Fly Ash as Fill and Base Material in Arkansas Highways

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16. Abstract

Fly ash, similar to that to be produced in Arkansas, reacts chemically like quick lime, generating heat and possessing self hardening characteristics. Reactivity of the ash may be due to the relatively high Ca0 content of 20%.

Two Arkansas soils, an organic clay and a sand (classified OH and SP-SM by the Unified system) were stabilized with the fly ash. Addition of 20% fly ash to the clay reduced the fraction of less than 2 micron particles from 58% to 8%. Twenty percent fly ash increased modified compaction density by 0.96 g/cc (6 pcf) in the clay and .32 g/cc (10 pcf) in the sand. Unconfined compressive strengths with 20% fly ash increased by 15.5 Kg/cm^2 (220 psi) in clay and 51 Kg/cm^2 (720 psi) in sand when compacted immediately and cured 7 days. Unconfined compressive strengths were improved with lime and cement admixtures.

A delay in compaction causes large decreases in strength and density of sand-fly ash mixtures. After a one hour delay, only 18% of the initial strength and 83% of initial dry density are retained. Delays of 4 hours produced strengths and densities at the same level as 1 hour delays. Addition of salt retards the sand-fly ash reaction. After a one hour delay with 2% salt added, 66% of initial strength and 98% of initial dry density are retained. After 4 hours delay in compaction, however, only 22% of the initial strength and 86% of initial dry density are retained.

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FLY ASH AS FILL AND BASE MATERIAL IN ARKANSAS HIGHWAYS

by

Sam I. Thornton

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FINAL REPORT
HIGHWAY RESEARCH PROJECT 43

conducted for

The Arkansas State Highway Department

in cooperation with

The U.S. Department of Transportation

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SUMMARY

Fly ash, a pozzolanic by-product of coal burning power plants, is an abundant potential source of highway and embankment construction material. Some fly ashes are suitable for use as a supplement or replacement for lime and Portland Cement in soil stabilization applications. Production of lime and Portland Cement requires heat and will become more costly as energy costs rise. Fly ash, however, is a by-product of power productions.

Production of fly ash in the United States was 3.67×10^{10} Kilograms (40.4 million tons) in 1973 and is projected to be 4.53×10^{10} Kilograms (50 million tons) by 1980. Less than 10% of the fly ash produced is used in commercial applications. The remainder of the fly ash is wasted either by sluicing to ponds or hauling to solid waste disposal areas. Disposal operations are quite expensive and require the use of land which could be used for other purposes.

The fly ash used in this study, produced from Wyoming low sulfur coal, contains 20% CaO causing it to react something like quick lime. In addition, the fly ash takes a pozzolanic set when mixed with water. Reported herein are the engineering properties of this fly ash, fly ash-soil mixtures, and mixtures with lime and Portland Cement.

EARLIER STUDIES

Most fly ash investigations to date were performed on ash originating from coal mined in the central and central and eastern United States. The following is a review of some of these studies.

Reaction

Combining lime and fly ash with water forms a centitious material on the fly ash surface (Herzog and Brock, 1964). The reaction product formed is initially a non-crystalline gel, but eventually becomes calcium silicate hydrate I, a compound found in hydrated portland cements (Croft, 1964; Leonard and Davidson, 1959).

Chemical content, fineness and temperature all affect the cementing reaction. Cementing increases with mullite ($3\ Al_2O_3$-$2\ S_iO_2$) (Croft, 1964), Calcium oxide (Sutherland, et. al., 1968), sulfur trioxide, and magnesium oxide content (Minnick, 1953). Unburned organics reduce cementing apparently, by covering reactive surfaces and preventing contact of cementitous material (Davidson, et. al., 1958; Leonard and Davidson, 1959; Thorne and Watt, 1965). Smaller particles are more reactive due to a larger surface area per unit weight and, therefore, provide cementing strengths quicker.

Little reaction takes place between lime and fly ash below temperatures of 20° C (68° F) (Minnick, 1953). The rate of the lime-fly ash reaction increases, however, when the mixtures are cured at elevated temperatures. An increase of the curing temperature from 20° C (68° F) to 50° C (122° F) increases the initial rate of development of strength by a factor of 10 (Thorne and Watt, 1965). The period required for maximum strength development is reduced from 300 days at 20° C (68° F) to 40 days at 50° C (122° F). However, maximum strengths are as much as 20% lower for samples cured at 50° C (122° F) as compared to those cured at 20° C (68° F).

Fly Ash as Fill

Dry unit weight of fly ash is lower than most fill material, usually 1.1 to 1.3 g/cc (70 to 80 pdf). Placed loose over an embankment, unit weights are as low as .72 to .80 g/cc (45 to 50 pcf) (DiGioia and Nuzzo, 1972). Compacted fly ash may weigh 1.5 g/cc (95 pcf). Low unit weight is due partly to a low specific gravity, usually near 2.40, but varying from 1.88 to 2.84 (Abdun-Nur, 1961). Low unit weight of fly ash is also due to uniform size (0.15 mm to .05 mm) and a solid or hollow spherical shape. Low unit weight is an asset where embankments are constructed over compressible and weak bearing strata.

Vibratory compaction is best for fly ash fills (DiGioia and Nuzzo, 1972). Vibratory loads destroy the apparent cohesion in the fly ash by breaking the surface tension of the pore water. Steel wheeled rollers are not effective for compaction because the fly ash forms a wave in front of the forward roller which may bring the roller to a standstill. Sheepsfoot rollers are not suitable for compaction because the rolled surface tends to be overstressed and excessively disturbed (Smith, 1973).

The strength of fly ash depends on its self-hardening characteristics. Fly ash without self-hardening characteristics is without cohesion, except for capillary forces which may be destroyed by flooding. Self-hardening fly ash may have cohesion up to 4.9 kgs/sq cm (70 psi). The remainder of shear strength in fly ash is due to the angle of internal friction which depends on density and ranges from 29° to 46° (Sutherland, et. al., 1968).

Fly ash with self-hardening characteristics is incompressible relative to a fly ash without self-hardening characteristics. After three days cure, Grand Avenue fly ash, a self-hardening fly ash, had a coefficient of compressibility of only .061 (Joshi, et. al., 1974). A non self-hardening Western Pennsylvania fly ash had settlement characteristics of a typical cohesive soil (DiGioia and Nuzzo, 1972). Fly ash compresses much more quickly than clays, however, because the permeability of ash (10^{-4} tp 10^{-5} cm/sec) is much greater than clay (10^{-7} to 10^{-9} cm/sec). Field settlements of self-hardening British fly ashes were less than 2.5 cm in fills up to 15 m (50 feet) thick, even though settlements were computed from a consolidometer test at .3 to .4 m (12 to 16 inches) (Raymond and Smith, 1966).

Soil-Lime-Fly Ash Stabilization

Compacted soil-lime-fly ash mixtures may have strengths of 70.3 Kgs/sq cm (1000 psi) at 28 days (Minnick and Meyers, 1953). An increase in compactive effort from Standard to Modified Proctor increases strength from 50 to 160%, usually a linear increase (Viskochil, et. al., 1957). Addition of lime and fly ash to the soil usually decreases maximum Proctor density and increases the optimum water content (Chu, et. al., 1955). Maximum strength of stabilized sand is obtained when compaction is dry of optimum, but maximum strength of stabilized clay is obtained when compacted wet of optimum.

There is no optimum ratio of lime-fly ash for stabilizing all soils because a range of ratios will produce satisfactory results (Croft, 1964; Mateos and Davidson, 1963). The selection of trial proportions will depend upon the soil gradation, clay content, quality of fly ash and, to a lesser extent, the kind of lime. Soils containing expansive clays require a larger lime-fly ash ratio to ensure there is enough lime for the lime-clay reaction and the lime-fly ash reaction. Sandy soils will derive initial strengths from improvement of gradation and ultimate strengths from the lime-fly ash reaction (Croft, 1964).

In clay soils, the range of lime content should be 5 to 9% and range of fly ash should be 10 to 25% for the maximum value of unconfined compressive strength. For granular soils, the amount of lime should be between 3 and 6% and the amount of fly ash between 10 and 25% (Mateos and Davidson, 1963).

Cement-Fly Ash Stabilization

Compacted strengths of portland cement-fly ash mixtures may be in excess of 176 Kgs/sq cm (2500 psi) (Sutherland, et. al., 1968). Maximum strength was obtained when compacted slightly above optimum moisture content. British fly ashes stabilized with cement are stronger at early ages, but are generally not as strong as lime stabilized fly ashes for periods of cure greater than three months.

Generally, 2 to 4% cement will stabilize fly ash to the extent that the ash will not be susceptible to frost heave. However, some British fly ashes require cement contents of 6 to 15% to reduce the heave of some fly ashes to 0.01 m. (0.5 inches) after 250 hours (Sutherland, et. al., 1968).

PROPERTIES OF FLY ASH

Fly ash generally exhibits a wide range in chemical and physical properties. These properties determine the effectiveness of the ash for use in soil stabilization. The characteristics of a particular fly ash is dependent on the coal source, coal preparation procedures, boiler type, and the ash collection device.

The fly ash used in this study was collected by an electrostatic precipitator from a 350 megawatt tangential burner boiler. The coal was a low sulfur coal obtained from Campbell County, Wyoming and was pulverized before injection into the burner. The fly ash has a light cream color and particles are spherical in shape. Chemical and physical properties of the fly ash are shown in Table 1.

The fly ash under investigation has self-hardening characteristics when mixed with water. Twenty-eight day unconfined compressive strengths in excess of 70 Kgs/sq cm (1000 psi) were obtained from samples compacted immediately after mixing with water. Furthermore, temperatures up to 66^{o} C (150^{o} F) were observed within 30 minutes after compaction of fly ash soil mixtures.

One possible explanation for the apparent reactivity of the fly ash is the relatively high calcium oxide (CaO) content of the ash. Most investigators report CaO contents between 1 and 11% while the ash under study has a concentration of 20%. The CaO in the ash may be acting like quick lime, causing the observed temperature increases and enhancing the pozzolanic activity of the other constituents in the ash.

SUMMARY TABLE 1

PROPERTIES OF FLY ASH

Chemical Properties

Compound	Chemical Composition % by weight
SiO	34.0
Al_2O_3	13.0
Fe_2O_3	6.0
CaO	20.0
MgO	6.0
K_2O	0.8
Na_2O	2.8
SO_3	13.7
TiO_2	1.0
Undetermined	2.7

Physical Properties

Property	Value
Loss on Ignition	0.0%
pH	11.2%
Water Soluble Fraction	1.0%
Pozzolanic Activity Index	75.5 Kgs/sq cm
Specific Gravity	2.75
Minimum Density	1.00 g/cc
Maximum Density (Modified Proctor)	1.89 g/cc
Optimum Moisture Content	9.0%
% Passing #40 Sieve	99.5%
% Passing #100 Sieve	98.0%
% Passing #200 Sieve	94.0%
% Passing #325 Sieve	86.6%

SOIL - FLY ASH MIXTURES

Two Arkansas soils, a clay (OH) and a sand (SP-SM) were used in the study. The clay, 59% by weight less than 2 micron, contained 11.4% organic material (Table 2) and had kaolin as its predominant clay mineral. The sand was non-plastic and contained only 5% clay size particles (Table 2). Liquid limit of the clay was 59 and the plastic index was 19.

Effect of Fly Ash

Generally, the addition of 5% fly ash to the clay slightly increased the plasticity index of the clay and the addition of 10% and 20% fly ash reduced the plasticity index of the clay. Atterberg limits had considerable scatter, however, possibly due to sample preparation and the presence of organics (Arman, 1975).

The grain-size of the kaolinite clay was significantly increased with the addition of fly ash in the amounts of 10% and 20% (Figure 1). Of the clay, 58% was finer than two microns. When 10% and 20% fly ash was added to the clay, the percent finer than two microns was 32% and 8% respectively. Addition of fly ash to the clay caused inter-particle cementation to take place between clay and fly ash particles, enlarging the grain size of the clay.

Fly ash improved the California Bearing Ratio (CBR) of sand enough to meet the requirements for a base directly beneath pavement. The addition of 20 percent fly ash increased the CBR of sand from 22% to 104% which is in excess of the 80% requirement. In clay, addition of 20% fly ash increased the CBR from 4% without fly ash to 15%.

Addition of fly ash increased the density of both sand and clay at modified compactive effort (Figure 2). Addition of 20% fly ash by weight increased clay density by 0.1 g/cc (6 pcf) and reduced optimum moisture by 3%. Twenty percent fly ash increased the sand density by 0.32 g/cc (20 pcf) and increased the optimum moisture content by 2%.

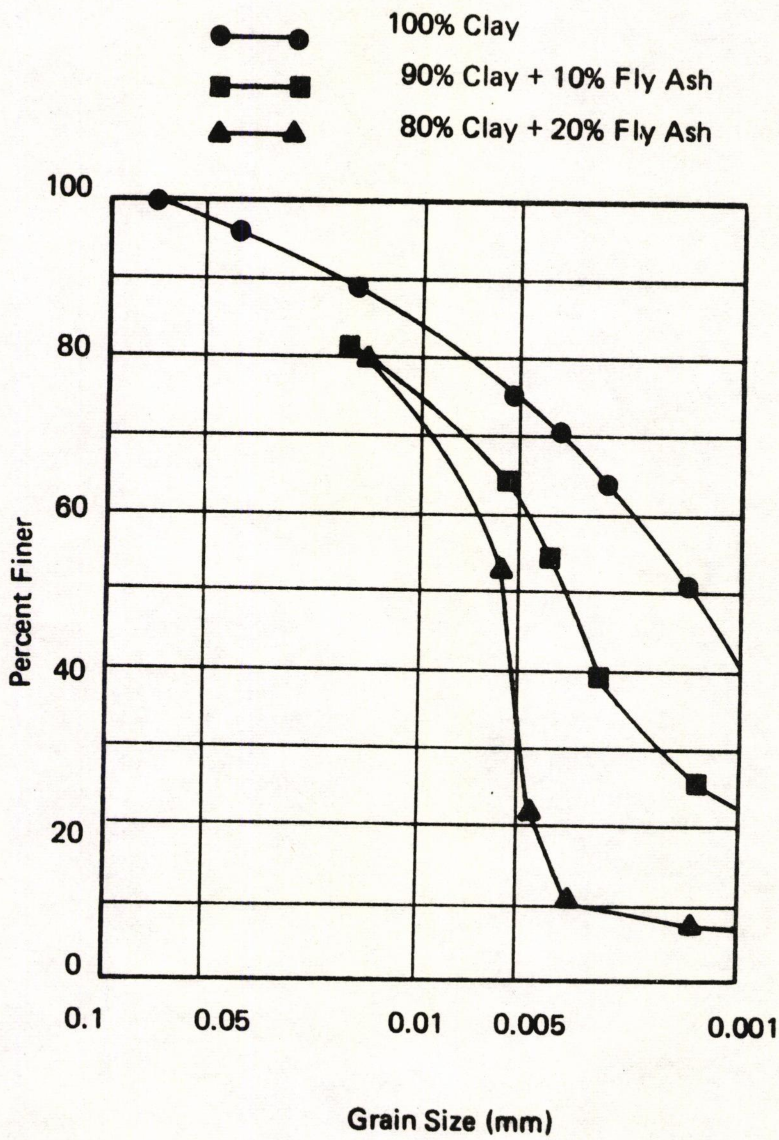
Unconfined compressive strength of both sand and clay specimens compacted immediately after mixing was increased by addition of fly ash (Table 3). Twenty percent fly ash raised the strength of clay from 13.3 to 28.8 Kgs/sq cm (190 to 410 psi) at seven days cure. In sand, 20% fly ash increased strength from 4 psi to 51.3 kgs/sq cm (730 psi) at 7 days.

A small delay in compaction causes a substantial decrease in both the 7-day compressive strength and the dry density of the 80% sand + 20% fly ash mixture (Figure 3). After a delay of only two minutes, the 7-day strength was reduced from 51.3 to 25.7 Kgs/sq cm (730 to 365 psi) and the dry density was reduced by 0.19 g/cc (12 pcf). After a one hour delay in

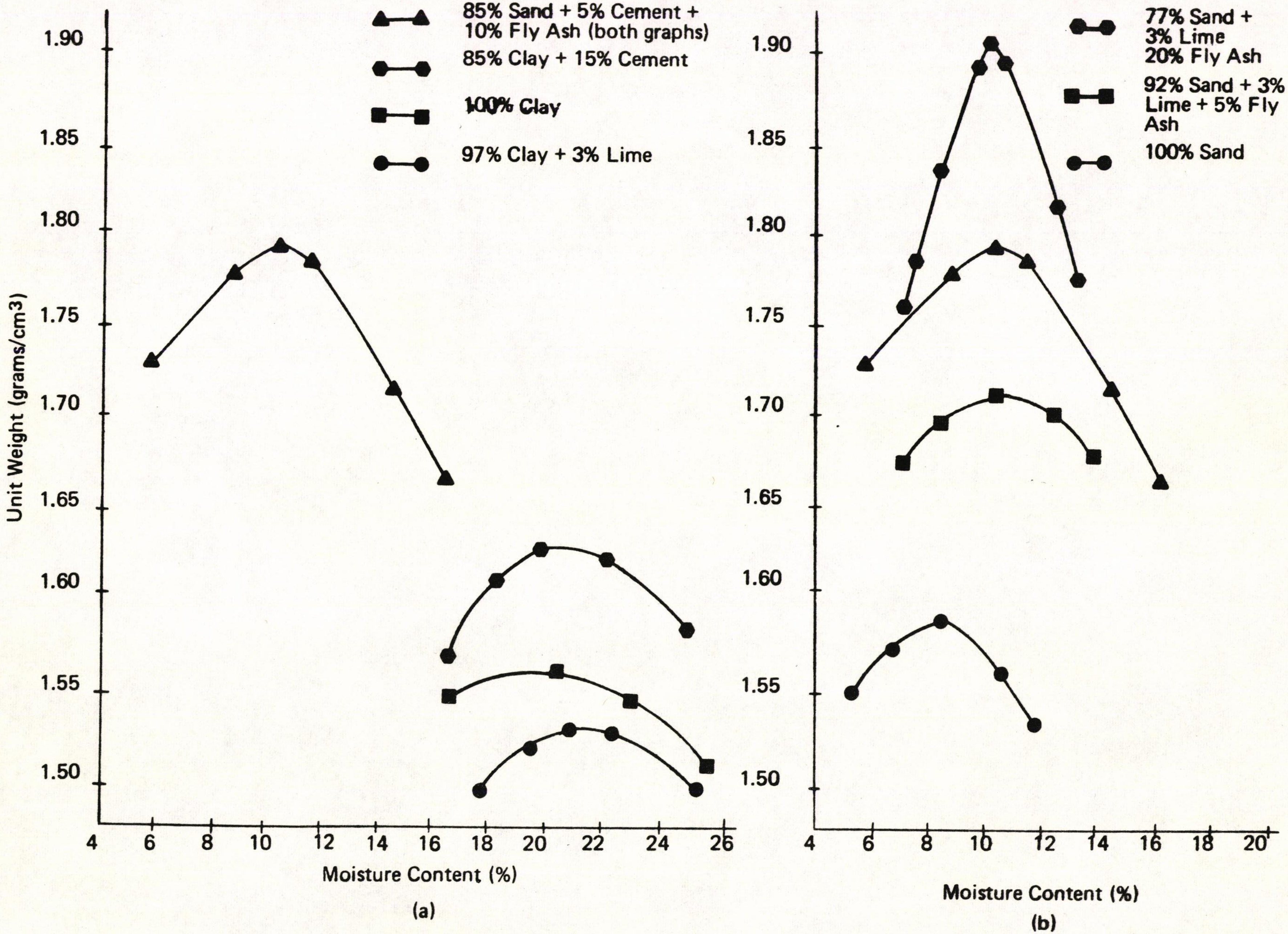
SUMMARY TABLE 2

PROPERTIES OF SOILS

Property	Clay	Sand
Percent Sand	0.0%	92.9%
Percent Silt	41.0%	1.8%
Percent Clay	59.0%	5.3%
Liquic Limit	54.0%	Non Plastic
Plastic Limit	35.0%	Non Plastic
Shrinkage Limit	19.0%	Non Plastic
Plasticity Limit	19.0%	Non Plastic
Permeability at 68% Relative density	---	3.3×10^{-3} cm/sec
Specific Gravity	2.62	2.67
pH	3.9	4.3
Organic Content (ASTM D 2974-71)	14.9%	---
Organic Content (4)	11.4%	0.75%
Predominant Clay Mineral	Kaolinite	---
Minimum Density	---	1.22 g/cc (76 pcf)
Maximum Density (Mod. Proct.)	1.56 g/cc (97.5 pcf)	1.59 g/cc (99 pcf)
Optimum Moisture Content	20.0%	8.0%
Unified Classification	OH	SP-SMu
AASHTO Classification	A-7-5 (14)	A-3



SUMMARY FIGURE 1. Effect of fly Ash on the Grain Size of Clay

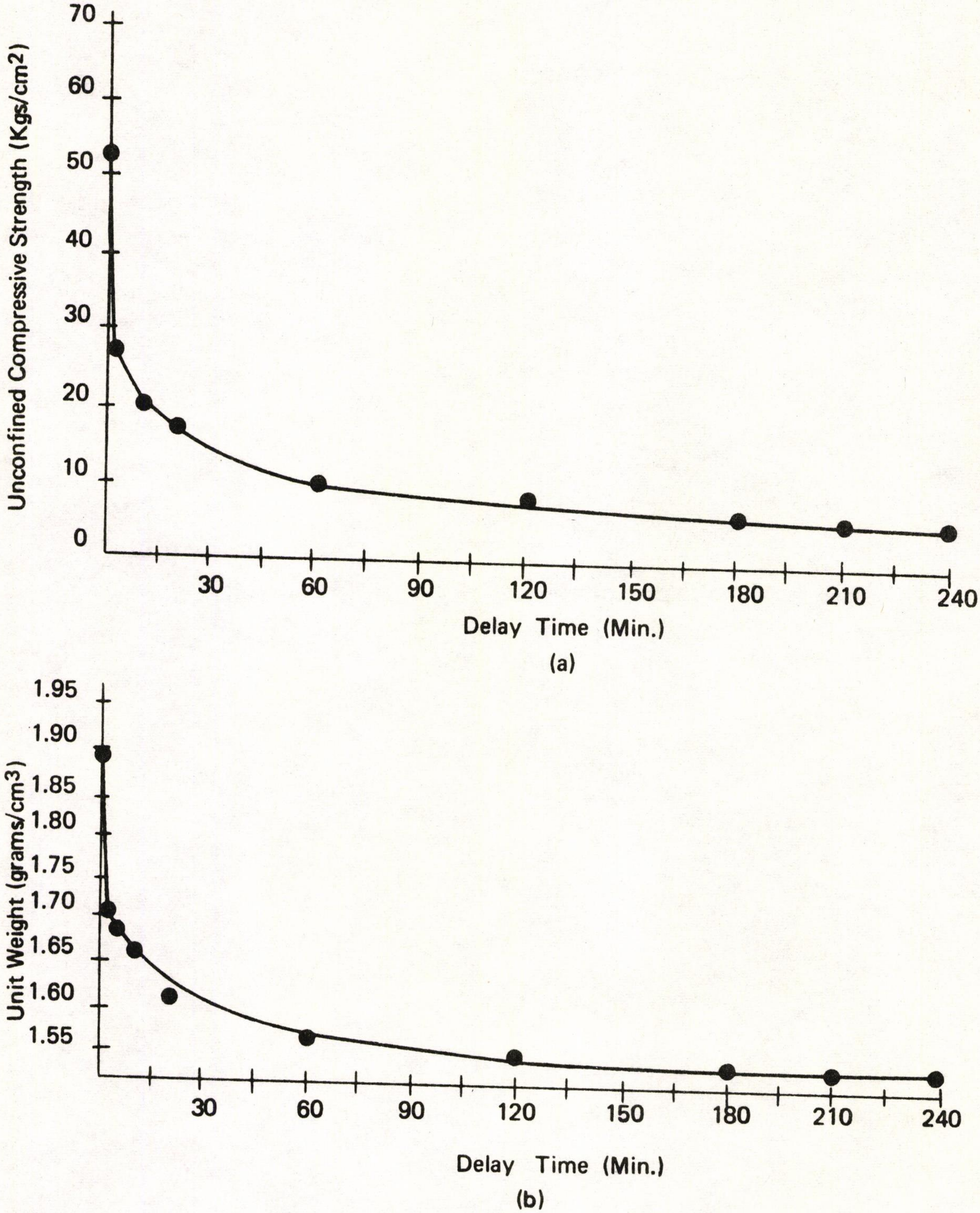


SUMMARY FIGURE 2. Moisture-Density curves for: (a) Stabilized Clay Mixtures, (b) Stabilized Sand Mixtures

SUMMARY TABLE 3

UNCONFINED COMPRESSIVE STRENGTH OF SOIL-FLY ASH

Soil, %	Fly Ash, %	Clay Strength Kgs/sq cm (psi)		Sand Strength Kgs/sq cm (psi)	
100	0	13.4	(190)	0.3	(4)
95	5	18.6	(264)	5.5	(78)
90	10	21.4	(305)	15.0	(213)
80	20	28.8	(410)	51.3	(730)



SUMMARY FIGURE 3. Effect of delay of compaction on 80% Sand + 20% Fly Ash mixture; (a) 7-day unconfined compressive strength vs. delay time, (b) unit weight vs. delay time.

compaction, 18% of the initial strength and 83% of the initial dry density was retained. The rate of the reduction in strength and density gets slower with time, however. The strength and density corresponding to a four hour delay period is not significantly less than the strength and density corresponding to a one hour delay period.

