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16. Abstract Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used in lime-fly ash soil mixtures for highway construction. Unconfined, compressive strength, and freeze-thaw and wet-dry durability are included in the development of a mix design procedure aimed at optimizing the proportions of fly ash and lime.					
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FINAL REPORT
UTILIZATION OF WASTE BOILER ASH
IN HIGHWAY CONSTRUCTION IN ARIZONA

PART II - SOIL STABILIZATION

by
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Highways Division

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of data presented herein. The contents do not necessarily reflect the official views or policies of the State of Arizona or the Federal Highway Administration. This report does not constitute a standard specification or regulation.

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ABSTRACT

Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used in lime-fly ash soil mixtures for highway construction. Unconfined compressive strength, and freeze-thaw and wet-dry durability are included in the laboratory test series. Test data are utilized in the development of a mix design procedure aimed at optimizing the proportions of fly ash and lime.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHO	American Association of State Highway Officials*
ADOT	Arizona Department of Transportation
ASTM	American Society for Testing and Materials
A, B	Constants
Btu	British thermal unit
°C	Degrees Celsius
cc	Cubic centimeters
CD	Coefficient of determination
CLC	Coefficient of linear correlation
cm	Centimeters
cy	Cubic yard
e	Natural logarithm base (2.718---
ETL	Engineers Testing Laboratories, Inc.
°F	Degrees Farenheit
FA	Fly ash
ft, ft ³	Feet, cubic feet
gal.	Gallons U.S.
G _s	Specific Gravity of Solids
gm	Grams
in.	Inch
Kg	Kilogram
KW	Kilowatt
KWH	Kilowatt-hour
lb.	Pound
LL	Liquid Limit
MW	Megawatt
m, m ³	Meter, cubic meter
n	Number of samples
NP	Non-Plastic
psi	Pounds per square inch gauge
pcf	Pounds per Cubic Foot

*Since changed to AASHTO, American Association of State Highway and Transportation Officials.

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

PI	Plasticity Index
PL	Plastic Limit
s	Standard deviation
σ	Unconfined Compressive strength
V_1	Within-test coefficient of variation
Vol.	Volume
W	Water (usually weight)
X	Independent variable
Y	Dependent variable

CONVERSION FACTORS

To convert from	To	Multiply by
Cubic foot	Cubic meter	2.832×10^{-2}
Cubic inches	Cubic meter	1.639×10^{-5}
Cubic yard	Cubic meter	7.646×10^{-1}
Foot	Meter	3.048×10^{-1}
Gallon (U.S. Liquid)	Cubic Meter	3.785×10^{-3}
Inch	Centimeter	2.540
Pound-force	Kilogram-force	4.536×10^{-1}
Pounds per square inch	Kilograms per square centimeter	7.031×10^{-2}
Sack (U.S. cement)	Kilograms	4.264×10
Tons	Kilograms	9.072×10^2
Degrees Farenheit	Degrees Celsius	*

$$*^{\circ}\text{C} = (5/9) \times (^{\circ}\text{F} - 32)$$

PROJECT SUMMARY

Coal-fired steam generating stations in and around Arizona produce millions of tons of waste boiler ash (fly ash) per year, most of which is not utilized in any way. Research has shown fly ash to possess pozzolanic properties thereby making it potentially useful, as a cementitious material, in a variety of construction applications.

The Arizona Department of Transportation, in October, 1974, commissioned Engineers Testing Laboratories, Inc., to undertake a study for the purpose of evaluating potential uses of fly ash in Arizona highway construction. The program was to serve the multiple objectives of developing a low cost construction material, utilizing a previously wasted by-product, and aiding in the conservation of the non-renewable resources, lime and portland cement.

The study was divided into two parts. Part I concerned the utilization of fly ash in portland cement concrete for Arizona highway construction. Included were a literature review, laboratory test program, engineering analysis of data, and the development of a mix design method. The laboratory procedures were directed toward evaluation of compressive strength, flexural strength, freeze-thaw durability and resistance to sulfate attack. Forty-eight mix designs were tested in the strength test series. A number of the mixes were then subjected to the durability and soundness test series. Strengths were determined to be predictable utilizing the proposed mix design method. Fly ashes from the four available sources were found to be beneficial admixtures for portland cement concrete.

An interim report was submitted to the Arizona Department of Transportation in January, 1976. The purpose of the interim

report was to present the preliminary fly ash concrete mix design procedure for review prior to the completion of the study.

Part II concerned the utilization of fly ash in soil stabilization for Arizona highway construction. The study program included a literature review, laboratory test series, engineering analysis of data and the development of a mix design procedure for lime-fly ash stabilized soil. Four typical Arizona soils were utilized in the test series, with fly ash from the four principal sources available in Arizona. Laboratory evaluations included combinations of zero to eight percent lime and zero to thirty percent fly ash for each soil type and fly ash source. Unconfined compressive strength, wet-dry durability and freeze-thaw durability were evaluated in the test series. The fly ashes were found beneficial in varying degrees, depending primarily on soil characteristics.

The two year project was completed with the general conclusion that available fly ash could be efficiently utilized in highway construction in Arizona.

CHAPTER 1. INTRODUCTION

The search for more efficient construction materials, and the problem of industrial waste disposal have been combined in the development of uses for waste boiler ash (fly ash) produced by coal-fired power generating stations. Fly ash is a pozzolan, a material with cementitious properties which can be utilized in many construction materials applications. The purpose of this report is to technically evaluate the use of fly ash from local sources, in combination with a particular lime, as a stabilization method with selected Arizona soils.

The study has been conducted through literature search, laboratory testing and engineering analysis of the data developed. In carrying out the literature search, an effort was made to review all English language literature pertinent to the subject, with no regard for geographic origin. The laboratory studies utilized fly ash from the four principal sources which were found to be available to the Arizona construction market. Lime was obtained from a single source, thereby making fly ash source and soil type the principal variables in the test program. Test series were designed to evaluate unconfined compressive strength, resistance to wetting and drying and resistance to deterioration from freezing and thawing.

Review of the literature and engineering analysis of the test data culminated in the development of a mix design procedure for lime-fly ash soil mixtures, based on unconfined compressive strength and economic optimization of lime and fly ash proportions.

The results of the literature survey are presented in the chapter entitled Literature Review. Comment on the literature has been categorized by subject, for convenience (i.e., compressive strength, field performance, mix design). References have also been organized by subject in the Subject Index to References immediately following the References near the end of the report.

Laboratory test procedures and results are presented in the middle chapters of the report along with analyses of the data. The principal topics, strength and durability, are the subjects of separate chapters.

The mix design chapter includes an introductory evaluation of methods presently in use and a final section on evaluation of the proposed mix design method. The middle sections of the chapter can be independently used as a working outline for the proposed mix design method.

Information relative to the production and quality of fly ash sources used in the study has been placed in an appendix, since the evaluation of time variation in fly ash quality was not a principal objective of the program.

CHAPTER 2. LITERATURE REVIEW

2.1 Historical Development

2.1.1. Ancient Applications

In the third century B.C., the Roman builders made a significant discovery. At the port of Pozzvoli, near Vesuvius, were deposits of sandy volcanic ash which, when added to lime and water, made a cement which dried to rocklike hardness and even hardened under water. They called this material "pulvis puteolanus". By mixing this cement with sand and gravel they made concrete. First use of this material was as a filler between veneer finishes since durability to exposure was questioned. Nonetheless, some of the more daring builders of that time began using the material in exposed construction and surprisingly found the durability satisfactory. Thus, the material use spread widely. Structures, the Colosseum and the Basilica of Constantine, and distribution systems, the Cloaca Maxima and the Aqueducts, were just a few of the facilities built utilizing this new material. Many of these structures still exist today and attest to the durability of the new found material.

The Roman method of making cement, combining lime and pulverized volcanic ash, was essentially the only method employed until 1824, although numerous processes had been attempted. At that time, the first successful process of artificially combining and calcifying clay and limestone to form a hydraulic cement was realized. With the development of a manufacturing process to produce high quality hydraulic cement, known today as portland cement, the use of natural cementing agents declined rapidly.

The natural material employed by the Romans is classified today as a pozzolan. A pozzolan is defined as a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans may be either natural materials or synthetics which consist of glassy materials produced by rapid cooling of molten silicate mixtures. Fly ash, the finely divided residue that results from the combustion of ground or powdered coal that is subsequently collected from the flue gases, is an example of a synthetic pozzolan. Fossil fuel power plants are the major producers of the material.

- 2.1.2. Fly Ash in Soil Stabilization and Highway Construction
Following World War II, the enormous expansion in the construction of the inter-state highway system revealed a critical shortage of satisfactory road-making aggregate within economic haul distances of the construction sites. This shortage and the early post-war success of the Texas Highway Department in the widespread use of lime to stabilize roads prompted an intensive program of laboratory and field testing by a number of state and federal government institutions (35).*

Lime-fly ash soil stabilization was developed partially as a result of the poor pozzolanic quality of natural soils in many regions and the relative ineffectiveness of lime stabilization. Probably the most significant early post-war research relating

*Numbers in parenthesis in this section and throughout the report correspond to source title listed in the Reference section.

specifically to lime-fly ash soil stabilization was performed by Minnick and Miller around 1950. These researchers concluded that the addition of lime and fly ash to a soil generally increased the strength and durability of that soil appreciably (35, 82).

Since that time extensive research has been undertaken regarding the use of fly ash and lime in soil stabilization. Most researchers have concluded that lime-fly ash addition to soils in the correct proportions can greatly increase the strength and durability of a soil while at the same time providing an ecologically and economically preferable mix.

One of the best testimonials to the performance of lime-fly ash materials is the growth in their use. The first lime-fly ash pavements were placed in the Philadelphia area in the late 1940's. Growth in the use of this type of material was slow for the first several years until the profession developed a backlog of engineering data and confidence in the material. Since the mid to late 1950's, growth in the use of lime-fly ash pavement materials has been increasing at an increasing rate (10).

2.1.3. Specifications for Fly Ash

As will be discussed later, fly ash varies from one power plant to another and from time to time in a given plant. Due to this variability, specifications have been established to use as a guide for assessing the general characteristics of the fly ash. The first specifications issued in 1954 by the American Society for Testing and Materials applied only to the use of fly ash as an admixture to concrete. Numerous modifications were later adopted and in 1960 specifications

were issued relative to the acceptance of fly ash as a pozzolan. The current ASTM specification, Designation: C618-73, segregated all pozzolans into three classes; raw or calcined natural pozzolans, Class N; fly ash, Class F; and others, Class S. This specification is applicable for both the chemical and physical requirements of the pozzolanic material. The current ASTM specification forms the basis for all standard and/or special provision specifications issued by the state highway agencies. Table 2-1 contains the current ASTM specification for fly ash and the specifications issued by some of the state highway agencies and other public agencies. For the state specifications, entries have been designated only for those requirements which are in variance with the ASTM specification. In general, the state's specifications are more restrictive than the ASTM, particularly in regard to the loss on ignition requirements.

It is noted that a modification of ASTM Designation: C618-73 is presently under review by ASTM Committee C-9 and is to be voted upon for possible adoption. The review specification contains two classes for fly ash as a pozzolanic material: Class F, fly ash derived from anthracite or bituminous coal; and Class C, fly ash derived from lignite or subbituminous coal. The review specification for Class F fly ash is the same as the current specification given in Table 2-1 with the following exceptions:

- a) Blaine fineness requirement has been eliminated;
- b) Pozzolanic Activity Index with portland cement has been lowered to 75% minimum;
- c) Autoclave soundness has been increased to 0.8%

TABLE 2.1 Specifications for Fly Ash

Property	ASTM C-618 Class F (6)	Std. Ala.	(1) S.P. Fla.	S.P. Ga.	S.P. Ind.	S.P. Ky.	S.P. Neb.	S.P. W.Va.	S.P. Mich.	S.P. Wisc.	Std. Minn.	(3) N. Dak.		Corps of Engrs.	Federal	
												F1	F2			
pH min.		7.0		7.0												
SiO ₂ %				40.0												
Al ₂ O ₃ %		15.0		15.0												
Fe ₂ O ₃ %																
Sum of Oxides % min.	70.0										45.0	70.0	5.0	70.0	75.0	
MgO % max.		5.0		3.0								5.0		5.0	5.0	
SO ₃ % max.	5.0	3.0		3.0							12.0		7.0	4.0	4.0	
Moisture % max.	3.0	1.0												3.0	3.0	
LOI % max.	12.0	6.0	6.0	6.0	8.0	6.0	6.0	6.0	4.0	5.0	5.0		6.0	6.0	6.0	
Available Alk. as Na ₂ O % max.	1.5 ⁽²⁾	1.5									3.0		2.5	1.5	2.0	
CaO % max.											35.0		35.0			
Free Carbon % max.							3.0									
Fineness cm ² /cm ³ min.	6500			3000 ⁽⁴⁾										6500	6500	
Retained #325 % max.	34	25		20.0					10.0		30.0	20.0	30.0	(7) N.S.	N.S.	
Multiple Factor	255.0											150	150	N.S.	N.S.	
Pozz. Act. Index - 28 Days % min.	85										75		75	75	75	
w/lime psi min.	800		NOTES:											900	900	
Water Requirement % max.	105		(1) Special Provision (2) Optional test (3) Sub-bituminous and lignite coal sources (4) cm ² /gm											(5)	(5)	
Shrinkage % max.	0.03	0.09	(5) This specification requires that a mortar of fly ash pozzolan and 103 percent of the water content of the control shall have a flow equal to or greater than that of the reference mortar.											N.S.	N.S.	
Soundness % max.	0.50		(6) Uniformity requirements not presented (7) Not specified											.50	.50	
Expansion 14 day % max.	0.02		(8) Weight or volume replacement not specified											N.S.	N.S.	
FA Proportion Specified			20% by wt.	25% by wt.	100 lb. per cy no red. in PC	94 lb. per cy		equal vol. to 1 bag	used 72 lb. FA to repl. 47 lb. PC	used 75 lb. FA per cy	10% by wt.	(8) 15%	(8) 15%			

- maximum; and
- d) A uniformity requirement on the fineness, as measured by the percent retained on the #325 sieve, has been added.

As this review specification has not been approved, the above are presented only for informational purposes and distribution of the Class C requirements is considered inappropriate at this time.

Other federal agencies, Federal Housing Administration, Federal Aviation Administration and U. S. Department of the Navy, have issued their own specifications, but all cite the ASTM specification as a guide.

The highway departments of most states which have significant fly ash production also have specifications for inclusion of fly ash in subgrade, subbase and base courses. Acceptance of these specifications is usually based on the performance records of the materials in those states (10).

2.2 Fly Ash-Lime Stabilization

2.2.1. General

Available references relative to the use of lime-fly ash in soil stabilization are listed in the reference section of this report. The literature has been reviewed and summarized in logical categories which are then presented in the section entitled Subject Index to References, immediately following the references. In addition, outstanding or particularly relevant comment from the literature has been summarized in this section.

The literature available on the use of fly ash is voluminous. The scope of the presentation here is necessarily limited to highly selective comment on each topic. As in the Subject Index to References, topics in this section are organized in alphabetical order for easy reference.

2.2.2. Chemical Additives and Accelerators

A number of chemicals used in trace amounts have proven effective in the laboratory by both accelerating strength gain and possibly increasing the ultimate strength of the material. Agents such as calcium chloride and sodium carbonate have increased 7-day strength as much as 60 times and 120-day strengths 2 times (23). Cement added in amounts of 1% + can also accelerate curing by as much as three weeks (65). In field trials, sodium silicate solutions increased bearing strength, determined from plate loading tests, by as much as four times over that of the untreated lime-fly ash-soil mixes. The silicate crust formed by the addition of sodium silicates also acted as a moisture shield, keeping out excess water (45).

2.2.3. Curing Conditions

Curing conditions have a tremendous effect on the strength and durability characteristics of a lime-fly ash-soil mixture. The pozzolanic reaction between lime and fly ash is most sensitive to temperature (67). High temperature cures (120°F, 49°C) have greatly accelerated early strength development. The rate of gain in tensile strength is primarily a function of temperature (42, 50, 67). Temperatures below 50°F (10°C) have produced no appreciable strength

gain in lime-fly ash-soil mixes (50). For this reason cut off dates for the construction of fly ash pavements in cold-weather states have been established to insure that sufficient strength gain is achieved before the pavement is put into service (51). Increased long term strengths have been achieved in the laboratory when samples were completely sealed to prevent any moisture loss during curing (25, 42). Other factors aiding in the increased strength of fly ash mixes are longer curing times and a combination of moist and immersed curing (42).

2.2.4. Fatigue Due to Repeated Loading

Repeated flexural loads applied to lime-fly ash-aggregate mixtures caused the material to fracture at stresses considerably below the static strength. The stress level and number of cycles to produce failure were related; a small reduction in applied stress greatly increased the number of cycles required to cause failure (3). Increased curing prior to loading also increased the number of cycles required to cause failure (7). Because of the slow but constant strength gain of pozzolanic materials, pavements made of these materials that do not fail during the first several days of loading will probably not fail due to repeated load applications only (7).

2.2.5. Field Performance

Lime-fly ash stabilized soils have found widespread use throughout the country. Applications include highways, airfields, agricultural uses, heavy structural fills, and numerous others, (18, 32, 38, 54, 57, 72, 77, 78, 82, 128). Freeze-thaw durability and resistance to frost damage have been good in

cold-weather applications (56, 72). Lime-fly ash mixes have been called the strongest subbase and base materials per dollar in the country today (128).

2.2.6. Fly Ash Quality and Characteristics

Desireable fly ash properties, in relation to soil stabilization with lime, include a low loss on ignition (LOI), high surface area (Blaine fineness), high proportion of specific gravities in the range of 2.1 to 2.7, and a high SiO_2 plus Al_2O_3 content (105). Of these properties, LOI, which is a direct measure of carbon content, is probably the most important and seems to be a reliable indicator of pozzolanic reactivity of fly ashes with lime (24). The amount retained on the number 325 sieve is a less direct measure of carbon content in fly ash, the carbon content having a high inverse correlation with strength (124). Some fly ashes exhibit cementitious properties in themselves without the addition of lime. In granular soils, these fly ashes, in the right combination, are sufficient to stabilize the soils without lime additions (68). Fly ashes of this type usually derive their cementitious properties from high CaO contents in the fly ashes themselves (105).

2.2.7. Freeze-thaw Durability

The freeze-thaw durability of a lime-fly ash-soil mixture was shown to be heavily dependent on the density of the mix as well as proportions of the constituents, gradation of the soil, and length of curing prior to the onset of testing (4, 8, 42, 55). Molding to modified rather than standard Proctor densities can greatly increase the freeze-thaw dur-

ability (55). The addition of portland cement can also be beneficial to freeze-thaw durability (25). Standard testing procedures seem to lead to conflicting and often erroneous data and do not take into account such important factors as cooling and warming rates, indicating a need for revised test procedures (29). High correlations between freeze-thaw durability and tensile strength have been established along with the following general guidelines: tensile strength less than 50 psi (3.5 Kg/cm²) means poor durability, 50 to 80 psi (3.5 to 5.6 Kg/cm²) means marginal durability and over 80 psi (5.6 Kg/cm²) indicates good freeze-thaw durability (50, 51, 82).

2.2.8. Molding Conditions and Compaction

An increase in the molded density of a lime-fly ash-soil mixture greatly increases strength (55, 69, 75, 121). A 10% increase in the density of some mixtures can result in a doubling of compressive strength (121). As previously mentioned, molding to modified rather than standard Proctor densities can also greatly increase the freeze-thaw durability (55). Maximum soaked unconfined compressive strength is not necessarily obtained at the optimum moisture content; sandy soils attain maximum strength when compacted below optimum moisture content whereas clayey soils reach their maximum strength when compacted above optimum. Increased curing periods required increased moisture contents for maximum strength, also. Clayey soils can lose ultimate strength if the mixing temperatures are too high, suggesting pre-compaction reactions; delays in compaction after mixing of some other soils also results in strength losses (69).

2.2.9. Special Test Methods

In order to properly assess the characteristics of lime-fly ash mixes, new test procedures and new applications of existing test procedures have been utilized by researchers. Triaxial and California Bearing Ratio tests have been performed on lime-fly ash mixes and the results discussed (77). An indirect measure of strength has been made by measuring the water absorption of a mix and utilizing the strong correlation between water absorption and strength (75). Autoclave curing of lime-fly ash mixes yields the pozzolanic activity, another measure of possible strength, but in much less time than the standard test due to a high-temperature cure (46). Another characteristic, fatigue under repeated loading, utilizes flexural beams to determine the load and number of cycles required to produce fatigue failure (3). Suggestions have been made to change the existing freeze-thaw test procedures for lime-fly ash mixes in order to obtain more consistent and reliable results (29). An indirect measure of freeze-thaw durability has been developed by first measuring the tensile strength and then utilizing an established correlation between tensile strength and durability by applying the guidelines mentioned in section 2.2.7. (50, 51).

2.2.10. Strength Recovery

Lime-fly-ash mixes possess the unique property of strength recovery after a limited amount of structural damage, i.e. autogenous healing. If damage is

done to the pavement in the early stages of curing, the lime-fly ash mix will continue its strength gain, often healing the old fractures, returning to normal strength (10).

2.2.11. Wet-Dry Durability

Wet-dry durability, much like freeze-thaw durability, is heavily dependent on the relative density of the lime-fly ash-soil mixture, the durability increasing with increasing density (4, 55). If the density of the specimen is high enough, wet-dry cycles actually improve strength and durability (55, 82). Gradation, i.e. sufficient fines to "float" the coarser aggregate, is important for good wet-dry durability. An excess of fines is preferable to a deficiency. Longer curing as well as increased fly ash contents also contribute to increased wet-dry durability (4).

2.3 Proportioning Techniques

Methods for proportioning of lime-fly ash-soil mixtures for highway construction are few in current literature. However, at least two methods are available at present. The first method utilizes predetermined lime and fly ash ratios which are dependent on the type of soil being stabilized. For example, by this method a granular soil would require 3 to 6% lime and 10 to 25% fly ash while a clayey soil would need 5 to 9% lime and 10 to 25% fly ash (71). A second method, used mainly for portland cement-fly ash stabilization for base courses, simply specifies that a mix must achieve a 7 day unconfined compressive strength of 400 to 450 psi (28 to 32 Kg/cm²) and then increase with continued curing (74). Both of these methods must employ high factors of safety.

2.4 Pavement Design

Two methods for pavement design were discussed in the literature. The first method involves a detailed analytical analysis of a lime-fly ash-aggregate mixture. A series of equations is used to relate pavement thickness to flexural strength, modulus of elasticity, subgrade support value, critical load, loaded area, type of loading and safety factor (2). The second method utilizes the AASHO design method and structural coefficients specially derived for fly ash mixes (118).

CHAPTER 3. SOILS AND MATERIALS

3.1 General

Materials utilized in the study were obtained in Arizona, or from producers immediately adjacent to Arizona, and were selected on the basis of potential use in Arizona highway construction. Lime and fly ash were obtained from commercial production runs and were not specially produced for use in the study. Four distinctly different soil types were selected, each of which has been encountered in street and highway construction at various locations throughout the state. Characteristics and performance of the soils have been established, relative to highway construction, through wide experience.

3.2 Soils

3.2.1 General Descriptions

Four soils were utilized in the program, each common to a different area of the state: clayey sand, poorly graded sand, highly plastic clay, and volcanic cinders. Throughout the remainder of the report the four soil types will be identified by the simplified terms clayey sand, sand, clay and cinders, respectively. The Arizona Department of Transportation (ADOT) supplied representative samples of the soils to Engineers Testing Laboratories (ETL), obtained from the locations noted on Figure 3-1.

The clayey sand was brown, medium to well graded, with low plasticity and dry strength. The sand was tan, medium to fine and poorly graded, with no plasticity or dry strength. The clay was brown to reddish brown, with high plasticity and dry strength. The cinders were of volcanic origin, grey, poorly graded with no plasticity or dry strength.

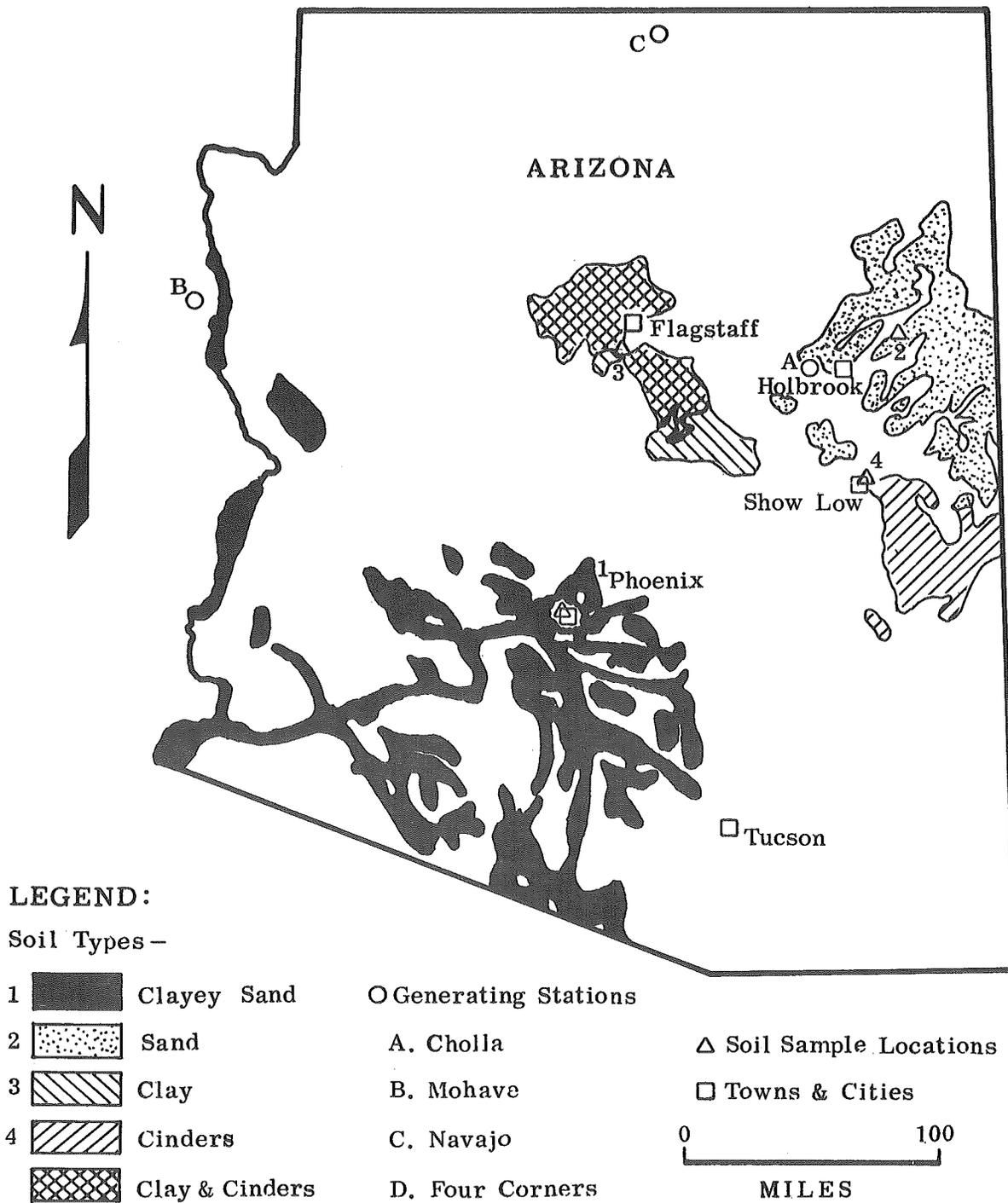


FIGURE 3-1. LOCATIONS OF FLY ASH SOURCES AND SOILS USED IN TESTING

The clayey sand was described as an hyperthermic arid soil, probably derived from erosion of surrounding mountains and weathered under climatic conditions of mean annual temperature greater than 72°F and less than 10 inches mean annual precipitation. Parent rock sources consisted of a diverse suite of igneous, sedimentary and metamorphic rocks typical of the ranges surrounding the Phoenix Basin.

The sand was described as mesic semiarid soil probably derived from erosion of numerous sandstone formations and intra formational sandstone strata typical of the Plateau Province in Navajo County. Disintegration of sandstone bedrock was accelerated by large diurnal changes in temperature, intermittent rainfall and wind, under climatic conditions of mean annual temperatures ranging between 47°F to 59°F and 10 to 16 inches of mean annual precipitation.

Clay was described as a frigid subhumid soil probably derived from chemical weathering of basic extrusive igneous rocks under climatic conditions with mean annual soil temperatures less than 47°F and more than 16 inches of mean annual precipitation.

Cinders were described as shallow talus, probably derived from mechanical disintegration of vesicular basic igneous rocks associated with volcanic vents and cinder cones.

3.2.2 Soil Properties

Grain size analyses were performed on each soil, the results of which appear in Table 3-1 and Figure 3-2. The results of further physical and chemical test series are presented in Tables 3-2 and 3-3. Test data were

used to classify the soils in both the AASHO and Unified Soil Classification systems as a general basis for comparison of the four soil types.

Standard moisture-density tests were performed on the soils in accordance with AASHO Designation: T99-70. Method A was employed for the clayey sand, sand and clay, and Method C was used for the cinders. The optimum moisture contents and corresponding standard maximum densities are included in Table 3-2 and the moisture-density curves are presented in Figure 3-3.

3.3 Fly Ash

Fly ash from four available sources was utilized in this study. The sources and general locations were:

Four Corners Generating Station - near Fruitland,
New Mexico

Navajo Generating Station - near Page, Arizona

Mohave Generating Station - near Laughlin, Nevada

Cholla Generating Station - near Joseph City, Arizona

Coal used at these plants was obtained from bituminous-to-subbituminous sources in Arizona and New Mexico. Information on coal sources and quality is included in Appendix A.

Test results from samples of the fly ash used in the study specimens are presented in Table 3-4. Periodic sampling and testing of fly ash from each of the sources were performed during the course of the study; however, such sampling and testing were unscheduled and incidental to this study. The data were accumulated for the purpose of providing information

TABLE 3-1. Grain Size Analysis

Grain Size		% Finer by Weight				
		Clayey Sand*	Sand *	Clay * **		Cinders **
Inches	1 1/2					100
	1					96
	3/4				100	94
	1/2				99	87
	3/8				99	75
	1/4				99	46
U. S. Standard Sieve Sizes	# 4	100	100	100	98	27
	# 8	93	98	98	96	11
	# 10	91	98	98	96	9
	# 16	84	96	97	95	6
	# 30	73	85	95	94	4
	# 40	68	69	94	93	3
	# 50	63	44	94	93	2
	#100	52	14	92	91	1
#200	38	7	89	88	1	
mm	0.050		4			<0.1
	0.042	27				
	0.037			82	81	
	0.035		3			
	0.031	21				
	0.027			73	74	
	0.022		3			
	0.020	16				
	0.018			64	64	
	0.013		3			
	0.012	14				
	0.011			56	56	
	0.009	12	3			
	0.008			52	52	
	0.007		3			
	0.006	11	3	48	48	
0.003	9	2	42	42		
0.001	8	2	37	37		

*Minus #4 Material Only

**As Received

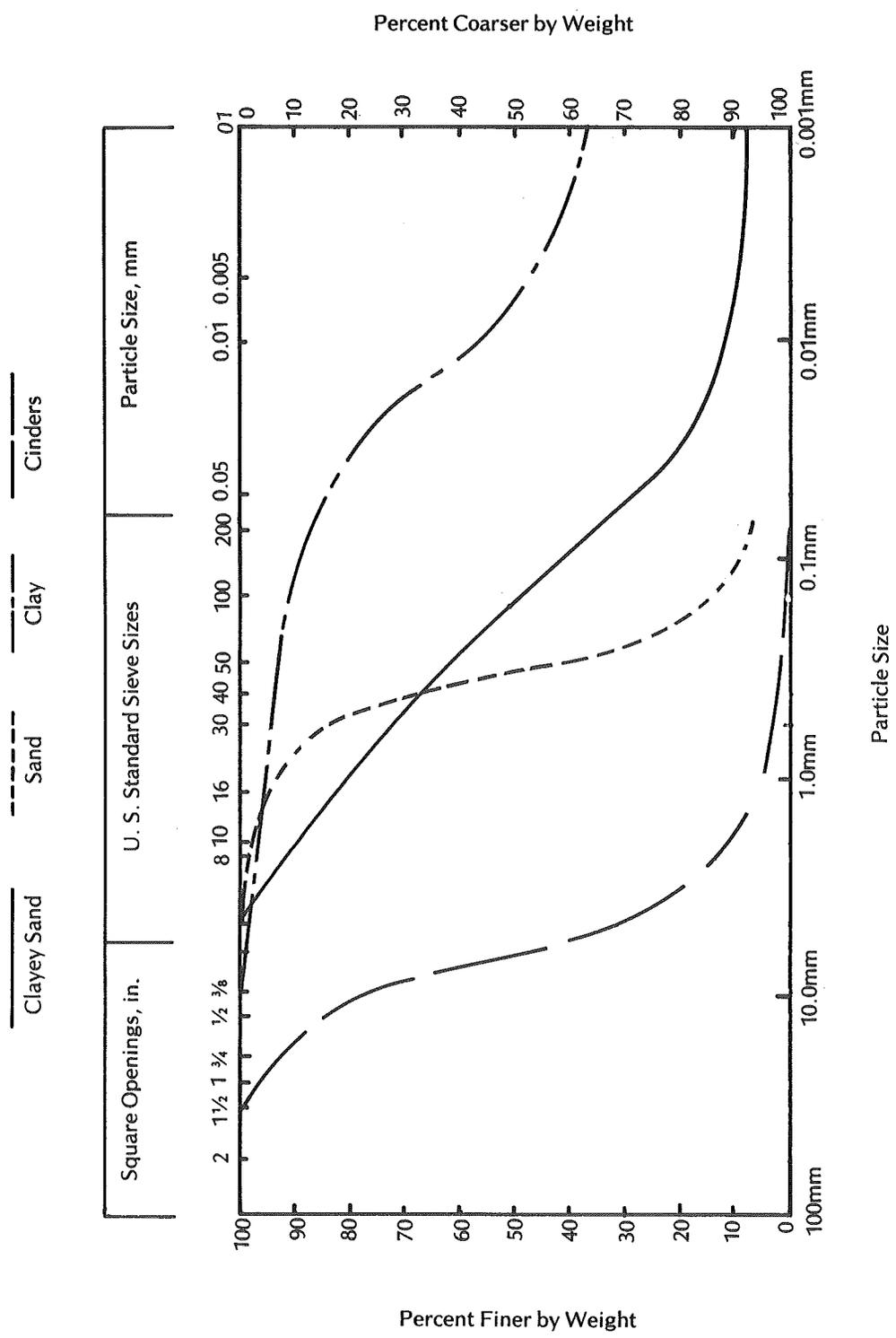


FIGURE 3-2. PARTICLE SIZE DISTRIBUTION CURVES.

TABLE 3-2. Engineering/Index Properties

PROPERTY	SOIL			
	Clayey Sand	Sand	Clay	Cinders
Unified Soil Classification	SC	SP	CH	GP
AASHO Classification	A-4	A-3	A-7-6	A-1-a
Specific Gravity of Solids	2.70	2.66	2.76	2.59 (2)
Atterberg Limits				
Liquid Limit	22	14	63	NP
Plastic Limit	18	NP(4)	17	NP
Plasticity Index	4	NP	46	NP
Resistance Value	69	75	<5	-
Bulk Density (3)				
SSD	-	-	-	1.68
OD				1.37
Absorption, %				23.1
Maximum Dry (1) Density, pcf	128	112	103	61
Optimum (1) Moisture Content, %	10	13	21	29

NOTES:

1. AASHO: T99-70
2. Minus #4 Material Only
3. Plus #4 Material Only
4. Non-Plastic

TABLE 3-3. Chemical Characteristics of Soils Used. *

Soil	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Cation Exchange Capacity
Clayey Sand	28.19	3.15	0.64	0.72	32.70
Sand	14.47	0.26	0.07	0.54	15.34
Clay	47.41	14.06	0.42	0.68	62.57
Cinders	17.47	3.10	0.46	0.81	21.84

*Results are expressed as milliequivalents per 100 grams air dry soil.

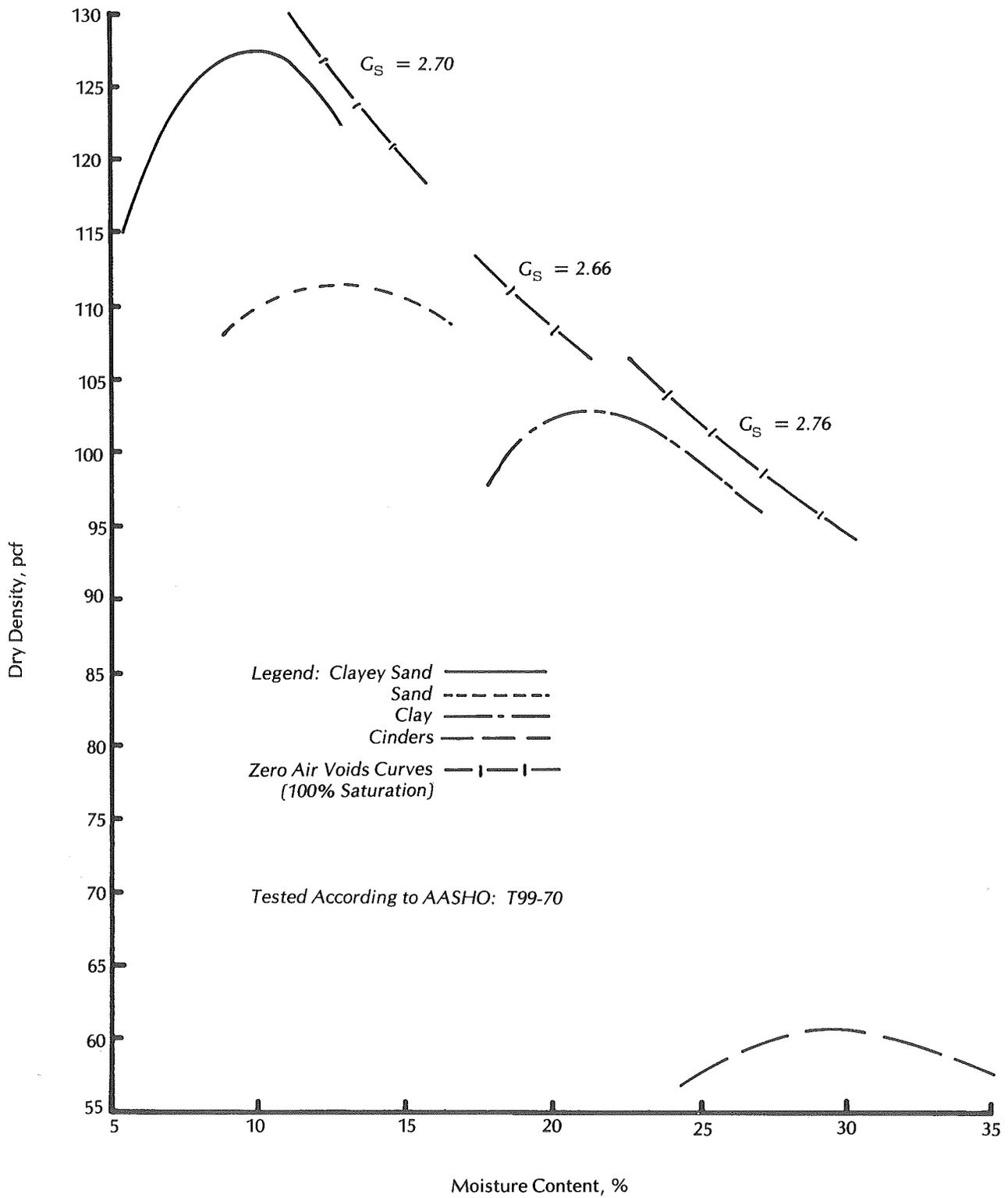


FIGURE 3-3. SOILS COMPACTION CURVES.

