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FOSSIL ENERGY

EVALUATION OF SULFATE-BEARING WASTE MATERIAL FROM FLUIDIZED BED COMBUSTION OF COALS FOR SOIL STABILIZATION

Final Report

By
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MASTER

September 1977

Work Performed Under Contract No. EX-76-A-01-2491

Midwest Research Institute
Kansas City, Missouri

U. S. DEPARTMENT OF ENERGY

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FOREWORD

This report presents the results of a laboratory study to evaluate the effects of sulfate waste derived from the fluidized bed combustion of coal on the engineering properties of fine-grained soils.

The results were developed under Midwest Research Institute Project 3960-L conducted for the Federal Highway Administration, Office of Research, Washington, D.C., under contract DOT-FH-11-8515, Modification No. 4. Funds for this research were provided by the Energy Research and Development Administration (ERDA) under Interagency Agreement No. E(49-18)2491 with the FHWA, U.S. Department of Transportation.

Copies of the report are being distributed by the Materials Division, Office of Research, to the FCP Project 4C team and appropriate members of the FCP Project 4D team.

MASTER

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16. Abstract

The effects of spent bed material from the fluidized bed combustion of coal in the physical and strength properties of selected fine-grained soils has been evaluated. The spent bed material is a mixture of lime and calcium sulfate (together with some fly ash) obtained from a process being evaluated by the Energy Research and Development Administration in which pulverized coal is burned in a fluid bed of finely ground calcitic or dolomitic limestone. Results of the study indicate that spent bed material is an excellent substitute for lime for soil stabilization. The material behaves as a mixture of lime, calcium sulfate, and fly ash towards development of unconfined compression strength when mixed with soils. It has been concluded that use of spent bed material for soil stabilization is a viable alternative to disposal when full-scale fluidized bed coal combustion plants become a reality.

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PREFACE

This draft report is submitted in partial fulfillment of Contract No. DOT-FH-11-8515, Modification No. 4, "Use of Waste Sulfate for Remedial Treatment of Soils, Phase II--Evaluation of Sulfate-Bearing Waste Materials from Fluidized Bed Combustion of Coal." The report contains discussion and interpretation of the experimental findings of the study. The report has been prepared by Dr. John W. Nebgen, Principal Chemist, who has served as principal investigator of the program. Experimental work has been conducted by Mr. James G. Edwards and Ms. Dyan Conway who are included as coauthors.

Approved for:

MIDWEST RESEARCH INSTITUTE

L. J. Shannon, Director
Environmental and Materials
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INTRODUCTION

In an earlier study,[1/] Midwest Research Institute (MRI) demonstrated the effectiveness of using waste sulfate in conjunction with lime or lime/fly ash for stabilizing several fine-grained soils. The waste sulfates evaluated in the previous study included (a) phosphogypsum by-product from phosphoric acid manufacture, (b) flue gas desulfurization solids from power plants using wet-limestone scrubbers, and (c) neutralized acid mine drainage solids. The study discussed in this report describes results obtained with a fourth waste sulfate--spent bed material (SBM) obtained from the fluidized bed combustion of coal.

The fluidized bed combustion of coal involves the burning of pulverized coal in a bed of calcitic or dolomitic limestone. This process permits efficient utilization of heat for operating steam turbines as well as providing an in situ scrubber for sulfur oxides. The residue from the fluidized combustion thus is a mixture of calcium sulfate and calcium oxide (lime), along with silica and alumina from the limestone and ash. This combination of ingredients is similar to the waste sulfate/lime/fly ash composition of scrubber solids evaluated in the earlier study.

The SBM was mixed with 15 soils selected from those used in the previous study. The mixtures were molded into specimens for uncombined compressive strength testing using a Harvard Miniature Compaction apparatus. The specimens were cured at 100% relative humidity for specified periods prior to their sacrifice in the unconfined compressive strength test. Results indicate that the SBM/soil mixtures developed a high degree of strength similar to phosphogypsum/lime/fly ash/soil mixtures evaluated in the earlier study.

Further strength testing was conducted with soils treated with binary combinations of SBM/phosphogypsum, SBM/lime, and SBM/fly ash. Results indicate that phosphogypsum has little effect in strength development of SBM treated soils. Marked improvement in strengths were achieved when soils were treated with SBM/lime and SBM/fly ash.

Another finding of this study is that treatment of soils with SBM results in lower uncured densities at constant compaction. Also the SBM has a marked drying effect in the soils. These effects on moisture/density are similar to those found with lime treated soils, and reflect a great

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1/ Nebgen, J. W., J. G. Edwards, and D. F. Weatherman, "Use of Waste Sulfate for Remedial Treatment of Soil," Federal Highway Administration, Office of Research and Development, Reports Nos. FHWA-RD-76-143 and FHWA-RD-76-144, Volumes 1 and 2, Washington, D.C., August 1976.

similarity between SBM and lime as soil stabilizers. The similarity between SBM and lime is also observed in freeze-thaw durabilities of SBM-treated soil specimens--soils treated with SBM are generally more resistant to deterioration in freeze-thaw than are untreated soils.

In general, SBM behaves very much like lime or lime/fly ash when used as a soil stabilizer, even though the lime content of the SBM is only about 30%.

At the present time, SBM is being produced only at small-scale pilot plants. A demonstration plant is scheduled to go on line soon at Rivesville, West Virginia. Thus, quantities of available SBM are small compared to other waste sulfates. However, when fluidized bed combustion of coal becomes wide-spread, the use of SBM as a soil stabilizing agent for fine-grained soils should also become widespread. Unlike many waste materials, SBM contains useful soil stabilizing materials--calcium sulfate, lime, and ash--in one product and in proper combinations which augurs well for its utilization.

In subsequent sections of this report, we will present details of the experimental work along with interpretation of the data. Conclusions and recommendations are presented in Sections VI and VII. The raw data have been reduced for graphical and tabular forms to facilitate discussion. The actual unconfined compressive strength data obtained from the specimen testing are attached in the Appendix to this report.

CHARACTERIZATION OF SOILS AND SBM

The soils used for the evaluation of SBM were selected from among the soils used in the earlier study.[1] Fifteen soils were selected on the basis of proximity to projected location of fluidized bed coal combustion facilities. The soils and their locations are presented in Table 1.

TABLE 1

TYPE LOCATIONS AND SAMPLING SITES FOR SOIL SERIES USED FOR THE EXPERIMENTAL STUDY

Soil Series	Type Location County, State	Sampling Site County, State
Atkins	Raleigh, WV	Raleigh, WV
Coxville	Pitt, NC	Pitt, NC
Craven	Craven, NC	Craven, NC
Exum	Wayne, NC	Wayne, NC
Fellowship	Marion, FL	Marion, FL
Mahoning	Lorain, OH	Lorain, OH
Manor	Prince Georges, MD	Prince Georges, MD
Miami	Rush, IN	Boone, IN
Sassafras	New Castle, DE	Queen Annes, MD
Sharkey	West Feliciana, LA	St. John the Baptist, LA
Shelby	Adair, IA	Adair, IA
Summit	Rogers, OK	Woodson, KS
Tama	Tama, IA	Tama, IA
Upshur	Wood, WV	Wood, WV
Wharton	Indiana, PA	Indiana, PA

The 15 soils were categorized into four classes according to their plasticity index, mineralogy, and physical properties. The four soil classes are:

Class I: Plasticity Index NP (Nonplastic) to 10
Class II: Plasticity Index 10 to 25
Class III: Plasticity Index $>$ 25, Nonmontmorillonitic
Class IV: Plasticity Index $>$ 20, Montmorillonitic

A description of each of the soils as reported by the U.S. Department of Agriculture Soil Conservation Service is shown in Table 2.

TABLE 2

SOIL CLASSIFICATION AND PHYSICAL PROPERTY DATA FOR SOILS USED IN THE EXPERIMENTAL STUDY

Soil	Family[a/]	AASHTO Classification	% of Material Passing Sieve[a/] No. 10 (2.0 mm)	No. 40 (0.425 mm)	No. 200 (0.075 mm)	Liquid Limit	Plastic Limit	Plasticity[b/] Index	Maximum Dry[b/] Density, pcf (AASHTO T 99)	Optimum Moisture[b/] Content, %	pH[a/]
Class I Soils: Plasticity Index NP-10											
Atkins	Fine-loamy, mixed, acid mesic	A-4	80-100	60-100	40-85	25	NP	NP	112	15	4.5-5.5
Coxville	Clayey, kaolinitic, thermic	A-4	100	91-98	53-81	23	14	9	116	13	4.5-5.5
Manor	Coarse-loamy, micaceous, mesic	A-4 (A-2-4)[c/]	NA			35	NP	NP	113	16	NA
Class II Soils: Plasticity Index 10-25											
Exum	Fine-silty, siliceous, thermic	A-6	NA			34	17	17	109	17	NA
Mahoning	Fine-illitic, mesic	A-7-6	90-100	85-100	80-95	42	22	20	104	20	4.5-6.5
Miami	Fine-loamy, mixed, mesic	A-6	89-97	78-95	64-95	34	18	16	108	17	5.6-6.0
Sassafras	Fine-loamy, siliceous, mesic	A-6	NA			28	14	14	117	13	NA
Shelby	Fine-loamy, mixed, mesic	A-7-6	85-98	75-90	55-70	47	23	24	102	20	5.6-6.0
Tama	Fine-silty, mixed, mesic	A-7-6	100	100	95-100	50	28	22	98	23	5.1-5.5
Wharton	Clayey, mixed, mesic	A-7-6	70-100	65-95	60-90	47	24	23	99	24	4.5-5.5
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic											
Craven	Clayey, mixed, thermic	A-7-6	100	90-100	70-95	62	25	37	94	26	4.5-5.5
Upshur	Fine, mixed, mesic	A-7-6	70-100	55-100	55-100	54	28	26	98	24	4.5-7.3
Class IV Soils: Plasticity Index > 20, Montmorillonitic											
Fellowship	Fine, montmorillonitic, hyperthermic	A-7-6	NA			51	28	23	87	30	NA
Sharkey	Very fine, montmorillonitic, nonacid, thermic	A-7-5	100	100	95-100	91	30	61	87	26	5.1-8.4
Summit	Fine, montmorillonitic, thermic	A-7-5	100	96-100	80-99	69	30	39	96	26	NA

a/ Obtained from SCS soil survey interpretations for individual soil series.
b/ Determined from laboratory characterization.
c/ Two classes are shown for soils with a range of particle size distribution greater than and less than 35% passing a No. 200 sieve. The value in parenthesis is for soil with less than 35% passing.
NA Not Available

The SBM used in the studies was supplied by the Energy Research and Development Administration (ERDA) from a fluidized bed coal combustion pilot plant in Alexandria, Virginia. SBM is a granular material consisting of a calcined limestone product containing free lime, calcium sulfate (from the in situ scrubbing of SO_x and coal combustion products), and some fly ash (probably combined with calcined limestone). The material is orange-brown due to the iron oxide in the ash. There are also minor amounts of unburned or partially burned coal fragments, which show up as coarse black particles in the SBM.

The chemical analysis of SBM used in this study is presented in Table 3. Major constituents are calcium oxide, calcium sulfate, and silica with lesser amounts of iron oxide, alumina, and magnesia. The as-received material is very dry (no weight loss was observed when heated to 105°C). The loss on ignition value of 1.4% indicates virtually complete calcination of the limestone in the fluidized bed combustion. Very little sulfite is present in SBM, which may be indicative of excess air in the combustion.

The calcium oxide, sulfate, magnesium oxide, and loss on ignition (assumed to be CO_2 loss) values were used to estimate compound composition in the SBM. These results indicate that two-thirds of the calcium present as CaO (or perhaps in combination with silica or alumina) and one-third as calcium sulfate. Thus, SBM containes both calcium sulfate and lime, which are essential ingredients for a calcium sulfate-based soil stabilizer as was established in the previous study. The strengths of soils treated with SBM are enhanced further by the ash content of the material.

TABLE 3

CHEMICAL ANALYSIS OF SBM

Constituent		Quantity (%)
Calcium as CaO		39.9
Magnesium as MgO		3.2
Sulfate as SO3		15.3
Silica as SiO_2		29.6
Iron as Fe_2O_3		1.6
Aluminum as Al_2O_3		6.2
Loss on Ignition at 900° C		1.4
	Total	97.2
Sulfite as SO_2		7.5 ppm
Fluoride as F		4 ppm
Phosphorus as P_2O_5		10 ppm

Major Compound Analysis

$CaCO_3$	3.2
$MgSO_4$	9.6
$CaSO_4$	15.1
CaO	31.9
SiO_2	29.6

EFFECT OF SBM ON UNCONFINED COMPRESSIVE STRENGTHS IN SOILS

Cylindrical specimens (1.3125 in. diameter x 2.815 in.) of soil and SBM mixtures were prepared in a Harvard Miniature Compaction apparatus. The specimens were prepared with constant compaction (25 tamps per layer for five layers using a 20-lb spring). As will be discussed in Section IV, the uncured dry density of the SBM treated soil specimens is less than that of the untreated soils, which may have an affect on ultimate strength. After specimens were prepared, they were wrapped in Saran wrap and cured at 100% relative humidity. At 7, 14, 21, and 28 days, the cured specimens were tested for unconfined compressive strength using an Instron Universal Testing Instrument (Model No. TT-CM-M1) at a loading rate of 0.1 cm/min.

The use of SBM in soils prov ed to be quite beneficial with regard to strength development. SBM treated soils consistently developed higher strengths than untreated soils, with the exception of Class IV montmorillonitic soils. The dry densities of montomorillonitic soils were low (generally about 80 to 85 lb/cu ft), and it is believed that the low densities are a major contributing factor to the low strengths of SBM (and lime) treated montomorillonitic soils.

In addition to the SBM treated specimens, soils treated with binary combinations of SBM/phosphogypsum, SBM/fly ash, and SBM/lime were fabricated and tested. The binary combinations were included to determine whether additional benefits regarding strength development above those observed with SBM alone could be achieved. In general, it was found that lime and fly ash improved the strengths of SBM-treated soils, whereas phosphogypsum has little effect.

Unconfined compressive strength data were analyzed using the linear regression procedures established in the previous study.[1] The strengths were considered to be the dependent variable, and were regressed against the independent variables of moisture content, curing time, and level of SBM treatment. The analysis of strength data obtained from specimens treated with binary combinations of SBM and additive included the level of additive treatment as a fourth independent variable.

The following discussion presents the detailed findings of the unconfined compressive strength studies. The 15 soils evaluated have been divided into the four classifications based on plasticity index described in Section II. The regression equations established by the data analysis have been plotted for each of the soils evaluated to show strength development with time. The regression coefficients, their standard deviation, and statistical significance are also tabulated. Raw unconfined compressive strength data obtained from the testing are presented in the Appendix.

Class I Soils: Plasticity Index NP to 10

Three soils are in Class I category: Atkins (NP), Coxville (PI-9), and Manor (NP). Equations relating unconfined compressive strength to SBM and SBM additive treatment are plotted in Figures 1 (Atkins), 2 (Coxville), and 3 (Manor). The figures are strength versus curing time plotted for the soils treated at the 6% level and at the "average" moisture content established by moisture contents of specimens sacrificed in the strength tests. For purposes of plotting the regression equations, the additives used with SBM are assumed to be present at the 2% level. Results of the statistical analysis are given in Table 4 for the three soils. Also included in Table 4 are the values obtained for soil/lime and soil/phosphogypsum mixtures obtained in the previous study.

Treatment of soils with SBM results in marked strength increases for all three Class I soils. The strength dev lopment with time is more pronounced with the SBM treated soils in contrast to observations made earlier with lime or phosphogypsum treated soils. In lime treated soils, most of the strength was developed within the first 7 days, whereas in SBM treated soils strengths continued to increase through 28 days.

Addition of more water to the formulation (Manor/SBM + 2% H_2O) does not have any marked effect on strength development for the soil tested in this manner. This result is believed due to the extreme dryness of the SBM. Any excess moisture present appears to be soaked up by the SBM but with little if any significant impact on strength development.

The three soils were treated with SBM and fly ash in binary combination of 6% SBM/6% fly ash and 12% SBM/6% fly ash. Analysis of the strength data for these tests indicates that fly ash additives had no statistically significant effect on the strength of two of the three soils (Atkins and Manor). The Atkins and Manor strength-time plots in Figures 1 and 3 indicate that fly ash addition does not result in strengths substantially different from those achieved with SBM alone.

A different response is noted with the Coxville/SBM/fly ash system. Fly ash coefficient is seen to be significant at the 99.9 % level in the Coxville soil; however, the SBM coefficient is significant at only the 95% level. When the regression equations are plotted for Coxville (Figure 2), it would appear that the combination of SBM-fly ash does have a much greater effect on strength development than that observed with only SBM treatment. These results are very similar to those obtained with the lime/phosphogypsum/fly ash system evaluated in Phase I,[1/] and may be associated with the kaolinitic composition of the Coxville series.