Effect of Fly Ash and Lime or Cement

Unconfined compressive strengths of clay and sand were improved with admixtures (Table 4). Seven day unconfined compressive strengths in clay increased from 13.4 Kgs/sq cm (190 psi) without admixture to 30.2 Kgs/sq cm (429 psi) with 3% lime and 20% fly ash. Sand with 3% lime and 20% fly ash improved from 0.3 to 66.6 Kgs/sq cm (4 to 947 psi).

Admixtures increased modified compaction densities of the soils (Figure 4). The addition of 15% portland cement to the clay increased the maximum density from 1.56 to 1.64 g/cc (97.5 to 102.2 pcf) and increased the optimum moisture content to 21.0%. In sand, the maximum density was increased from 1.6 g/cc (99 pcf) without additive to 1.92 g/cc (119.5 pcf) with 3% lime and 20% fly ash. With 5% cement and 10% fly ash, the sands maximum density was 1.79 g/cc (112 pcf).

All of the additives tested improved the CBR of the sand in excess of 80% (Table 5). Clay with 15% portland cement also exceeded 80% CBR, but with 3% lime had a CBR of only 12%.

Effects of Retardants on Delayed Compaction:

Since the soil-fly ash reaction seemed to take place immediately after mixing, a study was conducted to determine the effects of retardants on delayed compaction on the 7-day compressive strength and dry density of some soil-additive mixtures. Two products were tested to retard the effects of delayed compaction; salt and TMP. TMP is a chemical retarder reported by Arman (1972) to work in some soil cement mixtures. Salt retarded the soil-fly ash reaction better than TMP (Figure 5). After a one hour delay with 2% salt added, 66% of the initial strength and 98% of the initial dry density are retained. After a 4 hour delay in compaction, however, only 22% of the initial strength and 87% of initial dry density are retained.

CONCLUSIONS

The following are conclusions based on a study of a Western low sulfur coal fly ash.

1. The fly ash under study generates heat when mixed with water and has self-hardening properties.

2. Fly ash effectively stabilizes sandy and organic clay soils when compacted immediately after mixing.

3. Lime improves the early strength and rate of strength gain in sandy soil fly ash mixtures.

4. Strength development of soil fly ash mixtures takes place rapidly up to 30 minutes. A small time delay in compaction substantially reduces the effectiveness of the fly ash to stabilize soils.

5. Salt retards the soil-fly ash reaction.

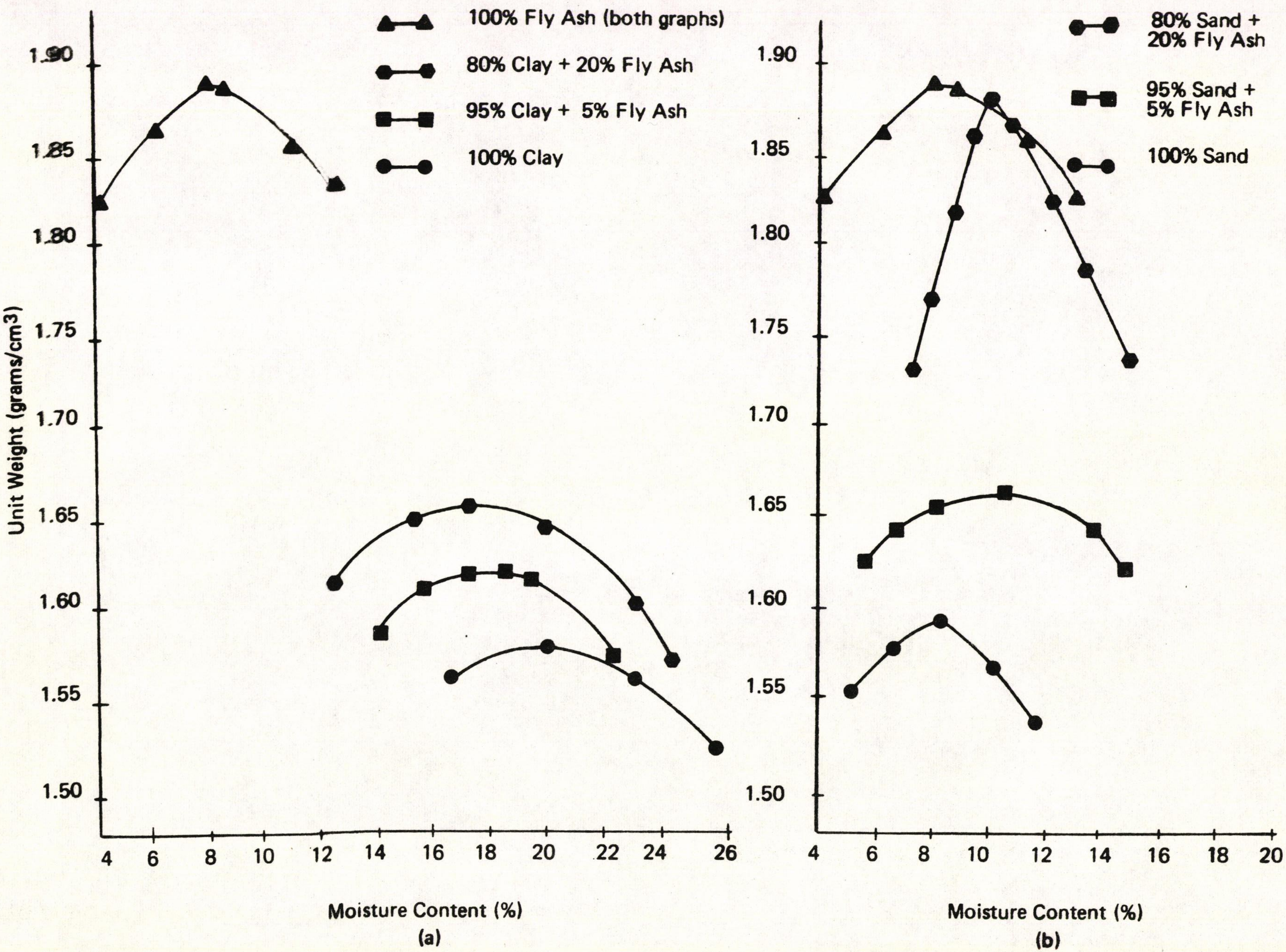
SUMMARY TABLE 4

7 DAY COMPRESSIVE STRENGTH OF SOILS WITH ADMIXTURES

Specimen	Unconfined Compressive Strength Kgs/sq cm	(psi)[a]
100% Clay	13.4	(190)
97% Clay + 3% Lime	16.9	(240)
92% Clay + 3% Lime + 5% Fly Ash	20.1	(286)[b]
87% Clay + 3% Lime	26.6	(379)[b]
77% Clay + 3% Lime + 20% Fly Ash	30.2	(429)
85% Clay + 15% Cement	42.6	(606)
100 Sand	0.3	(4)
97% Sand + 3% Lime	3.8	(54)
92% Sand + 3% Lime + 5% Fly Ash	10.5	(150)
87% Sand + 3% Lime + 10% Fly Ash	21.8	(310)
77% Sand + 3% Lime + 20% Fly Ash	66.6	(947)
92% Sand + 8% Cement	38.3	(545)
85% Sand + 5% Cement + 10% Fly Ash	49.8	(709)

[a]Performed on specimens compacted to Modify Proctor density at optimum moisture content. Specimens were compacted immediately after mixing

[b]28 day cure

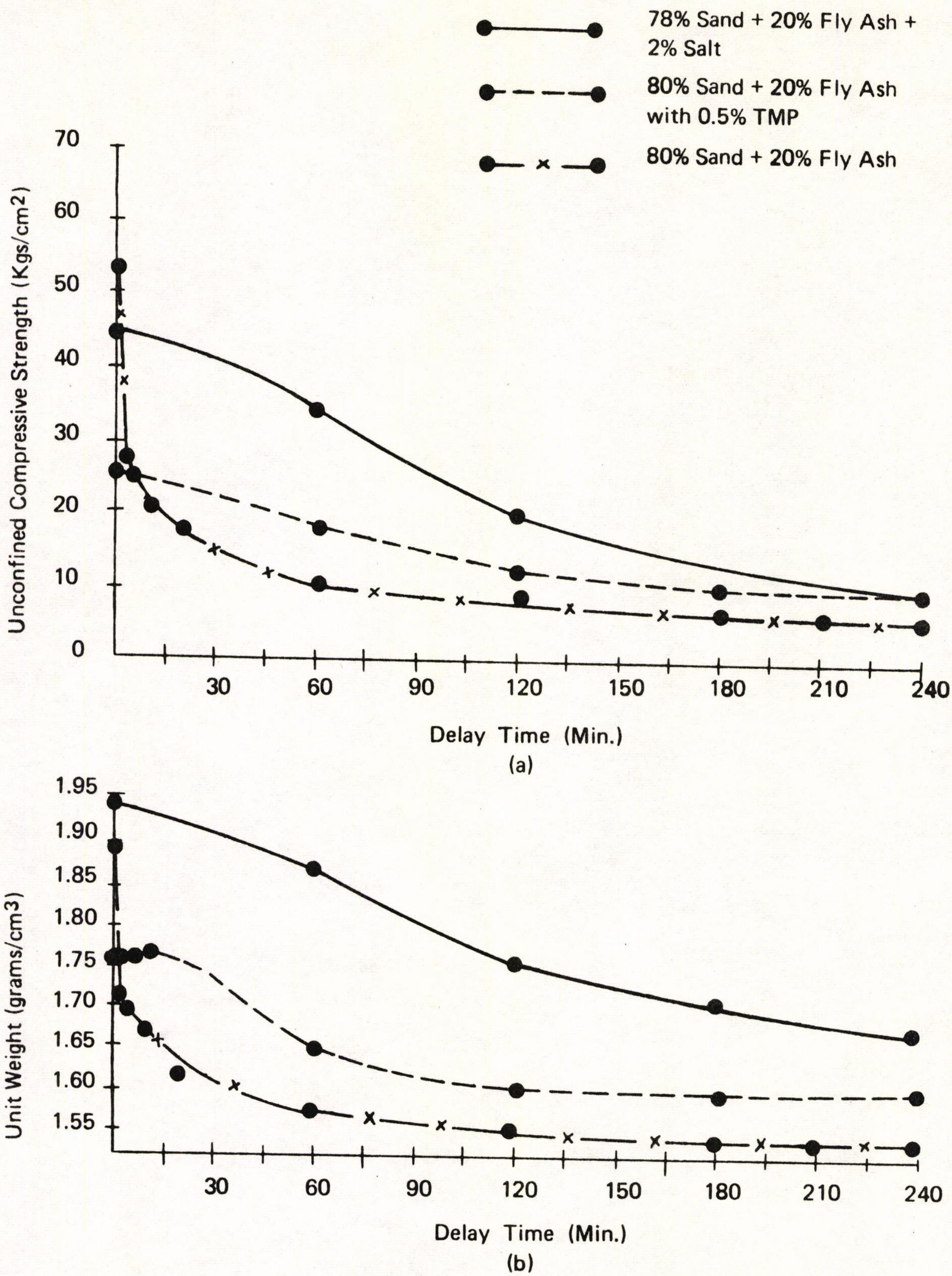


SUMMARY FIGURE 4. Moisture-Density Curves for: (a) Fly Ash Clay Mixtures
(b) Fly Ash Sand Mixtures

SUMMARY TABLE 5

CBR OF SOILS WITH ADDITIVES

Specimen	CBR (%)
100% Clay	4
Clay with 3% lime	12
Clay with 15% portland cement	113
100% Sand	22
Sand with 3% lime + 10% fly ash	220
Sand with 3% lime + 20% fly ash	350
Sand with 8% portland cement	356
Sand with 5% P.C. + 10% fly ash	285



SUMMARY FIGURE 5. The effect of delay of compaction on Sand + Fly Ash Mixtures; (a) 7-day Unconfined Compressive Strength vs. Delay Time, (b) Unit weight vs. Delay Time.

GAINS, FINDINGS AND CONCLUSIONS

Fly ash produced from Wyoming low sulfur coal is an abundant source of pozzolanic construction material. By the late 1970's, coal fired power plants in Arkansas are expected to be producing 1,400 tons of this type of fly ash per day or 520,000 tons per year.

The fly ash under study reacts with water, generates heat, and has self-hardening properties. The reactivity of the ash is thought to be due to a high CaO content of 20% as compared to the more normal range of 1-11% CaO of most ashes.

The two Arkansas soils tested were a sand and an organic clay. Both soils could be stabilized effectively with ash if they were compacted immediately after mixing. Lime was found to improve the early strength and the rate of strength gain in the sand soil-fly ash mixtures.

The strength development of the soil-fly ash mixtures takes place rapidly and is most effective within 30 minutes after mixing. A small time delay in compaction substantially reduces the effectiveness of fly ash to stabilize soils.

Salt was found to be of some benefit in reducing the detrimental effects of delayed compaction. Delays in excess of 4 hours could not be effectively controlled by any of the additives tested.

IMPLEMENTATION

The fly ash from Wyoming low sulfur coal was found to be effective as a soil stabilizing agent for two Arkansas soils. However, the actual use of fly ash similar to that tested in Arkansas highway construction cannot start until the late 1970's because production is not expected until that time.

Delay is useful, however, because some questions still need to be answered before fly ash should be used in Arkansas highways. One problem which needs investigation is the effect of fly ash on permeability of soil. Permeability, the subject of a proposal now pending before the Highway Department, affects the potential for frost heave, durability, and potential for pollution through percolation of ground water. The adverse effect of delayed compaction on strength and density of soil-fly ash mixtures is another problem which was identified during the course of this investigation. Admixtures which delay the reaction or rapid compaction procedures should be developed in order to take best advantage of the pozzolan reaction.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

More than 2,000 years ago, the Romans found that by mixing lime and water with volcanic cinders, a hard water-tight cement could be produced. Famous structures such as the Colosseum, the Basilica of Constantine, the Pantheon, the Cloaca Maxima, and the Aqueducts were constructed by use of this cement. The volcanic ash used by the Romans came from a deposit at Pozzuoli near Naples. The ash became known as "pozzuolana", from which the word "pozzolan" is derived (Kapler, 1962, p. 2).

The American Society for Testing and Materials (ASTM) defines a pozzolan as "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" (ASTM Standards, Part 10, 1973, p. 354).

A more recent day pozzolan is fly ash, a by-product of coal burning power plants. Basically, fly ash is produced when powdered coal is blown into a boiler and burned in suspension. The mineral remainder, now in a molten state, is blown up the stack with the flue gas. The fine particles of ash are recovered from the gas by cyclone or electrical precipitators.

Fly ash consists of solid or hollow spherical bodies, primarily of siliceous and aluminous glass. The chemical and physical properties of fly ash vary with the type of coal used, degree of fineness of the powdered coal, method of burning, variation of load on the boiler, and the method of collection.

In 1973, power plants in the United States produced 34.6 million tons of fly ash and the National Ash Association predicts that 40 million tons will be produced annually by 1980. As shown in Table 1, only 11.3% of this amount was used in commercial applications such as lightweight aggregate, stabilization agents in soils, admixtures in concrete and asphalt, and fill material. The remainder of the fly ash is wasted and is either sluiced to ponds or lagoons or is hauled dry to solid waste disposal areas and tailgated over slopes. These disposal operations are quite expensive and a considerable amount of land is tied up which could be used for agriculture, forestration, or other purposes.

Table 1

Fly Ash Collection and Utilization in the United States (Thousand Tons).[a]

	1970	1971	1972	1973
1. Total Fly Ash Collected	26,538	27,751	31,808	34,594
2. Fly Ash Utilized				
a. Used in Type I portland cement or mixed with raw material before forming cement clinker	158	121	188	524
b. Partial replacement of cement in concrete or concrete products	536	434	513	978
c. Lightweight aggregate	207	179	133	131
d. Stabilization and roads	432	400	738	1,486
e. Filler in asphalt mix	131	147	140	105
f. Miscellaneous	167	99	426	473
Total Item # 2	1,632	1,380	2,140	3,297
3. Fly Ash Removed from plant sites at no cost to Utility	526	1,873	1,495	621
Total Fly Ash Utilized	2,158	3,253	3,635	3,918
Percent Fly Ash Utilized	8.1	11.7	11.4	11.3

[a] Data collected by Edison Electric Institute.

Two proposed coal-fired power stations are scheduled to begin operation in Arkansas in the late 1970's. One 530 megawatt unit will be near Gentry and two 750 megawatt units will be near Redfield. The total fly ash production in Arkansas should average about 523 thousand tons annually or approximately 1,434 tons of fly ash per day.

The purpose of this report is twofold. First, a literature review will be presented on the use of fly ash as a fill material, soil stabilizer, and an additive in lime-fly ash-aggregate compositions. Second, the results of a soil stabilization study using a high calcium fly ash will be presented. The fly ash used in the investigation is thought to be similar to the fly ash which will be produced in Arkansas. The stabilized soil mixtures in the investigation are evaluated on the basis of moisture-density relations, unconfined compressive strength, California Bearting Ratio (CBR), freeze-thaw, and delayed compaction.

CHAPTER 2

LITERATURE REVIEW

LIME–FLY ASH REACTIONS AND REACTION PRODUCTS

Combining lime and fly ash with water causes a reaction to take place between the lime and the pozzolan forming a cementitious material on the surface of the pozzolan. For more of the reaction to take place, calcium must be diffused through the reacted layer to combine with the unreacted pozzolan. The pozzolanic reaction depends not only on the chemical reaction between the lime and pozzolan, but also on the time rate and amount of diffusion of calcium through the reacted layer (Leonard and Davidson, 1959, pp. 10-11).

Many soils and aggregates which are combined with lime-fly ash mixtures do not contribute to the chemical reaction. Since the cementitious material is formed on the fly ash grains, the strength of a soil-lime-fly ash mixture is a function of interparticle cementation at soil-fly ash grain contact points (Herzog and Brock, 1964, p. 1227). However, if the soil in the mixture possesses pozzolanic properties, simultaneous reactions between the lime and soil and the lime and fly ash will occur.

X-ray diffraction studies suggest the reaction product formed by the pozzolanic reaction is initially a non-crystalline gel. However, the final reaction product appears to be calcium silicate hydrate I, a compound found in hydrated portland cements (Leonard and Davidson, 1959, pp. 9-10).

Later studies by Croft (1964, pp. 1160-1166) using X-ray diffraction, differential thermal analysis, and electron microscopy techniques have also indicated the presence of calcium silicate hydrate I in the reaction products of lime-fly ash mixtures. Also present were hydrated calcium aluminates in the form $4CaO.Al_2O_3.13H_2O$. The first indications of crystalline reaction products in the lime-fly ash mixtures began to appear after 28 days at a curing temperature of 104° F. Combination of montmorillonite clay with lime and fly ash produced no reaction products other than those present in the lime-fly ash mixtures alone. However, combination of kaolinite with lime and fly ash produced calcium silicate hydrate I and aluminates of the hydrogarnet series.

FACTORS AFFECTING THE POZZOLANIC REACTION

Mullite Content and Fineness:

Croft (1964, p. 1167) in working with lime-fly ash mortars, observed that higher strengths and larger amounts of reaction products were obtained from fly ashes with higher contents of mullite ($3Al_2O_3.2SiO_2$). Mullite content can be correlated only loosely to strength of lime-fly ash mortars for periods of cure less than three months. However, for periods of cure greater than one year, the strength of lime-fly ash mortars correlates with the mullite content of fly ash better than with any other factor (Thorne and Watt, 1965, p. 604). Based on mole fraction percentage, the $SiO_2+Al_2O_3+FE_2O_3$ content of fly ash definitely correlates with strength of lime-fly ash mixtures (Vincent, Mateos, and Davidson, 1961, p. 1111).

Specific surface of fly ash as determined by particle size analysis provides the best correlation with strength of lime-fly ash mortars cured up to three months. The correlation with specific surface becomes poorer as the curing period is increased suggesting that longer term reaction is dependent not on the fineness of the ash, but on the mullite content which represents the amount of material which is available for pozzolanic reaction.

Carbon Content:

The presence of unburned organics in fly ash may act as a detriment to strength development and compacted density of lime-fly ash mixtures. Apparently, the carbon tends to adhere and partially cover reactive surfaces and forms a porous aggregated structure which acts to prevent contacts of cementitious materials that form on the surface of the pozzolan. A fly ash having loss on ignition greater than 10% would probably not be a good pozzolan (Davidson, Sheeler, and Delbridge, 1958, pp. 31-32; Leonard and Davidson, 1959, p. 10). Thorne and Watt (1965, p. 596) report there is not a good correlation between loss on ignition and strength of fly ash mortars. Thorne and Watt did conclude, however, that the source of pozzolanic activity is not in the spongy organic particles in the ash but in the glassy particles which are formed from the clay minerals originally present in the coal. Croft (1964, p. 1167) suggest the presence of carbon in fly ash is not detrimental to strength development of lime-fly ash-soil mixtures when the carbon exists in contents of 15% or less.

Calcium Oxide Content:

Some Scottish fly ashes are reported to have "self hardening" properties which cause 100% fly ash specimens to exhibit strength development with age (Sutherland, Finlay and Cram, 1968, p. 5). The "self hardening" tendencies are attributed to the free lime or water soluble lime content in the fly ash. The lime reacts with the fly ash to form the high strength bonding agent of calcium silicate hydrate I and the weak bonding agent of calcium sulfate aluminate.

Hardening of stockpiled fly ash in New South Wales is attributed to high water soluble concentrations of Ca^{++} and Na^{+} ions in the fly ash (Croft, 1964, p. 1159).

Sulfur Trioxide and Magnesium Oxide Content:

The compressive strength of portland cement-fly mortars tends to increase with increase in sulfur trioxide content. The compressive strength also tends to increase with increase in magnesium oxide content (Minnick, 1953, p. 1156).

Curing Temperature:

Little reaction takes place between lime and fly ash below temperatures of 68°F (Leonard and Davidson, 1959, p. 7). The rate of the lime-fly ash reaction increases, however, when the mixtures are cured at elevated temperatures. An increase of the curing temperature from 68° to 122° F increases the initial rate of development of strength by a factor of 10 (Thorne and Watt, 1965, p. 599). The period required for maximum strength development is reduced from 300 days at 68°F to 40 days at 122°F as compared to those cured at 68°F (Figure 1).

Reaction products of lime-fly ash mortars at elevated temperatures are superior in crystallinity to those produced at ordinary temperatures, even for long periods of cure (Croft, 1964, p. 1160). In contradiction, Leonard and Davidson (1959, p. 10) report the largest crystal growth occurs at ordinary temperatures, though more slowly.

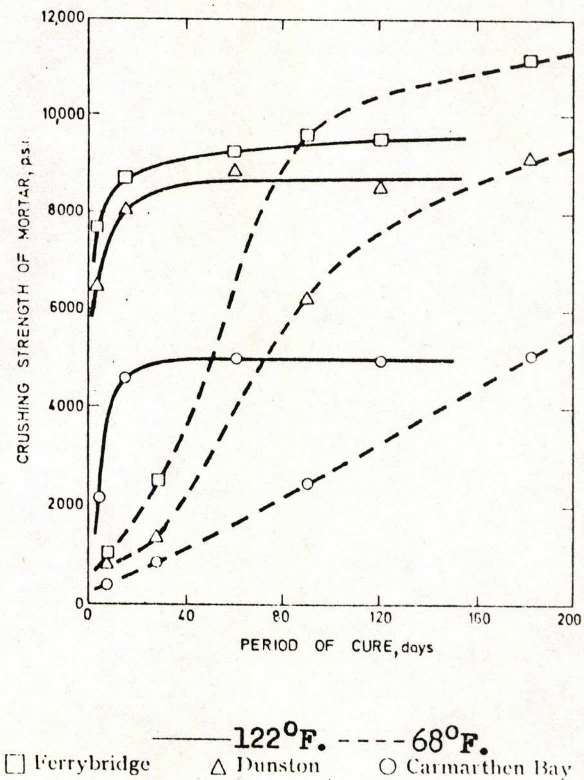


Figure 1. Crushing strength of lime-fly ash mortars in relation to time of cure at 68° and 122° F. (From Thorne and Watt, 1965).

PROPERTIES OF TYPICAL FLY ASH

Fly ashes vary in color from light gray to black or brown. Generally, the fly ashes which are darker in color will contain a larger amount of carbon (Abdun-Nur, 1961, p. 5).

Most fly ashes are composed of non-plastic silt sized particles with the median particle size ranging from 0.015 to 0.05 mm. For the most part, the finer particles are composed of $SiO_2Al_2O_3$ and Fe_2O_3 and the coarser porous particles are composed predominantly of carbon. Figure 2 shows the grain size distribution range of most fly ashes.

Fineness of fly ash as determined by the air permeability or Blaine method usually ranges from 2,007 to 6,073 sq. cm. per gram (Abdun-Nur, 1961, p. 5).

Aside from the spongy particles of carbon in fly ash, most of the particles are solid or hollow spherical bodies; the latter being known as "cenospheres".

