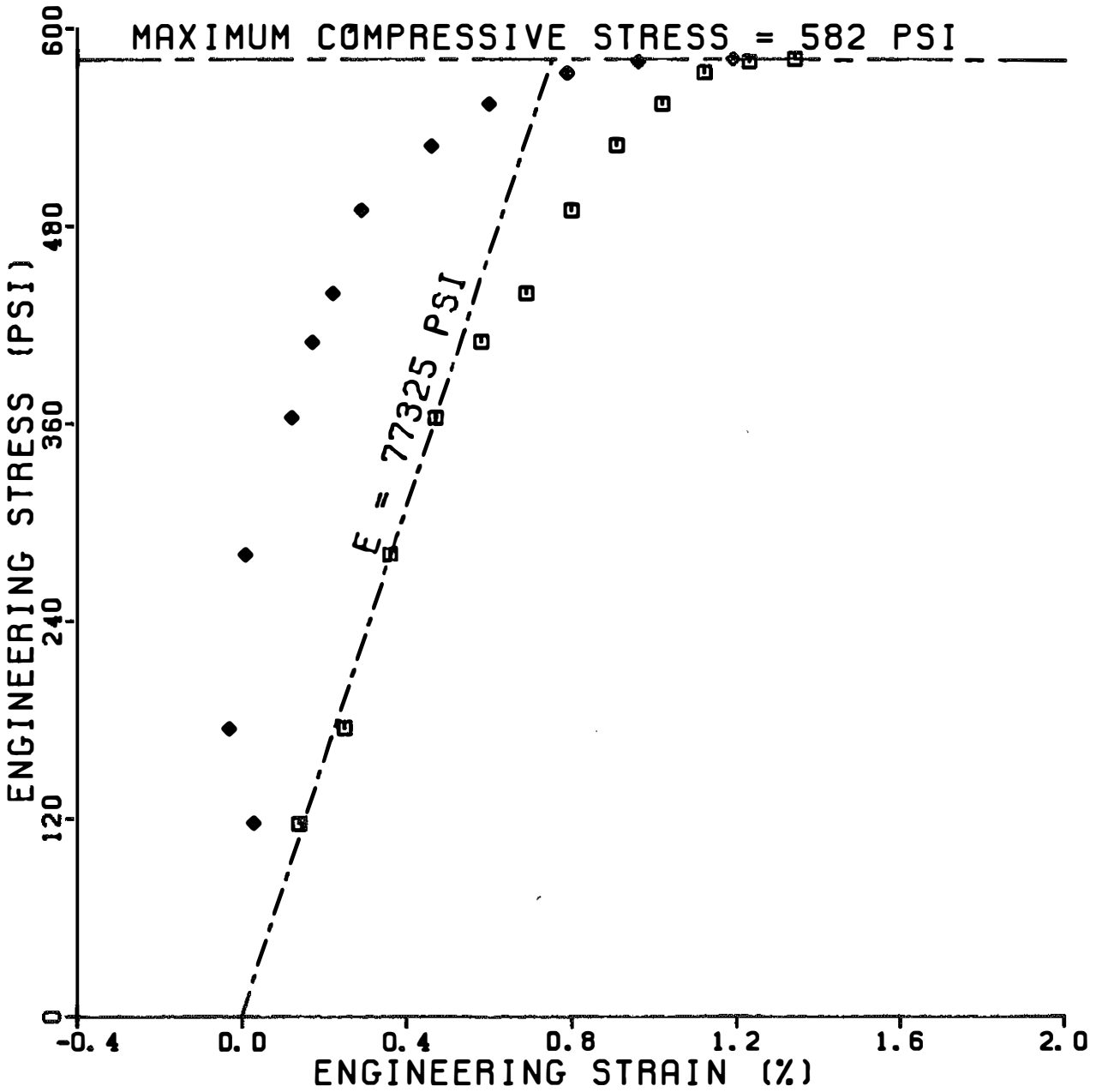


SAMPLE NUMBER : 6-8
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 28 DAYS



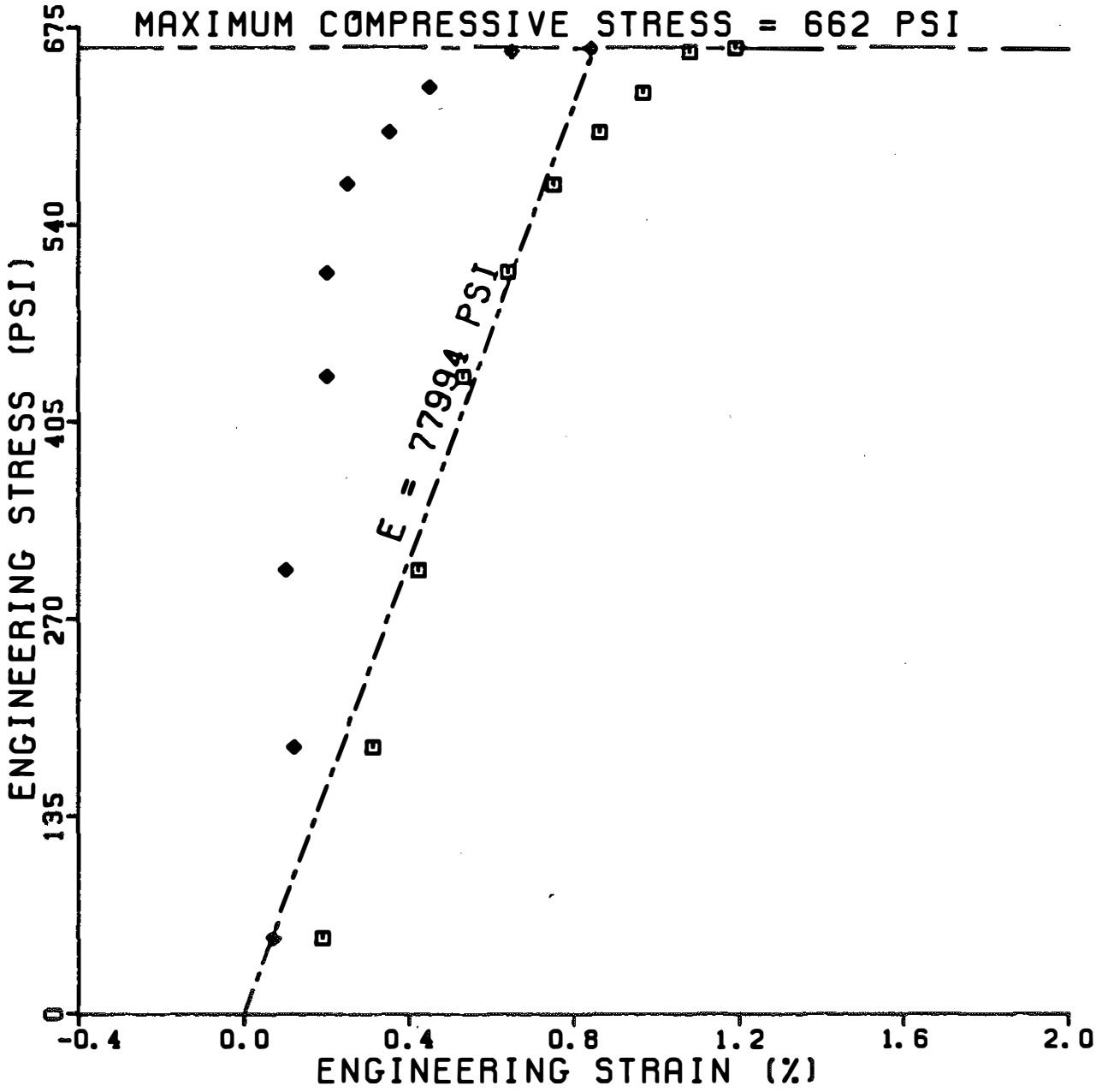
SAMPLE NUMBER : 6-9
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 662 PSI



SAMPLE NUMBER : 6-10
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

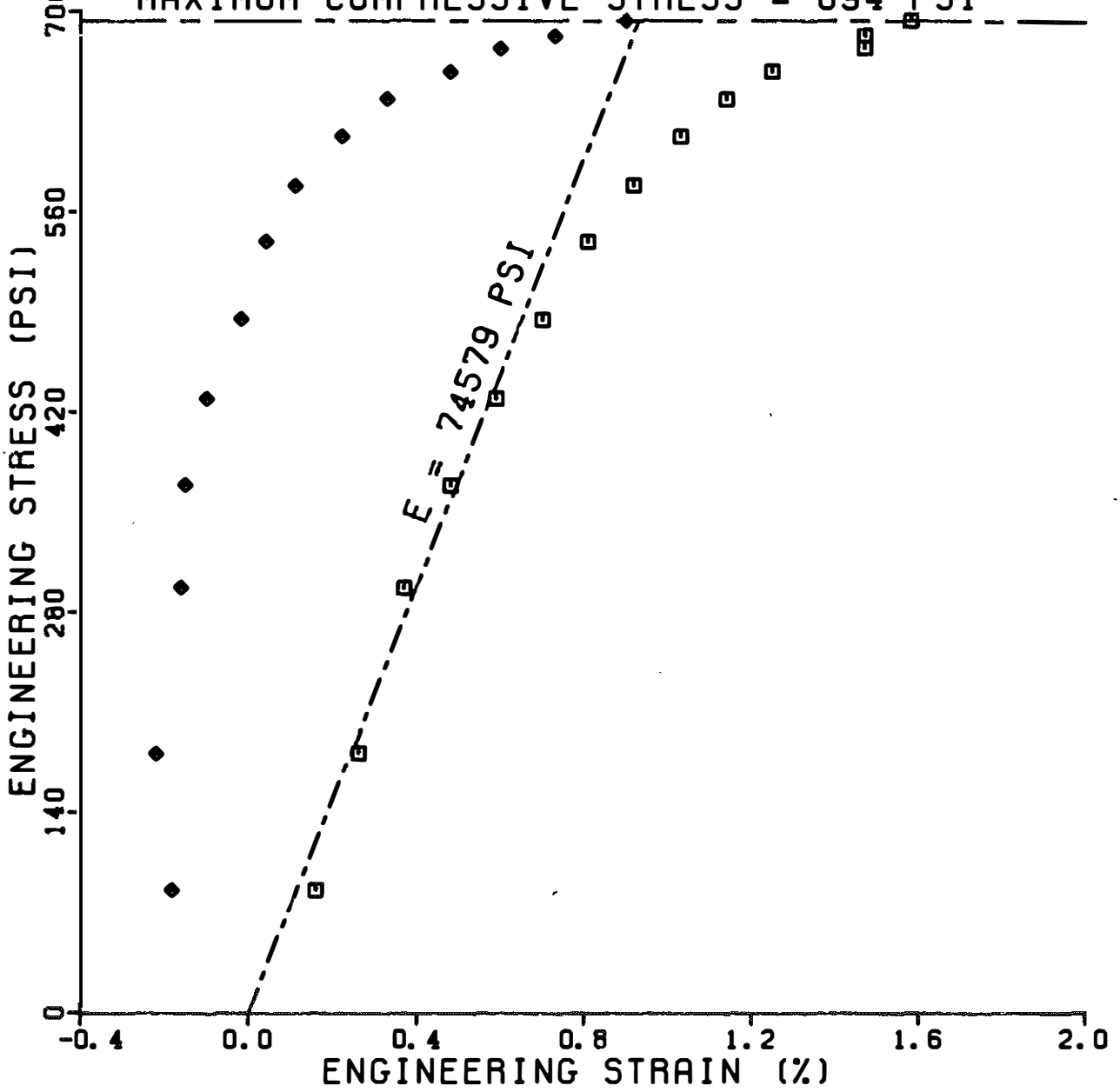
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 694 PSI



SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT

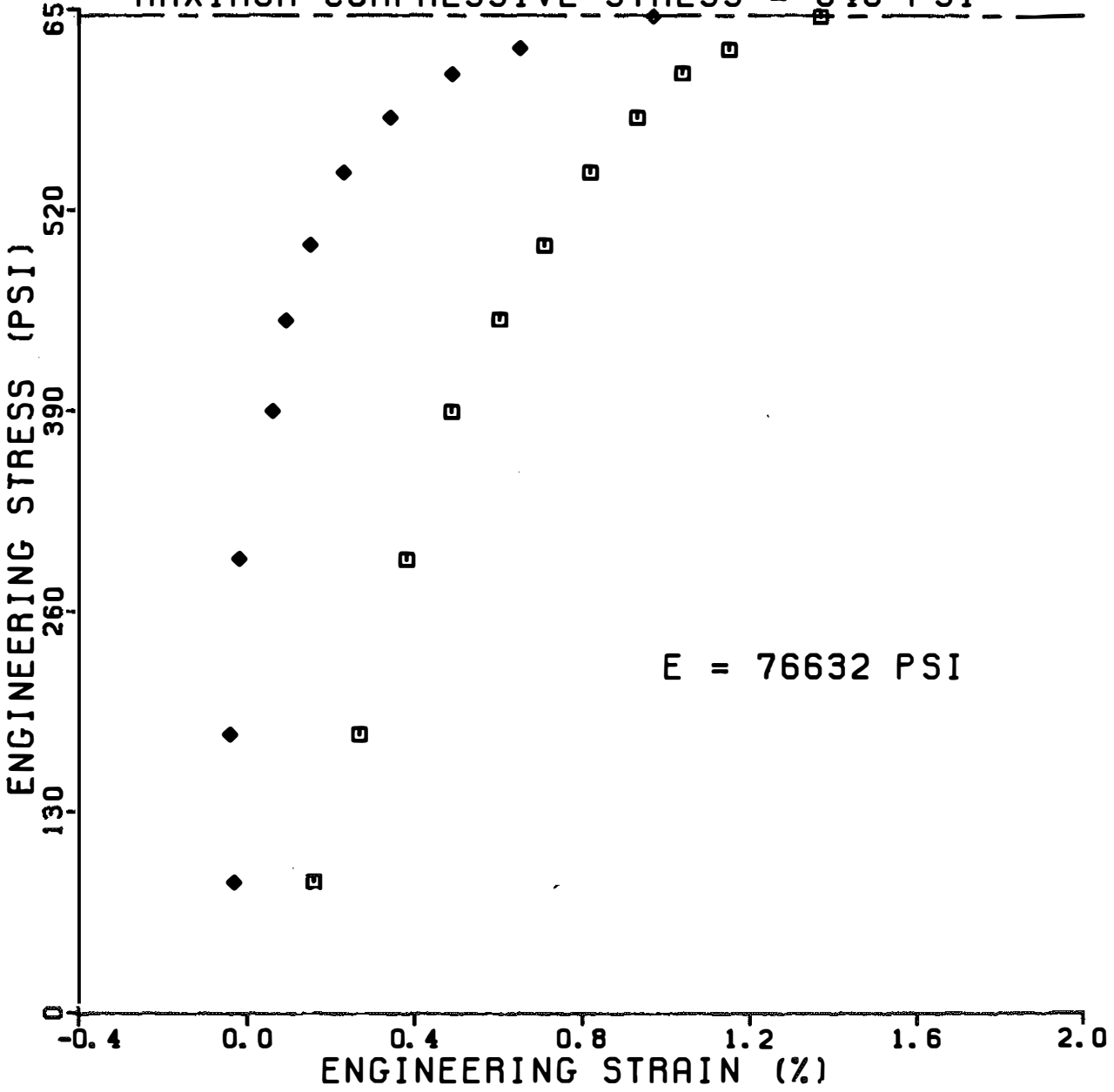
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % POND ASH
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 151 PCF
OPTIMUM MOISTURE = 11.2 %

MADE 3-24-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 646 PSI

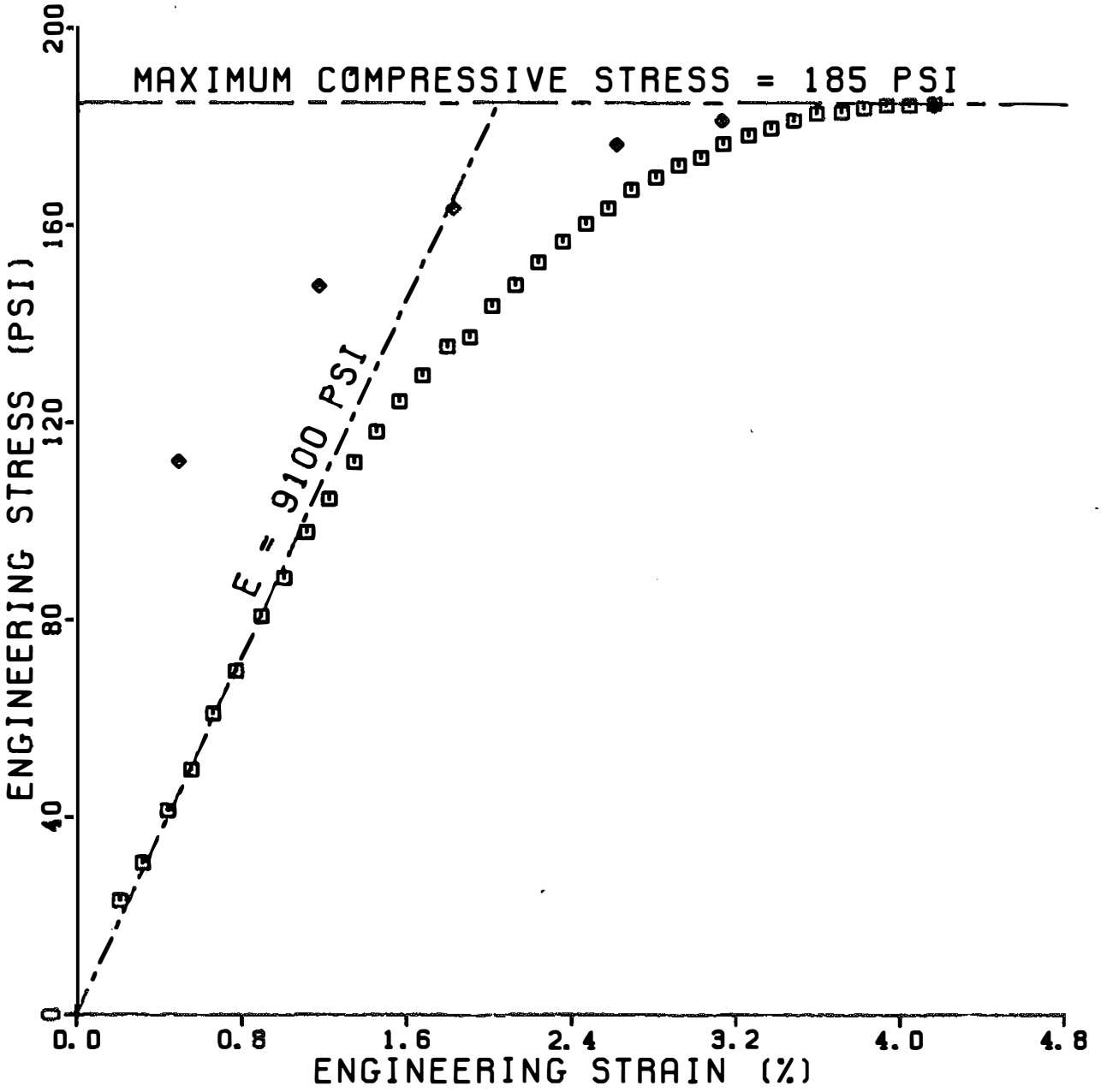


SAMPLE NUMBER : 7-1
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % DGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 7 DAYS