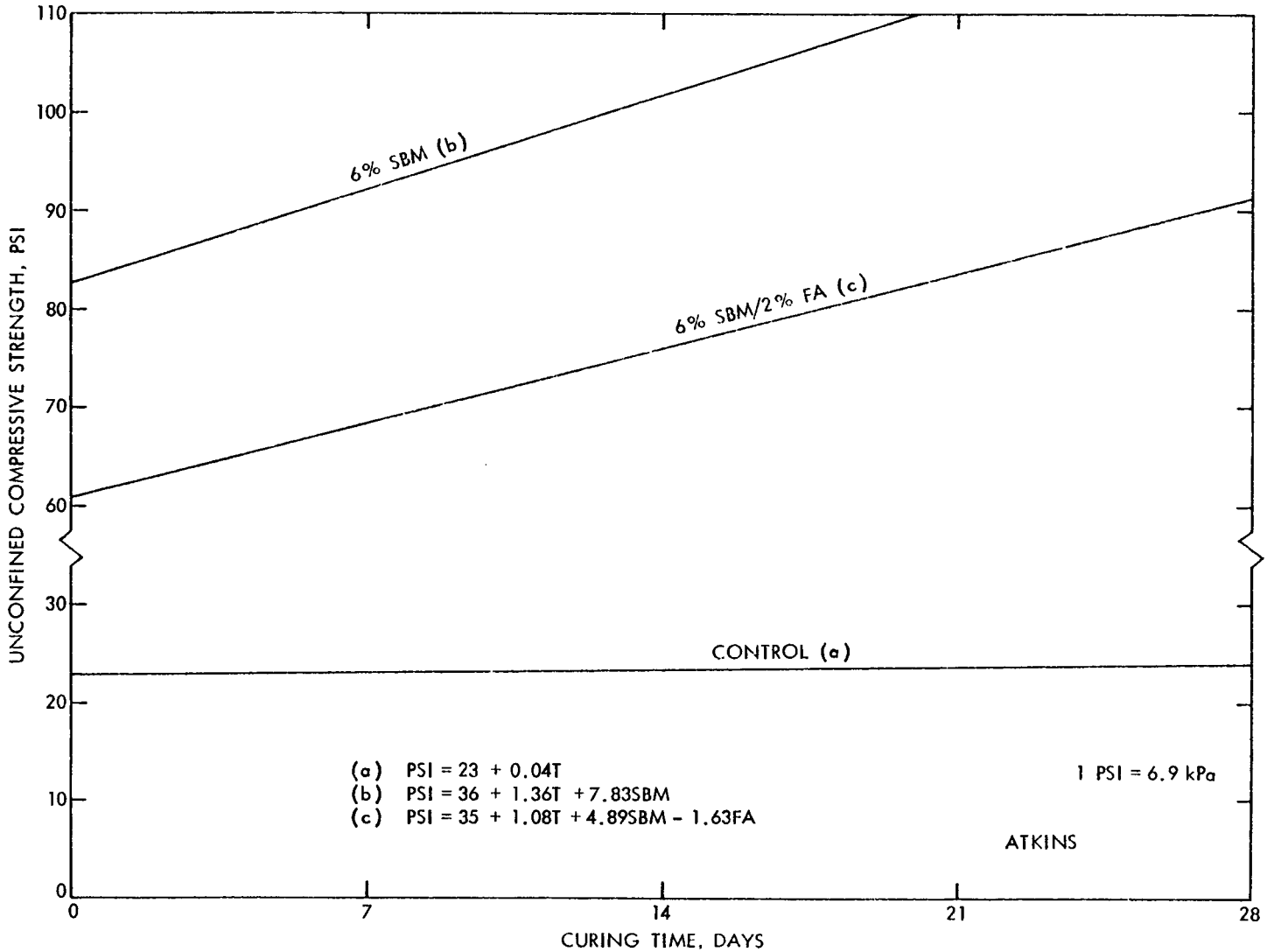

FIGURE 1. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: ATKINS SERIES

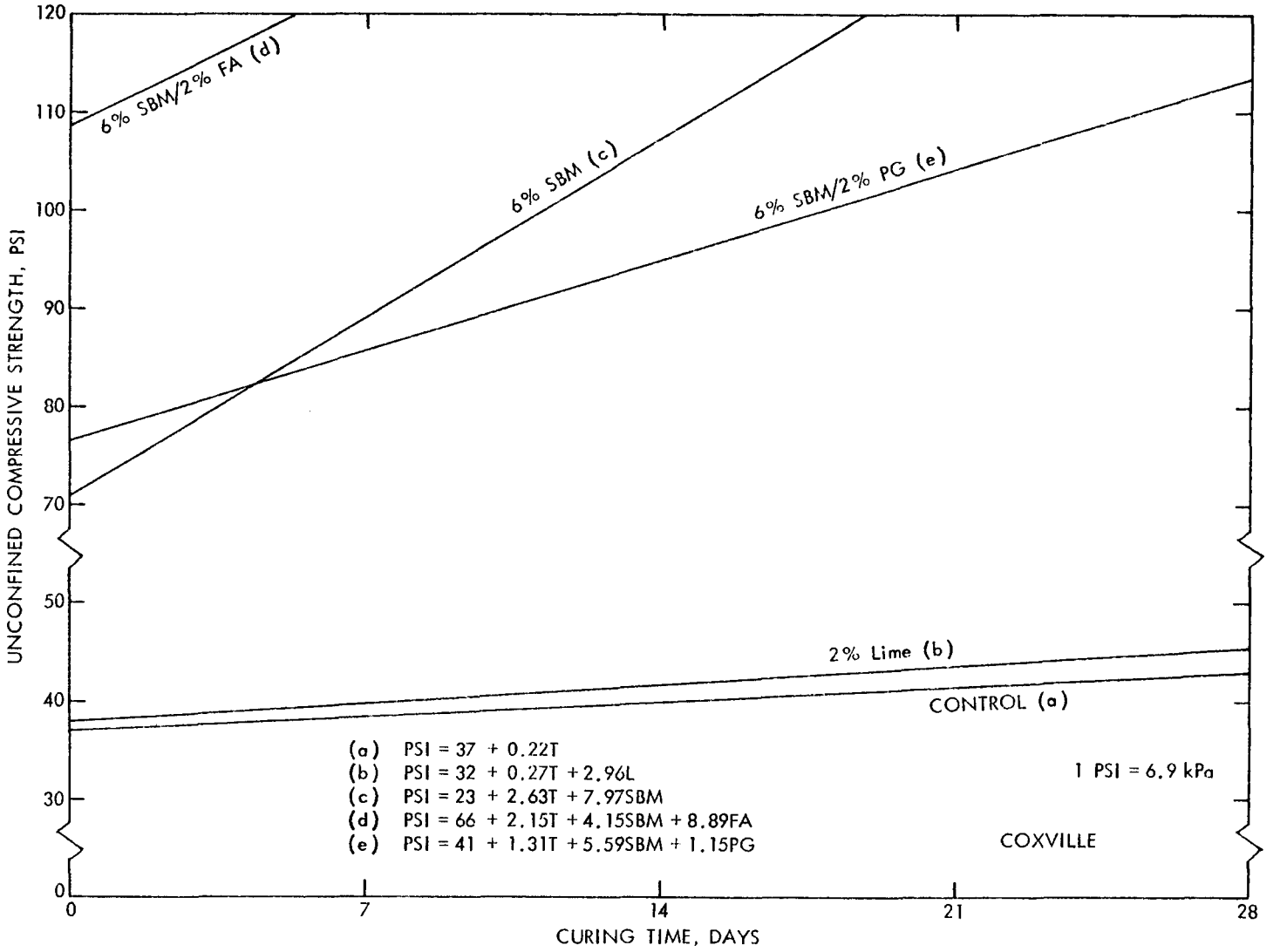

FIGURE 2. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: COXVILLE SERIES

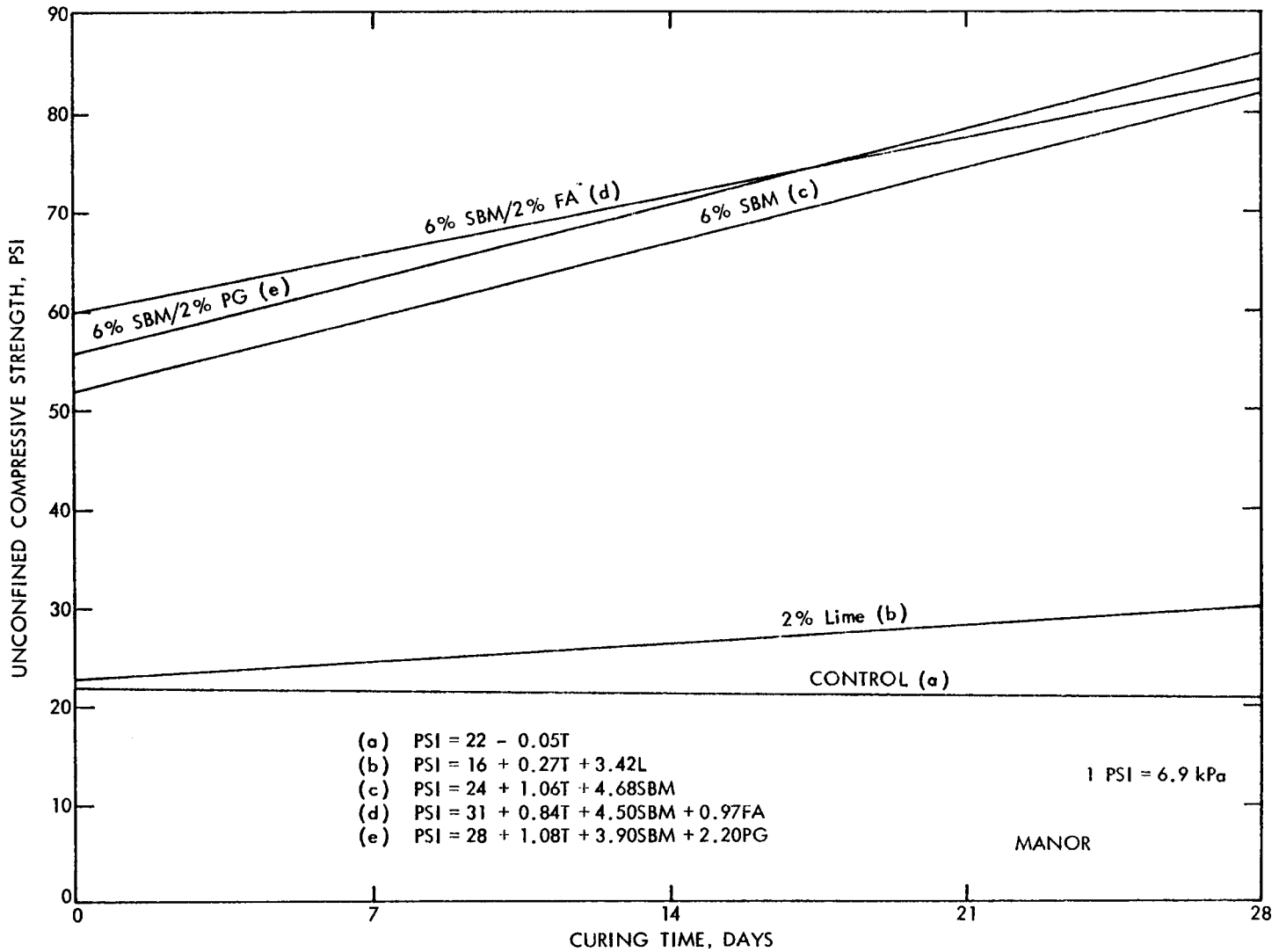

FIGURE 3. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: MANOR SERIES

TABLE 4

LINEAR REGRESSION COEFFICIENTS FOR STRENGTH DEVELOPMENT IN SOILS TREATED WITH SPENT BED MATERIAL (SBM), SBM/LIME, SBM/FLY ASH, AND SBM/PHOSPHOGYPSUM

(Class I Soils: Plasticity Index 10-25)

System	Moisture, psi/% H_2O			Time, psi/day			Spent Bed Material, psi/% SBM			Additive, psi/% Add			
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Additive	Regression Coefficient	Standard Deviation	Significance
Atkins Control DF=7, r^2=0.424	-12.76	5.89	ns	0.04	0.16	ns	-	-	-	-	-	-	-
Atkins/SBM DF=30, r^2=0.836	1.22	4.86	ns	1.36	0.31	***	7.83	0.94	***	-	-	-	-
Atkins/SBM/Fly Ash DF=40, r^2=0.656	-11.39	3.56	***	1.08	0.35	**	4.89	0.89	***	Fly ash	-1.63	1.47	ns
Coxville Control DF=1, r^2=0.439	4.87	6.52	ns	0.22	0.25	ns	-	-	-	-	-	-	-
Coxville/Lime DF=6, r^2=0.710	-4.27	5.76	ns	0.27	0.21	ns	-	-	-	Lime	2.96	1.63	ns
Coxville/SBM DF=24, r^2=0.769	-7.01	14.90	ns	2.63	0.50	***	7.97	2.66	**	-	-	-	-
Coxville/SBM/Fly Ash DF=35, r^2=0.836	-30.99	8.09	***	2.15	0.43	***	4.15	1.68	*	Fly ash	8.89	1.85	***
Coxville/Phosphogypsum DF=15, r^2=0.640	-2.57	1.49	ns	-0.04	0.07	ns	-	-	-	Phosphogypsum	-0.50	0.27	ns
Coxville/SBM/Phosphogypsum DF=50, r^2=0.816	-21.18	4.17	***	1.31	0.34	***	5.59	1.09	***	Phosphogypsum	1.15	1.16	ns
Manor Control DF=1, r^2=0.183	0.46	2.95	ns	-0.05	0.14	ns	-	-	-	-	-	-	-
Manor/Lime DF=10, r^2=0.777	-2.33	1.60	ns	0.27	0.17	ns	-	-	-	Lime	3.42	0.68	***
Manor/SBM DF=23, r^2=0.847	-17.23	7.35	*	1.13	0.36	**	4.74	1.49	**	-	-	-	-
Manor/SBM + 2% H_2O DF=35, r^2=0.739	-14.76	3.26	***	1.06	0.30	**	4.68	0.90	***				
Manor/SBM/Fly Ash DF=45, r^2=0.639	-7.91	1.79	***	0.84	0.29	**	4.50	0.85	***	Fly ash	0.97	1.29	ns
Manor/SBM/Phosphogypsum DF=46, r^2=0.710	-14.76	2.09	***	1.08	0.26	***	3.90	0.75	***	Phosphogypsum	2.10	1.10	ns

DF = Degrees of freedom
r^2 = Index of determination (square of correlation coefficient)
* = Statistically significant at 95% confidence level
** = Statistically significant at 99% confidence level
*** = Statistically significant at 99.9% confidence level
ns = Not significant at 95% confidence level

Two of the three soils (Coxville and Manor) were treated with SBM/phosphogypsum. In both cases, the phosphogypsum had no significant effect on strength development. The phosphogypsum thus appears to behave as an inert filler in SBM treated soils

Thus, SBM treatment increases unconfined compressive strengths of Class I soils. Addition of fly ash to the SBM may benefit strength development in some Class I soils, and will not diminish strengths in others. Phosphogypsum does n ot either benefit nor degrade strength development in Class I soils treated with SBM.

Class II Soils: Plasticity Index 10 to 25

The second class is medium textured soils having plasticity indexes between 10 and 25. Seven soils were studied, and strength-curing time plots developed from the data analysis are shown in Figures 4 through 10.

Exum (PI = 17): Figure 4
Mahoning (PI =20): Figure 5
Miami (PI = 16): Figure 6
Sassafras (PI = 14): Figure 7
Shelby (PI = 14): Figure 8
Tama (PI = 22): Figure 9
Wharton (PI = 23): Figure 10

The regression coefficients developed from the unconfined compressive strength data in the Appendix for the Class II soils are tabulated in Table 5, along with their standard deviations and statistical significances.

As was observed with the Class I soils, SBM treatment results in significant increases of soil strengths in all cases. In two of the soils (Exum and Tama), experiments were run in which extra moisture was used in the regression analysis (Exum/SBM + 3% H_2O and Tama/SBM + 2% H_2O), one finds that the effect of SBM treatment on strength becomes more pronounced both in magnitude and significance. By including specimens with a greater variation in moisture, it is possible to distinguish more precisely the effects of moisture and SBM on soil strengths. The data from the experiments with Exum/SBM + 3% H_2O and Tama/SBM + 2% H_2O suggest that SBM reacts with moisture to produce strength. Again, this effect is believed due to the very dry nature of SBM.

Three of the soils were treated with SBM/lime combinations: Exum, Mahoning, and Miami. In all three cases lime addition resulted in a significant increase in strength over that achieved with SBM alone.