The specific gravity of fly ash varies from 1.88 to 2.84 (Abdun-Nur, 1961, p. 5). Most fly ashes will have a specific gravity near 2.40. The larger carbonaceous particles and the cenospeheres compose the lower density portion of fly ash while the small solid spherical bodies compose the high density portion.

The primary constituents of fly ash in order of prominence are silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), calcium-oxide (CaO), and magnesium (MgO). Minor constituents which are usually present are sulfur trioxide (SO_3), sodium oxide (Na_2O), potassium oxide (K_2O), and titanium dioxide (T_iO_2). Carbonaceous material in fly ash may range from a negigible quantity to as much as 32%. The chemical constituents of most fly ashes will fall within the range of values listed in Table 2.

FLY ASH AS A FILL MATERIAL

Engineering Properties of Fly Ash Fill:

The dry density of fly ash is generally less than that of most conventional fill materials. For the most part, compacted dry densities of fly ash range form 70 to 80 pcf. Fly ash tailgated over embankment slopes produce densites as low as 45 to 50 pcf (DiGioia and Nuzzo, 1972, pp. 78-80). Some Michigan fly ashes, however, produce dry densities as high as 95 pcf when compacted at optimum moisture content with Modified Proctor compactive effort. The low unit weight of fly ash can be an asset in cases where high embankments have to be constructed on compressible or low-load bearing strata (Smith, 1973, p. 2).

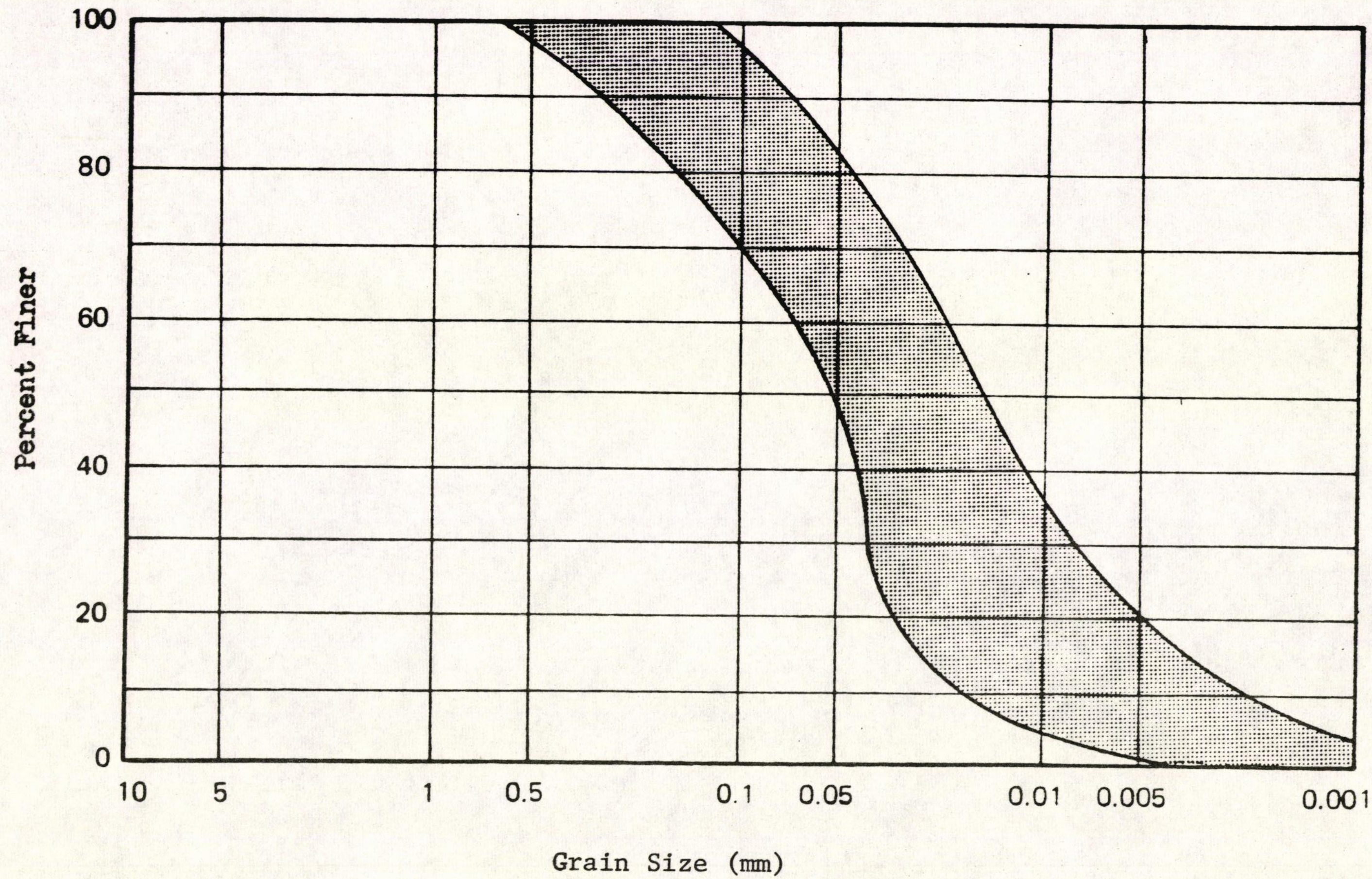


Figure 2. Grain size distribution range of most fly ashes. (From Abdun-Nur, 1961, and DiGioia and Nuzzo, 1972).

Table 2. Range of Values for Chemical Constituents of Most Fly Ashes. (From Abdun-Nur, 1961, and Gray and Lin, 1972).

	Percent
Silica (SiO_2)	28-58
Alumina (Al_2O_3)	15-40
Iron Oxide (Fe_2O_3)	4-26
Calcium Oxide (CaO)	1-11
Magnesium (MgO)	1-3.5
Sulfur Trioxide (SO_3)	0.5-4
Alkalies (Na_2O, K_2O)	2-5.5

The measured coefficient of permeability of some typical Western Pennsylvania fly ashes is about 3×10^{-4} cm. per sec. or about 300 feet per year (DiGioia and Nuzzo, 1972, p. 78). The permeability of British fly ash compacted at Standard Proctor compactive effort is 5×10^{-5} to 8×10^{-5} cm. per sec. (Gray and Lin, 1972, p. 371). Many of the British fly ashes possess self hardening properties which cause the fly ash particles to become cemented or partially cemented and renders the fly ash fill less permeable.

The self hardening property found in many British fly ashes is a very desirable property when these ashes are used in embankments (Smith, 1973, p. 3). The load is carried by grain-to-grain contact of the fly ash particles and is not transferred to the pore water. Furthermore, the cohesion of the cementitious properties of the ash is relatively high and contributes significantly to the stability. The cohesion of these self hardening fly ashes increases with age as shown in Table 3.

Fly ash from the Grand Avenue plant in Kansas City, Missouri is also found to exhibit self hardening characteristics as shown in Table 4 (Joshi, Duncan, and McMaster, 1974, p. 14).

Most of the research in the United States has been conducted on fly ash which does not possess self-hardening characteristics. The apparent cohesion of these fly ashes comes form capillary forces produced by pore water and is not a very significant contribution to the shear strength of fly ash. The greatest portion of the shear strength is due to the angle of internal friction. Before larger strengths can be obtained with these fly ashes, a stabilization agent such as lime or cement will have to be added to the ash.

Terzaghi's equation for the general shear failure of shallow foundations is generally used to evaluate the bearing capacity of fly ash fill (DiGioia and Nuzzo, 1972, pp. 89-90; Smith, 1973, p. 6). If the cohesion value of the fly ash is due to pore water capillary forces, the cohesion should not be used in the design. A safety factor of 3.0 is generally used to obtain reasonable values of safe bearing capacity.

The e-log p curve from a consolidation test performed on the self hardening Grand Avenue fly ash shows this fly ash is not susceptible to significant compression under ordinary loads (Figure 3). After three days cure, the coefficient of compressibility for the fly ash was 0.061.

Fly ashes which do not possess self hardening properties may consolidate quite differently from those that do possess self hardening properties. The settlement characteristics of Western Pennsylvania fly ashes are very similar to the settlement characteristics of a typical cohesive

Table 3. Values of Cohesion, Angle of Shearing Resistance, and Unconfined Compressive Strength with Time. (From Sutherland, Finlay, and Cram, 1968).

Age (days)	Ash Source											
	Barony			Braehead			Kincardine			Portobello		
	c_u	ϕ_u	u.c.s.	c_u	ϕ_u	u.c.s.	c_u	ϕ_u	u.c.s.	c_u	ϕ_u	u.c.s.
1	11	38	45	9	34	34	14	33.5	52	13	35	50
7	29	41	127	29	39	122	14	34	53	17	41	75
28	32	42	144	32	41	140	12	35.5	47	20	43	92
91	38	42	171	35	42	157	15	35.5	58	22	43	101
182	40	42	180	39	41	171	16	37	64	24	43	111
371	42	42	189	43	40	185	18	38	74	25	43	115
749	51	45	246	45	39	189	19	40	81	25	46	124
1230 (3.4 years)	79	41	346	70	40	300	30	36	117.5	29	44.5	138

c_u denotes cohesion (undrained) (lb/in^2) ϕ_u denotes angle of shearing resistance (undrained) (Degrees)
u.c.s. denotes unconfined compression strengths (lb/in^2)

Table 4. Influence of Age on Values of Cohesion and Angle of Shearing Resistance for Compacted Grand Avenue Fly Ash. (From Joshi, Duncan, and McMaster, 1974).

Age (Days)	Lab Samples		Field Samples	
	c	ϕ_u	c	ϕ_u
0	5.2	29	--	--
7	89	45	4	43
28	170	45	67	43

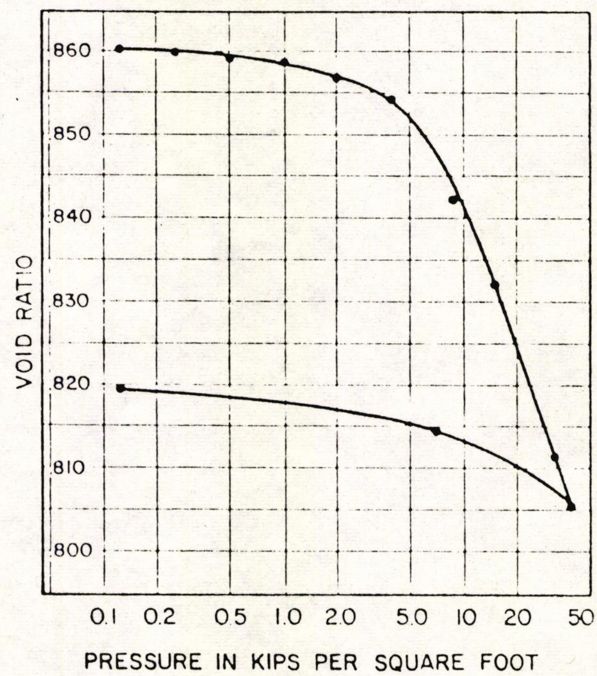


Figure 3. Pressure-void ratio relationship of compacted Grand Avenue fly ash. (From Joshi, Duncan, and McMaster, 1974).

soil (DiGioia and Nuzzo, 1972, pp. 85-86). The major difference is that the Pennsylvania fly ash compresses much more quickly becuase the permeability of the ash is larger than that of the soil. Michigan fly ashes also have rapid dissipation of pore pressures (Gray and Lin, 1972, pp. 369-371). Thus, primary consolidation is rapid in fly ashes which do not possess self hardening properties. Rapid consolidation is an advantage when constructing structures on fills composed of fly ashes without self hardening properties because most of the settlement will occur during construction.

The results of laboratory consolidation tests do not correlate well with observed settlement for self hardening British fly ashes used in fill (Raymond and Smith, 1966, p. 7). In one field situation, the fly ash fill was about 50 ft. thick. Settlements computed from consolidometer tests were on the order of 12 to 16 in. However, settlements estimated from plate bearing tests were between 0.26 and 0.73 in. and observed settlements were even less than this.

Because of self hardening characteristics, a fill of British fly ashes is ideal for trenching. Neat deep trenches can be excavated in British Fly ash with hardly any requirement for bracing. (Smith, 1973 p. 7). Also, British fly ashes are inert and alkaline and have no deleterious effects on cast-iron, lead, copper, P.V.C., or glazed stoneware pipes.

The sulfate content of fly ashes might require precautions to be taken when the fly ash is placed next to concrete. The sulfate in British fly ashes is present mainly as calcium sulfate and is low in solubility. The use of sulfate resisting cement is not necessary and the usual practice is to coat the surface of existing concrete with a bituminous material in order to protect the concrete from sulfate attack (Smith, 1973, p. 9).

Most British fly ashes are susceptible or at least marginally susceptible to frost heave (Sutherland, Finlay, and Cram, 1968, p. 7). The Road Research Laboratory recommends fly ash fills should be provided with 18 in. of cover in order to be adequately protected against freezing (Smith, 1973, p. 9).

Stabilization of Fly Ash Fills:

Generally 2 to 4% cement will stabilize fly ash to the extent that the ash will not be susceptible to frost heave. However, some British fly ashes require cement contents of 6 to 15% to reduce the heave of some fly ashes to within the Road Research Laboratory specifications of 0.5 in. after 250 hours (Sutherland, Finlay, and Cram, 1968, pp. 7-8).

British fly ashes stabilized with cement are stronger at early ages but are generally not as strong lime stabilized fly ashes for periods of cure greater than three months (Table 5).

The compressive strength of Michigan fly ashes increased more than 10-fold after one month cure when the ashes were mixed with 10% hydrated lime and compacted at optimum moisture content with Modified Proctor compactive effort (Gray and Lin, 1972, pp. 374-378). Also, the addition of lime to the ashes significantly reduced the compressibility of the ashes. Furthermore, the permeability of Michigan fly ashes is reduced by one order of magnitude when lime or cement is added in amounts up to 10%.

The CBR values for mixtures of ponded ash, hopper ash, and admixtures are shown in Figure 4. The mixture of 75:25 + 10L refers to a proportioned mixture of ponded ash to dry hopper ash with the total mixture being stabilized with 10% lime. As the proportion of hopper ash in the mixture is increased, the CBR of the total mixture is increased. Thus, the hopper ash is shown to be more active than the ponded ash (Joshi, Duncan, and McMaster, 1974, pp. 18-25).

British fly ashes are also found to exhibit different degrees of activity (Raymond and Smith, 1966, p. 8). Freshly produced hopper ash exhibits the greatest degree of self hardening. Stockpiled ash exhibits a lesser amount of self hardening and ponded ash exhibits the least amount of self hardening of the three. The decrease in the activity of the ash is probably due to leaching out of the water soluble alkalies in the ash when the ash is exposed to water.

Compaction of Fly Ash Fill:

A study was conducted at the University of Glasgow to determine the effects of relative compaction and compaction moisture content on the strength of cement stabilized fly ash (Sutherland, Finlay, and Cram, 1968, p. 7). Maximum strength was obtained at 100% relative compaction slightly above optimum moisture content (Table 6). There was a significant decrease in strength as the relative compaction was decreased while at the same time maintaining constant moisture content. Change in relative compaction influenced the strength much more than change in moisture content.

Vibratory compaction is best for fly ash fills (DiGioia and Nuzzo, 1972, p. 86). Vibratory loads probably destroy the apparent cohesion in the fly ash by breaking the surface tension of the pore water. There is probably an optimum vibrating frequency for each fly ash which is

Table 5. Unconfined Compressive Strength of Cement and Lime Stabilized Fly Ashes. (From Sutherland, Finlay, and Cram, 1968).

Station	Test Series	Unconfined Compression Strength (lb/in^2) at age (days) stated											
		10 per cent Cement						10 per cent Lime					
		7	28	56	91	182	581	7	28	56	91	182	581
Barony	1	670	1220	1320	—	—	—	538	2505	3123	—	—	—
Barony	2	1087	1780	—	3435	3790	4447	455	1905	—	3370	4010	5000
Braehead	1	187	334	444	—	—	—	66	270	410	—	—	—
Braehead	2	239	356	—	599	663	775	84	299	—	520	603	848
Kincardine	1	316	543	835	—	—	—	104	317	439	—	—	—
Kincardine	2	266	397	—	759	956	1296	90	212	—	436	739	1205
Portobello	1	392	936	1061	—	—	—	134	675	1604	—	—	—
Portobello	2	469	1027	—	1313	1517	1843	122	407	—	1316	1933	2620

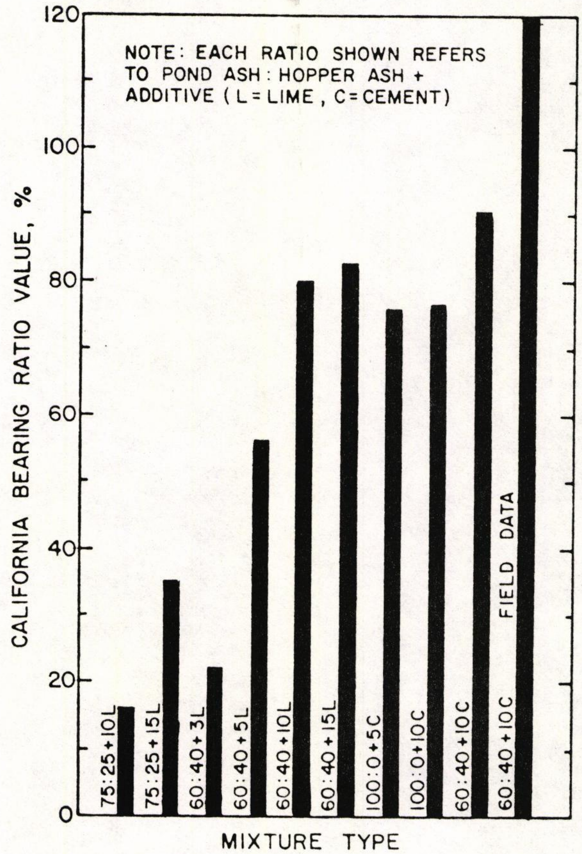


Figure 4. Average CBR values of lime and cement stabilized pond and hopper ashes. (From Joshi, Duncan, and McMaster, 1974).

Table 6. Unconfined Compressive Strengths of 10 percent Cement Stabilized Fly Ash at Different Densities and Moisture Contents. (From Sutherland, Finlay, and Cram, 1968).

Moisture Content		Dry Density		Compression Strength (lb/in^2)	
Per cent	Related to Opti-mum	lb/ft^3	Relative Comp. per cent	7 days	28 days
20.5	Opt.	75	85	311	705
20.5	Opt.	80	90	558	1318
20.5	Opt.	85	96	1015	1799
20.5	Opt.	88.5	100	1157	2929
12.5	—8%	88.5	100	1166	1636
17.5	—3%	88.5	100	1025	2125
20.5	Opt.	88.5	100	1157	2429
22.5	+2%	88.5	100	1245	3465
25.0	+4½%	88.5	100	918	2483

dependent upon the graduation and water content of the ash. An operating frequency of 2,000 rpm produced greater density of some Western Pennsylvania fly ashes than did lower frequencies.

Laboratory maximum dry density may not be obtained in the field, even at optimum moisture contents (Raymond and Smith, 1966, pp. 4-5). However, densities in excess of 90% of maximum laboratory dry density are not usually difficult to obtain in the field. To achieve the greatest densities of British fly ashes, the following type of compaction equipment is considered most suitable:

1. Tandem vibrating roller with a minimum dead weight of 17 cwt (1,700 lbs.)
2. Towed vibrating roller with a minimum dead weight of 30 cwt (3,000 lbs.)
3. Pneumatic tired rollers
4. Impact rammers with large shoes.

Steel wheeled rollers of any size have not proven effective for compaction because the fly ash forms a wave in front of the forward roller which brings the roller to a standstill. Sheepsfoot rollers are not suitable for compaction because the rolled surface tends to be overstressed and excessively disturbed. Once the fly ash is spread, the fly ash should be "tracked" once or twice by a caterpillar or any tracked machine prior to rolling (Smith, 1973, p. 8). Tracking tends to tighten the fly ash and provides a surface for the compaction machine to operate on.

The Central Electricity Generating Board of London has drafted the following specification in regard to compaction of fly ash:

1. The fly ash shall be supplied from approved power stations of Central Electricity Generating Board.
2. Once the fly ash is spread, it shall be compacted immediately.
3. Each layer shall be such that, when compacted, it does not exceed 6 in. in thickness.
4. The minimum dry density after compaction shall be 90% of the laboratory dry density as obtained with Standard Proctor compactive effort. This may be subject to adjustment as agreed from the results of field trials.
5. The compaction shall be carried out by a suitable approved compactor to achieve the specified dry density.

Item 2 is important because, unless the fly ash is compacted immediately, moisture will be lost and compaction made difficult.

USES OF FLY ASH IN SOIL STABILIZATION

Fly ash is used either alone or in combination with lime to improve the load-bearing capacity of soils and to increase the dimensional stability of soils. Most fly ashes do not contain a sufficient amount of calcium to be an effective stabilizer and therefore lime is usually added to the soil-fly ash mixture in order to satisfy this deficiency.

Fly Ash Used Alone as a Soil Stabilizer:

Two fly ashes were found to be effective in reducing the plasticity of a plastic clay in Kansas City, Missouri (Joshi, Duncan, and McMaster, 1974, pp. 5-13). One fly ash was from the LaCygne power station and the other fly ash was from the Hawthorne power station. For pollution control purposes, limestone dust is injected into the boiler along with the powdered coal at the LaCygne power station. As a result, the LaCygne ash contains a significant amount of calcium. The Hawthorne ash used in the study contained some free lime. Figure 5 presents a summary of the results of the plasticity tests. Both fly ashes reduced the plasticity of the clay when the ashes were added in amounts of 15 and 20%. The liquid limit was affected more by the addition of the fly ashes than was the plastic limit.

The addition of LaCygne fly ash to the clay increased the maximum density and decreased the optimum moisture content of the clay. Higher densities are probably due to a higher specific gravity in the LaCygne fly ash than in most fly ashes.

The results of CBR tests which were conducted in the Kansas City study are shown in Figure 6. The addition of both the LaCygne and Hawthorne fly ashes to the clay increased the CBR of the clay. A smaller amount of lime, however, produced a greater improvement in the CBR value of the clay.

The addition of 15% LaCygne ash to the clay produced a greater increase in the unconfined compressive strength than did the addition of 15% Hawthorne ash (Table 7). Also, the rate of strength gain with the LaCygne fly ash was much greater than the rate of strength gain with the Hawthorne fly ash.

Lime-Fly Ash-Soil Stabilization:

The additions of small amounts of lime and fly ash to soils will produce concrete-like compositions which develop relatively high early strengths at early ages. These compositions, when compacted at optimum moisture contents and cured at normal temperatures, will exhibit

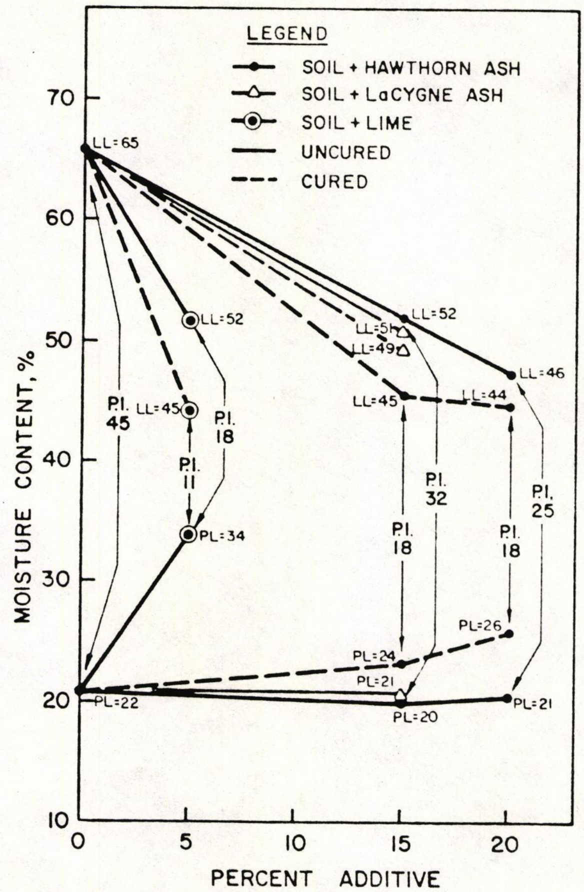


Figure 5. Effect of Lime and fly ash on the plasticity of a highly plastic clay. Some mixtures were compacted by kneading and tested for plasticity immediately. Others were compacted, allowed to cure for 5 days, and then tested. (From Joshi, Duncan, and McMaster, 1974).