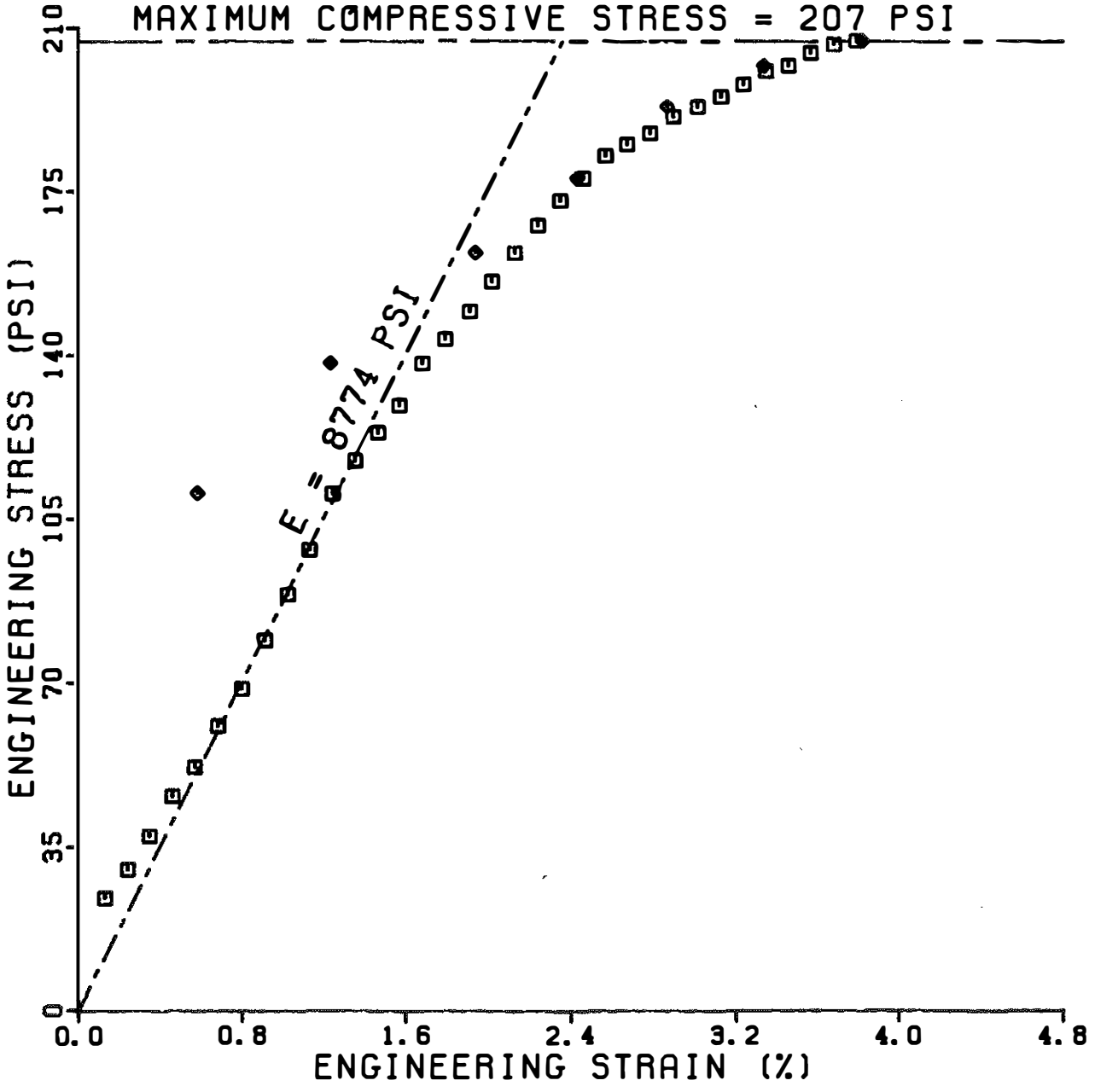
SAMPLE NUMBER : 7-2
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % DGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 7 DAYS

MAXIMUM COMPRESSIVE STRESS = 207 PSI

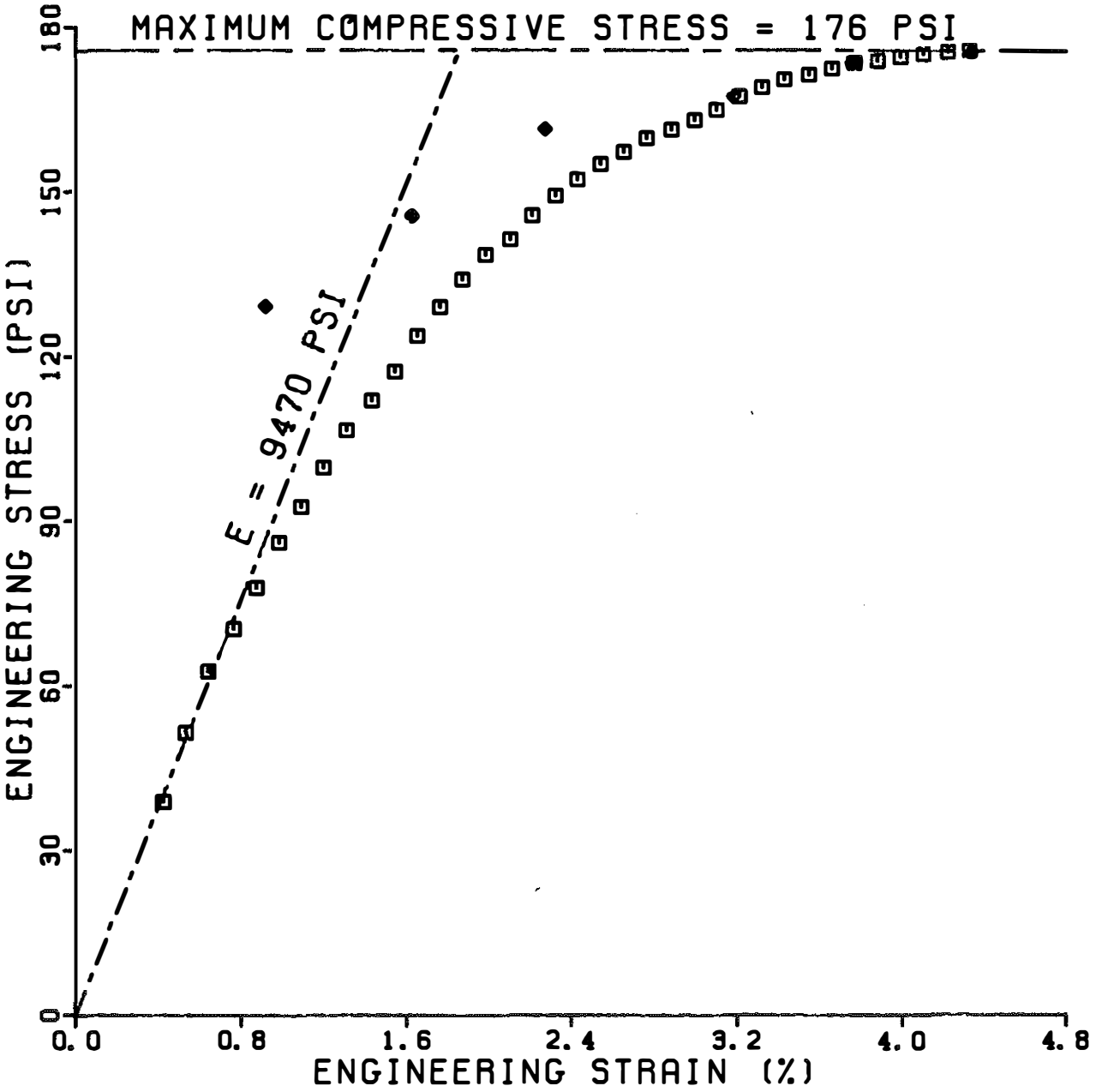


SAMPLE NUMBER : 7-3
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % DGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 7 DAYS

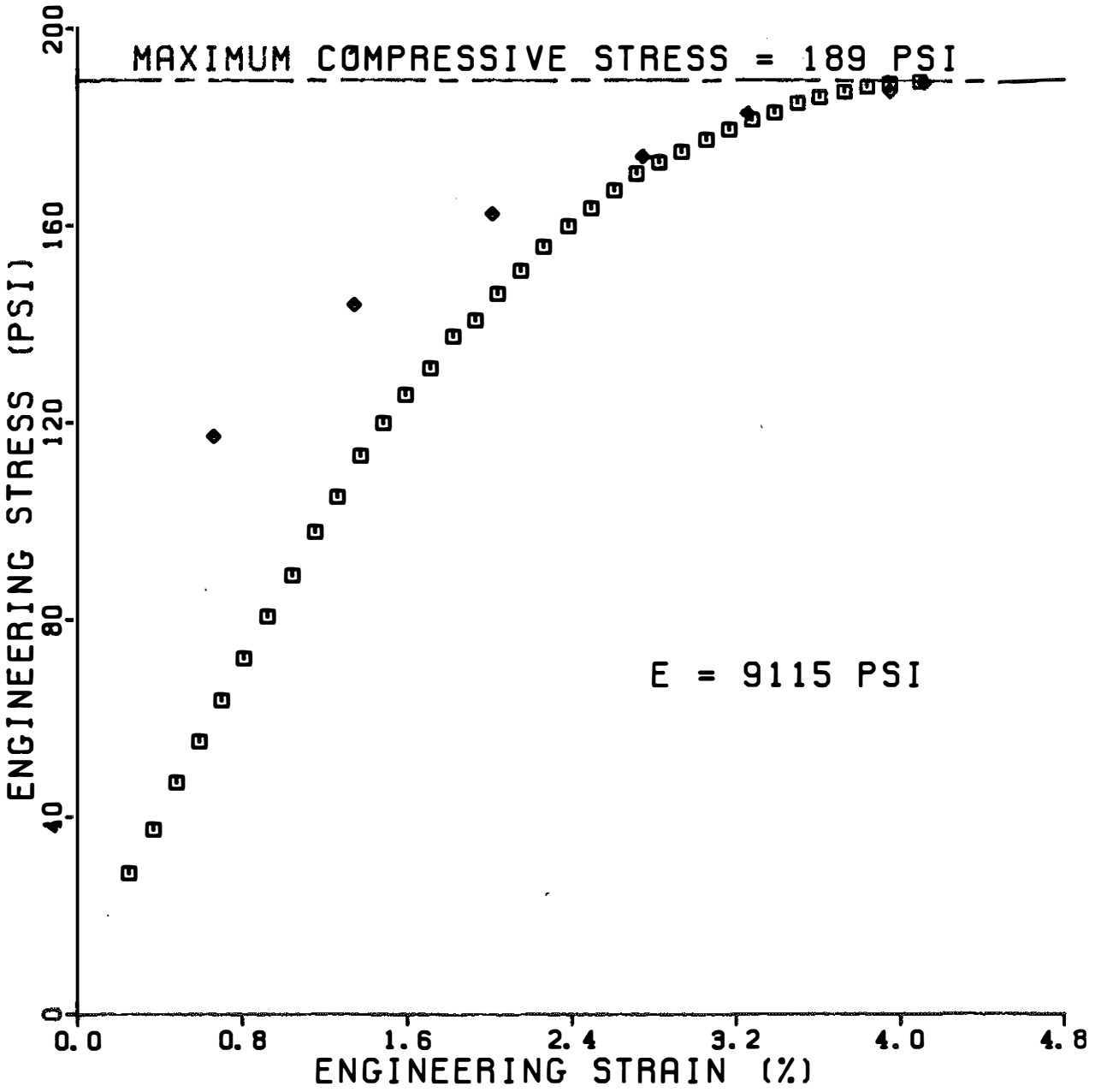


SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % DGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 7 DAYS

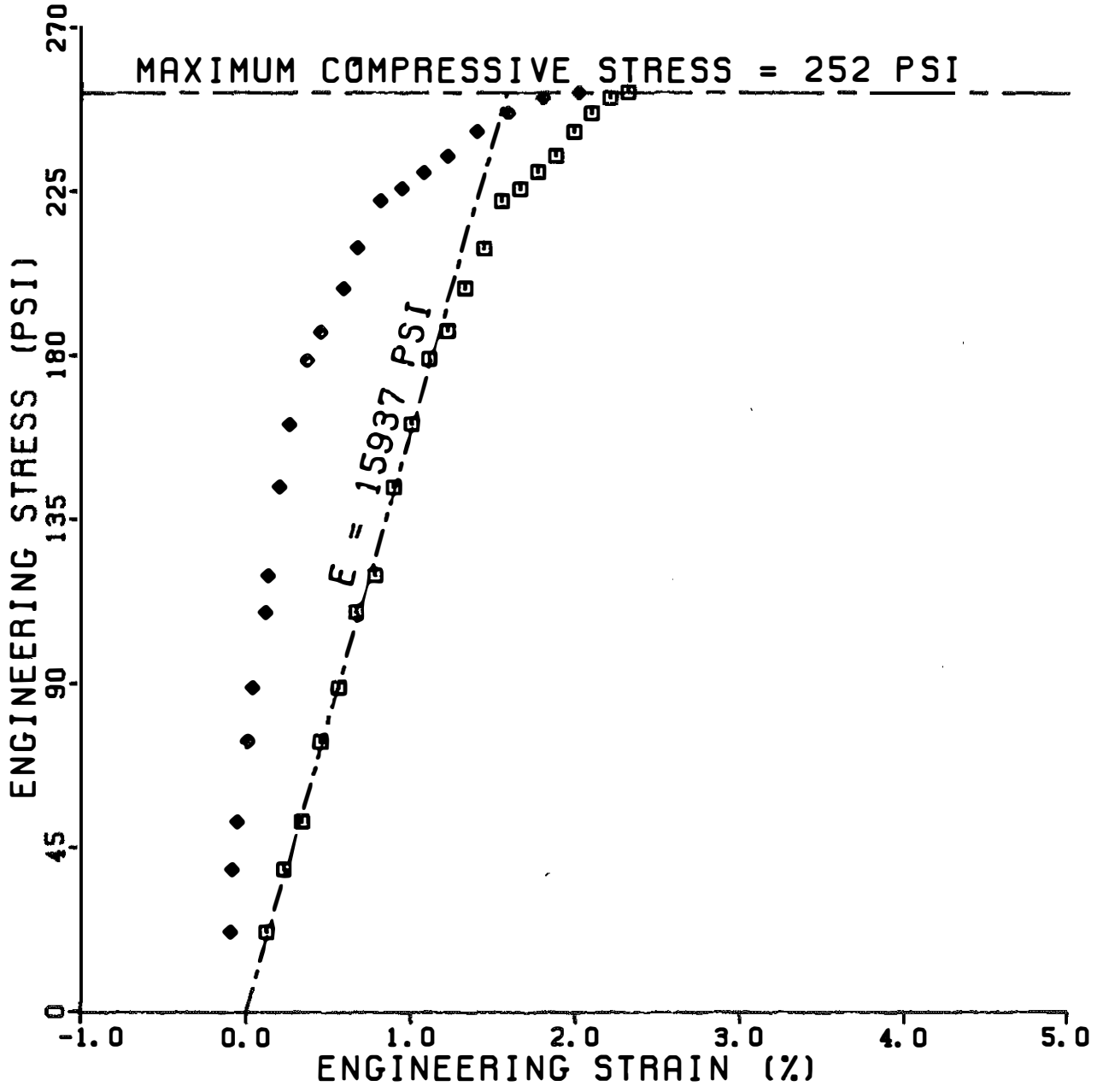


SAMPLE NUMBER : 7-8
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % OGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 28 DAYS

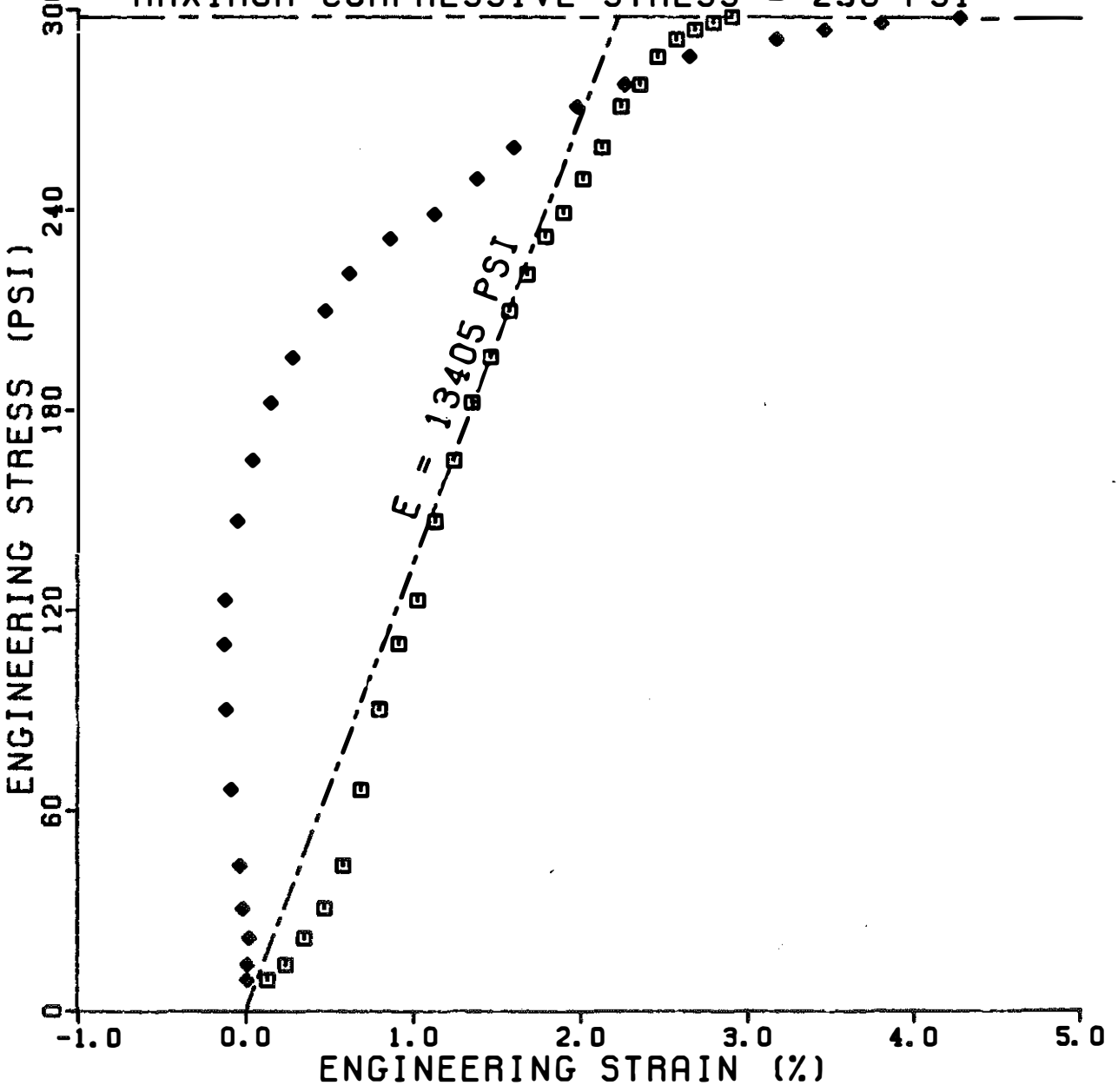


SAMPLE NUMBER : 7-9
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % DGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 298 PSI