TABLE 3-4. Fly Ash Used in Strength and Durability Test Specimens

Property	Cholla *	Four * Corners	Navajo **	Mohave **	ASTM: C 618 Class F Specifications
SiO ₂ %	58.4	58.4	52.7	52.6	
Al ₂ O ₃ %	31.4	31.4	20.5	16.3	
Fe ₂ O ₃ %	1.3	0.8	4.9	5.5	
Sum of oxides %	91.1	90.6	78.1	74.4	70.0 min.
MgO %			2.0	2.5	-
SO ₃ %	0.3	0.3	0.5	1.13	5.0 max.
Moisture %	0.01	0.04	0.02	0.02	3.0 max.
Loss on Ignition %	0.34	0.44	2.77	0.77	12.0 max.
Available Alkalies					
As Na ₂ O %	0.28	0.52	1.31	1.14	1.5 max.
CaO %	4.5	3.3	8.7	16.4	-
Fineness					
Surface Area cm ² /cm ³	4560	5000	6835	9145	6500 min.
Retained #325 %	36.2	29.8	34.4	36.2	34 max.
Multiple Factor %	12.3	13.1	95.3	27.9	255.0 max.
Pozzolanic Activity Index:					
Cement, % control	60.0	56.0	67.0	84.0	85 min.
Lime, psi	-	-	-	-	800 min.
Water requirement					
% of control	102	98.5	-	-	105 max.
Shrinkage,					
Increase %	0.077	-	-	-	0.03 max.
Soundness,					
Autoclave %	0.048	0.048	0.053	0.13	0.5 max.
Expansion - 14 day %	-	-	-	-	0.02 max.
Air-Entraining Admixture ml.	1.68	1.44	-	-	Not applicable
Specific gravity	2.07	1.92	2.12	2.46	Not applicable
Cation Exchange Capacity ***	26.6	30.5	59.4	33.9	Not applicable

*Samples obtained from commercial carriers.

**Samples obtained from storage bins.

***Expressed as milliequivalents per 100 grams air dry soil.

on the variation of fly ash properties. Test data relating to the periodic sampling as well as a discussion of the methods of fly ash recovery at each plant are included in Appendix A.

The data of Table 3-4 apply to samples which represent only the fly ash used in the strength and durability test specimens. Data in Appendix A apply to all samples, including those used in the test series.

The test results indicate that each fly ash failed in some respect to meet the ASTM Designation: C618 for Class F Pozzolan. The failures occurred in the areas of fineness (Blaine surface area and % passing the #325 sieve) and pozzolanic activity index.

3.4 Lime

High-calcium hydrated lime used in the study was produced at the City of Industry, California, plant of the U. S. Lime Division of the Flintkote Company in a regular production run. Nominal chemical test data were supplied by the manufacturer and are reported in Table 3-5.

Several choices are normally available when selecting lime for soil stabilization, including waste lime, quicklime and hydrated lime. Waste lime is frequently composed of both hydrated and quicklime, as well as impurities, and is difficult to use due to usual lack of control over quality and uniformity. Quicklime (calcium and/or calcium-magnesium oxide) has been successfully used although hazards inherent in handling have been a major objection. Hydrated lime (calcium and/or calcium-magnesium hydroxide) has apparently been most frequently used. Both high calcium and magnesium (dolomitic) limes have been successfully used. The high calcium-hydrated lime used for this study series was selected on the basis of availability as well as characteristics.

TABLE 3-5. Hydrated Lime Test Data

Property	Representative Analysis *
Acid Insoluble %	1.5
Fe ₂ O ₃ %	0.1
Al ₂ O ₃ %	0.5
MgO %	1.0
Ca(OH) ₂ %	94.6
Pass 200 Sieve %	97.0
Pass 325 Sieve %	88.0

*Flintkote California High Calcium Hydrated Lime. Test data are typical analyses provided by the manufacturer.

3.5 Lime-Fly Ash-Soil Combinations

At least three distinct phenomena have normally been associated with the addition of lime and fly ash. The first reaction tends to lower the plasticity and give the soil a more friable appearance immediately upon mixing. This change in itself frequently results in a significant improvement in the engineering characteristics of the soil. The second phenomenon involves the apparent reaction between the calcium and available silica or alumina (in soil or fly ash) which results in the formation of a matrix of one or more cementitious compounds. This reaction is relatively slow at normal temperatures, usually requires several days to be measurable to any significant degree and continues over a period of months and possibly years (pozzolanic reaction). The third and slowest reaction involves absorption of carbon dioxide from the air and the formation of calcium carbonate. This last reaction is not considered significant in the context of soil stabilization. The results of the pozzolanic reaction were the primary subject of this study.

The lime-fly ash-soil combinations selected for strength and durability testing were subjected to a preliminary test series to establish moisture-density relationships and relative plasticity.

The moisture-density testing was performed in accordance with AASHTO Designation: T99-70, Method A for all Cholla fly ash combinations without cinders and Method C for all combinations with cinders. The standard maximum dry densities and corresponding optimum moisture contents are presented in Table 3-6 for all Cholla fly ash tested.

To evaluate plasticity, Atterberg limits tests were performed on the lime-fly ash-soil combinations in accordance with AASHTO Designation: T89-68 and T90-70, the results of which are presented in Table 3-7. The clay was the only soil with appreciable plasticity, and some conclusions can be drawn from the

TABLE 3-6. Compaction Data for Lime-Fly Ash-Soil Combinations

Soil	% Lime	% Fly Ash**			
		0	10	20	30
Clayey Sand	0	128 @ 10*	122 @ 11	117 @ 11	113 @ 12
	2	128 @ 11	116 @ 12	112 @ 12	107 @ 13
	4	124 @ 11	116 @ 11	112 @ 11	109 @ 11
	6	120 @ 12	114 @ 12	112 @ 12	110 @ 12
	8	116 @ 12	111 @ 14	110 @ 14	107 @ 14
Sand	0	112 @ 13	114 @ 10	116 @ 9	115 @ 10
	2	113 @ 12	116 @ 9	115 @ 9	111 @ 10
	4	115 @ 12	116 @ 9	115 @ 9	112 @ 10
	6	116 @ 12	116 @ 9	115 @ 9	114 @ 10
	8	118 @ 11	***	***	***
Clay	0	103 @ 21	102 @ 19	100 @ 20	99 @ 20
	2	102 @ 21	102 @ 19	99 @ 19	95 @ 17
	4	101 @ 21	98 @ 20	97 @ 18	95 @ 16
	6	96 @ 22	97 @ 21	95 @ 18	96 @ 19
	8	95 @ 22	***	***	***
Cinders	0	61 @ 29	***	78 @ 29	***
	2	***	***	79 @ 29	***
	4	63 @ 36	74 @ 32	79 @ 29	***
	6	64 @ 35	75 @ 31	79 @ 29	***

* Maximum dry density of 128 pcf at optimum moisture content of 10% according to AASHTO: T99-70, Method A for all except Cinders combinations, Method C for Cinders combinations.

** Cholla Fly Ash

*** Combination not tested.

TABLE 3-7. Atterberg Limits of Lime - Fly Ash - Soil Combinations.

Soil	% Lime	% Fly Ash											
		0			10			20			30		
		LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI
Clayey Sand	0	22	18	4	NP								
	2	26	21	5	NP								
	4	30	NP										
	6	33	NP										
	8	32	NP										
Sand	0-8	All Combinations Non-Plastic											
Clay	0	63	17	46	56	15	41	53	17	36	50	18	32
	2	45	34	11	41	28	13	40	28	12	40	30	10
	4	44	34	10	47	33	14	43	32	11	38	28	10
	6	50	36	14	47	33	14	44	30	14	40	30	10
	8	49	36	13	48	33	15	40	29	11	38	27	11
Cinders	0-6	All Combinations Non-Plastic											

lime-fly ash-clay combination data presented in Figure 3-4.

Generally, the addition of fly ash decreased the liquid limit, plastic limit, and plasticity index of the mixture, regardless of the lime content. The test results also indicated that the addition of 2% lime to any combination of fly ash and clay, or clay alone, reduced the liquid limit and increased the plastic limit, and thereby significantly reduced the plasticity index of the combination.

These preliminary test data are presented as a part of this materials section to aid in the description and classification of the soils considered in the study.

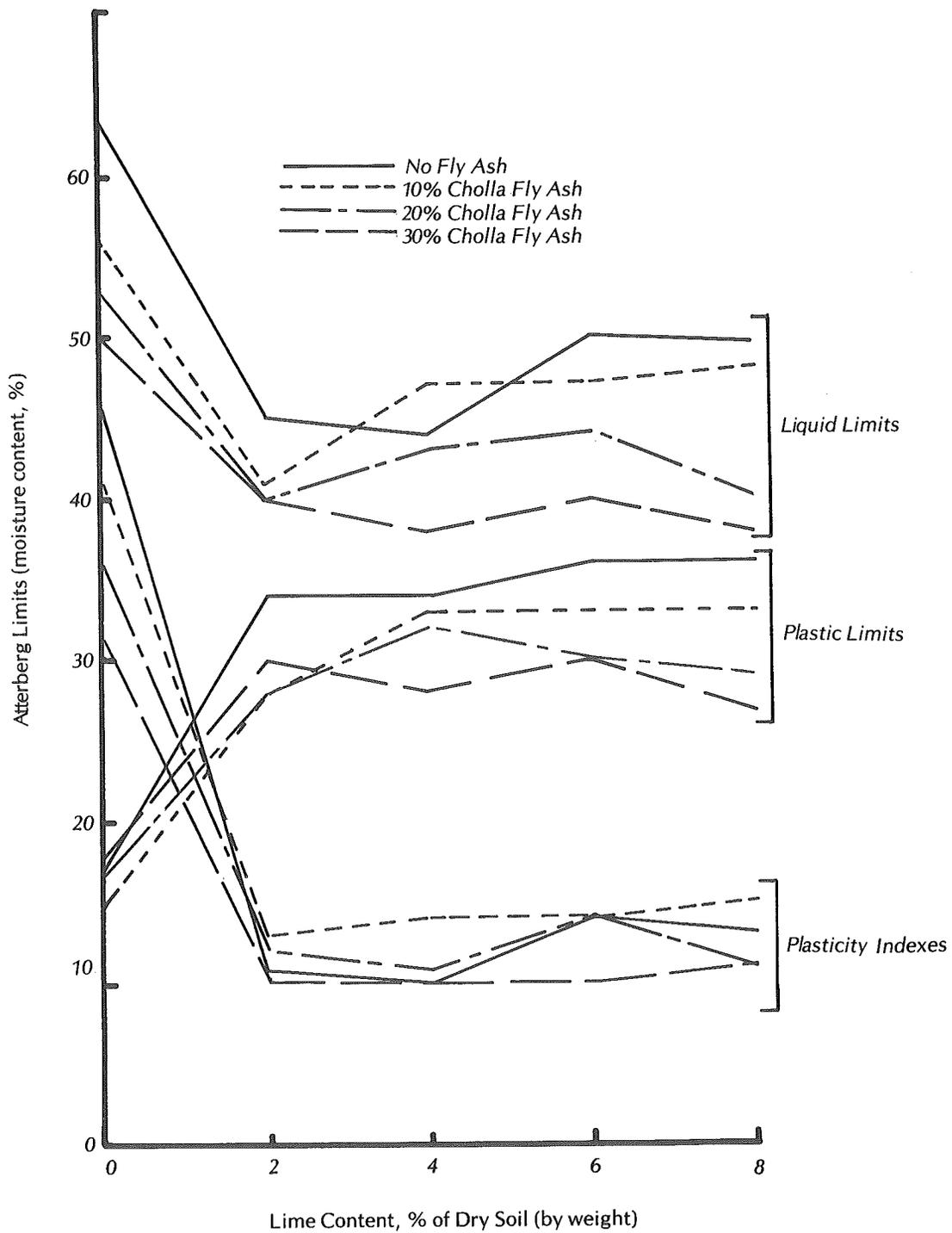


FIGURE 3-4. ATTERBERG LIMITS OF LIME-FLY ASH-CLAY COMBINATIONS.

CHAPTER 4. STRENGTH CHARACTERISTICS

4.1 General

The effects of various combinations of lime and fly ash on unconfined compressive strength were evaluated for each of the four soil types. The major test series, discussed in this chapter, was conducted on specimens which were tested at molding water content. This procedure had the effect of avoiding one uncontrolled variable, degree of saturation, which would be expected to influence compressive strength. The data therefore provided a basic assessment of the effects of lime and fly ash proportions on the unconfined compressive strength of each soil type. The effects of saturation on unconfined compressive strength are discussed in a later section on durability.

A broad range of lime-fly ash-soil mix combinations was tested for each soil type. Lime proportions were varied from 0 to 8% (by weight of dry soil) in increments of 2%. Fly ash proportions were varied from 0 to 30% in increments of 10%. The variable considered in the laboratory test program can be most easily described by reference to the following breakdown:

- Soil Type - SC, CH, SP and GP (Unified Soil Classification designations).
- Fly Ash Type - C, M, N, F (Cholla, Mohave, Navajo and Four Corners, respectively).
- Lime Content - 0, 2, 4, 6, and 8%.
- Fly Ash Content- 0, 10, 20 and 30%.
- Age at Test - 7, 28 and 56 days.
- Specimen No. - A, B or C (three specimens averaged for each strength determination).

A specimen designated SC-4-C10-28A, for example, would identify the SC soil type with 4% lime, 10% Cholla fly ash, and

one of three companion specimens to be tested at 28 days age.

4.2 Laboratory Test Procedures

Standard maximum densities were determined for each of the lime-fly ash-soil combinations, in accordance with AASHTO Designation: T99-70, Method A. (ASTM Designation: D698-70, Method A), for all soil types except cinders (GP). Method C was used for cinder (GP) specimens since the Method-A would have resulted in rejecting well over half the material. Moisture density curves were developed with a minimum of five test points for each curve.

Test specimens were molded in a Harvard miniature apparatus, yielding specimens 1.3 in. in diameter and 2.8 in. high (3.3 x 7.1 cm), for the CH, SP and SC soil types. Cinder (GP) specimens were molded in 4 in. diameter by 4.6 in. high (10.2 x 11.7 cm) cylindrical molds. The relatively small Harvard miniature mold was selected for the fine grained soils primarily due to the large number of specimens needed (more than 500 for the complete series for each soil type). The coarse-grained cinder (GP) soil could not be compacted in the small molds due to large grain size. In all cases, mixtures were blended at optimum moisture content and compacted to a density at or near the standard maximum. Specimen molding data are presented in Appendix B, including the standard maximum densities and optimum moisture contents, and the as-molded densities and moisture contents.

Dry soil, lime and fly ash were machine-blended for one minute before adding water. After adding water the mixtures were machine blended for two minutes, allowed to rest for one minute, and machine-blended again for two minutes.

Specimens were molded immediately upon completion of the blending and mixing. Specimens were extruded from the molds immediately after compaction, individually sealed in 2 mil (0.05 mm) polyethylene and stored in a moist-room at a temperature of $73 \pm 3^{\circ}\text{F}$ ($23 \pm 1.7^{\circ}\text{C}$) and relative humidity of 90% or higher.

Unconfined compressive strength was determined using a Soil-Test triaxial shear apparatus with a proving ring for load determination and a controlled rate of strain of 1% per minute. Maximum load was recorded as the load at failure or at 20% strain, whichever occurred first. Stresses were calculated assuming a constant volume for the specimen and correcting for the strain-induced increase in cross sectional area.

4.3 Unconfined Compressive Strength

4.3.1 General

Unconfined compressive strengths were determined in the laboratory for a broad range of lime-fly ash-soil mix combinations. In each case the reported value was an average representing three companion test specimens. These data are tabulated in Appendix B.

4.3.2 Strength vs. Lime Content

4.3.2.1 Clayey Sand

The relationship between lime content and strength for various fly ash contents is illustrated by the curves of Figures 4-1A, B, C and D. Each Figure represents the complete range of data developed from the test series for a particular fly ash source.

In the no-fly-ash series, strength remained essentially constant for lime contents of 2% and above.

The Cholla fly ash did not appear to provide any increase in soil strength when not accompanied by lime. Fly ash in the amount of 10% did cause a significant increase in strength compared to the lime-only mixtures. The data indicated that strength gain was dependent on specific proportions of both lime and fly ash. With 10% fly ash, for example, no significant strength increase was noted as lime content was increased above 4%. Similar plateaus were observed with other combinations of lime, fly ash and soil.

The specimens containing Four Corners fly ash exhibited strength characteristics nearly identical to the Cholla specimens.

Mohave fly ash appeared to cause a significant increase in strength when used alone as a soil additive. Strength peaked with about 20% fly ash, yielding a value of over 400 psi (28 Kg/cm²). Continued strength gain was noted for all increases in either fly ash, or lime content.

Navajo fly ash did not provide a strength gain when used without lime. The 30% fly ash series appeared to lose strength, com-

pared to the 10% and 20% series except for high (8%) lime content.

The clayey sand (SC) soil exhibited relatively high increases in compressive strength with each of the fly ash types. Peak strengths for the range of proportions tested were:

Cholla	880 psi	(62 Kg/cm ²)	SC-8-C30-56
Four Corners	1110 psi	(78 Kg/cm ²)	SC-8-F30-56
Mohave	1270 psi	(89 Kg/cm ²)	SC-8-M30-56
Navajo	1130 psi	(80 Kg/cm ²)	SC-8-N30-56
No Additive	30 psi	(2 Kg/cm ²)	SC-0- 0-56

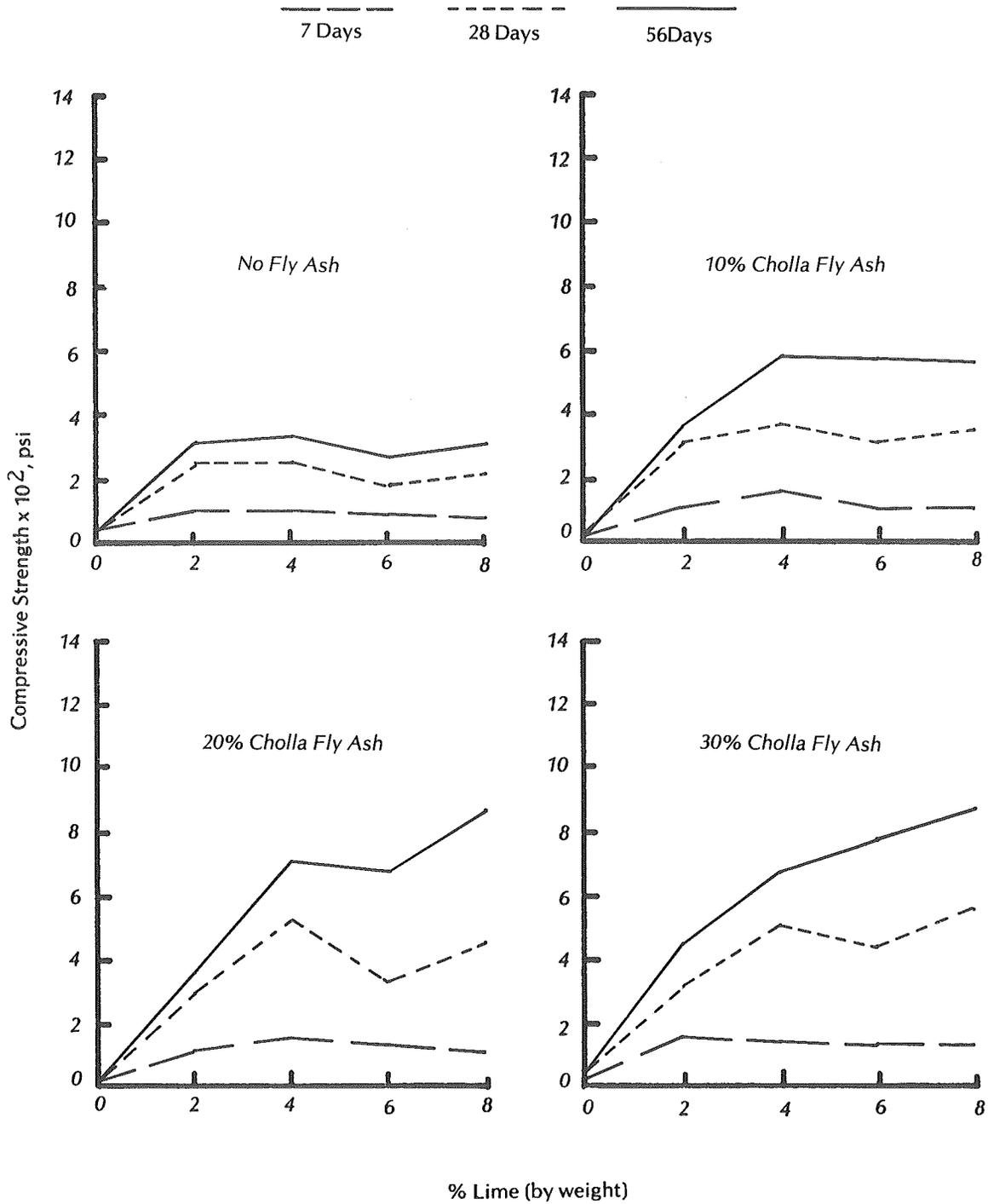


FIGURE 4-1A. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND CHOLLA FLY ASH.

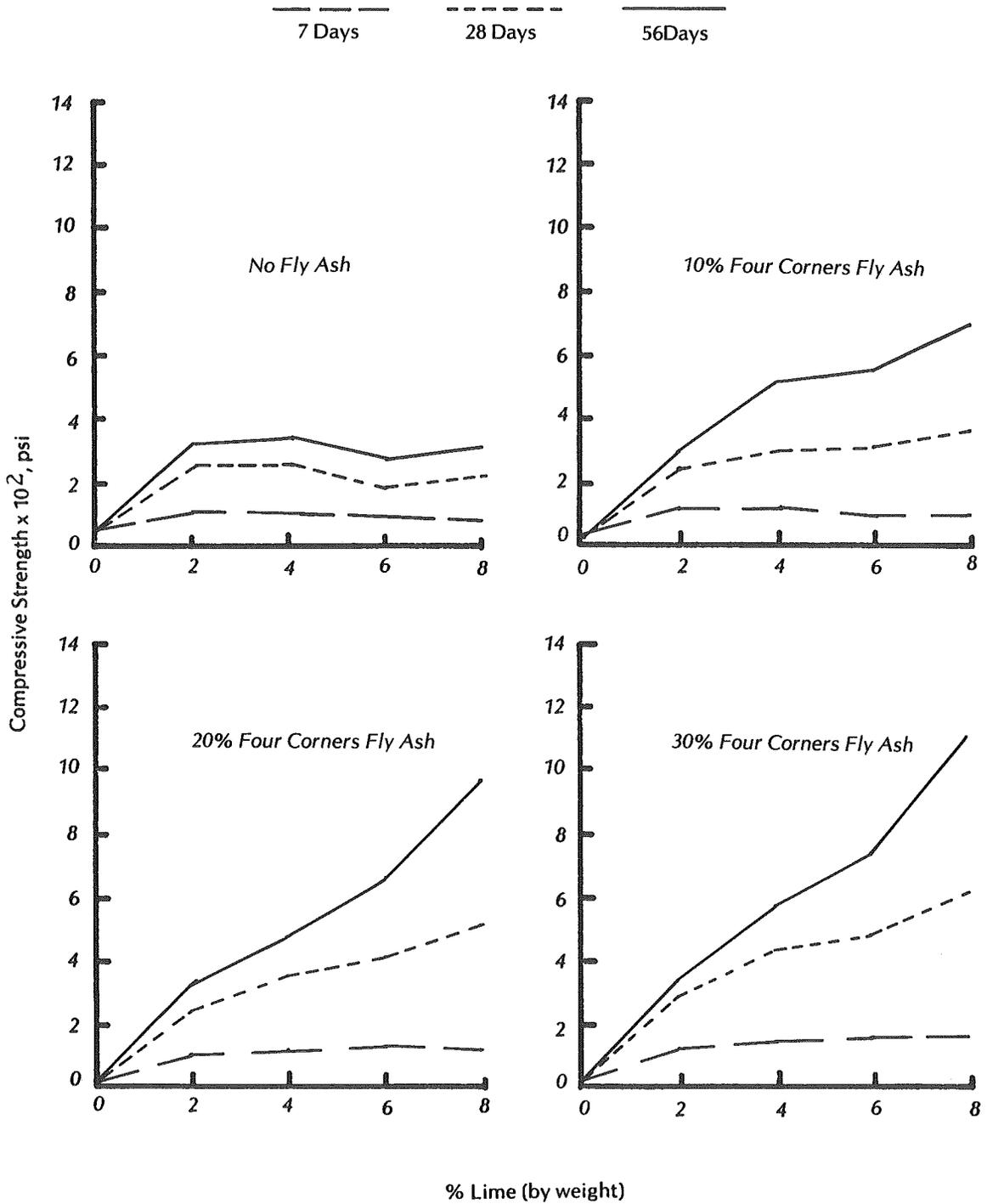


FIGURE 4-1B. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND FOUR CORNERS FLY ASH.

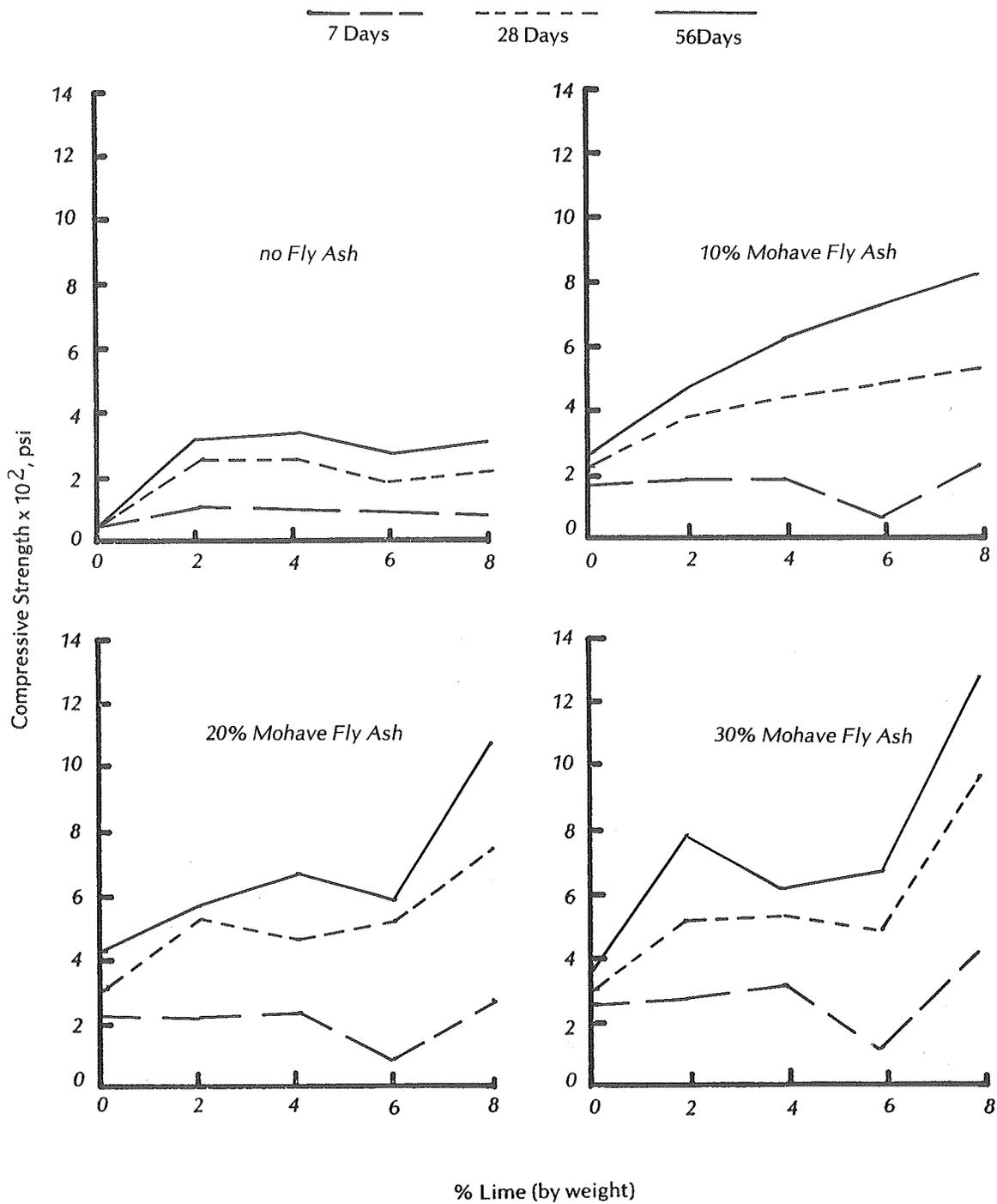


FIGURE 4-1C. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND MOHAVE FLY ASH.

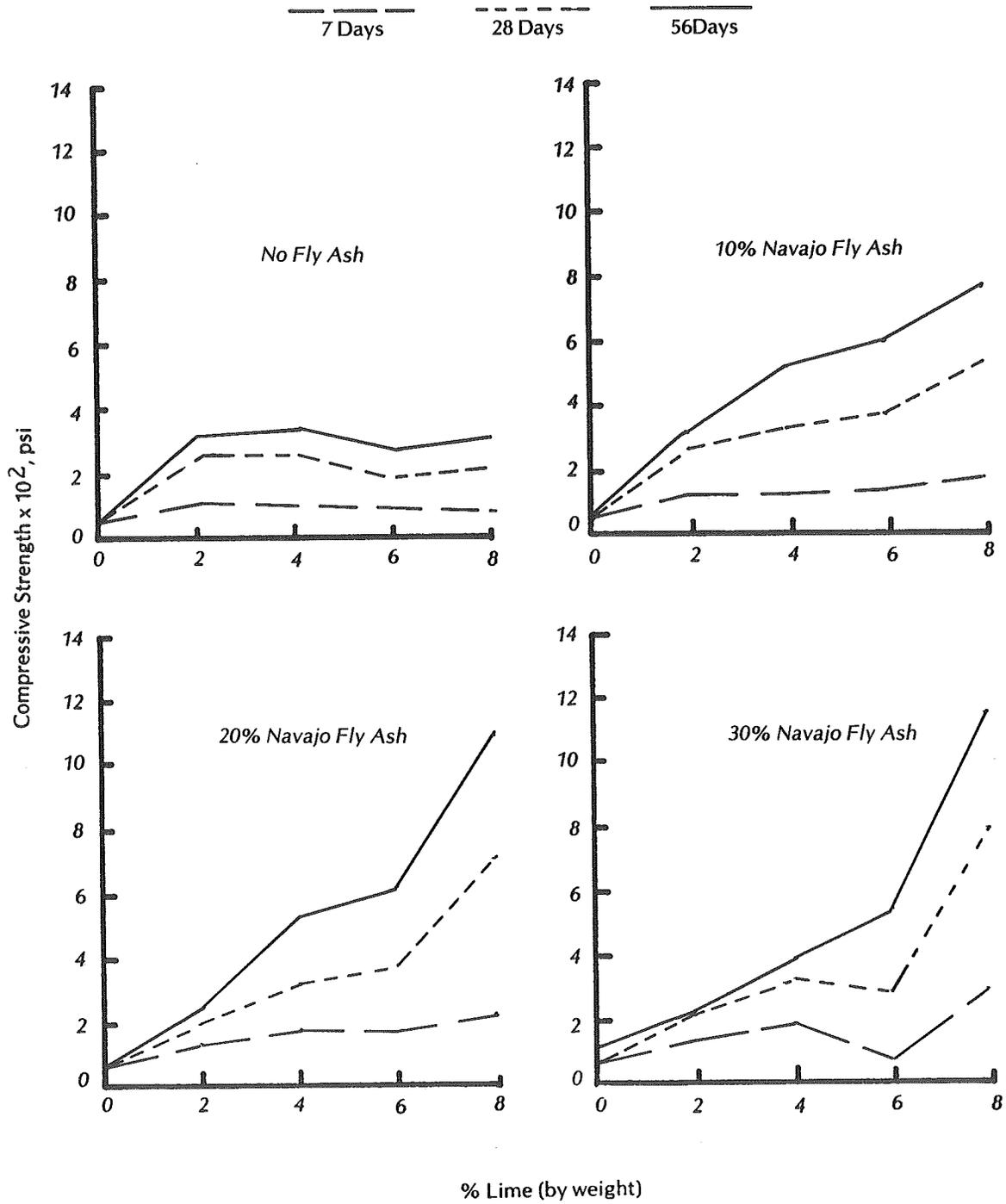


FIGURE 4-1D. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND NAVAJO FLY ASH.

4.3.2.2 Sand

The lime content-strength relationships are illustrated in Figures 4-2A, B, C and D for the sand (SP).

Test data indicated that lime, alone, was not effective in developing significant compressive strength for the sand soil type. In proportions up to 8% the addition of lime increased the strength to only about 40 psi (3 Kg/cm^2).

The Cholla fly ash increased strength significantly throughout the range of mix proportions when used in combination with lime. Used alone, in proportions of 20% or more, the fly ash resulted in minor strength gains in about the same range as for lime alone. The data tended to indicate that for a given fly ash content an optimum lime content existed above which the further addition of lime was ineffective.

Specimens molded with the Four Corners fly ash alone exhibited virtually no strength gain for any proportion of fly ash. In combination with lime the Four Corners specimens showed significant strength gain for each increase in lime or fly ash proportions.

Mohave fly ash produced some gains in strength when used alone, particularly in the 30% fly ash series. When added in combination with lime strength gains were noted for each increase in lime or fly ash content.

The Navajo fly ash resulted in noticeably less

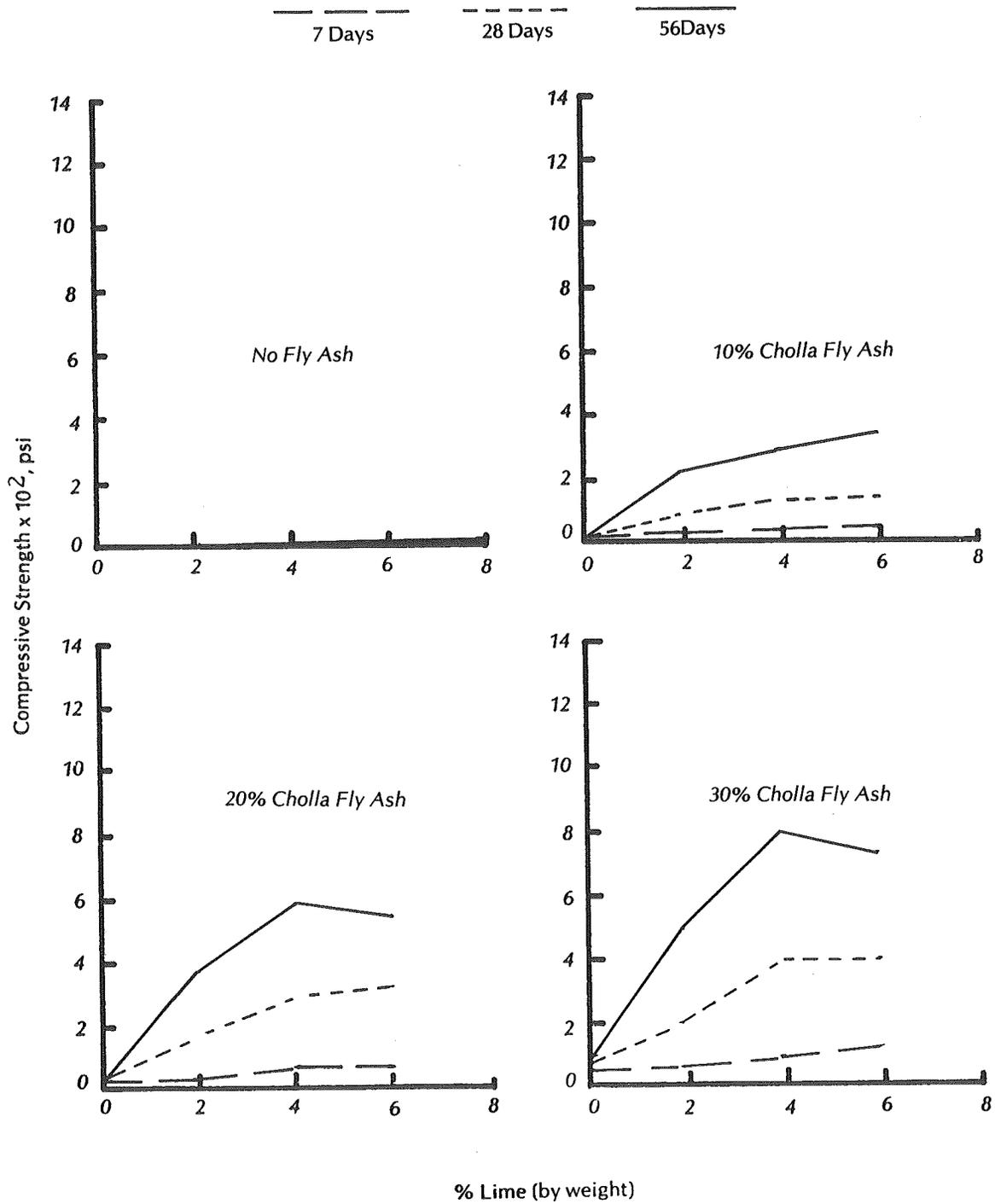


FIGURE 4-2A. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND CHOLLA FLY ASH.