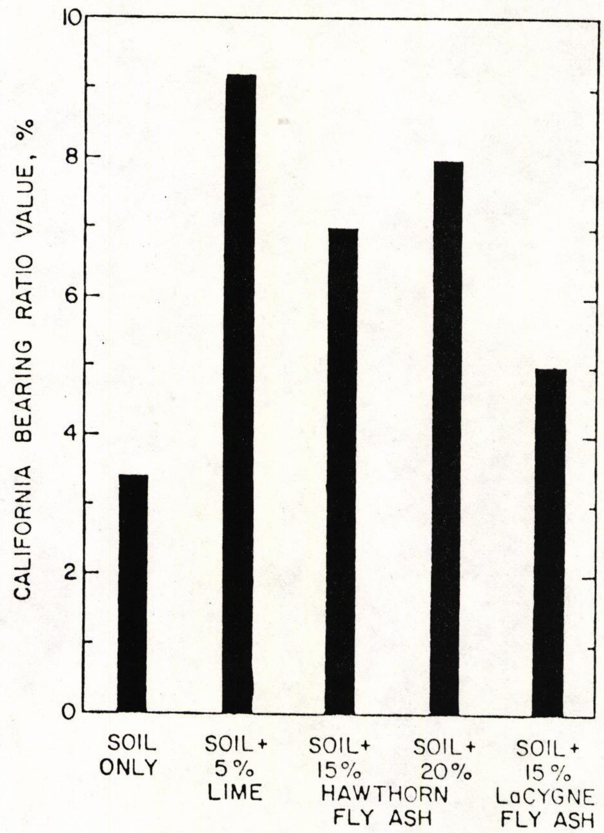


Figure 6. Effect of lime and fly ash on California Bearing Ratio Values of a highly plastic clay. (Taken from Joshi, Duncan, and McMaster, 1974).

Table 7. Results of Unconfined Compressive Strength Tests Performed on Soil, Soil-Lime, and Soil-Fly Ash Mixes. (Taken from Joshi, Duncan, and McMaster, 1974).

	Unconfined Compressive Strength (Psi)			
Soil+Admixture	0 days cure Field	0 days cure Lab	5 days cure Lab	28 days cure Lab
Soil Only	--	28	--	---
Soil + 15% Hawthorne Ash	21	21	56	204
Soil + 20% Hawthorne Ash	--	14	67	166
Soil + 15% LaCygne Ash	--	25	55	538
Soil + 5% Lime	--	17	56	131

strengths on the order of 1000 psi at 28 days (Minnick and Meyers, 1953, pp. 1-28).

Soil Types Amenable to Lime-Fly Ash Stabilization:

Soils which are amenable to improvement from lime-fly ash additions are alluvial soils, natural and crushed gravels, laterites, and horizons from the bottom of residual clay soil profiles (Croft, 1964, p. 1164). Silts and sands can be effectively stabilized with lime-fly ash mixtures, but friable loess-lime mixtures can only be stabilized by a high quality fly ash (Mateos and Davidson, 1962, pp. 40-64; Chu, Davidson, Goecker, and Moh, 1955, pp. 102-112).

Generally, silty or sandy soils containing expansive clay minerals in their clay fraction will produce the highest early strengths from lime-fly ash stabilization. Soils containing expansive clays will probably require a larger lime-fly ash ratio to ensure there is enough lime available after the lime-clay reaction for the lime-fly ash reaction. Soils which do not contain clay will derive initial strengths from improvement of gradation and ultimate strengths from the lime-fly ash reaction (Croft, 1964, p. 1163).

For clayey soils, the range of lime content should be 5 to 9% and range of fly ash should be 10 to 25% for the maximum value of unconfined compressive strength. For granular soils, the amount of lime should be between 3 and 6% and the amount of fly ash between 10 and 25% (Mateos and Davidson, 1962, p. 63).

Lime-Fly Ash Ratio for Soil Stabilization:

There is no optimum ratio of lime–fly ash for stabilizing all soils because a range of ratios will produce satisfactory results (Croft, 1964, p. 1163; Mateos and Davidson, 1962, pp. 40-64). The selection of trial proportions will depend upon the soil gradation, activity of the clay content, the quality of the fly ash, and to a lesser extent, the kind of lime.

Optimum proportions of lime and fly ash cannot be determined using maximum density criterion (Minnick and Miller, 1952, p. 526). The lime-fly ash ratio can be determined, however, from examination of the results of unconfined compression tests, sonic beam tests, and group velocity measurements or all three of these tests taken together. The method of test for the sonic beam test is described in ASTM C 215-60 (reapproved 1970). The methods for group velocity measurements are described by Minnick and Meyers (1953, pp. 1-28).

Compaction Considerations of Soil-Lime-Fly Ash Mixtures:

Maximum density of a soil is usually decreased and the optimum moisture content is usually increased by the addition of lime-fly ash admixtures (Chu, Davidson, Goecker, and Moh, 1955, p. 106).

Maximum strength of stabilized sand is obtained when the mixture is compacted dry of optimum and maximum strength of stabilized clay is obtained when the mixture is compacted wet of optimum.

Increased compactive effort from Standard to Modified Proctor increases the strength of soil-lime-fly ash mixtures from 50 to 160%. Viskochil, Handy and Davidson, (1957, p. 14) found for clays, silts, and sands, that the strength of soil-lime-fly ash mixtures increased linearly as the compactive effort is increased. The compressive strength in psi for a specific compactive effort can be expressed as:

$$S = S_o + 43.5\,p$$

where So, is the strength at Standard Proctor density and p, is the percent increase in density over Standard Proctor.

The optimum lime-fly ash ratio is little influenced by increased compactive effort. Durability of soil-lime-fly ash mixtures is increased as the compactive effort is increased (Hoover, Handy, and Davidson, 1958, p. 10).

Overcompaction of soil-lime-fly ash mixtures does not appear to be detrimental to the long term strength of the composition. Over compaction of stabilized silts produced lower strengths at 7-days cure, but at 28 days cure, this deleterious influence on strength had vanished. Apparently, overcompaction shear planes tend to heal at longer periods of cure (Viskochil, Handy, and Davidson, 1957, p. 14).

Mateos and Davidson (1963, p. 40) suggest compaction of a soil-lime-fly ash mixture should proceed as soon as possible after mixing or there will be a substantial decrease in strength. Clays should be compacted not later than four hours after mixing, whereas compaction of stabilized sands can be delayed until the next day.

LIME-FLY ASH-AGGREGATE COMPOSITIONS

The strength of lime-fly ash-compositions depends upon several factors. Among these factors are the properties of the constituent materials; the relative density of the compacted mixtures; and the curing temperature, length of curing, and the moisture conditions under which the mixtures are cured.

The aggregates which are used in lime-fly ash-aggregate compositions cover a wide range of materials including sands, gravels, crushed stone, and slag. Generally, aggregates should be free of organics which might tend to hinder the reaction between lime, fly ash, and water, (Barenberg, 1974, p. 182). The aggregates should have the desirable properties of hardness and soundness.

The single most important factor governing the quality of lime-fly ash-aggregate compositions is the compacted density (Barenberg, 1974, p. 191). A reduction of only five percent in the compacted density of a composition can result in a loss of 40% to 60% in the compressive strength of the composition. Furthermore, lime-fly ash-aggregate compositions will develop little strength at densities less than approximately 85% of Standard Proctor density. The gradation of a composition influences the density and thus, the strength of the composition. Figure 7 shows the effect of relative density on the compressive strengths of cores from lime-fly ash-aggregate mixtures. As the densities of the cores increase, the compressive strengths of the cores increase.

Curing conditions and time of curing influence the strength of lime-fly ash-aggregate compositions. Higher curing temperatures increase the rate of strength gain of lime-fly ash-mixtures. For lime-fly ash-aggregate compositions, the pozzolanic reaction nearly stops at temperatures below 40° F. Therefore, strength gain of lime-fly ash compositions in the field will be slow during winter months. These compositions should be placed during the summer months in order to optimize the strength gain before traffic is allowed on the pavement.

The pozzolanic reaction will not take place in lime-fly ash-aggregate compositions unless sufficient moisture is present. If the composition should dry out, the hardening process will stop and carbonation may inhibit further reaction (Croft, 1964, p. 1166). Therefore, watering the compositions during the early stages may prove beneficial.

The rate of the pozzolanic reaction is faster at first, but continues to become slower with age. Nevertheless, there have been no lime-fly ash-aggregate compositions observed in which the pozzolanic activity has completely ceased.

Generally, the core strengths of lime-fly ash-aggregate compositions may range from 750 to 2500 psi after several years of service. Strengths are reported as high as 4000 psi, but such strengths are unusual (Barenberg, 1974, p. 185).

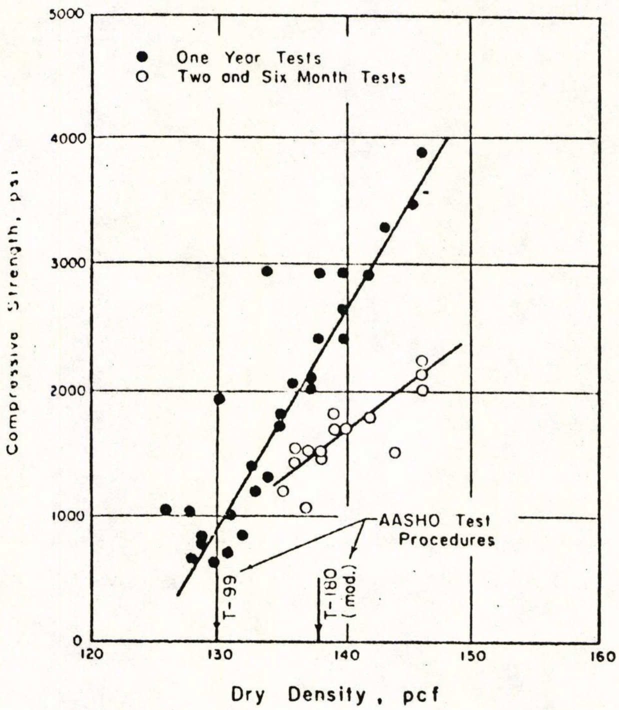


Figure 7. Effect of relative density on the compressive strengths of cores from lime-fly ash-aggregate mixtures. (From Barenberg, 1967).

Durability of Lime-Fly Ash-Aggregate Compositions:

Generally, lime-fly ash-slag compositions which are allowed a sufficient amount of cure may be classified as low in frost susceptibility. But, when these mixtures are not allowed the proper amount of cure, the resistance of these mixtures to freeze-thaw may be reduced (Kaplar, 1962, p. 14). If the lime-fly ash-aggregate compositions can be shown to gain strength, even under cycles of freeze-thaw, the compositions are assured of durability (Barenberg, 1974, p. 185).

Subjecting lime-fly ash-aggregate compositions to cycles of wetting and drying were reported to increase compressive strength of some mixtures (Hollon and Marks, 1960, pp. 30-33). Croft (1964, p. 1166) attributes these improvements in strength to an affinity of the new crystalline phases for water. However, no explanation of reaction mechanisms is given.

Self Healing of Lime-Fly Ash-Aggregate Compositions:

One phenomenon which has been observed in lime-fly ash-aggregate compositions is their ability to recement across a crack that has developed due to overstress. The degree to which this self-healing will take place is dependent upon the age at which the cracks develop, the degree of contact of the fractural surfaces, and the curing conditions (Barenberg, 1974, pp. 186-187).

Thermal Expansion, Stiffness, and Flexural Strength:

Thermal expansion of lime-fly ash-aggregate compositions is generally a function of the dry density of these compositions (Miller and Couturier, 1961, p. 91). Thermal expansion of these compositions is on the same order of magnitude as the thermal expansion of portland cement concrete. The coefficient of linear thermal expansion of lime-fly ash-aggregate compositions can be taken as 6×10^{-6} in. per inch. (Barenberg, 1974, p. 185). The stiffness of a lime-fly ash-aggregate composition will depend upon the properties of the principal aggregate in the mixture, the density of the mixture, and the curing of the mixture. Generally, mixtures with aggregates such as sands will have lower moduli of elasticity than will mixtures containing larger aggregate. Since most paving materials, including lime-fly ash-aggregate compositions, are not truly elastic, the modulus of elasticity for these materials is generally taken as the secant modulus at 50% ultimate strength. The modulus of elasticity for most lime-fly ash-aggregate mixtures can be assumed to range from 5×10^5 psi to 2×10^6 psi (Barenberg, 1974, p. 185-186).

The flexural strength (modulus of rupture) of lime-fly ash-aggregate compositions can be taken as 1/8 to 1/10 of the unconfined compressive strength (Barenberg, 1974, p. 186).

CHAPTER 3

THE LABORATORY INVESTIGATION

INTRODUCTION

Two soils were tested in the laboratory investigation. Soil No. 1 was an organic clay and Soil No. 2 was sand. The high calcium fly ash which was used was produced from Wyoming coal. The high calcium fly ash should have much the same properties as the fly ash to be produced in Arkansas in the late 1970's. Other materials used were hydrated lime, protland cement, brown mud (a byproduct of the aluminum refining industry), and sodium chloride (table salt), and tri methylol propane (TMP).

Stabilized soil mixtures were evaluated on the basis of Modified Proctor moisture-density relations, unconfined compressive strength, California Bearing Ratio, freeze-thaw, Atterberg limits, and delayed compaction.

MATERIALS USED IN THE INVESTIGATION

Fly Ash:

For pollution control purposes, both the power plants to be built in Arkansas in the late 1970's propose to use a low sulfur coal from Roland and Smith seams in Wyoming. The fly ash will be collected by electrostatic precipitators. The Arkansas fly ash is expected to have essentially the same properties as the fly ash used in this soil stabilization study.

The fly ash used in this study was collected by a Research Cottrell electrostatic precipitator from a 350 megawatt Combustion Engineering boiler at the Public Service Company power station in Pueblo, Colorado. The coal, obtained from Roland and Smith seams in Campbell County, Wyoming, was pulverized to pass the No. 200 mesh and then injected into the tangential burner boiler. An analysis of the coal is shown in Table 8. The Pueblo fly ash has a light cream color. Photomicrographs of the fly ash show the particles to be spherical in shape (Figure 8 and 9). The chemical and physical properties of the fly ash are shown in Tables 9 and 10.

Soils:

Two soils were extensively tested in the laboratory investigation. Soil No. 1 was a clay from Section 24, Township 4 South, Range 17 West of the Fifth Principal Meridian in Hot Springs

Table 8. Representative Coal Analysis, Roland and Smith Seams, Campbell County, Wyoming.[a]

	Proximate Analysis: As Received % by weight	Proximate Analysis: Dry % by weight	Ultimate Analysis	Ultimate Analysis: Dry % by weight
Moisture	30.00	-----		70.00
Volatile Matter	32.50	46.43	Hydrogen	4.86
Fixed Carbon	32.50	46.43	Oxygen	16.61
Ash	5.00	7.14	Nitrogen	0.86
	100.00	100.00	Sulfur	0.50
Sulfur	0.35	0.50	Ash	7.14
			Chlorine	0.03
				100.00
Gross Heating Value, Btu/lb.	8,250	11,780		

Ash Fusibility, ^{o}F

	Initial Deformation	Softening (h = w)	Fluid
Reducing	2060	2120	2180
Oxidizing	2070	2160	2220

Grindability

Hardgrove No. = 55

[a]Determined by Sargent and Lundy Engineers, Chicago.

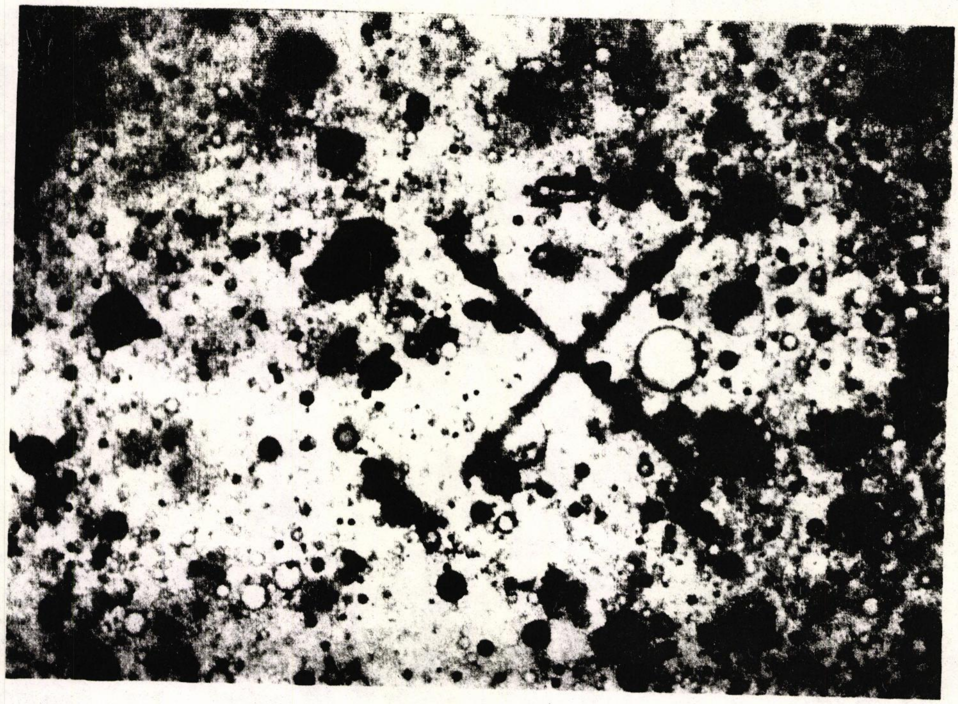


Figure 8. Photomicrograph of Fly Ash Magnified 100 Times.

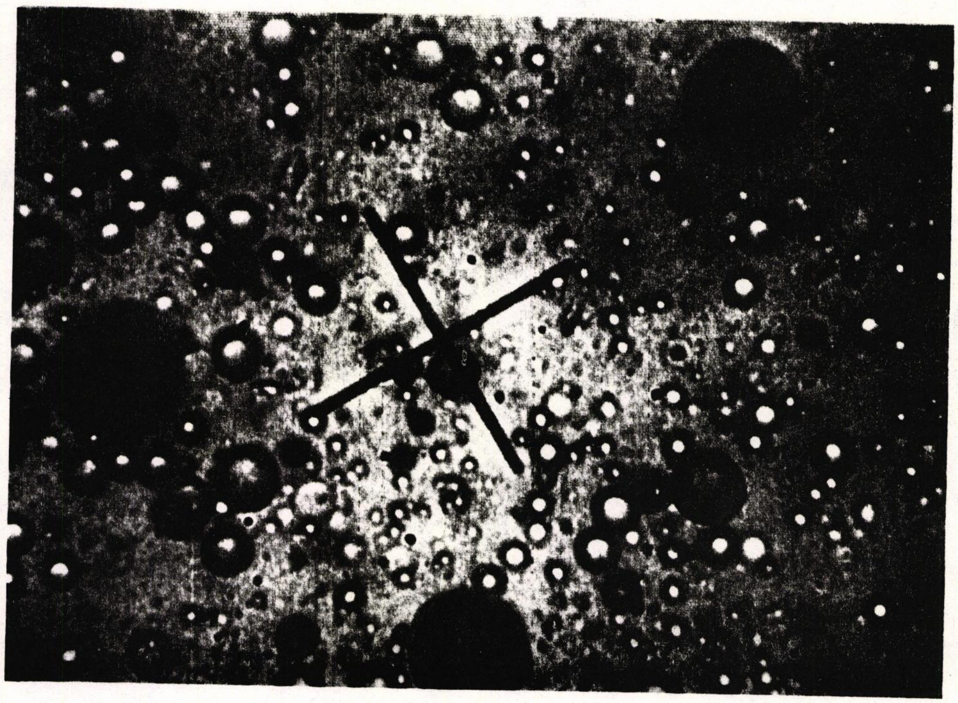


Figure 9. Photomicrograph of Fly Ash Magnified 450 Times.

Table 9. Chemical Analysis of the Fly Ash.[a]

	Chemical Composition, % by weight
SiO	34.0
Al_2O_3	13.0
Fe_2O_3	6.0
CaO	20.0
MgO	6.0
K_2O	0.8
Na_2O	2.8
SO_3	13.7
TiO_2	1.0
Undetermined	2.7
	100.0

Table 10. Physical Properties of the Fly Ash.[b]

Loss on Ignition	0.0%
pH	11.2
Water Soluble Fraction	1.0%
Pozzolanic Activity Index	1074.3 psi
Specific Gravity	2.75
Minimum Density	62.2 pcf
Maximum Density (Modified Proctor)	118.0 pcf
Optimum Moisture Content	9.0 %
% Passing #40 Sieve	99.5 %
% Passing #100 Sieve	98.0 %
% Passing #200 Sieve	94.0 %
% Passing #325 Sieve	86.6 %

[a] Determined by Sargent and Lundy, Engineers, Chicago.
[b] Determined in the University of Arkansas Soils Laboratory.

County, Arkansas. The clay was taken from the clay pit of the Acme Brick Company plant just east of Malvern on U.S. Highway 270. The clay is part of the Wilcox Formation (Williams and Plummer, 1951, pp. 1-35). An X-ray diffraction analysis of the clay determined the predominant clay mineral to be kaolinite. The properties of the clay are shown in Table 11. As shown in this list of properties, the dark gray clay is quite high in organic content (14.9%).

The second soil tested was a light brown, fine sand from Section 20, Township 4 South, Range 11 West of the Fifth Principal Meridian in Grant County, Arkansas. The sampling site is approximately 7 miles southwest of the site of the proposed coal-fired power station near Redfield. According to the Soil Conservation Service, General Soil Map of Grant County, the soil is part of the Angie-Sacul Association. The properties of the sand are shown in Table 12. The grain size distribution curves for both the clay and the fine sand are shown in Figure 10.

Lime:

The hydrated lime used in the investigation was obtained from the Rangaire Corporation, Batesville White Lime Division at Batesville, Arkansas. Table 13 lists the chemical and physical properties of the hydrated lime.

Cement:

Type 1 Portland Cement used in the investigation was Foreman brand, manufactured in Foreman, Arkansas by the Arkansas Cement Corporation.

Brown Mud:

Brown mud, a byproduct of the aluminum refining industry, was also used to a limited extent in the investigation. The brown mud was obtained from the Reynolds Aluminum, Hurricane Creek Plant at Bauxite, Arkansas. Table 14 shows the monthly tonnage of brown mud produced and the chemical composition for the years of 1968 through 1972. The table also gives a sieve analysis of the brown mud.

Salt:

The salt (sodium chloride) used in the investigation was fine-grained common table salt.

Tri Methylol Propane:

The Tri Methylol Propane (TMP) used in the study is a hydrophillic material produced in a highly refined crystalline form. The TMP was obtained from Prof. Ara Arman at Louisiana State University.

Table 11. Properties of Soil #1 (Clay)

Percent Silt	41.0%
Percent Clay	59.0%
Liquid Limit	54%
Plastic Limit	35%
Shrinkage Limit	19%
Plasticity Index	19%
Specific Gravity	2.62
pH	3.9
Organic Content[a]	14.9%
Organic Content[b]	11.4%
Predominant Clay Mineral	Kaolinite
Modified Proctor Density	97.5 pcf
Optimum Moisture Content	20.0%
Unified Classification	OH
AASHTO Classification	A-7-5 (14)

[a]Determined in accordance with ASTM D 2974-71
[b]Determined in accordance with procedures outlined by Arman and Munfakh, 1970, p. 18.

Table 12. Properties of Soil #2 (Sand)

Percent Sand	92.9%
Percent Silt	1.8%
Percent Clay	5.3%
Liquid Limit	NP
Plastic Limit	NP
Plasticity Index	NP
Permeability at 68% relative density	3.3×10^{-3} cm/sec
Specific Gravity	2.67
pH	4.3
Organic Content	0.75%
Minimum Density	76 pcf
Maximum Density (Modified Proctor)	99 pcf
Optimum Moisture Content	8.0%
Predominant Clay Mineral	ND
Unified Classification	SP-SMu
AASHTO Classification	A-3

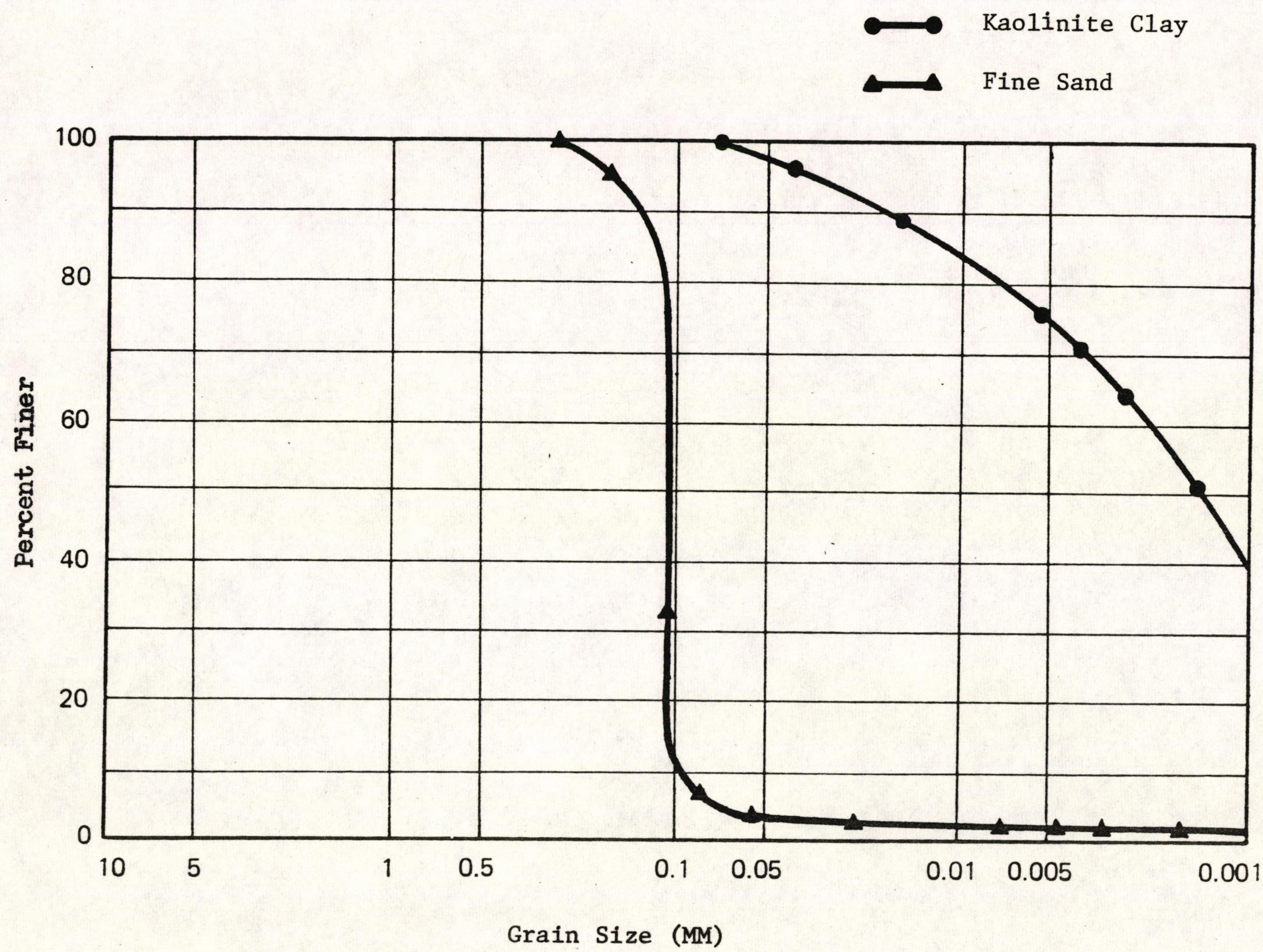


Figure 10. Grain size distribution of clay and sand.