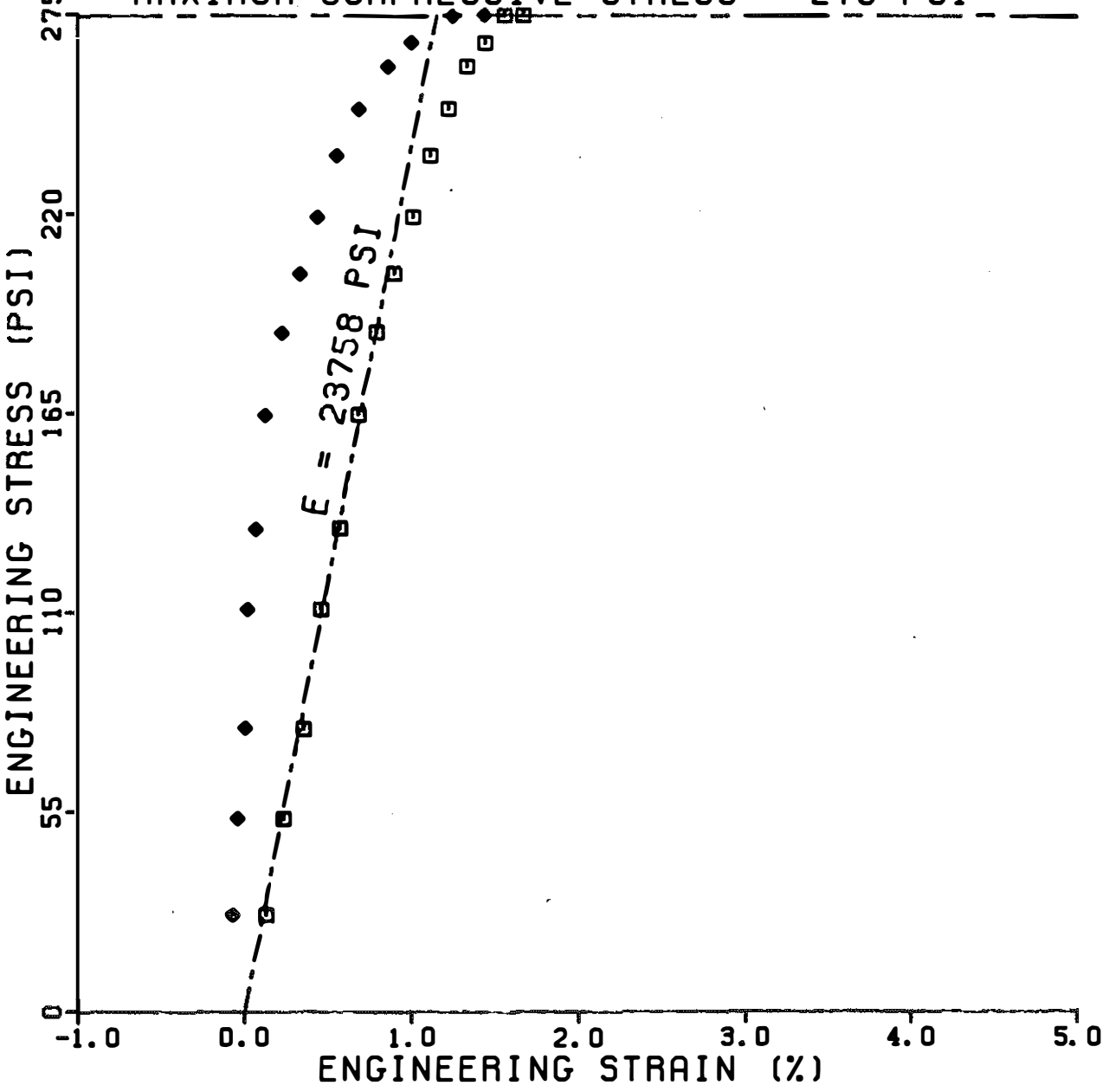


SAMPLE NUMBER : 7-10
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % OGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 275 PSI

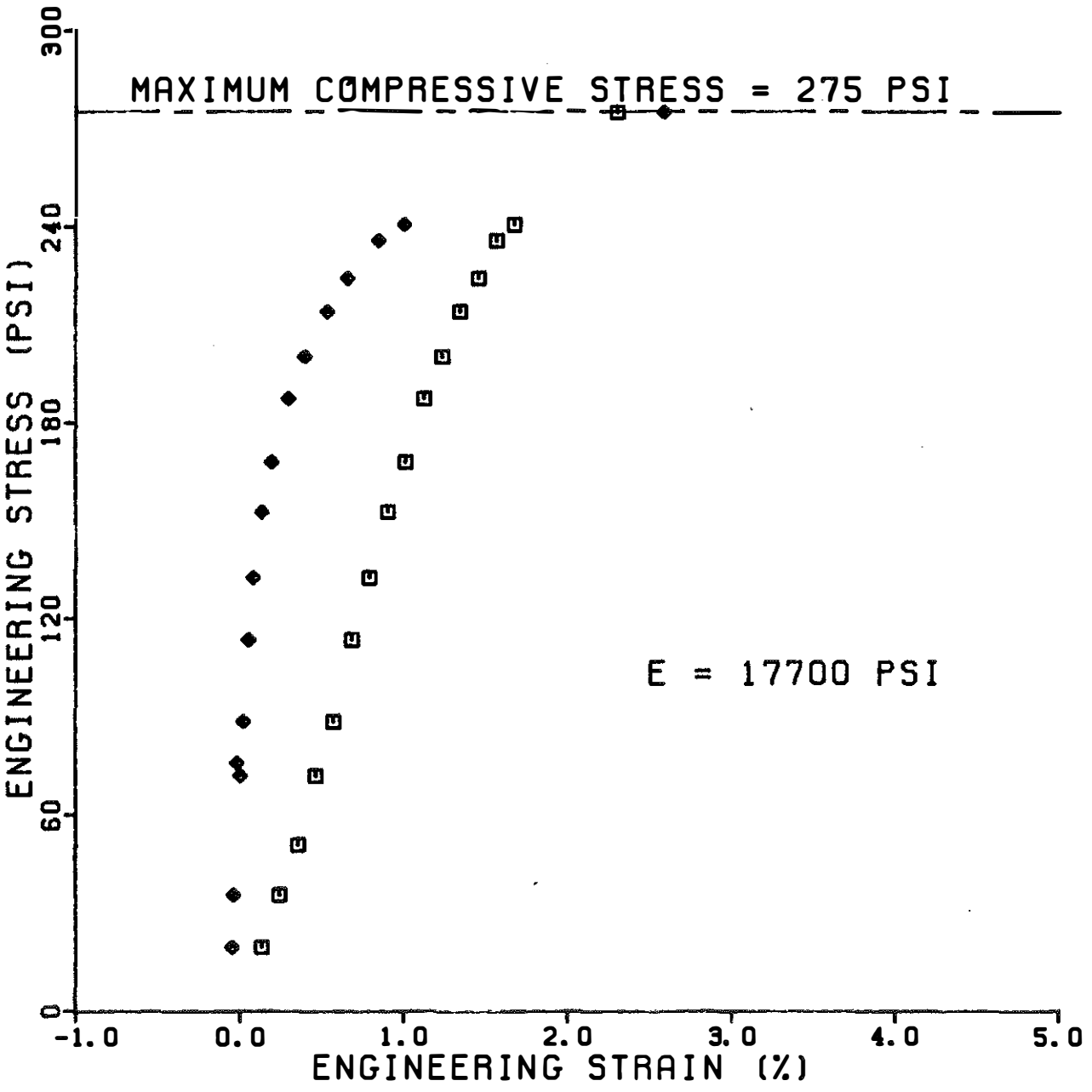


SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
85 % DGA
15 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 131 PCF
OPTIMUM MOISTURE = 10.9 %

MADE 4-5-83 -- CURED 28 DAYS

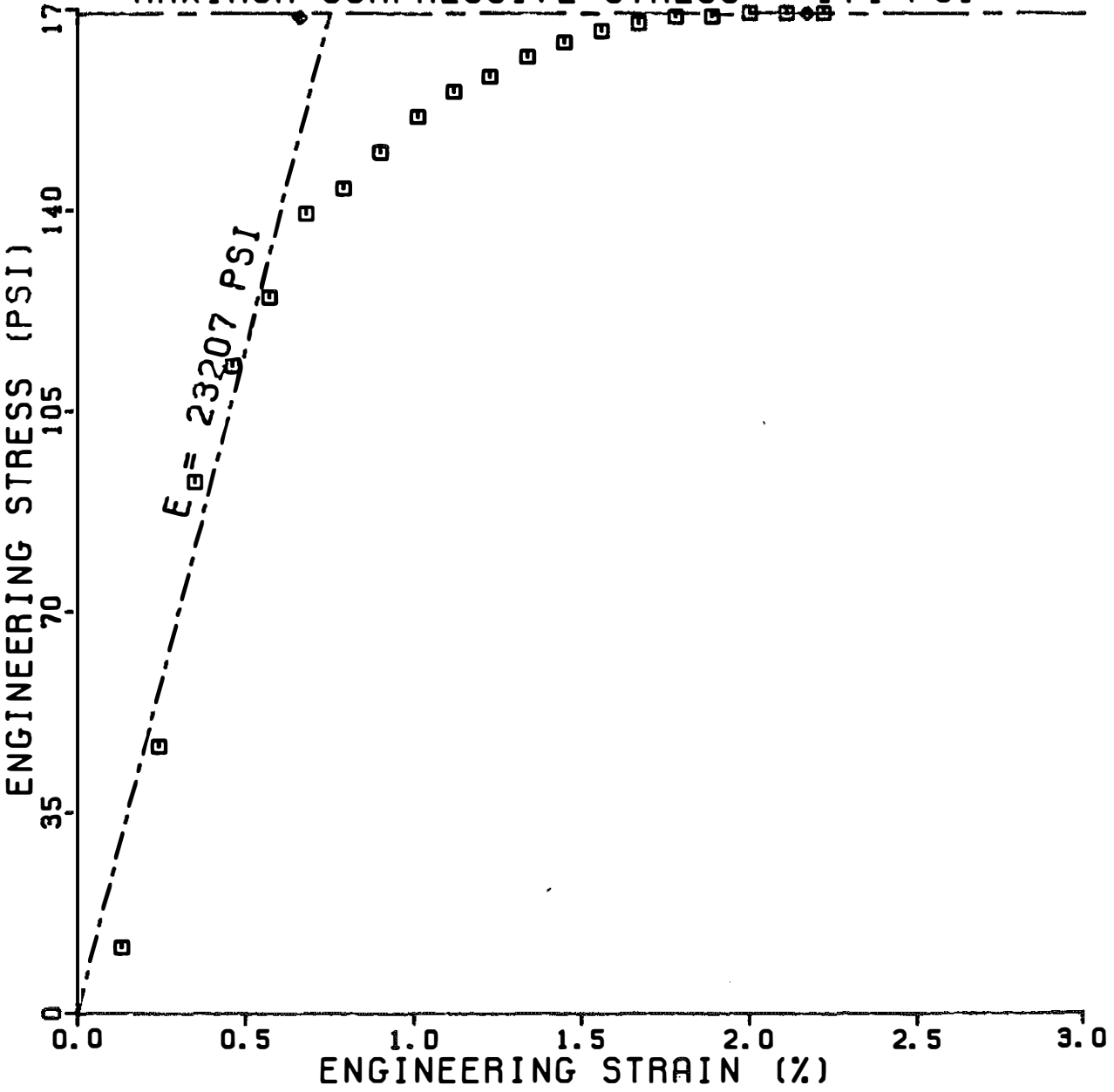


SAMPLE NUMBER : 8-1
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 7 DAYS
MAXIMUM COMPRESSIVE STRESS = 174 PSI



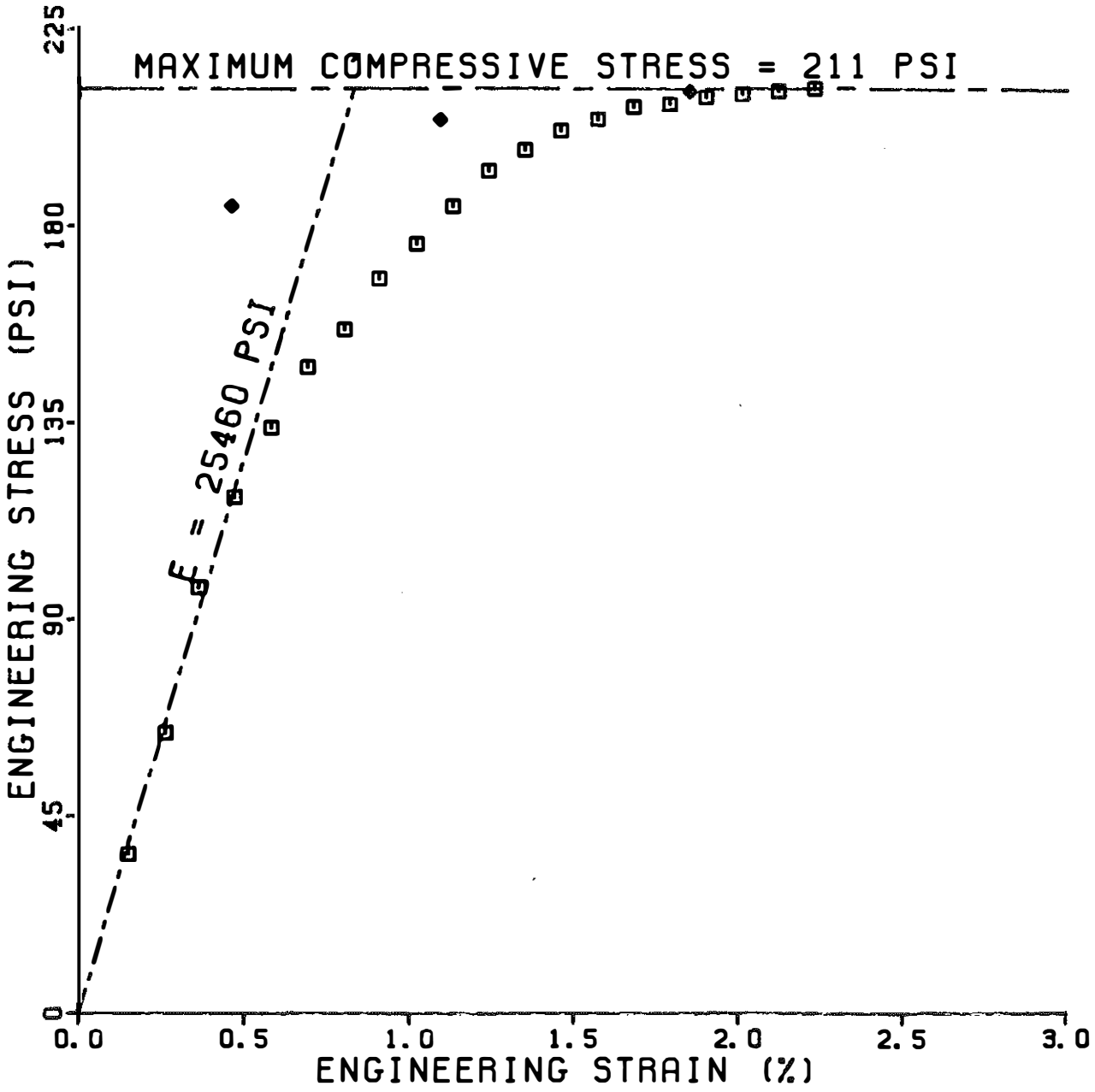
SAMPLE NUMBER : 8-2
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 7 DAYS