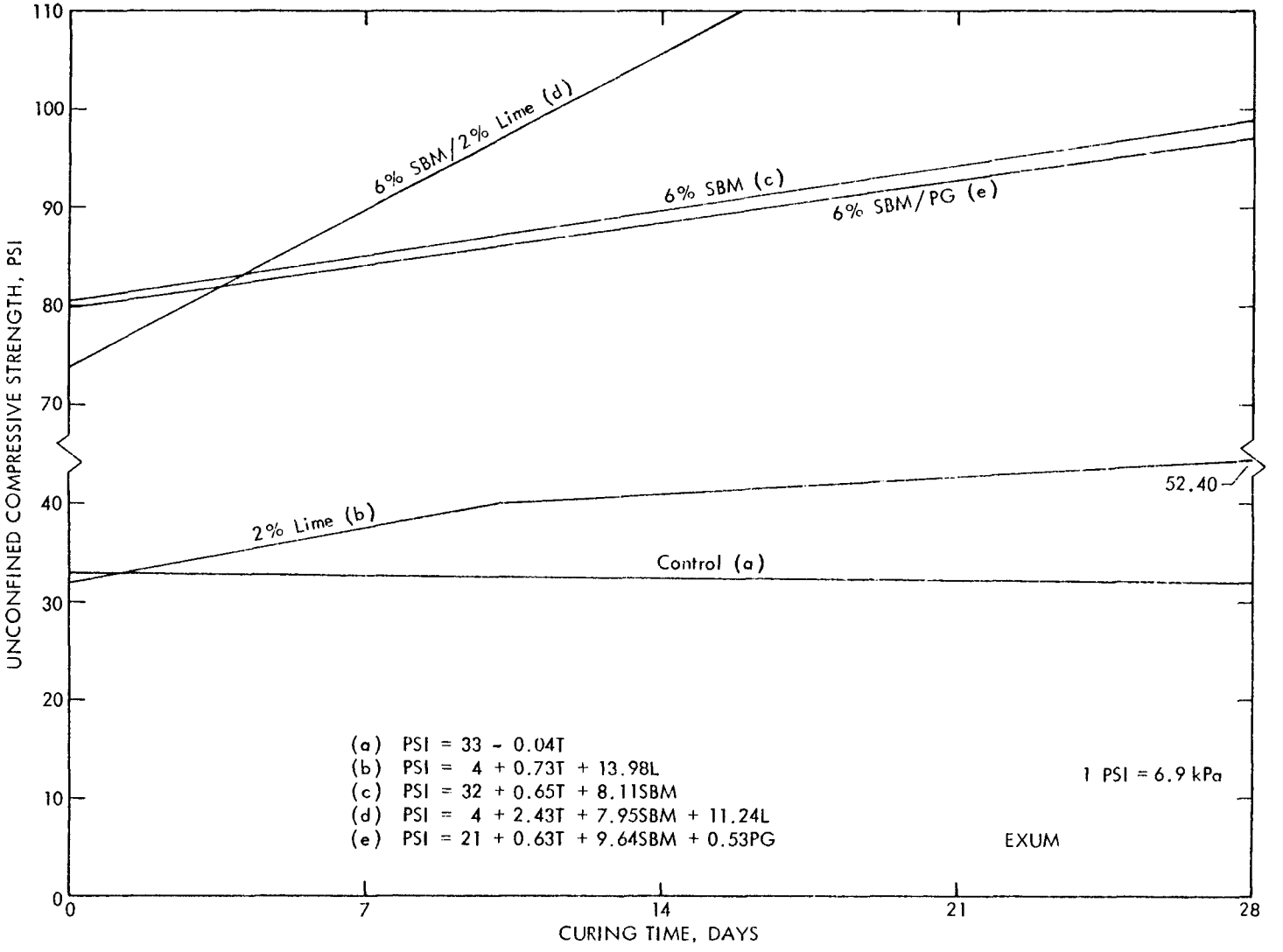

FIGURE 4. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: EXUM SERIES

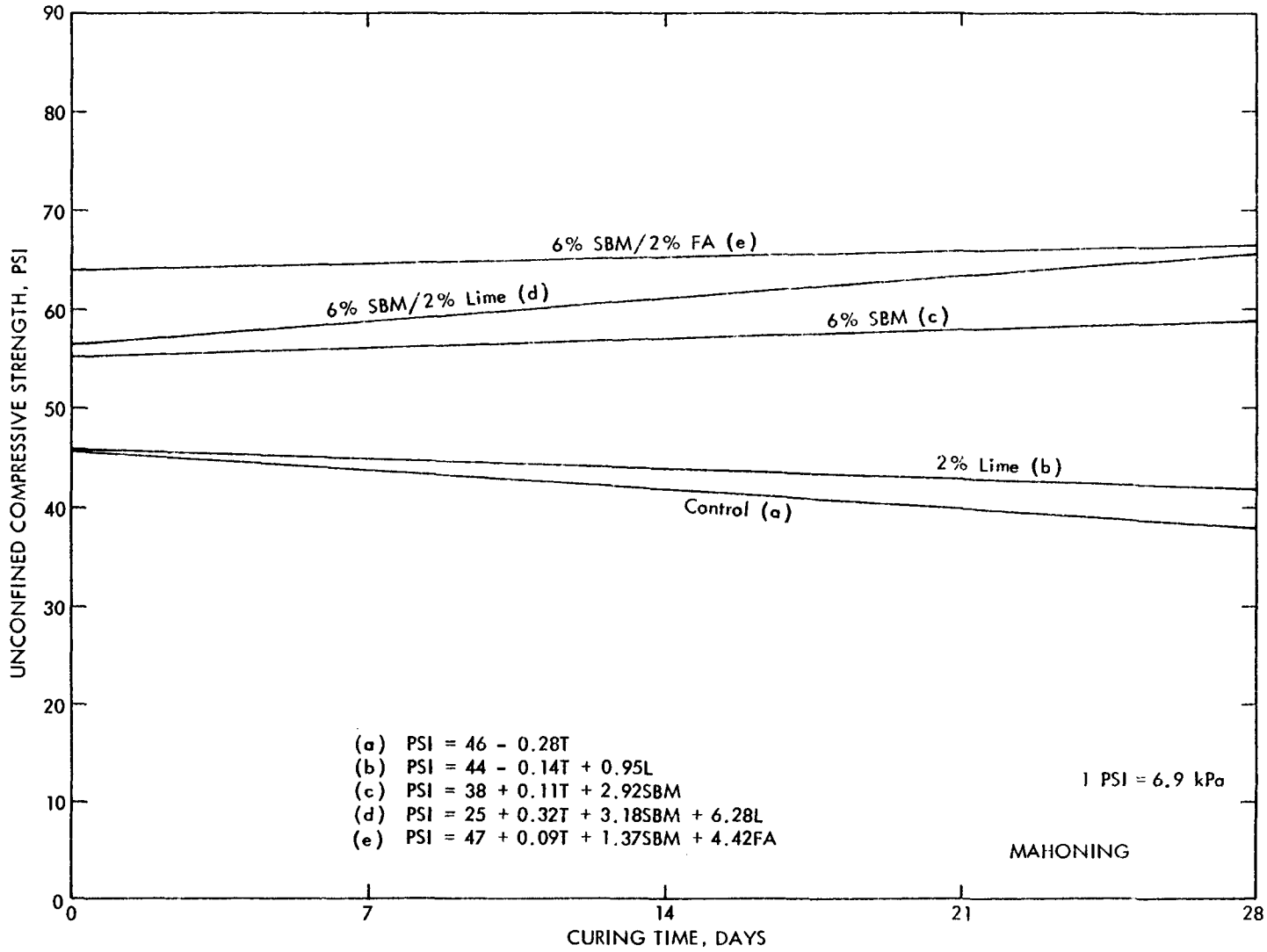

FIGURE 5. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: MAHONING SERIES

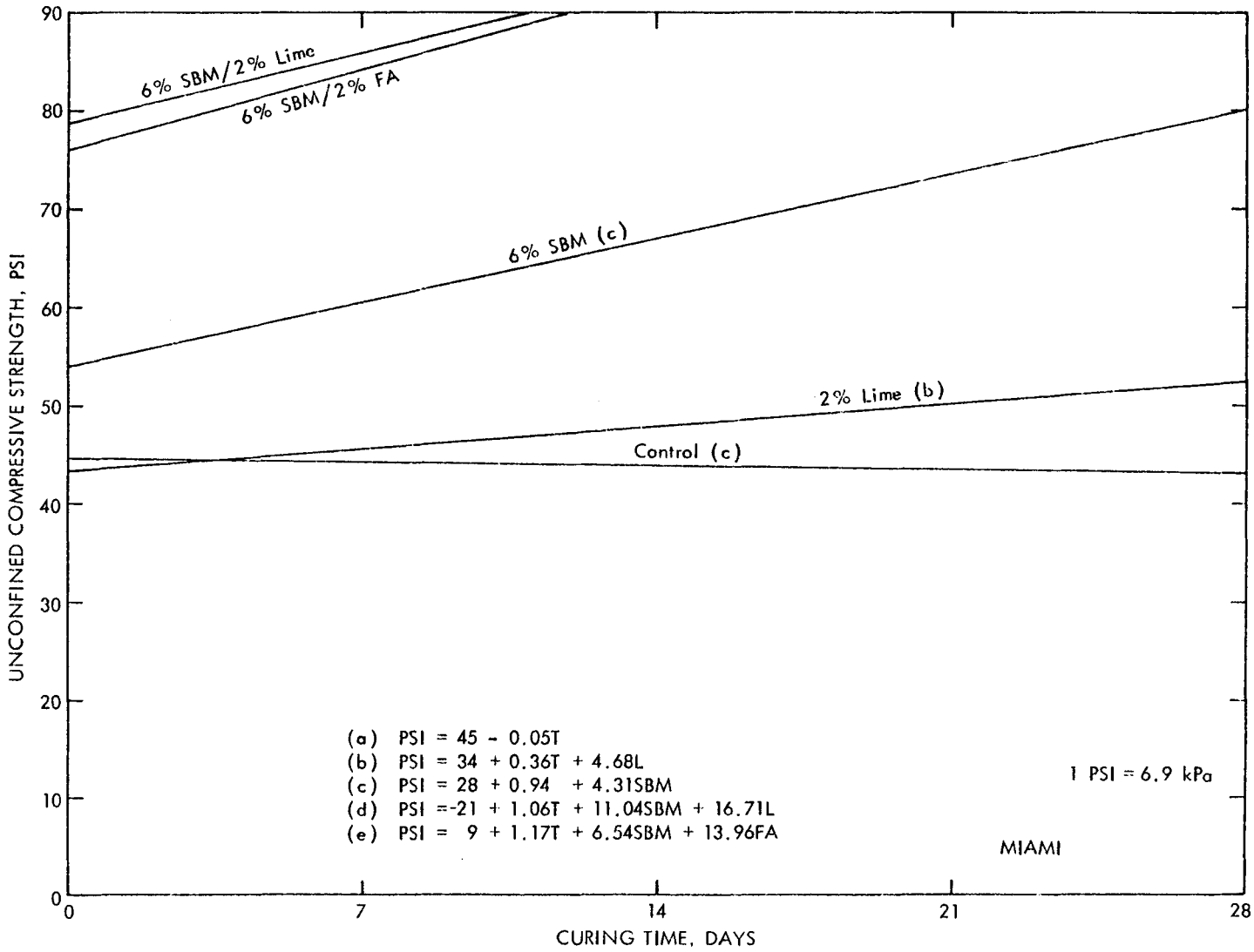

FIGURE 6. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: MIAMI SERIES

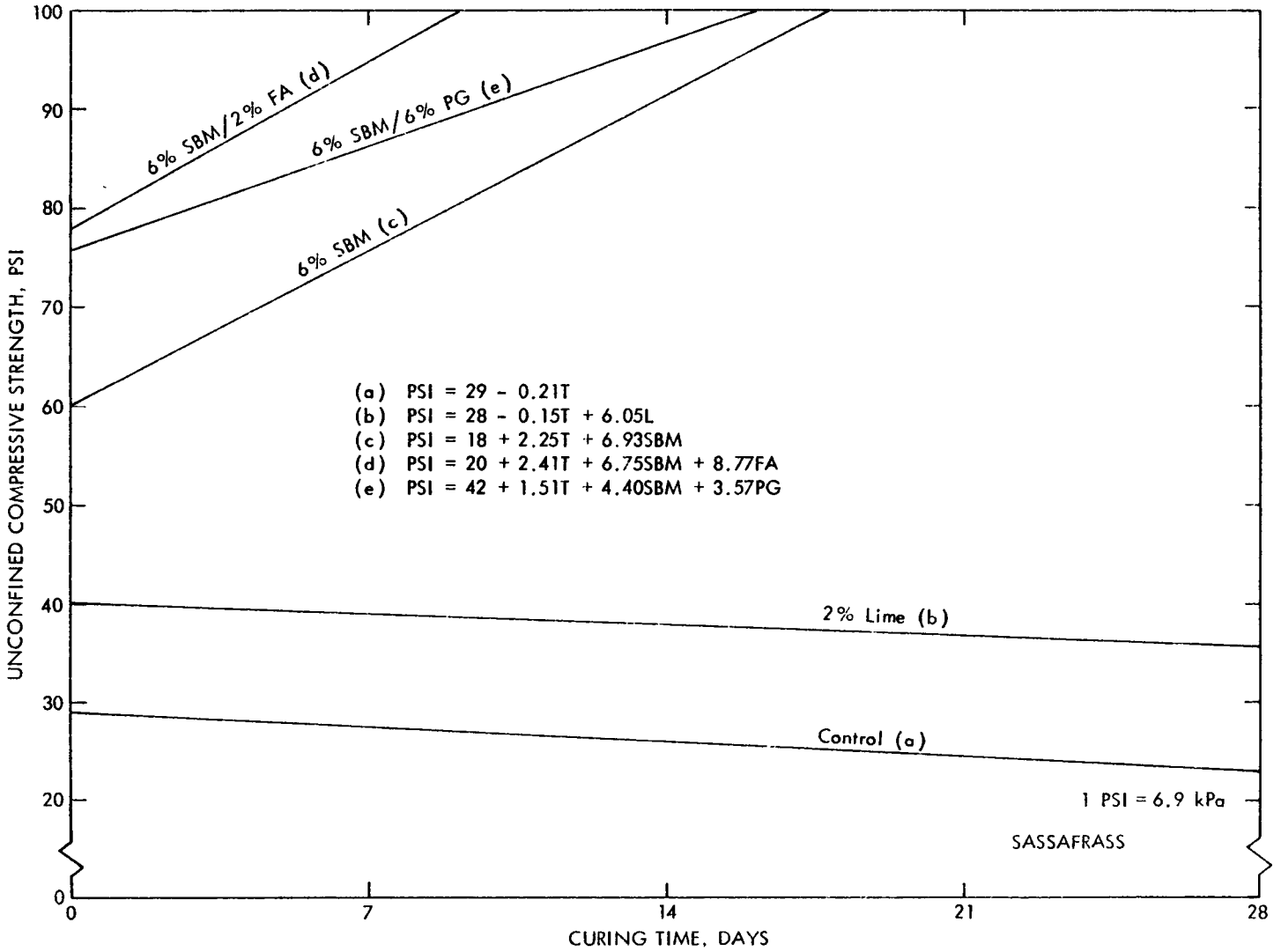

FIGURE 7. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: SASSAFRAS SERIES

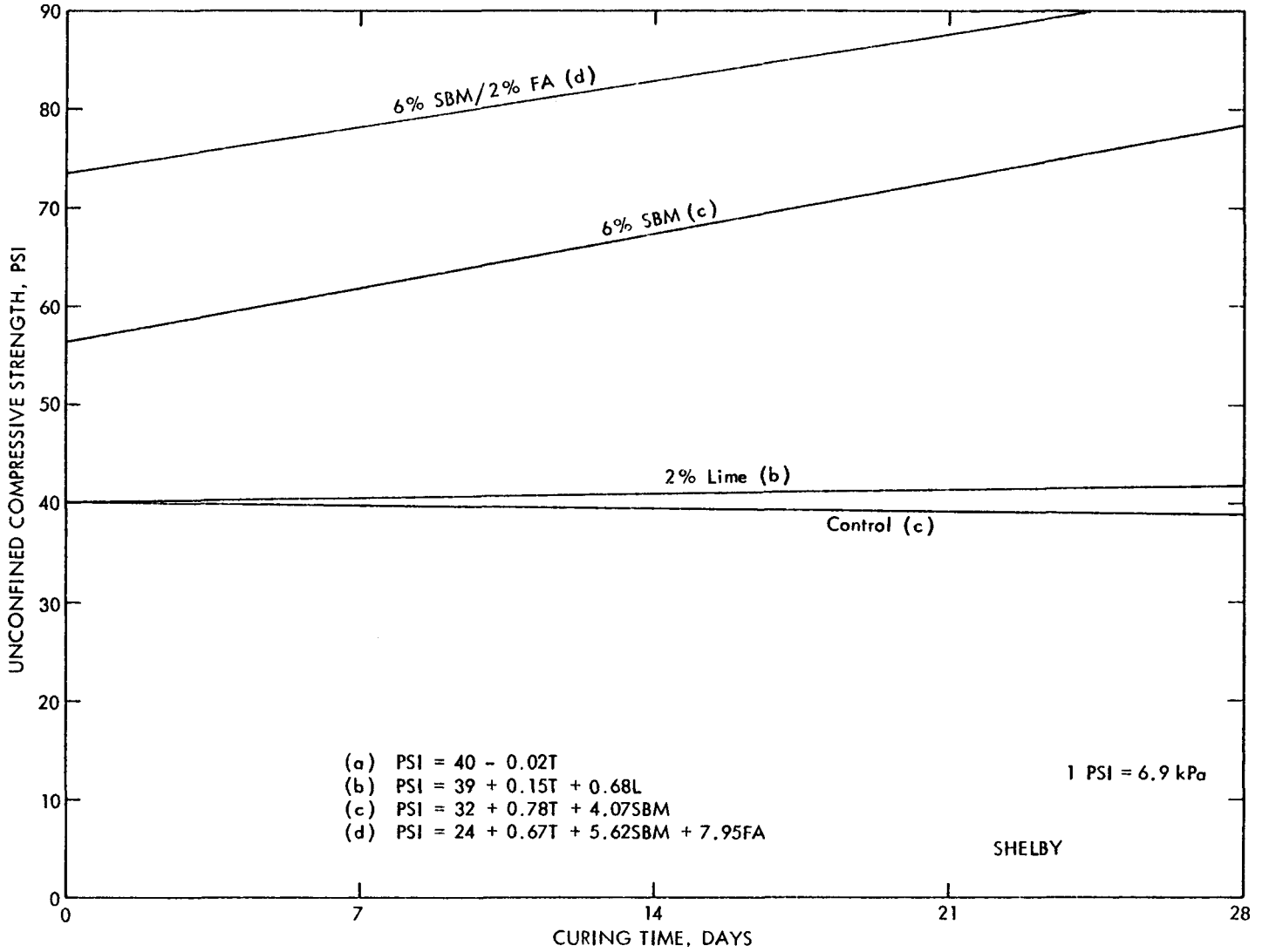

FIGURE 8. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: SHELBY SERIES

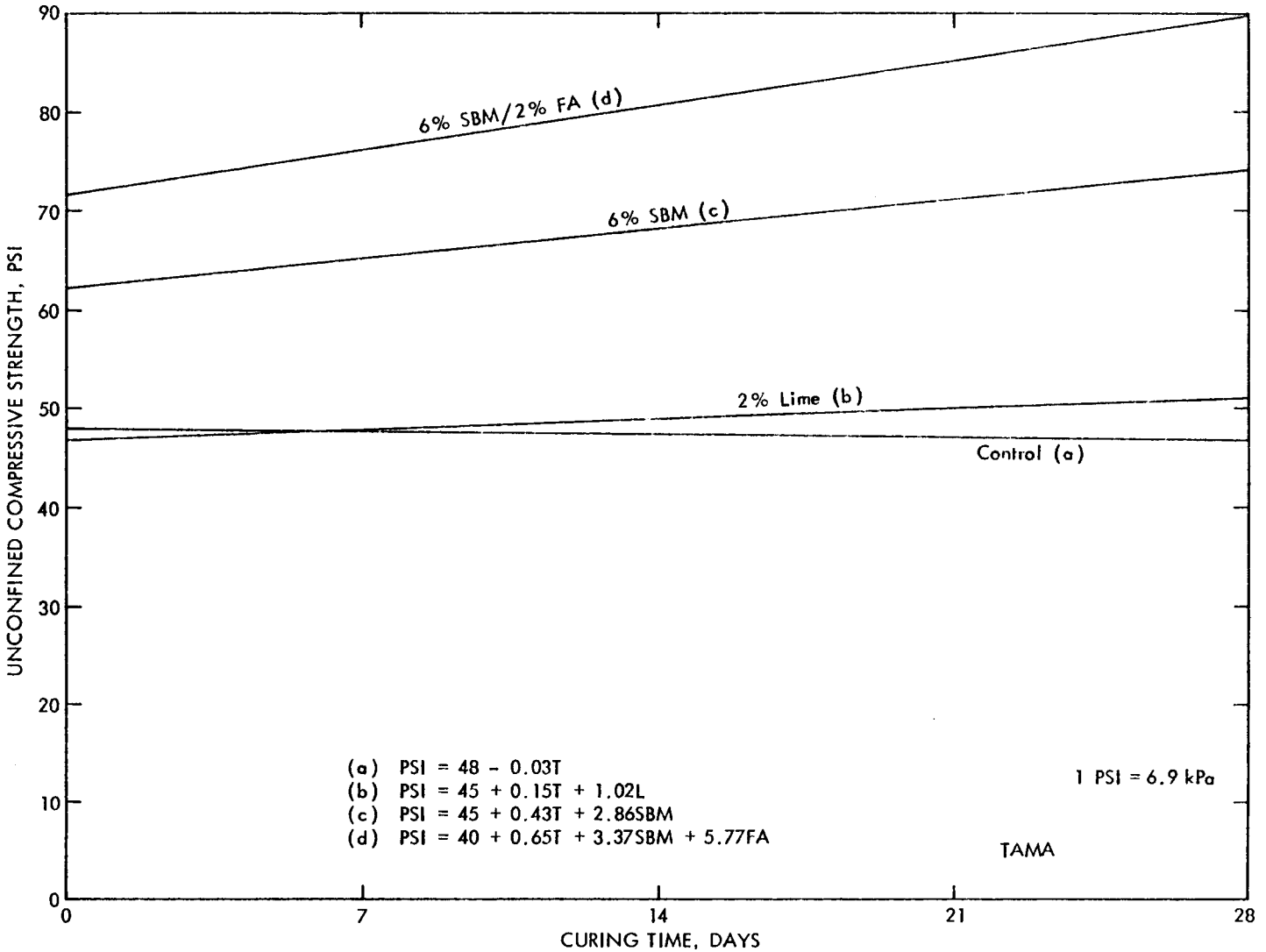

FIGURE 9. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: TAMA SERIES

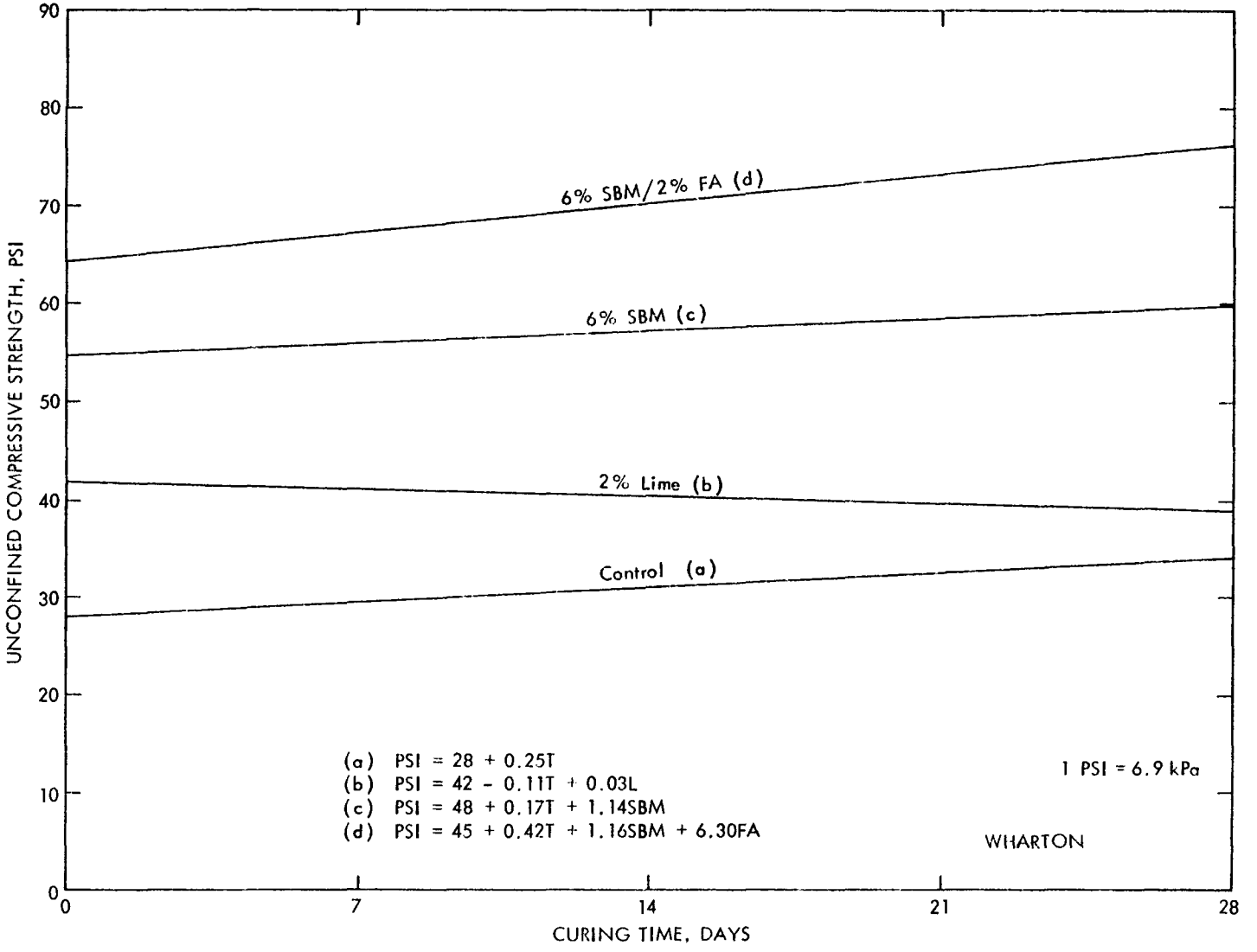

FIGURE 10. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: WHARTON SERIES

TABLE 5

LINEAR REGRESSION COEFFICIENTS FOR STRENGTH DEVELOPMENT IN SOILS TREATED WITH SPENT BED MATERIAL (SBM), SBM/LIME, SBM/FLY ASH, AND SBM/PHOSPHOGYPSUM
(Class II Soils: Plasticity Index 10-25)