Table 13, Chemical and Physical Properties of the Hydrated Lime.[a]

Analysis on Basis Received:

Silica	SiO_2	0.45%
Aluminum Oxide	Al_2O_3	0.19%
Ferric Oxide	Fe_2O_3	0.104
Titanium Oxide	TiO_2	None
Total Calcium Oxide	CaO	73.24%
Magnesium Oxide	MgO	0.70%
Sulphur Trioxide	SO_3	0.041%
Carbon Dioxide	CO_s	0.90%
Mechanical Moisture	H_2O	1.15%
Chemically Combined Moisture	H_2O	23.15%
Phosphorus Pentoxide	P_2O_5	0.028%
Manganese Dioxide	MnO_2	0.043%
Undetermined		0.007%

Combined as follows:

Calcium Hydroxide	$Ca(OH)_2$	94.31%
Magnesium Hydroxide	$Mg(OH)_2$	1.01%
Calcium Sulfate	$CaSO_4$	0.070%
Calcium Carbonate	$CaSO_3$	2.05%
Tri-Calcium Phosphate	$Ca_3(PO)_2$	0.061%
Silica	SiO_2	0.45%
Aluminum Oxide	Al_2O_3	0.19%
Ferric Oxide	Fe_2O_3	0.104%
Titanium Oxide	TiO_2	None
Manganese Dioxide	MnO_2	0.043%
Mechanical Moisture	H_2O	1.15%
Trace Uncombined Oxide	CaO	0.55%
Undetermined		0.007%

Screen Analysis:

% Passing 200 Mesh	100.00%
% Passing 325 Mesh	98.62%
% Passing 400 Mesh	98.28%

Available Lime CaO	71.64%
Plasticity	2.59%
% Residue on 200 Mesh	None
Specific Gravity of Lime[b]	2.34

[a]Determined by Bruce Williams Laboratory, Joplin, Missouri.
[b]Determined in the University of Arkansas Soils Laboratory.

Table 14. Quantity Available, Chemical Composition, and Sieve Analysis of Brown Mud Used in the Laboratory Investigation.

Quantity Available[a]

Monthly average for the following years: Tons of Brown Mud produced.

1968	1969	1970	1971	1972 (6 Mo.)
53,688	49,885	48,746	48,603	48,850

Composition Chemical[a]

	1968	1969	1970	1971	1972 (6 Mo.)
SiO_2	24.10	24.58	24.30	24.95	25.79
Fe_2O_3	10.67	9.54	9.78	8.48	8.79
TiO_2	4.91	4.93	4.70	3.85	3.21
Al_2O_3	6.67	6.22	6.41	5.33	5.18
Na_2O	2.54	2.44	2.28	2.24	2.14
CaO	45.88	45.95	46.28	48.19	49.40
SO_4	.03	.12	.20	.20	.21
CO_2	.78	.83	.99	1.11	.91

Sieve Analysis[b]

% Passing #40	99.5
% Passing #100	97.5
% Passing #200	67.5
% Passing #325	51.5

[a]Data supplied by Reynolds Metals Company, Hurricane Creek Plant, Bauxite, Arkansas
[b]Data obtained in University of Arkansas Soils Laboratory.

PREPARATION OF MATERIALS

The fly ash was in the dry state when received and was placed in barrels designed to protect the contents from moisture in the air.

The soils were sampled by hand in the field and carried in large sample bags to the laboratory. The samples were placed in large pans and allowed to dry in ovens at temperatures not exceeding 140° F.

After drying, the sand could be easily crumbled by hand or by means of a laboratory jaw crusher. The clay developed hard lumps upon drying. The lumps were broken into smaller lumps by means of the jaw crusher. These small lumps of clay were further pulverized by placing the soil in a laboratory disc type material grinder. Care was taken so that the soil would not be ground so fine as to excessively disturb the structure. The clay was pulverized to the extent that all the soil passed the No. 10 sieve. After preparation, both the soils were placed in large covered barrels for storage.

The hydrated lime, portland cement, salt, and TMP were all stored in air tight containers.

The brown mud was received in the saturated condition from the processing plant and was prepared in the same method as the clay. The brown mud was ground much finer, however, and then placed in a covered container.

TESTS TO DETERMINE PROPERTIES OF THE MATERIALS

The tests used to determine the properties of the materials in the study are referenced and/or described in Appendix I.

A hydrometer analysis of the fly ash could not be run. When the fly ash was introduced to water, the cementing properties of the ash caused the particles to flocculate and settle out quickly. The dispersing agent Cagon (sodium hexametaphospate buffered with Na_2CO_3) was not effective in preventing flocculation of the fly ash particles.

Kerosene was effective in preventing cementation of fly ash particles but consistent hydrometer results could not be obtained. Some of the lower specific gravity particles (probably cenospheres) were observed to float on the surface of the kerosene.

It is difficult to find a liquid which will effect complete dispersion of fly ash particles (Holton and Reynolds, 1954, p. 45). Even if an effective dispersing agent is found, there is no assurance the cenospheres will be filled to result in accurate analysis.

Much of the error in the results of hydrometer analysis performed on fly ash is due to the fly ash being made up of hheterogeneous particles (Holton and Reynolds, 1954, p. 46). The basis of the hydrometer analysis is Stoke's Law which was derived mathematically for solid spherical particles. Most fly ashes are composed of a hetergeneous mixture of solid spherical particles, hollow shperical particles, coarse irregularly shaped spongy particles, and broken hollow spheres. The specific gravities of these particles may vary over a range form less than 1.5 for particles high in organics to more than 3.0 for particles high in iron.

MIXING THE SOIL–ADDITIVE MIXTURES

A standard method of mixing the soil-additive mixtures was used throughout the laboratory investigation. First, the constituents were proportioned and dry mixed by hand. The mixture was then dry mixed in a Hobart 1/8 h.p. mixer for one minute. Next, a predetermined quantity of water was added and the mixture was stirred in the mixer for one minute. The sides of the bowl were scraped clean by hand and then, mixing was continued for an additional one-half minute.

COMPACTING THE SOIL–ADDITIVE MIXTURES

All soil-additive mixtures were compacted with Modified Proctor compactive effort in accordance with ASTM D 1557-70. A Rainhart automatic laboratory compaction apparatus equipped with a sector-faced tamper was used. Fresh material was used for each compaction specimen. All mextures were compacted immediately (within 30 seconds) after mixing except for those specimens which were evaluated for the effects of delayed compaction.

Some 100% fly ash specimens were molded using the Harvard minature compaction apparatus. Specimens molded for the unconfined compressive strength test were compacted at optimum moisture content using 50 tamps on 5 layers with a 40 lb. spring. This procedure is outlined in ASTM Procedures for Testing Soils, 1964, pp. 160-162.

CURING THE SOIL–ADDITIVE MIXTURES

After compaction, molded specimens were placed in plastic bags and cured for the desired period of time in a 100% relative hunidity moisture chamber at a temperature of $75^{\circ} \pm 3^{\circ}$ F.

TESTING THE STABILIZED SOIL MIXTURES

Atterberg Limits:

Soil-additive mixtures were tested for liquid limit and plastic limit in accordance with ASTM procedures listed in Appendix I. The soil and additives were first thoroughly dry mixed in plastic bags. Distilled water was then added to bring the consistency of the mixtures well past the liquid limit to that of a slurry. The bags were then sealed and placed in the humidity chamber for a curing period of 24 hours. The mixtures were then taken out of the bags and manipulated by hand under a fan until a consistency slightly wet of the liquid limit was reached. Several liquid limit determinations were then made as the mixtures were dried from wet of the liquid limit to dry of the liquid limit. The plastic limit determinations were made on the mixtures which contained a moisture content below the liquid limit.

Grain Size Analysis:

Soil-fly ash mixtures were tested in accordance with ASTM D 422-63 (reapproved 1972). The soil-fly ash mixtures were allowed to slake in the calgon solution for 24 hours before the hydrometer analysis was made.

Unconfined Compressive Strength:

Upon completion of the curing period, compacted specimens were placed in a Soiltest Versatester and tested for unconfined compressive strength. The method of test was in accordance with ASTM D 2166-66 (reapproved 1972) except that the height to diameter ratio requirement was neglected on the Proctor-sized specimens. The strain rate was 1% strain per minute until failure was reached. Samples were tested without soaking.

California Bearing Ratio:

Specimens were tested for California Bearing Ratio (CRB) in accordance with ASTM D 1883-67 except that Modified Proctor Compactive effort was used. Compaction was accomplished with the Rainhart Laboratory compactor equipped with a sector-faced tamper. After compaction, molded specimens were immersed in water under a 20 lb. surcharge for four days and then tested.

Freeze Thaw:

Specimens for the freeze-thaw test were tested in accordance with ASTM D 560-57 (reapproved 1971) except Modified Proctor compactive effort was used. Also, specimens were compacted with the Rainhart laboratory compactor equipped with a sector-faced tamper. Specimens were cured for 14 days and then subjected to 20 cycles of freeze-thaw.

Tests to Determine the Effects of Delayed Compaction:

All of the mixtures in this test series were mixed using Modidied Proctor optimum moisture content. Some of the specimens contained TMP. The TMP was dissolved in the mixing water and then added to the dry mixture. The mixing procedures described previously were then followed.

Salt, which was included in some mixtures, was added dry to the other dry materials in the mixture. The mixing procedures previously described were then followed.

Instead of compacting the mixtures immediately, a cloth was placed over each mixing bowl and the mixtures were allowed to set for various periods of time up to four hours. Metal stem thermometers were inserted into the mixtures to monitor the temperature of the mixtures with time. At the end of the desired time of set, clumps in the mixtures were broken up with a spatula and the mixtures were compacted. All specimens were cured for 7 days in a 100% humidity chamber at $75^{o} \pm 3^{o}$ F.

CHAPTER 4

TEST RESULTS

ATTERBERG LIMITS

Generally, the addition of 5% fly ash to the clay soil slightly increased the plasticity index of the clay and the addition of 10% and 20% fly ash slightly reduced the plasticity index of the clay (Figure 11).

EFFECT OF FLY ASH ON GRAIN SIZE OF CLAY

The grain size of the clay was significantly increased with the addition of fly ash in the amounts of 10% and 20% (Figure 12). Of the 100% clay soil, 58% was finer than two microns. When 10% and 20% fly ash was added to the clay, the percent finer than two microns was 32% and 8% respectively. Addition of fly ash to the clay caused flocculation of the clay particles, enlarging the grain size of the clay.

MOISTURE DENSITY RELATIONS

Both the clay and the fine sand were evaluated for changes in the moisture-density relations with the addition of the several additives tested. Each point on the moisture-density curves for the soil-additive mixtures is the average of two or more determinations.

The Modified Proctor dry density and the optimum moisture content of the kaolinite clay was 97.5 pcf and 20.0% respectively (Figure 13). The addition of 5% fly ash increased the maximum density to 100.3 pcf and decreased the optimum moisture content to 18.5%.

The maximum density was increased to 101.2 pcf and the optimum moisture content was decreased to 18.0% with the addition of 10% fly ash to the clay. The addition of 20% fly ash produced a maximum density of 102.6 pcf at a moisture content of 17.5%.

Overall, the greatest change in the moisture density relations per quantity of fly ash added was observed with the addition of 5% fly ash to the clay.

The addition of 15% portland cement to the clay increased the maximum density to 102.2 pcf and increased the optimum moisture content to 21.0% (Figure 14). However, the addition of 3% lime to the clay decreased the maximum density to 95.5 pcf and increased the optimum moisture content to 22.0%. When 5% brown mud was added to the clay, the maximum density was reduced to 97.0 pcf but the optimum moisture content of the clay remained unchanged.

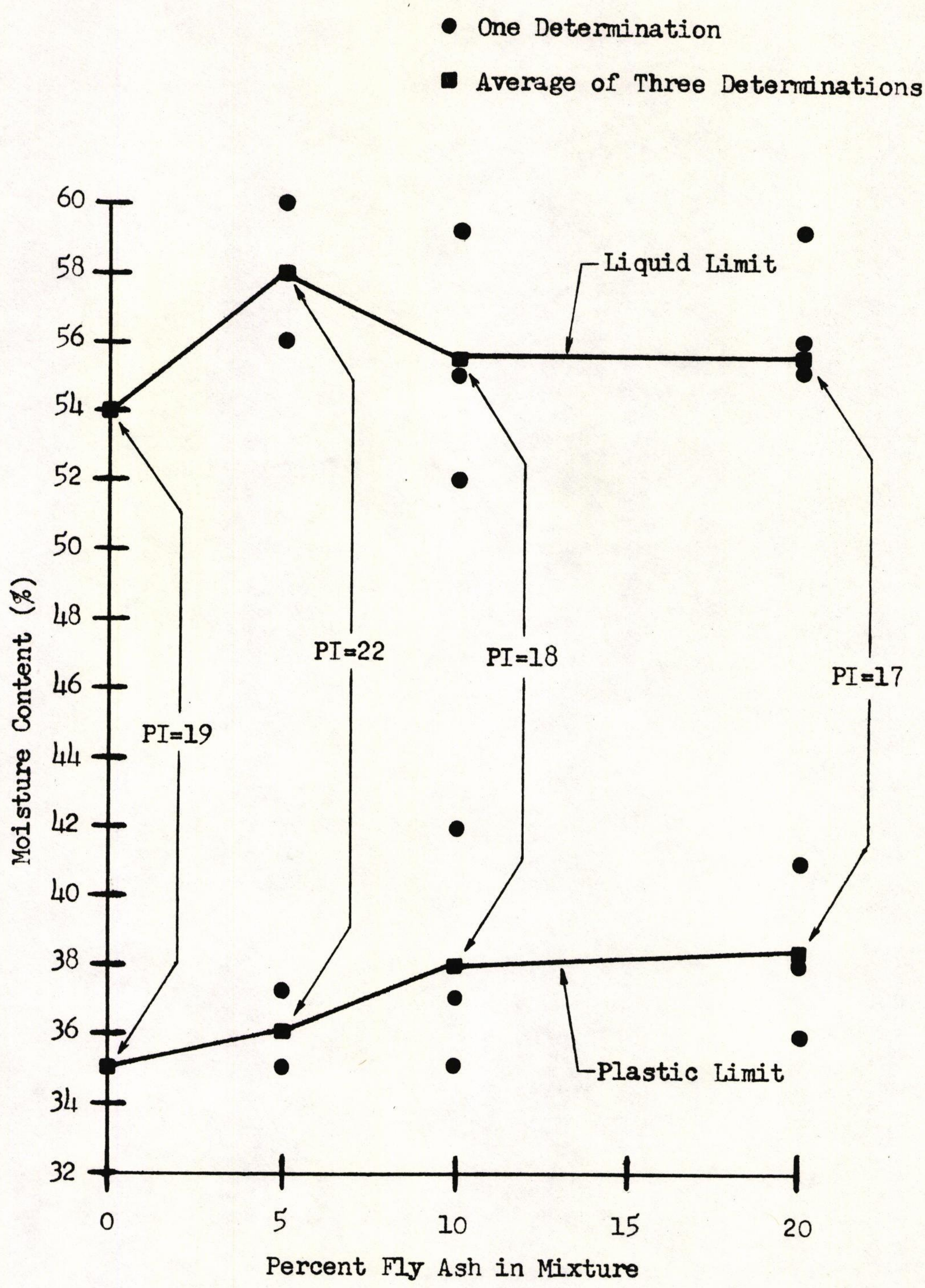


Figure 11. Results of liquid limit and plastic limit tests performed on clay soil-fly ash mixtures.

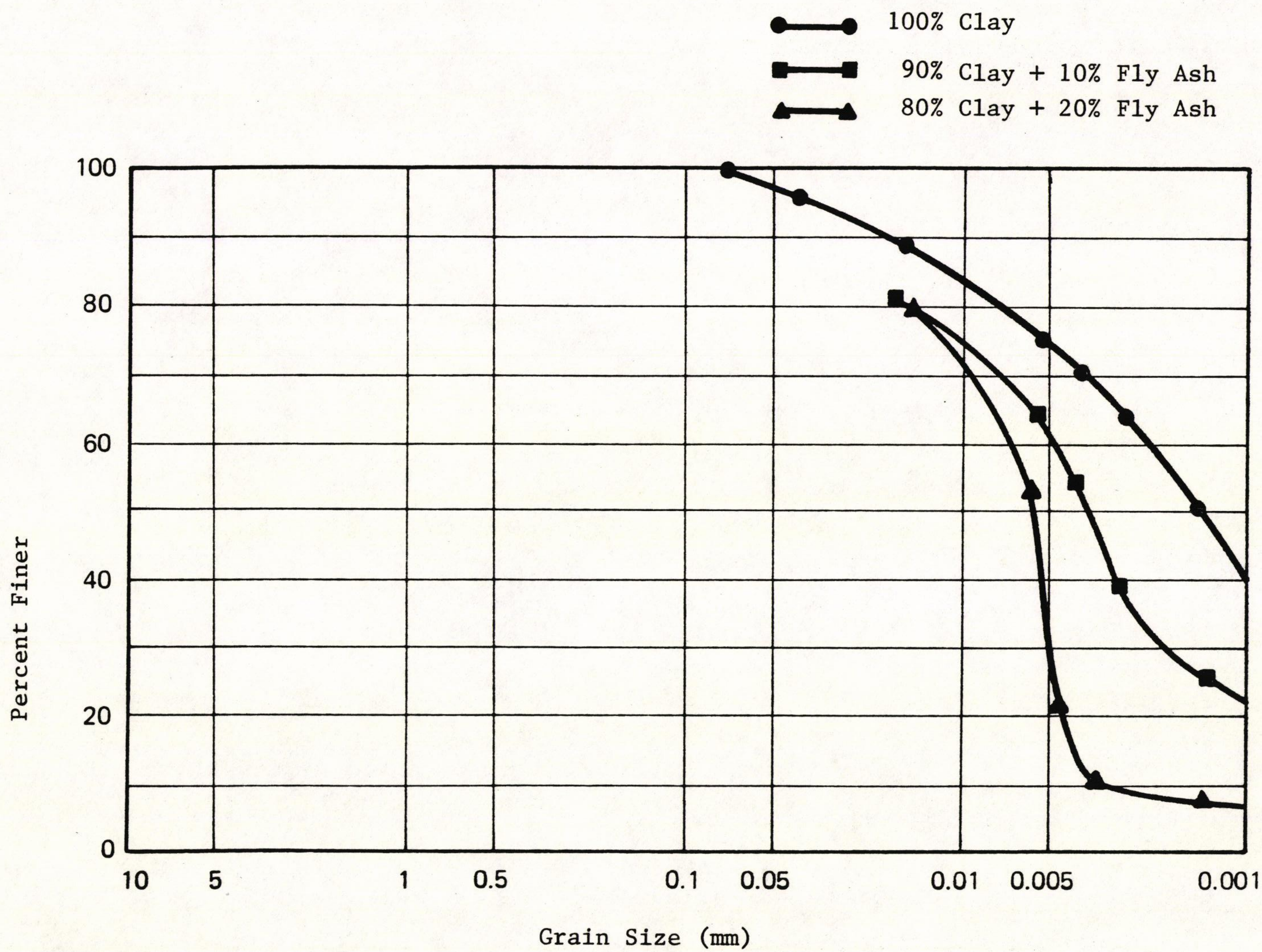


Figure 12. Effect of fly ash on the grain size of clay.

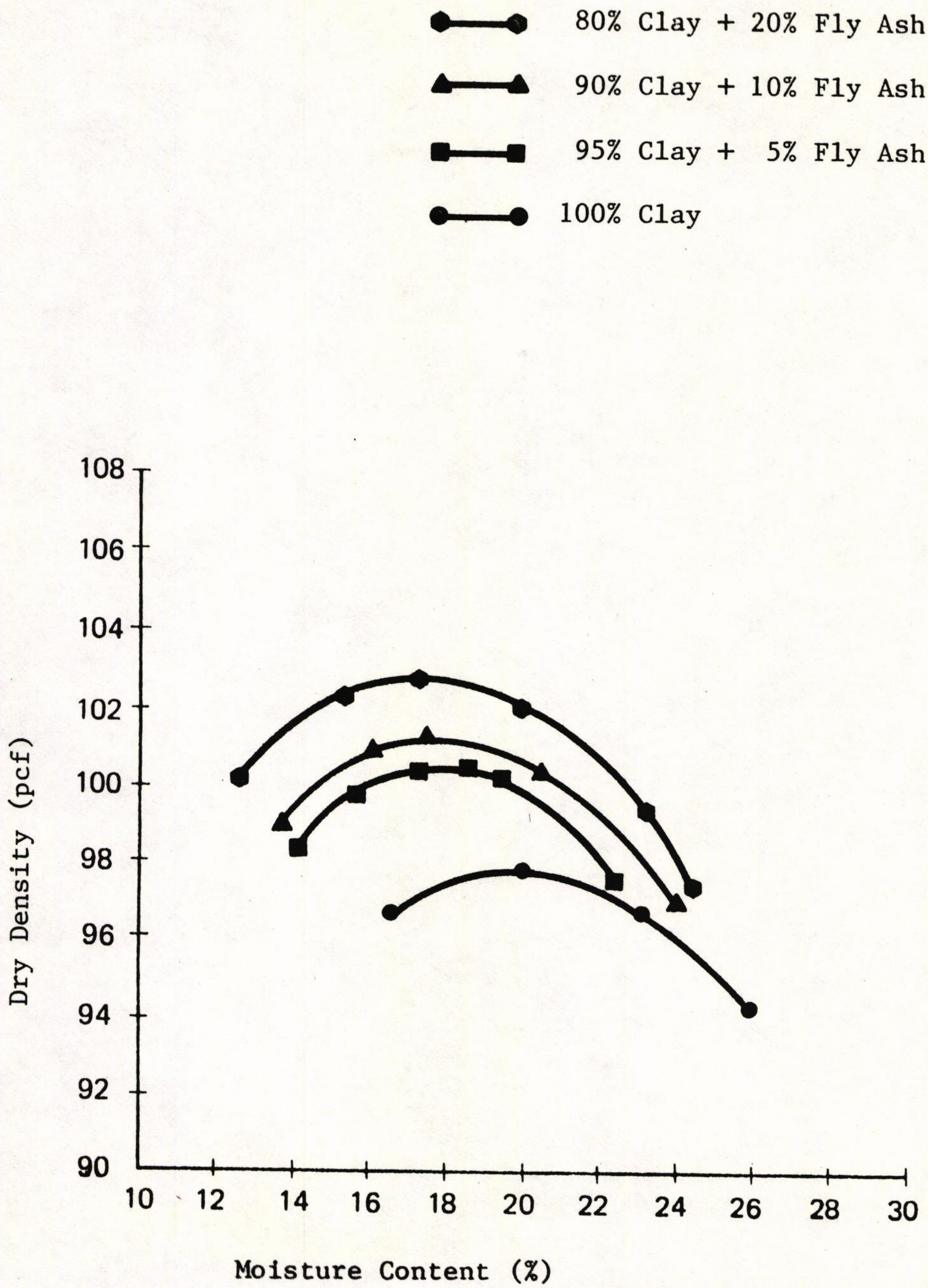


Figure 13. Moisture-density curves for stabilized clay mixtures.