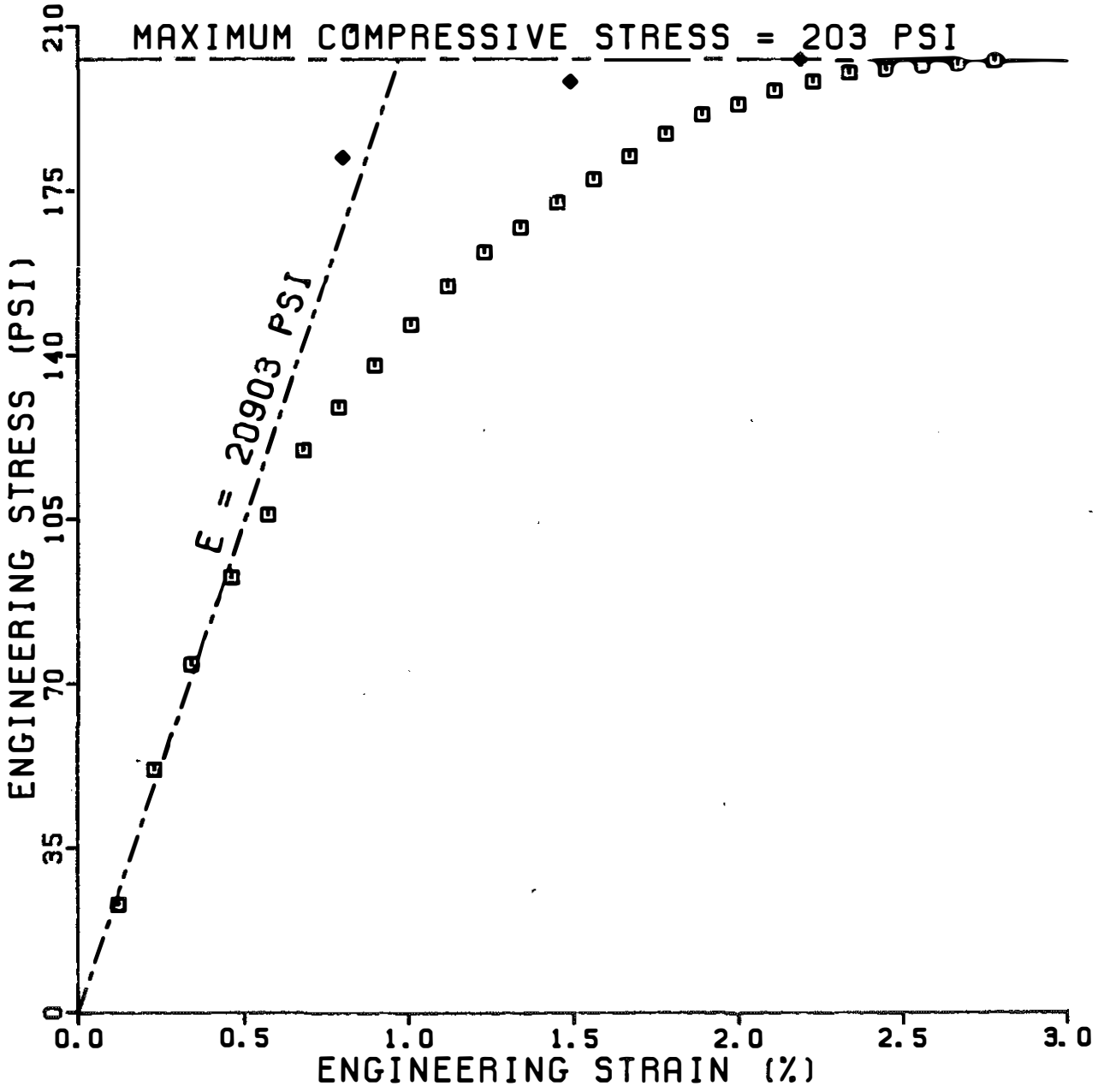


SAMPLE NUMBER : 8-3
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 7 DAYS



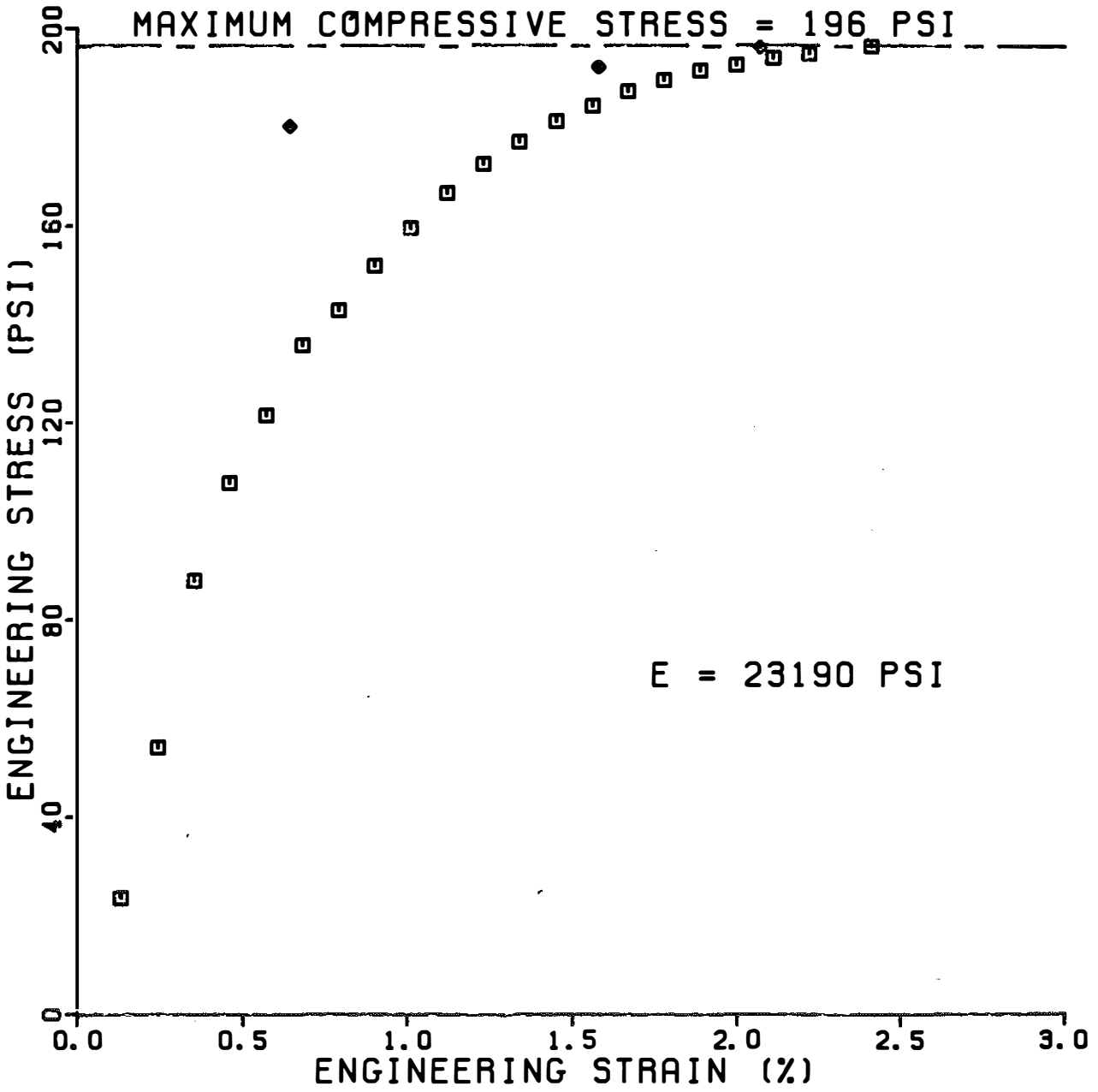
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 7 DAYS

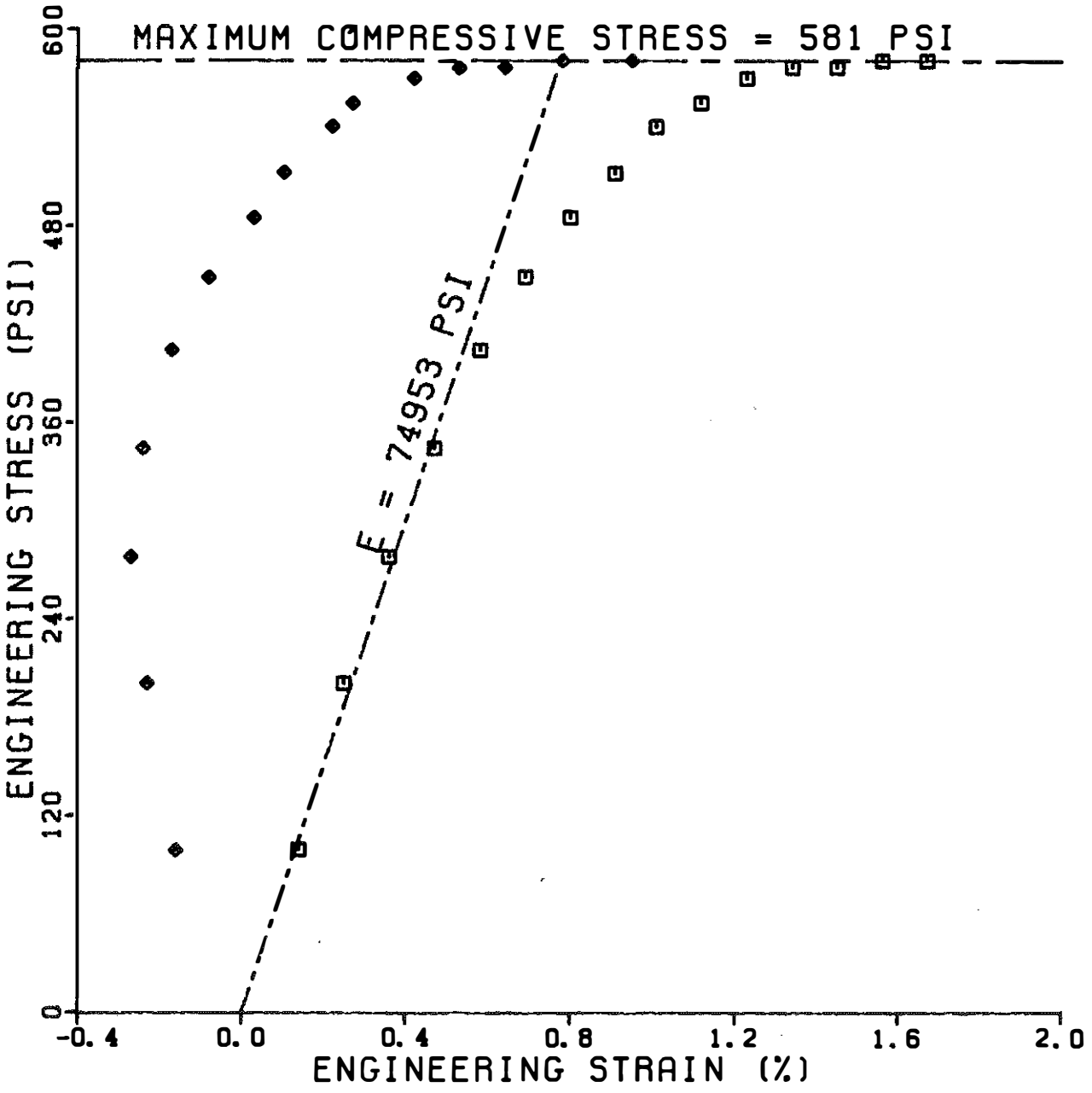


SAMPLE NUMBER : 8-8
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 28 DAYS



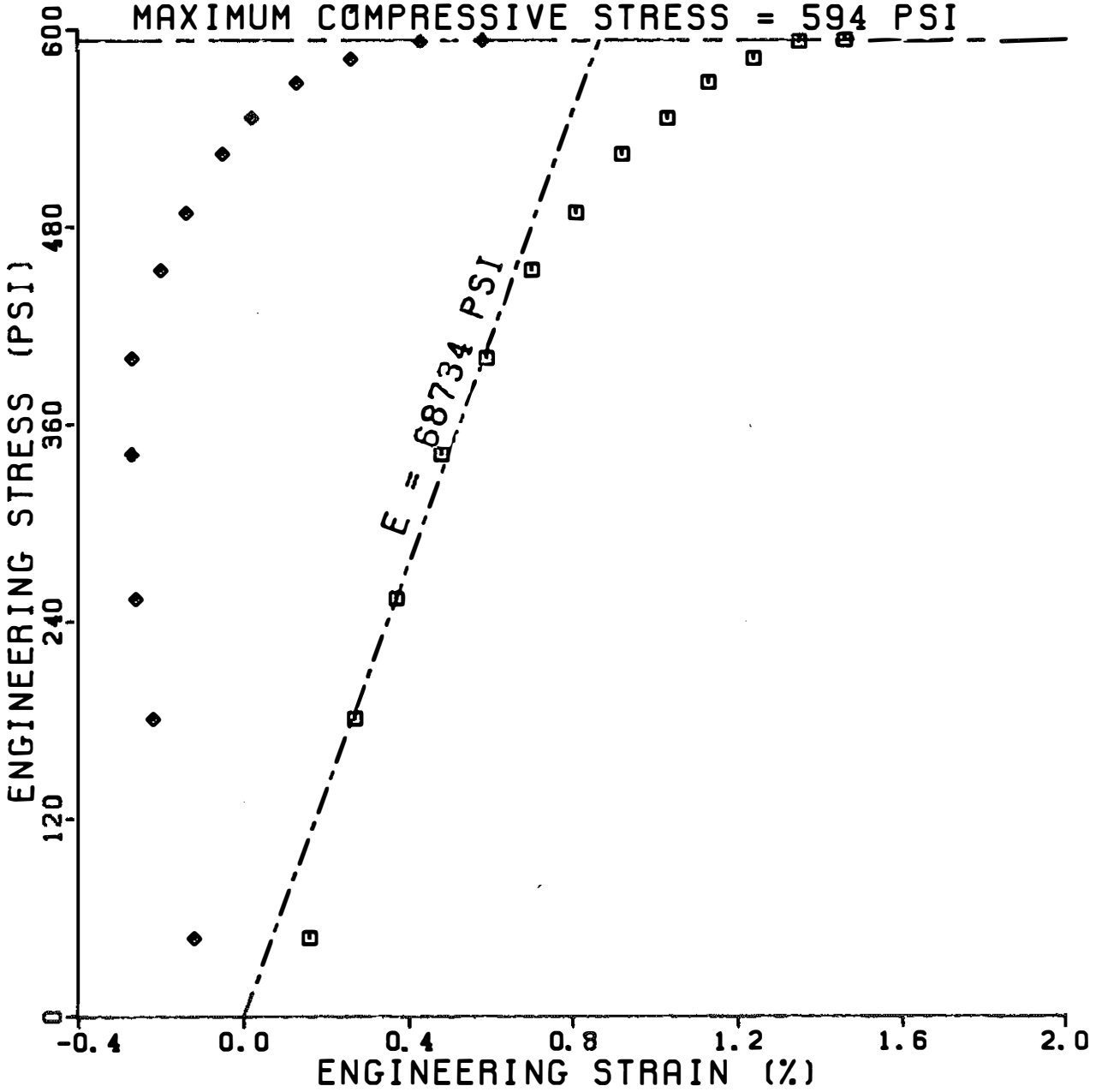
SAMPLE NUMBER : 8-9
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 594 PSI