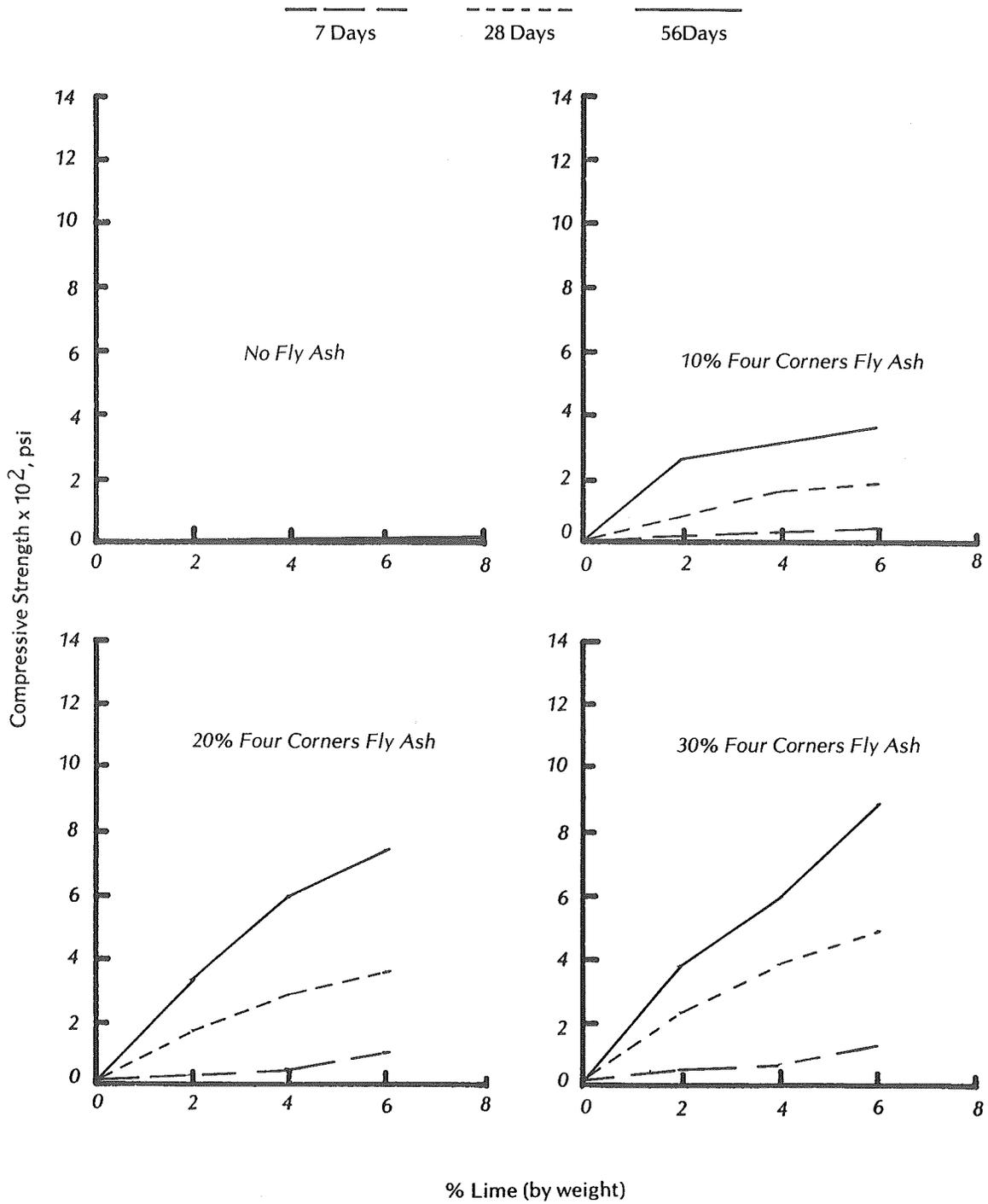


FIGURE 4-2B. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND FOUR CORNERS FLY ASH.

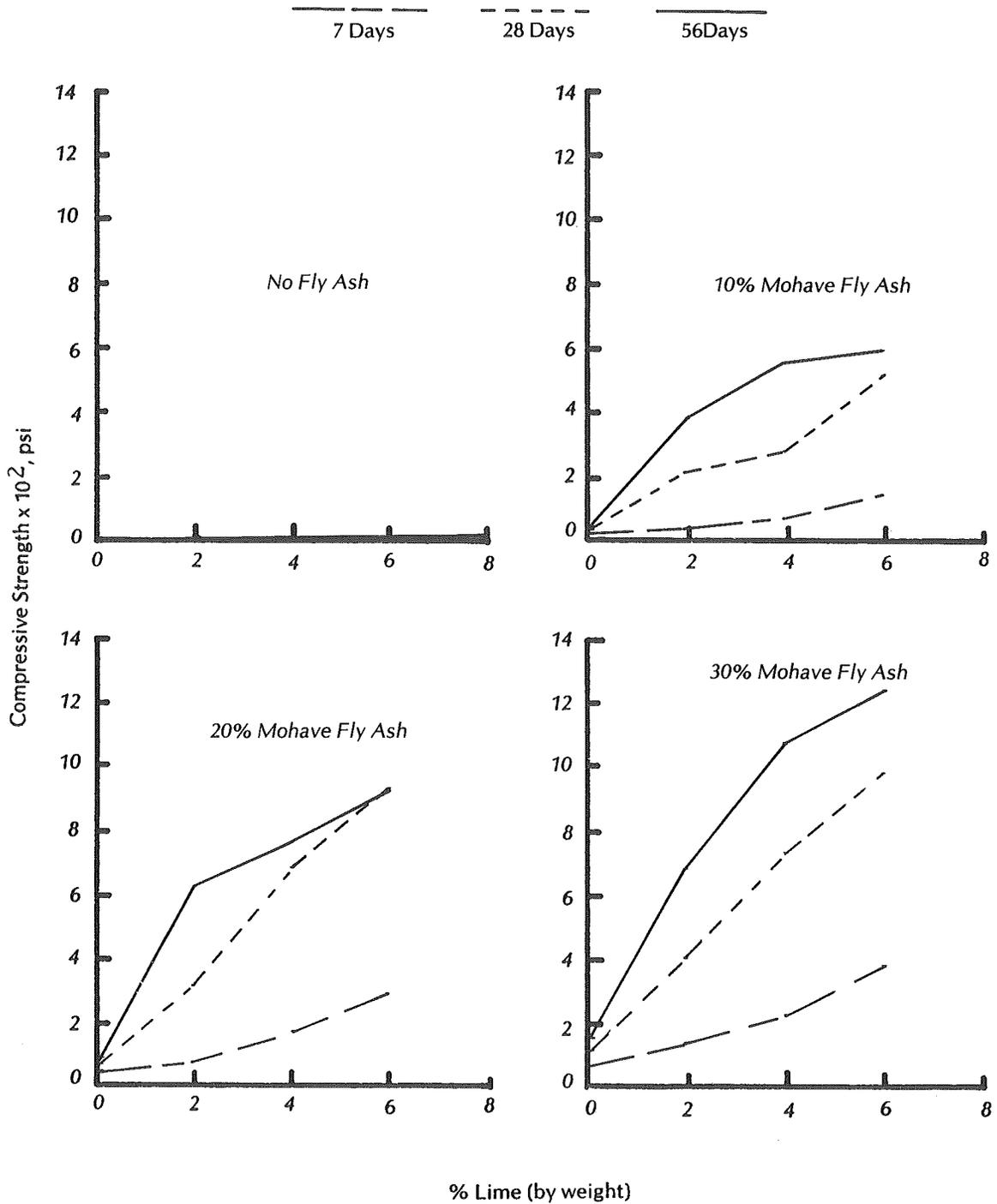


FIGURE 4-2C. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND MOHAVE FLY ASH.

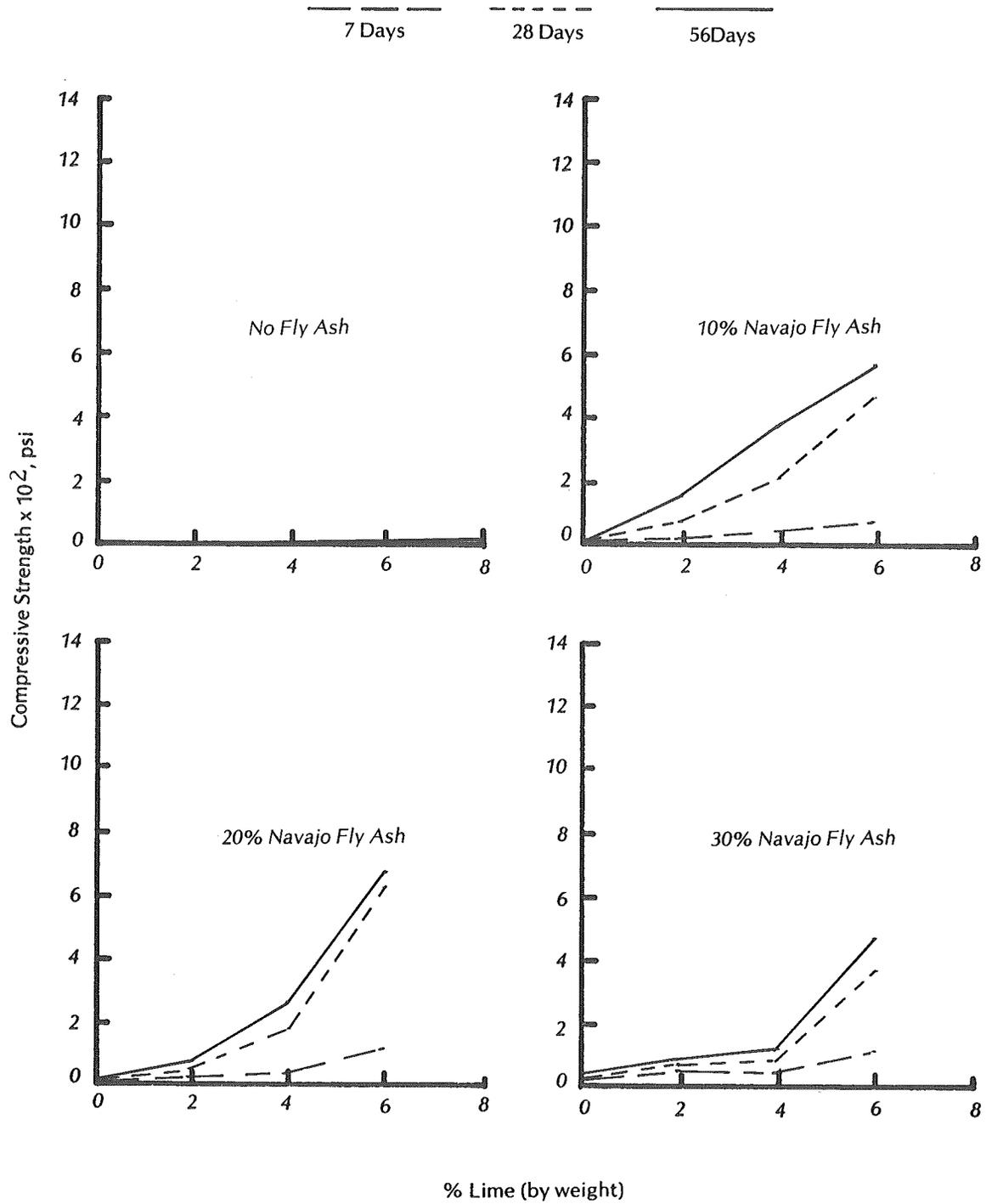


FIGURE 4-2D. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND NAVAJO FLY ASH.

significant strength gains than the other three ashes. Strength was low when lime was excluded from the mixture. Increased lime content resulted in increased strength throughout the full range of lime contents. Increased fly ash content beyond 10%, however, did not result in increased strength.

The sand (SP) soil type exhibited significant but unique compressive strength characteristics for each of the fly ash types. Peak strengths for the range of proportions tested were:

Cholla	780 psi (55 Kg/cm ²)	SP-4-C30-56
Four Corners	870 psi (61 Kg/cm ²)	SP-6-F30-56
Mohave	1250 psi (88 Kg/cm ²)	SP-6-M30-56
Navajo	670 psi (47 Kg/cm ²)	SP-6-N20-56
No Additive	0 psi	SP-0- 0 -(56)

4.3.2.3 Clay

Strength vs. lime content relationships are illustrated in Figures 4-3A, B, C and D for the clay (CH) soil type.

Test data indicated that the addition of lime alone resulted in significant strength gain. Increased lime content resulted in increased strength throughout the full range of lime contents tested.

The addition of Cholla fly ash alone (with no lime) increased strength slightly when compared to soil specimens with no additives. The

Cholla ash resulted in significant strength gains when combined with lime contents of 4% or more.

The Four Corners fly ash specimens exhibited little or no strength gain with no lime but otherwise were nearly identical to the Cholla specimens in behavior.

The addition of Mohave fly ash alone resulted in significant strength gain, particularly at the highest fly ash content (30%). Test data indicated that at the higher fly ash contents (20% - 30%), increased lime, within the range tested, was not effective in increasing compressive strength.

Navajo fly ash, without lime, resulted in a significant strength increase, about the equivalent of 2% lime and no ash. The addition of fly ash (without lime) above 10%, however, resulted in no further gain in strength. Considered overall, the Navajo ash contributed to compressive strength primarily in the specimens with no lime and 10% ash, and with 6% lime and 30% fly ash. Intermediate combinations resulted in little improvement over the use of lime alone.

The clay (CH) soil type yielded moderate unconfined compressive strength with selected combinations of lime and fly ash proportions. The peak strengths within the range of proportions tested were:

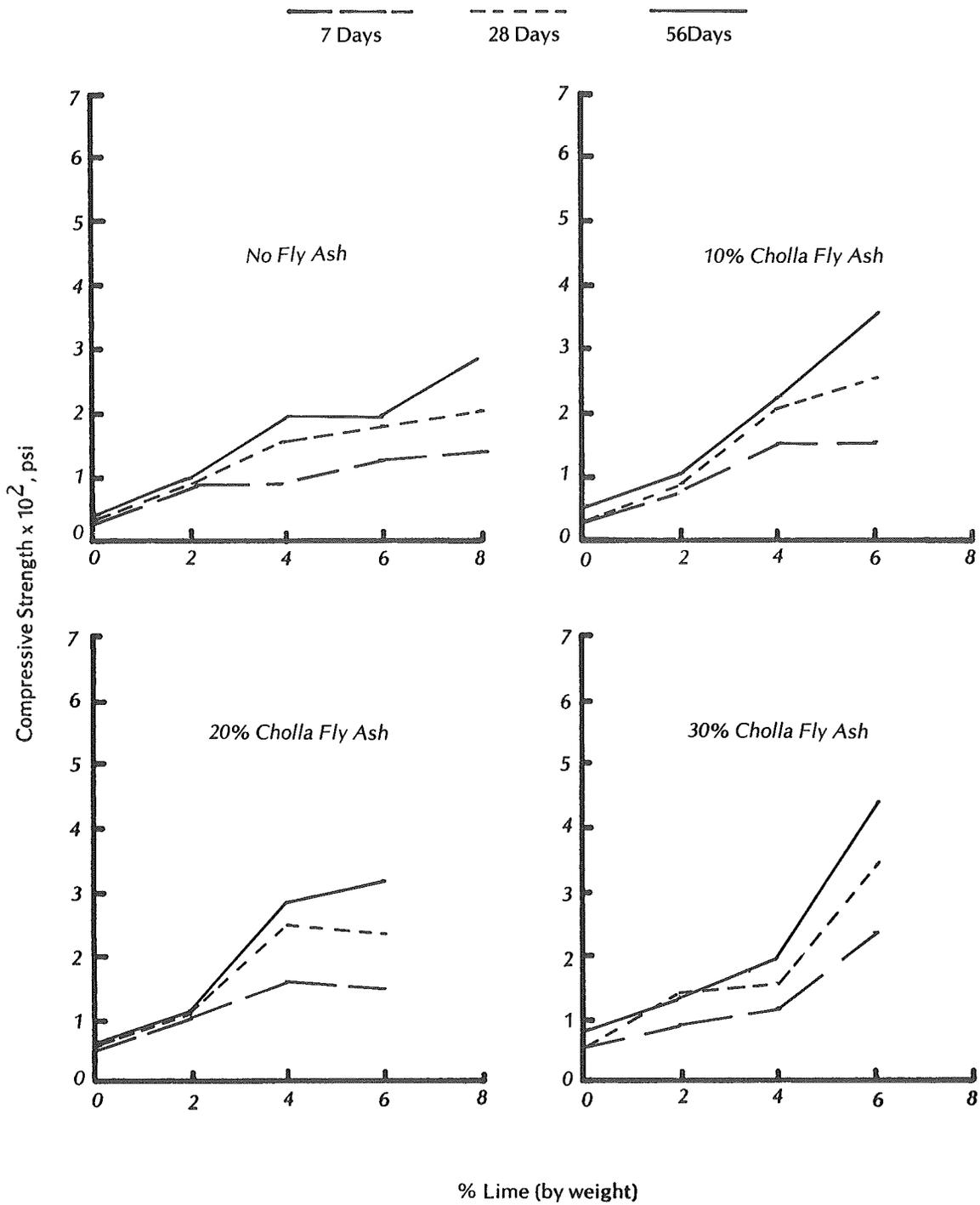


FIGURE 4-3A. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND CHOLLA FLY ASH.

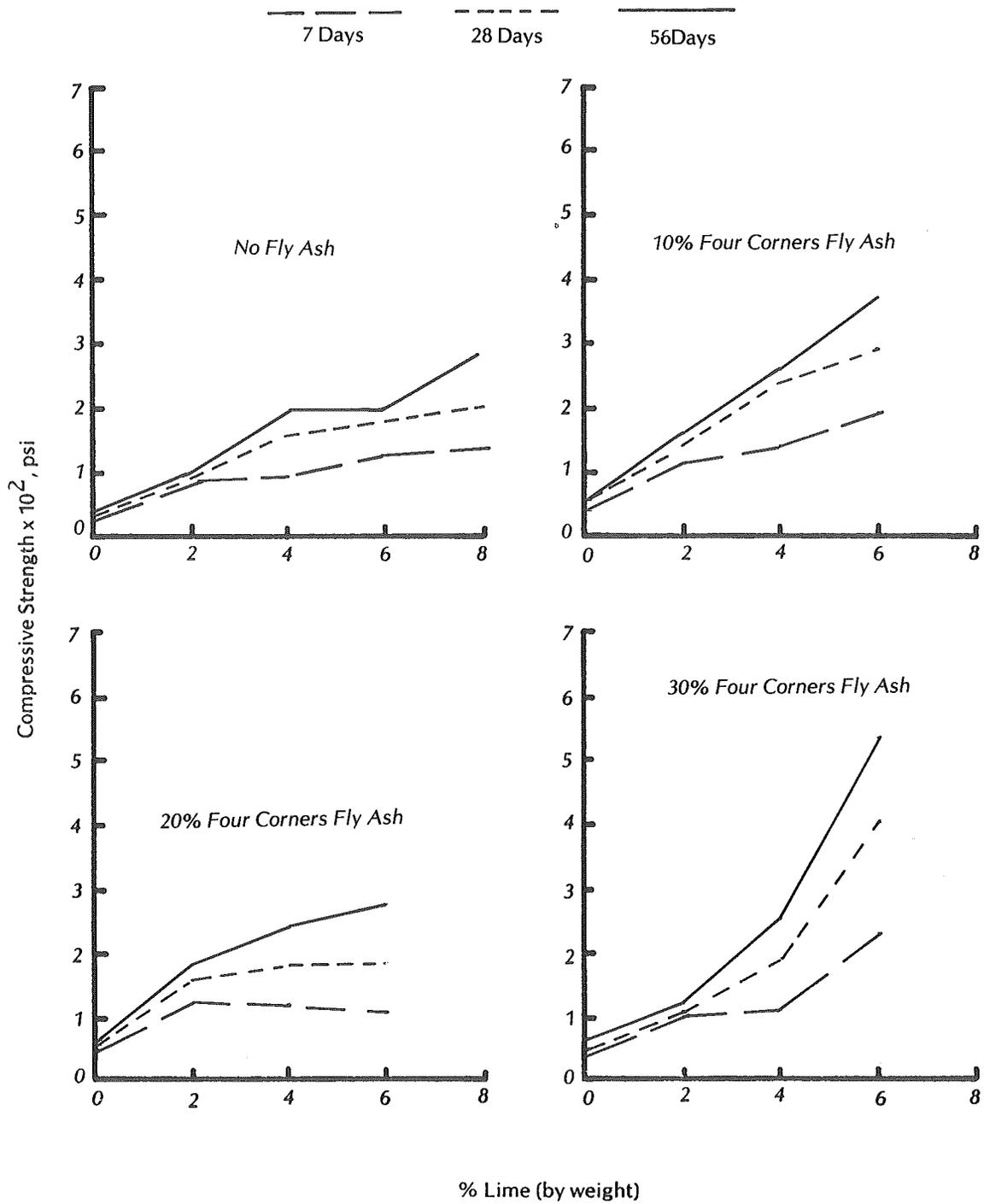


FIGURE 4-3B. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND FOUR CORNERS FLY ASH.

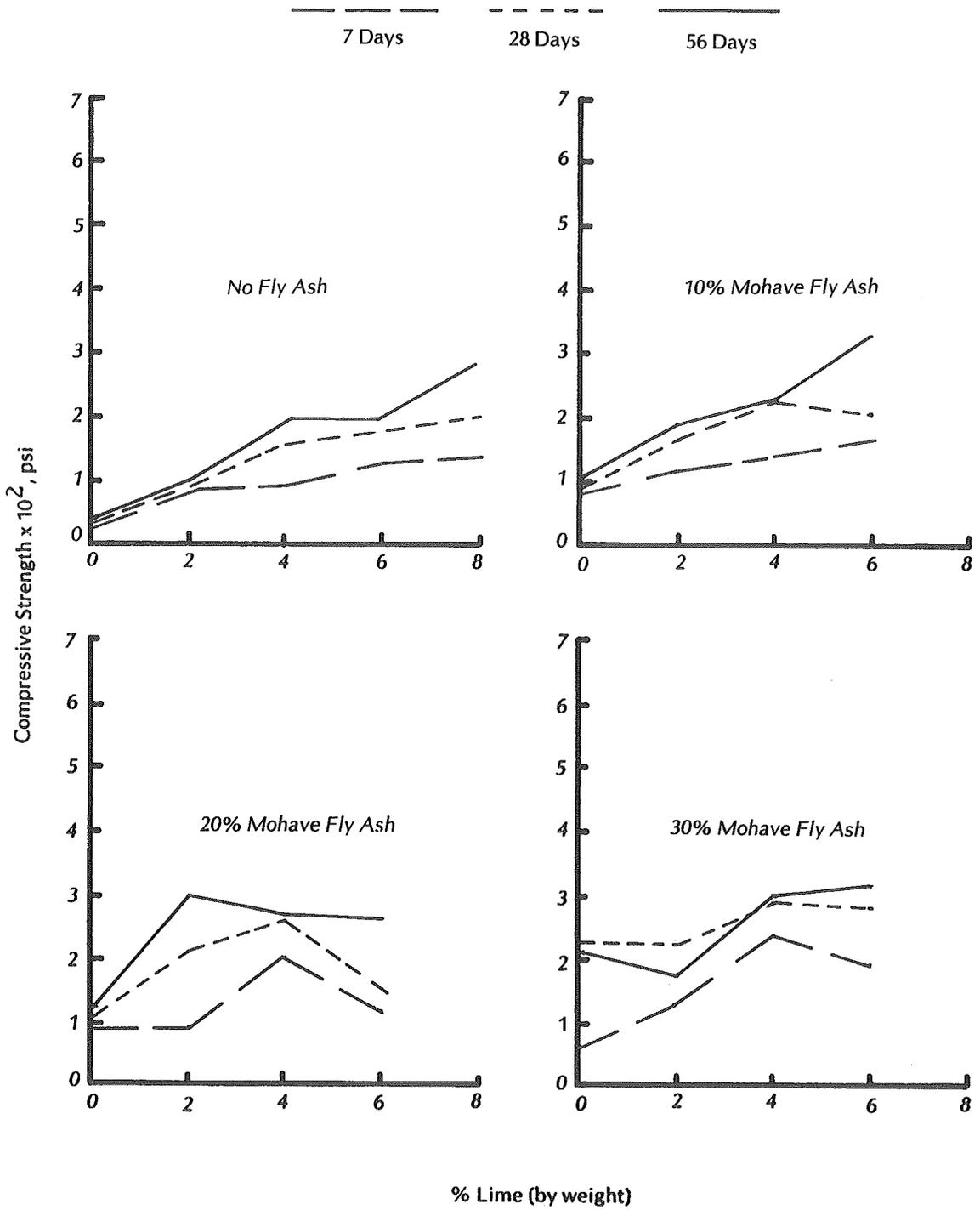


FIGURE 4-3C. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND MOHAVE FLY ASH.

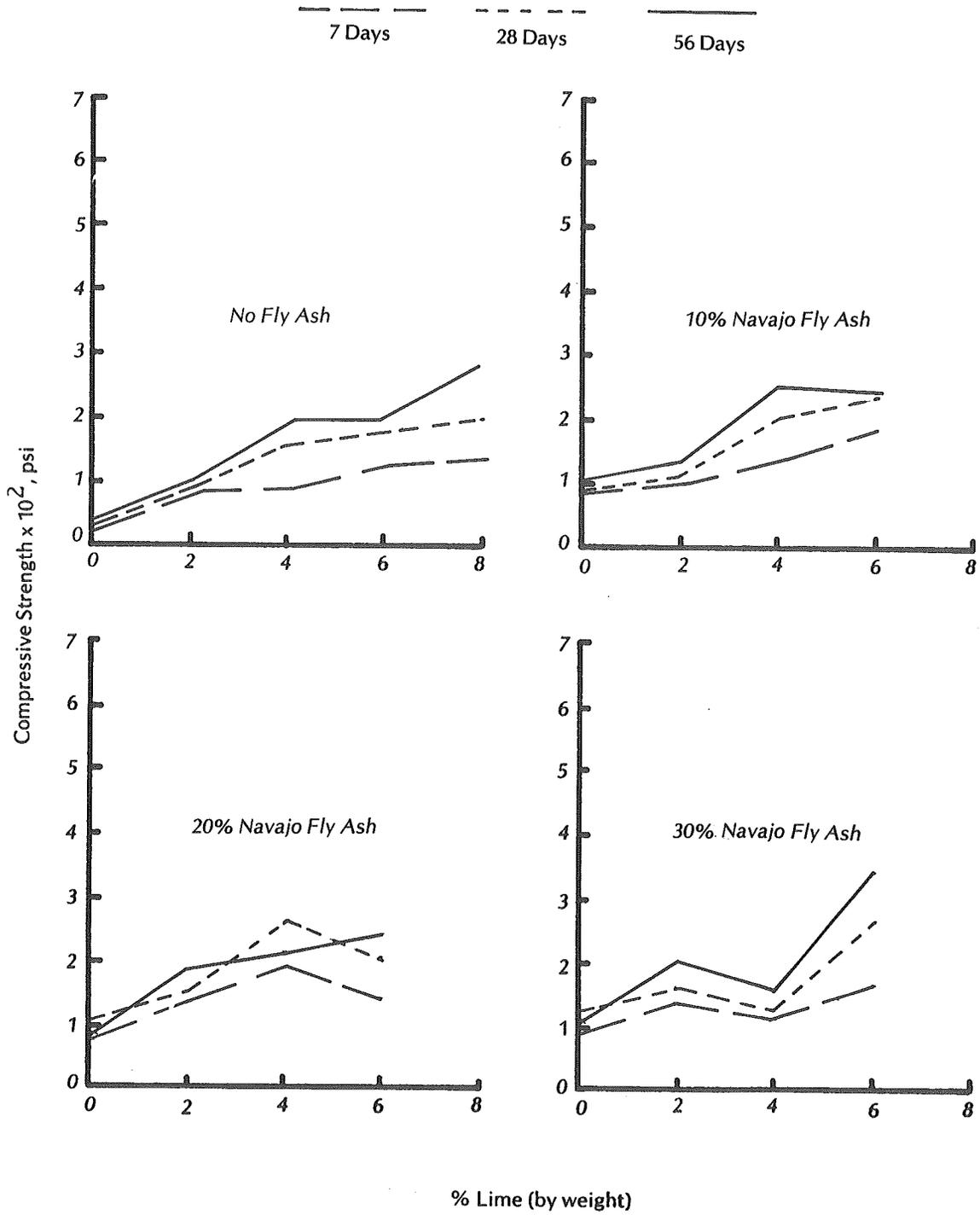


FIGURE 4-3D. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND NAVAJO FLY ASH.

Cholla	430 psi (30 Kg/cm ²)	CH-6-C30-56
Four Corners	530 psi (37 Kg/cm ²)	CH-6-F30-56
Mohave	320 psi (23 Kg/cm ²)	CH-6-F10-56
Navajo	340 psi (24 Kg/cm ²)	CH-6-N30-56
No Additive	40 psi (3 Kg/cm ²)	CH-0-0-56

4.3.2.4 Cinders

The compressive strength vs. lime content test data for the cinder (GP) soil type are illustrated in Figure 4-4. Specimen geometry, as previously discussed, differed considerably from that of the other three soil types. Direct comparisons should only be made therefore, with due consideration for the differences in specimen sizes as well as the length-to-diameter ratios.

The cinder soil without additives did not have measurable unconfined compressive strength. The addition of fly ash, without lime, did not result in any measureable strength; however lime, alone, did result in the development of a low strength. Moderate strengths were achieved with 6% lime and 20% fly ash, the maximum for the series. Peak strengths for the single source of fly ash used (Cholla) were:

Cholla	320 psi (23 Kg/cm ²)	GP-6-C20-56
No Additive	0 psi	GP-0-0-56

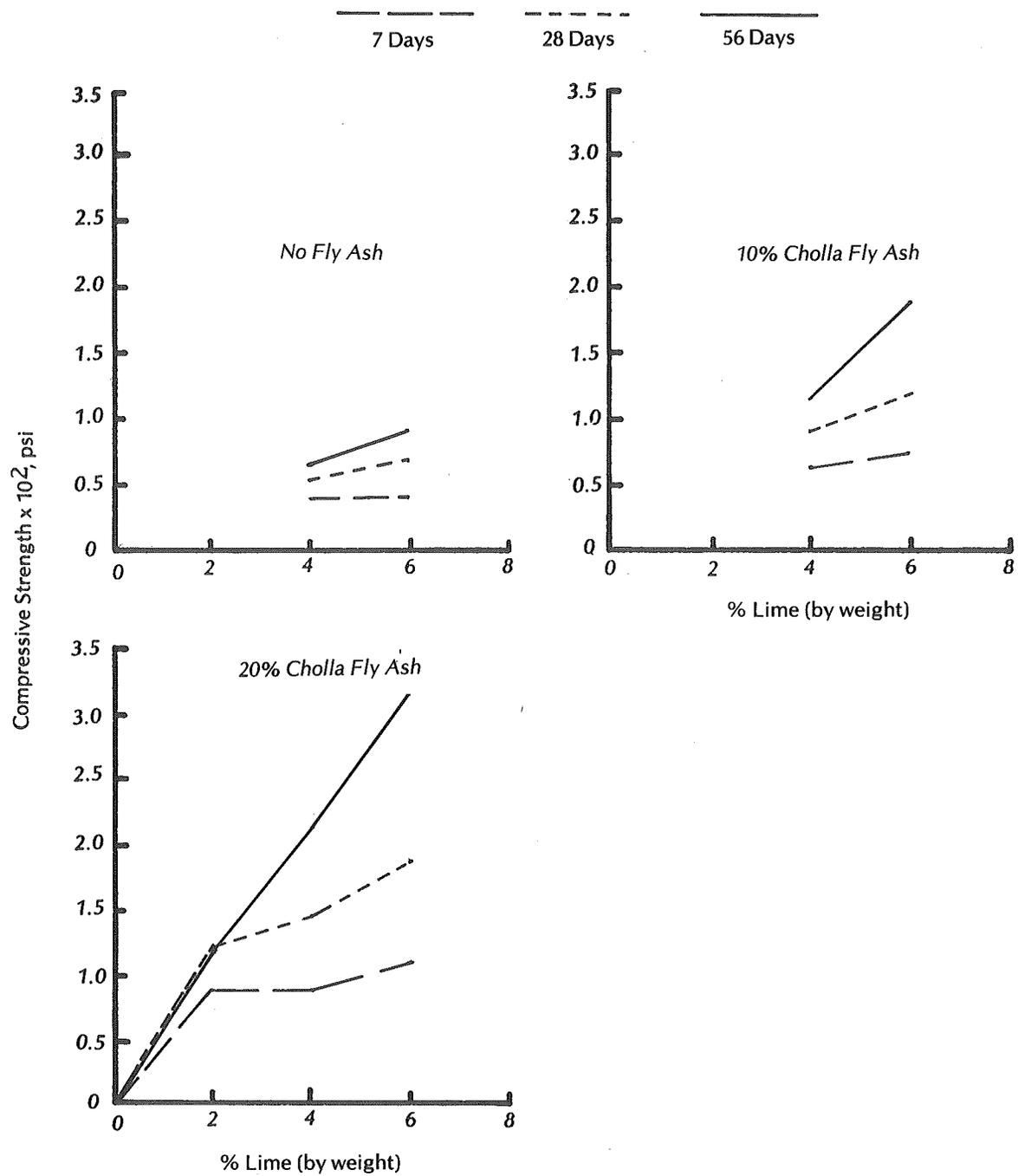


FIGURE 4-4. LIME CONTENT VS. UNCONFINED COMPRESSIVE STRENGTH, CINDERS AND CHOLLA FLY ASH.

4.3.3 Unconfined Compressive Strength vs. Age

The discussion in the previous section generally dealt with the relationship between strength and lime content for various fly ash contents and ages. The direct relationship between strength gain and age is also of prime importance since the strength gain takes place over a relatively long period of time. Rates of strength gain are illustrated in the curves of Figures 4-5, 6, 7 and 8. The age-strength curves include all data developed in the study and included in Appendix B. Each soil type and fly ash source combination is presented separately with all tested proportions of lime and fly ash.

4.3.3.1 Clayey Sand

The clayey sand demonstrated similar performance when combined with the Cholla, Four Corners and Navajo fly ashes. Most combinations, including lime without fly ash, exhibited a continued significant strength gain up to the final test age of 56 days. The rate of strength gain appeared only slightly less from 28 to 56 days than from 7 to 28 days, and therefore indicated probable continued gain for some undetermined time. The exceptions to this were the specimens with no lime which, irrespective of fly ash content, did not gain strength with time.

The Mohave fly ash combinations behaved uniquely in that a moderate rate of strength gain occurred for specimens with no lime. This was observed for all fly ash proportions and was attributed to the fly ash since no strength gain was observed for the clayey sand soil alone.

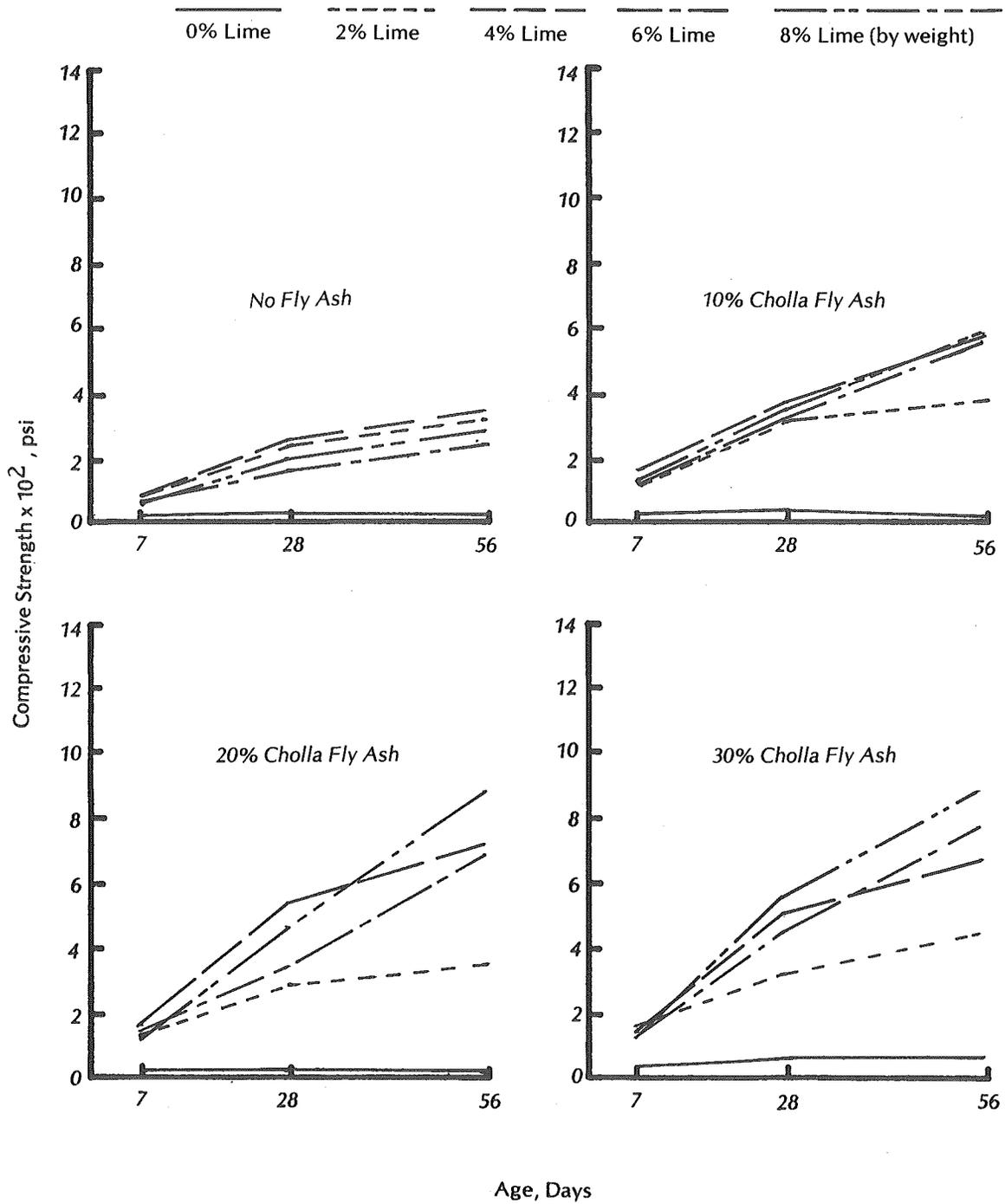


FIGURE 4-5A. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND CHOLLA FLY ASH.