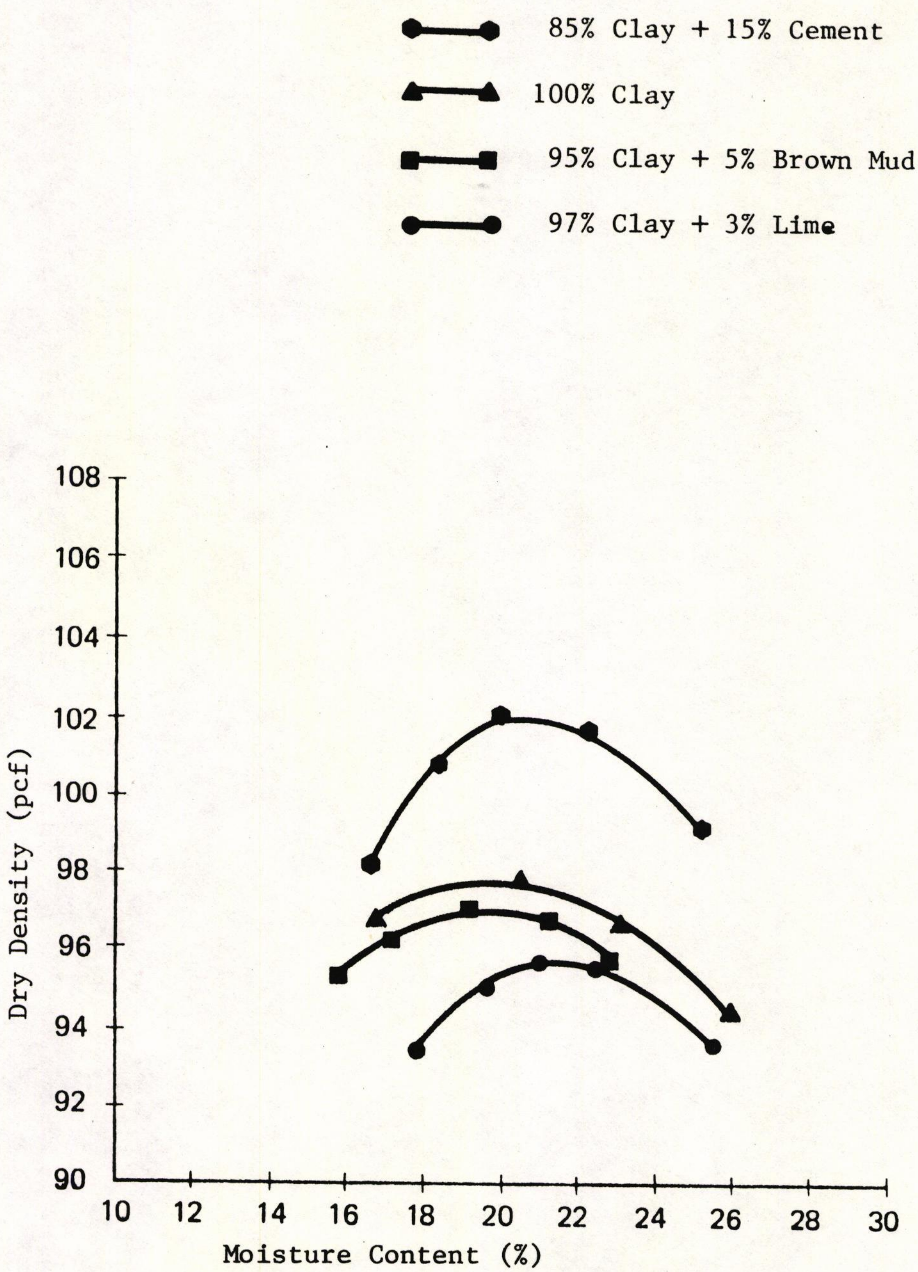


Figure 14. Moisture-density curves for stabilized clay mixtures.

The maximum Modified Proctor density of the fine sand was 99.0 pcf at a moisture content of 8.0% (Figures 15, 16, and 17). All the additives increased both the dry density and the optimum moisture content of the sand.

The additions of 20% fly ash and 20% fly ash + 3% lime to the sand produced peaked moisture density curves. The maximum density for the 80% sand + 20% fly ash mixture was 117.5 pcf and the maximum density for the 77% sand + 3% lime + 20% fly ash mixture was 119.5 pcf. The optimum moisture content for both these mixtures was 10.3%.

The mixtures of 87% sand + 3% lime + 10% fly ash and 85% sand + 5% cement + 10% fly ash produced slightly peaked moisture curves. The maximum densities for the two mixtures were 112.4 pcf and 112.2 pcf respectively. The optimum moisture content for both mixtures was 10.5%.

The remainder of the stabilized sand mixtures produced rounded moisture-density curves.

The Modified Proctor density of 100% fly ash was 118.0 pcf at an optimum moisture content of 9.0% (Figure 18). The Modified Proctor density for the fly ash used in this investigation is considerably higher than the Modified Proctor density for the Michigan fly ash of 95 pcf.

Addition of water to the fly ash resulted in an immediate increase in the temperature of the ash. After compaction, some of the specimens were broken open and a thermometer placed against the interior portions of the specimens. Temperatures up to 150° F were observed.

The fly ash-water mixture tended to dry out quickly. By the time the fifth layer in the specimens was compacted, the fly ash-water mixtures were so dry that the mixtures were difficult to compact.

Mixing bowls and equipment used to mix fly ash-water mixtures had to be washed soon after the mixing operation because the fly ash-water mixture would adhere to the equipment and form a very ahrd cement-like material if left unattended. The hardened material was very difficult to remove.

UNCONFINED COMPRESSIVE STRENGTH

The results of the unconfined compressive strength tests for the kaolinite clay and fine sand mixtures are shown in Tables 15 and 16. Each value of strength in tables is the average of the results from three or more tested specimens.

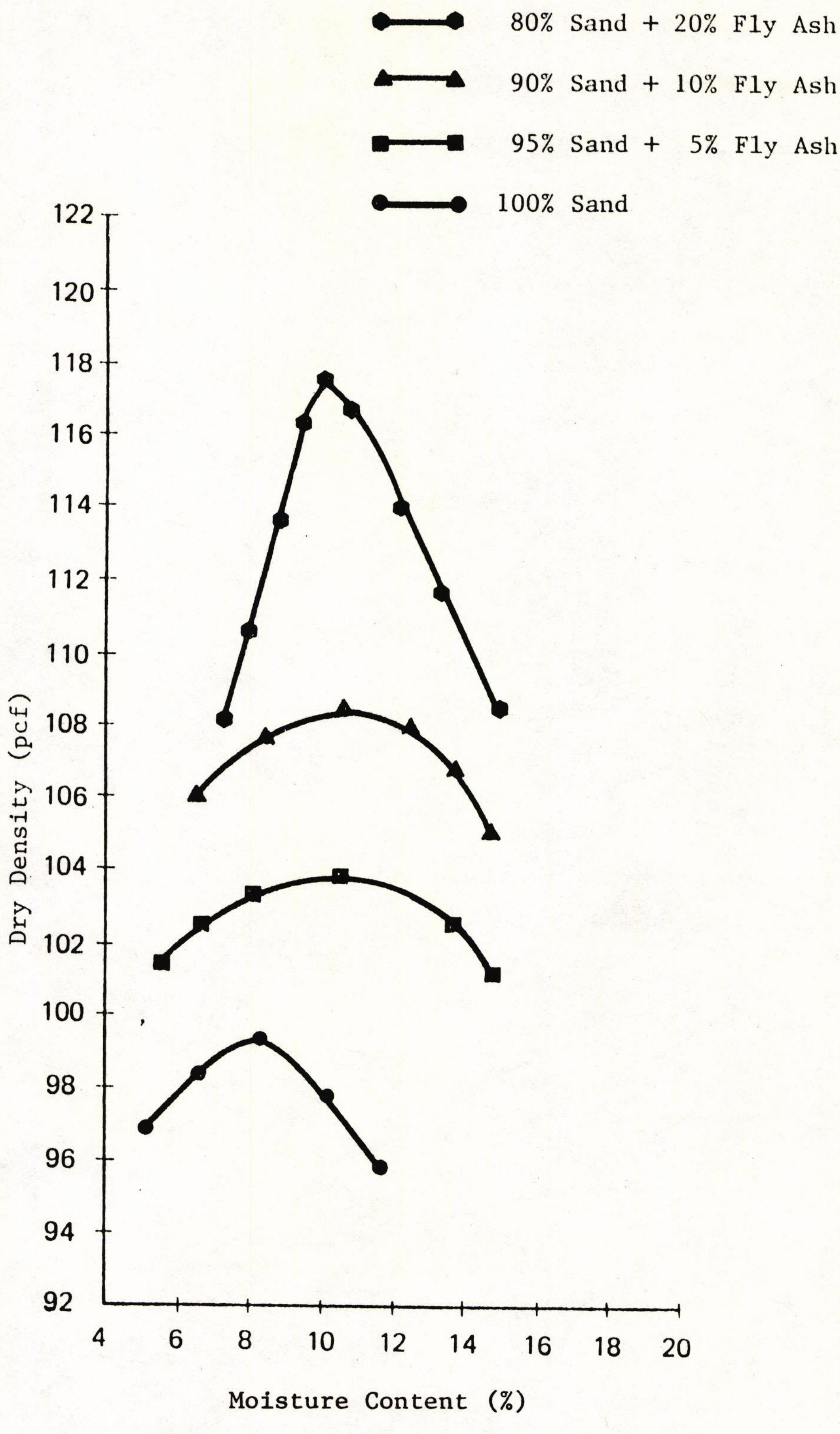


Figure 15. Moisture-density curves for stabilized sand mixtures.

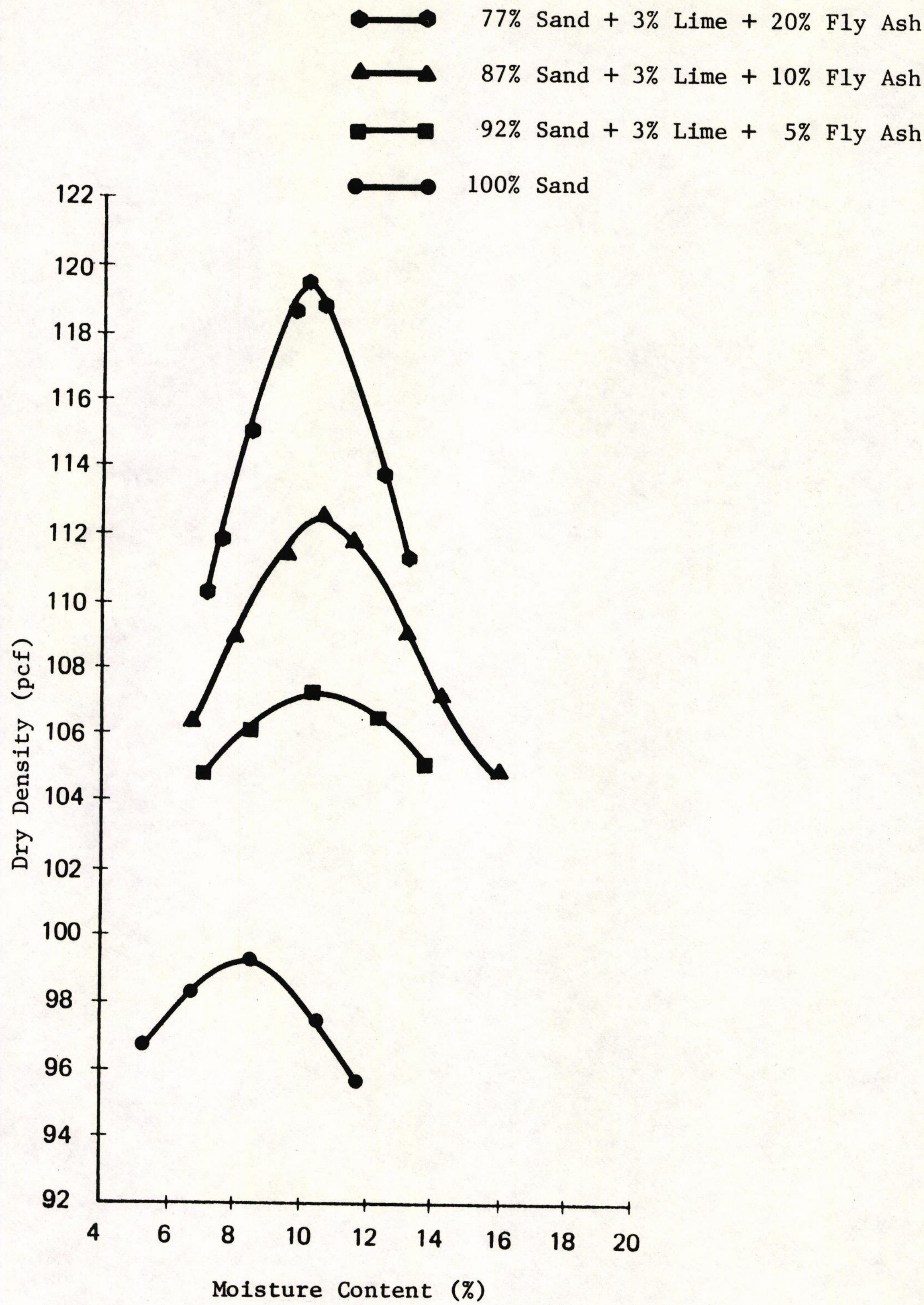


Figure 18. Moisture-density curve for 100% fly ash.

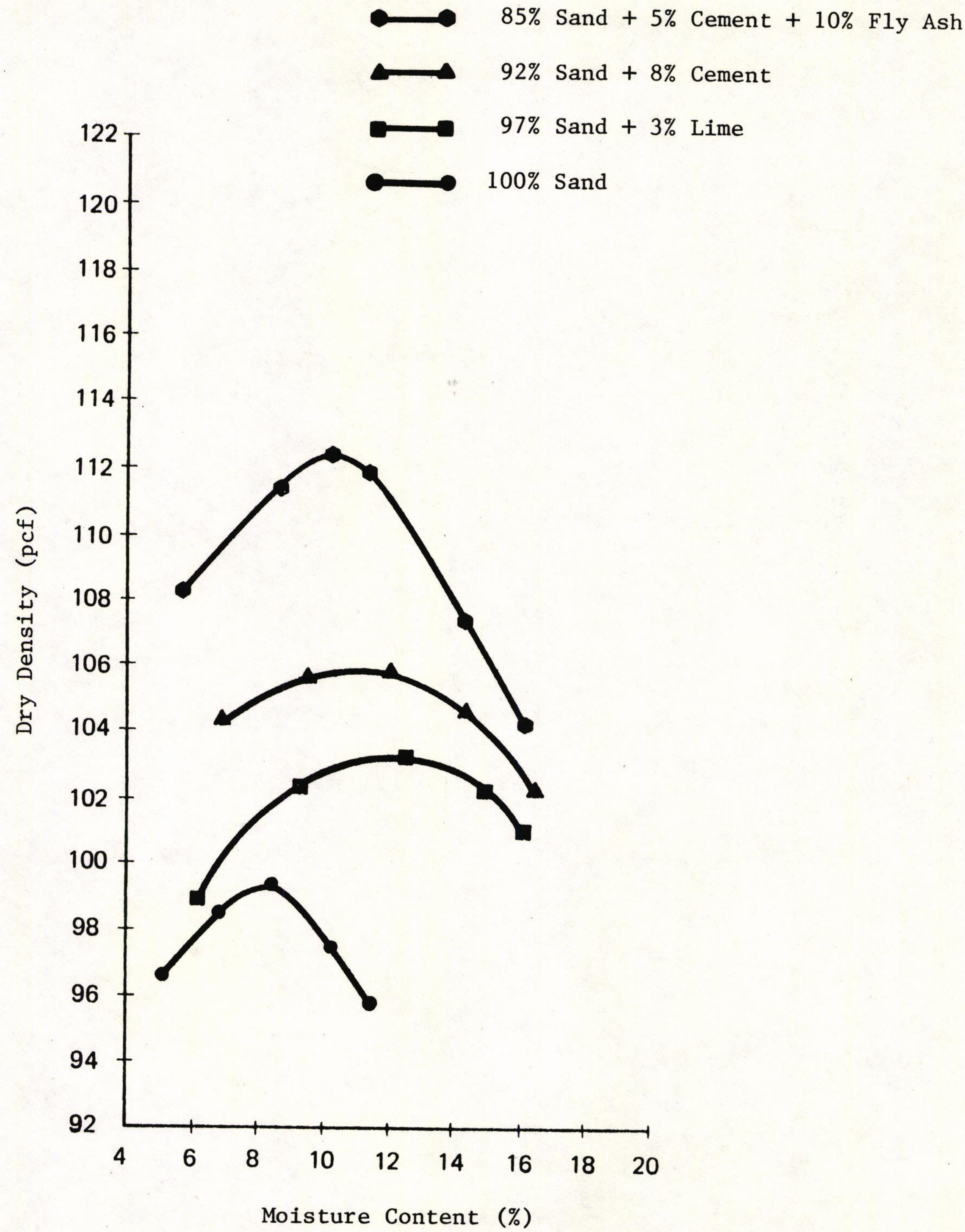


Figure 17. Moisture-density curves for stabilized sand mixtures.

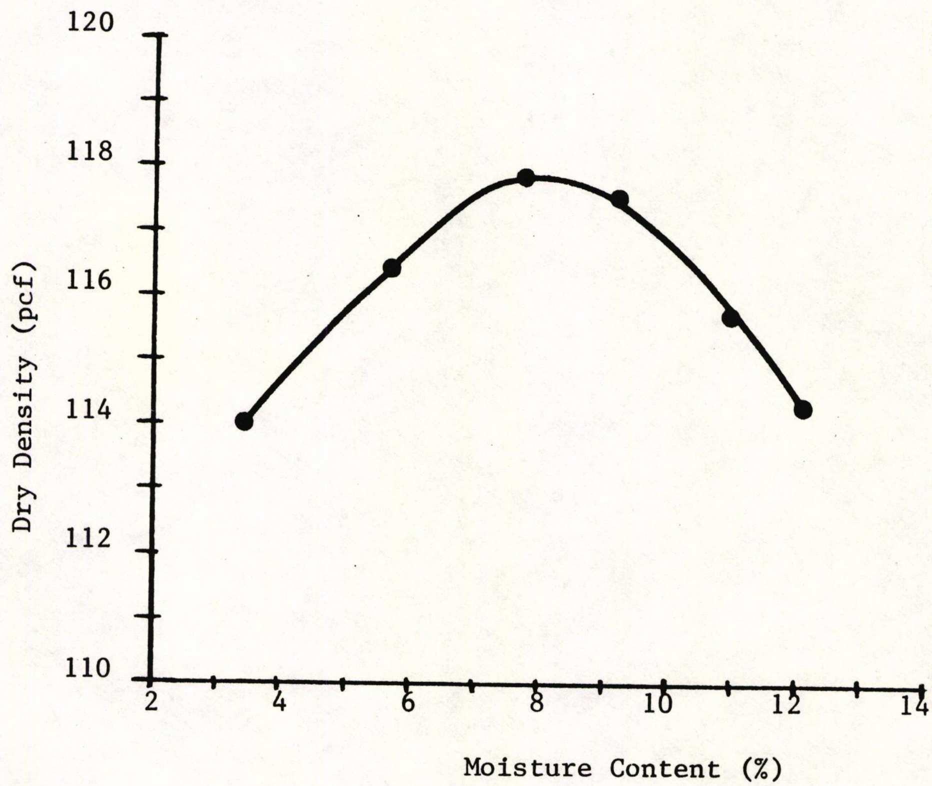


Figure 18. Moisture-density curve for 100% fly ash.

Table 15. Compressive Strength of Specimens Molded from Clay with Various Admixtures.

Kaolonite Clay + Admixture	Unconfined Compressive Strength (psi)[a]	
	7 day cure	28 day cure
100% Clay	190	---
97% Clay + 3% Lime	240	---
92% Clay + 3% Lime + 5% Fly Ash	---	286
87% Clay + 3% Lime + 10% Fly Ash	---	379
77% Clay + 3% Lime + 20% Fly Ash	429	---
95% Clay + 5% Fly Ash	264	---
90% Clay + 10% Fly Ash	305	---
80% Clay + 20% Fly Ash	410	---
95% Clay + 5% Brown Mud	261	---
85% Clay + 15% Cement	606	---

[a]Performed on specimens compacted to Modified Proctor density at optimum moisture content. Specimens were compacted immediately after mixing.

Table 16. Compressive Strength of Specimens Molded From Sand with Various Admixtures.

Sand + Admixtures	Unconfined Compressive Strength (psi)[a]		
	7 day cure	28 day cure	90 day cure
100% Sand	4	---	---
97% Sand + 3% Lime	54	205	450
92% Sand + 3% Lime + 5% Fly Ash	150	220	533
87% Sand + 3% Lime + 10% Fly Ash	310	519	816
77% Sand + 3% Lime + 20% Fly Ash	947	---	1488
95% Sand + 5% Fly Ash	78	110	----
90% Sand + 10% Fly Ash	213	240	----
80% Sand + 20% Fly Ash	730	---	868
92% Sand + 8% Cement	545	---	----
85% Sand + 5% Cement + 10% Fly Ash	709	---	----
77% Sand + 3% Brown Mud + 20% Fly Ash	542	---	----

[a]Performed on specimens compacted Modified Proctor density at optimum moisture content.

All of the additives improved the strength of the kaolinite clay. The largest strength was produced when 15% portland cement was added to the clay.

The mixture of 77% clay + 3% lime + 20% fly ash produced a 7-day strength of 429 psi. The mixture of 80% clay + 20% fly ash produced a 7-day strength of 410 psi. The addition of lime to the clay-fly ash mixture did not improve the strength significantly.

The addition of 5% brown mud to the clay produced a 7-day strength which was approximately equal to the 7-day strength produced by the addition of 5% fly ash. The 28-day strengths of these mixtures were not determined so the rate of strength gain with time is not known.

The unconfined compressive strength of 100% fine sand was 4 psi. This was probably due to apparent cohesion.

All of the additives improved the strength of the fine sand. The mixture which produced the highest 7-day strength was 77% sand + 3% lime + 20% fly ash. This mixture gained strength with age and at 90 days cure exhibited a strength of 1488 psi.

Brown mud did not prove to be an acceptable replacement for lime in the sand mixtures. In fact, the 7-day strength produced by the mixture of 77% sand + 3% brown mud + 20% fly ash was less than the 7-day strength produced by the mixture of 80% sand + 20% fly ash.

The 100% fly ash specimens molded in the Harvard miniature compaction apparatus developed shrinkage cracks soon after compaction due to the development of high temperatures in the mixtures. The cracks were on exterior portions of the specimens and probably decreased the compressive strengths of the specimens somewhat. Nevertheless, the average compressive strength was 2100 psi after 14 days cure.

CALIFORNIA BEARING RATIO

The results of the CBR tests for the stabilized soil mixtures are shown in Figures 19 and 20. Each value reported is the test data from one specimen.

The addition of 3% lime produced essentially the same improvement to the kaolinite clay as did 20% fly ash. At any rate, neither the lime nor fly ash produced a substantial increase in the CBR of the clay. However, the addition of 15% portland cement of the clay produced a CBR value of 112%. Since this value is greater than a CBR value of 80%, the 85% clay + 15% cement mixture meets CBR requirements for a base directly beneath pavement.

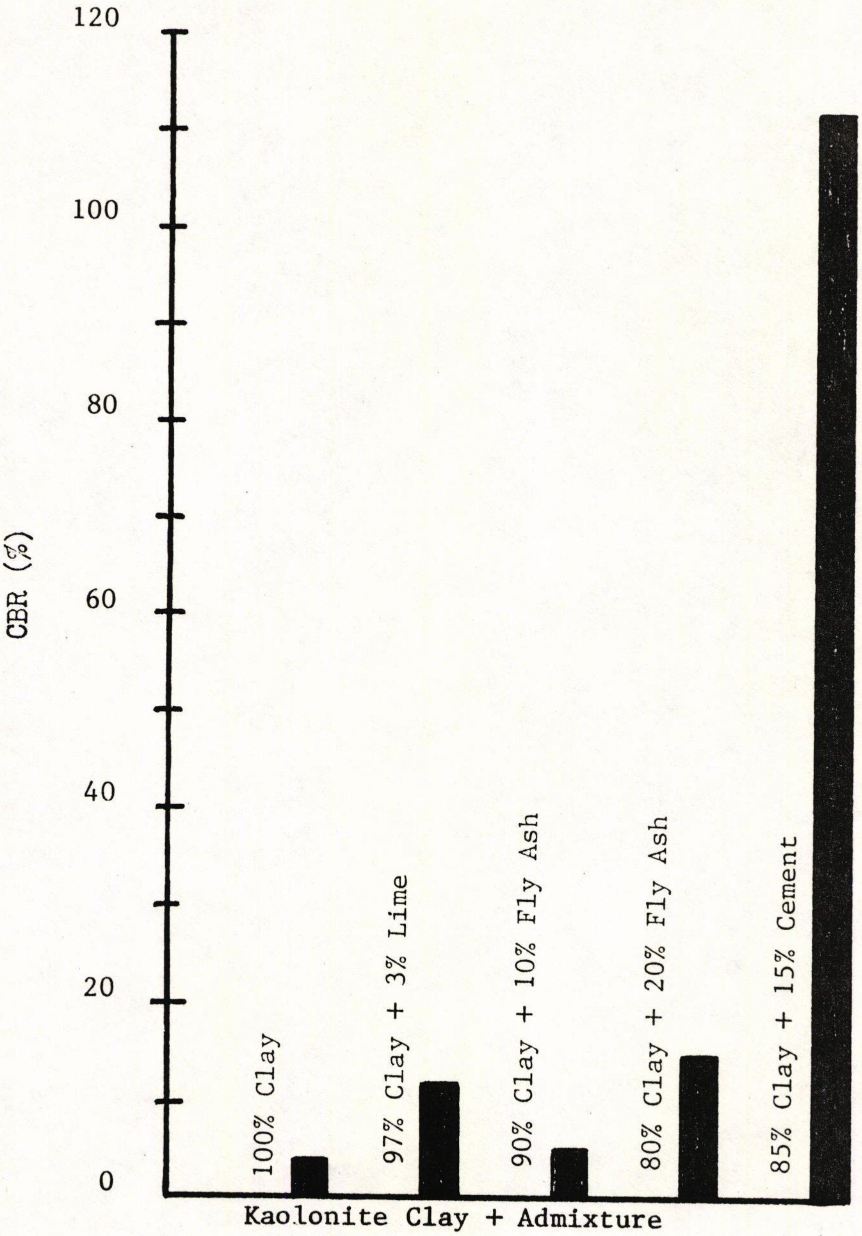


Figure 19. Values of California Bearing Ratio for stabilized clay mixtures.