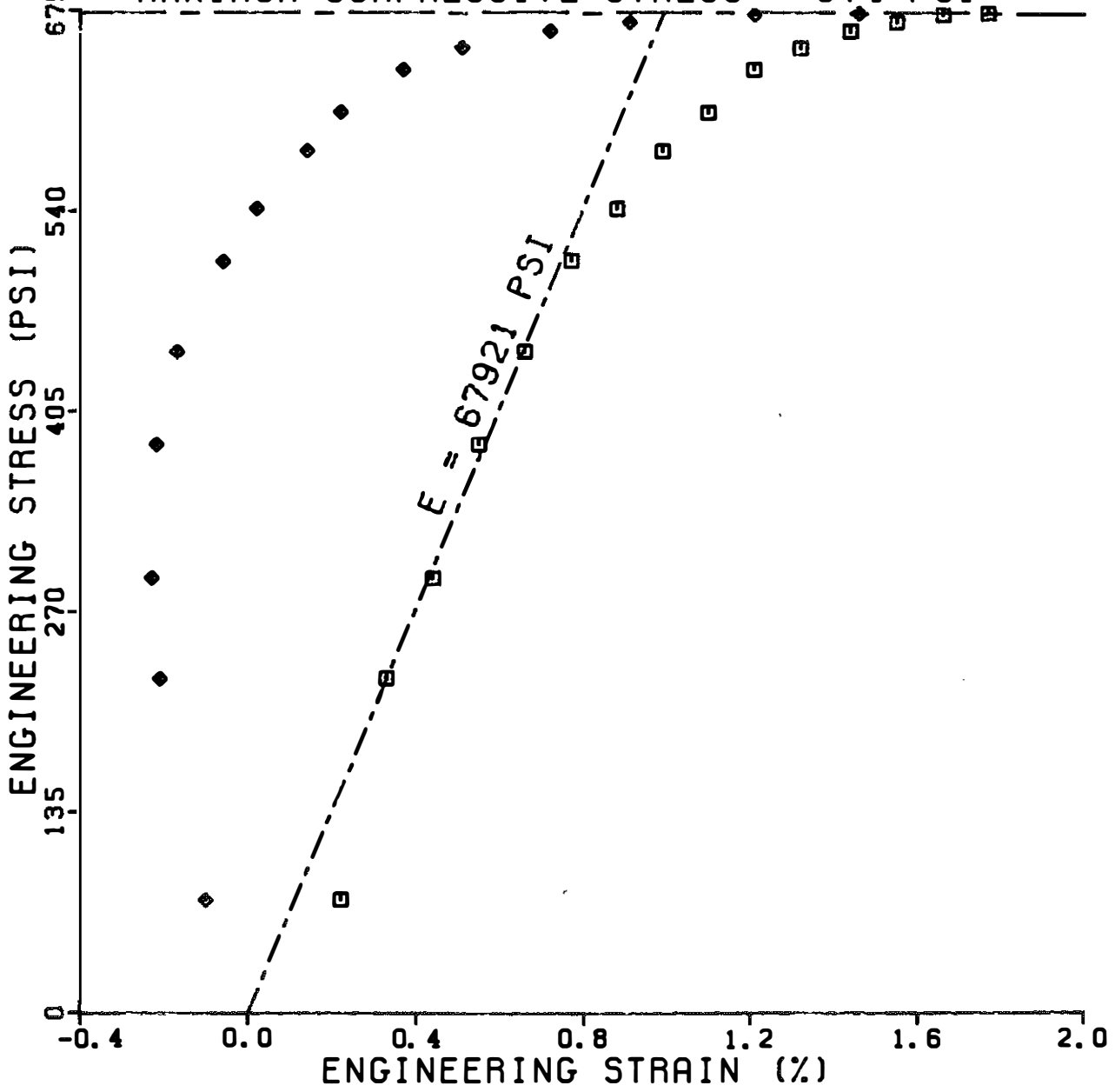


SAMPLE NUMBER : 8-10
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 28 DAYS
MAXIMUM COMPRESSIVE STRESS = 674 PSI



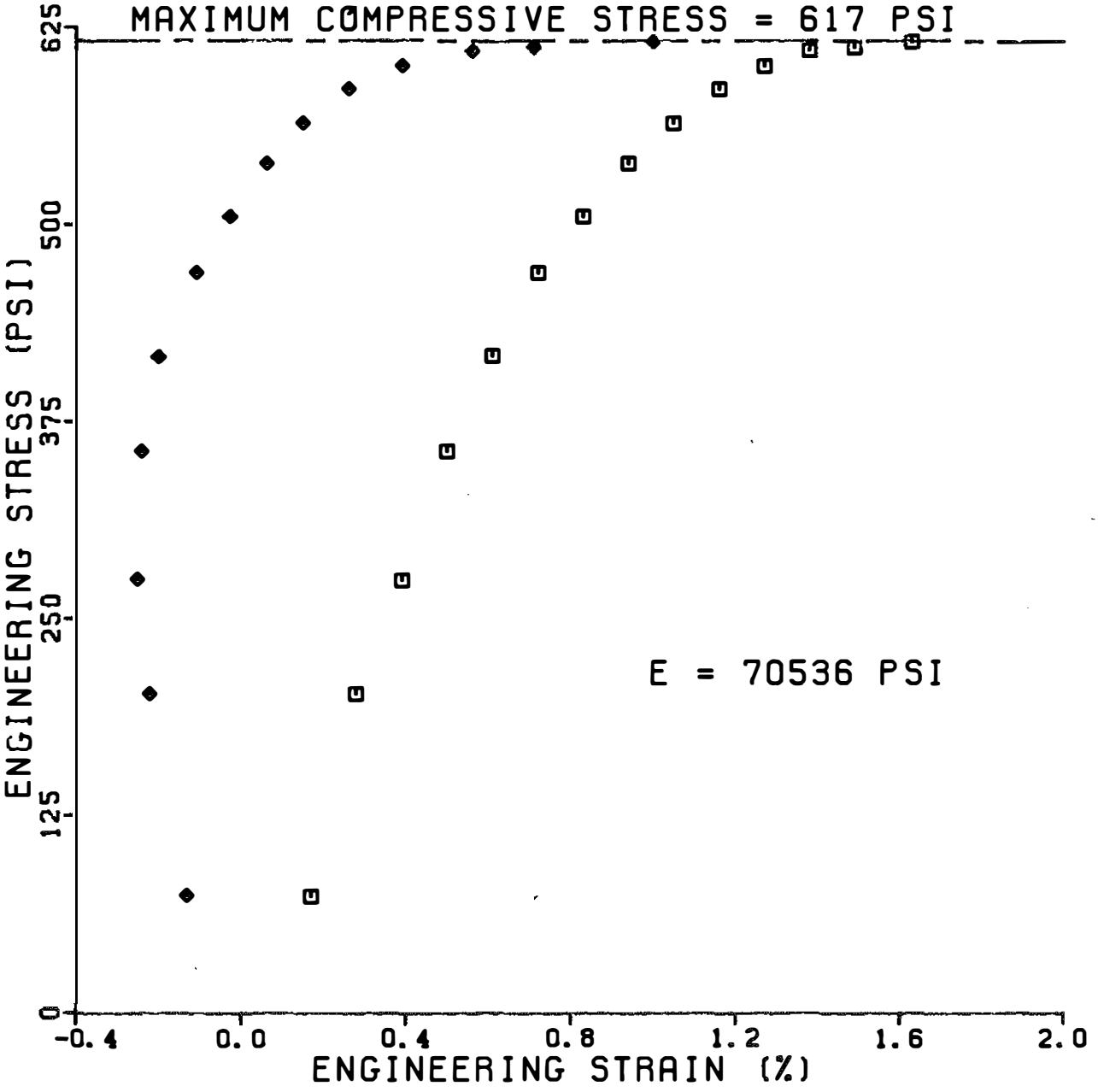
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % POND ASH
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 133 PCF
OPTIMUM MOISTURE = 11.0 %

MADE 4-5-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 617 PSI

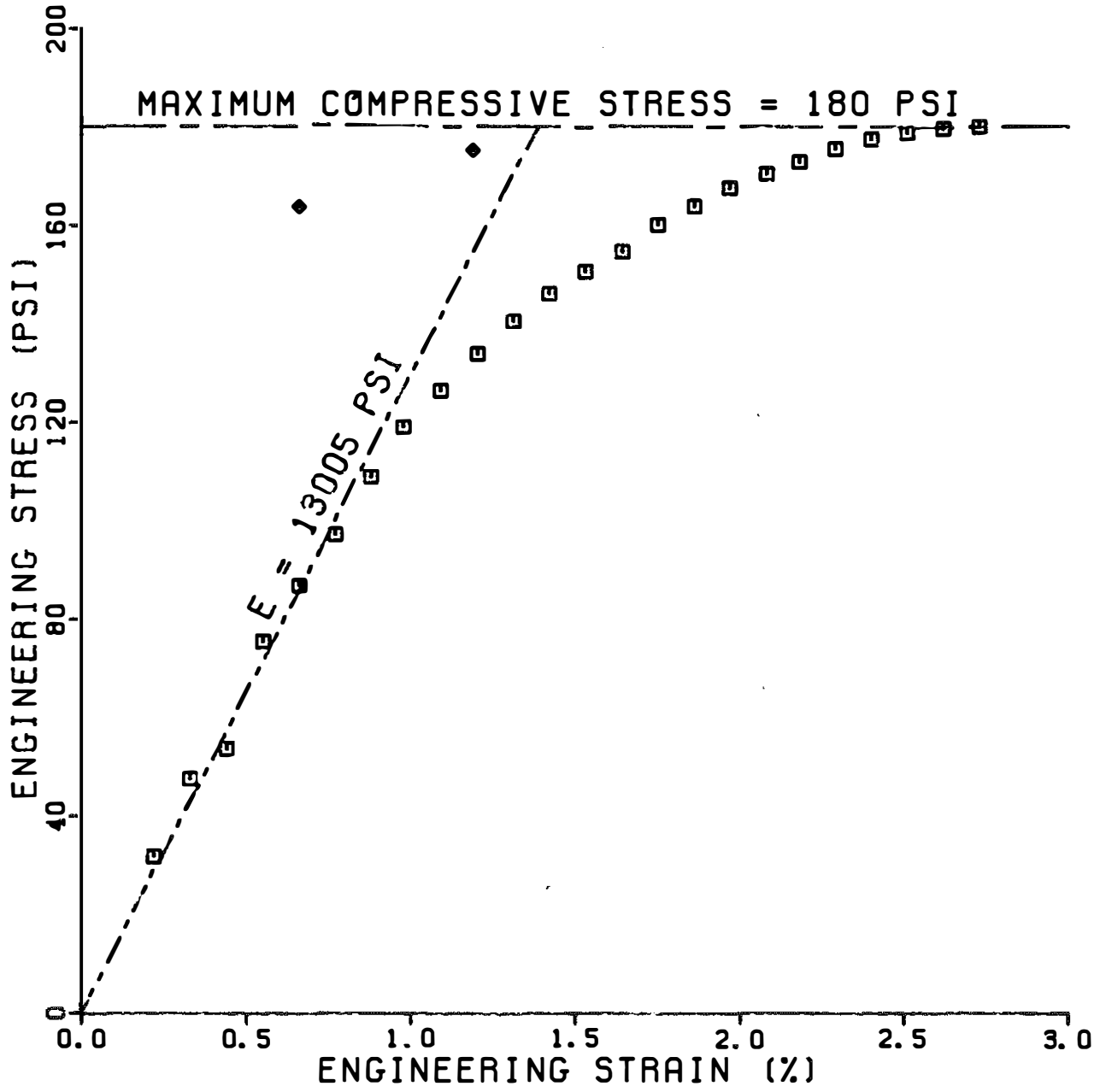


SAMPLE NUMBER : 9-1
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % DGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 7 DAYS

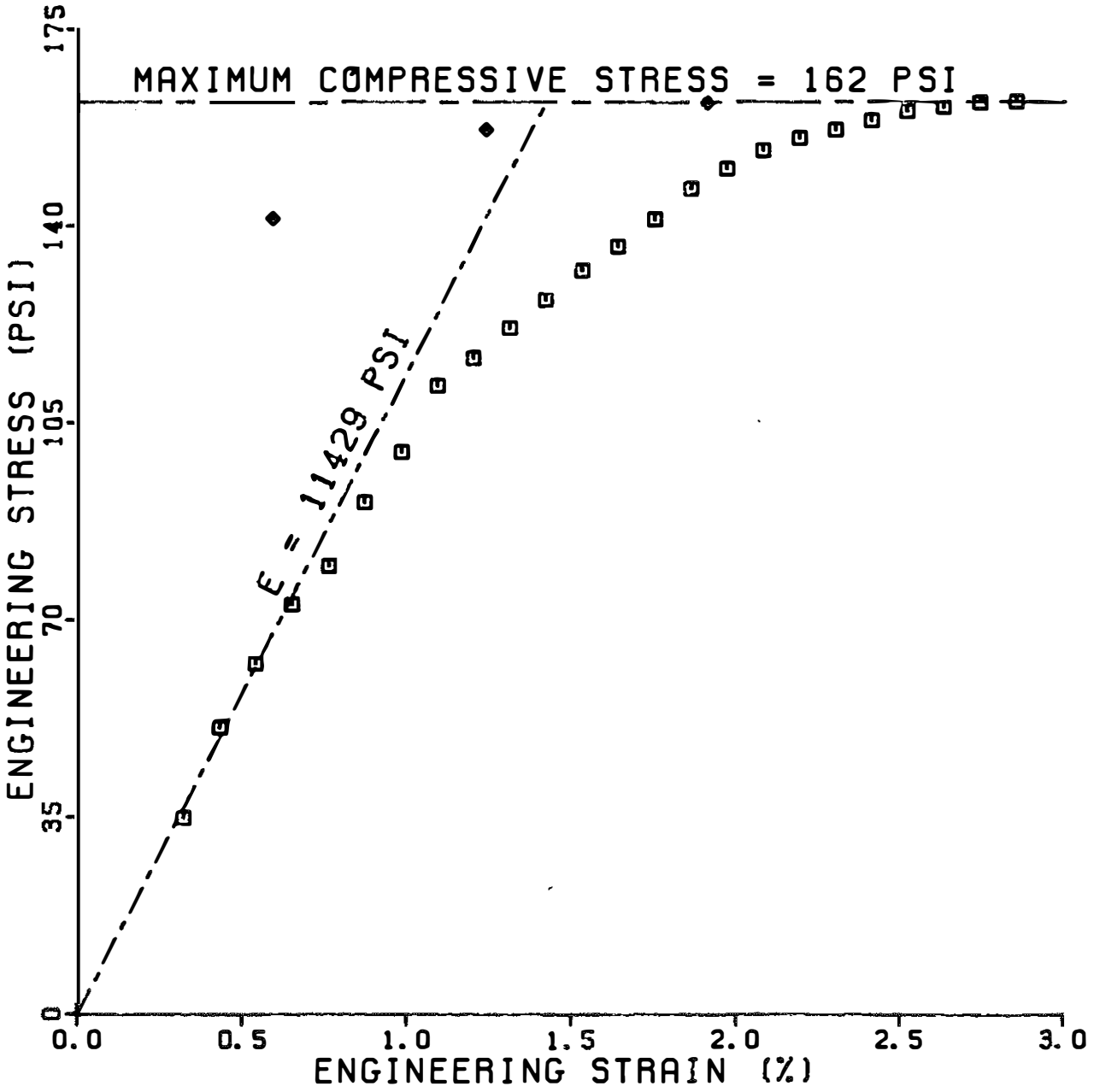


SAMPLE NUMBER : 9-2
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % OGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 7 DAYS

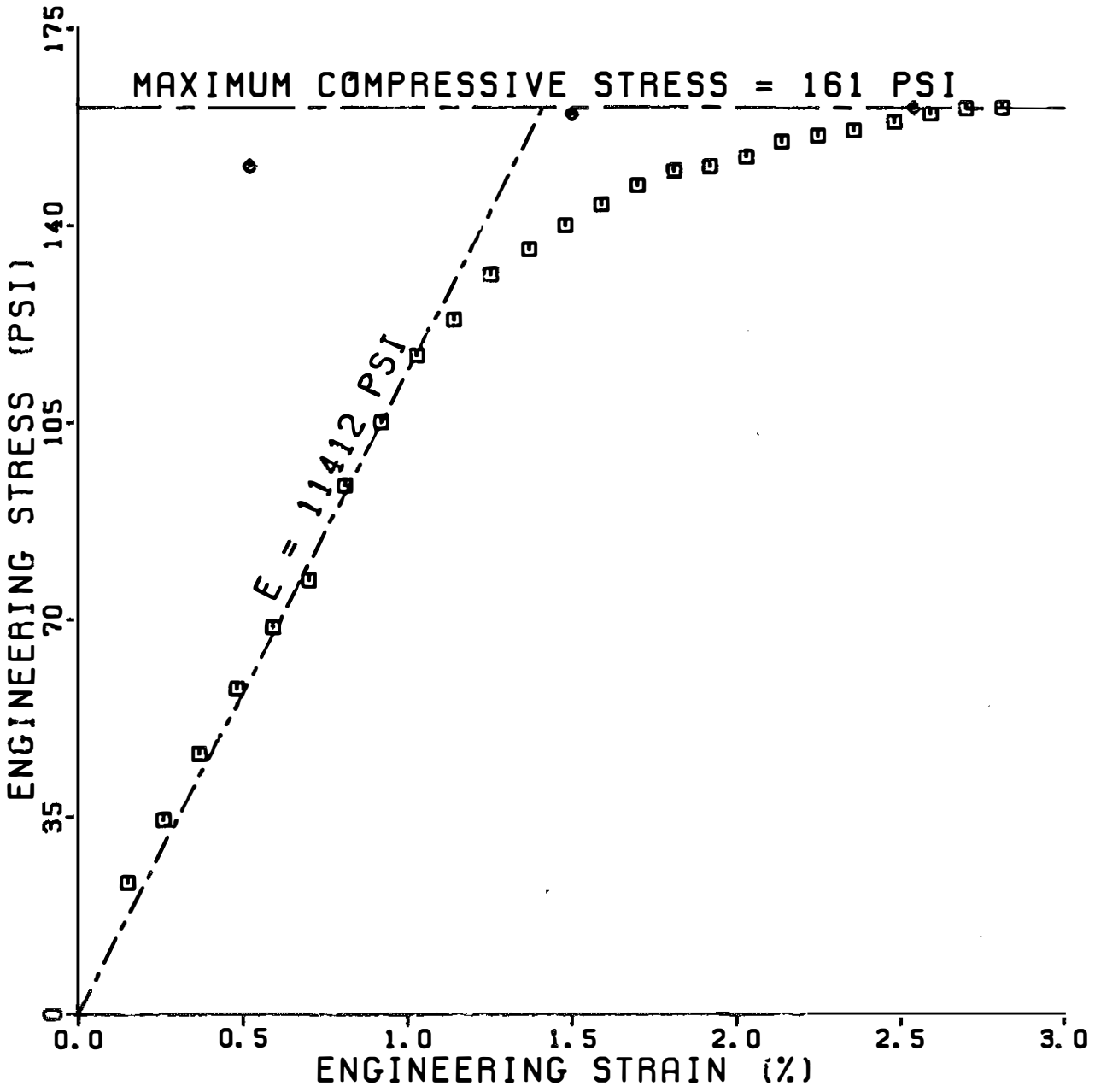


SAMPLE NUMBER : 9-3
LAB SLUDGE, 7-DAY OVEN CURED
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % DGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 7 DAYS



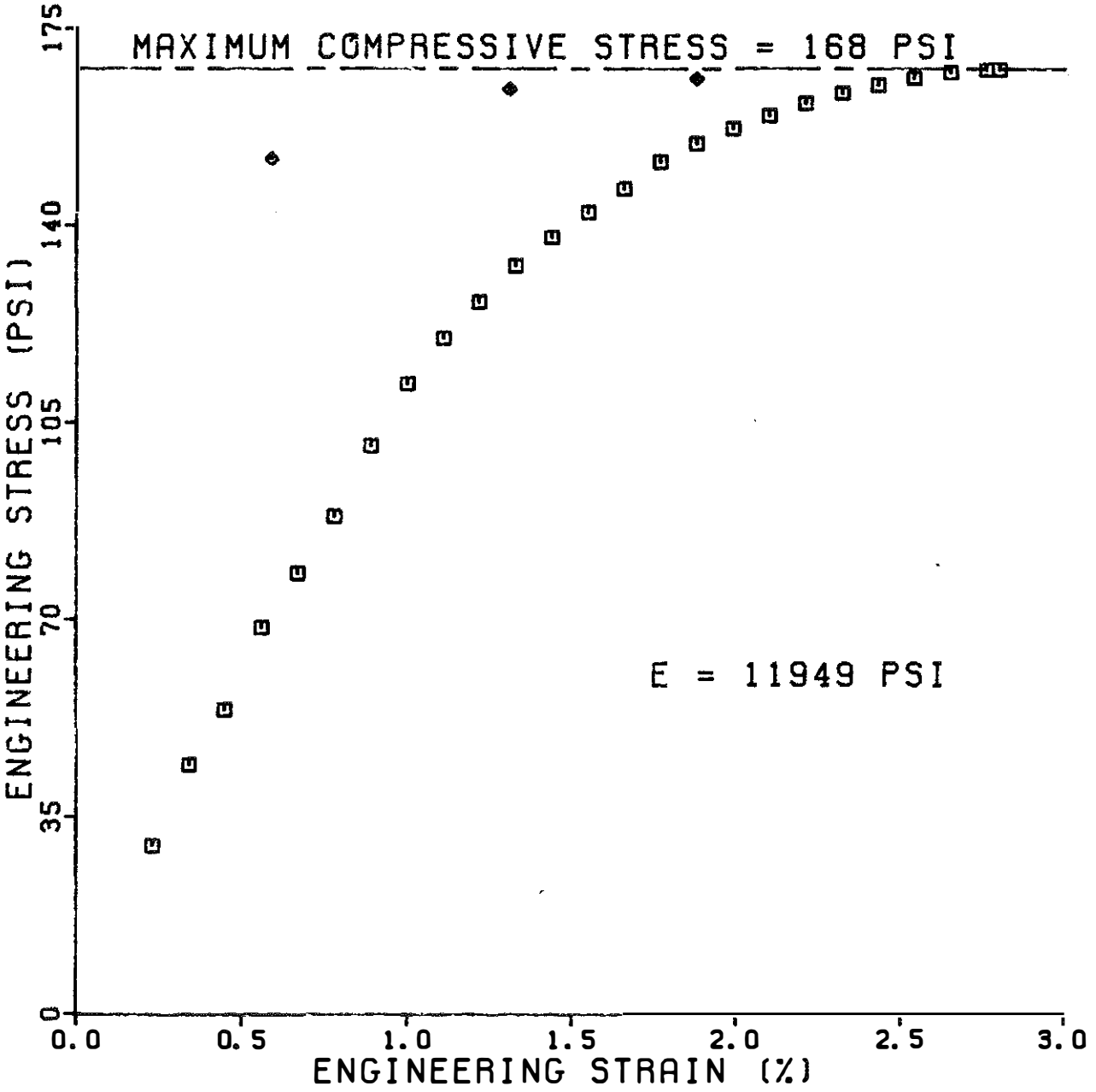
SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN CURED