System	Moisture, psi/% H_2O			Time, psi/day			Spent Bed Material, psi/% SBM			Additive, psi/% Add			
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Additive	Regression Coefficient	Standard Deviation	Significance
Exume Control													
DF=2, r^2=0.863	-3.07	0.89	ns	-0.04	0.03	ns	-	-	-	-	-	-	-
Exume/Lime													
DF=7, r^2=0.902	-20.69	9.72	ns	0.73	0.40	ns	-	-	-	Lime	13.98	2.76	**
Exume/SBM													
DF=25, r^2=0.785	-21.57	6.26	***	2.00	0.37	***	0.08	2.08	ns	-	-	-	-
Exume/SBM + 3% H_2O													
DF=37, r^2=0.451	-2.57	3.71	ns	0.65	0.68	ns	8.11	1.81	***				
Exume/SBM/Lime													
DF=54, r^2=0.524	-7.00	4.38	ns	2.43	0.68	***	7.95	1.88	***	Lime	11.24	2.72	***
Exume/Phosphogypsum													
DF=16, r^2=0.598	-2.15	1.10	ns	-0.05	0.05	ns	-	-	-	Phosphogypsum	-0.20	0.22	ns
Exume/SBM/Phosphogypsum													
DF=63, r^2=0.667	-0.96	2.70	ns	0.63	0.42	ns	9.64	1.10	***	Phosphogypsum	0.53	1.35	ns
Mahoning Control													
DF=13, r^2=0.288	-0.87	1.07	ns	-0.28	0.12	*	-	-	-	-	-	-	-
Mahoning/Lime													
DF=18, r^2=0.239	-0.53	1.22	ns	-0.14	0.12	ns	-	-	-	Lime	0.95	0.59	ns
Mahoning/SBM													
DF=34, r^2=0.763	0.69	0.87	ns	0.11	0.12	ns	2.92	0.40	***	-	-	-	-
Mahoning/SBM/Lime													
DF=51, r^2=0.634	-3.23	2.23	ns	0.32	0.31	ns	3.18	0.96	**	Lime	6.28	1.20	***
Mahoning/SBM/Fly Ash													
DF=45, r^2=0.695	-2.73	1.27	*	0.09	0.18	ns	1.37	0.60	*	Fly Ash	4.42	0.82	***
Miami Control													
DF=6, r^2=0.047	1.16	2.13	ns	-0.05	0.18	ns	-	-	-	-	-	-	-
Miami/Lime													
DF=14, r^2=0.611	3.66	3.76	ns	0.36	0.25	ns	-	-	-	Lime	4.68	1.46	**
Miami/SBM													
DF=28, r^2=0.840	-0.87	2.68	ns	0.94	0.18	***	4.31	0.74	***	-	-	-	-
Miami/SBM/Lime													
DF=48, r^2=0.880	18.70	4.27	***	1.06	0.30	**	11.04	0.92	***	Lime	16.71	1.28	***
Miami/SBM/Fly Ash													
DF=39, r^2=0.818	3.91	5.52	ns	1.17	0.38	**	6.54	1.57	***	Fly Ash	13.96	1.98	***

TABLE 5 (Concluded)

System	Moisture, psi/% H_2O			Time, psi/day			Spent Bed Material, psi/% SBM			Additive, psi/% Add			
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Additive	Regression Coefficient	Standard Deviation	Significance
Sassafras Control DF=6, r^2=0.812	-6.04	1.60	**	-0.21	0.13	ns	-	-	-	-	-	-	-
Sassafras/Lime DF=11, r^2=0.936	-2.51	0.52	***	-0.15	0.14	ns	-	-	-	Lime	6.05	0.50	***
Sassafras/SBM DF=29, r^2=0.721	-13.46	11.88	ns	2.25	1.89	ns	6.93	3.07	*	-	-	-	-
Sassafras/SBM/Fly Ash DF=40, r^2=0.795	-16.30	7.99	*	2.41	0.51	***	6.75	2.03	**	Fly Ash	8.77	2.06	***
Sassafras/SBM/Phosphogypsum DF=40, r^2=0.662	-23.21	6.21	***	1.51	0.52	**	4.40	1.68	*	Phosphogypsum	3.57	2.18	ns
Shelby Control DF=10, r^2=0.510	-4.92	1.55	**	-0.02	0.16	ns	-	-	-	-	-	-	-
Shelby/Lime DF=15, r^2=0.643	-6.32	1.52	***	0.15	0.14	ns	-	-	-	Lime	0.68	0.56	ns
Shelby/SBM DF=33, r^2=0.742	-2.71	3.50	ns	0.78	0.25	**	4.07	1.18	**	-	-	-	-
Shelby/SBM/Fly Ash DF=44, r^2=0.806	-0.20	4.45	ns	0.67	0.28	*	5.62	1.46	***	Fly Ash	7.95	1.54	***
Tama Control DF=14, r^2=0.012	-0.54	1.52	ns	-0.03	0.13	ns	-	-	-	-	-	-	-
Tama/Lime DF=22, r^2=0.341	-3.42	2.09	ns	0.15	0.17	ns	-	-	-	Lime	1.02	0.88	ns
Tama/SBM DF=37, r^2=0.669	-6.40	1.41	***	0.47	0.19	*	1.12	0.53	*	-	-	-	-
Tama/SBM + 2% H_2O DF=49, r^2=0.515	-4.90	2.12	*	0.43	0.28	ns	2.86	0.75	***	-	-	-	-
Tama/SBM/Fly Ash DF=60, r^2=0.649	-5.31	2.27	*	0.65	0.27	*	3.37	0.79	***	Fly Ash	5.77	1.25	***
Wharton Control DF=1, r^2=0.155	-4.73	12.09	ns	0.23	0.54	ns	-	-	-	-	-	-	-
Wharton/Lime DF=10, r^2=0.588	-4.03	1.45	*	-0.11	0.14	ns	-	-	-	Lime	0.03	0.73	ns
Wharton/SBM DF=22, r^2=0.760	-6.21	1.56	***	0.17	0.19	ns	1.14	0.74	ns	-	-	-	-
Wharton/SBM/Fly Ash DF=33, r^2=0.803	-7.94	2.17	***	0.42	0.23	ns	1.16	1.04	ns	Fly Ash	6.30	0.89	***

DF = Degrees of freedom
r^2 = Index of determination (square of correlation coefficient)
* = Statistically significant at 95% confidence level
** = Statistically significant at 99% confidence level
*** = Statistically significant at 99.9% confidence level
ns = Not significant at 95% confidence level

In addition, two soils (Exum and Sassafras) were treated with SBM and phosphogypsum. As was observed with the Class I soils, phosphogypsum had no effect on the strength properties of the SBM treated soils. On the basis of these experiments, it would appear that SBM behaves as a mixture of lime and calcium sulfate when used alone. However, the calcium sulfate fraction of SBM is the controlling factor in establishing ultimate properties of SBM treated soils. As has been observed with other sulfate wastes, strength properties of soils are not drastically changed by the addition of phosphogypsum. These observations are certainly substantiated with the experiments conducted with SBM/lime and SBM/phosphogypsum treated soils.

Fly ash was added in combination with SBM to six of the Class II soils: Mahoning, Miami, Sassafras, Shelby, Tama, and Wharton. Strengths of all of the soils treated with the SBM/fly ash mixtures are increased significantly over strengths obtained with SBM alone. This finding is consistent with results observed in the Phase I study where Class II soils were treated with lime/phophogypsum/fly ash.[1/] The strength increase afforded by the fly ash is probably because it provides alumina and silica, not available in these medium textured soils, for the pozzolanic reaction.

Class III Soils: Plasticity Index $\geq$25, Nonmontmorillonitic

The third class is fine-grained soils having plasticity indexes greater than 25 and nonmontmorillonitic mineralogy. Results obtained from the two Class III soils evaluated have been analyzed to obtain strength strength-time plots. The soils are:

Craven (PI = 37): Figure 11
Upshur (PI = 26): Figure 12

The linear regression coefficients computed for Figures 11 and 12, and their standard deviations and significances, are presented in Table 6.

Treatment of the two Class III soils with SBM at optimum moisture resulted in increased strengths for both. However, the strength increase for the Craven series formulated at optimum moisture appeared to be associated with the drying of the soil rather than to any real effect of the SBM. When the two soils were retested using specimens fabricated two percentage points over optimum moisture, the SBM treatment continued to result in increased unconfined compressive strength. Statistical significance of the SBM coefficient in the experiments with added moisture indicates that the increased strengths can be largely attributed to the SBM treatment.

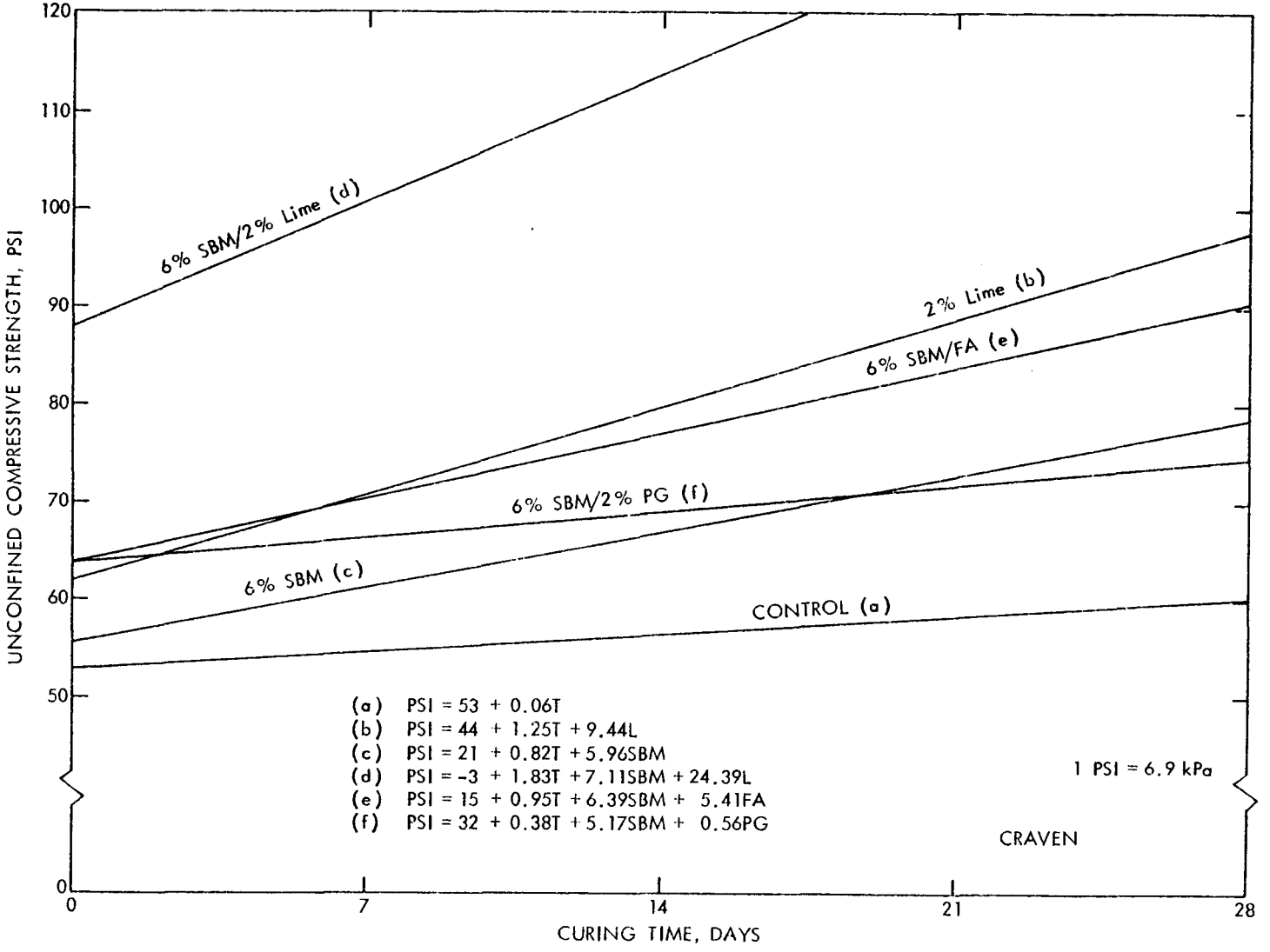

FIGURE 11. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: CRAVEN SERIES

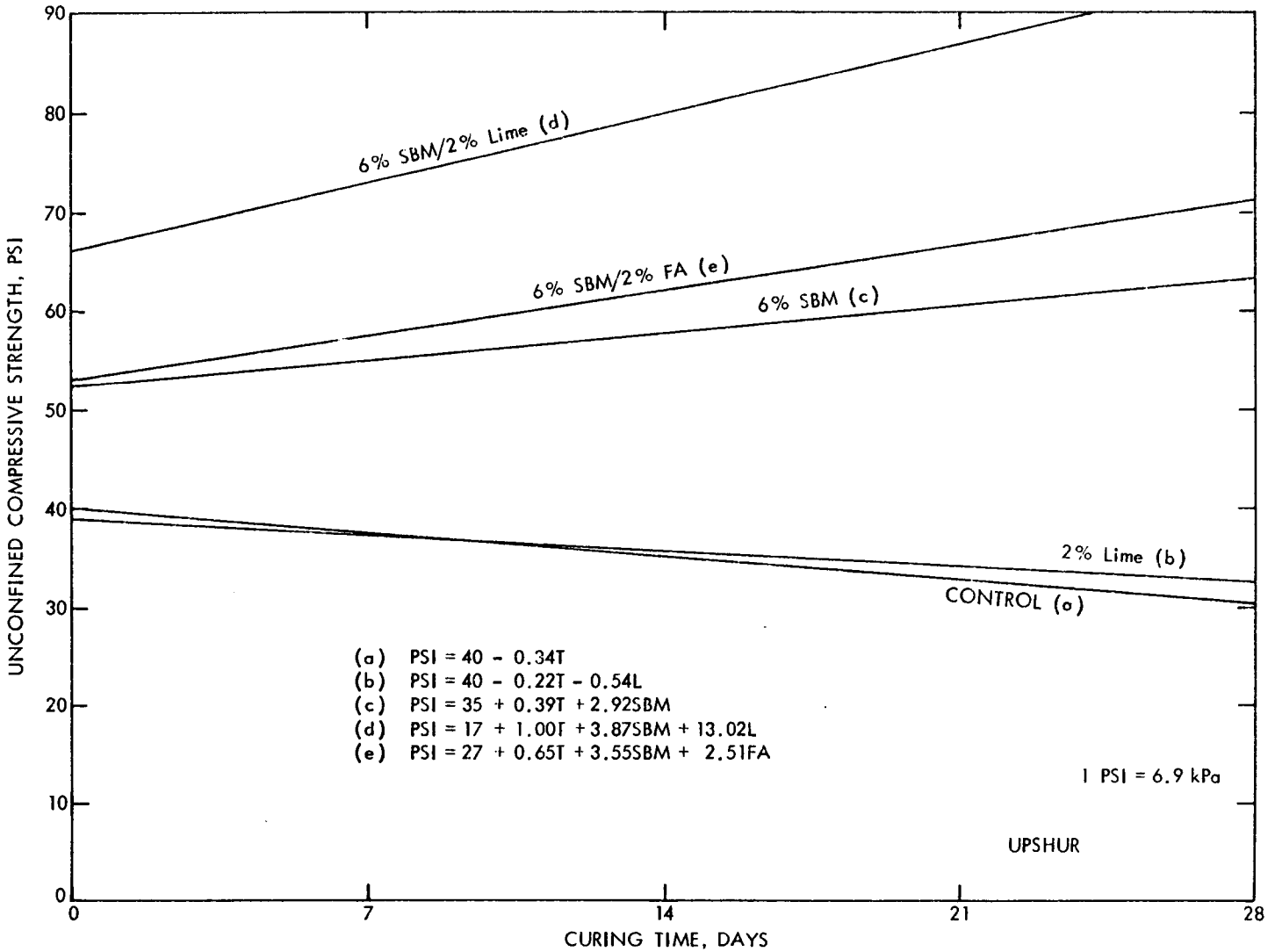

FIGURE 12. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: UPSHUR SERIES

TABLE 6

LINEAR REGRESSION COEFFICIENTS FOR STRENGTH DEVELOPMENT IN SOILS TREATED WITH SPENT BED MATERIAL (SBM, SBM/LIME, SBM/FLY ASH, AND SBM/PHOSPHOGYPSUM
(Class III Soils: Plasticity Index > 25, Nonmontmorillonitic)

System	Moisture, psi/% H_2O			Time, psi/day			Spent Bed Material, psi/% SBM			Additive, psi/% Add			
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Additive	Regression Coefficient	Standard Deviation	Significance
Craven Control DF=2, r^2=0.170	-2.89	5.27	ns	0.06	0.19	ns	-	-	-	-	-	-	-
Craven/Lime DF=7, r^2=0.904	-31.68	13.81	ns	1.25	0.57	ns	-	-	-	Lime	9.44	2 17	**
Craven/SBM DF=25, r^2=0.741	-11.12	4.65	*	0.87	0.34	*	1.77	1.33	ns	-	-	-	-
Craven/SBM + 2% H_2O DF=37, r^2=0.662	-0.05	2.59	ns	0.82	0.29	**	5.96	0.91	***	-	-	-	-
Craven/SBM/Lime DF=54, r^2=0.823	-8.25	3.96	*	1.83	0.47	***	7.11	1.31	***	Lime	24.39	1.85	***
Craven/SBM/Fly Ash DF=48, r^2=0.772	-0.42	2.37	ns	0.95	0.25	***	6.39	0.83	***	Fly Ash	5.41	1.10	***
Craven/Phosphogypsum DF=16, r^2=0.709	-3.98	0.77	***	-0.05	0.08	ns	-	-	-	Phosphogypsum	-1.23	0.22	***
Craven/SBM/Phosphogypsum DF=63, r^2=0.624	-4.33	2.14	*	0.38	0.26	ns	5.17	0.17	***	Phosphogypsum	0.56	0.79	ns
Upshur Control DF=2, r^2=0.897	0.16	1.54	ns	-0.34	0.11	ns	-	-	-	-	-	-	-
Upshur/Lime DF=5, r^2=0.802	-1.08	1.21	ns	-0.22	0.07	ns	-	-	-	Lime	-0.54	0.64	ns
Upshur/SBM DF=25, r^2=0.833	-1.63	2.97	ns	0.60	0.18	**	3.90	0.85	***	-	-	-	-
Upshur/SBM + 2% H_2O DF=37, r^2=0.701	-7.36	2.43	**	0.39	0.24	ns	2.92	0.90	**	-	-	-	-
Upshur/SBM/Lime DF=52, r^2=0.811	-6.29	2.50	*	1.00	0.28	***	3.87	0.87	***	Lime	13.02	1.18	***
Upshur/SBM/Fly Ash DF=48, r^2=0.739	-6.47	2.37	**	0.65	0.22	**	3.55	0.90	***	Fly Ash	2.51	0.89	**

DF = Degrees of freedom
r^2 = Index of determination (square of correlation coefficient)
* = Statistically significant at 95% confidence level
** = Statistically significant at 99% confidence level
*** = Statistically significant at 99.9% confidence level
ns = Not significant at 95% confidence level

Both soils were also treated with SBM/lime combinations, and Craven was treated with SBM/phosphogypsum. As was obtained with the Class II soils, SBM/lime treatment enhanced strength development, whereas SBM/phosphogypsum was neutral when compared to strengths developed with the SBM treated soils.