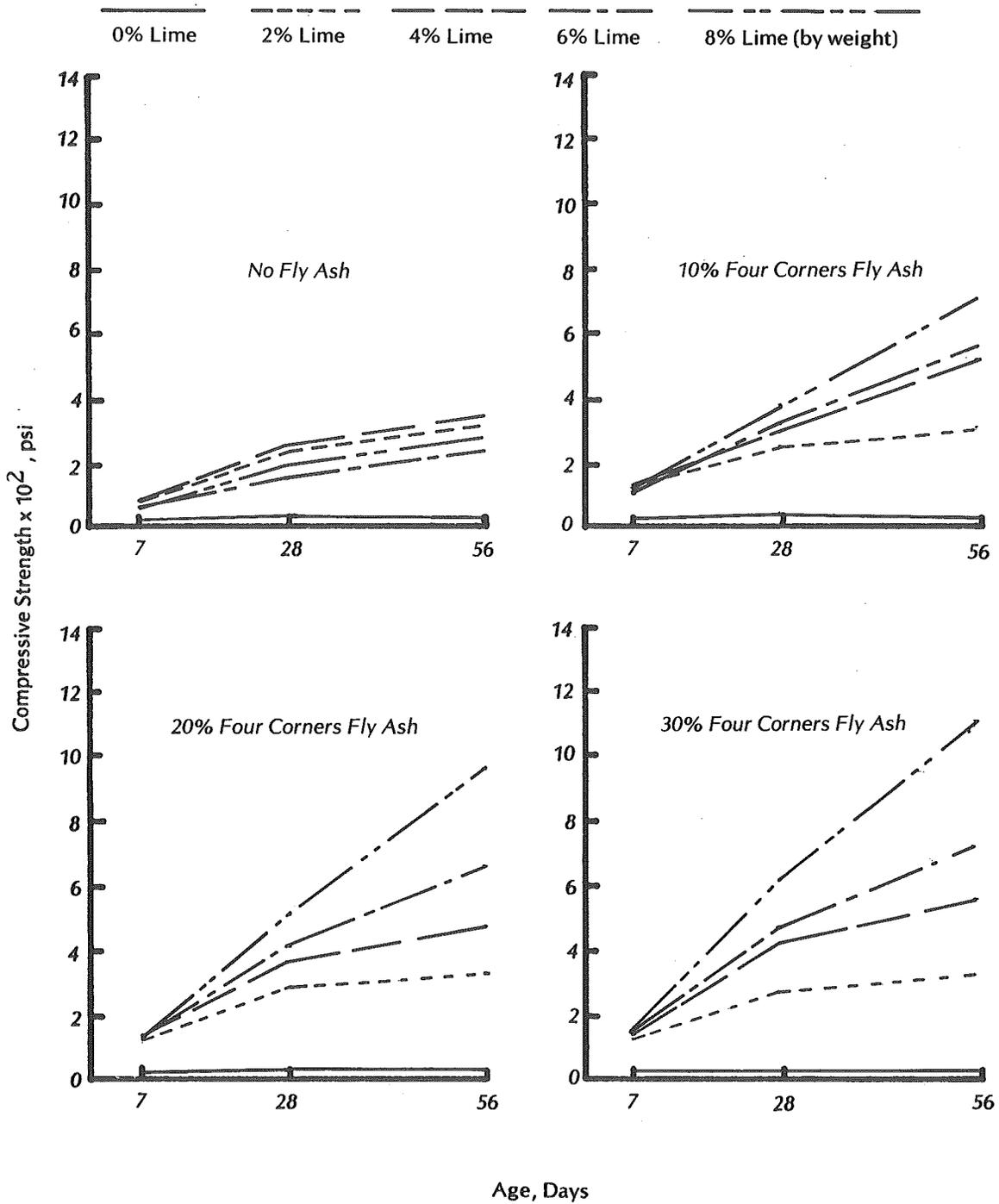


FIGURE 4-5B. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND FOUR CORNERS FLY ASH.

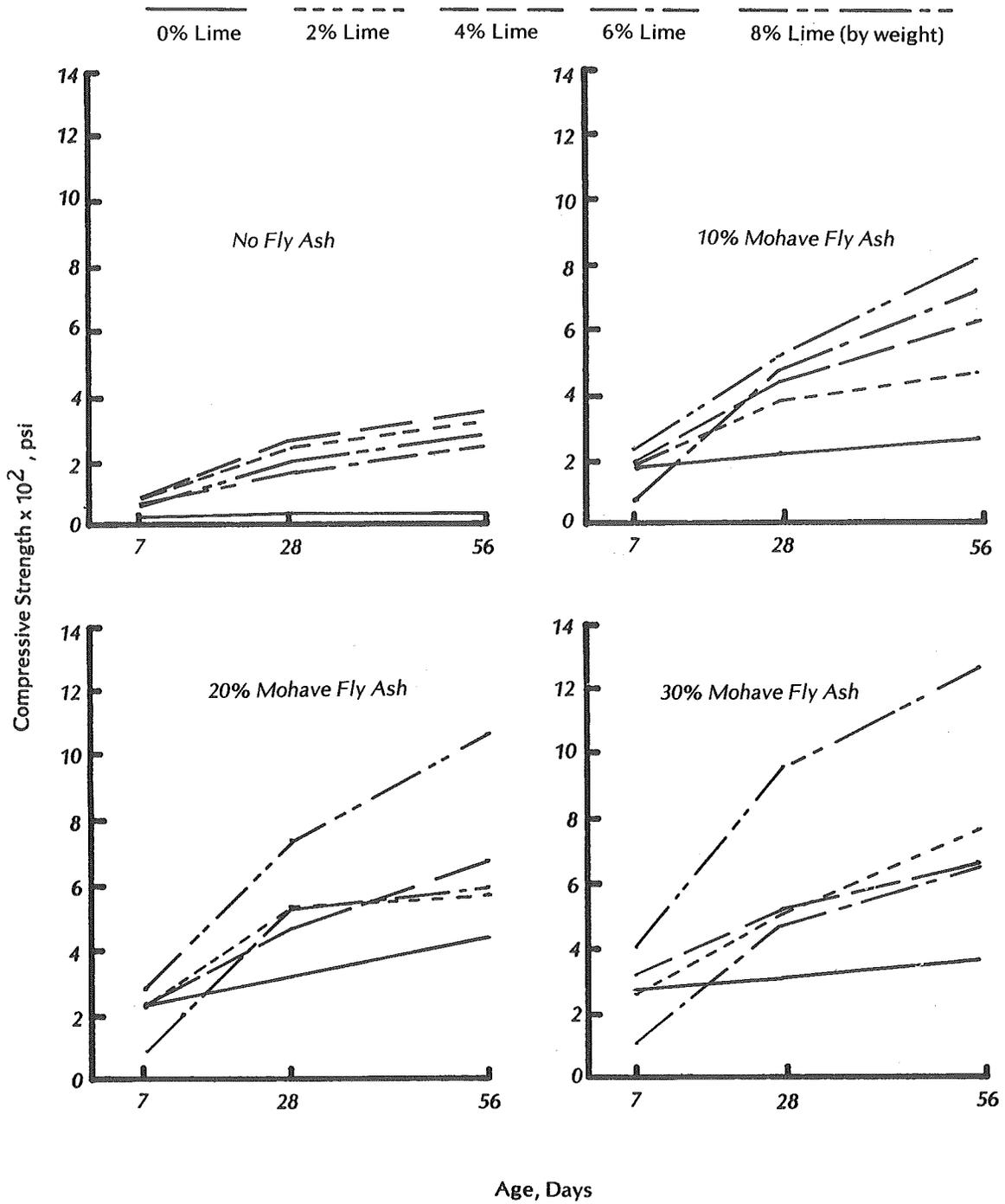


FIGURE 4-5C. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND MOHAVE FLY ASH.

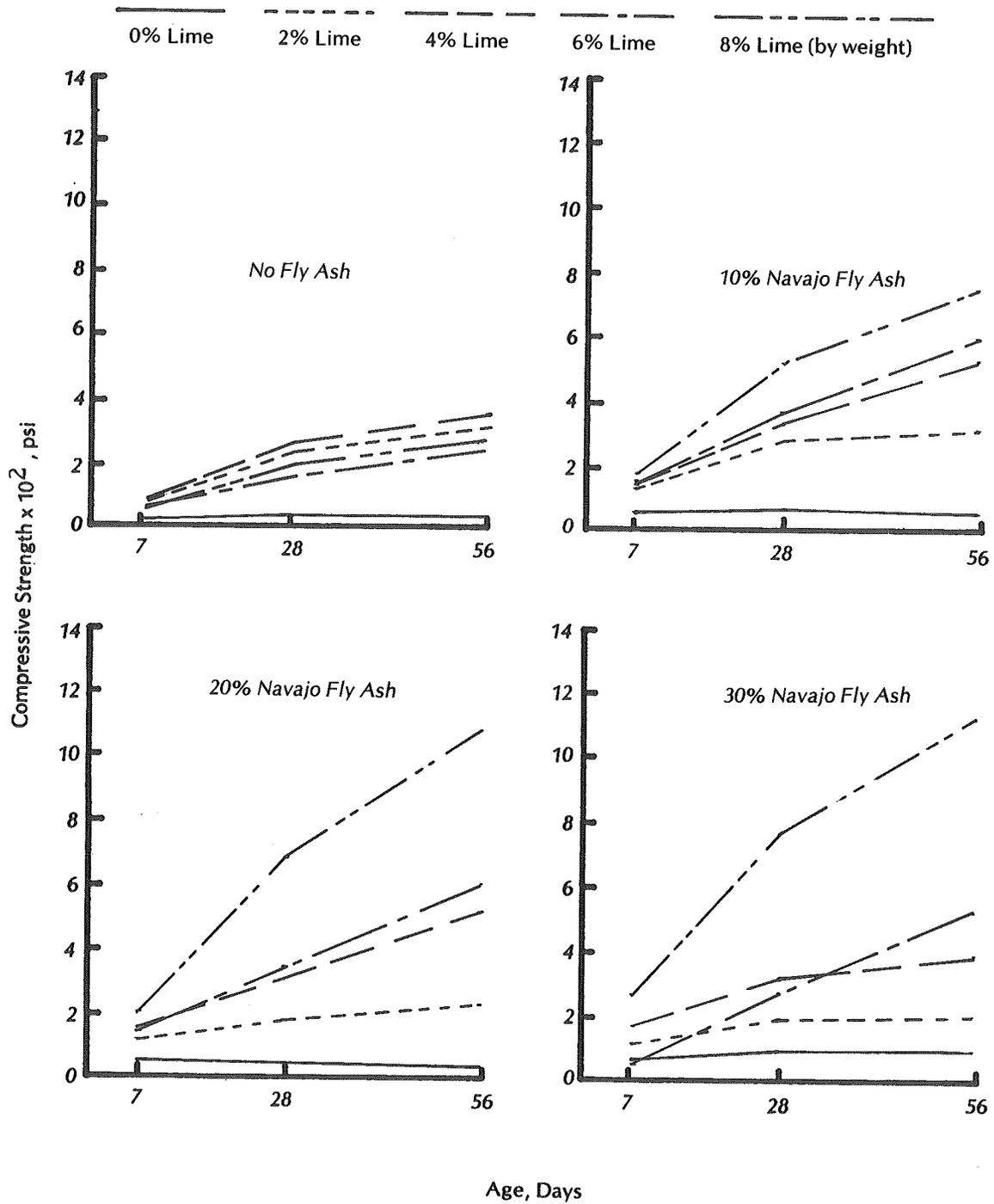


FIGURE 4-5D. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAYEY SAND AND NAVAJO FLY ASH.

4.3.3.2 Sand

Lime without fly ash did not result in strength gain with time for any combination tested. Fly ash alone resulted in a moderate rate of strength gain for the Mohave 30% series only.

The Cholla and Four Corners ash series showed similar rates of strength gain for all comparable combinations. Rates of strength increase remained nearly constant, for each mix combination, throughout the range of test ages. Combinations with high lime and fly ash proportions indicated probable significant strength gain beyond the final 56 day test age. Both the Mohave and Navajo series showed a general decrease in the rate of strength gain after 28 days, particularly for the higher lime proportions.

4.3.3.3 Clay

The rate of strength gain for the clay in combination with all fly ashes appeared to be strongly dominated by the lime content. The addition of fly ash alone resulted in moderate rates of strength gain for the Mohave fly ash series but no significant rates of increase for any other series. Several mix combinations, particularly in the Mohave and Navajo series and in the lower ranges of lime proportions showed no strength gain, or very slight strength gain, with time.

4.3.3.4 Cinders

The cinders test series was relatively limited compared to the other soil types. For most test series, the rate of strength gain was relatively uniform throughout the range of test ages, which indicated that significant continued gain in

strength could be expected beyond the 56 day test age. A moderate rate of strength gain was noted for the lime-only series.

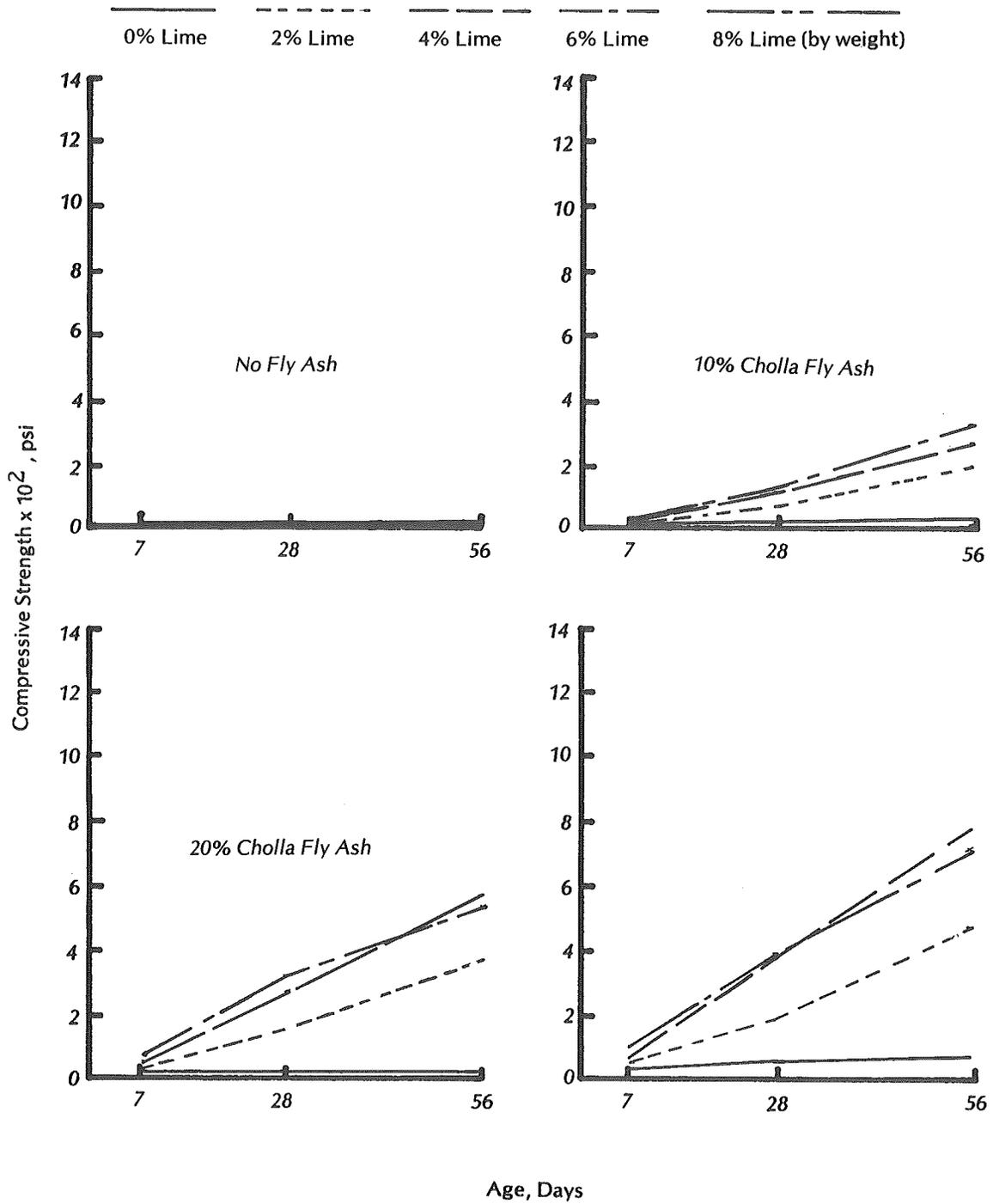


FIGURE 4-6A. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND CHOLLA FLY ASH.

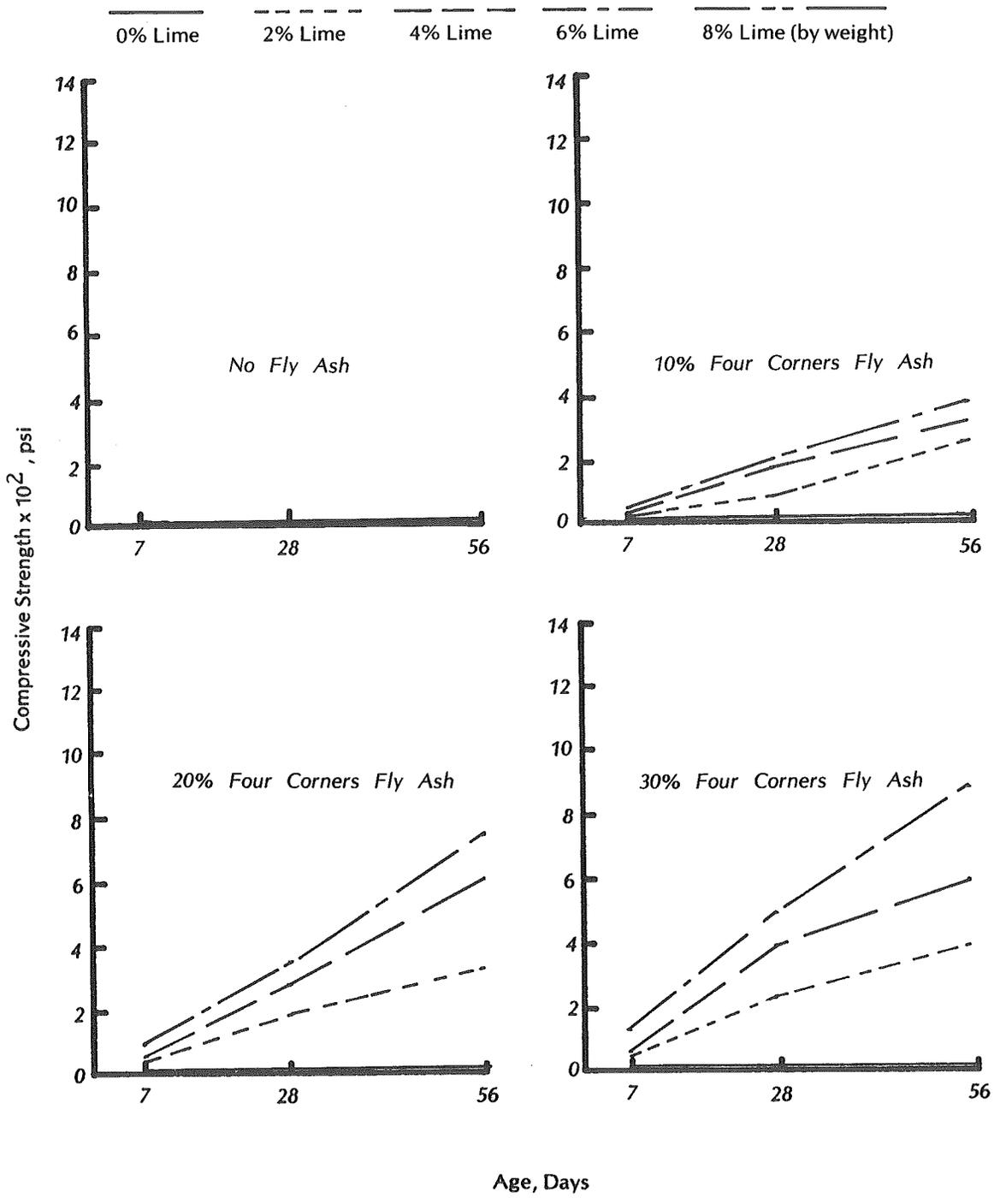


FIGURE 4-6B. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND FOUR CORNERS FLY ASH.

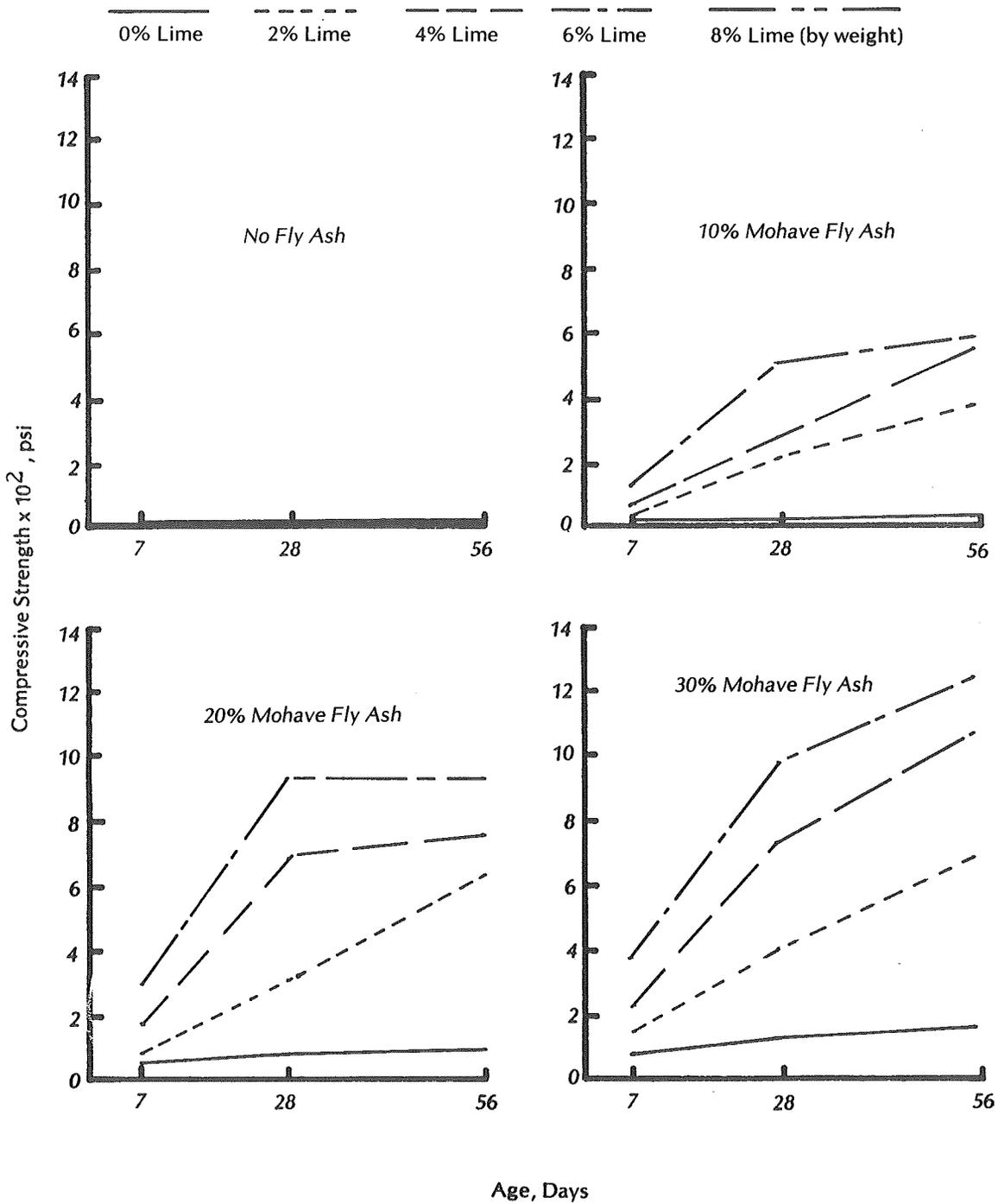


FIGURE 4-6C. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND MOHAVE FLY ASH.

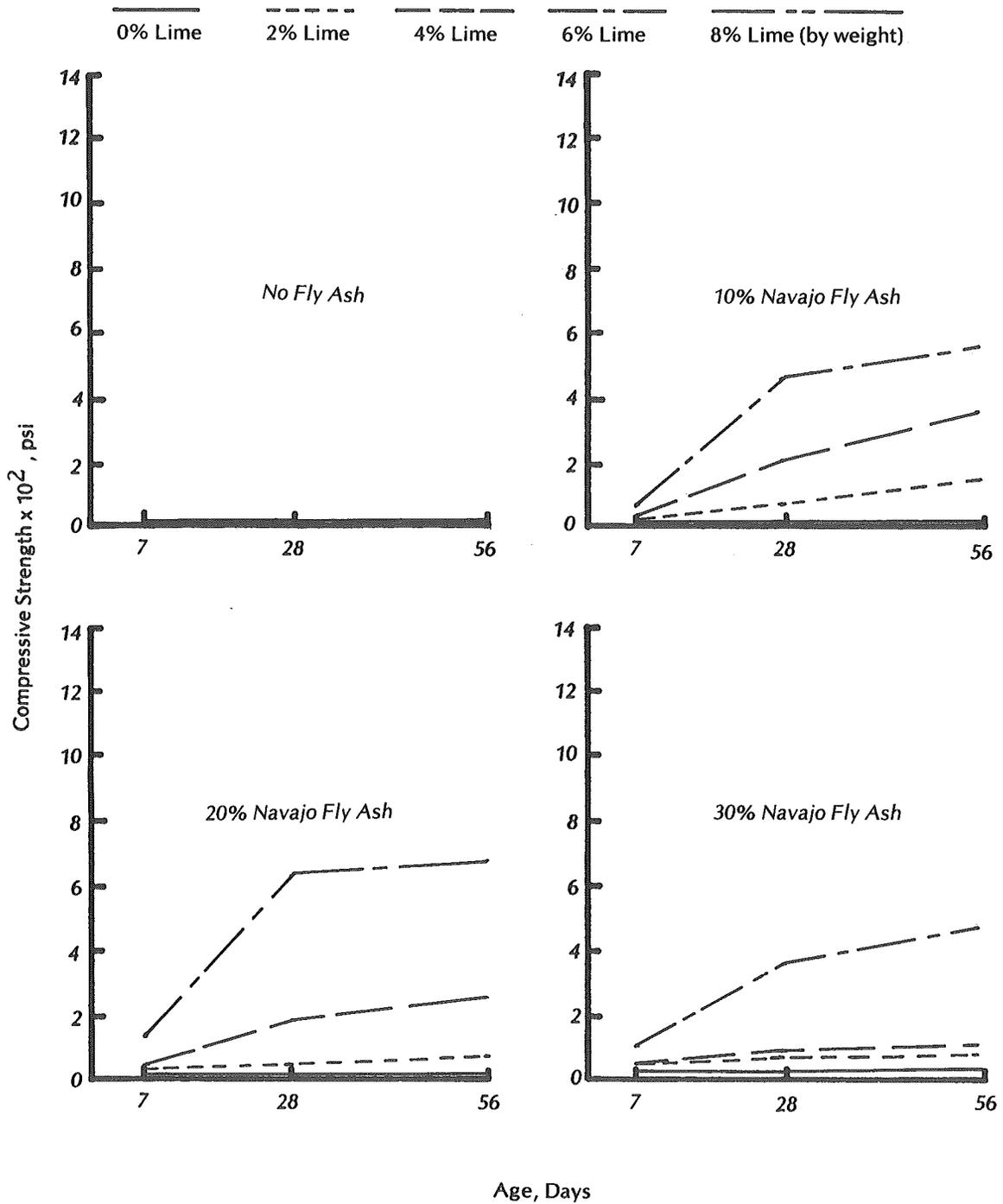


FIGURE 4-6D. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, SAND AND NAVAJO FLY ASH.

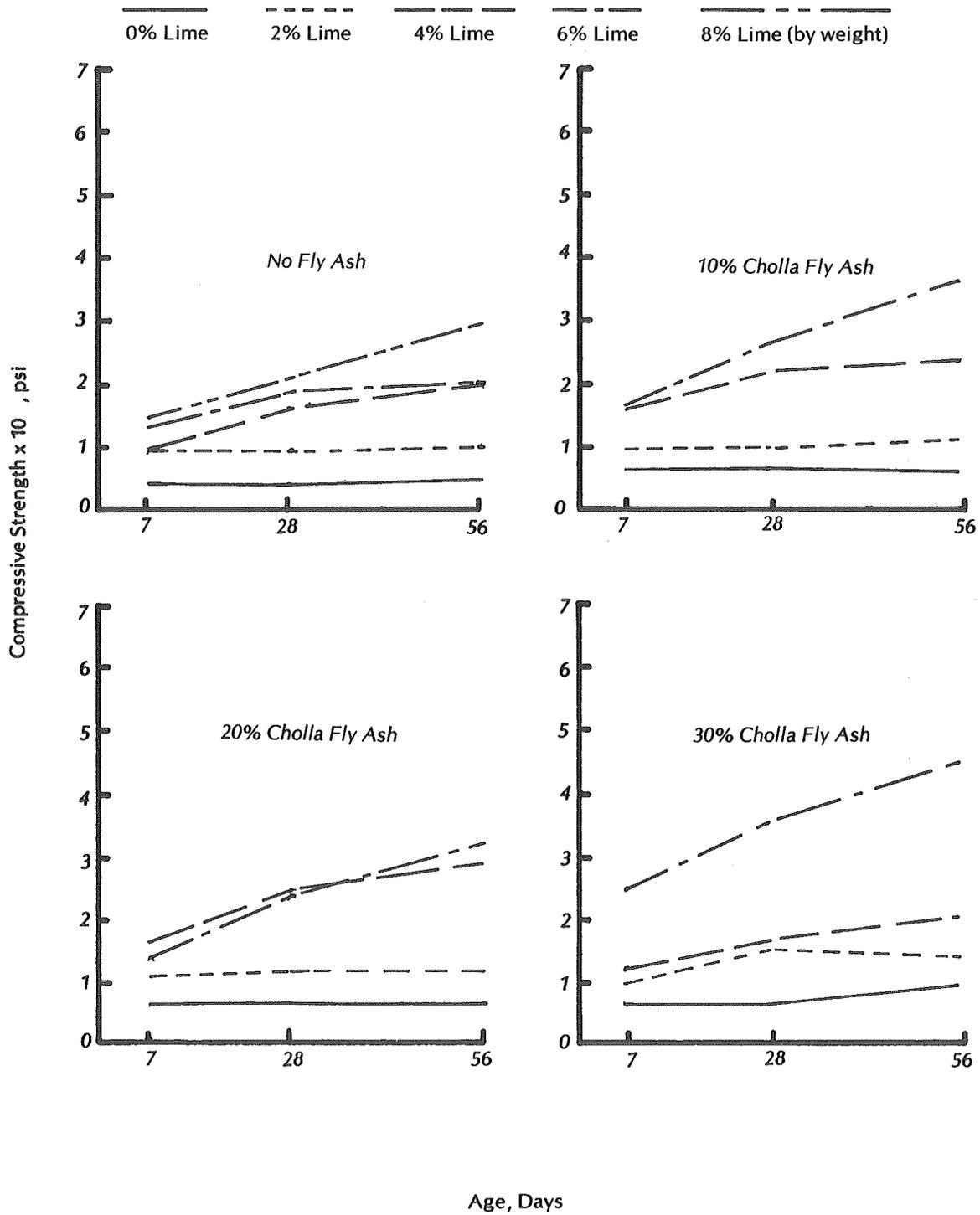


FIGURE 4-7A. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND CHOLLA FLY ASH.

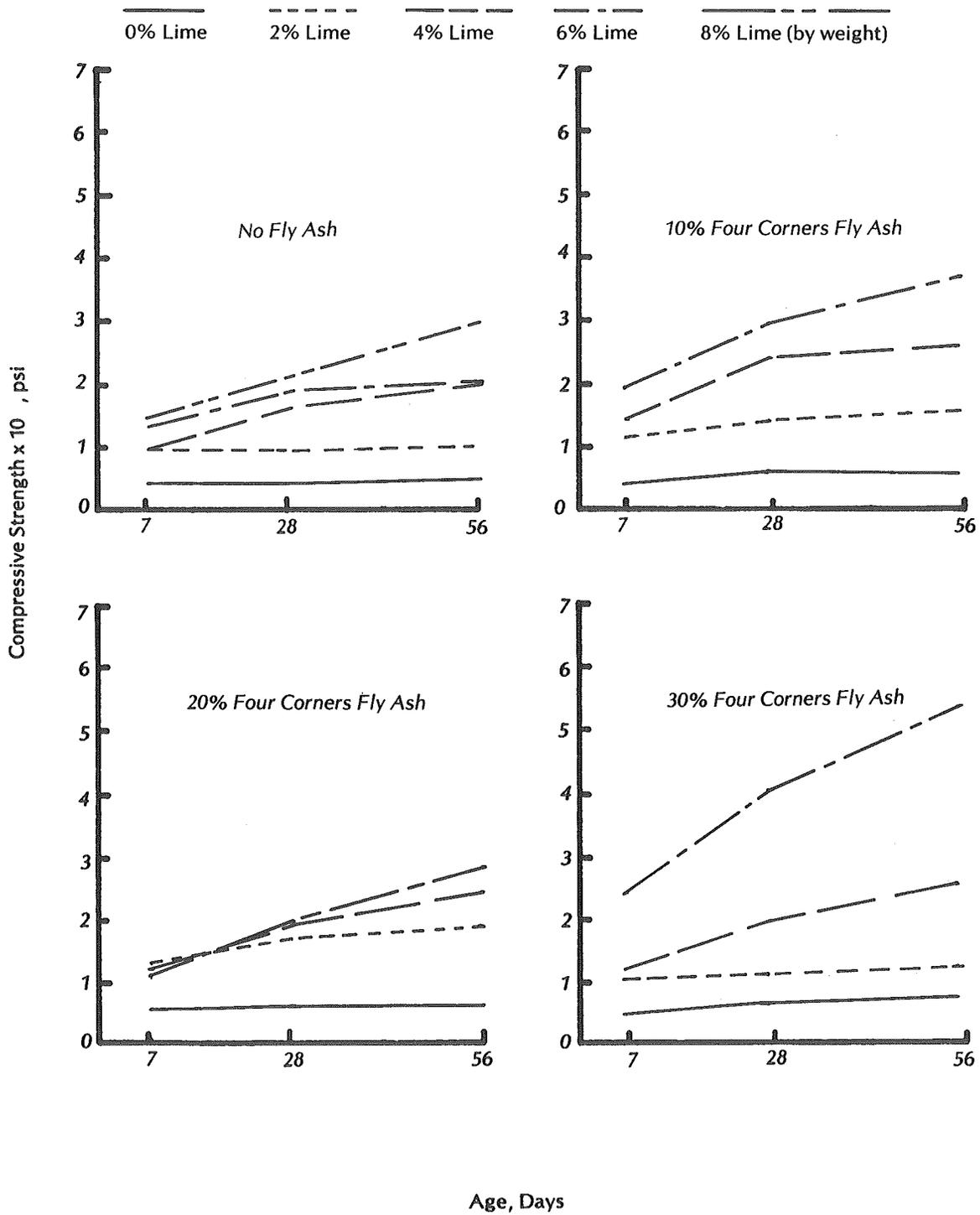


FIGURE 4-7B. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND FOUR CORNERS FLY ASH.

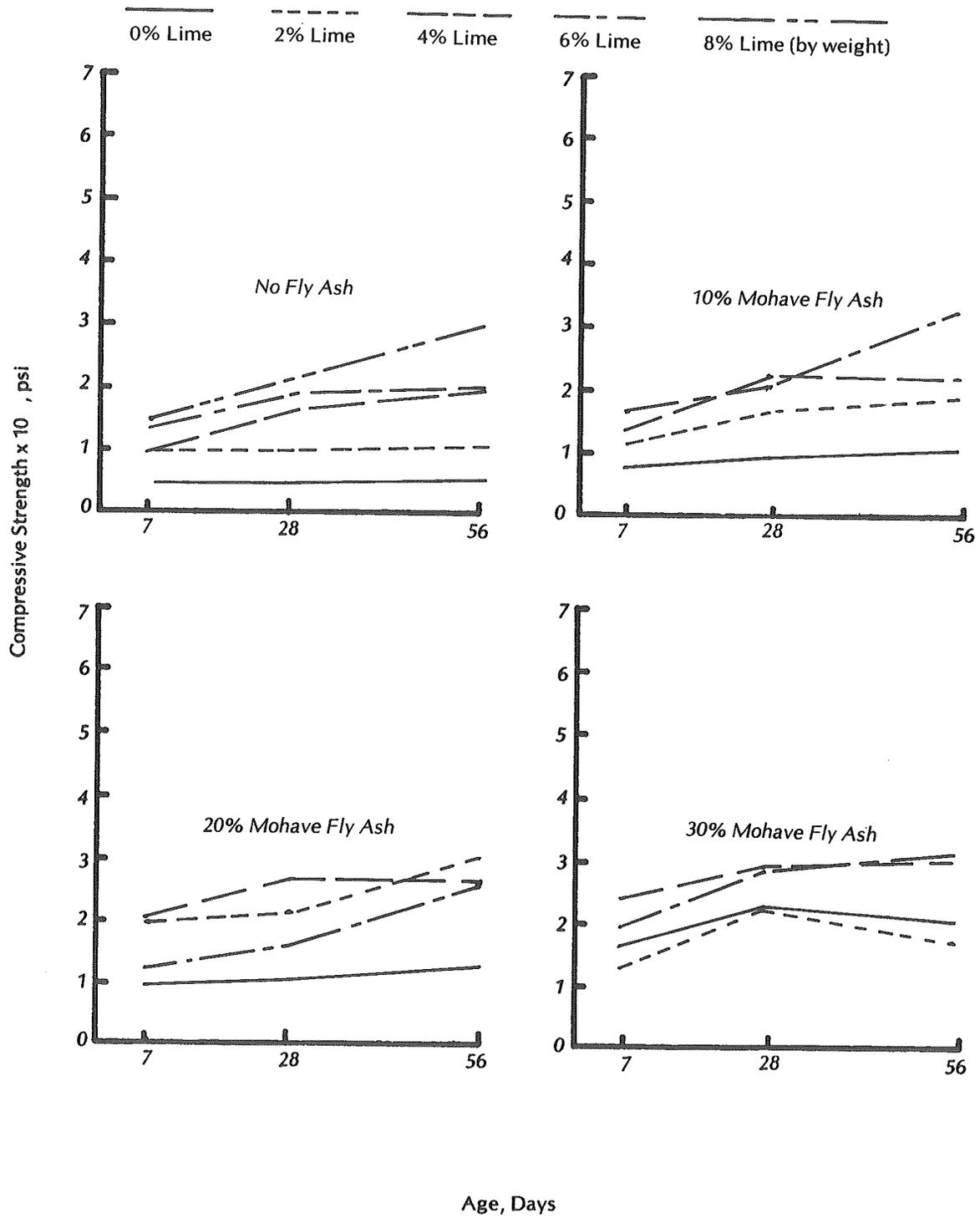


FIGURE 4-7C. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND MOHAVE FLY ASH.