□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % OGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 7 DAYS



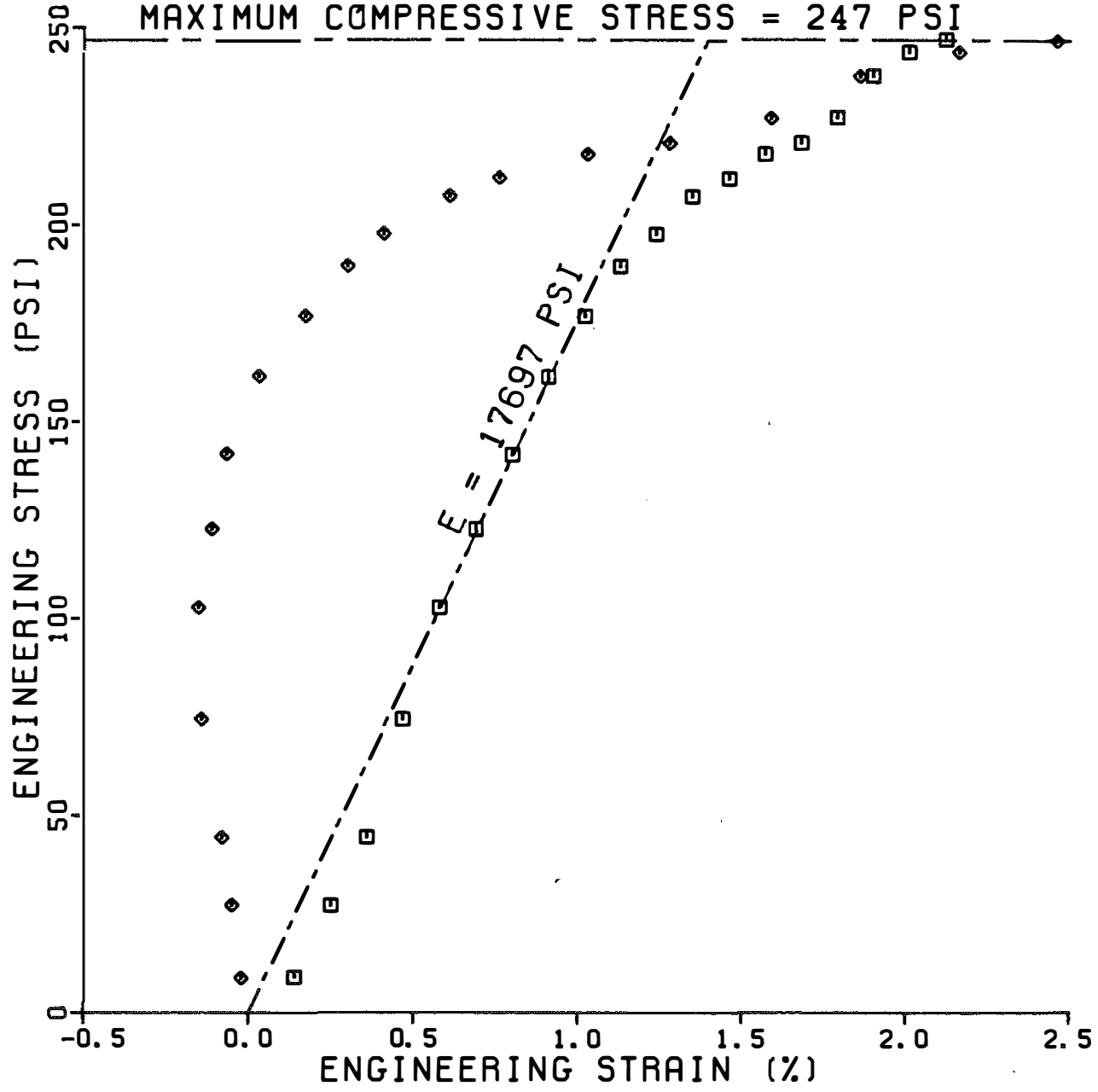
SAMPLE NUMBER : 9-8
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % DGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 247 PSI



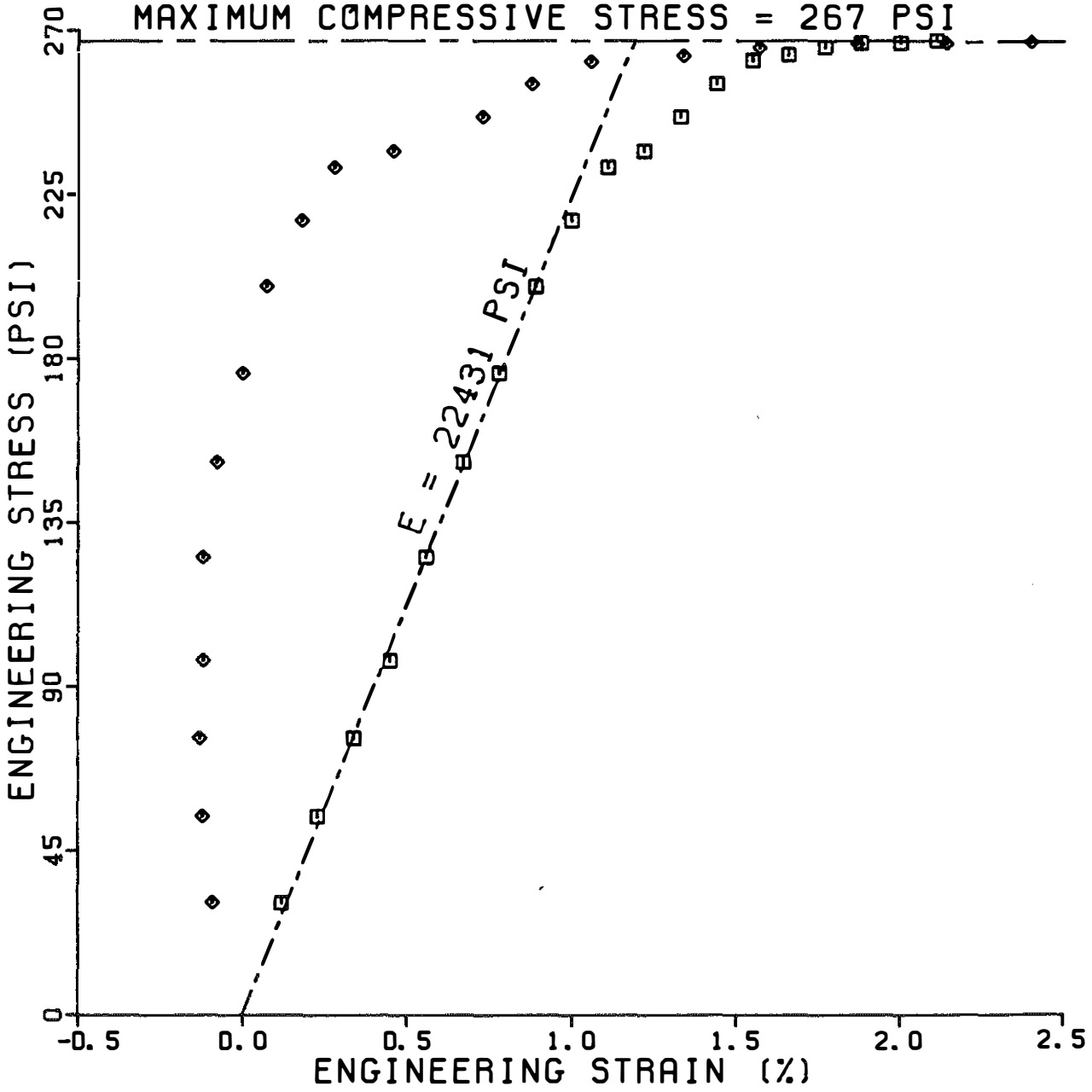
SAMPLE NUMBER : 9-9
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % DGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 267 PSI



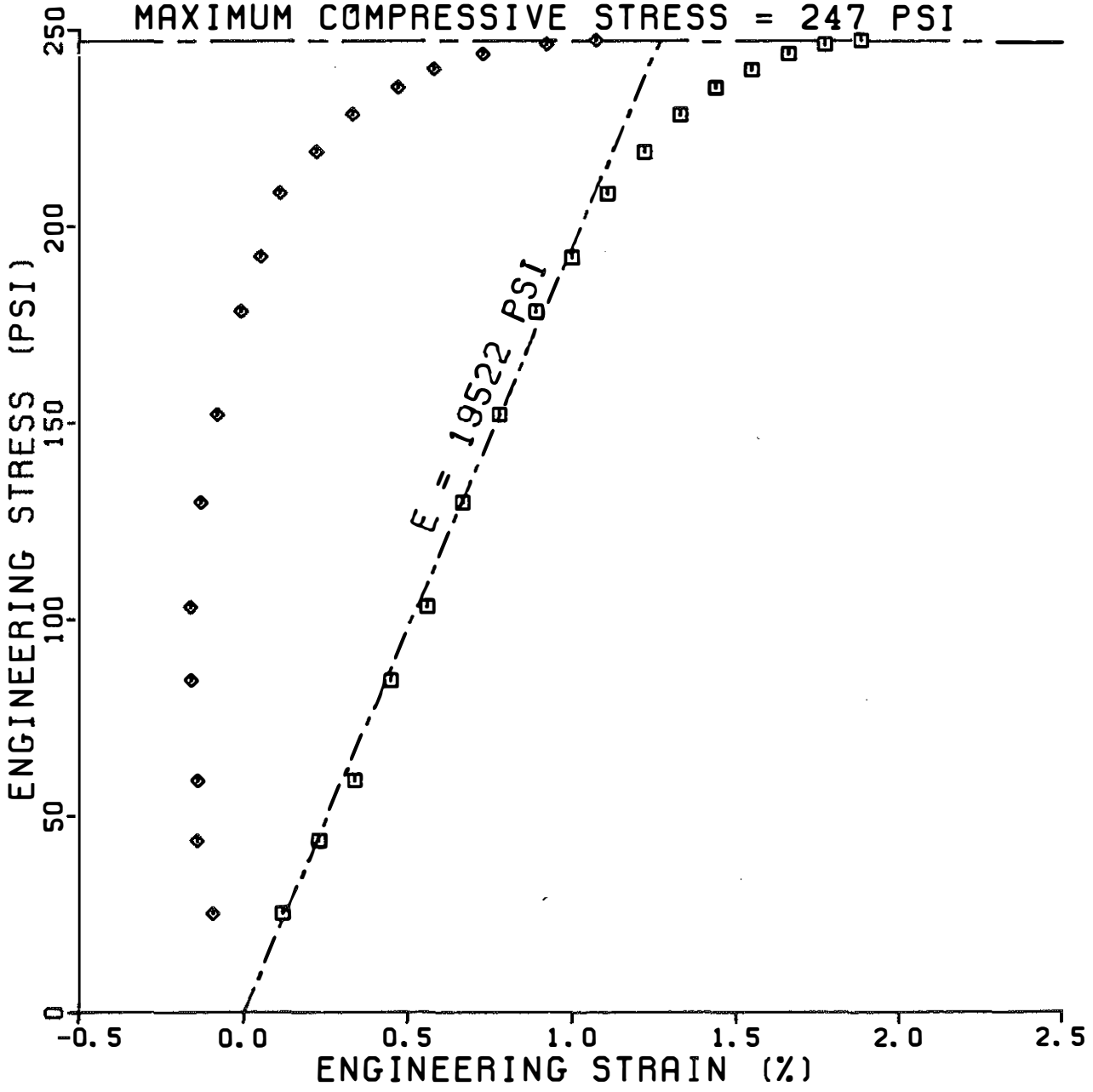
SAMPLE NUMBER : 9-10
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % DGA
20 % FINES

COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

MADE 4-5-83 -- CURED 28 DAYS

MAXIMUM COMPRESSIVE STRESS = 247 PSI

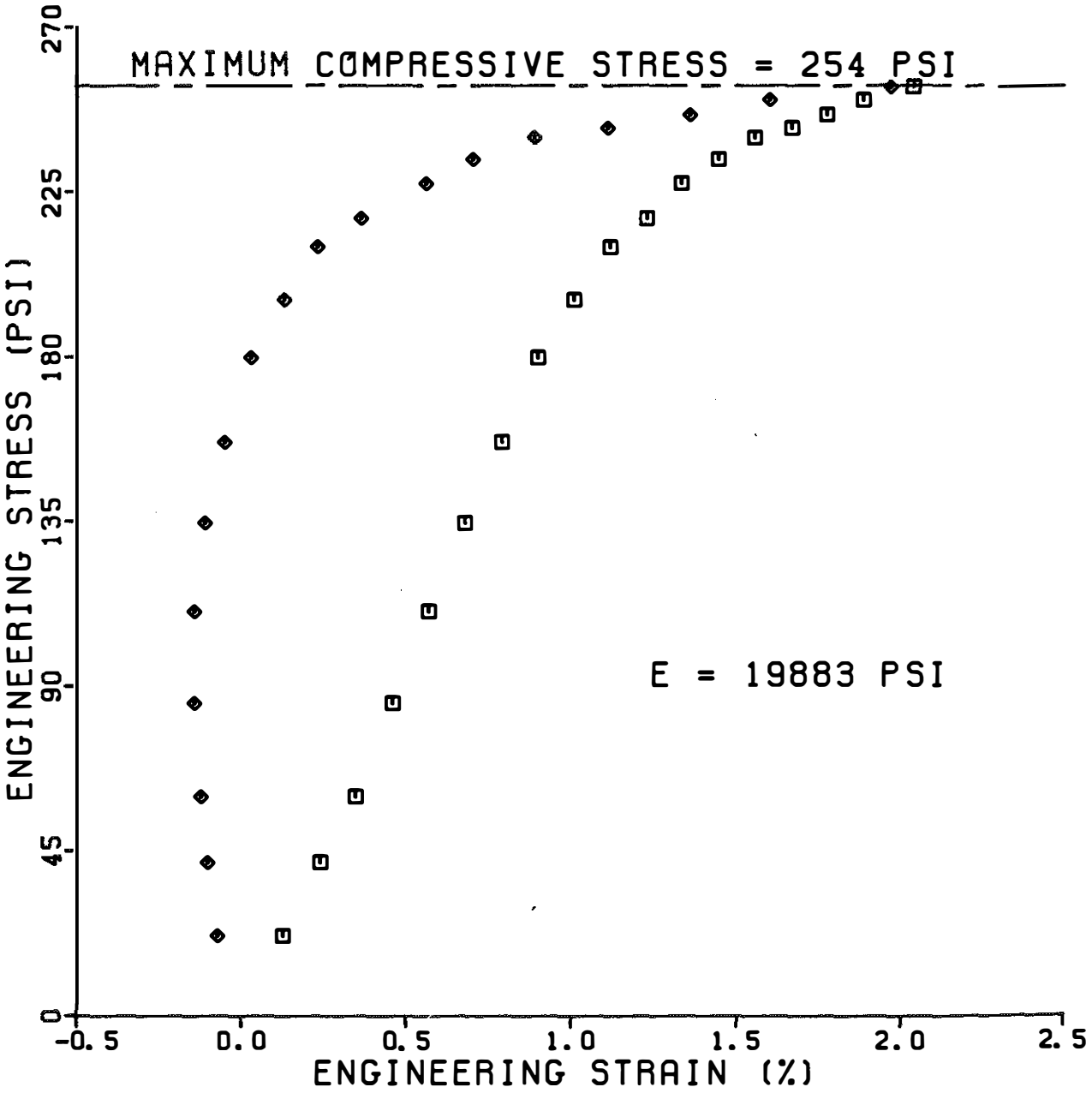


SAMPLE NUMBER : AVG.
LAB SLUDGE, 7-DAY OVEN, 21-DAY AMBIENT
□ = AXIAL STRAIN, ◇ = LATERAL STRAIN

MIX DESIGN
80 % DGA
20 % FINES

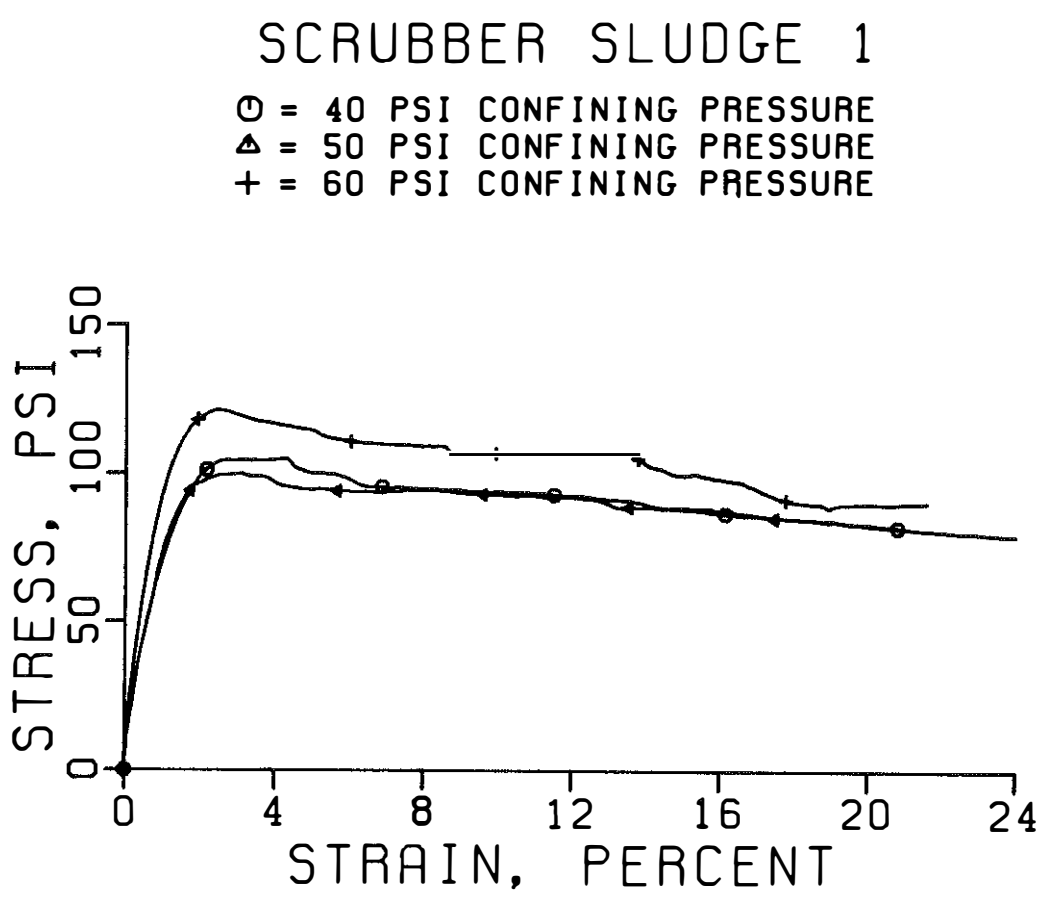
COMPACTION DATA
MAX. DRY DENSITY = 125 PCF
OPTIMUM MOISTURE = 11.8 %