When the soils were treated with SBM/fly ash, on the other hand, strengths were not improved greatly over those treated with SBM alone. These results suggest that the lime values in the SBM are more easily used by the soil than by the fly ash.

Class IV Soils: Plasticity Index >20, Montmorillonitic

The last three soils studied had montmorillonite as their principal mineral constituent. The montmorillonitic soils are plastic soils which can be usually stabilized with lime. However, the Class IV soils evaluated in this study and in the earlier study[1/] did not respond well to lime (or any other addition) in terms of strength development.

The montmorillonitic soils used for the testing included:

Fellowship (PI = 23): Figure 13
Sharkey (PI = 61): Figure 14
Summit (PI = 39): Figure 15

The regression coefficients developed from the strength data are listed in Table 7, along with the standard deviations and statistical significances.

Examination of the plots in Figures 13 through 15 and the information in Table 7 indicates that neither SBM nor lime, nor a combination of both, has a great effect on strength development in the soils. Nor does treatment with SBM/fly ash or SBM/phosphogypsum have an effect on strength development.

As will be seen in the next section of this report, inclusion of the alkaline materials--lime and SBM--to montmorillonitic soils result in dry densities of about 80 to 85 lb/cu ft. Thus, it is conceivable that the strengths could be improved in the lime or SBM treated soils if greater compactive effort would have been applied in the formulation of specimens. In other words, a new set of experiments in which specimens of lime and SBM treated soils are compacted to known density may result in strengths which are different from those found in this study.

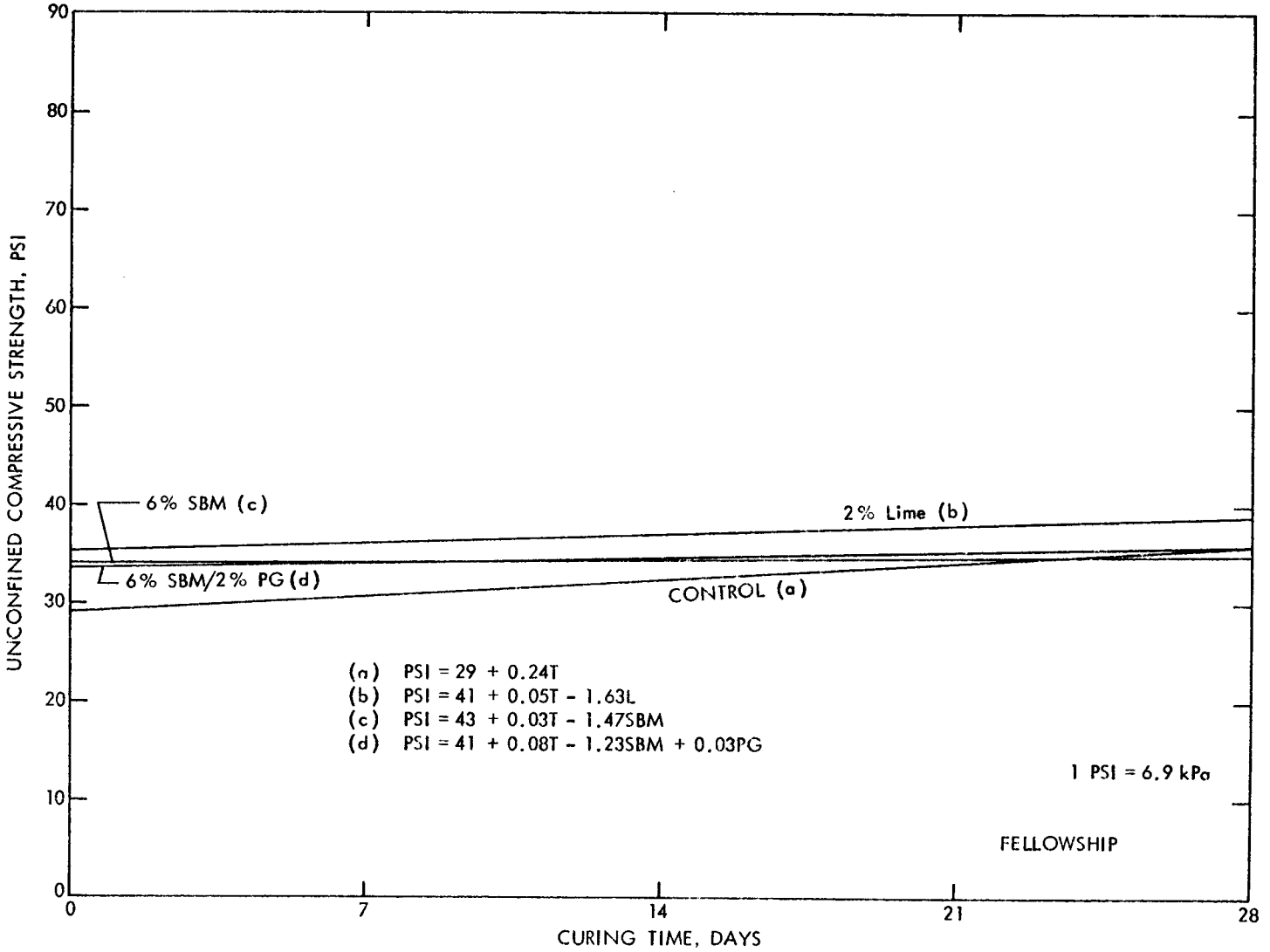

FIGURE 13. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: FELLOWSHIP SERIES

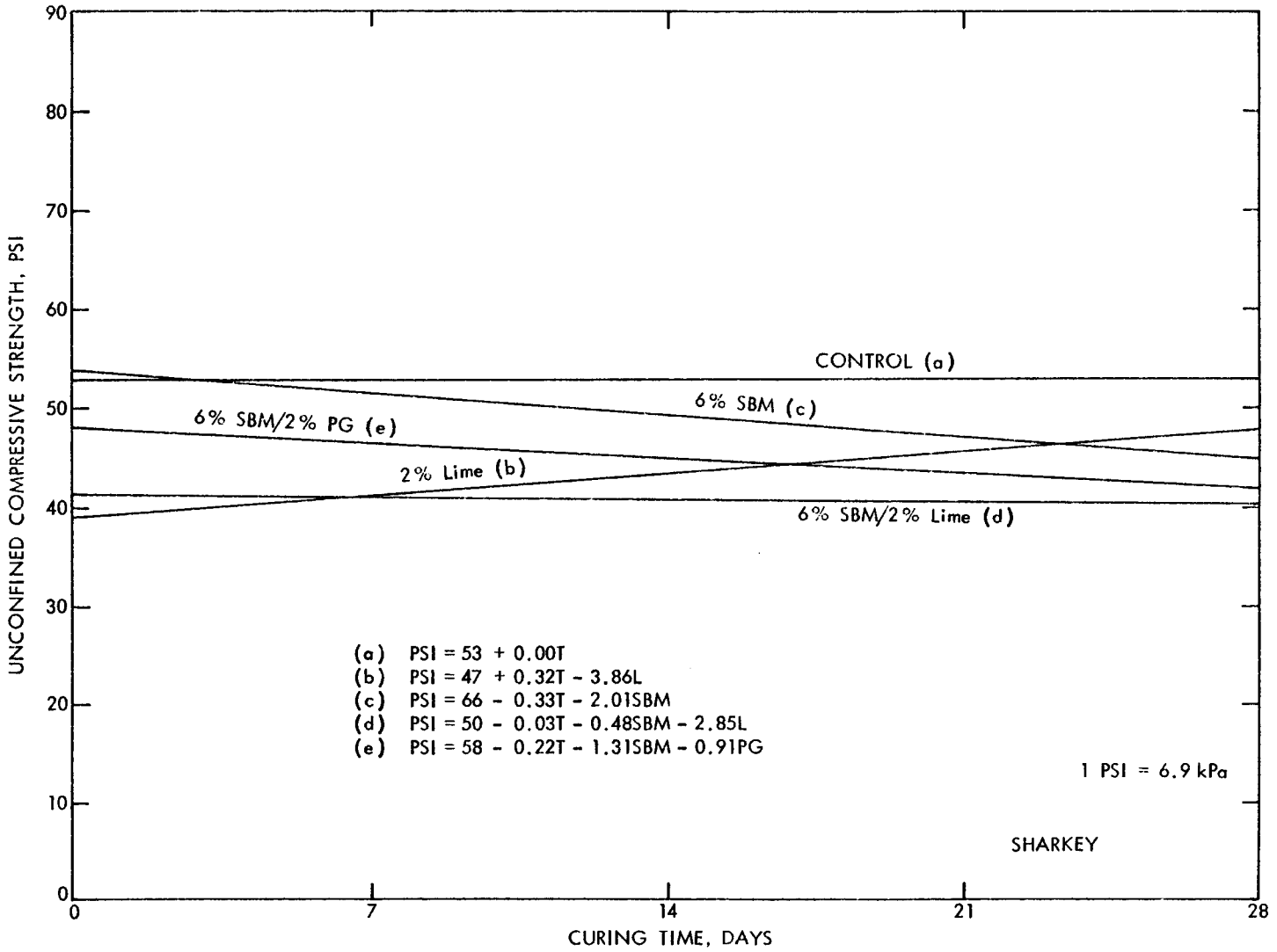

FIGURE 14. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: SHARKEY SERIES

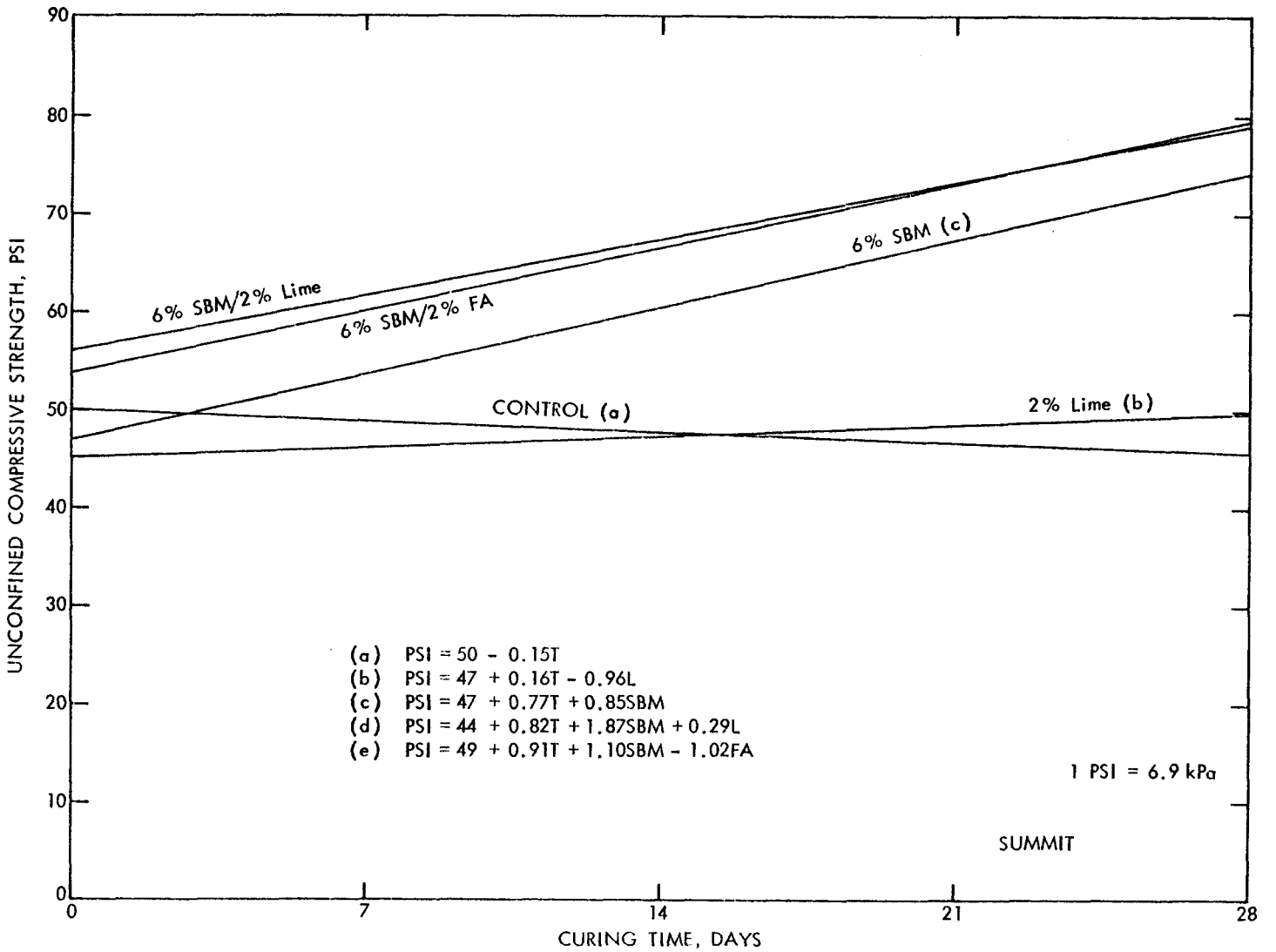

FIGURE 15. LINEAR REGRESSION PLOTS OF UNCONFINED COMPRESSIVE STRENGTH VERSUS CURING TIME: SUMMIT SERIES

TABLE 7

LINEAR REGRESSION COEFFICIENTS FOR STRENGTH DEVELOPMENT IN SOILS TREATED WITH SPENT BED MATERIAL (SBM, SBM/LIME, SBM/FLY ASH, AND SBM/PHOSPHOGYPSUM

(Class IV Soils: Plasticity Index > 20 Montmorillonitic)

System	Moisture, psi/% H_2O			Time, psi/day			Spent Bed Material, psi/% SBM			Additive, psi/% Add			
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Additive	Regression Coefficient	Standard Deviation	Significance
Fellowship Control DF=3, r^2=0.200	5.50	2.69	ns	0.24	0.12	ns	-	-	-	-	-	-	-
Fellowship/Lime DF=7, r^2=0.768	0.00	2.36	ns	0.05	0.10	ns	-	-	-	Lime	-1.63	0.38	**
Fellowship/SBM DF=24, r^2=0.636	-3.99	1.56	*	-0.34	0.11	**	-2.16	0.39	***	-	-	-	-
Fellowship/SBM + 3% H_2O DF=37, r^2=0.203	-3.14	1.37	*	0.03	0.13	ns	-1.47	0.49	**	-	-	-	-
Fellowship/Phosphogypsum DF=14, r^2=0.183	-0.82	0.70	ns	-0.05	0.07	ns	-	-	-	Phosphogypsum	-0.27	0.16	ns
Fellowship/SBM/Phosphogypsum DF=59, r^2=0.283	-2.03	0.88	*	0.08	0.09	ns	-1.23	0.30	***	Phosphogypsum	0.03	0.29	ns
Sharkey Control DF=2, r^2=0.872	3.56	0.97	ns	0.00	0.01	ns	-	-	-	-	-	-	-
Sharkey/Lime DF=6, r^2=0.935	0.58	1.37	ns	0.32	0.13	*	-	-	-	Lime	-3.86	0.83	**
Sharkey/SBM DF=25, r^2=0.616	-0.65	1.11	ns	0.05	0.09	ns	-1.57	0.43	**	-	-	-	-
Sharkey/SBM + 2% H_2O DF=37, r^2=0.267	-4.0[illegible]	1.33	**	-0.33	0.18	ns	-2.01	0.66	**	-	-	-	-
Sharkey/SBM/Lime DF=52, r^2=0.233	-0.73	0.60	ns	-0.03	0.17	ns	-0.48	0.46	ns	Lime	-2.85	0.74	***
Sharkey/Phosphogypsum DF=16, r^2=0.366	-1.26	0.63	ns	-0.02	0.10	ns	-	-	-	Phosphogypsum	-0.16	0.32	ns
Sharkey/SBM/Phosphogypsum DF=61, r^2=0.179	-0.13	0.75	ns	-0.22	0.14	ns	-1.31	0.54	*	Phosphogypsum	-0.91	0.45	*
Summit Control DF=7, r^2=0.127	1.24	1.94	ns	-0.15	0.15	ns	-	-	-	-	-	-	-
Summit/Lime DF=12, r^2=0.117	-0.92	2.22	ns	0.16	0.14	ns	-	-	-	Lime	-0.96	1.62	ns
Summit/SBM DF=30, r^2=0.503	-4.94	3.56	ns	0.77	0.24	**	0.85	1.09	ns	-	-	-	-
Summit/SBM/Lime DF=47, r^2=0.559	-3.73	3.34	ns	0.82	0.22	***	1.87	0.90	*	Lime	0.29	2.09	ns
Summit/SBM/Fly Ash DF=41, r^2=0.548	-5.42	2.80	ns	0.91	0.24	***	1.10	0.94	ns	Fly Ash	-1.02	1.75	ns

DF = Degree of freedom
r^2 = Index of determination (square of correlation coefficient)
* = Statistically significant at 95% confidence level
** = Statistically significant at 99% confidence level
*** = Statistically significant at 99.9% confidence level
ns = Not significant at 95% confidence level

EFFECT OF SBM ON MOISTURE/DENSITY RELATIONSHIPS OF SOILS

As has been stated earlier in this report, the as-received SBM is an extremely dry material. Although nonhygroscopic, it appears to react readily with available moisture when mixed with soils. Thus, the soil/SBM mixtures appear to become dryer during cure, i.e., the moisture content of the cured specimen is less than that of the newly prepared specimen. The drying effect is probably the fixing of available moisture by the SBM/soil mixture.