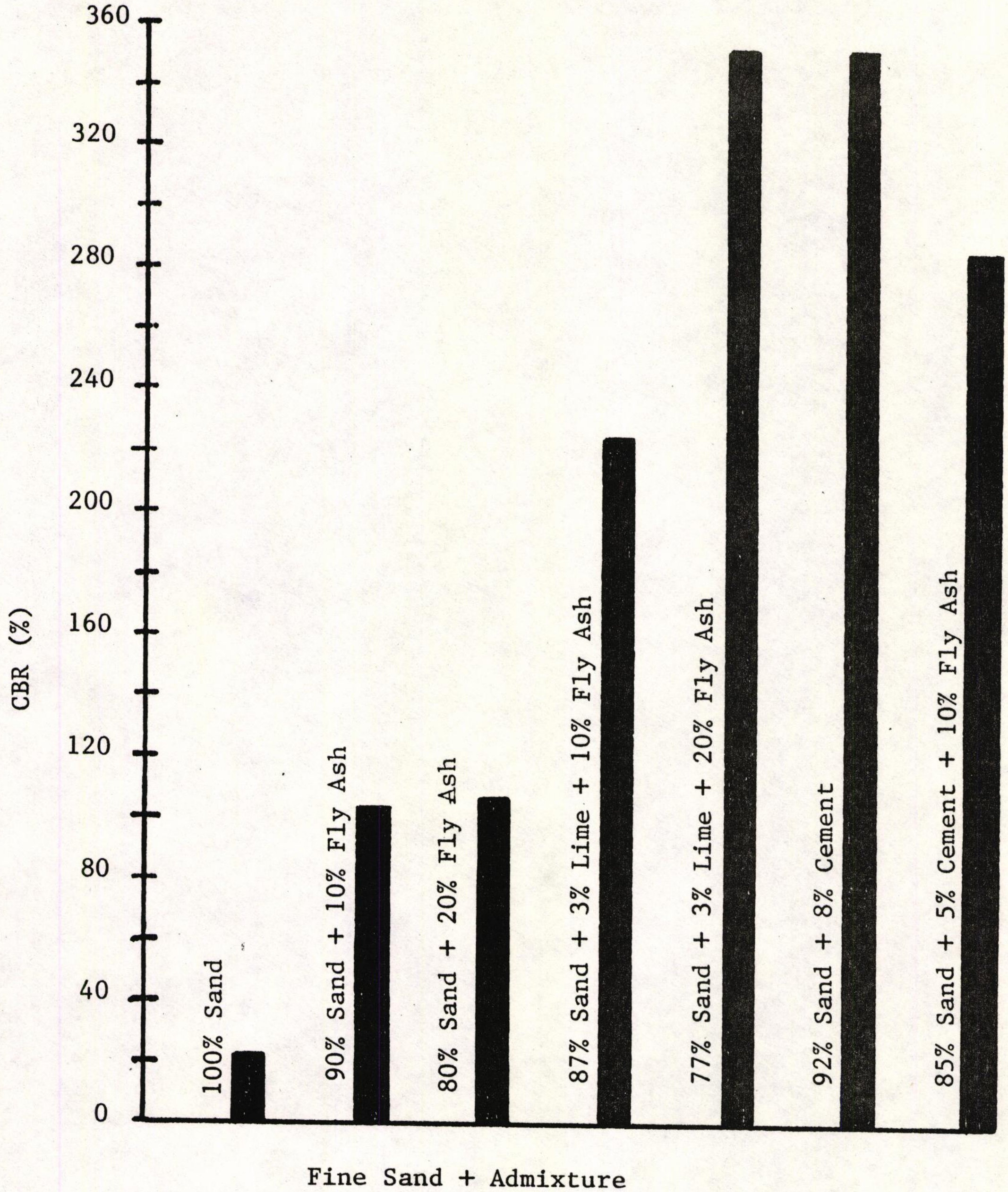


Figure 20. Values of California Bearing Ratio for stabilized sand mixtures.

All of the additives shown in Figure 20 improved the fine sand to produce CBR values in excess of 80%. Therefore, all of these mixtures meet CBR requirements for a base directly beneath pavement.

The CBR value for the 80% sand + 20% fly ash mixture was 106%. However, a CBR value of 356% was produced when lime was added to make a mixture composed of 77% sand + 3% lime + 20% fly ash. A CBR value of 356% was also produced when portland cement was added to make a mixture of 92% sand + 8% cement.

FREEZE—THAW

Only sand mixtures were evaluated with the freeze-thaw test. The results of the tests on these mixtures are shown in Figures 21 & 22. Each point on the curves is the average of the results from two specimens.

None of the specimens exhibited any significant amount of heave during the test. The largest heave observed was 0.16% which corresponded to the heave of the sand stabilized with 20% fly ash.

Two of the mixtures exhibited excellent resistance to freeze-thaw. One was sand stabilized with 10% fly ash + 5% cement. After 20 cycles, the weight loss of this mixture was 2.03% and the compressive strength was 1340 psi. The other mixture was 92% sand + 8% cement. After 20 cycles, the weight loss was 2.08% and the compressive strength was 640 psi.

The sand mixtures stabilized with 5% and 10% fly ash exhibited poor resistance to freeze-thaw and had 100% weight loss after 9 and 10 cycles respectively.

EFFECTS OF DELAYED COMPACTION

Since the soil-fly ash reaction seemed to take place immediately after mixing, a study was conducted to determine the effects of delayed compaction on the 7-day compressive strength and dry density of some soil-additive mixtures. A small delay in compaction will cause a substantial decrease in both the 7-day compressive strength and the dry density of the 80% sand + 20% fly ash mixture (Figure 23). after a delay of only two minutes, the 7-day strength was reduced from 730 psi to 365 psi and the dry density was reduced by 12 pcf. After a one hour delay in compaction, 18% of the initial strength and 83% of the initial dry density was retained. The rate of the reduction in strength and density grew slower with time, however. The strength and density corresponding to a four hour delay period is not significantly less

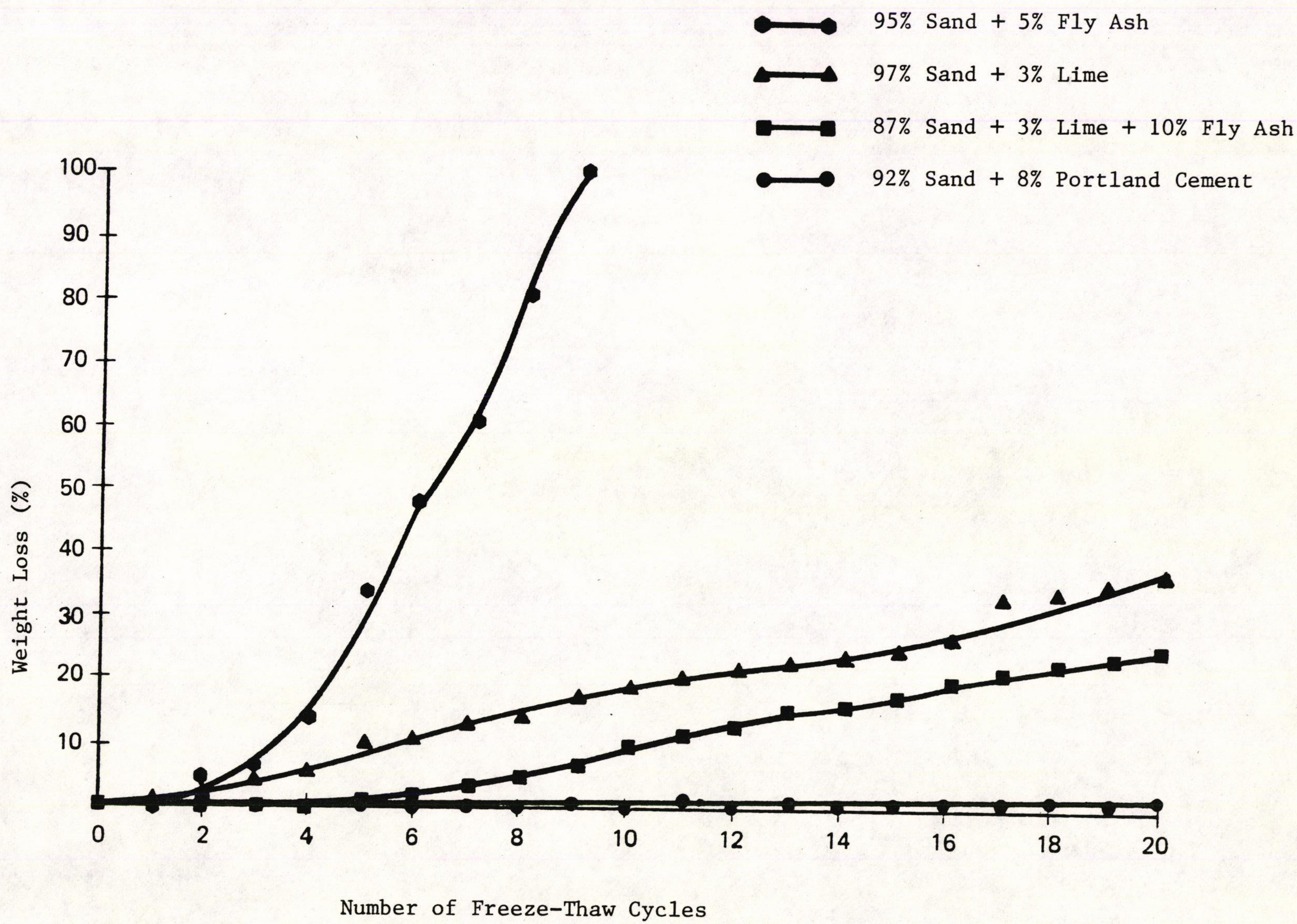


Figure 21. Effect of freeze-thaw on stabilized sand mixtures.

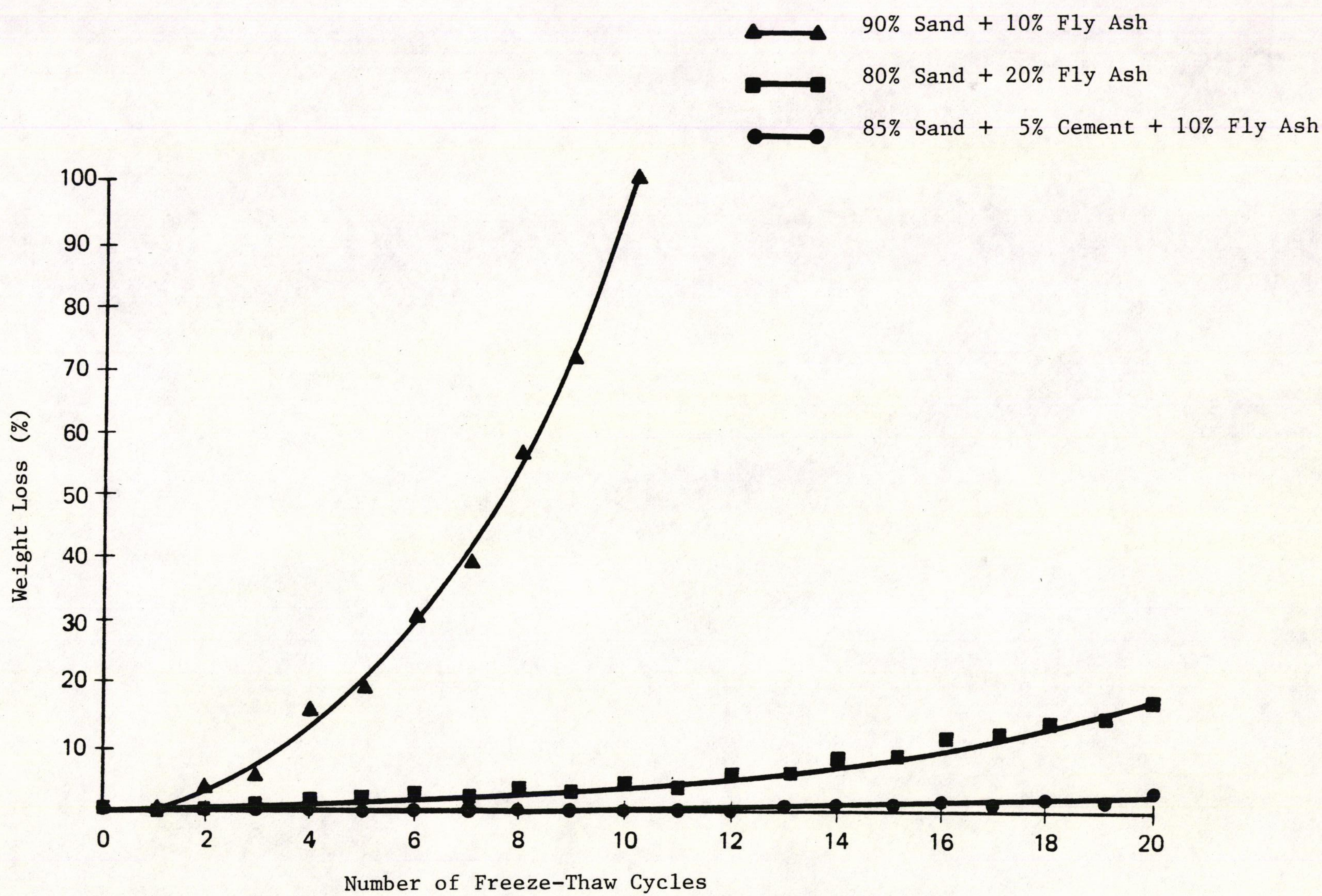


Figure 22. Effect of freeze-thaw on stabilized sand mixtures

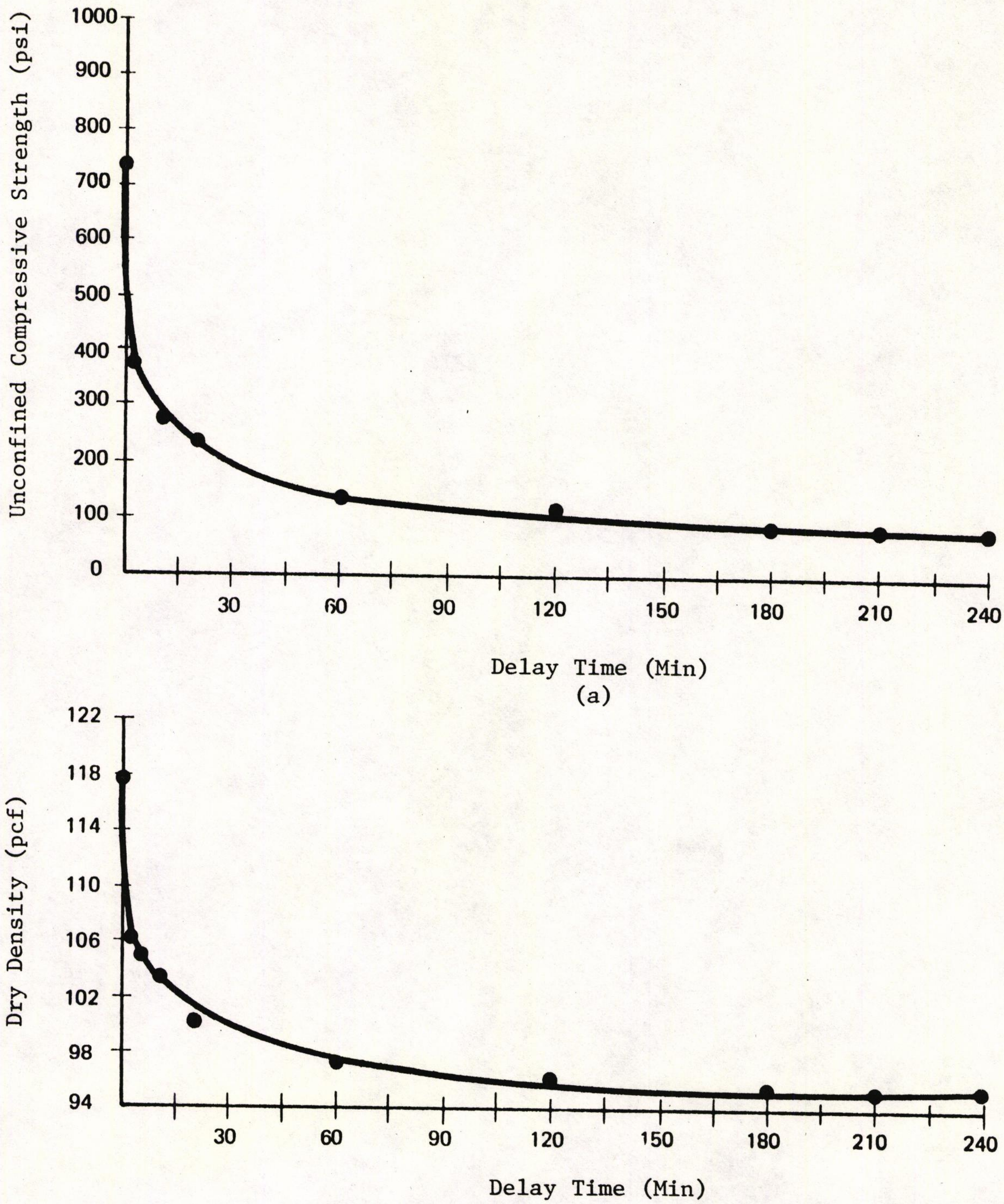


Figure 23. Effect of delay of compaction on 80% Sand + 20% Fly Ash mixture; (a) 7-day unconfined compresive strength vs. delay time, (b) dry density vs. delay time.

than the strength and density corresponding to a one hour delay period.

Since the density and strength of the soil-fly ash mixture were substantially reduced after only a short delay time a search was made for an additive which would counteract the deterimental effects of delayed compaction. Arman (1972, p. 125) reports that TMP has worked to counteract the deterimental effects of delayed compaction in some soil cement mixtures. The TMP temporarily fixes the water in some form of chemical degrading product. As the degradation of this chemical product continues, the fixed water is freed and made available to the mixture. Generally, this chemical product degrades in 4 to 18 hours.

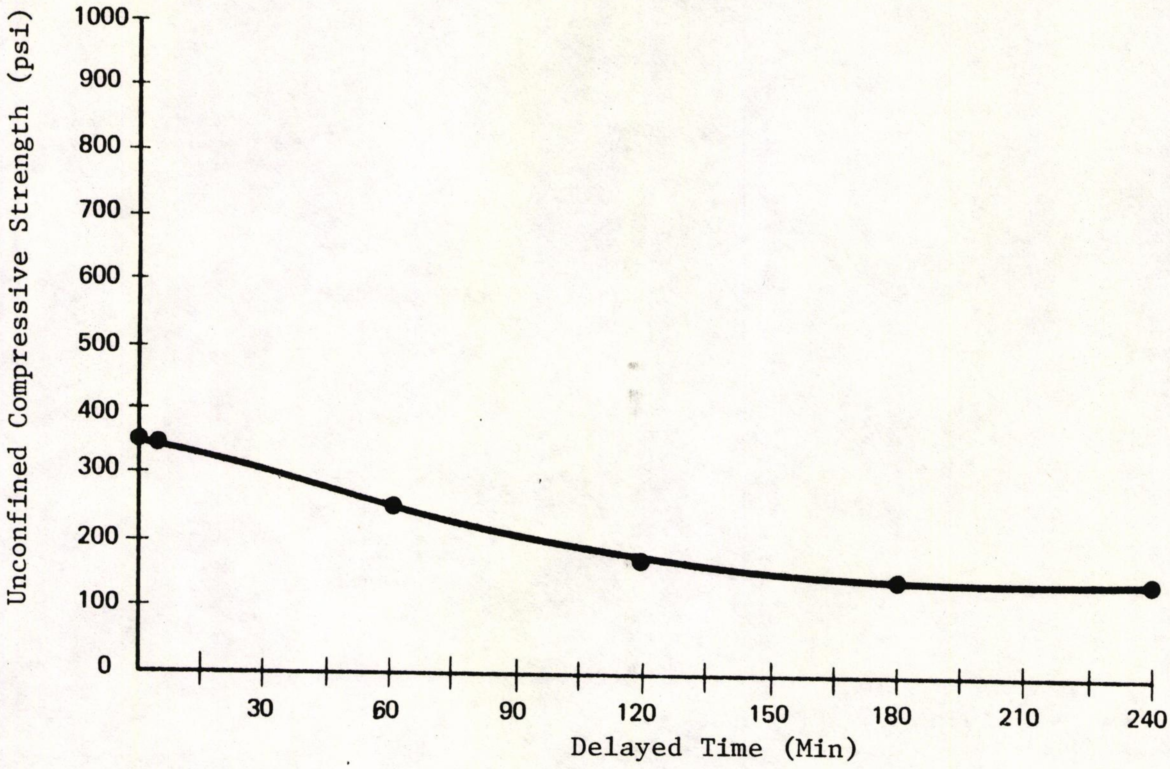
TMP in the amount of 0.5% was dissolved in the mixing water and added to the 80% sand + 20% fly ash mixture. As shown in Figure 24, the initial 7-day strength of the soil-fly ash mixture with TMP was 320 psi whereas the initial strength of the mixture without TMP was 730 psi. The dry density of the mixture with TMP was also lower than the dry density of the mixture without TMP. After a four hour delay period, the strength of the mixture containing TMP was about 30 psi greater than the strength of the mixture without TMP.

Salt is known to reduce moisture content changes in soils (Thornburn and Mura, 1969, p. 4). A test series was conducted to determine the effect of salt on the soil-fly ash mixtures. The results of the tests on the 78% sand + 20% sly ash + 2% salt mixtures are shown in Figure 25.

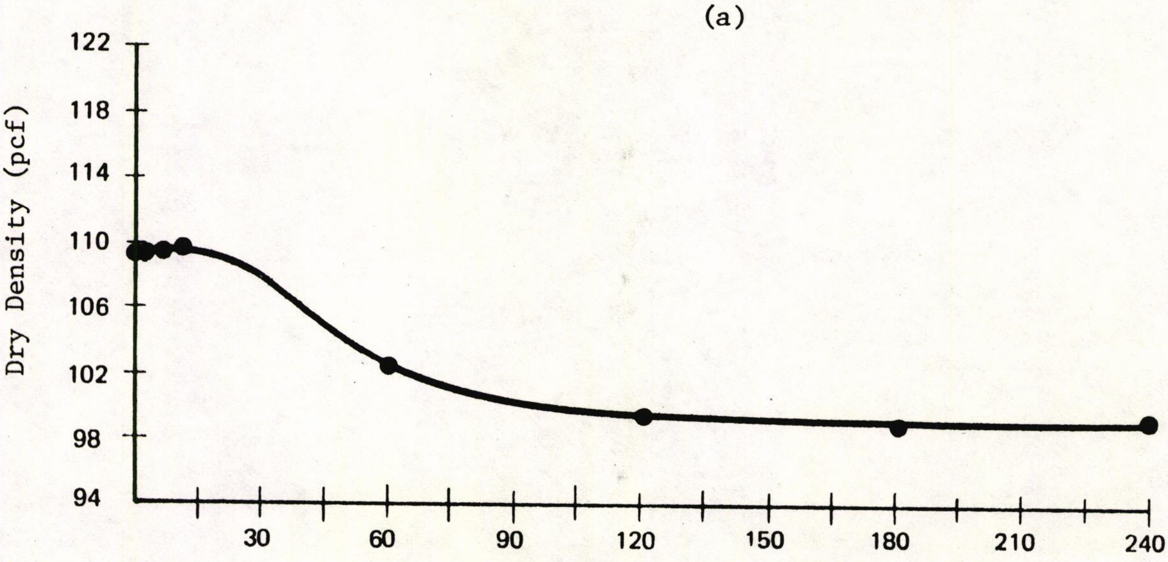
The addition of salt influenced the rate of reduction in strength and density. After a one hour delay in compaction, approximately 80% of the initial 7-day strength and 96% of the initial dry density was retained. After a four hour delay in compaction, approximately 22% of the initial strength and 86% of the initial density was retained.