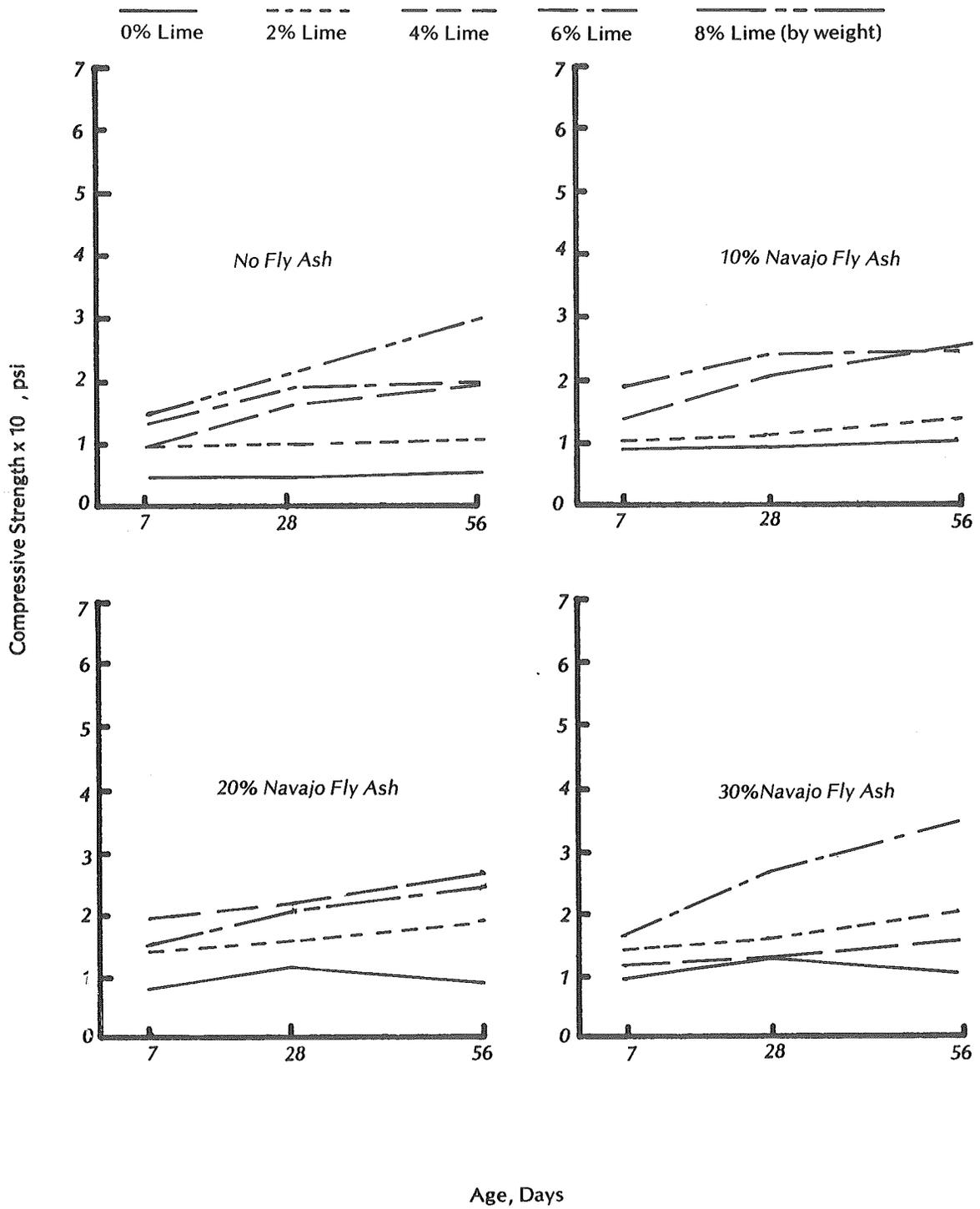


FIGURE 4-7D. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CLAY AND NAVAJO FLY ASH.

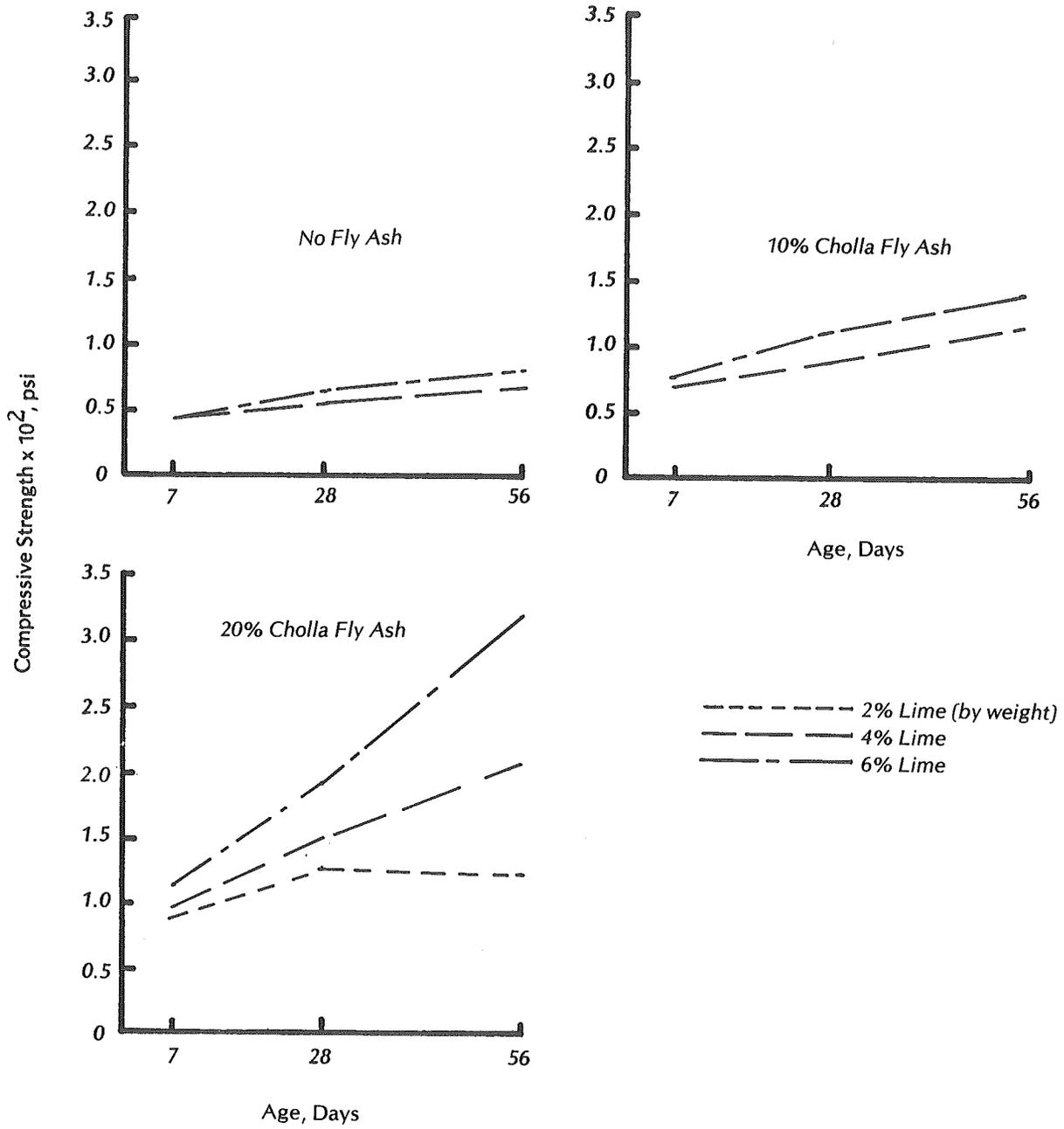


FIGURE 4-8. AGE VS. UNCONFINED COMPRESSIVE STRENGTH, CINDERS AND CHOLLA FLY ASH.

4.4 Data Uniformity and Reliability

4.4.1 General

Laboratory test data was evaluated in two areas to assess the general reliability and reproduceability of results. The range of variation within sets of companion specimens was evaluated to determine what specimens, if any, should be discarded as suspect. In addition, selected sets of companion specimens were duplicated for comparison with the originals.

4.4.2 Within-Test Variation

Several randomly selected sets of companion specimens were duplicated using sets of 10 specimens rather than the usual 3. Evaluation of these sets of 10 indicated that a coefficient of variation of about 15% was present in the test results. Based on judgement and the simple statistical evaluation of these small groups of observations, it was decided that test results which fell within $\pm 45\%$ of the average for the set should be included in the average. This rule was applied in the determination of unconfined compressive strength for each set of companion specimens.

4.4.3 Duplication of Results

The data represented by the strength vs. time curves of Chapter 4 (Figures 4-5, 6, 7 and 8) indicated a number of outstanding deviations from the trends established by the data as a whole. Data points which appeared to deviate markedly from the established pattern were checked by preparing and testing duplicate sets of specimens. Such duplicate data were developed for 23 of the lime-soil-fly ash combinations in the clayey sand test series.

Strengths of the duplicate sets varied from 54% to 129% of those of the original sets. Approximately half of the

retest sets resulted in no significant change in the apparent strength-time trends. Of the remaining sets, a few introduced new apparent anomalies in the relationships and the remainder tended to move the strength-time curves in the direction of the established patterns.

The retest data were used only for subjective evaluation of the overall data and were not otherwise incorporated into the study program.

CHAPTER 5. DURABILITY

5.1 General

The test series described in the previous sections were designed to establish basic strength relationships for various combinations of the four soils, four fly ashes and lime. Unconfined compressive strength data were intended as an indication of the potential for a given set of soil-lime-fly ash proportions and not necessarily as an indicator of field performance. The purpose of this chapter is to study certain weathering characteristics of the lime-fly ash stabilized soils in order to bring the evaluation one step closer to field performance.

Three test series were performed to evaluate durability, including standardized wet-dry and freeze-thaw cycles and the testing of soaked specimens in unconfined compression.

5.2 Wetting and Drying

5.2.1 Laboratory Procedures

Testing was performed in accordance with a modification of AASHTO Designation: T135-70, Wetting-and-Drying Test of Compacted Soil-Cement Mixtures (ASTM Designation: D 559-57). The curing period was revised from 7 to 28 days, since the soil-lime-fly ash reactions were known to develop more slowly than the cement hydration anticipated in the standard procedure. Molding data, including unit weights and as-molded moisture contents, are tabulated in Appendix B. The standard soil-cement test procedure was selected as a logical starting point for evaluation of wet-dry durability. In addition to rating the resistance of the mixtures to deterioration from wetting and drying, a secondary objective was to evaluate the suitability of the standard soil cement procedure for use with lime-soil-fly ash mixtures.

5.2.2 Test Results

Laboratory results for all series tested are tabulated in Tables 5-1a, b, c and d. Data include cycles completed, maximum volume change, maximum moisture content and final weight loss.

The clayey sand test series involved 15 lime-soil-fly ash mixtures, including 3 fly ash sources, lime proportions from 2% to 8% and fly ash proportions from 0% to 20%. All sets of specimens survived the 12 cycles of wetting and drying established by the standard test procedure. Volume changes overall ranged from -3.0% to 0.9%, although the range was reduced to -0.5% to +0.9% for those sets of specimens with 4% lime or more (irrespective of fly ash content). Maximum moisture contents ranged from 1% to 5% above optimum with no particular trends evidenced. Final weight losses were in the range of about 3% to 25%, and generally with increased lime content. The Mohave ash specimens appeared to outperform the Cholla and Navajo specimens (no Four Corners ash was included) by a clear margin.

The sand test series involved 8 lime-soil-fly ash mixtures, and included lime contents from 2% to 6%, fly ash contents from 0% to 20% and the Cholla fly ash only. Specimens with lime only failed to complete the 12 test cycles; however, the number of cycles completed increased with lime content. All specimens with lime and fly ash completed the 12 cycles. Maximum volume changes were in the general range of -2.4% to +3.3%. Maximum moisture contents increased from 0% to 4% above optimum during the test series. Weight losses were severe, and only the higher lime and fly ash contents (SP-4-20, SP-6-10 and SP-6-20) survived with losses of 10% or less.

TABLE 5-1a. Wet-Dry Durability Characteristics, Clayey Sand.

Wet-Dry Characteristic	% Lime	0% Fly Ash	% Cholla Fly Ash		% Mohave Fly Ash		% Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	***	12	***	12	***	12	***
	4	12	12	12	12	12	12	12
	6	12	***	12	***	12	***	12
	8	12	***	***	***	***	***	***
Maximum Volume Change, %	2	***	-3.0	***	0.9	***	-2.8	***
	4	0.7	0.2	-0.2	0.7	0.4	0.4	0.4
	6	0.4	***	-0.5	***	0.9	***	0.2
	8	0.9	***	***	***	***	***	***
Maximum Moisture Content, %	2	***	15.0	***	13.3	***	13.7	***
	4	13.2	14.5	15.9	14.5	14.8	14.6	15.5
	6	14.0	***	16.2	***	15.4	***	16.0
	8	14.7	***	***	***	***	***	***
Final Weight Loss, %	2	**	25.1	***	14.8	***	18.5	***
	4	9.1	15.8	8.1	3.9	3.4	8.9	15.7
	6	3.6	***	4.7	***	3.3	***	5.9
	8	3.2	***	***	***	***	***	***

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-1b. Wet-Dry Durability Characteristics, Sand.

Wet-Dry Characteristics	% Lime	0% Fly Ash	% Cholla Fly Ash	
			10	20
* Cycles Completed	2	2	12	***
	4	7	12	12
	6	8	12	12
Maximum Volume Change, %	2	**	-1.2	***
	4	3.3	-2.4	1.5
	6	1.4	0.9	1.2
Maximum Moisture Content, %	2	12.0	13.2	***
	4	11.4	13.0	12.2
	6	11.3	12.2	12.5
Final Weight Loss, %	2	**	44.6	***
	4	68.6	21.8	10.1
	6	54.1	6.5	4.5

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-1c. Wet-Dry Durability Characteristics, Clay.

Wet-Dry Characteristics	% Lime	0% Fly Ash	% Cholla Fly Ash		% Mohave Fly Ash		% Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	1	1	***	2	***	1	***
	4	1	2	1	2	2	1	1
	6	1	4	3	3	2	2	3
Maximum Volume Change, %	2	6.7	**	***	13.8	***	5.1	***
	4	12.9	-11.3	2.4	-3.3	2.2	4.2	4.1
	6	2.4	-7.2	-12.9	-6.9	2.4	0.9	2.4
Maximum Moisture Content, %	2	21.1	30.3	***	29.0	***	30.0	***
	4	26.7	26.0	25.4	25.6	25.7	28.0	28.6
	6	27.1	24.4	25.8	24.6	28.0	24.9	25.4
Final Weight Loss, %	2	**	**	***	39.9	***	19.2	***
	4	**	24.5	**	13.4	20.4	5.2	8.0
	6	**	19.0	28.6	18.8	22.0	11.4	16.0

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-1d. Wet-Dry Durability Characteristics, Cinders.

Wet-Dry Characteristics	% Lime	0% Fly Ash	% Cholla Fly Ash	
			10	20
* Cycles Completed	0	***	***	0
	2	***	***	1
	4	***	***	2
	6	2	2	12
Maximum Volume Change, %	0	***	***	**
	2	***	***	-1.9
	4	***	***	-2.7
	6	-4.0	0.6	-1.0
Maximum Moisture Content, %	0	***	***	**
	2	***	***	30.2
	4	***	***	28.0
	6	35.7	30.3	28.4
Final Weight Loss, %	0	***	***	**
	2	***	***	**
	4	***	***	11.1
	6	43.7	21.3	50.8

* In cases where the cycles completed are less than 12, the wet-dry characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

Eighteen mixtures were tested in the clay soil series including lime contents from 2% to 6%, fly ash contents from 0% to 20% and 3 fly ashes (Cholla, Mohave and Navajo). No specimens survived more than 4 cycles of the scheduled 12. The number of cycles completed appeared to increase with lime content, irrespective of fly ash content or source. Volume changes were relatively high, in the general range of -13% to +14%. The maximum increase in moisture content varied from about 0% to 11% above optimum during the tests. Moisture change appeared to increase with higher fly ash contents and decrease with higher lime contents. Both volume changes and moisture changes should be considered as estimates since specimens deteriorated too rapidly for reliable weights and measurements to be obtained. Weight losses were high and in some cases the control sample deteriorated more rapidly than the brushed sample. The few low values of weight loss were misleading since companion samples had deteriorated so badly they could no longer be handled. The weight loss criteria did not provide any basis for ranking the mixtures since completed cycles varied and weight losses were erratic and misleading.

The cinder test series was performed using only the Cholla fly ash and with lime and fly ash contents in the ranges of 0% to 6% and 0% to 20% respectively. Of the 6 mixtures tested, only one (GP-6-20) survived the standard 12 test cycles. The remaining series failed in from 0 to 2 cycles. Indicated volume changes were in the range of -4% to +1% and moisture changes appeared to be negligible. Both volume and moisture observations were estimated since most specimens deteriorated too rapidly for accurate weight and measurements to be obtained. Weight loss for the single specimen to survive

12 cycles was 50%. Indicated weight loss for the remainder of the specimens was less than 50% although the values are not comparable due to great differences in completed cycles.

5.3 Freezing and Thawing

5.3.1 Laboratory Procedures

Freeze-thaw testing was performed in accordance with a modification of AASHTO Designation: T136-70 (ASTM Designation: D560-57). The curing period was revised from 7 days to 28 days, since the soil-lime-fly ash reactions were known to develop more slowly than the cement hydration anticipated in the standard procedure. Molding data, including unit weight and as-molded moisture contents are tabulated in Appendix B. The standard soil-cement test procedure was selected as a logical starting point for evaluation of freeze-thaw durability. In addition to rating the resistance of the specimen to deterioration from freezing and thawing, a secondary objective was to evaluate the suitability of the standard soil cement procedure for use with lime-soil-fly ash mixtures.

5.3.2 Test Results

Laboratory results for all series tested are tabulated in Tables 5-2a, b, c and d. Data include cycles completed, maximum volume change, and final weight loss.

The clayey sand test series involved 15 lime-soil-fly ash mixtures, and included 3 fly ash sources, lime proportions from 2% to 8% and fly ash proportions from 0% to 20%. All sets of specimens survived the 12 freeze-thaw cycles established by the standard test procedure. Volume changes were erratic and difficult to evaluate

TABLE 5-2a. Freeze-Thaw Durability Characteristics,
Clayey Sand

Freeze-Thaw Characteristic	% Lime	0% Fly Ash	%Cholla Fly Ash		%Mohave Fly Ash		%Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	***	12	***	12	***	12	***
	4	12	12	12	12	12	12	12
	6	12	***	12	***	12	***	12
	8	12	***	***	***	***	***	***
Maximum Volume Change, %	2	***	4.9	***	5.9	***	9.8	***
	4	6.6	7.5	8.3	10.1	-12.1	15.5	18.7
	6	10.7	***	10.1	***	-10.1	***	12.8
	8	21.9	***	***	***	***	***	***
Final Weight Loss, %	2	***	33.0	***	20.7	***	37.5	***
	4	32.3	27.4	35.5	24.2	23.5	37.2	55.5
	6	40.5	***	31.9	***	20.6	***	52.1
	8	51.6	***	***	***	***	***	***

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

*** Combination not tested.

TABLE 5-2b. Freeze-Thaw Durability Characteristics, Sand

Freeze-Thaw Characteristics	% Lime	0% Fly Ash	%Cholla Fly Ash	
			10	20
* Cycles Completed	2	1	12	***
	4	1	12	12
	6	1	12	12
Maximum Volume Change, %	2	2.2	-2.5	***
	4	0.7	8.2	8.3
	6	4.3	3.7	-7.3
Final Weight Loss, %	2	**	64.0	***
	4	**	59.8	36.0
	6	**	60.8	37.6

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-2c. Freeze-Thaw Durability Characteristics, Clay

Freeze-Thaw Characteristic	% Lime	0% Fly Ash	%Cholla Fly Ash		%Mohave Fly Ash		%Navajo Fly Ash	
			10	20	10	20	10	20
* Cycles Completed	2	1	0	***	3	***	0	***
	4	1	5	3	3	6	2	4
	6	5	8	8	8	7	7	7
Maximum Volume Change, %	2	7.6	**	***	9.5	***	3.7	***
	4	6.3	10.8	7.8	8.8	11.6	5.3	2.8
	6	7.9	12.6	11.8	10.5	23.5	12.1	26.4
Final Weight Loss, %	2	**	**	***	**	***	**	***
	4	**	**	**	**	40.6	**	**
	6	**	42.9	54.3	36.8	46.6	52.7	59.5

* In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.

** Deterioration of specimen prevented measurement.

*** Combination not tested.

TABLE 5-2d. Freeze-Thaw Durability Characteristics, Cinders

Freeze-Thaw Characteristic	% Lime	0% Fly Ash	%Cholla Fly Ash	
			10	20
* Cycles Completed	0	***	***	1
	2	***	***	1
	4	***	***	7
	6	2	3	5
Maximum Volume Change, %	0	***	***	2.0
	2	***	***	3.3
	4	***	***	-2.3
	6	-2.3	1.6	3.5
Final Weight Loss, %	0	***	***	**
	2	***	***	**
	4	***	***	57.3
	6	39.2	50.4	45.9

- * In cases where the cycles completed are less than 12, the freeze-thaw characteristics represent values at the end of the last cycle and cannot be compared to other values unless the cycles completed are the same.
- ** Deterioration of specimen prevented measurement.
- *** Combination not tested.

due to weight losses and consequent dimensional changes which occurred in the control specimens. Maximum volume change data, tabulated in Table 5-2a was therefore not considered reliable or indicative. Weight losses were high, and varied from about 21% to 56%. Variations in weight loss nevertheless appeared to provide a clear correlation between durability and fly ash source. Ranked from most durable to least durable, Mohave, Cholla and Navajo fly ash specimens compared in that order for each comparable series.

The sand test series involved 8 lime-soil-fly ash mixtures and included lime contents from 2% to 6%, fly ash contents from 0% to 20% and the Cholla fly ash only. Specimens with lime only (no fly ash) deteriorated to failure within the first freeze-thaw cycle. All specimens with lime and fly ash completed the 12 standard cycles. Maximum volume changes could only be estimated due to spalling which rendered accurate measurement impossible. Weight losses were very high, 36% to 64%, at completion of the 12 cycles. The higher lime and fly ash contents suffered the lower weight losses (SP-4-20C and SP-6-20C).

Eighteen mixtures were tested in the clay soil series, including lime contents from 2% to 6%, fly ash contents from 0% to 20% and 3 fly ashes (Cholla, Mohave and Navajo). No mixture completed the standard 12 cycles. The number of cycles completed varied from 0 for two of the low lime mixtures to a high of 8 for three of the high lime mixtures. Cycles completed increased with lime content and with the addition of fly ash. Volume changes were again only estimated due to spalling of the control specimens. Weight losses were very high, 37% to 60%, in specimens which remained in

suitable condition for weight determination. In general only the high (6%) lime specimens could be weighed. Based on weight loss, the Mohave ash specimens deteriorated slightly less than the Cholla and Navajo specimens.

The cinder test series was performed using only the Cholla fly ash and with lime and fly ash contents in the ranges of 0% to 6% and 0% to 20% respectively. None of the mixtures survived the 12 standard test cycles. The highest number of cycles completed by the 6 mixtures was 7 cycles for the GP-6-20C mix. Volume changes were inconclusive due to deterioration of control specimens. Weight losses were very high, 39% to 57%, with no trends indicated.

5.4 Soaked Compressive Strength

5.4.1 Laboratory Procedures

Thirteen sets of specimens in the clayey sand soil series were tested in soaked unconfined compressive strength. Soil-lime-fly ash mixtures were selected to represent the Cholla and Navajo fly ash, lime contents of 2% to 6%, fly ash contents of 10% to 30% and curing periods of 28 and 56 days. Specimens were molded along with the regular unconfined compressive strength samples. Molding densities and moisture contents are therefore represented by the data in the appropriate categories of Appendix B.

Except for the 24 hours immediately preceding testing, specimens were cured in the same manner as specimens to be tested at molding (optimum) water content. Specimens were soaked in distilled water at moist room temperature for the 24 hours prior to testing.

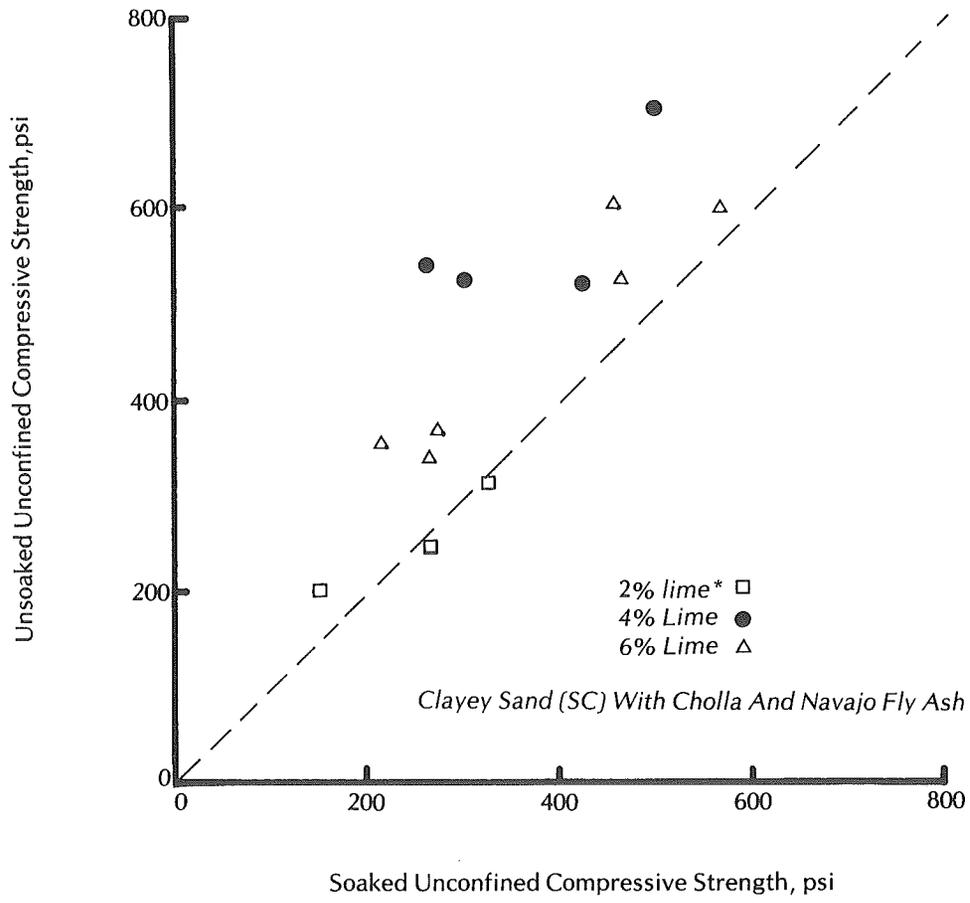
After curing and soaking, specimens were tested in unconfined compression as previously described in Chapter 4.

5.4.2 Test Results

Unconfined compressive strengths of soaked specimens were compared to the strengths of companion specimens tested at molding water content. Expressed as a percentage of the strength of the unsoaked specimens, the strengths ranged from 48% to 107% with a median value of 77% and an average of 79%. The comparison between comparable soaked and unsoaked strengths is illustrated in Figure 5-1.

Ranked in order of per cent retained strength, the data indicated that age was the significant factor in maintaining a high retained strength. All 28 day specimens ranked at or below the average strength, as can be seen in Table 5-3. Lime and fly ash contents did not appear to correlate well with retained strength. Absolute values of compressive strengths also provided little clear indication of potential retained strength; higher compressive strengths (at optimum moisture) tended toward lower retained strengths.

Soaked compressive strength data are included in Appendix B. Each tabulated value is an average for 3 companion specimens.



*By Weight

FIGURE 5-1. SOAKED VS. UNSOAKED UNCONFINED COMPRESSIVE STRENGTH

TABLE 5-3. Unconfined Compressive Strength Retained after 24 Hour Soak, Clayey Sand

% Lime	Fly Ash Source	% Fly Ash	Cure, Days	Unconfined Compressive Strength		
				Unsoaked, psi	Soaked, psi	$\frac{\text{Soaked}}{\text{Unsoaked}}, \%$
2	Navajo	20	56	242	260	107
2	Navajo	10	56	312	321	103
6	Navajo	10	56	594	574	97
6	Navajo	30	56	534	467	87
4	Navajo	10	56	521	426	82
6	Cholla	20	28	339	269	79
6	Navajo	10	28	363	281	77
6	Navajo	20	56	601	463	77
2	Navajo	20	28	195	146	75
6	Navajo	20	28	353	225	72
4	Cholla	20	56	705	497	70
4	Navajo	20	56	522	299	57
4	Cholla	20	28	538	259	48

CHAPTER 6. MIX DESIGN

6.1 General

The mix proportions utilized in the study were selected on the basis of assumed practical ranges of lime and fly ash proportions. One objective of the study was to evaluate the possibility of developing a rational method of proportioning using strength as a target parameter. The results of the unconfined compressive strength tests were used in the development of such a mix design procedure.

The term "unconfined compressive strength" can be misleading if a definition of terms is not developed. Compressive strength as applied to stabilized soil specimens is a relative rather than an absolute parameter. The strength discussed throughout this chapter is that of specimens molded at an optimum moisture content and tested at the as-molded moisture content. The strength results are, in a sense, ideal or at least controlled in a manner not to be expected in the field. Considerations of durability (saturation and wet-dry or freeze-thaw cycling) must be superimposed on the conclusions developed from compressive strength test results. In addition, sample geometry is known to influence compressive strength test results; therefore data presented here should be examined with full consideration of the size and shape of test specimens. Particularly, the comparison between the cinder specimens and the other three soil types is certain to be affected by the size and relative proportions of the samples. As explained in detail in Chapter 4, cinder specimens were 4 in. diameter by 4.6 in. high (10.2 x 11.7 cm.) while the remainder of the soil specimens were 1.3 in. diameter by 2.8 in. high (3.3 x 7.1 cm.).

6.2 Development of Iso-Strength Curves

The data illustrated in the strength curves of Chapter 4 (Figures 4-1, 2, 3 and 4) were analyzed with the objective of developing a family of design curves relating compressive strength to lime

and fly ash proportions. Each age, fly ash source, fly ash content and soil type was treated separately. The strength vs. % lime data were fitted, using the least squares method, by a linear equation of the general form;

$$Y = A + BX, \text{ in which:}$$

Y = compressive strength (psi)

A = constant (initial compressive strength, psi)

B = constant

X = lime content, %

Statistical correlations of the straight line equations were judged adequate for the purpose and no equations other than the straight line were fitted to the data.

The % lime vs % fly ash design curves were developed from data generated from the best fit equations described above. Data were plotted on % lime vs % fly ash grids and iso-strength contours were fitted to the plotted data. The families of iso-strength curves are presented in Figures 6-1 through 6-6.

Clayey sand iso-strength curves are presented for ages of 7, 28 and 56 days on Figures 6-1A, 6-1B and 6-1C, respectively. All four fly ash sources are included on each Figure for comparison at a selected age. The curves provide quick insight relative to the strength gain characteristics of each ash. The tendency for mixtures with Mohave ash, for example, to develop relatively high strength at low lime contents is clearly illustrated.

Curves representing the sand and clay soil series are similarly presented in Figures 6-2 and 6-3, respectively.

The change in the sign of the slope for several of the sand sets illustrates the reduction in strength which can occur as fly ash

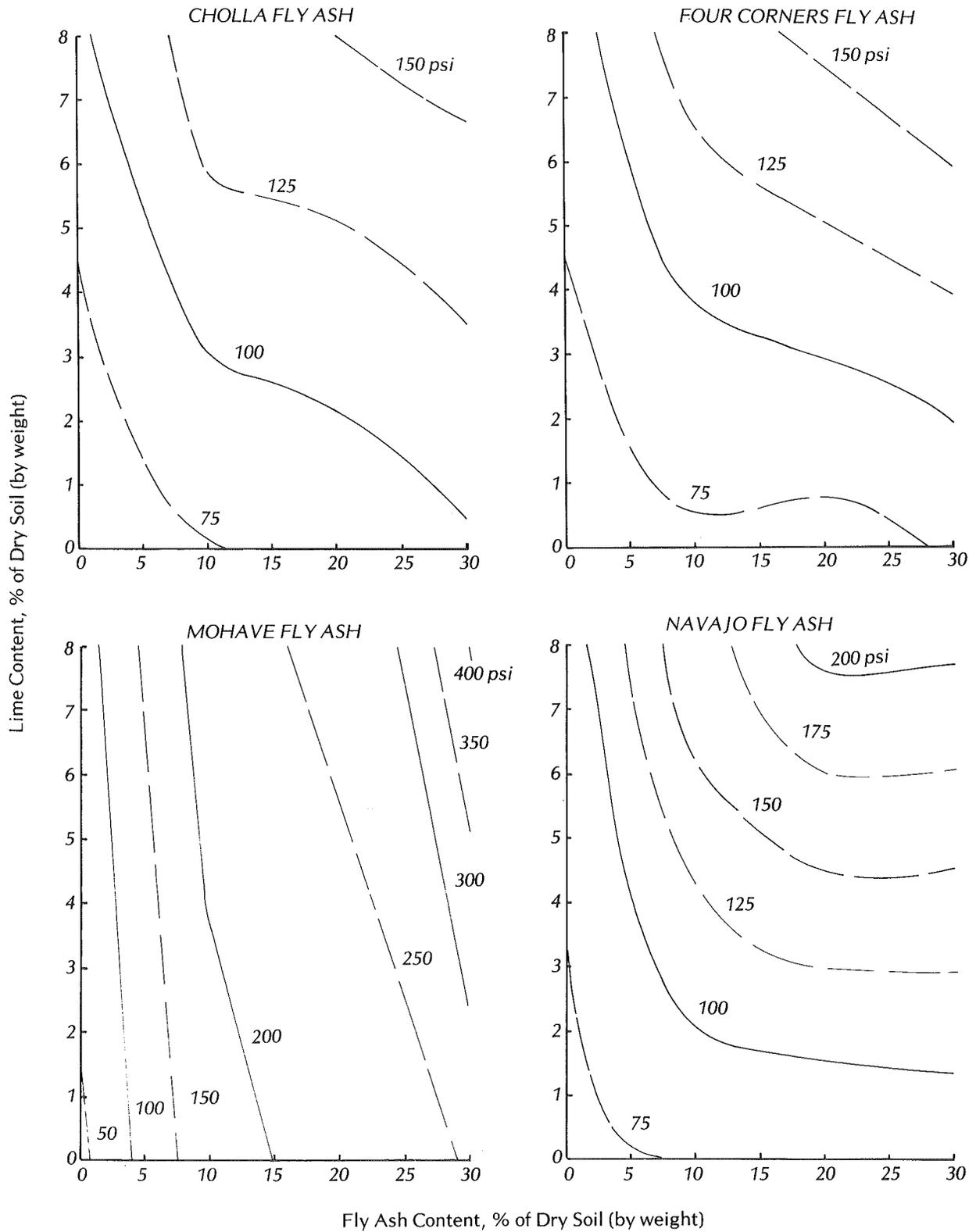


FIGURE 6-1A. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CLAYEY SAND AT 7 DAYS.

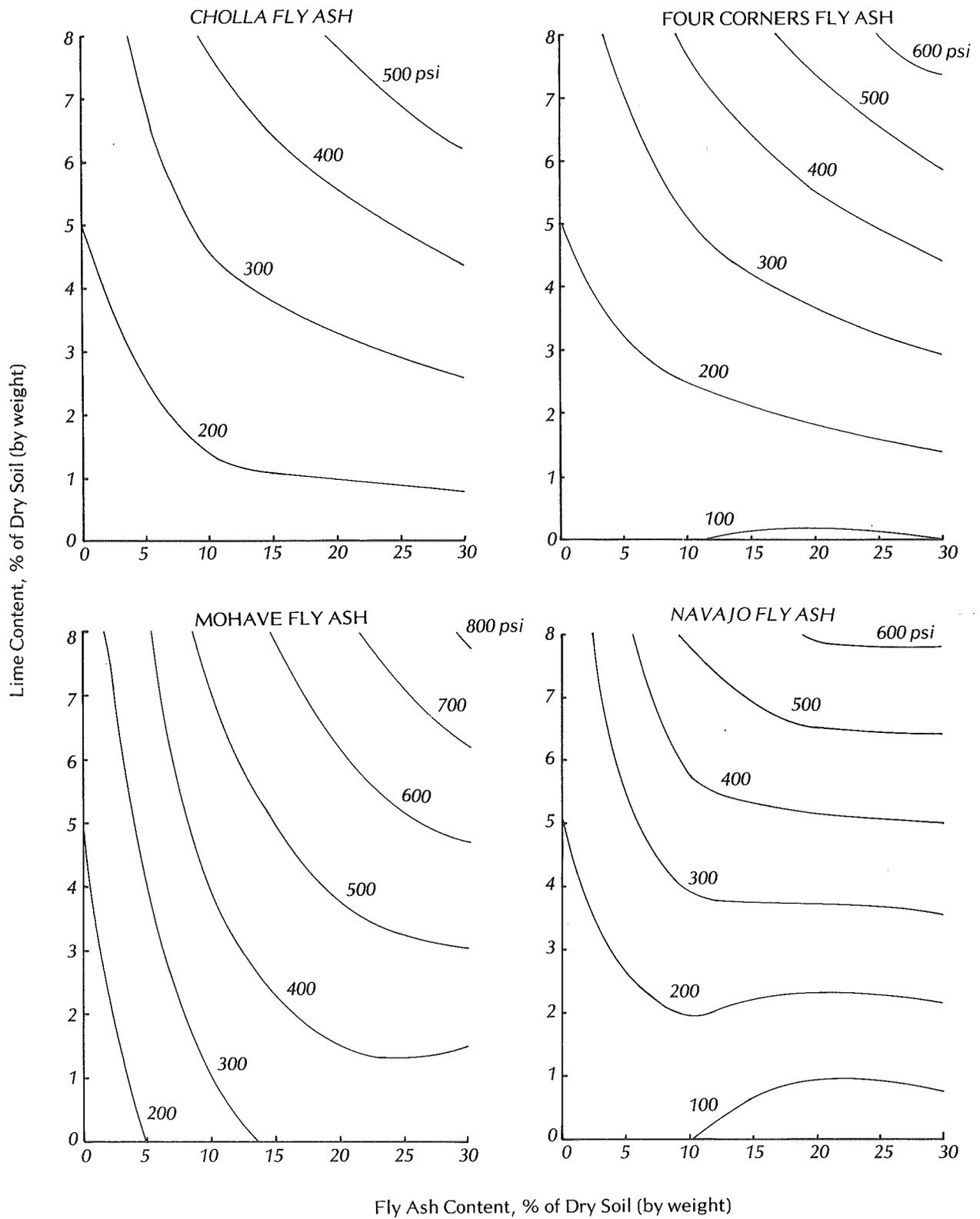


FIGURE 6-1B. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CLAYEY SAND AT 28 DAYS.