The extent of moisture fixation has been evaluated in the soil/SBM systems using the multiple regression techniques developed from the strength data. The difference between initial moisture and moisture after cure has been used as the dependent variable, and curing time and level of SBM treatment as independent variables. Results of these regression analyses are presented in Table 8.

In every case, the regression coefficient for SBM treatment is negative indicating that SBM is fixing water from the soil. Furthermore, the SBM coefficients are significant at the 99.9% confidence level suggesting that the behavior is general, i.e., it is not soil type dependent. The time coefficients are of about the same magnitude as the coefficients themselves, indicating that SBM will fix soil moisture at different rates depending upon how much moisture is available.

Increased strengths associated with SBM treatment of soils may involve two factors. The first factor would be the reaction of SBM with soil, probably through the soil moisture, to produce structurally stable reaction products. The second factor would be the fixation of excess soil moisture by the SBM to produce a dryer system with greater compressive strength. It is believed that the formation of stable reaction products is the principal mechanism for strength development bacause of the gradual increase in strength with corresponding decrease in moisture with time. This behavior is indicative of compound formation during cure, although simple dessication of the soil by the SBM cannot be ruled out.

After the moisture effects described above were observed, it became evident that density might also be a factor in strength development. Therefore, the weights of the specimens being fabricated were recorded in order to establish density relationships in SBM treated soils. Uncured dry densities of soil/SBM specimens were established for seven systems by using the weight of the uncured specimen and moisture content of the soil/SBM mixture. Average dry densities with one standard deviation on either side of the average have been plotted in Figures 16 through 22 for the following soils.

TABLE 8

LINEAR REGRESSION ANALYSIS OF MOISTURE CHANGES IN SOILS TREATED WITH SPENT BED MATERIAL

System	Time, Δ^2 H_2O/day			Spent Bed Material, Δ% H_2O/% SBM		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class I Soils: Plasticity Index NP-10						
Atkins DF = 31, r^2 = 0.578	0.021	0.011	ns	-0.142	0.024	***
Coxville DF = 25, r^2 = 0.798	-0.010	0.006	ns	-0.159	0.016	***
Manor[a] DF = 36, r^2 = 0.265	0.000	0.019	ns	-0.180	0.050	***
Class II Soils: Plasticity Index 10-25						
Exum[a] DF = 38, r^2 = 0.698	0.051	0.013	***	-0.288	0.034	***
Mahoning DF = 38, r^2 = 0.594	-0.017	0.023	ns	-0.355	0.050	***
Miami DF = 29, r^2 = 0.755	-0.021	0.011	ns	-0.235	0.025	***
Sassafras DF = 30, r^2 = 0.836	0.011	0.009	ns	-0.236	0.019	***
Shelby DF = 34, r^2 = 0.812	-0.006	0.012	ns	-0.302	0.025	***
Tama[a] DF = 50, r^2 = 0.494	0.003	0.018	ns	-0.275	0.039	***
Wharton DF = 23, r^2 = 0.612	0.018	0.025	ns	-0.368	0.062	***
Class III Soils: Plasticity Index > 25, nonmontmorillonitic						
Craven[a] DF = 38, r^2 = 0.634	0.004	0.012	ns	-0.242	0.030	***
Upshur[a] DF = 38, r^2 = 0.433	0.023	0.024	ns	-0.328	0.062	***
Class IV Soils: Plasticity Index > 20, montmorillonitic						
Fellowship[a] DF = 27, r^2 = 0.434	-0.028	0.024	ns	-0.320	0.061	***
Sharkey[a] DF = 38, r^2 = 0.563	-0.022	0.022	ns	-0.386	0.056	***
Summit DF = 31, r^2 = 0.790	0.003	0.012	ns	-0.273	0.025	***

DF = Degree of freedom (number of specimens - 3)
r^2 = Index of determination (square of correlation coefficient)
* = Statistically significant at 95% confidence level
** = Statistically significant at 99% confidence level
*** = Statistically significant at 99.9% confidence level
ns = Not significant at 95% confidence level
a/ Includes specimens sets to which extra moisture was added.