The shape of the strength vs. delay time curve for the mixture containing 77% sand + 20% fly ash + 3% brown mud is essentially the same shape as the strength vs. delay time curve for the mixture containing 80% sand + 20% fly ash as shown in Figure 26. The initial strength of the mixture containing brown mud is somewhat less, however, than the initial strength of the 80% sand + 20% fly ash mixture. The rate of reduction in dry density for the brown mud mixture is approximately constant throughout the four hour delay period.

Figure 27 shows the change in temperature of various mixtures with time. The initial temperature of all the mixtures was 74° F. The mixture of 80% sand + 20% fly ash reached a maximum temperature of 110° F eight minutes after water was added to the mixture. The



(a)



(b)

Figure 24. Effect of delay of compaction on 80% Sand + 20% Fly Ash mixture with 0.5% TMP; (a) 7-day unconfined compressive strength vs. delay time (b) dry density vs. delay time.

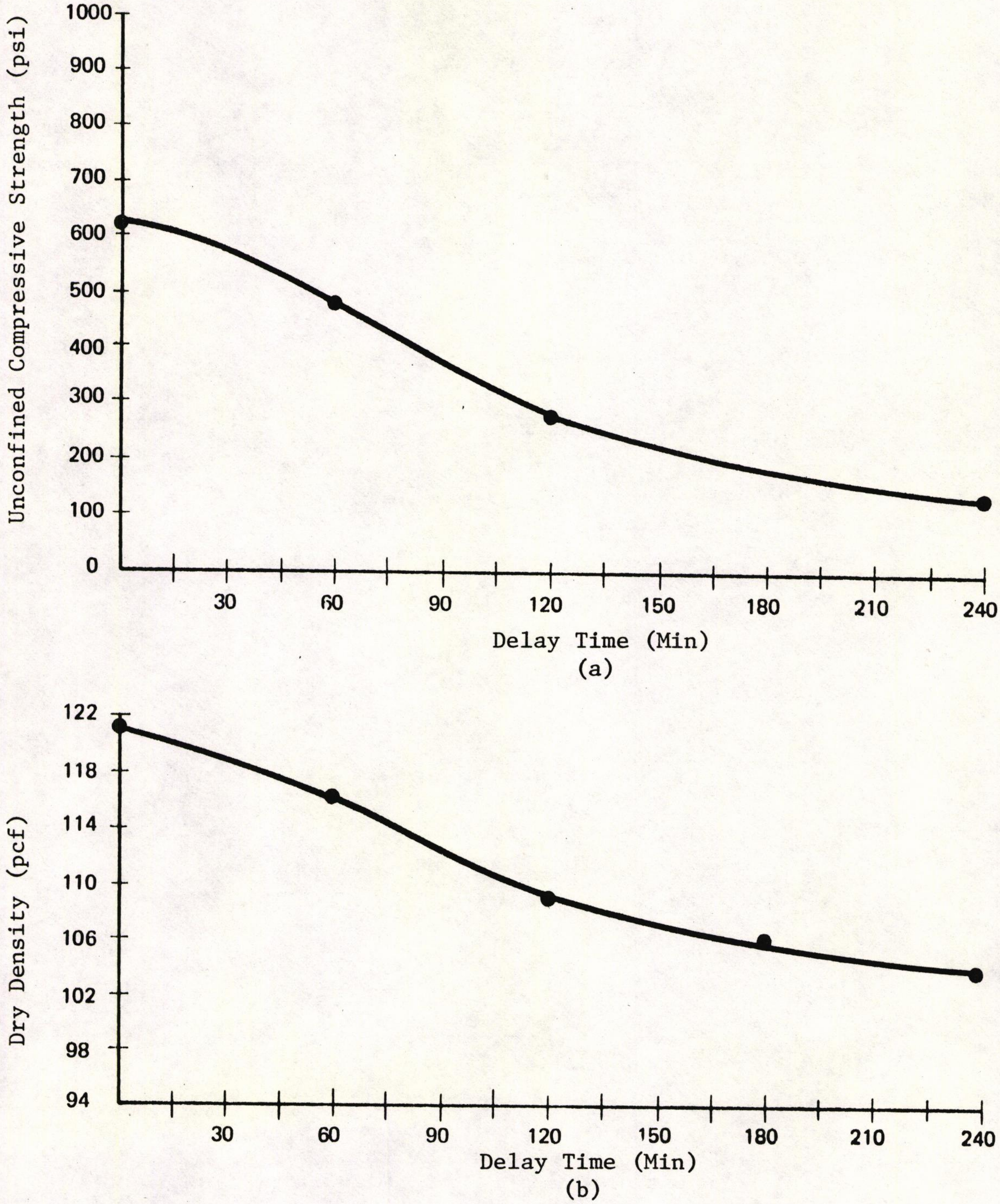


Figure 25. Effect of delay of compaction on 78% Sand + 20% Fly Ash + 2% Salt mixture; (a) 7-day unconfined compressive strength vs. delay time, (b) dry density vs. delay time.

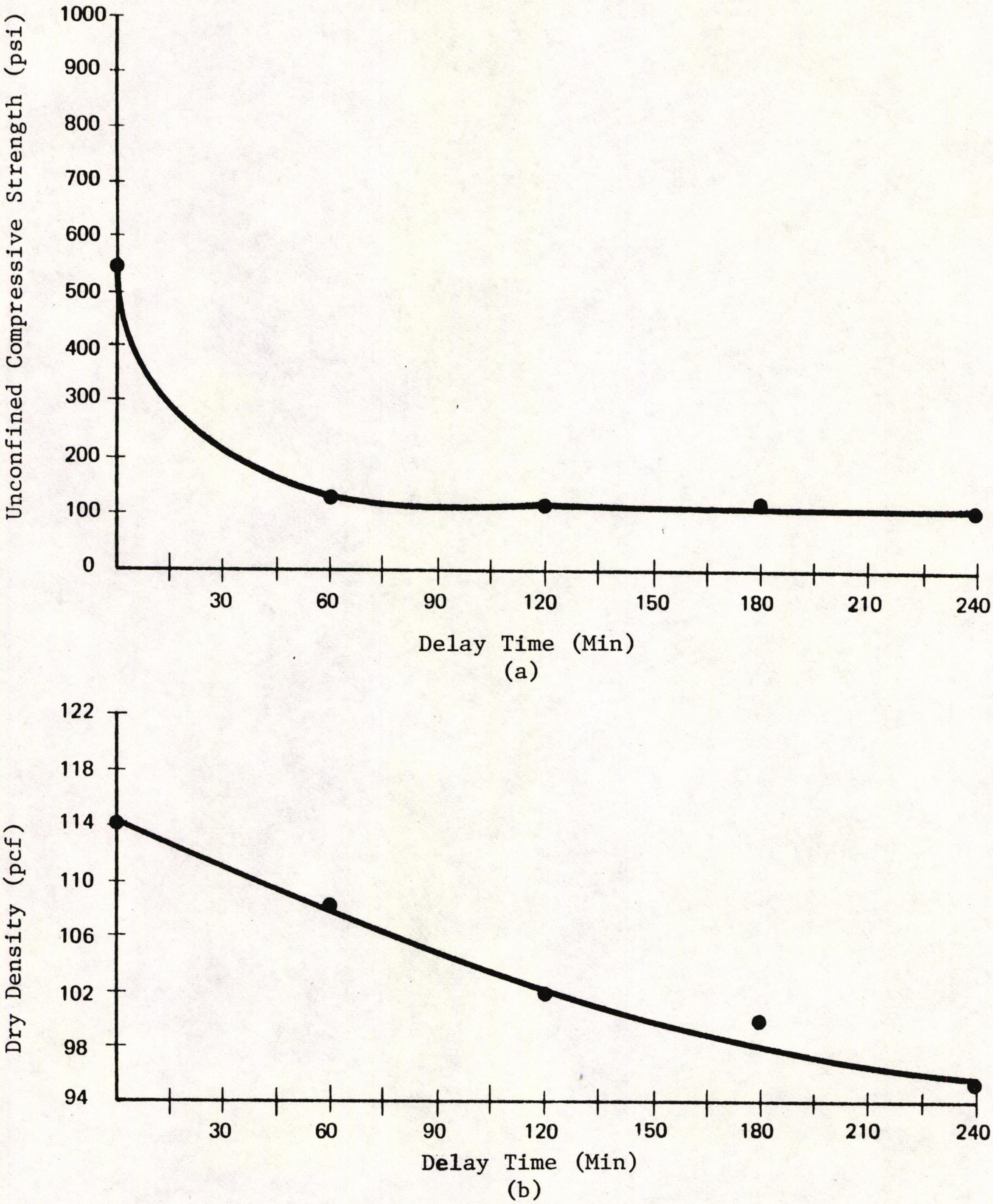


Figure 26. Effect of delay of compaction on 77% Sand + 3% Brown Mud + 20% Fly Ash mixture; (a) 7-day unconfined compressive strength vs. delay time, (b) dry density vs. delay time.

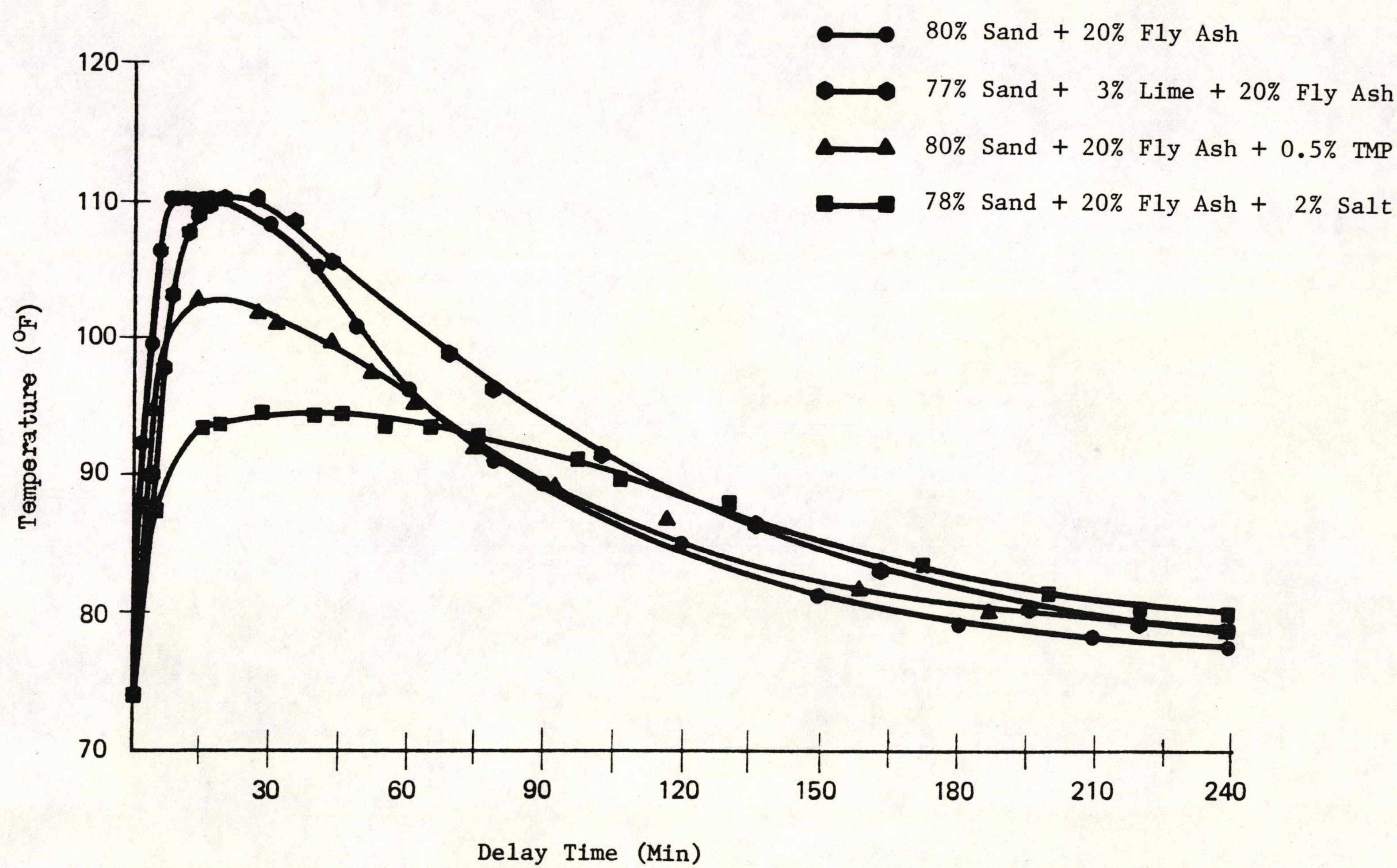


Figure 27. Temperature-time characteristics for sand mixtures.

maximum temperature remained constant for about 12 minutes and then the temperature of the mixture began to decrease. After four hours, the temperature of the mixture was 77° F.

The addition of 0.5% TMP to the 80% sand + 20% fly ash mixture influences the temperature chacteristics of the mixture. The maximum temperature produced is 103° F. After about one hour, the temperature vs. time curve for the TMP mixture is almost identical to the temperature vs. time curve for the mixture without TMP.

The maximum temperature produced when salt is added to the mixture is 94° F at 30 minutes. After this, the temperature gradually reduces to reach a value of 80° F at four hours.

The temperature vs. time curve for the mixture of 77% sand + 20% fly ash + 3% lime is also plotted in Figure 27 to show the effects of adding the lime. The maximum temperature observed was the same as that for the 80% sand + 20% fly ash mixture but the time required to reach this temperature was 20 minutes. After maximum temperature was reached, the temperature of the mixture began to decrease until a value of 79° F was reached after four hours. The rate of the temperature decrease of the 77% sand + 20% fly ash + 3% lime mixture was not as fast as the rate of temperature decrease for the 80% sand + 20% fly ash mixture.

CHAPTER 5

DISCUSSION OF TEST RESULTS – COSTS

PROPERTIES OF FLY ASH

The fly ash used in this study varies from most of the fly ashes reported on in the literature. First of all, the light cream color does not fall within the range of colors reported for most fly ashes. Also, the specific gravity of the fly ash is 2.75 which is higher than that of most fly ashes. Furthermore, the fly ash contains virtually no organics as determined by the loss on ignition test.

The fly ash contains 6.0% MgO which is higher than the upper range of MgO content of 3.5% for most fly ashes. Also, the fly ash contains 20.0% CaO which is higher than the upper range of CaO content of 11.0% for most fly ashes.

The pozzolanic activity index of 1074 psi is well above the ASTM minimum requirement of 800 psi, even though common hydrated lime was used in this determination rather than the reagent grade.

The Modified Proctor density of the fly ash is 118 pcf which is well above the dry density of any fly ash reported in the literature. The fact that the fly ash develops temperatures as high as 150° F. when water is added and the mixture compacted to Modified Proctor density, indicates a chemical reaction is taking place. No mention of gain in temperature of fly ash-water mixtures is made in the literature.

The fly ash reaction with water was also observed while performing the hydrometer analysis of the fly ash. Even though approximately 87% of the fly ash passed the No. 325 sieve, all fly ash particles flocculated and settled out of suspension about five minutes after the test was begun. This flocculating action of the fly ash was again observed in the hydrometer analysis of the clay-fly ash mixtures (Figure 12).

PROPERTIES OF CLAY MIXTURES

The plasticity tests run on the clay soil-fly ash mixtures indicated the plasticity index of the soil to be little affected by the addition of fly ash. These results are not conclusive, however, because it was difficult to obtain consistent values for the liquid and plastic limits of the clay soil-fly ash mixtures. Perhaps modification of the methods of mixing, curing, and testing the mixtures would produce consistent results. Also, the low degree of activity of the kaolinite clay minerals and the high organic content (14.9%) of the soil might have an influence on the observed behavior of the plasticity of the clay soil-fly ash mixtures (Arman, 1975).

The addition of fly ash to the clay soil increased the dry density and decreased the optimum moisture content of the clay. Since all mixtures were compacted immediately after mixing, the change in gradation of the clay by the addition of the fly ash could have caused these changes in the moisture-density relations. As expected when lime is added to clay, the optimum moisture content was increased and the dry density decreased by the addition of the hydrated lime to the clay. The addition of brown mud served to decrease the dry density, but had no effect on the optimum moisture content. A possible explanation is that the brown mud contains less calcium than does the hydrated lime.

All of the additives increased the strength of the clay to some extent. The addition of 15% portland cement improved the clay to the largest degree. The addition of 20% fly ash was effective also and more than doubled the strength of the clay. The addition of 3% lime + 20% fly ash did not make a significant strength improvement over the strength obtained with the addition of 20% fly ash alone. The high organic content of the clay might be the reason for the lack of improvement with the addition of lime.

Neither the lime nor fly ash produced any great improvement in the CBR of the clay. The addition of lime produced essentially the same improvement as did the addition of 20% fly ash. The CBR of the clay was improved by the addition of cement to the extent the mixture met CBR requirements for a base beneath pavement.

PROPERTIES OF FINE SAND MIXTURES

All of the additives increased both the dry density and the optimum moisture content of the fine sand. As with the clay, these changes in the moisture-density relations can be attributed to changes in the gradation of the sand by the addition of the additives. When additives were added in quantities of 20% or more, peaked curves were observed which are characteristic of silty soils.

All of the additives increased the strength of the sand. The initial strength of the fine sand was only 4 psi and this was probably due to apparent cohesion. The strength produced with the addition of 20% fly ash was the value of 730 psi. After 90 days cure, the strength of this mixture increased by 19% to the value of 868 psi. Most of the strength gain with this mixture occurred in the early stages of cure. The addition of 3% lime and 20% fly ash produced a strength value of 947 psi. After 90 days, this strength increased by 57% to the value of 1488 psi. The lime not only improves the early strength of the soil-fly ash mixture, but also increases the rate of strength gain with time.

The addition of brown mud did not increase the strength of the sand-fly ash mixture, but, in fact, reduced the strength.

Portland cement was quite effective in improving the strength of the fine sand. The mixture of 85% sand + 5% cement + 10% fly ash, however, produced a 7-day strength which was 30% greater than the strength produced with the addition of 8% cement alone.

All of the additives in the CBR tests improved the sand to the extent that each mixture met CBR requirements for a base directly beneath the pavement. As with the strength tests, the addition of 3% lime to the soil-fly ash mixtures improved the CBR values of the mixtures substantially. The CBR value of the 80% sand + 20% fly ash mixture was increased by 234% by the addition of 3% lime.

The sand mixtures stabilized with 5% and 10% fly ash exhibited poor resistance to freeze-thaw and did not perform as well as the sand mixture stabilized with 3% lime. The sand mixture stabilized with 20% fly ash performed well in the freeze-thaw test. After 20 cycles, the weight loss for these mixtures was only about 20%. None of the specimens tested exhibited any significant amount of heave. The maximum amount of heave observed for any of the specimens was 0.16%.

EFFECT OF DELAYED COMPACTION

Throughout the laboratory investigation, soil-fly ash mixtures were observed to gain temperature when water was added. Since a reaction appeared to be taking place immediately, a test series was included in the testing program to determine the effect of delayed compaction on the strength and density of the sand mixtures. The results of these tests showed there is a reaction immediately after water is added to the mixture. Apparently, the calcium in the fly ash is in the form of quick-lime and is hydrated upon introduction of water. Hydration would account for the observed increase in temperature. As shown in Figure 27, the addition of lime to the sand-fly ash mixture does not increase the temperature of the mixture, but does prevent the development of the maximum temperature for a few minutes. Possibly the lime absorbs some of the mixing water and hinders complete hydration of the CaO in the ash for a few minutes.

The addition of TMP to the soil-fly ash mixture lowered the reaction temperature. The TMP fixes the water into some sort of a chemical degrading product which releases the water with time. Since not all of the mixing water was available to the Ca0, a lower reaction temperature resulted.

The addition of salt to the sand-fly ash mixture lowered the reaction temperature even more so than did the TMP. Apparently, the salt was somewhat effective in preventing the mixing water from totally hydrating the CaO in the fly ash.

A delay of only a few minutes resulted in a substantial decrease in both the strength and dry density of the 80% sand + 20% fly ash mixture (Figure 24). If the mixture is in the compacted state when the hydration of the CaO takes place, a greater degree of cementation takes place between the fly ash and the sand. However, if the CaO in the fly ash of the mixture is allowed to hydrate while the mixture is in the uncompacted state, the cementation which does take place is of no benefit. When the reacted mixture is compacted, the bonded particles are broken up.

The CaO is hydrated so quickly once water is added that a delay in compaction of only 15 minutes results in a reduction in strength of 67%. A 50% reduction in strength is observed after only two minutes delay in compaction. Field compaction is difficult, if not impossible, to achieve within even 15 minutes after mixing.

Although TMP does hinder the hydration of the CaO in the fly ash somewhat, this additive does not significantly improve the "delayed" strength of the mixture.

The addition of salt to the soil-fly ash mixture counteracts the effects of delayed compaction considerably. After a one-hour delay in compaction, a reduction in strength of only 20% was observed. However, the effect of salt on the long-term strength of the soil-fly ash mixture is not known.

COSTS

The cost of using fly ash depends on the initial cost of the ash, the hauling cost to the job and the cost of placement at the job. In order to be useful, a cost comparison between fly ash and the alternatives of lime and portland cement will be made.

The fly ash at the power plant will cost very little and will probably be free. Lime costs $26.50 per ton and portland cement costs $32.30 per ton at the point of manufacture.

Lime and portland cement must be hauled in covered trucks and, therefore, will cost approximately 2.5 cents per ton mile. It can be safely assumed that the haul cost for fly ash would not be more than for lime or portland cement. Furthermore, the placement cost of each of the materials at the job would be approximately the same.

The quantity of fly ash used for a particular soil stabilization job would be larger than the quantity of either lime or portland cement. Fly ash stabilization usually requires 10-20% by weight as compared to 3-8% for lime and 4-10% for portland cement. Therefore, fly ash would cost approximately 2.7 times as much to haul as lime and approximately 2.1 times as much as portland cement.

Considering the cost of lime and portland cement and the high hauling cost of fly ash, it appears that fly ash can be hauled over 300 miles and be competitive with lime and over 500 miles and be competitive with portland cement.

CHAPTER 6

CONCLUSIONS

The following are conclusions based on a study of a Western low sulfur coal fly ash.

1. The fly ash under study generates heat when mixed with water and has self-hardening properties.
2. Fly ash effectively stabilizes sand and organic clay soils when compacted immediately after mixing.
3. Lime improves the early strength and rate of strength gain in sandy soil fly ash mixtures.
4. Strength development of soil fly ash mixtures takes place rapidly up to 30 minutes. A small time delay in compaction substantially reduces the effectiveness of the fly ash to stabilize soils.
5. Salt retards the soil-fly ash reaction.
6. Due to the low cost compared to lime or portland cement, fly ash can be hauled from 200 to 500 miles and still be a competitive soil stabilizing agent.

Appendix I

Tests Used to Determine Properties of the Materials

1. Grain size analysis of soils - ASTM Standard Method of Test for Particle-Size Analysis of Soils, D 422-63.

2. Soil plasticity - ASTM Standard Method of Test for Liquid Limit of Soils, D 423-66 (Reapproved 1972), ASTM Standard Method of Test for Plastic Limit and Plasticity Index of Soils, D 424-69 (Reapproved 1971), and ASTM Standard Method of Test for Shrinkage Factors of Soils, D 427-61 (Reapproved 1967).

3. Moisture content determinations - ASTM Standard Method of Test for Laboratory Determination of Moisture Content of Soils, D 2216-71.

4. Organic content of soils (used two methods) - (a) ASTM Standard Method of Test for Moisture, Ash, and Organic Matter of Peat Materials and (b) Method of test described by Arman and Munfakh, 1970, p. 18. The organic content of the soil as determined by method (b) is determined by placing a 50 gm. sample of oven-dried soil in an oven heated to 450° C. The sample remains in this oven for 6 hours and then the organic content is calculated by:

$$\text{Organic content (\%)} = \frac{\text{wt. loss} \times 100}{\text{Total dry wt.}}$$

5. Specific gravity of soils - ASTM Standard Method of Test for Specific Gravity of Soils, D854-58 (Reapproved 1972).

6. Minimum density of sand and fly ash - ASTM Standard Method of Test for Relative Density of Cohesionless Soils, D 2049-69.

7. Pozzolanic activity index of fly ash-ASTM Standard Specification for Blended Hydraulic Cements, section 7.16, C 595-73 except that the hydrated lime used throughout the investigation was used in place of reagent grade calcium hydroxide.

8. Water soluble fraction of fly ash - ASTM Standard Specification for Fly Ash and other Pozzolans for Use with Lime, C 593-69.

9. Loss on Ignition of fly ash - ASTM Standard Methods of Sampling and Testing Fly Ash for Use as an Admixture in Portland Cement, C 311-68.

10. Wet sieve analysis of fly ash, lime, and brown mud - ASTM Standard Method of Test for Amount of Material in Soils Finer than the No. 200 (75-um) Sieve, D 1140-54 (Reapproved 1971). This method was employed for each of the sieve sizes used.

11. Specific gravity of the fly ash and lime-ASTM Standard Methods of Sampling and Testing Fly Ash for use as an Admixture in Portland Cement, C 311-68.

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