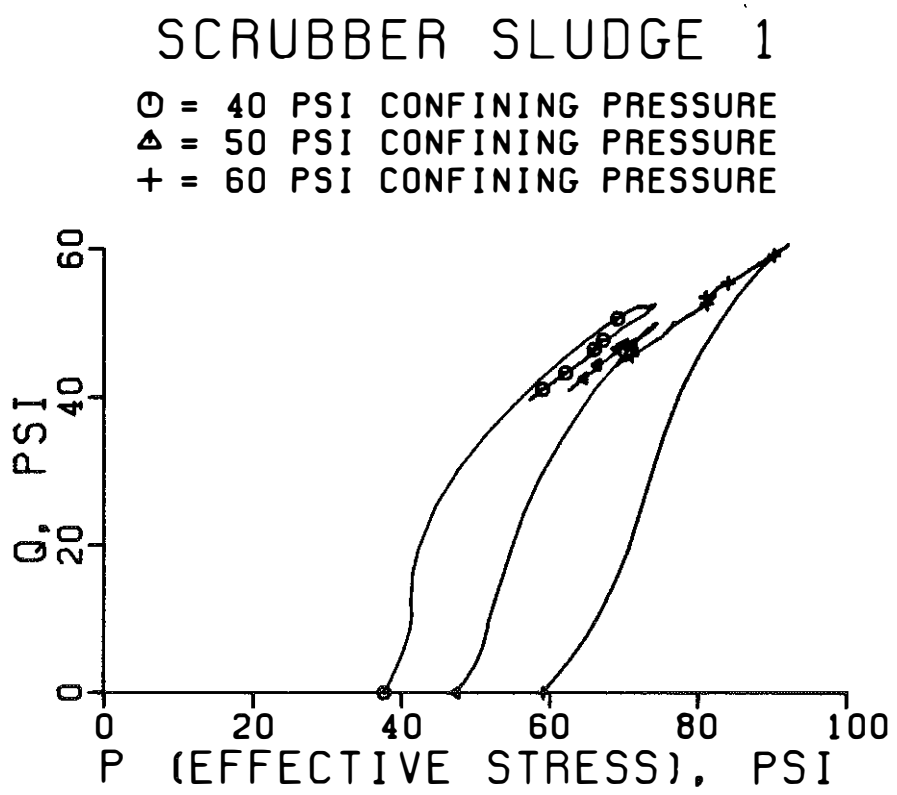
MADE 4-5-83 -- CURED 28 DAYS



APPENDIX F

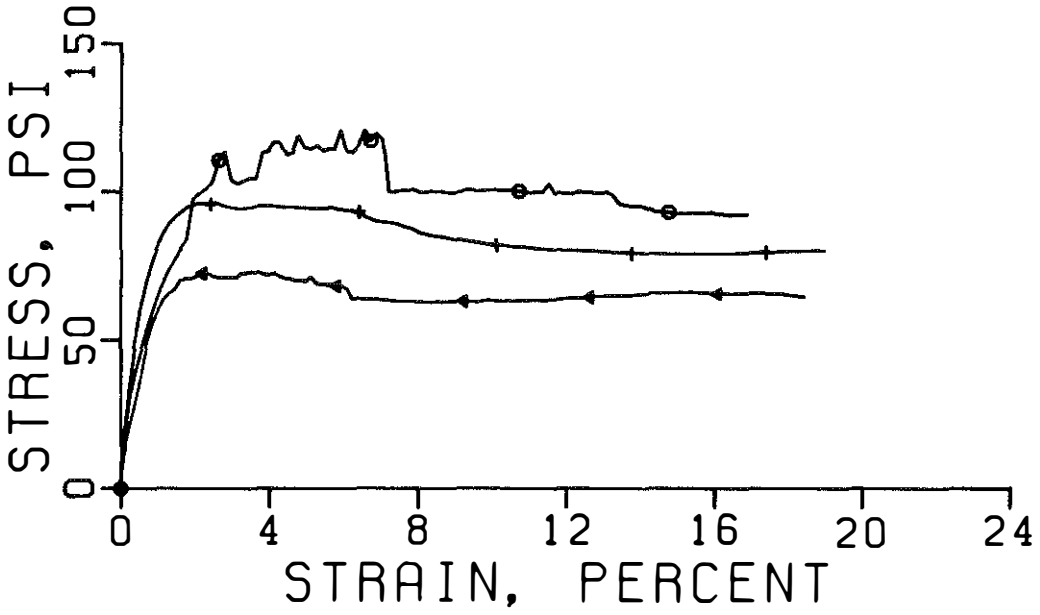
TRIAXIAL TESTS


SCRUBBER SLUDGE 1
⊖ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
+ = 60 PSI CONFINING PRESSURE
STRESS, PSI
0
50
100
150
0
4
8
12
16
20
24
STRAIN, PERCENT


SCRUBBER SLUDGE 1
⊖ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
+ = 60 PSI CONFINING PRESSURE
Q, PSI
0
20
40
60
0
20
40
60
80
100
P (EFFECTIVE STRESS), PSI

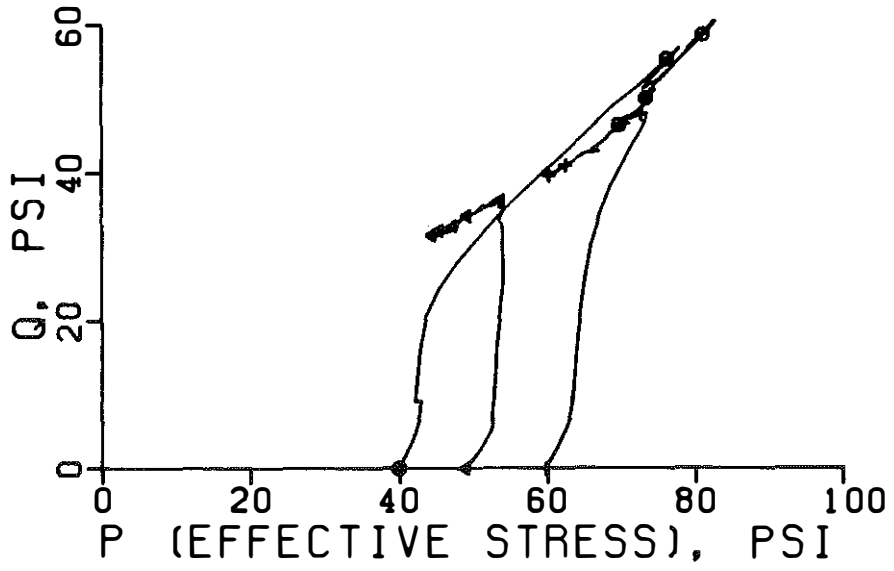
SCRUBBER SLUDGE 2

⊙ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
\+ = 60 PSI CONFINING PRESSURE



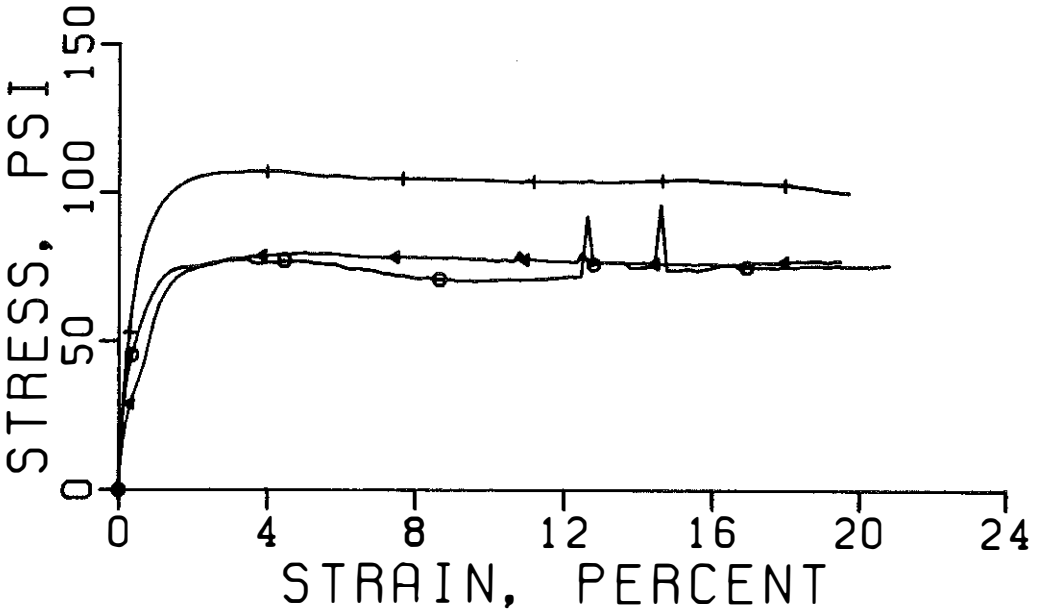
SCRUBBER SLUDGE 2

⊙ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
\+ = 60 PSI CONFINING PRESSURE



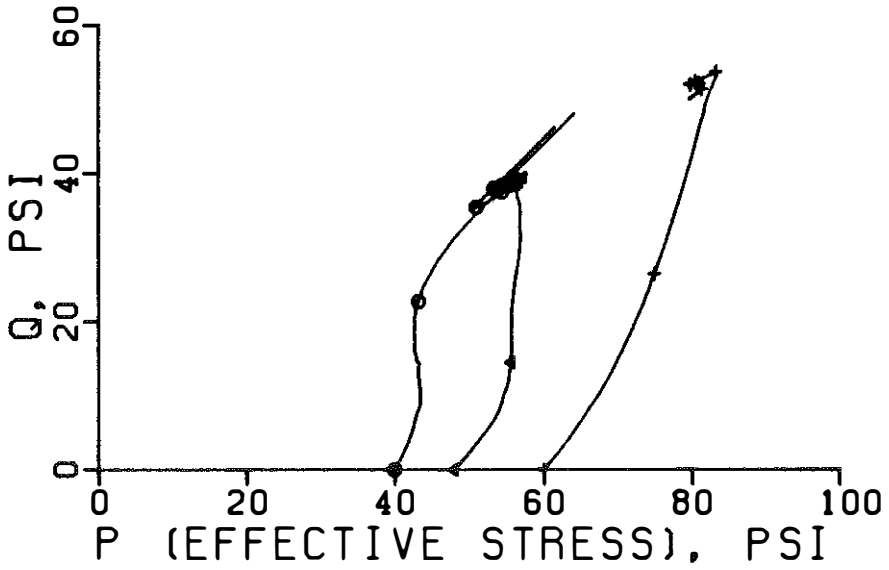
SCRUBBER SLUDGE 3

⊙ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
\+ = 60 PSI CONFINING PRESSURE



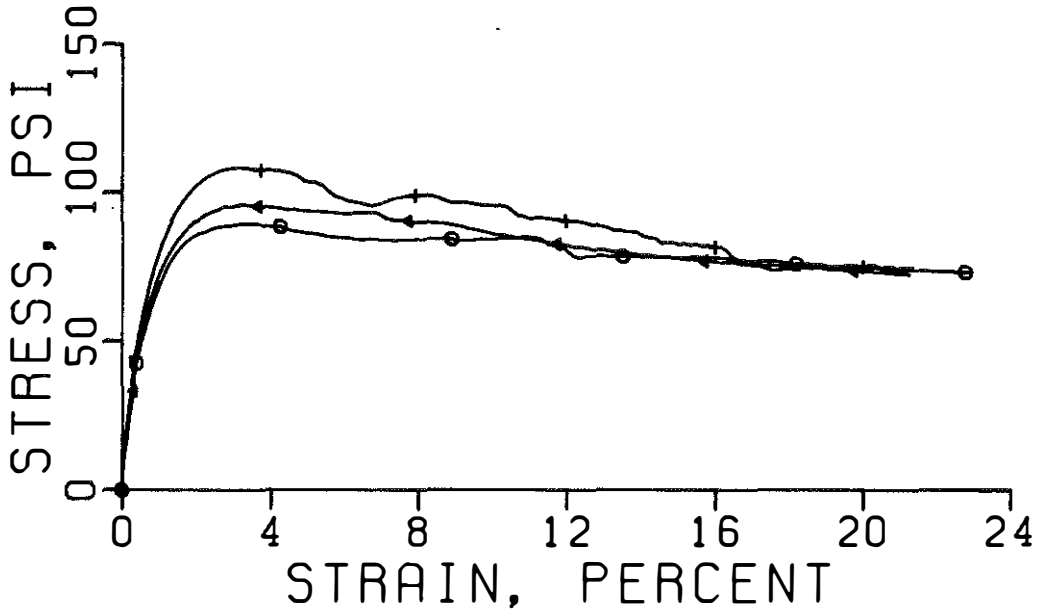
SCRUBBER SLUDGE 3

⊙ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
\+ = 60 PSI CONFINING PRESSURE



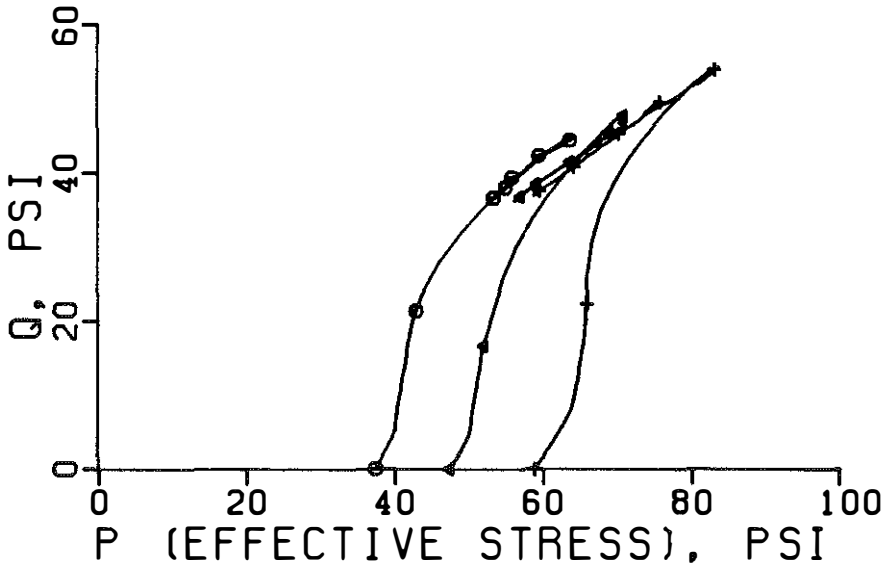
WET OF OPTIMUM

○ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
\+ = 60 PSI CONFINING PRESSURE