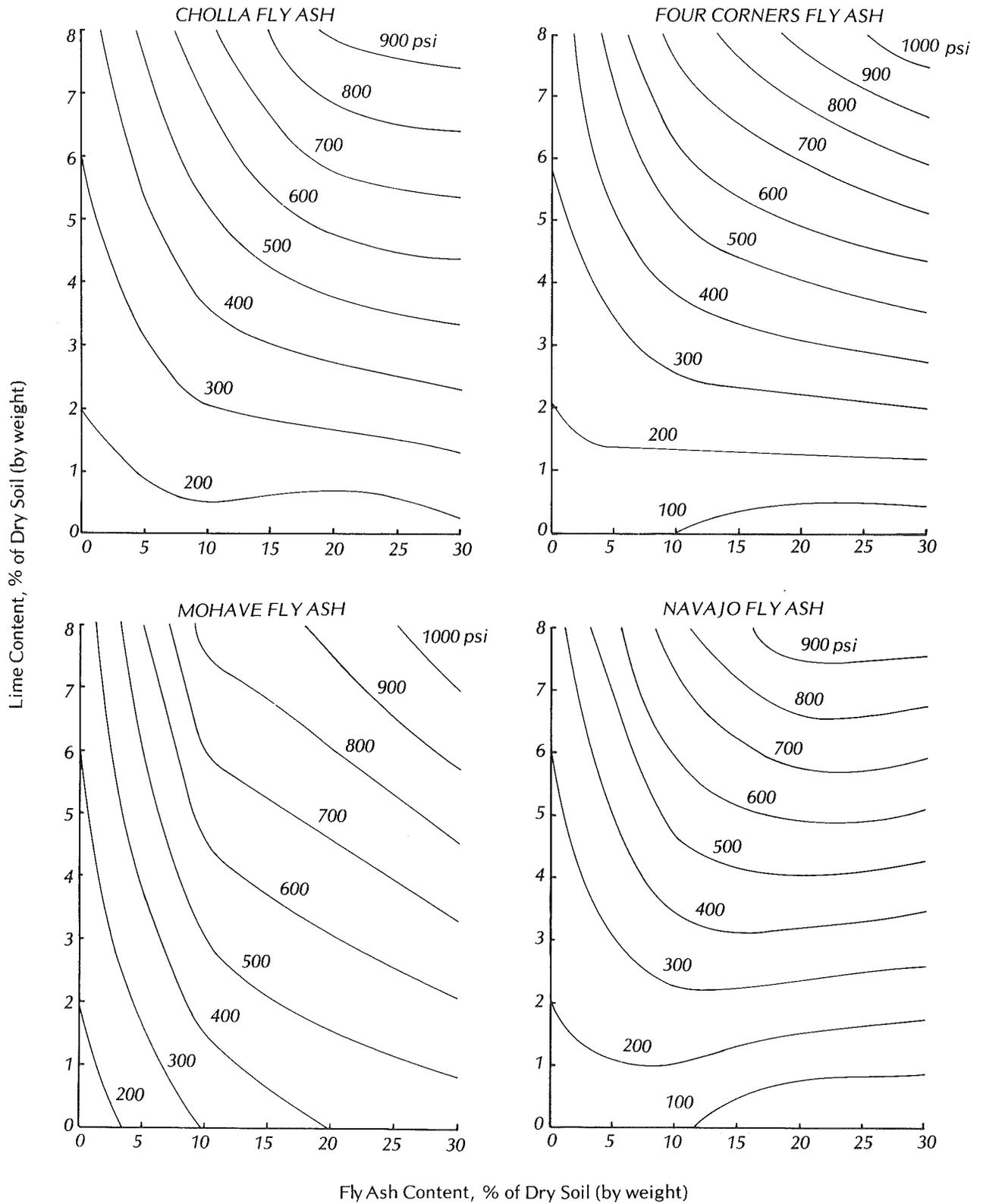


FIGURE 6-1C. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CLAYEY SAND AT 56 DAYS.

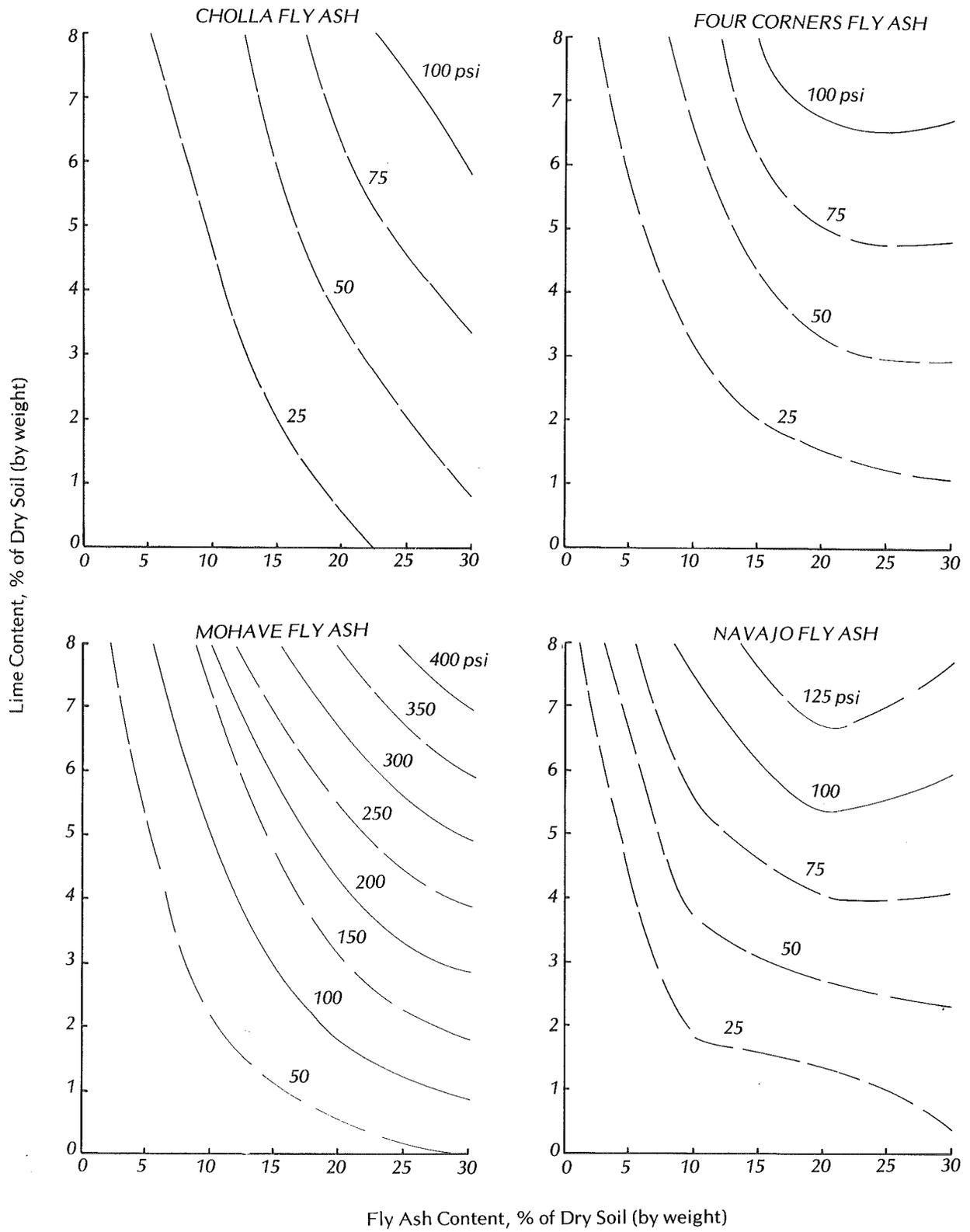


FIGURE 6-2A. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, SAND AT 7 DAYS.

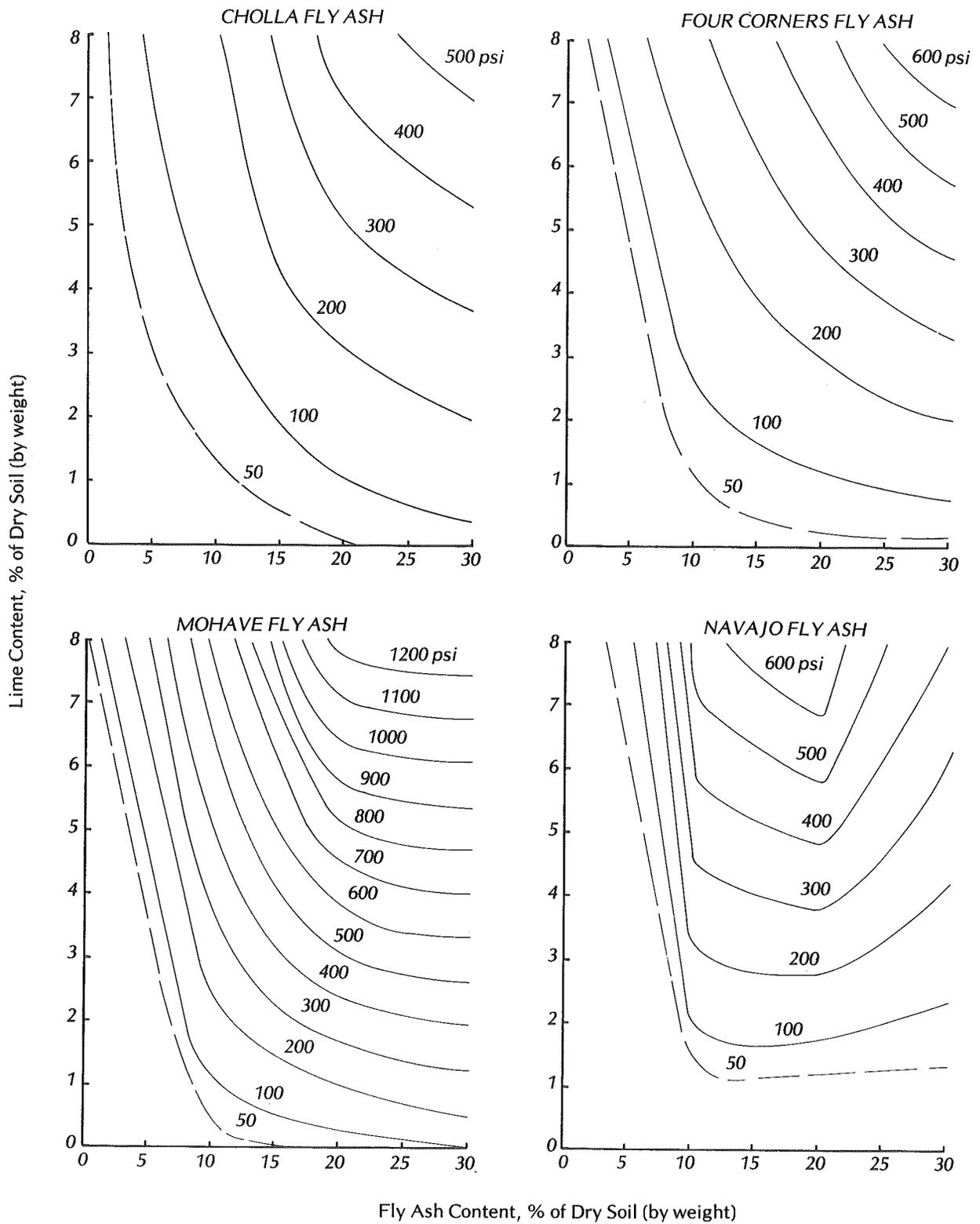


FIGURE 6-2B. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, SAND AT 28 DAYS.

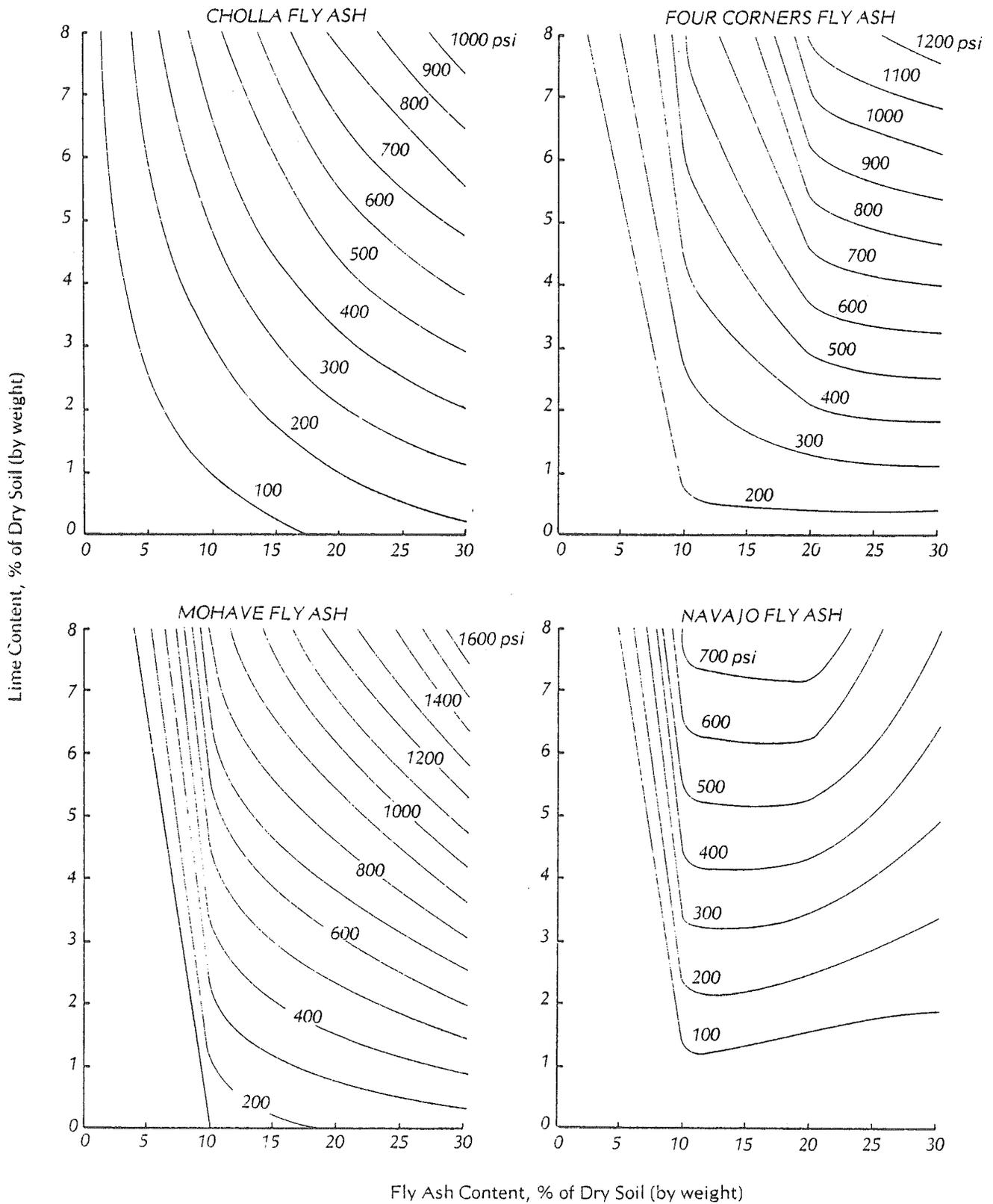


FIGURE 6-2C. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, SAND AT 56 DAYS.

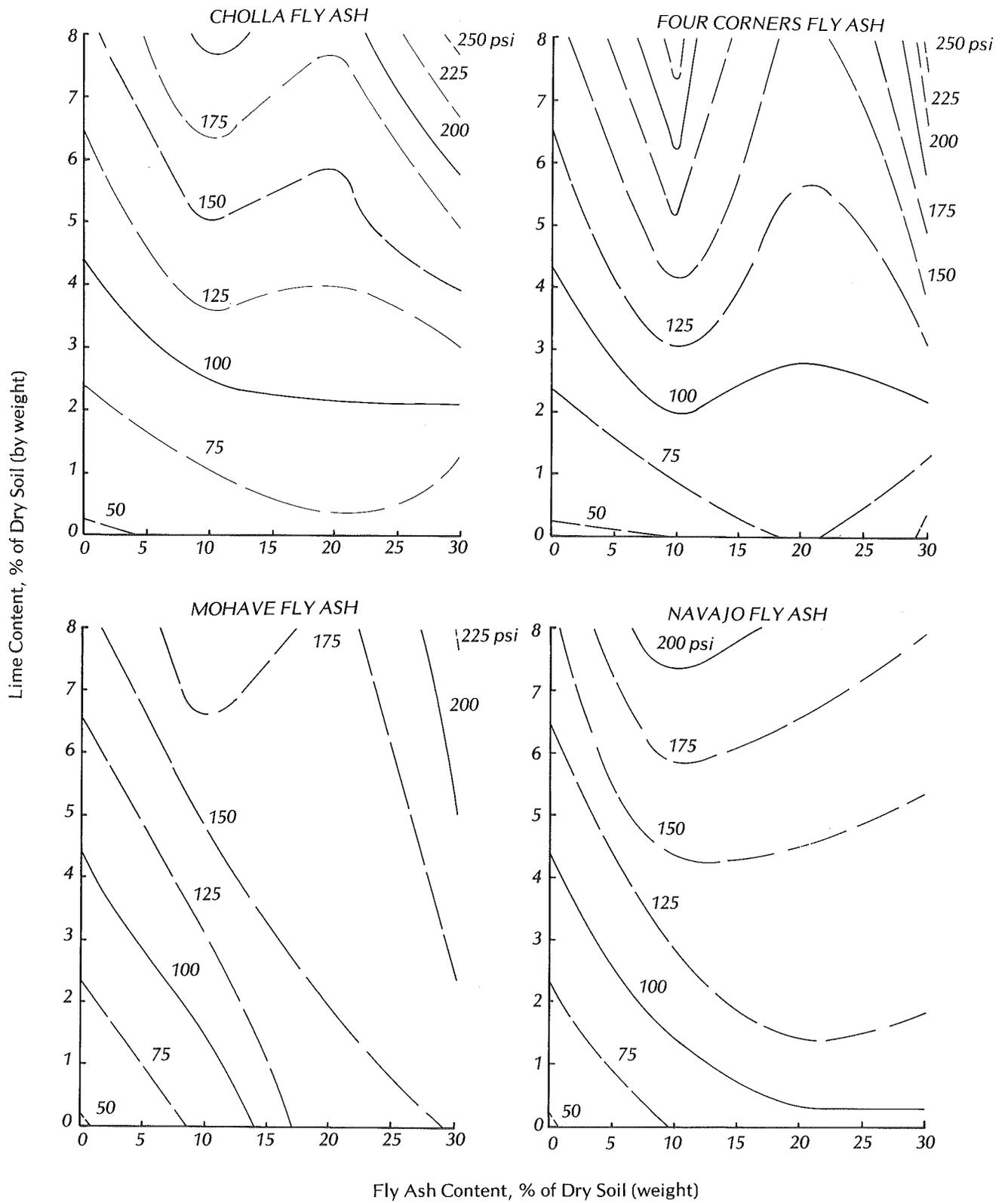


FIGURE 6-3A. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CLAY AT 7 DAYS.

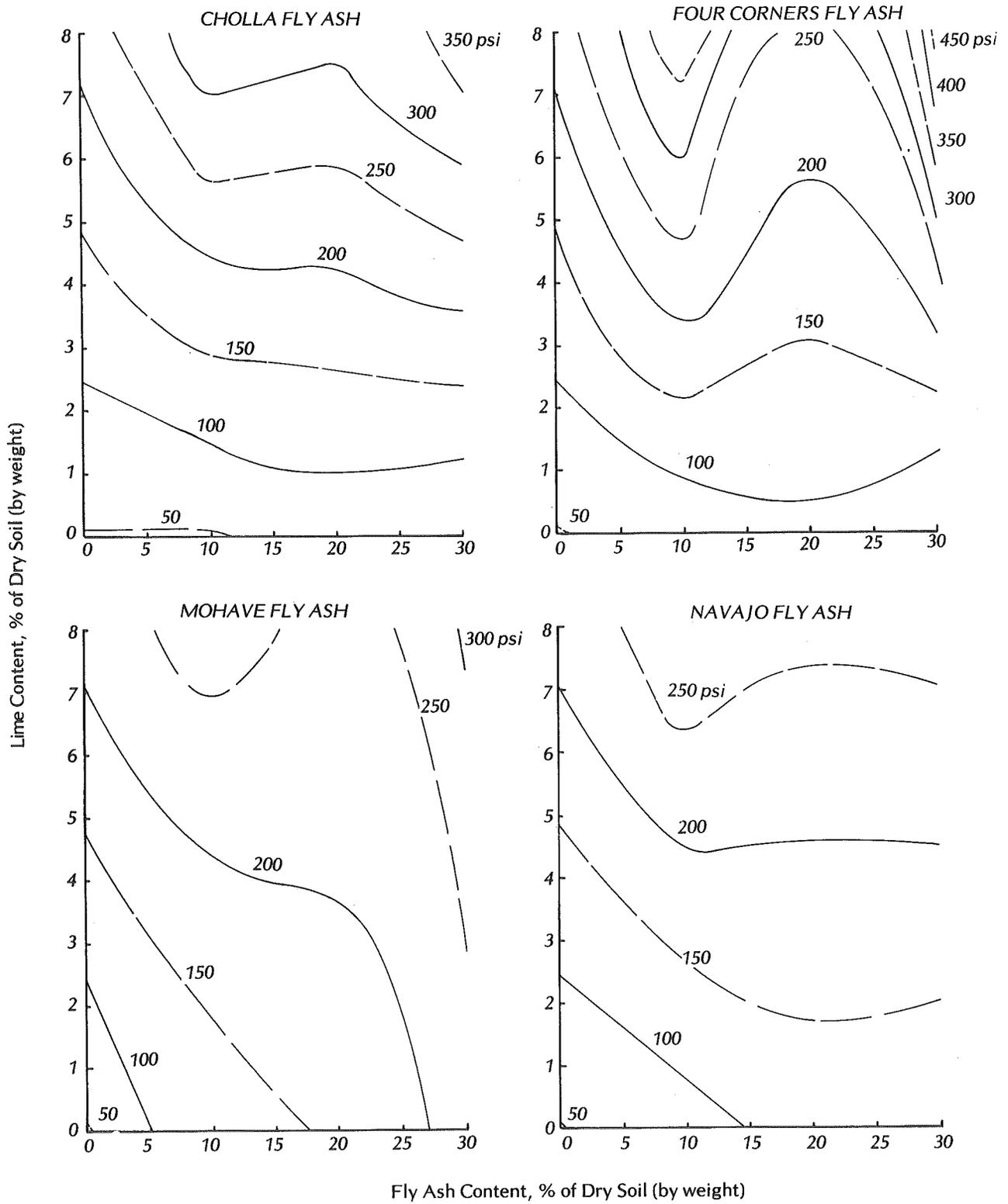


FIGURE 6-3B. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CLAY AT 28 DAYS.

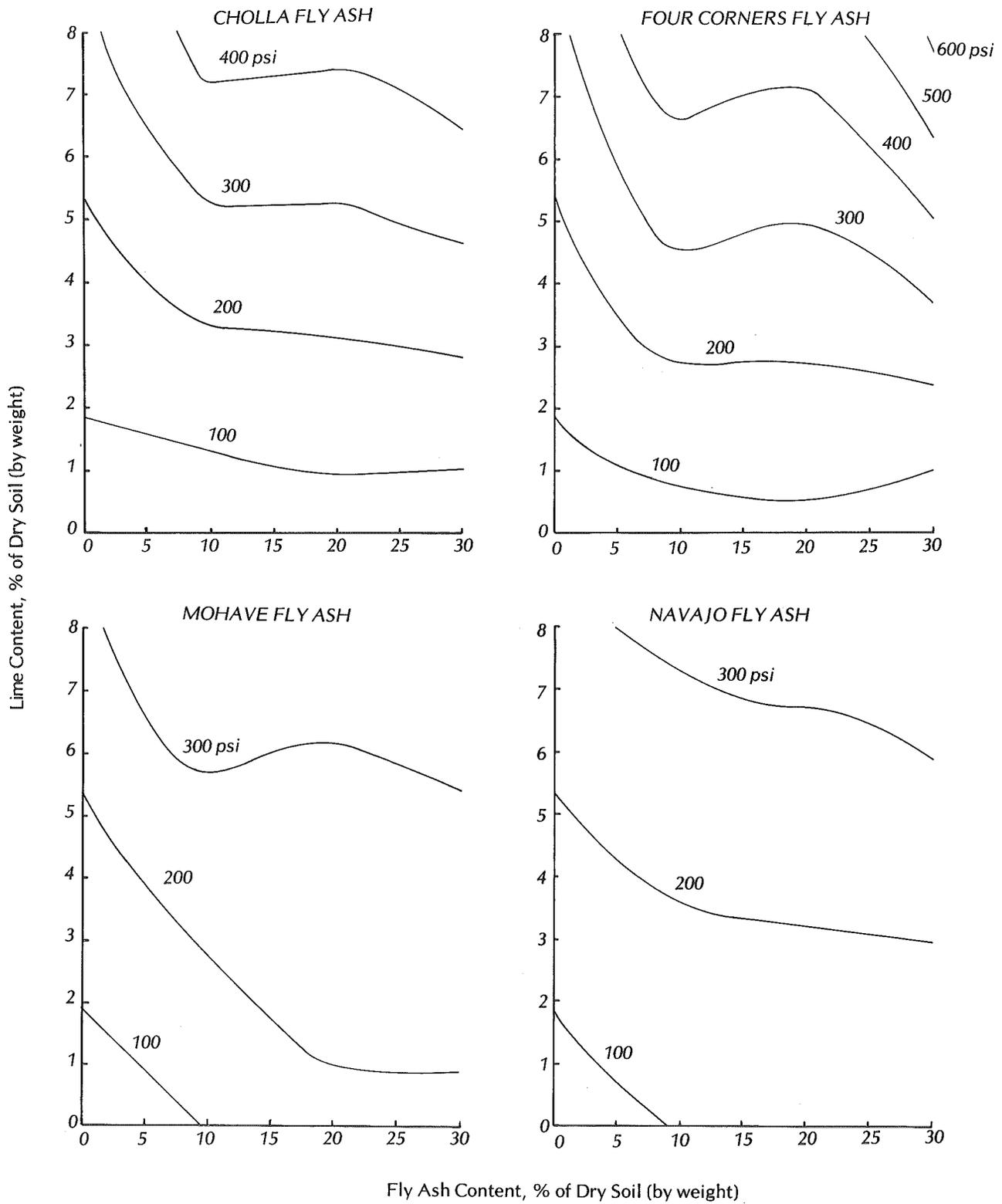


FIGURE 6-3C. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES CLAY AT 56 DAYS.

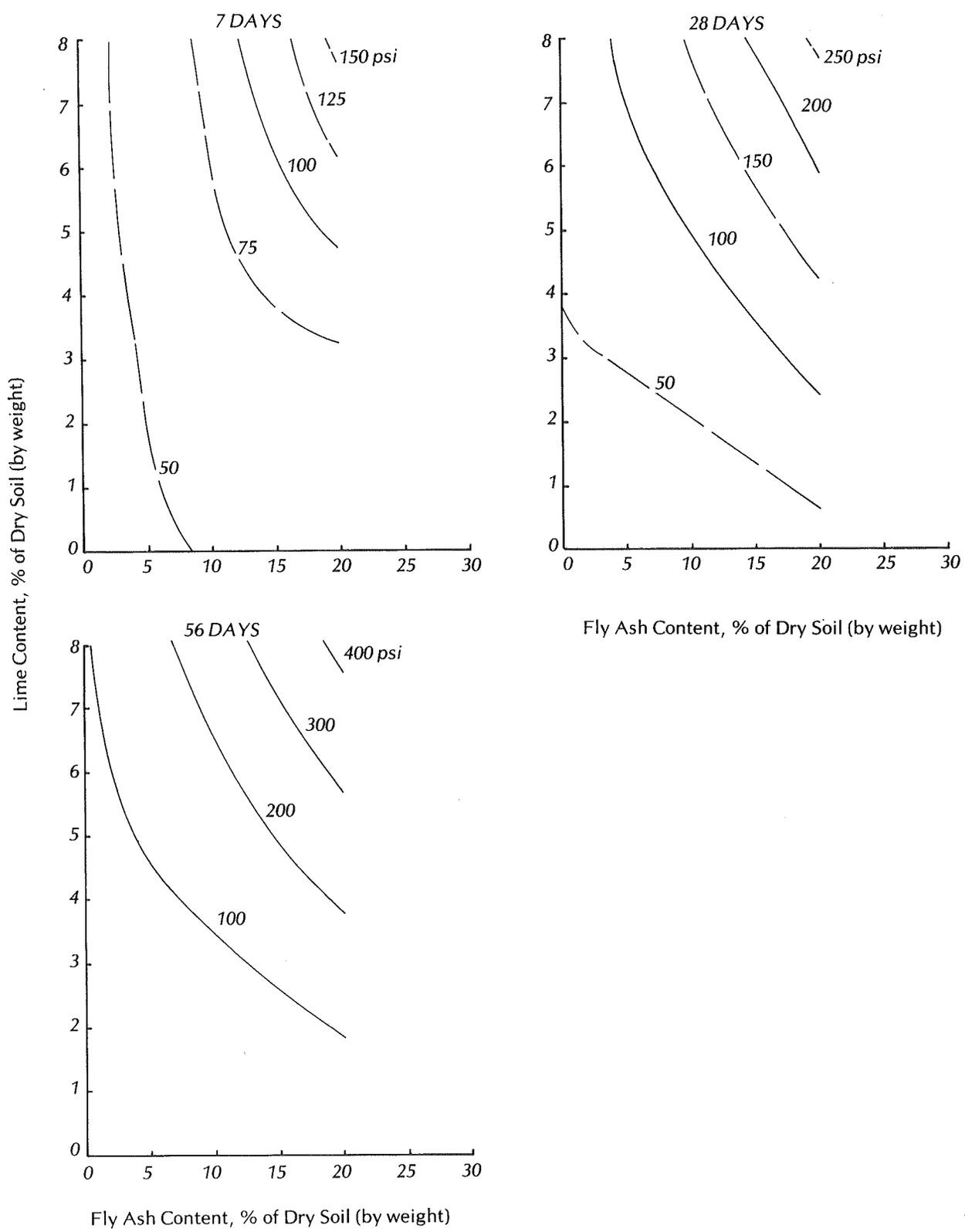


FIGURE 6-4. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CINDERS WITH CHOLLA FLY ASH.

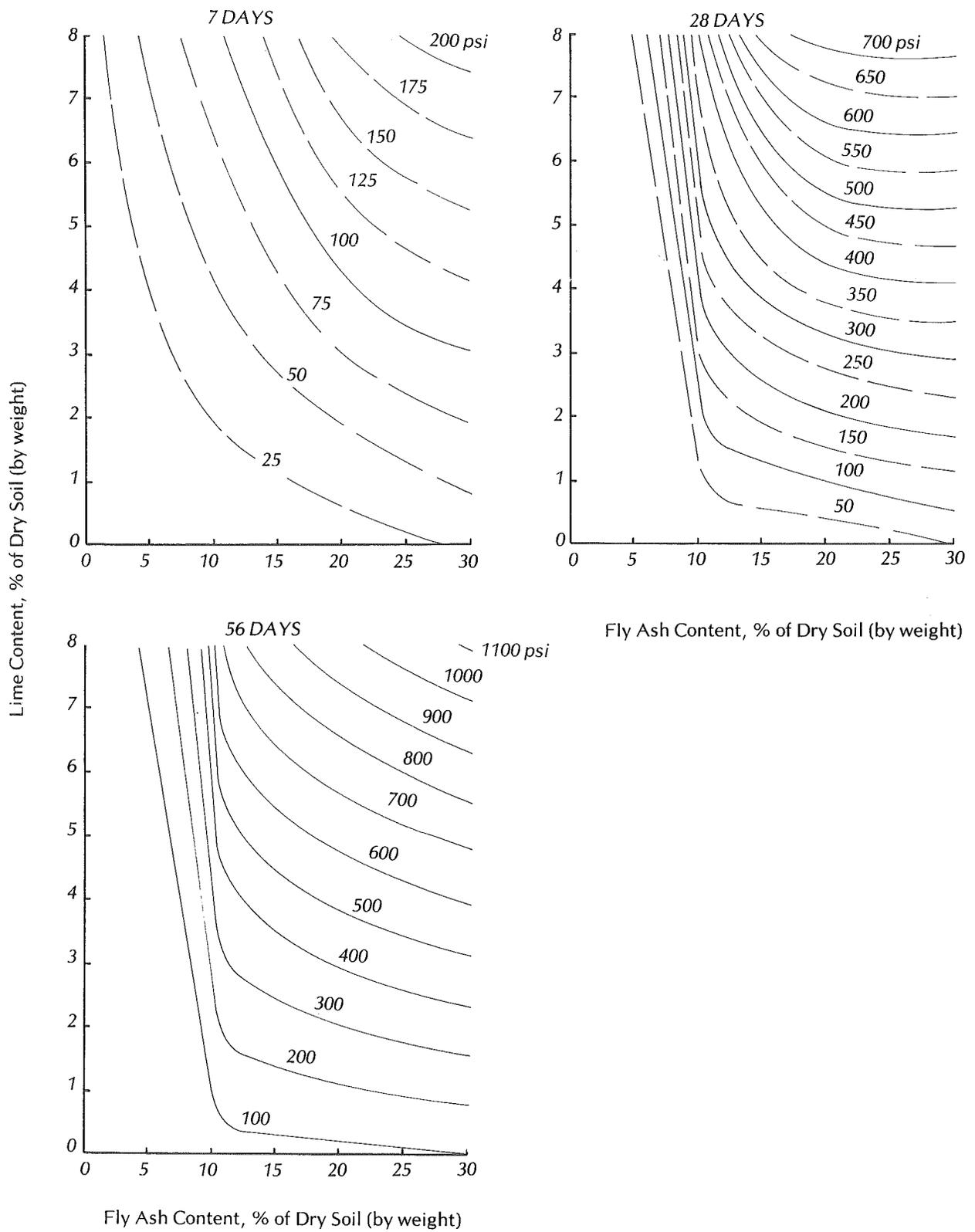


FIGURE 6.5. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, SAND WITH ANY OF THE FOUR FLY ASHES.

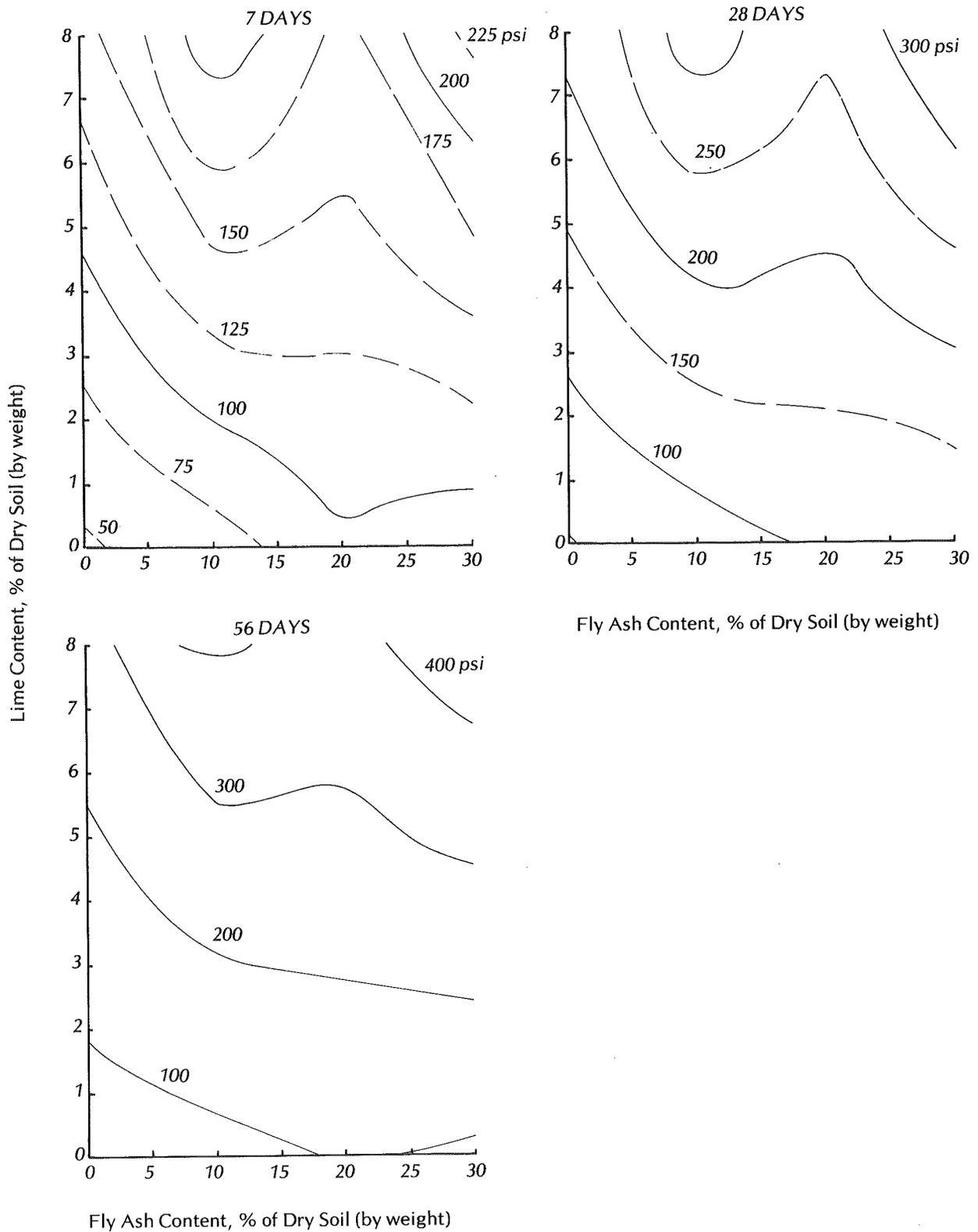


FIGURE 6-6. FLY ASH VS. LIME CONTENT: ISO-STRENGTH CURVES, CLAY WITH ANY OF THE FOUR FLY ASHES.

content is increased beyond an optimum limit. If such optimum always exists it is apparently outside the range of proportions tested for some mix combinations. The clay soil series produced relatively erratic test data as evidenced by the families of iso-strength curves. Data did smooth out considerably, however, at the later age of 56 days.