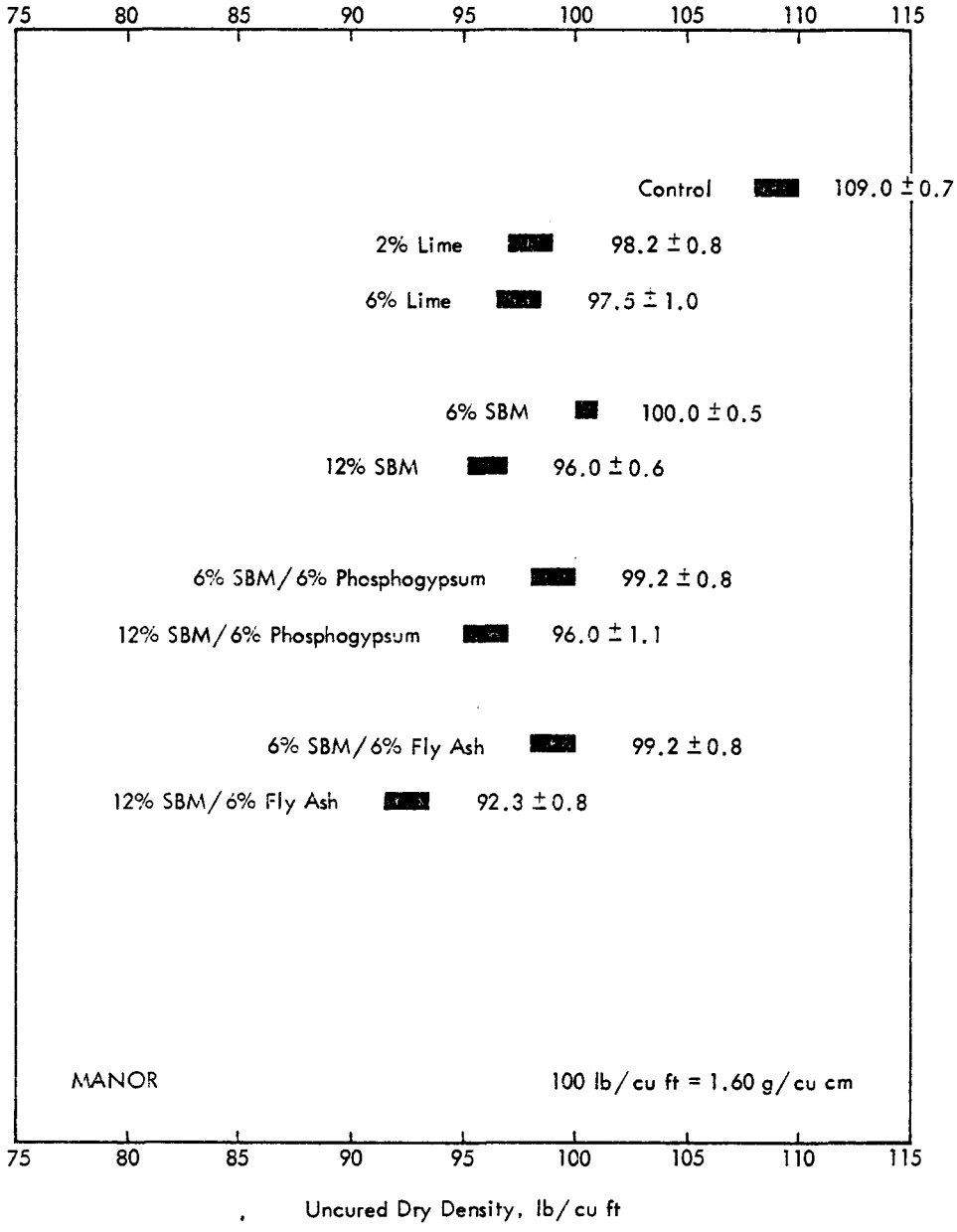

FIGURE 16. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: MANOR SERIES

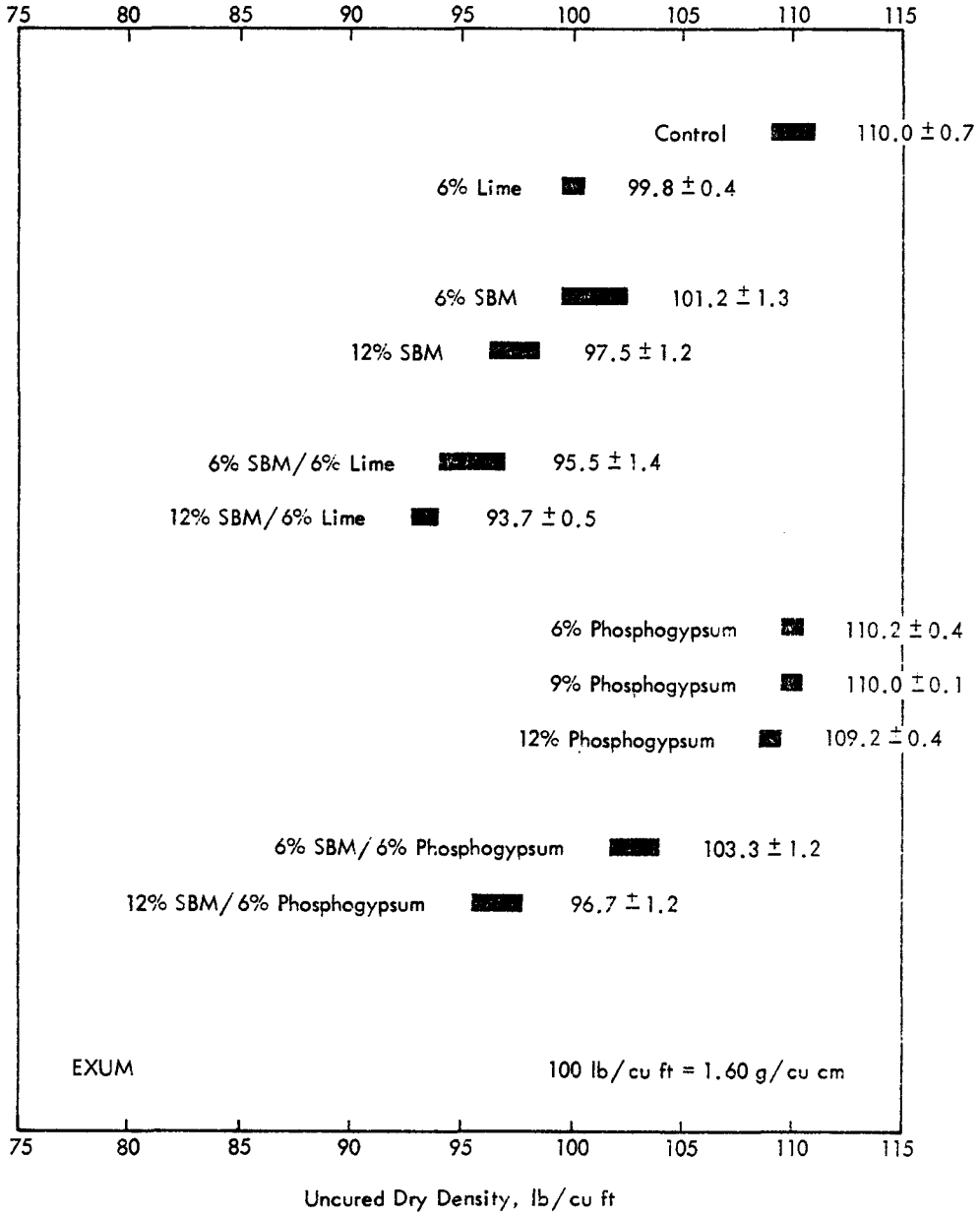

FIGURE 17. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: EXUM SERIES

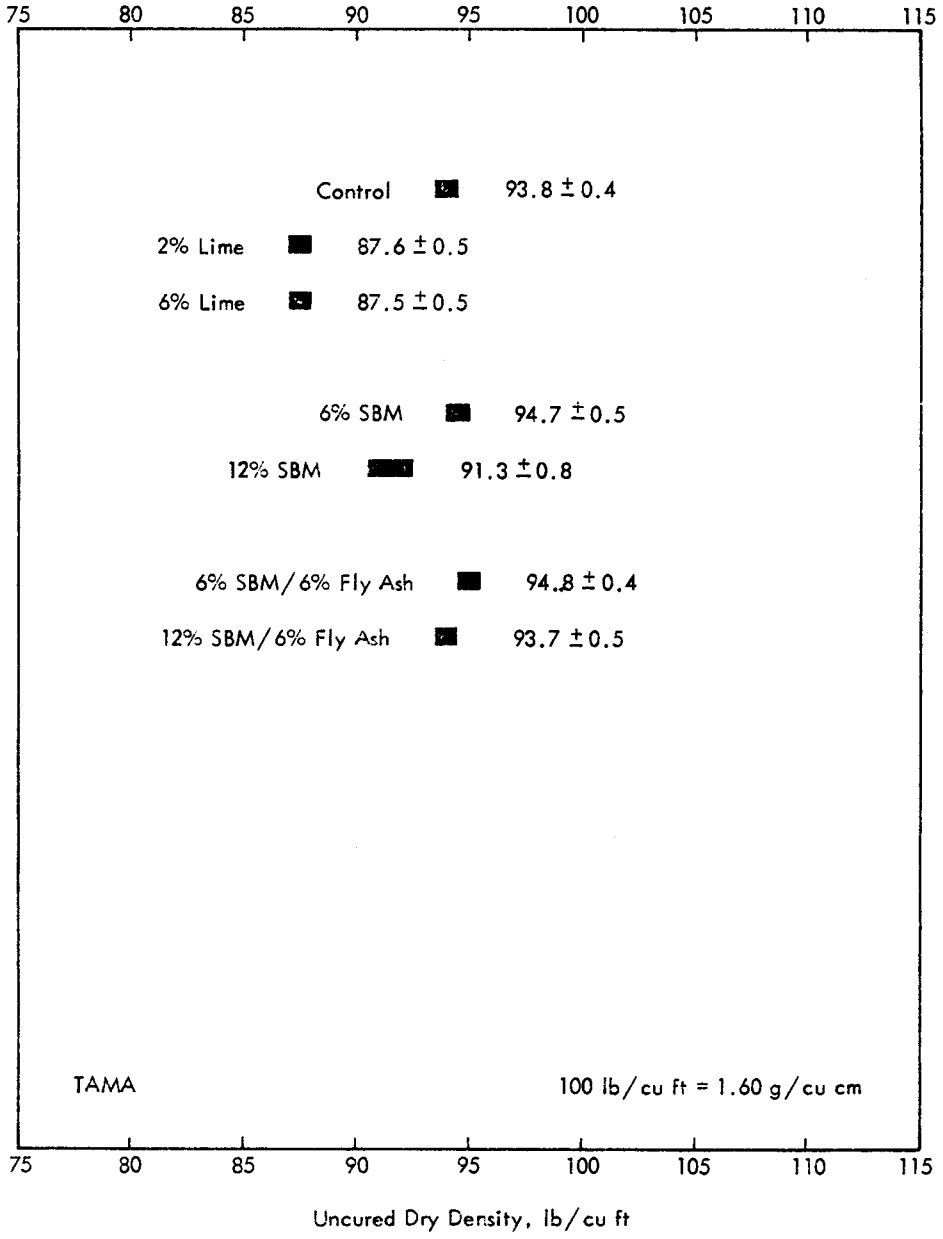

FIGURE 18. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: TAMA SERIES

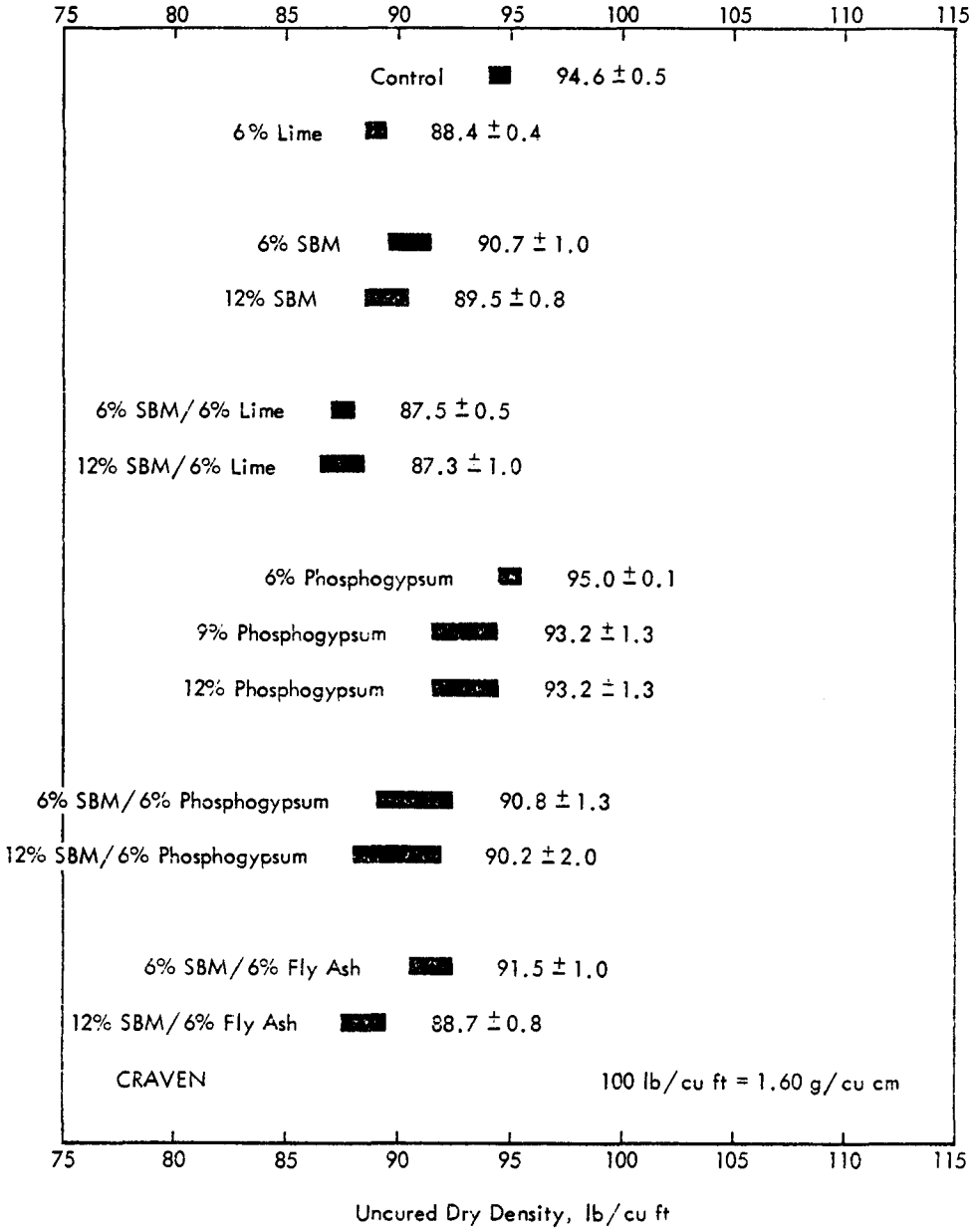

FIGURE 19. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: CRAVEN SERIES

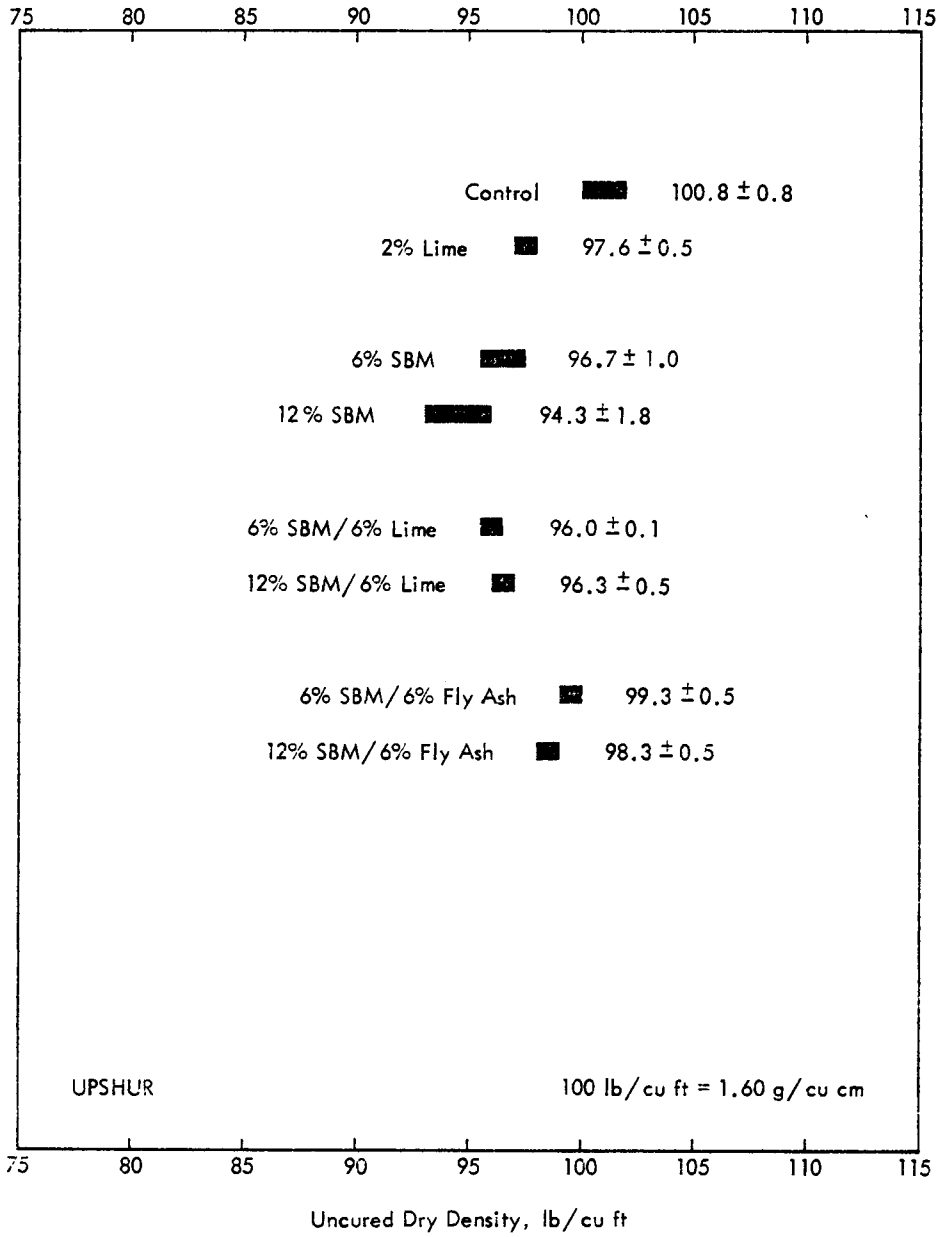

FIGURE 20. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: UPSHUR SERIES

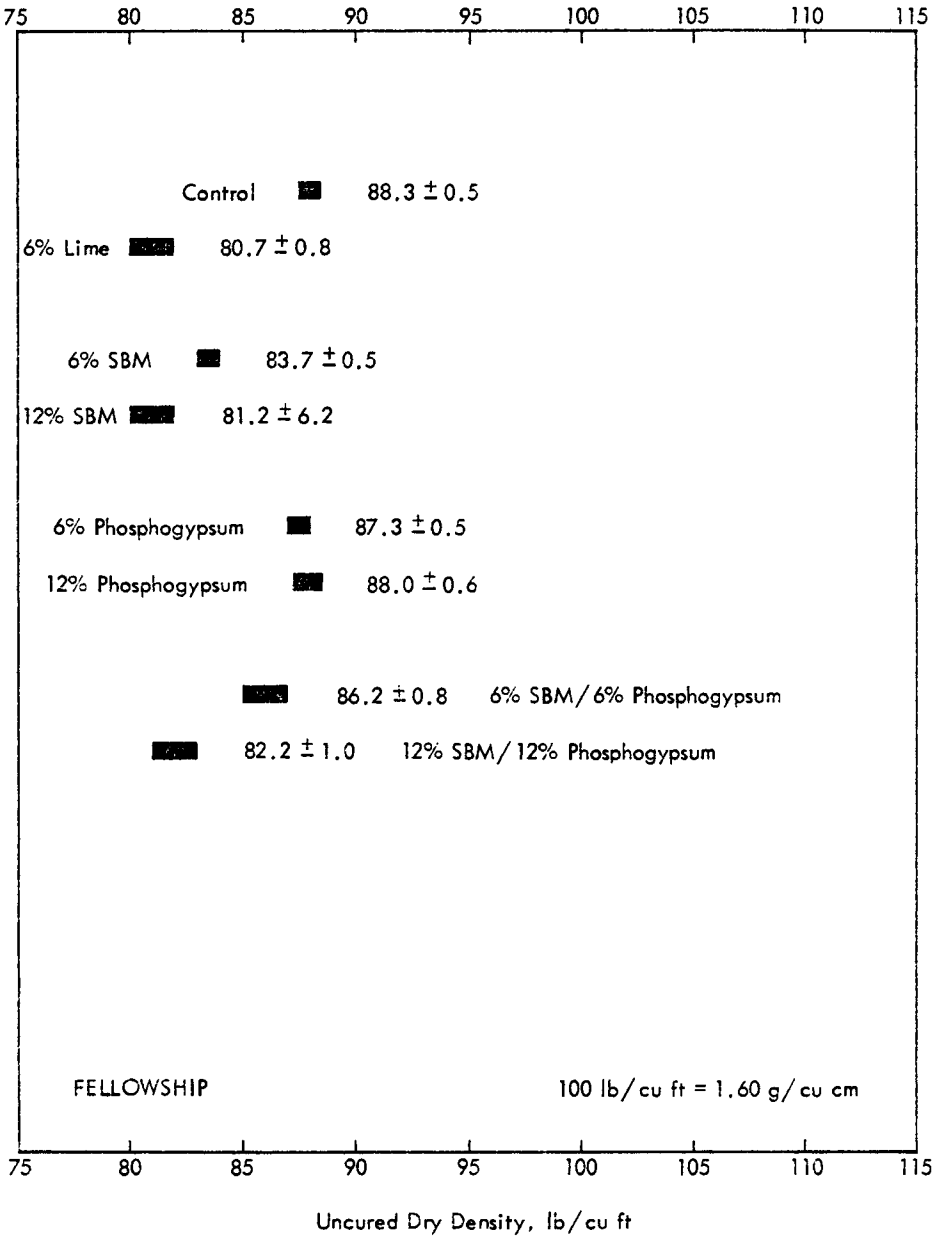

FIGURE 21. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: FELLOWSHIP SERIES

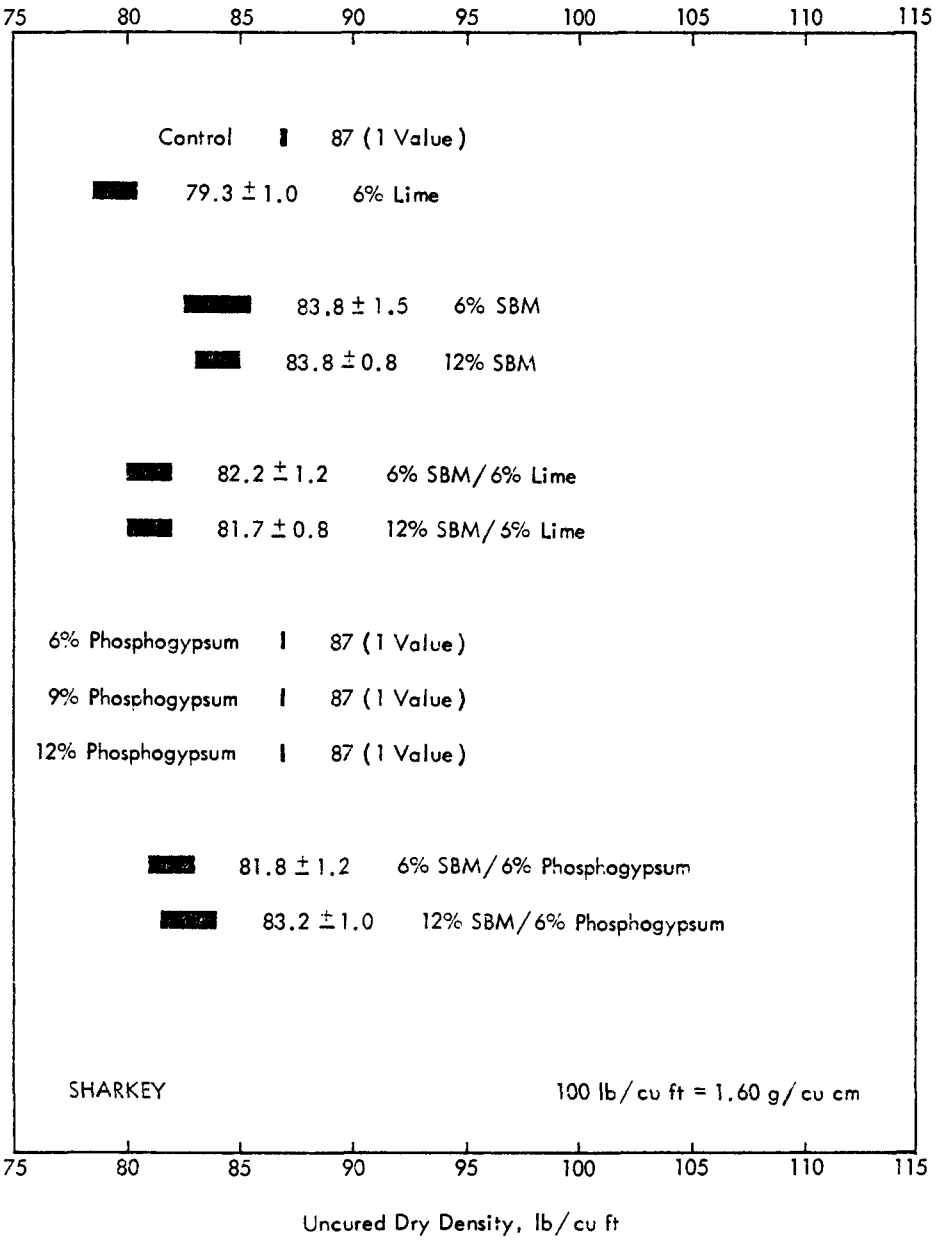

FIGURE 22. UNCURED DRY DENSITY OF SOILS TREATED WITH SPENT BED MATERIAL AND OTHER ADDITIVES: SHARKEY SERIES

Class I soil: Manor (Figure 16)
Class II soils: Exum (Figure 17)
Tama (Figure 18)
Class III soils: Craven (Figure 19)
Upshur (Figure 20)
Class IV soils: Fellowship (Figure 21)
Sharkey (Figure 22)

Also plotted in the figures are results obtained for untreated soil (control), for soil/lime and soil/phosphogypsum specimens, and for soil/SBM/additive specimens. The vertical axis in the figures has no significance.

In almost every case, the uncured dry densities of lime and SBM treated soils are less than the uncured dry density of the untreated soil. The effect is particularly pronounced in the Manor (Figure 16), Exum (Figure 17), Fellowship (Figure 21), and Sharkey (Figure 22) systems. The latter two soils are Class IV montmorillonites, and the uncured dry densities (in the 80 to 85 lb/cu ft range for lime and SBM treated soils) are quite low. It is believed that poor results obtained in the unconfined compressive strength testing is associated with the low densities.

When soils are treated with phosphogypsum alone (Figures 17, 19, 21, and 22), the dry density of soils does not change much from those of the untreated soils. However, when SBM is added to the soil/phosphogypsum mixtures, dry densities fall markedly. When fly ash is added to SBM (Figures 16, 18, 19, and 20), the densities tend to be a little greater than those of the soils treated with SBM alone. Thus, fly ash tends to add density to most of the SBM treated soils.

The decrease in density when soils are treated with alkaline SBM or lime is indicative of reaction between alkali values and soils. It would appear that soil particles swell when treated to occupy more volume. Hence, when soil/SBM or soil/lime systems are compacted, less material can be forced into a given volume. The converse of this concept suggests that lime or SBM treated soils require a greater compactive effort to achieve a given density than do the untreated soils.

Thus, SBM behaves in a manner identical with lime regarding density. This observation, coupled with observations made earlier in Section III, suggests that SBM can be considered as a lime substitute for stabilization purpose.

FREEZE-THAW STABILITY OF SBM TREATED SOILS

Freeze-thaw durability measurements have been made on selected soil/SBM systems using the vacuum saturation technique described by Dempsey and Thompson.[2/] Experimental results are presented in Table 9. In general, SBM treatment increased resistance to freeze-thaw in the soils tested. The one exception is the Upshur system, where the SBM appeared to degrade freeze-thaw properties. It is believed that the Upshur samples may have been improperly compacted for these tests, since the freeze-thaw tests do not fall into line with other observations with SBM treatment described in Section III. Thus, we view the Upshur results as an anomaly rather than representative of Class III soils as a generality.

The Class I, II, and IV soils all show greater durabilities in freeze-thaw when treated with SBM. The amount of strength loss in the SBM treated soils tends to be smaller than that of the untreated soils. This observation, coupled with the fact that SBM treatment markedly increases unconfined compressive strength in the absence of freeze-thaw, that there should be significant benefit to freez-thaw resistance when soils are treated with SBM.

The freeze-thaw results obtained for SBM treated soils are similar to the comparable results obtained with the lime/sulfate waste treated soils evaluated in the initial study.[1/] Thus, the combination of calcium sulfate and free lime in SBM yields a material which exhibits the characteristics of lime/phosphogypsum or lime/flue gas desulfurization solids.

When one examines the moisture contents of SBM specimens having undergone the vacuum saturation test, there may be a slight trend towards greater moistures in SBM treated systems. A similar observation has been made for the lime/phosphogypsum specimens evaluated during Phase I. The tendency towards greater moistures in the SBM and lime/phosphogypsum system is probably associated with the lower dry densities of the systems. The lower densities may permit more available volume in the treated soils for water ingress. If this hypothesis is correct, then it is a negative factor with respect to long-term freeze-thaw resistance. However, the 28-day unconfined compressive strength data suggest that treatment with SBM or lime/sulfate waste yield structurally stable soils which may not be significantly affected by moisture ingress.

2/ Dempsey, B. J., and M. R. Thompson, "A Vacuum Saturation Method for Predicting the Freeze-Thaw Durability of Stabilized Materials," Highway Research Record No. 442, pp. 44-57 (1973).

TABLE 9

FREEZE-THAW DURABILITY AS MEASURED BY VACUUM SATURATION FOR SELECTED SYSTEMS

Soil Series	Treatment Level	7-Day Unconfined Compressive Strength, psi (Moisture, %)	28-Day Unconfined Compressive Strength, psi (Moisture, %)	Freeze-Thaw Unconfined Compressive Strength at 7 Days, psi (Moisture, %)	Percent of Original 7-Day Strength (Percent of Original 7-Day Moisture)	Freeze-Thaw Unconfined Compressive Strength at 28 Days, psi (Moisture, %)	Percent of Original 28-Day Strength (Percent of Original 28-Day Moisture)
Class I Soils: Plasticity Index NP-10							
Manor	None	23 (15)	22,20 (16,15)	3,4,3 (26,25,26)	14 (171)	2,1,1 (26,24,25)	6 (161)
	6% SBM	60,49,52 (15,15,15)	75,43,65 (14,15,14)	39,40,39 (21,21,21)	73 (140)	29,41,41 (22,24,22)	61 (158)
Class II Soils: Plasticity Index 10-25							
Mahoning	None	47,50 (19,19)	37,45,36 (19,19,20)	N.C.	N.C.	2,2,1 (26,26,27)	4 (136)
	6% SBM	59,54,56 (16,16,16)	50,53,69 (16,16,16)	N.C.	N.C.	10,4,10 (25,24,26)	14 (156)
Sassafras	None	26,34 (13,12)	28,15,22 (12,14,14)	N.C.	N.C.	10,20,20 (13,13,13)	77 (98)
	6% SBM	72,68,69 (11,11,11)	117,108,123 (11,11,11)	N.C.	N.C.	75,105,82 (17,16,17)	75 (152)
Wharton	None	34 (23)	20 (24)	7,3,3 (26,26,27)	13 (114)	9,3,2 (25,30,27)	16 (114)
	6% SBM	56,53,60 (20,19,19)	63,59 (19,19)	20,15,16 (29,29,30)	30 (152)	24,16,21 (28,29,28)	33 (147)
Class III Soils: Plasticity Index ≥ 25, Nonmontmorillonitic							
Upshur	None	39 (23)	30,33 (23,23)	17,14,28 (28,27,27)	86 (119)	7,7 (27,28)	22 (120)
	6% SBM	49,51,44 (21,20,22)	57,59,50 (21,21,22)	9,9,8 (25,27,27)	18 (125)	5,5 (27,25)	9 (122)
Class IV Soils: Plasticity Index ≥ 20, Montmorillonitic							
Summit	None	47 (25)	51,43,46 (26,28,26)	8,15,18 (33,30,31)	28 (125)	14,8,14 (30,32,29)	26 (114)
	6% SBM	62,60,59 (25,25,24)	81,85,67 (24,25,25)	31,35,41 (28,27,27)	59 (111)	44,43,28 (28,27,27)	49 (111)

N.C. Experiment not conducted.

CONCLUSION

The principal conclusion drawn from this study is that SBM from the fluidized bed combustion of coal is an excellent material for soil stabilization. It can be considered as a lime substitute, since its behavior in the soils is identical to lime on a pound for pound basis in practically all cases, despite the fact that SBM contains only about 30% free lime.