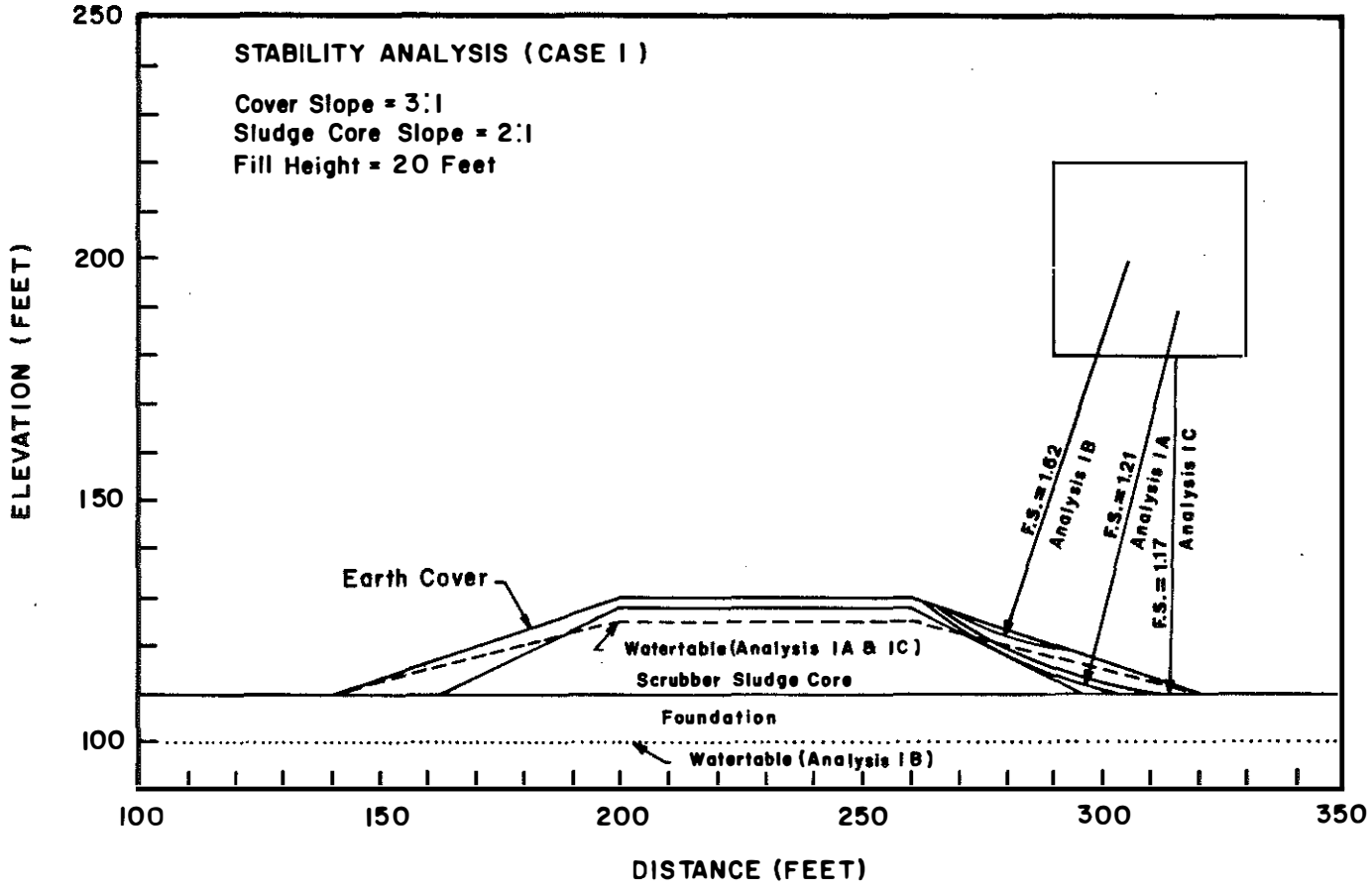
WET OF OPTIMUM

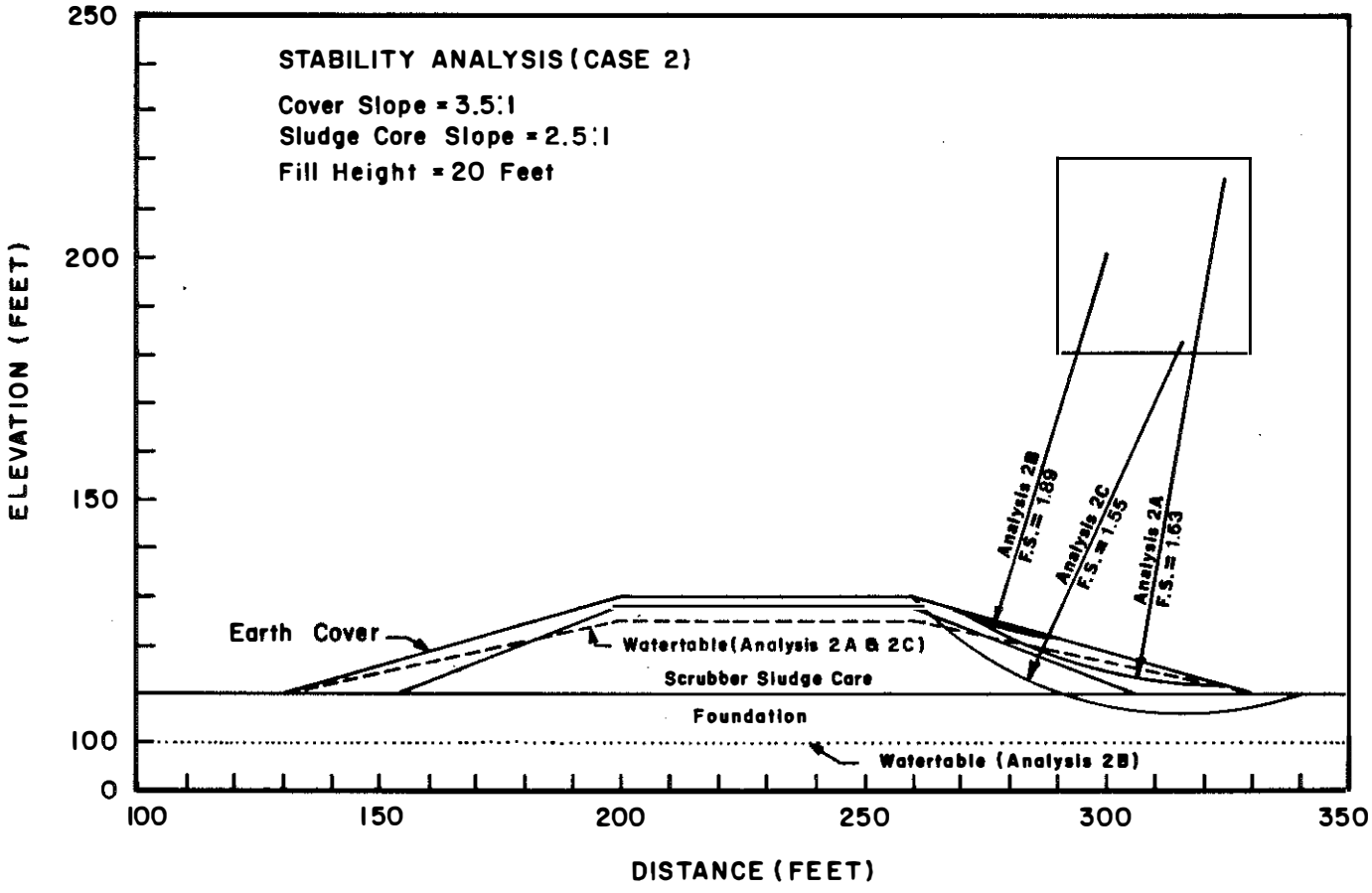
○ = 40 PSI CONFINING PRESSURE
△ = 50 PSI CONFINING PRESSURE
\+ = 60 PSI CONFINING PRESSURE

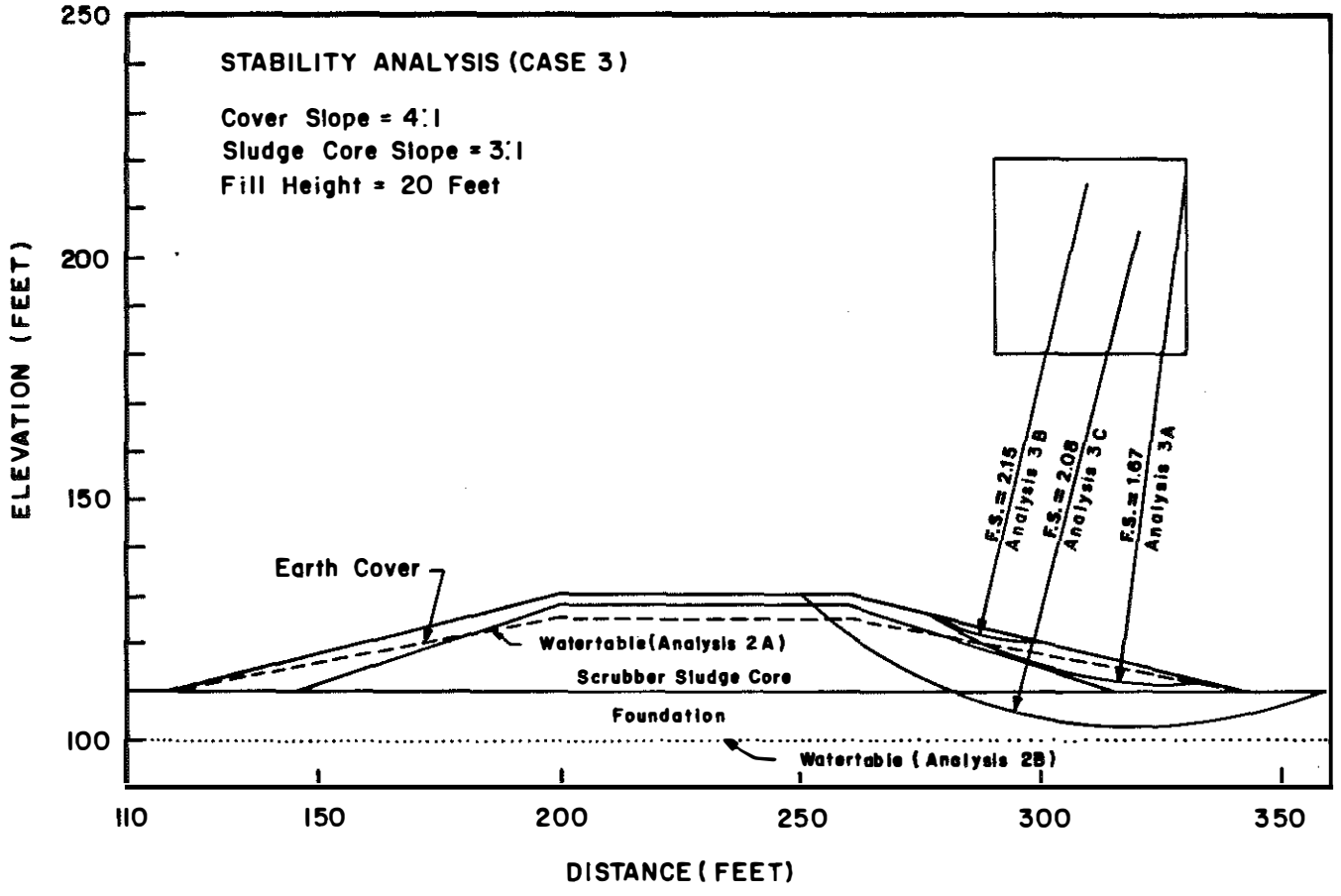


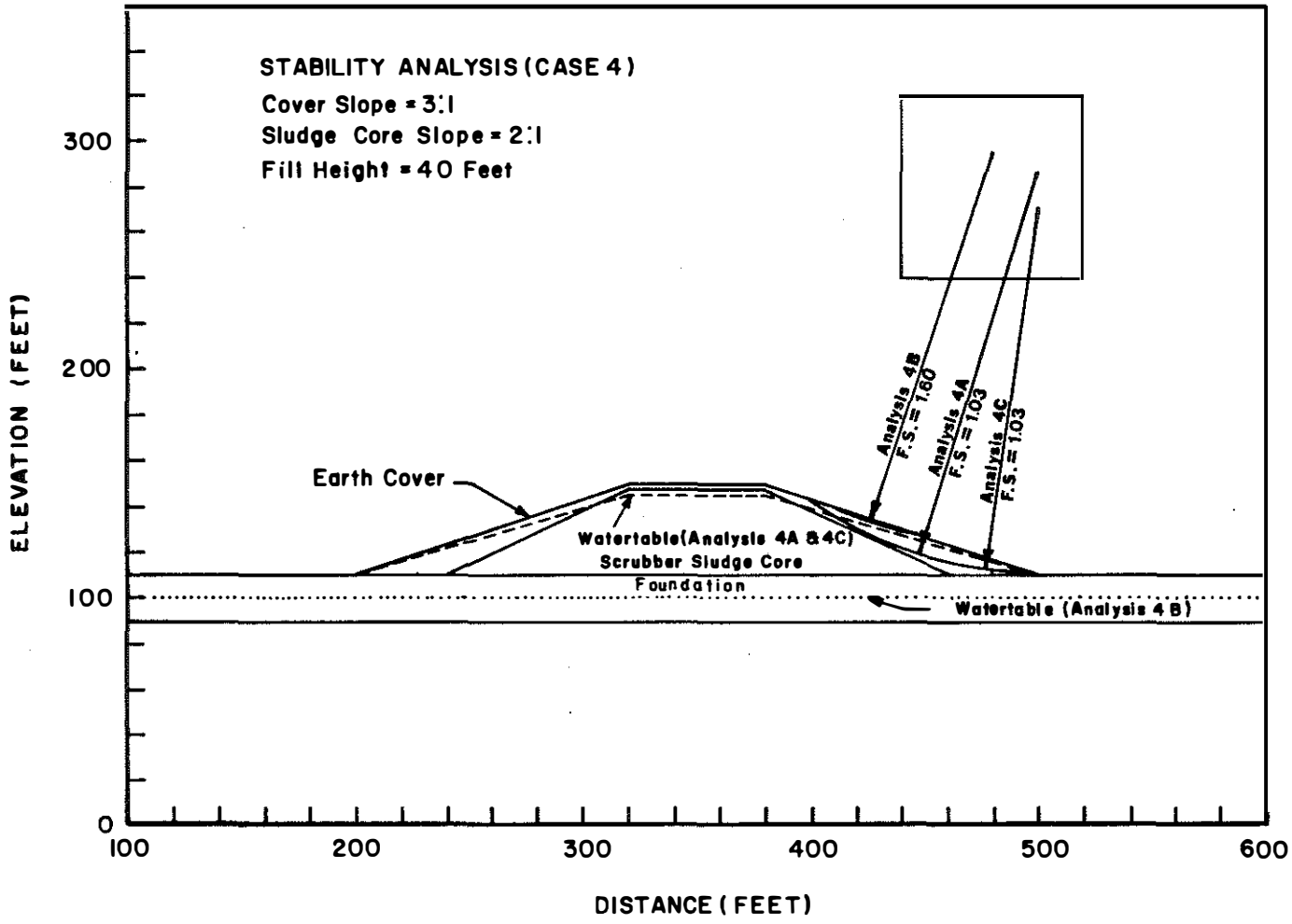
APPENDIX G

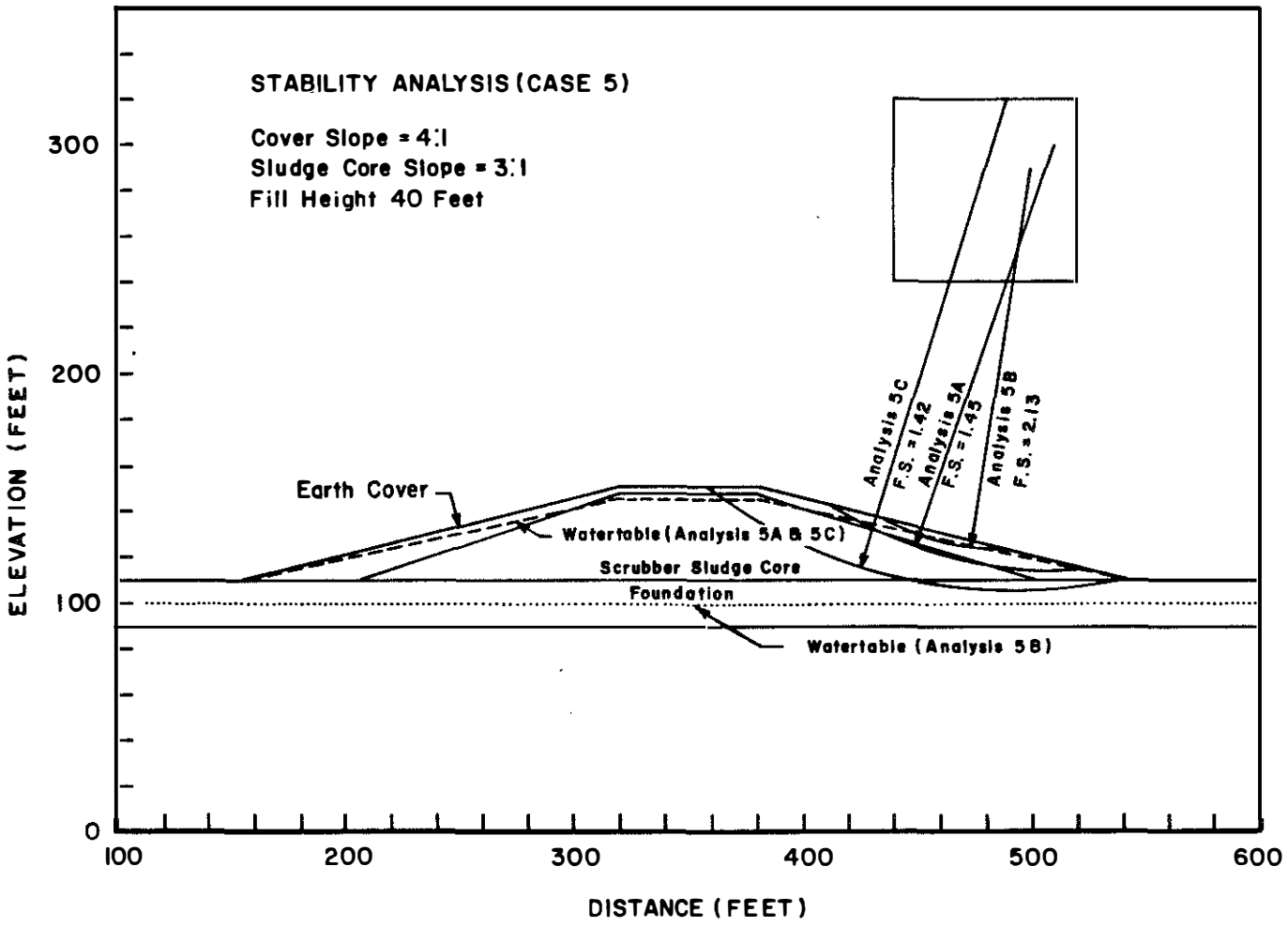
EMBANKMENT CROSS SECTIONS FOR SLOPE STABILITY ANALYSES


STABILITY ANALYSIS (CASE I)
Cover Slope = 3:1
Sludge Core Slope = 2:1
Fill Height = 20 Feet
ELEVATION (FEET)
250
200
150
100
Earth Cover
Watertable (Analysis IA & IC)
Scrubber Sludge Core
Foundation
Watertable (Analysis IB)
F.S. = 1.62
Analysis IB
F.S. = 1.21
Analysis IA
F.S. = 1.17
Analysis IC
100
150
200
250
300
350
DISTANCE (FEET)


STABILITY ANALYSIS (CASE 2)
Cover Slope = 3.5:1
Sludge Core Slope = 2.5:1
Fill Height = 20 Feet
Analysis 2B F.S. = 1.89
Analysis 2C F.S. = 1.55
Analysis 2A F.S. = 1.63
Earth Cover
Watertable (Analysis 2A & 2C)
Scrubber Sludge Core
Foundation
Watertable (Analysis 2B)
ELEVATION (FEET)
250
200
150
100
0
100
150
200
250
300
350
DISTANCE (FEET)


STABILITY ANALYSIS (CASE 3)
Cover Slope = 4:1
Sludge Core Slope = 3:1
Fill Height = 20 Feet
ELEVATION (FEET)
250
200
150
100
Earth Cover
Watertable(Analysis 2A)
Scrubber Sludge Core
Foundation
Watertable (Analysis 2B)
F.S.= 2.15 Analysis 3B
F.S.= 2.08 Analysis 3C
F.S.= 1.67 Analysis 3A
110
150
200
250
300
350
DISTANCE (FEET)


STABILITY ANALYSIS (CASE 4)
Cover Slope = 3:1
Sludge Core Slope = 2:1
Fill Height = 40 Feet
Analysis 4B F.S. = 1.60
Analysis 4A F.S. = 1.03
Analysis 4C F.S. = 1.03
Earth Cover
Watertable(Analysis 4A &4C)
Scrubber Sludge Core
Foundation
Watertable (Analysis 4 B)
ELEVATION (FEET)
DISTANCE (FEET)
0
100
200
300
100
200
300
400
500
600


STABILITY ANALYSIS (CASE 5)
Cover Slope = 4:1
Sludge Core Slope = 3:1
Fill Height 40 Feet
Analysis 5C
F.S. = 1.42
Analysis 5A
F.S. = 1.45
Analysis 5B
F.S. = 2.13
Earth Cover
Watertable (Analysis 5A & 5C)
Scrubber Sludge Core
Foundation
Watertable (Analysis 5B)
ELEVATION (FEET)
0
100
200
300
100
200
300
400
500
600
DISTANCE (FEET)