Cinders were tested with only the Cholla fly ash source. All test data is therefore included on the single Figure 6-4, including 7, 28 and 56 day ages.

Data were combined in Figures 6-5 and 6-6 to include all fly ash sources on the same family of curves for the sand and clay soil types. The curves serve only the purpose of presenting an idealized concept of the general relationship between mix proportions, age and unconfined compressive strength for a given soil type.

6.3 Evaluation of Iso-Strength Curves

The families of iso-strength curves were developed from data generated by best-fit straight line equations representing the strength vs. lime content (and fly ash content) test results. In order to assess the reliability of the curves for prediction of compressive strength, the proportions for each of the 573 mix combinations tested were entered in the curves. Predicted strengths obtained from the curves were compared to strengths obtained in the laboratory for each combination and test age.

The first comparison involved predicted compressive strengths of 400 psi or greater at 28 and 56 day test ages. The 400 psi value was selected as a likely minimum strength (at the as-molded water content) for design purposes. The tested strengths were within $\pm 10\%$ of the predicted value for 62% of the test mixes, and within $\pm 20\%$ for 89% of the test mixes. Coincidentally the same comparison held true for both 28 and 56 day ages. With one or two exceptions the data discussed here represented only

clayey sand and sand soil types since the clay and cinders did not develop strengths above 400 psi for the ranges of proportions tested. Test results which fell outside the $\pm 20\%$ predicted range represented the clayey sand in almost every case.

Data scatter for compressive strengths below 400 psi was considerably greater than for the higher strengths. Approximately 65% of the test values were within $\pm 20\%$ of the predicted value for both 28 and 56 day ages. The least reliable predictions appeared to be for very low strengths below about 200 psi.

Compressive strengths at the test age of 7 days were entirely in the range of 400 psi or less. The reliability of predictions decreased as strength decreased, similar to the trend for 28 day and 56 day test ages. Based on an arbitrary division at 150 psi, about 60% of test values were within $\pm 10\%$ of the predicted value and about 88% were within $\pm 20\%$ of predicted value in the higher range. Below 150 psi the reliability of prediction diminished.

The scatter diagrams of Figures 6-7A, B and C illustrate the comparisons between actual and predicted strength for 7, 28 and 56 day test ages, respectively. All compressive strength results for the four soil types studied are included in the data.

The tendency toward increased data scatter at low compressive strengths can be explained by reference to the strength vs. lime content curves of Chapter 4 (Figures 4-1, 2, 3 and 4). These data were represented by best fit straight line equations in the development of families of iso-strength curves. Visual examination of the curves indicates that deviation from a straight line approximation is most pronounced near the origin (low strength). The lower reliability of predictions in the low strength ranges is therefore to be expected. An equation of a type sensitive to the rate of change in slope could be used to increase

the reliability of the iso-strength curves at low strength. The practical significance might be slight, however, since field applications are more likely to be based on the higher ranges of compressive strengths.

6.4 Economics of Mix Design

The iso-strength curves of Figures 6-1, 2, 3 and 4 demonstrate that compressive strength is not sufficient in itself to establish a unique set of mix proportions. A given target strength can apparently be attained throughout a broad range of mix proportions. Durability considerations may narrow the range of suitable proportions in many cases but will probably not be sufficient to establish the unique "optimum" mix proportions for a particular design application. Where a choice is possible, the economics of the mix may enter into the selection of mix proportions.

Since the costs of lime and fly ash are in general not the same, overall costs can probably be minimized by selecting the lowest cost mix proportions which can meet design strength criteria. Such an optimum cost set of proportions might be selected from knowledge of the costs of lime and fly ash and with the use of the iso-strength curves. The procedure would work as follows:

1. Select design compressive strength at the desired age. Allowance should be made for effects of saturation, wet-dry cycling and freeze-thaw cycling.
2. Select the family of iso-strength curves which have been developed for the particular soil, fly ash source and age.
3. Determine unit costs of lime and fly ash. Establish any line intersecting the two axes, the intercepts of which correspond to the cost ratio of fly ash

to lime. For example, if lime cost is 3 times fly ash cost, by weight, the intercepts could be 5% lime and 15% fly ash, or any values with a similar ratio. The absolute slope of this line would then represent the fly ash to lime cost ratio.

4. A line parallel to the cost-ratio line and tangent to the desired strength contour would establish the unique least expensive combination of lime and fly ash to meet the selected strength. Any set of proportions other than those represented by the point of tangency would represent greater cost of lime and fly ash.

Feasibility of the lime-fly ash soil stabilization procedure would depend on overall economics, including materials costs (delivered on-site), construction costs and maintenance factors. Data relative to the evaluation of these factors were not developed in the course of this study. General market information provided some valuable insights into probable costs. Lime has historically cost approximately one-third to one-half the cost of portland cement in the Phoenix vicinity. The market has changed rapidly in recent years; therefore, current price data must be maintained for meaningful economic analysis.

6.5 Selection of Mix Proportions

A large number of variables are involved in the selection of mix proportions to meet a given set of design criteria. Input variables include the unique characteristics of the lime, fly ash and soil which are intended for use, as well as the unique interaction which occurs. The general state of the art of lime-soil-fly ash stabilization is such that

trial and error procedures are generally relied upon, based on initial educated estimates, to arrive at mix proportions. The data of this study provide the background for first estimates of mix proportions directly for the soils, fly ashes and lime included in the study and indirectly for similar soils, fly ashes and limes. Considerable laboratory testing is required to verify strength and durability of selected mixtures. In any case, present knowledge is such that the mixture finally selected for use in a given circumstance will usually be the "best" of the mixtures analyzed and tested and not necessarily the unique best solution to the particular problem.

A first estimate of the mix proportions may be developed from the most appropriate family of iso-strength curves presented in this section. Target strength should be retained strength after allowing for loss due to saturation. Cost data, if available, can be used to establish the proportions of lime and fly ash in an economical range. In the absence of cost data, a lime to fly ash cost ratio (by weight) of one-fourth to one-half might be assumed. Trial test specimens can then be prepared using mixtures which bracket the estimated proportions. The final mixture would be selected on the basis of strength and durability test results.

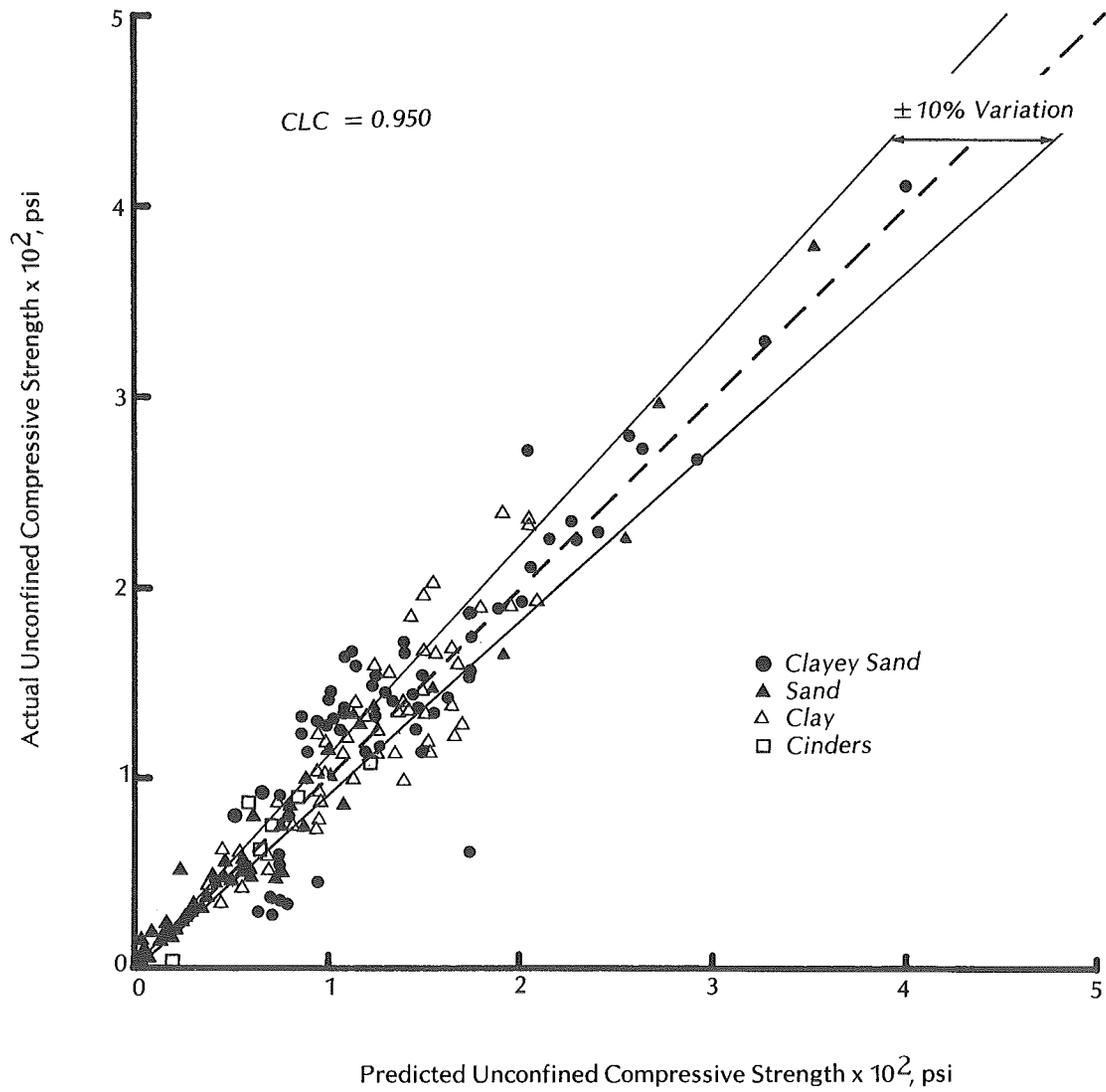


FIGURE 6-7A. PREDICTED VS. ACTUAL UNCONFINED COMPRESSIVE STRENGTHS AT 7 DAYS.

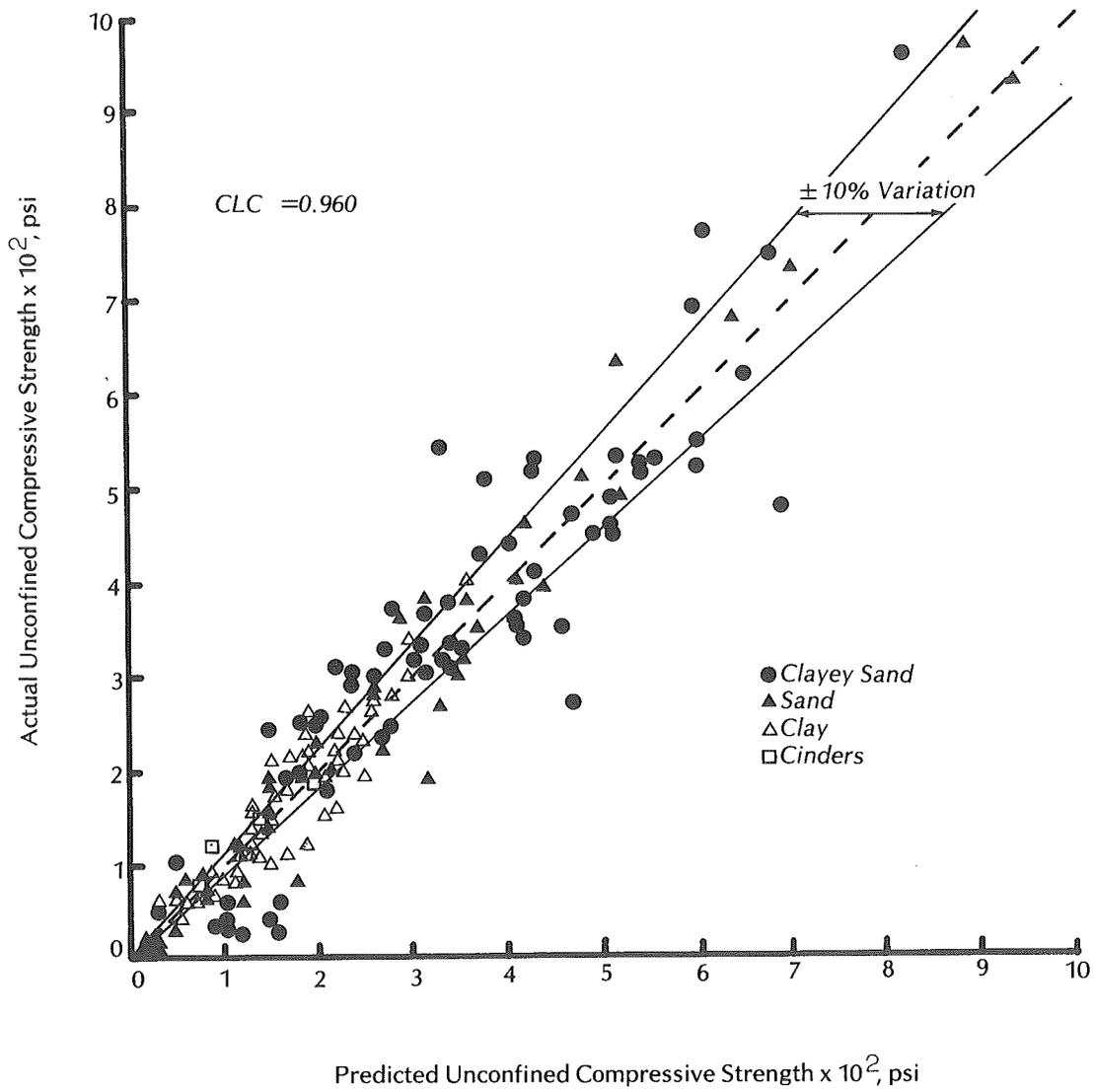


FIGURE 6-7B. PREDICTED VS. ACTUAL UNCONFINED COMPRESSIVE STRENGTHS AT 28 DAYS.

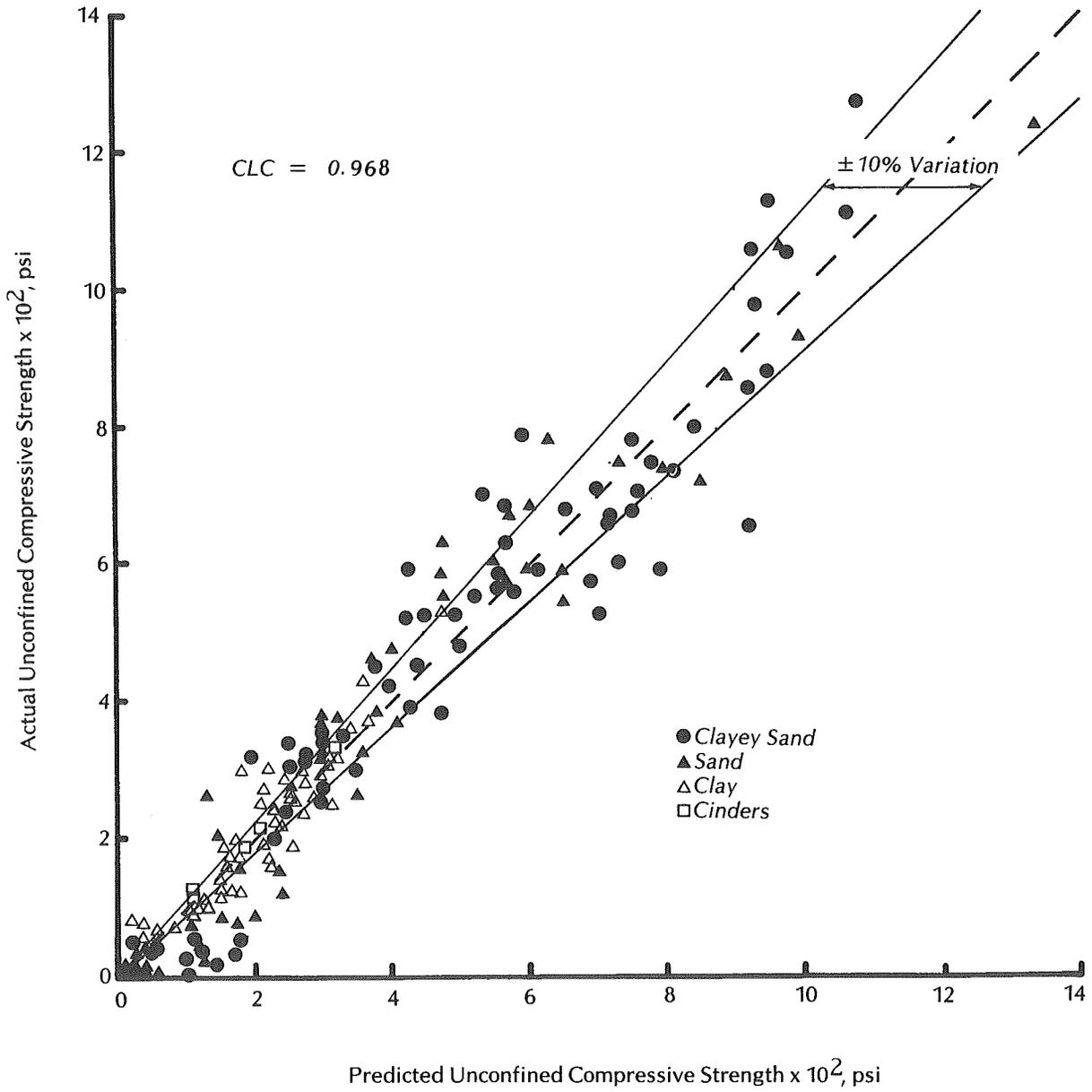


FIGURE 6-7C. PREDICTED VS. ACTUAL UNCONFINED COMPRESSIVE STRENGTH AT 56 DAYS.

CHAPTER 7. CONCLUSIONS

7.1 General

The data developed during the course of the study indicated that the Cholla, Four Corners, Mohave and Navajo fly ashes could be effectively utilized in certain soil stabilization applications. Each of the four soil types considered in the study was different in its response to lime-fly ash stabilization, as was to be expected. The four fly ashes were found also to be unique in their contributions to strength and durability of the lime-soil-fly ash mixture. Since only one source and type of lime was used, no data were developed regarding the effects of lime characteristics. The comments and conclusions which follow are based solely on test data developed in this study unless otherwise indicated.

7.2 Fly Ash Characteristics

The four fly ashes exhibited varying degrees of self cementing potential (without the addition of lime) which was apparently related to calcium oxide content. Mohave ash demonstrated significant self cementing action with clayey sand, sand and clay (SC, SP and CH) and had a calcium oxide content of about 16%. Navajo ash showed a slight degree of self cementing with the same soils and had a calcium oxide content of about 9%. Cholla ash, with a calcium oxide content of about 5%, exhibited a trace of self cementing with the sand and clay only. Four Corners ash had a calcium oxide content of about 3% and did not demonstrate self cementing characteristics with any soil. The self cementing characteristic can apparently be expected when calcium oxide content exceeds some lower limit in the range of 5% to 10%.

The addition of 10% to 30% fly ash to the highly plastic clay decreased the liquid limit and plasticity index significantly. The addition of a small amount of lime, 2%, however, was several times more effective. The relative costs are normally such that fly ash alone is probably not practical for use where simple modification of soil index properties is the objective. Since index properties were tested with Cholla fly ash only, the use of an ash with higher calcium oxide content might modify this conclusion.

Loss on ignition, as an indicator of carbon content, was expected to correlate with pozzolanic activity and the per cent retained on the No. 325 sieve. The loss on ignition for the four ashes, however, varied only through a small range and did not appear to correlate well with the widely varying pozzolanic activity and fineness. The LOI, at least for the ashes studied, may not be a reliable indicator of strength potential (pozzolanic activity) and may not be directly related to the amount of coarse material (+ No.325) in the ash.

7.3 Unconfined Compressive Strength

Lime-soil-fly ash mixtures gained strength slowly relative to, for example, soil cement. Strength continued to increase significantly out to maximum 56 day test ages and indications were that significant gain would continue well beyond 56 days. Efficient use of lime and fly ash for soil stabilization requires that design be based on ages of 28 days or more and that the ultimate strength be given at least indirect consideration.

Lime and fly ash optimum quantities are interdependent. Efficient and economical design requires that the fly ash to lime ratio be determined as well as the ratio of lime

and fly ash to soil. Excessively high quantities of lime or fly ash can be detrimental to quality as well as inefficient in cost.

Density appeared to be related to strength, although no direct study was undertaken to establish a relationship between density and strength for a given set of mix proportions. Increased density probably contributes to increased strength in at least two ways. First, closer particle spacing might be expected to contribute to strength mechanically, irrespective of the characteristics of lime and fly ash. Second, the closer particle spacing would be expected to aid the reaction between lime and the reactive components of fly ash and soil. The former might be independent of relative proportions of lime and fly ash while the latter would be dependent on the lime to fly ash ratio.

Calcium oxide content of the fly ash appeared to affect the relationship between strength and lime content for a given soil and fly ash content. Higher calcium oxide ash test specimens showed a different and less predictable response to additional lime than did specimens molded with ash of lower calcium oxide. Lime in the fly ash apparently upset the expected relationship by contributing to the net lime available for reaction.

7.4 Durability

The soil-cement durability test procedures used in the study, both wet-dry and freeze-thaw, may be suitable for ranking higher strength mixtures, but are probably too severe for differentiation between various lower strength mixes. Specimens which broke apart or otherwise failed to complete planned cycles provided scant and unreliable

information for comparison.

General examination of the durability specimens indicated that density may be a key parameter in durability. Two characteristic modes of deterioration were noted in many of the specimens. The rate of deterioration was frequently greater near the top of the specimen than near the bottom. In addition, specimens frequently separated along horizontal planes apparently corresponding to the surfaces between compacted lifts. In these cases the surface immediately above the plane of separation deteriorated more rapidly than the surfaces immediately below. Considering a single lift, the upper portion would receive the higher compactive effort. Considering the entire specimen, the lower lift would receive the highest compactive effort. Both of these circumstances suggested lower resistance to weathering in lower density portions of the specimen.

With regard to resistance to wetting and drying, the clayey sand and sand test series provided data which appeared to effectively rank the durability of various mix combinations. Weight losses of less than 5% were achieved for both soil types in the standard test procedure and the proportioning vs. weight loss relationships established useful guidelines for mix evaluation. Resistance to deterioration from wetting and drying appeared to be generally proportional to compressive strength for a given soil and fly ash. The clay and cinder soil series demonstrated some correlation between weight loss and compressive strength. However, it must be concluded that the standard test procedure did not effectively evaluate the relative durability of the mixtures tested for these soils.

The standard freeze-thaw test series resulted in high

weight losses, 20% to 64%, for all mixtures tested. The most outstanding result was the clear ranking of the ash sources. In order of decreasing durability potential, the ashes ranked Mohave, Cholla and Navajo. Freeze-thaw durability, as measured by weight loss, did not correlate well with compressive strength. The standard test procedure was ineffective in ranking the performance of the clay and cinders mixtures and only moderately effective in ranking the clayey sand and sand mixtures.

In general, it is suspected that somewhat higher densities would improve durability and that the standard test procedures would then serve as useful indicators of performance. If mixes with relatively low strengths and durabilities must be evaluated and differentiated, less severe test procedures would be required.

Durability test series were not conducted on the complete range of mixtures included in the strength series. The decision was based primarily on field and laboratory economics. High fly ash contents (30%) were not expected to be economically practical compared to lime or portland cement soil treatments. However, had the full effects of fly ash content in the higher ranges, as well as source of fly ash, been known during the test planning stage, additional testing may have been considered.

7.5 Soil Type

Test data indicated a considerable difference in response to the lime-fly ash treatment among the four soil types.

Based on compressive strengths alone, the improvement in the sand and clayey sand was roughly double the improvement in the clay and cinder soils. The sand and cinder soils were both characterized by zero unconfined compressive strength

with no additives. Maximum strengths attained with the trial mix combinations for the sand were more than double those achieved for the cinders. The clay and sandy clay had comparable unconfined compressive strengths without additives (40 and 30 psi, respectively). Maximum strengths attained with tested mix combinations for the sandy clay soil, however, were more than double those attained for the clay soil.

Durability test data provided an even sharper distinction between soil types and response. Clay and cinder specimens failed to complete the standard number of cycles for the Wet-Dry and Freeze-Thaw test series. Clayey sand and sand specimens completed the planned cycles, although with high weight losses for some combinations.

The sand and clayey sand soils clearly benefitted from the lime-fly ash treatment to a significantly greater extent than the clay and cinder soils. The reasons for this difference were not examined in this study and were not apparent from the available test data. It was concluded that further study relative to soil gradation in particular, engineering characteristics in general, and origin (minerology) would be required to fully evaluate relative soil behavior.

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SUBJECT INDEX TO REFERENCES

Numerous references relative to the use of fly ash in soil stabilization have been presented in the previous section, many of which have not been directly noted in the text. This index is included to aid in the identification of references pertinent to a specific topic concerning soil stabilization. No special significance has been accorded to selected topic areas. The topics are arranged in alphabetical order in this index. Several references contain material relevant to more than one selected topic area; in such cases, multiple citing of references is made with no special significance attached to the numerical ordering of the cited references.

Base Courses:

2, 7, 8, 9, 10, 18, 39, 40, 53, 75, 77, 79, 82, 118, 127 and 128.

Chemical Additives and Accelerators:

23, 45, 65 and 70.

Compressive Strength:

9, 46, 49, 62, 67, 68, 75, 82, 105, 116 and 128.

Construction Procedures:

8, 10, 51, 65 and 118.

Curing Conditions:

8, 42, 50, 51 and 67.

Fatigue Due to Repeated Loading:

3 and 7.

Field Performance:

18, 32, 38, 51, 54, 56, 57, 65, 72, 77, 78, 82 and 128.

Flexural Strength:

7.

Fly Ash Quality and Characteristics:

24, 62, 68, 80, 81 and 105.

Fly Ash with Portland Cement:

25, 40 and 90.

Freeze-Thaw Durability:

4, 8, 25, 29, 30, 31, 42, 50, 51, 53, 55, 72, 82 and 112.

General Information and Discussion:

12, 15, 25, 30, 36, 37, 44, 54, 56, 66, 68, 72, 73, 81, 83, 84, 86, 87, 88, 89, 91, 100, 105, 106, 110, 111, 119, 120, 125 and 127.

Historical Information:

10, 35 and 73.

Mix Design Methods:

2, 34, 71, 74, 114 and 118.

Molding Conditions and Compaction:

55, 69 and 121.

Non-Highway Oriented Fly Ash Uses:

6, 32, 43, 47, 57, 58, 59, 61, 101, 106 and 112.

Pozzolanic Chemical Reactions:

24, 35, 48, 49, 62 and 80.

Special Test Methods:

3, 29, 46, 50, 51, 75 and 77.

Stabilization with Fly Ash Only:

31, 68 and 105.

Stabilization with Lime Only:

27, 28, 30, 95, 98, 114 and 122.

Statistical Evaluations:

52.

Strength in General:

8, 25, 31, 42, 53, 54, 70, 71, 77, 118 and 127.

Strength Recovery:

10.

Wet-Dry Durability:

4, 25, 30, 42, 55 and 82.

APPENDIX A. FLY ASH CHARACTERISTICS

A.1 Fly Ash Source Facilities

A.1.1 General

Fly ash is the finely divided residue that results from combustion of ground or powdered coal. The ash is transported from the boilers by flue gases, and can be discharged into the atmosphere or collected by mechanical or electrostatic precipitation devices. Fly ash is a pozzolan and is usually formally described as a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Particulates are primarily composed of silica and alumina, with carbon, oxides of iron, calcium, magnesium and sulphur, and other minor constituents. The quality and uniformity of the ash are influenced by coal quality, plant combustion characteristics and the method of collection.

A.1.2 Coal Sources and Descriptions

The present sources of fly ash within practical hauling distance of Arizona construction sites include the Cholla, Four Corners, Mojave and Navajo power plants. Power plant locations, coal sources and typical data on coal characteristics are presented in Table A-1 and further illustrated on Figure A-1.

Coal from the Navajo Mine supplying the Four Corners Power Plant has approximately twice the ash content

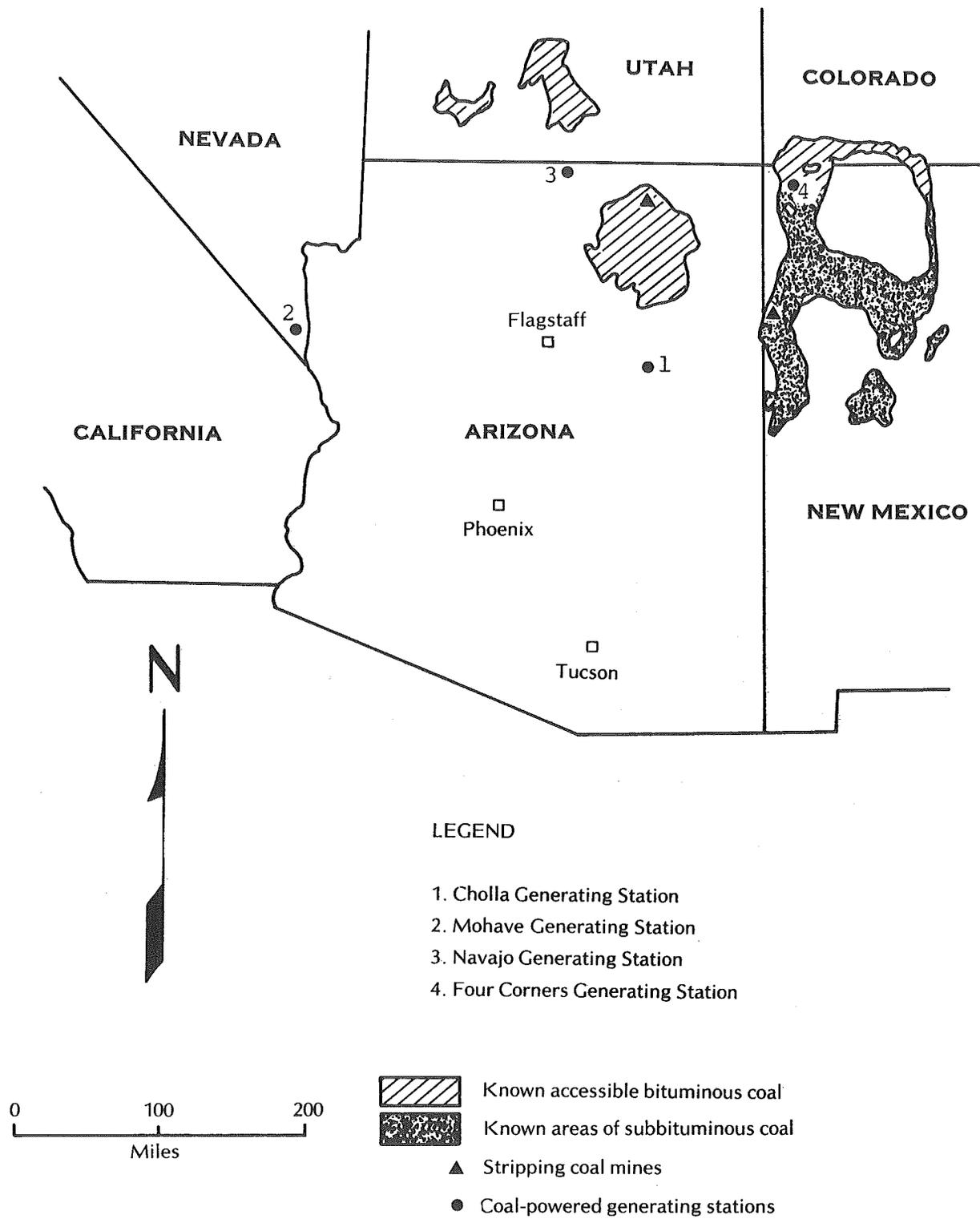


FIGURE A-1. COAL AND FLY ASH SOURCES

TABLE A-1. Coal Sources and Characteristics

Plant	Cholla	Four Corners	Mohave	Navajo
Plant Location	Joseph City, Ariz.	Fruitland, N.M.	Laughlin, Nev.	Page, Ariz.
Coal Source	McKinley Mine Gallup, N.M.	Navajo Mine Fruitland, N.M.	Black Mesa Mine Kayenta, Ariz.	Kayenta Mine Kayenta, Ariz.
Typical Coal Data				
Heat of Combustion, BTU/lb.	10,356	8,793	12,300	11,824
Ash, %	10.58	23.41	9.8	11.3
Sulfur, %	0.52	0.63	0.4	0.55
Moisture, %	15.35	11.24	(47% Slurry)	15.4
Coal Haulage, miles	Rail 109	Rail 7 Truck 3½	Slurry Pipeline 273	Conveyor 10 Rail 80
Coal Preparation	Pulverized	Pulverized	Wet ground to 8 mesh to establish 47% slurry; dewatered, dried & pulverized at plant.	Pulverized

of the other three sources which yield typically about 10% or 11% ash.

The Mohave plant is unique in that the coal is transported as a water slurry. Preparation of slurry is accomplished by dry crushing and wet grinding to about number eight mesh size. Water introduced during the wet grinding process brings the slurry to suitable consistency for pumping 273 miles to the power plant site. Coal is delivered through an 18 inch pipeline at the rate of approximately 600 tons per hour (dewatered coal at approximately 11% moisture). The slurry is stored in tanks and agitated to maintain suspension of solids. Centrifugal dewatering, pulverizing and drying are accomplished prior to pneumatic transfer to the furnaces. Fines are also collected from the centrifuge effluent for use in the furnaces.

The Cholla, Four Corners and Navajo plants utilize pulverized coal dry transported by truck, rail and conveyor.

A.1.3 Ash Production and Collection

Information relative to the production of fly ash at the four sources is presented in Table A-2. This type of data can be used to estimate the annual production of fly ash for a plant. The following example, for the Cholla Plant, illustrates a method which can be used to estimate annual production.

$$\text{Output} = \text{Gross Load} \times \frac{\text{Boiler Heat Rate}}{\text{Coal Heating Value}} \times \text{Coal Ash Ratio} \times \frac{\text{Fly Ash Collected}}{\text{Total Ash}} \times \text{Capacity Factor}$$

TABLE A-2. Fly Ash Source Plant Characteristics

Plant	Cholla Unit 1	Four Corners Unit 3		Units 4 or 5	Mohave Units 1 or 2	Navajo Units 1, 2 or 3
		Units 1 or 2	220			
Gross Load, MW	116	175	220	800	790	760
Boiler Heat Rate, BTU/KWH	10,453(1)	11,308(1)	11,308(1)	10,122(1)	-	9,500
Boiler Design Pressure, psig Superheat/Reheat Temperature OF	1,925	1,925	2,125	3,600	3,610	4,000
	1,005	1,000	1,005	1,000	1008/1003	1,000
Boiler Mfgr.	Combustion Engineering	Riley Stoker Reheat Type YPR	Foster Wheeler	Babcock & Wilcox	Combustion Engineering	Combustion Engineering
Combustion Method	Corner Fired	Front Fired	Front Fired	Corner Fired	Tangential Fired	Tangential Fired
Coal Consumption, Tons/Hr.	54.30 (1)	90 (2)	115 (2)	552 (1)	330 (2,3)	333
Capacity Factor	0.94 (1)	0.66 (1)	0.66 (1)	0.60 (1)	0.57 (4)	0.8 (4)

Notes: (1) 1974 Yearly Average (3) Dry Coal
(2) Full Load (4) 1975 Average

TABLE A-3. Fly Ash Collection Systems

Plant	Cholla Unit 1	Units 1 or 2	Four Corners Unit 3	Units 4 or 5	Mohave Units 1 or 2	Navajo Units 1, 2 or 3
Fly Ash Collection Equipment	Mechanical Collector & Wet Scrubber	Wet Scrubber	Wet Scrubber	Electrostatic Precipitators	Electrostatic Precipitators	Hot Electrostatic Precipitators
Fly Ash Recovery Method	Water Ejector	Wet	Wet	Pneumatic	-	Pneumatic
Ratio of Fly Ash Total Ash	0.8	0.8	0.8	0.8 nominal	0.7	0.8
Estimated Dry Fly Ash Recovery:						
% of Fly Ash	65	0	0	100	100	100
Tons/year, each unit	27,000	0	0	480,000	110,000	190,000
Tons/year, Plant total	27,000	0	0	1,000,000	220,000	600,000

For the Cholla Plant:

$$\text{Output} = 116000\text{KW} \times 10453 \frac{\text{Btu}}{\text{KWH}} \times \frac{1}{10356} \frac{\text{lb.}}{\text{Btu}} \times$$

$$0.106 \frac{\text{lb.}}{\text{lb.}} \times 0.94 \times 0.65(0.8) \times$$

$$8760 \frac{\text{Hr.}}{\text{Year}} \times \frac{1}{2000} \frac{\text{Ton}}{\text{lb.}} = 27000 \frac{\text{Ton}}{\text{Year}} \text{ Fly Ash}$$

The methods of fly ash collection for the four plants are summarized in Table A-3. Fly ash recovery rates are approximations and should be expected to vary at each plant due to variations in plant operation and coal quality. Fly ash dry recovery rates given are based on nominal coal burn rates rather than unit load and heat rates.