RECOMMENDATIONS

It is recommended that SBM be field tested as a soil stabilizer. The timing of this field test will depend upon the supply and availability of SBM which, at the present time, is quite limited.

APPENDIX

UNCONFINED COMPRESSIVE STRENGTH DATA

A. Class I Soils: Plasticity Index Nonplastic to 10

B. Class II Soils: Plasticity Index 10 to 24

C. Class III Soils: Plasticity Index > 25, Nonmontmorillonitic

D. Class IV Soils: Plasticity Index > 20, Montmorillonitic

A. Class I Soils: Plasticity Index Nonplastic to 10

ATKINS SERIES
FINE-LOAMY, MIXED, ACID MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	28, 32 (14, 14)	23, 33 (14, 14)	34, 32 (14, 14)	31, 37, 18, 23 (14, 14, 15, 14)
6% SBM	65, 56, 60 (13, 12, 13)	90, 69, 56 (13, 13, 15)	88, 97, 94 (13, 13, 13)	100, 93, 96 (14, 13, 13)
12% SBM	81, 76, 60 (12, 12, 12)	96,124,104 (12, 12, 12)	139,136,122 (12, 12, 13)	150,157,163 (12, 12, 15)
6% SBM - 6% FA	-	99,112,114 (12,12,12)	-	106,97,112 (12,12,12)
12% SBM - 6% FA	-	43, 106 (16,11)	-	98,79,62 (11,12,15)

COXVILLE
CLAYEY, KAOLINITIC, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	40 (13)	-	40 (12)	39, 44 (12, 12)
6% Lime	-	48, 44, 44 (14, 14, 14)	-	58, 51, 65 (14, 14, 13)
6% SBM	84, 72, 75 (11, 11, 11)	135,113, 91 (11, 11, 11)	108,131,131 (11, 11, 11)	156,147,151 (11, 11, 11)
12% SBM	83, 84, 86 (11, 10, 10)	146,122,138 (10, 10, 11)	175,179,162 (10, 10, 11)	196,199,226 (10, 10, 10)
6% SBM - 6% FA	-	188, 157, 207 (10, 10, 11)	-	193, 156, 209 (11, 11, 10)
12% SBM - 6% FA	-	254, 222, 220 (9, 9, 9)	-	266, 152, 314 (10, 12, 9)
6% SBM - 6% PG	-	110, 120, 126 (11, 11, 11)	-	81, 95, 70 (11, 11, 12)
12% SBM - 6% PG	-	153, 151, 171 (10, 10, 10)	-	204, 36, 216 (10, 16, 11)

MANOR
COARSE-LOAMY, MICACEOUS, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	23 (15)	20 (15)	22, 20 (16, 15)
2% Lime	23 (14)	30 (14)	24 (18)	26 (14)
6% Lime	-	25, 43, 43 (16, 14, 14)	-	54, 51, 38 (15, 14, 15
6% SBM	35, 37, 37 (15, 15, 15)	60, 49, 52 (15, 15, 15)	61, 65, 65 (14, 15, 15)	75, 43, 65 (15, 14, 15)
6% SBM + 2% H_2O	-	91, 102, 95 (14, 14, 14)	-	104, 88, 63 (14, 15, 17)
12% SBM	51, 55, 55 (14, 14, 14)	111, 102 (14, 13)	132, 113, 105 (13, 13, 14)	141, 144, 125 (13, 13, 13)
12% SBM + 2% H_2O	-	127, 106, 118 (13, 13, 13)	-	102, 86, 67 (15, 14, 18)
6% SBM - 6% FA	-	100, 93, 96 (14, 13, 14)	-	90, 111, 117 (14, 13, 13)
12% SBM - 6% FA	-	90, 112 (10, 10)	-	116, 48, 120 (11, 22, 10)
6% SBM - 6% PG	-	89, 88, 88 (14, 15, 14)	-	94, 104, 112 (15, 14, 15)
12% SBM - 6% PG	-	23, 94, 92 (18, 14, 13)	-	41, 101, 134 (20, 13, 14)

B. Class II Soils: Plasticity Index 10 to 25

EXUM SERIES
FINE-SILTY, SILICEOUS, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	33 (16)	34 (16)	30, 30 (17)	32, 33 (16, 16)
6% Lime	-	65, 70, 60 (18, 18, 18)	-	96,123,110 (18, 17, 17)
6% SBM	78, 66, 73 (13, 13, 13)	96, 92, 95 (13, 13, 13)	131, 68,131 (13, 14, 13)	116,133,114 (14, 14, 13)
6% SBM + 3% H_2O	-	109, 112, 111 (16, 16, 16)	-	45, 41, 45 (18, 20, 19)
12% SBM	65, 77, 77 (12, 12, 13)	113, 95, 117 (12, 12, 12)	114, 149, 146 (12, 12, 12)	155, 153, 144 (13, 12, 12)
12% SBM + 3% H_2O	-	234, 220, 200 (14, 15, 15)	-	244, 113, 101 (15, 17, 18)
6% SBM - 6% lime	-	101, 84, 105 (16, 16, 16)	-	266, 167, 185 (16, 18, 16)
12% SBM - 6% lime	-	109, 114, 115 (15, 15, 15)	-	206, 414, 347 (14, 15, 14)
6% SBM - 6% PG	-	101, 85, 87 (17, 17, 17)	-	155, 104, 109 (17, 17, 18)
12% SBM - 6% PG	-	115, 150, 162 (16, 16, 16)	-	206, 173, 154 (16, 16, 16)

MAHONING
FINE, ILLITIC, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	47, 33, 46 (20, 20, 20)	47, 50 (19, 19)	44, 44, 40 (21, 20, 20)	37, 45, 36 (19, 19, 20)
6% Lime	-	53, 43, 42 (19, 18, 18)	-	41, 56, 54 (19, 18, 18)
6% SBM	56, 48, 43 (16, 17, 16)	59, 54, 56 (16, 16, 16)	51, 54, 50 (17, 18, 17)	50, 53, 69 (16, 16, 16)
12% SBM	64, 61, 62 (16, 13, 20)	88, 78 (17, 16)	86, 70 (16, 16)	82, 73, 85 (16, 14, 16)
6% SBM - 6% lime	-	134, 81, 103 (16, 15, 16)	-	135,119,126 (16, 16, 18)
12% SBM- 6% lime	-	125, 98, 45 (15, 16, 20)	-	150,179,216 (15, 14, 14)
6% SBM - 6% FA	-	88, 93, 91 (16, 17, 18)	-	100, 72, 125 (16, 16, 16)
12% SBM - 6% FA	-	92, 85, 92 (14, 15, 14)	-	44, 83, 135 (20, 16, 14)

MIAMI
FINE-LOAMY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	50, 40 (17, 16)	51, 46 (16, 14)	40, 38 (16, 16)	41, 47, 46 (17, 17, 17)
2% Lime	34 (16)	35 (16)	-	32 (15)
6% Lime	-	68, 63, 49 (15, 14, 14)	-	69, 72, 73 (14, 14, 14)
6% SBM	54, 50, 50 (15, 15, 15)	61, 58, 74 (15, 15, 15)	63, 67, 59 (16, 14, 15)	71, 57, 65 (15, 15, 15)
12% SBM	70, 68, 62 (14, 13, 13)	93, 105, 99 (13, 14, 14)	89, 92 (14, 14)	114, 105, 134 (12, 14, 13)
6% SBM - 6% lime	-	131, 142, 146 (14, 15, 14)	-	205, 179, 176 (14, 14, 14)
12% SBM - 6% lime	-	201, 232, 214 (14, 14, 14)	-	268, 245, 264 (14, 14, 14)
6% SBM - 6% FA	-	106, 128, 98 (13, 13, 14)	-	173, 65, 171 (13, 16, 13)
12% SBM - 6% FA	-	180, 177, 199 (12, 12, 12)	-	250, 215, 268 (12, 13, 12)

SASSAFRAS SERIES
FINE-LOAMY, SILICEOUS, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	33, 33 (13, 12)	26, 34 (13, 12)	31, 14 (12, 14)	28, 15, 22 (12, 14, 14)
6% Lime	-	41, 59, 64 (23, 12, 11)	-	69, 62, 73 (11, 11, 11)
6% SBM	58, 67, 60 (11, 11, 11)	72, 68, 69 (11, 11, 11)	111,104,117 (11, 11, 12)	117,108,123 (11, 11, 11)
12% SBM	65, 61, 65 (17, 16, 17)	94, 91, 81 (16, 16, 16)	135,100,113 (17, 16, 16)	116, 135, 93 (16, 16, 16)
6% SBM - 6% PG	-	84, 129, 143 (12, 11, 11)	-	130, 105, 133 (11, 11, 11)
12% SBM - 6% PG	-	174, 161, 167 (12, 10, 10)	-	87, 83, 91 (12, 14, 13)
6% SBM - 6% FA	-	133, 142, 132 (10, 11, 11)	-	175, 159, 179 (10, 11, 10)
12% SBM - 6% FA	-	173, 190, 159 (11, 10, 10)	-	155, 305, 300 (12, 10, 10)

SHELBY SERIES
FINE-LOAMY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	36, 48 (21, 18)	34, 48 (21, 19)	28, 43, 43, 45 (21, 19, 19, 20)	43, 38, 51, 36, 28 (21, 20, 19, 19, 21)
6% Lime	-	37, 48, 49 (20, 19, 18)	-	41, 70, 53 (20, 18, 19)
6% SBM	56, 62, 42 (18, 18, 18)	56, 67, 47 (18, 18, 17)	81, 92, 66 (18, 18, 18)	81, 70, 65 (18, 17, 17)
12% SBM	65, 61, 65 (17, 16, 17)	94, 91, 81 (16, 16, 16)	135,100,113 (17, 16, 16)	116, 135, 93 (16, 16, 16)
6% SBM - 6% FA	-	87, 88, 83 (16, 16, 16)	-	98, 111, 116 (17, 17, 17)
12% SBM - 6% FA	-	154, 138, 163 (15, 15, 15)	-	177, 202, 200 (15, 15, 15)

TAMA SERIES
FINE-SILTY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compresive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	43, 46, 50, 46 (22, 22, 22, 20)	51, 51, 55, 47 (22, 22, 21, 20)	45, 49, 45, 49 (22, 22, 22, 20)	48, 46, 45, 44, 53 (22, 22, 22, 20, 20)
2% Lime	31 (21)	-	35 (21)	29 (23)
6% Lime	-	46, 57, 55 (20, 20, 20)	-	70, 69, 66 (20, 20, 19)
6% SBM	39, 47, 42 (20, 20, 20)	60, 60, 55 (20, 20, 20)	66, 64, 60 (20, 20, 20)	51, 73, 67 (20, 20, 20)
6% SBM + 2% H_2O	-	78, 76, 75 (20, 21, 20)	-	72, 85, 57 (21, 20, 22)
12% SBM	51, 56, 56 (18, 18, 18)	99, 82, 106 (18, 18, 18)	43, 125, 87 (24, 13, 18)	91, 68, 111 (18, 20, 18)
12% SBM + 2% H_2O	-	141, 134, 136 (19, 19, 20)	-	89, 76, 163 (21, 21, 18)
6% SBM - 6% FA	-	78, 79, 71 (20, 21, 20)	-	82, 90, 92 (21, 21, 20)
12% SBM - 6% FA	-	121, 119, 135 (19, 19, 19)	-	189, 174, 178 (19, 19, 19)

WHARTON SERIES
CLAYEY, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	21 (23)	34 (23)	36 (24)	29 (24)
2% Lime	54 (22)	42 (22)	36 (22)	47 (21)
6% Lime	-	39, 40, 41 (23, 22, 22)	-	44, 50, 46 (21, 19, 20)
6% SBM	54, 51, 56 (21, 21, 22)	56, 53, 60 (20, 19, 19)	59, 60, 69 (20, 19, 20)	63, 59, 15 (19, 19, 25)
12% SBM	57, 62 (19, 19)	83, 63, 79 (18, 19, 19)	75, 84 (18, 18)	55, 87, 95 (19, 19, 19)
6% SBM - 6% FA	-	61, 62, 68 (22, 21, 21)	-	81, 109, 106 (21, 21, 21)
12% SBM - 6% FA	-	91, 122, 144 (19, 19, 19)	-	150, 95, 144 (17, 19, 18)

C. Class III Soils: Plasticity Index > 25, Nonmontmorillonitic

CRAVEN SERIES
CLAYEY, MIXED, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	53 (24)	56 (24)	56 (25)	60, 51 (24, 24)
6% Lime	-	95, 96, 93 (24, 24, 24)	-	173,177,148 (23, 23, 24)
6% SBM	54, 37, 38 (23, 23, 23)	67, 60, 86 (24, 24, 22)	58, 56, 54 (23, 24, 23)	56, 62, 73 (24, 23, 23)
6% SBM + 2% H_2O	-	48, 52, 53 (25, 26, 24)	-	52, 60, 36 (27, 24, 23)
12% SBM	77, 93, 67 (22, 21, 21)	95, 91, 92 (22, 21, 21)	119,107,113 (21, 22, 21)	132,109,117 (21, 22, 21)
12% SBM + 2% H_2O	-	120, 122, 100 (23, 24, 23)	-	142, 140, 141 (25, 24, 23)
6% SBM - 6% PG	-	48, 62, 63 (24, 23, 24)	-	54, 48, 54 (24, 25, 25)
12% SBM - 6% PG	-	162, 102, 147 (22, 21, 21)	-	171, 49, 60 (23, 26, 24)
6% SBM - 6% FA	-	77, 90, 79 (22, 22, 22)	-	110, 97, 108 (23, 24, 24)
12% SBM - 6% FA	-	141, 126, 137 (21, 21, 20)	-	180, 176, 147 (21, 22, 21)
6% SBM - 6% lime	-	222, 210, 172 (23, 22, 23)	-	290, 308, 292 (23, 23, 23)
12% SBM - 6% lime	-	243, 244, 286 (22, 20, 20)	-	150, 366, 390 (27, 22, 22)

UPSHUR SERIES
FINE, MIXED, MESIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	40 (21)	39 (231)	38 (22)	30, 33 (23, 23)
2% Lime	38 (22)	36 (22)	37 (22)	34 (22)
6% SBM	47, 46, 47 (20, 21)	49, 51, 44 (21, 20, 22)	41, 49, 51 (20, 20, 21)	57, 59, 50 (21, 21, 22)
6% SBM + 2% H_2O	-	52, 66, 36 (18, 19, 20)	-	30, 18, 48 (21, 24, 20)
12% SBM	70, 60, 71 (19, 19, 19)	74, 75, 77 (20, 19, 19)	78, 92, 100 (19, 19, 20)	98, 96, 100 (19, 19, 20)
12% SBM + 2% H_2O	-	110, 105, 112 (18, 17, 17)	-	79, 52, 123 (18, 20, 19)
6% SBM - 6% FA	-	57, 54, 53 (21, 20, 20)	-	78, 79, 71 (21, 20, 20)
12% SBM - 6% FA	-	99, 98, 90 (17, 18, 17)	-	137, 121, 138 (19, 19, 19)
6% SBM - 6% lime	-	109, 120, 110 (20, 19, 20)	-	147, 156, 182 (20, 17, 21)
12% SBM - 6% lime	-	118, 90, 126 (21, 21, 20)	-	203, 216, 212 (20, 21, 21)

D. Class IV Soils: Plasticity Index > 20, Montmorillonitic

FELLOWSHIP SERIES
FINE, MONTMORILLONTIC, HYPERTHERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	-	41, 40, 42 (29, 29, 29)	-	46, 38, 43 (29, 28, 29)
6% Lime	-	28, 35 (28, 28)	-	29, 35, 33 (29, 28, 28)
6% SBM	30, 35, 32 (27, 29, 28)	28, 30 (28, 29)	25, 19 (30, 28)	28, 21, 16 (28, 28, 28)
6% SBM + 3% H_2O	-	34, 38, 29 (29, 29, 30)	-	29, 45, 42 (31, 30, 28)
12% SBM	31, 33, 35 (27, 26, 26)	22, 29, 29 (27, 27, 27)	18, 19 (26, 27)	23, 17, 28 (26, 26, 26)
12% SBM + 3% H_2O	-	48, 40, 41 (25, 25, 25)	-	39, 50, 43 (26, 26, 26)
6% SBM - 6% PG	-	39, 39, 51 (29, 28, 27)	-	44, 38, 38 (29, 28, 29)
12% SBM - 6% PG	-	33, 30, 33 (25, 27, 28)	-	26, 18, 18 (26, 28, 29)

SHARKEY SERIES
VERY FINE, MONTMORILLONITIC, NONACID, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	48 (25)	50 (26)	58, 58 (28)	51, 59 (27, 28)
6% Lime	-	21, 27 (24, 25)	-	36, 33, 31 (23, 23, 24)
6% SBM	52, 51, 55 (24, 24, 24)	41, 37, 43 (24, 24, 24)	48, 48, 52 (24, 24, 24)	48, 48, 49 (23, 23, 23)
6% SBM + 2% H_2O	-	58, 43, 11 (25, 24, 31)	-	25, 40, 45 (26, 25, 24)
12% SBM	35, 36, 37 (22, 23, 23)	36, 34, 36 (23, 23, 23)	48, 38, 43 (22, 22, 23)	41, 29, 39 (21, 24, 22)
12% SBM + 2% H_2O	-	72, 95, 52 (22, 23, 23)	-	16, 39, 57 (24, 22, 22)
6% SBM - 6% PG	-	25, 24, 30 (21, 22, 21)	-	35, 30, 28 (23, 22, 23)
12% SBM - 6% PG	-	30, 29, 27 (20, 21, 21)	-	31 (21)
6% SBM - 6% lime	-	11, 30, 20 (20, 21, 20)	-	24, 33, 42 (25, 21, 22)
12% SBM - 6 % lime	-	22, 25 (20, 19)	-	35, 54, 42 (19, 19, 19)

SUMMIT SERIES
FINE, MONTMORILLONITIC, THERMIC

Treatment	1 Day Unconfined Compressive Strength, psi (Moisture, %)	7 Day Unconfined Compressive Strength, psi (Moisture, %)	14 Day Unconfined Compressive Strength, psi (Moisture, %)	28 Day Unconfined Compressive Strength, psi (Moisture, %)
None	39, 51, 51 (25, 26, 26)	47 (25)	50, 50, 49 (26, 26, 27)	51, 43, 46 (26, 28, 26)
6% Lime	-	45, 41, 41 (22, 22, 22)	-	59, 45, 47 (22, 22, 22)
6% SBM	46, 50, 47 (25, 24, 25)	62, 60, 59 (25, 25, 24)	67, 62, 65 (24, 25, 24)	81, 85, 67 (24, 25, 25)
12% SBM	44, 49, 48 (24, 24, 23)	96, 96, 63 (23, 23, 22)	78, 57, 83 (22, 23, 22)	126, 62, 79 (23, 23, 22)
6% SBM - 6% lime	-	98, 96, 90 (21, 21, 21)	-	96, 118, 111 (21, 21, 21)
12% SBM - 6% lime	-	77, 65, 86 (20, 20, 20)	-	99, 88, 129 (20, 22, 19)
6% SBM - 6% FA	-	67, 49, 72 (22, 21, 20)	-	93, 74, 56 (21, 22, 22)
12% SBM 6% FA	-	100, 65, 72 (17, 23, 20)	-	72, 155, 126 (20, 20, 20)

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