A.2 Fly Ash Quality and Uniformity

A.2.1 Fly Ash Uniformity

During the course of the study samples were obtained from the various sources on a periodic but irregular basis. Many of the samples were obtained in connection with work unrelated to this study. Samples were generally subjected to all or a portion of the test series outlined in ASTM Designation: C618, Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolans for Use in Portland Cement Concrete. A summary of test results is presented in Tables A-4a and A-4b, including Chicago fly ash for comparison. In each case, the number of test results, the average result and the range of variation are given. Where ten or more test results are available the standard deviation and coefficient of variation are computed and listed. The averages in Table A-4a and A-4b are the arithmetic means of the test results available in each case. (The number of test results for each

TABLE A-4a. Fly Ash Uniformity

PROPERTY*	NAVAJO					MOHAVE				
	Average	Number of Samples	Standard Deviation	Coefficient of Variation, %	Range	Average	Number of Samples	Standard Deviation	Coefficient of Variation, %	Range
SiO ₂ %	53.06	29	4.86	9	39.11-60.90	51.58	31	3.77	7	41.72-59.96
Al ₂ O ₃ %	17.93	29	3.34	19	10.16-21.43	17.51	31	2.48	14	10.13-21.71
Fe ₂ O ₃ %	4.80	29	0.85	18	2.63-6.44	4.89	31	0.65	13	3.45-6.08
Sum of oxides %	76.00	30	7.48	10	51.90-84.78	73.87	32	4.26	6	66.20-84.01
MgO %	2.18	30	0.66	30	0.63-3.44	1.87	32	0.59	32	0.74-3.28
SO ₃ %	0.54	27	0.56	103	0.06-2.28	0.80	29	0.15	19	0.55-1.18
Moisture %	0.035	28	0.031	90	0-0.13	0.036	29	0.023	64	0.001-0.070
Loss on Ignition %	0.97	27	0.48	49	0.42-2.77	1.40	32	0.68	48	0.50-3.68
Available Alkalies As Na ₂ O %	0.99	22	0.26	26	0.48-1.57	1.10	32	0.21	19	0.44-1.46
Fineness Surface Area cm ² /gm ³	7500	8	-	-	6450-8236	10139	31	1275	13	5475-13561
Retained #325 %	25.3	50	4.7	19	14.9-36.8	30.7	61	8.6	28	15.3-75.5
Multiple Factor %	24.4	27	15.9	65	9.8-95.3	36.8	29	18.6	50	9.9-70.0
Pozzolanic Activity Index:										
Cement, % control	87.2	30	8.0	9	63.2-98.2	90.2	28	8.9	10	60.8-102.9
Lime, psi	714	16	172	24	579-1340	695	30	124	18	368-995
Water requirement % of control	96.7	27	1.5	2	94.8-100.5	97.0	28	1.7	2	93.0-99.3
Shrinkage, Increase %	0.011	16	0.005	51	-0.002-0.019	0.007	25	0.008	114	-0.015-0.020
Soundness, Autoclave %	0.044	19	0.010	23	0.030-0.070	0.065	12	0.025	37	0.043-0.130
Expansion-14 day %	0.017	6	-	-	0.005-0.027	0.024	23	0.010	43	0.012-0.054
Air-Entraining Admixture ml.	0.92	16	0.27	29	0.60-1.40	1.02	24	0.27	27	0.60-1.80
Specific gravity	2.25	56	0.11	5	2.10-2.70	2.37	60	0.06	2	2.26-2.50

*ASTM: C618 Test Series for Class F Pozzolan

TABLE A-4b. Fly Ash Uniformity

PROPERTY*	CHOLLA			FOUR CORNERS			CHICAGO
	Average	Number of Samples	Range	Average	Number of Samples	Range	
SiO ₂ %	59.6	5	58.4-60.7	58.3	6	57.0-59.7	50.2
Al ₂ O ₃ %	21.1	5	14.2-31.4	24.2	6	18.2-31.4	21.1
Fe ₂ O ₃ %	3.64	5	1.3-5.7	3.18	6	0.8-3.9	12.4
Sum of oxides %	84.3	5	78.3-91.1	85.7	6	80.3-90.6	83.7
MgO %	1.28	4	0.8-1.7	1.33	5	0.81-2.55	2.2
SO ₃ %	0.138	5	0.02-0.30	0.168	5	0.02-0.66	1.02
Moisture %	0.020	5	0.01-0.05	0.0283	6	0.01-0.05	0.06
Loss on Ignition %	0.64	5	0.6-2.85	0.623	6	0.21-1.35	1.53
Available Alkalies							
As Na ₂ O %	0.51	5	0.28-0.70	0.62	6	0.23-0.95	0.91
CaO %	4.46	5	3.7-5.4	3.53	6	3.10-3.84	5.9
Fineness							
Surface Area cm ² /gm ³	5096	4	4560-5461	4100	5	3350-5000	8569
Retained #325 %	36.2	1	-	45.9	5	29.8-62.3	22.7
Multiple Factor %	22.3	5	0.97-95.9	30.0	5	11.4-84.1	34.7
Pozzolanic Activity Index:							
Cement, % control	60.0	1	-	56.0	1	-	93.5
Lime, psi	-	0	-	-	0	-	.895
Water requirement % of control	102	1	-	98.5	1	-	-
Shrinkage, Increase %	0.077	1	-	-	0	-	0.007
Soundness, Autoclave %	0.048	1	-	0.048	1	-	0.04
Expansion - 14 day %	-	0	-	-	0	-	-
Air-Entraining Admixture ml.	1.68	1	-	1.44	1	-	-
Specific gravity	2.17	4	2.07-2.26	1.90	5	1.85-1.93	2.53

*ASTM: C618 Test Series for Class F Pozzolan

**Single Sample for Comparison Only

source and test procedure varies through a wide range for the reasons discussed above). The range indicated in the table is simply a presentation of the highest and lowest test value encountered. The standard deviation was obtained in accordance with the usual statistical procedure, using the number of observations less one to calculate the variance ($n-1$). The coefficient of variation is the ratio of the standard deviation to the average, expressed as a percent. The standard deviation bears the dimensional units of the variable; the coefficient of variation is dimensionless.

The data of Tables A-4a and A-4b can be used to some extent to compare the characteristics of the four fly ashes. Certainly the data cannot be utilized in accordance with the strictest mathematical interpretation of the statistical parameters, since the number of observations is, in most cases, too limited. Some qualitative comparisons can be made, particularly for the Navajo and Mohave sources where a relatively large number of test results are available for certain characteristic properties. If the test values can be considered normal random variables, then the dimensionless coefficient of variation can be used to establish the probable total range of variation to be expected for the given variable. Substantially all test results would be expected to fall within a range defined by the average value plus and minus three times the coefficient of variation. It is realized that the preceding statement is subject to qualification based on a number of considerations, not the least of which is a determination of whether or not the data was obtained under controlled conditions. The purpose here is to simply establish a method of

at least qualitative comparison of whatever data are available. It has been reasonably established elsewhere that plus and minus three times the standard deviation (or coefficient of variation in dimensionless terms) defines the range of variation about the average for substantially all expected data points (and for practical purpose "substantial" refers to greater than 95% compliance) for tests on materials and manufactured products.

With this explanation in mind, the specific gravities, for example, of the Navajo and Mohave sources can be compared. The Navajo test results appear to represent a material with a specific gravity of $2.25 \pm 14.4\%$. The Mohave source tests indicate in the same manner a specific gravity of $2.37 \pm 7.2\%$. Other characteristic properties can be similarly compared.

Fly ash in the present context of discussion is a by-product, or waste material, not manufactured to a set of standards. Much of the potential value, at present, lies in the fact that some benefit can be derived by using the material in the "as is" condition and thereby maintain costs at low levels (screening and other relatively inexpensive processes are occasionally being employed to improve desired characteristics). Some benefit can apparently be derived from the use of fly ash in portland cement concrete and soil stabilization irrespective of the character or quality of the ash. The potential usefulness may be proportional to, but not dependent on, compliance with some specification, such as the ASTM: C618. The process for manufacturing the end product must remain under

control, however, and to this end the variability (or uniformity) of the fly ash becomes a consideration at least as important as the absolute values of the characteristic properties. It follows that certain individual properties become more or less important depending on the end uses of the ash.

Finally if the end product, concrete or stabilized soil, or whatever, can be designed with the desired performance characteristics, then from a practical standpoint it is primarily the uniformity of the ash which is of concern rather than the individual values of the property characteristics.

The laboratory test procedures performed for these studies (both portland cement concrete and stabilized soil) utilized a single sample of fly ash with a fixed set of physical and chemical characteristics. There are no data, therefore, which may be used to assess the relationship between performance and individual fly ash characteristics. The four data points representing the four fly ash sources might be considered for this purpose. However, consideration of the variability indicated for each of the individual physical and chemical parameters quickly dispels any hope of gaining meaningful answers to this question from such limited data.

It can be readily observed from the test data that the fly ashes sampled during the course of the study did not generally comply with the requirements of ASTM Designation: C618 for Class F Pozzolans. The deviations were primarily in the area of fineness and Pozzolanic Activity Index.

The Cholla fly ash was found to be below the specified

6500 cm²/cm³ Blaine fineness for each of the four samples tested including the sample representing the ash used in the test program. The single samples tested for the percent retained on the #325 sieve and the Pozzolanic Activity Index also failed to meet the specifications.

The Four Corners fly ash test results fall below the minimum specified Blaine fineness for each of the five samples tested, including the sample representing ash used in the test program. The average percent retained on the #325 sieve, for five samples, was outside the specified limit; the extreme values exceeded the limit by a considerable margin. The one test result obtained for the Pozzolanic Activity Index was also outside the specified range.

The Navajo source was sampled more extensively than the previous two sources. The 50 samples tested for percent passing the #325 sieve were substantially within the specified limits although the result corresponding to the ash used in the test program was slightly out. The Pozzolanic Activity Indexes were outside specified limits for a large number of the test results.

The Mohave source was also sampled more extensively than the Cholla and Four Corners sources. The 61 samples tested for percent passing the #325 sieve indicated a broad range of variation with numerous samples outside the specified limit. The Pozzolanic Activity Indexes were also out of specification for a large number of the 30 samples tested.

A.2.2 Fly Ash Quality Variables

The fly ash characteristics defined by the test procedures of ASTM: C618 were compared to determine if any of the procedures might be redundant. A high degree of linear correlation between two of the fly ash properties might indicate that one of the properties, and therefore one of the tests, could be eliminated without sacrificing the reliability of the fly ash evaluation. The objective of any such approach would be to reduce the evaluation of fly ash to the least number of test procedures and to the most straightforward and repeatable test procedures.

The coefficient of linear correlation was computed for each combination of two variables, using the twenty principal variables of the ASTM: C618 test series. The correlation matrix is presented in Table A-5. The tabulated values are coefficients of determination (coefficient of correlation squared), written as percentages. A value of 100 would indicate precise linear correlation; zero would indicate no correlation. All of the data indicated in Tables A-4a and A-4b are included in the correlation matrix. The coefficients appear to indicate that the results of the various test procedures are in most cases relatively independent. Individual discussion of the 160 or so coefficients would be laborious and unrewarding; examination of Table A-5 will quickly reveal the variables which have any significant correlation. The coefficients are indicators of statistical correlation and no physical relationships are implied by the data.

TABLE A-5. Fly Ash Test Result Correlation Matrix
(Coefficients of Determination, %)

Blaine	G _s	+325	Sound.	Poz. Act. w/PC	Water Req.	LOI	SO ₃	Moist.	Shrink.	AEA	Expan.	Mult. Factor	Poz. Act. w/lime	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Oxides	MgO	Alk. Na ₂ O
Blaine 100	71	8	8	48	70	20	53	25	20	0	0	3	1	38	31	15	49	10	57
G _s , Sp. Gravity 100	11	13	13	28	5	13	36	7	15	0	6	2	24	48	39	20	53	21	31
+325	100	8	8	23	17	2	6	7	0	9	13	29	21	2	6	4	3	7	3
Autoclave Soundness		100	100	0	2	3	2	1	3	15	43	0	11	6	0	0	2	0	4
Poz. Act. w/PC				100	41	1	31	5	11	0	7	2	7	8	10	20	7	3	16
Water Requirement					100	14	0	0	NSD	76	NSD	18	NSD	67	75	62	77	27	78
LOI, Loss on Ignition						100	8	0	NSD	NSD	NSD	88	NSD	19	6	8	15	1	19
SO ₃							100	8	NSD	NSD	2	NSD	NSD	68	5	23	26	36	67
Moisture Content								100	33	1	NSD	9	NSD	6	1	8	0	9	3
Shrinkage (Drying)									100	14	6	NSD	0	1	23	9	10	2	23
AEA, Air Entraining Admixture										100	1	NSD	5	0	9	11	3	3	3
Mortar Expansion											100	NSD	1	25	0	0	15	0	0
Multiple Factor												100	NSD	22	13	14	17	1	24
Poz. Act. w/lime													100	1	0	6	0	20	21
SiO ₂														100	18	7	69	10	28
Al ₂ O ₃															100	11	67	3	15
Fe ₂ O ₃																100	3	0	19
Sum of Oxides																	100	7	22
MgO																		100	8
Alkalinity as Equivalent Na ₂ O																			100

*Not sufficient data, less than 4 results common to the two tests

APPENDIX B. TEST DATA

B.1 Unconfined Compressive Strength

Tabulated results of unconfined compressive strengths for all tested combinations of soil-lime-fly ash are included in the tables in this section. Each value represents the average strength determined for a companion group of three specimens. Specimens were tested at the as-molded moisture content after curing at standard moist room temperature. Lime and fly ash proportions are expressed as percent dry soil weight. Data are presented in the following order:

TABLE B-1a Clayey Sand

TABLE B-1b Sand

TABLE B-1c Clay

TABLE B-1d Cinders

B.2 Soaked Unconfined Compressive Strength

Unconfined compressive strength test results for soaked soil-lime-fly ash specimens are tabulated for those combinations selected for this series. Tabulated values are the average determined for three companion specimens. Specimens were cured at the as-molded moisture content at standard moist room temperature except for a twenty four hour immersion in distilled water immediately prior to testing. Lime and fly ash proportions are expressed as percent dry soil weight.

TABLE B-2 Clayey Sand

B.3 Specimen Molding Data-Unconfined Compressive Strength

Molding unit weights and moisture contents are tabulated for all combinations tested. Each reported value represents an average for nine companion specimens. Data are presented in the following order:

TABLE B-3a Clayey Sand

TABLE B-3b Sand

TABLE B-3c Clay

TABLE B-3d Cinders

B.4 Specimen Molding Data - Freeze/Thaw

Tabulated values represent average as-molded unit weights and moisture contents for sets of two companion specimens.

TABLE B-4 Freeze-Thaw Molding Data (All Soils)

B.5 Specimen Molding Data - Wet/Dry

Tabulated values represent average as-molded unit weights and moisture contents for sets of two companion specimens.

TABLE B-5 Wet-Dry Molding Data (All Soils)

TABLE B-1a. Unconfined Compressive Strength (psi)

Clayey Sand

Fly Ash Source	% Fly Ash	0% Lime		2% Lime		4% Lime		6% Lime		8% Lime	
		Age, Days		Age, Days		Age, Days		Age, Days		Age, Days	
		7	28	7	28	7	28	7	28	7	28
None	0	30	29	90	245	318	341	84	177	72	213
		34	41	114	316	361	587	114	329	122	356
Cholla	10	33	35	129	299	358	705	144	339	113	452
	20	33	35	129	299	358	705	144	339	113	452
	30	46	60	166	332	450	676	140	449	141	553
Four Corners	10	29	33	131	247	300	522	111	329	122	384
	20	29	37	123	247	334	481	138	414	134	518
	30	35	36	143	291	341	568	153	488	152	621
Mohave	10	184	233	187	379	457	626	70	468	234	514
	20	224	309	226	534	563	677	95	521	272	745
	30	277	308	269	515	788	675	112	484	409	964
Navajo	10	54	60	128	263	312	521	137	363	172	529
	20	57	52	126	195	242	522	151	353	210	692
	30	78	101	132	200	205	380	60	269	272	771

TABLE B-1b. Unconfined Compressive Strength (psi)

Sand

Fly Ash Source	% Fly Ash	0% Lime			2% Lime			4% Lime			6% Lime			8% Lime		
		Age, Days			Age, Days			Age, Days			Age, Days			Age, Days		
		7	28	56	7	28	56	7	28	56	7	28	56	7	28	56
None	0	-	-	-	4	8	14	6	15	23	7	17	28	13	28	39
Cholla	10	4	3	4	15	83	202	21	121	278	28	137	335	-	-	-
	20	22	26	27	33	163	371	55	288	585	75	325	544	-	-	-
	30	47	62	74	51	199	480	86	393	783	102	396	716	-	-	-
Four Corners	10	2	1	2	20	92	261	27	176	317	48	199	371	-	-	-
	20	5	5	4	33	186	333	49	281	599	97	351	737	-	-	-
	30	9	8	9	48	226	383	54	383	592	128	494	874	-	-	-
Mohave	10	17	27	44	45	203	379	72	271	549	138	508	589	-	-	-
	20	51	72	91	86	303	628	169	682	752	297	929	926	-	-	-
	30	78	124	152	145	400	684	223	731	1065	377	972	1246	-	-	-
Navajo	10	5	5	7	22	85	155	51	219	381	84	459	567	-	-	-
	20	13	14	17	31	56	82	48	195	257	132	630	667	-	-	-
	30	23	26	38	53	65	79	49	85	117	116	361	463	-	-	-

TABLE B-1c. Unconfined Compressive Strength (psi)

Clay

Fly Ash Source	% Fly Ash	0% Lime			2% Lime			4% Lime			6% Lime			8% Lime		
		Age, Days			Age, Days			Age, Days			Age, Days			Age, Days		
		7	28	56	7	28	56	7	28	56	7	28	56	7	28	56
None	0	37	39	44	88	85	95	88	156	193	124	179	191	138	204	282
Cholla	10	60	61	57	73	85	104	153	216	224	160	258	360	-	-	-
	20	59	64	64	100	116	113	154	239	278	132	228	317	-	-	-
	30	62	62	83	89	143	130	117	160	195	232	342	433	-	-	-
Four Corners	10	43	64	62	118	140	163	146	236	264	190	297	370	-	-	-
	20	52	62	69	124	165	181	120	180	245	111	187	277	-	-	-
	30	48	66	77	102	111	122	114	195	254	231	401	530	-	-	-
Mohave	10	78	93	104	114	168	184	134	225	221	167	206	323	-	-	-
	20	97	107	126	196	214	300	202	262	267	121	154	264	-	-	-
	30	166	225	206	127	222	170	238	281	299	192	278	313	-	-	-
Navajo	10	85	88	106	100	113	128	137	202	253	186	238	246	-	-	-
	20	76	111	84	131	154	182	182	218	268	139	207	244	-	-	-
	30	91	125	104	137	160	200	113	125	158	165	269	344	-	-	-

TABLE B-1d. Unconfined Compressive Strength (psi)

Cinders

Fly Ash Source	% Fly Ash	0% Lime			2% Lime			4% Lime			6% Lime		
		Age, Days			Age, Days			Age, Days			Age, Days		
		7	28	56	7	28	56	7	28	56	7	28	56
None	0	-	-	-	-	-	-	41	51	65	41	61	79
Cholla	10	-	-	-	-	-	-	66	84	114	73	119	185
	20	0	0	0	84	123	120	89	146	215	111	187	318
	30	-	-	-	-	-	-	-	-	-	-	-	-

TABLE B-2. Soaked Unconfined Compressive Strength (psi)
Clayey Sand

Fly Ash Source	% Fly Ash	2% Lime		4% Lime		6% Lime	
		Age, Days		Age, Days		Age, Days	
		28	56	28	56	28	56
Cholla	20	-	-	259	497	269	-
Navajo	10	-	321	-	426	281	574
	20	146	260	-	299	225	463
	30	-	-	-	-	-	467

TABLE B-3a. Unconfined Compressive Strength
Specimen Molding Data, Clayey Sand

Fly Ash Source	% Fly Ash	% Lime				
		0	2	4	6	8
None	0	124 @ 9*	121 @ 11	118 @ 11	116 @ 12	116 @ 12
Cholla	10	121 @ 12	118 @ 11	114 @ 11	114 @ 12	113 @ 13
	20	117 @ 11	113 @ 12	112 @ 12	110 @ 11	112 @ 14
	30	113 @ 12	109 @ 13	108 @ 12	107 @ 11	109 @ 13
Four Corners	10	118 @ 14	114 @ 11	113 @ 12	111 @ 12	114 @ 14
	20	115 @ 14	110 @ 12	106 @ 11	108 @ 12	110 @ 14
	30	111 @ 13	107 @ 13	104 @ 11	105 @ 13	106 @ 15
Mohave	10	119 @ 10	117 @ 11	115 @ 11	115 @ 12	116 @ 14
	20	118 @ 11	115 @ 12	113 @ 10	110 @ 11	114 @ 14
	30	117 @ 12	115 @ 13	113 @ 10	109 @ 10	114 @ 13
Navajo	10	120 @ 12	116 @ 12	114 @ 11	113 @ 12	115 @ 14
	20	116 @ 12	114 @ 13	111 @ 11	110 @ 11	113 @ 14
	30	115 @ 13	112 @ 13	110 @ 11	109 @ 12	111 @ 14

* Dry Density = 124 pcf, Moisture Content = 9%. Each value represents the average of 9 specimens.

TABLE B-3b. Unconfined Compressive Strength Specimen Molding Data,
Sand

Fly Ash Source	% Fly Ash	% Lime				
		0	2	4	6	8
None	0	**	113 @ 12*	114 @ 12	115 @ 12	118 @ 11
Cholla	10	113 @ 10	113 @ 9	114 @ 9	117 @ 9	**
	20	113 @ 9	114 @ 9	114 @ 9	115 @ 9	**
	30	112 @ 14	112 @ 10	114 @ 10	115 @ 10	**
Four Corners	10	112 @ 9	112 @ 9	114 @ 9	115 @ 9	**
	20	111 @ 9	111 @ 9	110 @ 9	113 @ 9	**
	30	109 @ 9	109 @ 10	109 @ 10	111 @ 9	**
Mohave	10	116 @ 9	116 @ 9	116 @ 9	118 @ 9	**
	20	119 @ 8	118 @ 9	118 @ 9	118 @ 9	**
	30	120 @ 9	120 @ 10	120 @ 9	120 @ 10	**
Navajo	10	114 @ 10	115 @ 9	115 @ 9	117 @ 9	**
	20	114 @ 9	115 @ 9	114 @ 9	115 @ 9	**
	30	115 @ 10	117 @ 9	115 @ 9	115 @ 10	**

* Dry Density = 113 pcf, Moisture Content = 12%. Each value represents the average of 9 specimens.

** Combination not tested.

TABLE B-3c. Unconfined Compressive Strength Specimen Molding Data, Clay

Fly Ash Source	% Fly Ash	% Lime				
		0	2	4	6	8
None	0	100 @ 22*	95 @ 23	97 @ 19	96 @ 21	95 @ 24
Cholla	10	103 @ 20	97 @ 20	97 @ 21	96 @ 21	**
	20	103 @ 19	97 @ 19	98 @ 20	96 @ 19	**
	30	101 @ 20	97 @ 17	96 @ 18	96 @ 20	**
Four Corners	10	101 @ 19	98 @ 22	96 @ 22	96 @ 22	**
	20	101 @ 19	97 @ 20	96 @ 19	95 @ 18	**
	30	100 @ 19	96 @ 17	95 @ 18	95 @ 20	**
Mohave	10	101 @ 21	98 @ 20	97 @ 21	96 @ 21	**
	20	99 @ 20	98 @ 20	98 @ 21	97 @ 17	**
	30	100 @ 20	98 @ 16	98 @ 20	96 @ 19	**
Navajo	10	103 @ 18	98 @ 20	96 @ 22	96 @ 22	**
	20	101 @ 18	97 @ 19	97 @ 21	96 @ 19	**
	30	101 @ 20	98 @ 19	96 @ 16	96 @ 20	**

* Dry Density = 100 pcf, Moisture Content = 22%. Each value represents the average of 9 specimens.

** Combination not tested.

TABLE B-3d. Unconfined Compressive Strength Specimen Molding Data, Cinders

Fly Ash Source	% Fly Ash	% Lime			
		0	2	4	6
None	0	**	**	62 @ 35*	64 @ 29
Cholla	10	**	**	70 @ 31	71 @ 29
	20	73 @ 24	76 @ 25	79 @ 26	76 @ 24

* Dry Density = 62 pcf, Moisture Content = 35%. Each value represents the average of 6 specimens.

** Combination not tested.

TABLE B-4. Freeze-Thaw Durability Specimen Molding Data

Soil	% Lime	0% Fly Ash	%Cholla Fly Ash	
			10	20
Clayey Sand	2	**	117 @ 12	**
	4	120 @ 12*	115 @ 12	111 @ 11
	6	118 @ 12	**	110 @ 12
	8	116 @ 12	**	**
Sand	2	114 @ 12	115 @ 13	**
	4	116 @ 11	116 @ 13	117 @ 12
	6	117 @ 11	117 @ 12	116 @ 13
Clay	2	99 @ 22	99 @ 19	**
	4	99 @ 21	98 @ 20	97 @ 19
	6	97 @ 20	96 @ 22	95 @ 20
Cinders	0	**	**	78 @ 23
	2	**	**	75 @ 28
	4	**	**	77 @ 26
	6	64 @ 28	72 @ 27	78 @ 26

Soil	% Lime	%Mohave Fly Ash		%Navajo Fly Ash	
		10	20	10	20
Clayey Sand	2	118 @ 12	**	117 @ 12	**
	4	116 @ 12	114 @ 11	115 @ 11	112 @ 11
	6	**	113 @ 12	**	111 @ 12
Clay	2	99 @ 20	**	99 @ 19	**
	4	98 @ 20	97 @ 19	97 @ 20	97 @ 19
	6	97 @ 21	96 @ 19	96 @ 21	96 @ 19

* Dry density = 120 pcf, Moisture Content = 12%. Each value represents the average of 2 specimens.

** Combination not tested.

TABLE B-5. Wet-Dry Durability Specimen Molding Data

Soil	% Lime	0% Fly Ash	%Cholla Fly Ash	
			10	20
Clayey Sand	2	**	117 @ 12	**
	4	119 @ 12*	115 @ 12	112 @ 11
	6	118 @ 12	**	110 @ 12
	8	115 @ 12	**	**
Sand	2	114 @ 12	115 @ 13	**
	4	115 @ 11	114 @ 13	117 @ 12
	6	117 @ 11	117 @ 12	117 @ 12
Clay	2	99 @ 22	98 @ 20	**
	4	98 @ 21	98 @ 20	97 @ 19
	6	96 @ 21	97 @ 22	96 @ 19
Cinders	0	**	**	77 @ 22
	2	**	**	74 @ 25
	4	**	**	74 @ 26
	6	64 @ 27	72 @ 27	77 @ 26

Soil	% Lime	%Mohave Fly Ash		%Navajo Fly Ash	
		10	20	10	20
Clayey Sand	2	118 @ 12	**	116 @ 12	**
	4	116 @ 12	115 @ 11	115 @ 12	112 @ 11
	6	**	113 @ 12	**	111 @ 12
Clay	2	99 @ 20	**	99 @ 19	**
	4	98 @ 20	97 @ 19	98 @ 20	97 @ 19
	6	97 @ 21	97 @ 19	96 @ 21	96 @ 20

* Dry density = 119 pcf, Moisture content = 12%. Each value represents the average of 2 specimens.

** Combination not tested.

APPENDIX C. IMPLEMENTATION PROJECT

C.1 Project and Purpose

Grade and drain construction of the Hackberry Wash to Junction I-17 section of the Dewey Cutoff (FAP058) was complete or nearly complete in March 1977. Sections of the project were considered for field study to evaluate the relative performances of cement stabilized and lime-fly ash stabilized base or subbase. Portland cement and lime-fly ash stabilization were proposed for the existing grade from Sta. 520 to 555 and Sta. 555 to 590, respectively. It was understood that construction of the test sections would be in conjunction with the paving contract anticipated to be let later in the year.

The objective of the sampling, testing and analysis presented here was to develop mix designs for the soil-cement and lime-soil-fly ash mixtures. Final selection of mix proportions was to be based on considerations of unconfined compressive strength and resistance to deterioration from cyclic freezing and thawing.

C.2 Scope of Work

C.2.1 Field Sampling

Samples of representative materials were provided by the Arizona Department of Transportation.

C.2.2 Soil-Cement

Proportions were analyzed based on a laboratory test program consisting of:

- a) Determination of Cement Content Required for Cement Treated Mixtures, Test Method ARIZ 220, and
- b) Freezing and Thawing Tests of Compacted Soil Cement Mixtures, AASHO: T136-70.

C.2.3 Lime-Soil-Fly Ash

Proportions were analyzed based on data developed in the general study as well as data derived from a laboratory test program, including:

- a) Moisture-density relationships for selected mixtures.
- b) Unconfined compressive strength of specimens molded in standard compaction molds at selected densities.
- c) Freezing and Thawing Tests of Compacted Soil Cement Mixtures, AASHTO: T136-70 (modified to include lime-soil-fly ash).

C.3 Test Results

Test data is presented in the following pages and includes:

- a) Report of Preliminary Test Data
- b) Report of Final Test Data
- c) Laboratory Data provided by the Arizona Department of Transportation.

Arizona Department of Transportation
Highways Division
Research Section
206 S. 17th Avenue
Phoenix, Arizona 85007

27 April 1977

Attention: Gene R. Morris
Research Engineer

Re: Utilization of Waste Boiler Ash in
Highway Construction in Arizona
HPR 1-13 (158) #74-28
Change Order No. 2

Job No. 416-685

In accordance with your request, we are submitting semi-final results of laboratory testing performed on stabilized soil mixes for sections of the Dewey Cutoff.

Final results for soil-cement mixes are presented, including resistance to deterioration from cyclic freezing and thawing, AASHO: T136, and unconfined compressive strength, ARIZ 220.

Preliminary unconfined compressive strengths are given for quick lime-soil-fly ash mixtures. Lime used in certain of these mixtures, however, was suspected of being partially unslaked, leading to possible damage of specimens due to expansion. Re-testing of these specimens is currently in progress.

Freeze-thaw testing of the hydrated lime-soil-fly ash mixtures is also in progress at this time.

Should any questions arise concerning these results, please do not hesitate to contact us.

Respectfully submitted,
ENGINEERS TESTING LABORATORIES, INC.

M. Kent Hamm, P.E.

Copies to: Addressee (3)

Job No. 416-685
Lab No. 01382

LABORATORY REPORT

Type of Material/Specimens Soil-cement
Source of Material/Specimens Dewey Cutoff
Test Procedure As noted Sampled By ADOT Date 2/77
Reviewed By MKH Date 4/22/77 Submitted By ADOT Date 2/77

RESULTS

Specimen Number	Dry ¹ Density	Cement Content, %	Water Content, %	Unconfined ² Compressive Strength at 7 days, psi		Weight ³ Loss
				Actual	Average	
3	127.4	3	10.3	313	324	16.5
4	127.1	3	10.4	334		
3	129.9	5	9.7	500	511	7.2
4	129.1	5	9.8	522		
3	130.0	7	9.9	643	636	2.9
4	129.1	7	10.0	629		
3	129.9	9	9.7	716	715	3.0
4	124.8	9	9.8	715		

1 Maximum 130.5 pcf at 9.6%

2 ARIZ 220

3 Base on assumed 1.5% moisture retention, AASHO: T136

Job No. 416-685
Lab No. 01460

LABORATORY REPORT

Type of Material/Specimens Quick lime-soil-fly ash mixtures
Source of Material/Specimens Dewey Cutoff
Test Procedure As noted Sampled By ADOT Date 2/77
Reviewed By MKH Date 4/22/77 Submitted By ADOT Date 2/77

RESULTS

<u>Lime Content, %</u>	<u>Fly Ash Content, %</u>	<u>Unconfined Compressive¹ Strength at 28 days, psi</u>
1-1/2	10	199
1-1/2	15	149
3	10	219
3	15	192
4-1/2	10	189
4-1/2	15	225

1. ARIZ 220, except cure for 28 days. Average value of four specimens.

Arizona Department of Transportation
Highways Division
Research Section
206 S. 17th Avenue
Phoenix, Arizona 85007

17 June 1977

Attention: Gene R. Morris
Research Engineer

Re: Utilization of Waste Boiler Ash in
Highway Construction in Arizona
HPR 1-13 (158) #74-28
Change Order No. 2

Job No. 416-685

In accordance with your request, we are submitting final results for laboratory testing performed on stabilized soil mixtures for sections of the Dewey Cutoff.

Final results for soil cement mixtures were submitted previously, with preliminary results for quicklime-soil-fly ash mixtures. The attached laboratory reports include final unconfined compressive strength and freeze-thaw test results for the lime-fly ash stabilized mixtures.

Field proportions for the soil-cement mixture may be based on the standard ADOT selection procedure utilizing unconfined compressive strengths.

Test results for the lime-fly ash mixtures indicate optimum proportions of 3% lime and 10% fly ash. Strength data tend to indicate that the lime-fly ash mixtures are significantly inferior to the soil-cement mixtures. Research data, however, indicate that a significant rate of strength gain should probably be expected well beyond the 28 day test age. Ultimately the relative field behavior

Utilization of Waste Boiler Ash in
Highway Construction in Arizona
HPR 1-13 (158) #74-28

of the mixtures will depend to a considerable extent on the effects of field curing conditions. The standard freeze-thaw test did not provide conclusive data for rating the lime-fly ash mixtures.

Respectfully submitted,
ENGINEERS TESTING LABORATORIES, INC.

M. Kent Hamm, P.E.

Copies: Addressee (3)

Specimen Number (1)	Molding Dry (2)	Molding Water	Quick Lime	Mohave Fly Ash	Unconfined Compressive (3)		Freeze-Thaw (4)	
	Density (pcf)	Content (%)	Content (%)	Content (%)	Strength at 28 Days Individual psi	Average psi	Cycles Completed	Wt. Loss (%)
247-3		10.5	1½	10	166			
4		10.5	1½	10	186			
5		10.5	1½	10	221			
6		10.5	1½	10	224	199		
7	123.6	10.7	1½	10	-	-	12	3.7
8	125.3	10.5	1½	10	-	-	7	68.4
248-3		10.5	3	10	218			
4		10.5	3	10	247			
5		10.5	3	10	211			
6		10.5	3	10	198	219		
7	123.3	10.4	3	10	-	-	12	6.9
8	122.1	10.5	3	10	-	-	8	78.8
249-3		10.5	4½	10	184			
4		10.5	4½	10	190			
5		10.5	4½	10	199			
6		10.5	4½	10	182	189		
7	120.4	10.0	4½	10	-	-	12	32.4
8	120.2	10.1	4½	10	-	-	6	82.2
250-3		11.0	1½	15	164			
4		11.0	1½	15	138			
5		11.0	1½	15	135			
6		11.0	1½	15	157	149		
7	125.1	11.0	1½	15	-	-	12	20.4
8	125.5	11.1	1½	15	-	-	1	17.1
251-3		11.0	3	15	195			
4		11.0	3	15	213			
5		11.0	3	15	162			
6		11.0	3	15	199	192		
7	124.1	11.2	3	15	-	-	12	10.7
8	123.8	10.9	3	15	-	-	8	79.5
252-3		11.0	4½	15	182			
4		11.0	4½	15	204			
5		11.0	4½	15	208			
6		11.0	4½	15	306	225		
7	124.3	11.3	4½	15	-	-	7	5.3
8	123.9	11.4	4½	15	-	-	7	60.9

(1) Specimens 1 and 2 used for 7 day strengths, not reported.

(2) ARIZ 220 maximum density and optimum moisture content:

Sample 246, 3% lime, 10% FA - 124.2 psf at 10.2%

249, 3% lime, 20% FA - 119.4 psf at 12.1%

253, 3% lime, 30% FA - 118.7 psf at 11.5%

(3) ARIZ 220, except cure for 28 days.

(4) Specimen 7 was control specimen, specimen 8 was brushed specimen. Cycles less than 12 indicate breaking apart or otherwise complete deterioration of specimen. AASHO: T136, 28 day cure.

ARIZONA DEPARTMENT OF TRANSPORTATION - MATERIALS DIVISION

MATERIAL PROSPECTED FOR SUBGRADE RECEIVED-01/12/77 TEST COMMENCED-01/13/77
 SAMPLED ON-01/10/77 EXISTING ROADWAY
 PROJECT NUMBER-S-447-305PE SAMPLE SOURCE- SUPPLY -STA 522+00 TO 590+00
 PROJ. NAME-YARBER WASH-JCT I-17 LCC. CF SPEC. SAMPLED BY-L.H.BEST
 CONTRACTOR- DATE PRINTED-01-24-77
 REMARKS-DEPTH RECORDED IN INCHES

HOLE NO.	DEPTH	LOC.	STATION	LL	PI	PASS 200	PASS 40	PASS NO.8	PASS NO.4	PASS 1/4	PASS 3/4	SS	LAB.NO.
1-	0-8.0	0	CL 522+	0	3	21.9	50	91	100	100	100	8.63	7700239
2-	0-12.0	0	CL 525+	0	3	14.6	36	88	100	100	100	8.88	7700240
3-	0-12.0	0	CL 530+	0	4	13.8	37	79	93	93	97	8.78	7700241
4-	0-12.0	0	CL 535+	0	3	13.0	35	81	90	92	97	8.92	7700242
5-	0-12.0	0	CL 540+	0	NP	13.0	38	85	91	95	99	9.78	7700243
6-	0-12.0	0	CL 545+	0	NP	14.5	45	85	92	94	97	9.74	7700244
7-	0-12.0	0	CL 550+	0	3	12.4	34	78	87	91	98	8.99	7700245
8-	0-12.0	0	CL 555+	0	6	15.1	31	71	88	91	98	8.42	7700246
9-	0-12.0	0	CL 560+	0	NP	14.7	34	79	88	93	97	8.75	7700247
10-	0-12.0	0	CL 565+	0	5	14.3	38	80	89	92	98	8.65	7700248
11-	0-8.0	0	CL 570+	0	2	14.8	40	81	91	93	97	9.15	7700249
12-	0-8.0	0	CL 580+	0	2	18.0	35	82	92	94	98	9.08	7700250
13-	0-8.0	0	CL 585+	0	2	13.0	35	80	91	93	97	9.20	7700251
14-	0-12.0	0	CL 590+	0	4	14.6	35	87	88	91	97	8.74	7700252
15-	0-12.0	0	CL 590+	0	4	14.6	35	87	88	91	97	8.74	7700253

ARIZ. DEPT. OF TRANSPORTATION-MATERIALS DIVISION

PROJECT NUMBER-S-447-305PE

WT= 1000000. REGIONAL= 2.0 PT= 2.5

HOLE NO.	DEPTH	SS	R	K	SN	AASHO SOIL CLASS
1-	0.0-8.0	8.63	73.2	983	1.99	A-1-B(0)
2-	0.0-12.0	8.88	75.9	1079	1.92	A-1-B(0)
3-	0.0-8.0	8.78	74.8	1041	1.95	A-1-B(0)
4-	0.0-12.0	8.92	76.3	1094	1.91	A-1-B(0)
5-	0.0-12.0	9.78	85.4	1500	1.68	A-1-B(0)
6-	0.0-12.0	9.77	85.3	1494	1.69	A-1-B(0)
7-	0.0-8.0	9.74	85.0	1480	1.69	A-1-B(0)
8-	0.0-12.0	8.99	77.1	1125	1.89	A-1-B(0)
9-	0.0-12.0	8.42	71.0	1191	2.06	A-1-B(0)
10-	0.0-8.0	8.75	85.2	1487	1.69	A-1-B(0)
11-	0.0-8.0	8.65	73.4	991	1.99	A-1-B(0)
12-	0.0-8.0	9.15	78.8	1193	1.87	A-1-B(0)
13-	0.0-8.0	9.08	78.0	1162	1.85	A-1-B(0)
14-	0.0-8.0	9.20	79.3	1213	1.83	A-1-B(0)
15-	0.0-12.0	8.74	74.4	1024	1.96	A-1-B(0)