Use of Flyash with Portland Cement for Stabilization of Soils

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This paper presents the results of a laboratory investigation of soil stabilization with portland cement and flyash. The flyash was used as a partial replacement for portland cement or as an additive to mixtures already meeting the requirements of soil-cement. Seven-day, 28-day and 120-day unconfined compressive strength results were used as criteria for evaluating the soil-cement-flyash mixtures.

As an additive to soil-cement mixture, flyash increased the 120-day unconfined compressive strength of sand-cement mixtures. Similar effect was observed with friable loess-cement-flyash mixes containing amounts of cement equal to or higher than the soil-cement requirement.

In the case of plastic loess and alluvial clay little strength gain was realized with flyash as an additive. However, 120-day strength results show that shrinkage cracking in clay-cement mixes is appreciable reduced by the addition of flyash. Addition of flyash to soil-cement mixtures of friable loess did not improve the freeze and thaw resistance of the mixtures.

A part of the cement can be replaced with flyash in soil-cement mixtures of friable loess-cement without loss of strength. The replacement of cement with flyash resulted in reduction in strength of the clay-cement flyash mixes except at 120-days, where strength remains higher due to reduced shrinkage cracking.

An attempt is made to interpret test results on the basis of pozzolanic activity with the lime liberated during cement hydration.

● ONE OF THE MOST common methods of soil stabilization in use today is with portland cement. In this method pulverized soil is mixed with a predetermined amount of cement (water is added during mixing if the moisture content is less than required for compaction) and the mixture is shaped, compacted and moist-cured. The resulting product is "soil-cement," this term implying that the mixture is designed to meet specifications of strength and durability established by the Portland Cement Association (1). Soil-cement, properly designed and constructed, has a world-wide record of satisfactory field performance as a base course material for roads and airfields

Despite the commendable performance record of soil-cement, there is still room for improvement in its properties and in its economy of use, particularly with silty and clayey soils. Property improvements to be desired include decreased shrinkage and permeability and increased resistance to freezing and thawing. A reduction of of the cement requirement without sacrificing needed strength and durability is desirable from the standpoint of both cost and the limited availability of cement in many areas during the last few years. The possibility of using flyash to improve the properties and/or economy of soil-cement was suggested by the extensive use of flyash in concrete for these purposes.

Flyash in Concrete

Flyash is the most commonly used commercial pozzolan[1]. It is collected in large

[1] A pozzolan is defined in ASTM Standard Definition of Terms Relating to Hydraulic

TABLE 1

BRIEF DESCRIPTION OF SOILS USED

	Friable loess (Lab. No. 20-2 (V)	Plastic loess (Lab. No. 44A-1)	Alluvial clay (Lab. No. A1-1)	Dune sand (Lab. No. S-6-2)
Location	Harrison County, SW Iowa	Page County, SW Iowa	Woodbury County, W Iowa	Benton County, E Iowa
Geological description	Wisconsin age friable loess, oxidized Thickness over 100 ft.	Wisconsin age plastic loess, oxidized Total thickness 15-20 ft.	Recent backswamp clay from Missouri River. Thickness undetermined.	Wisconsin age eolian sand, fine-grained oxidized. Thickness over 20 ft.
Soil series	Hamburg	Marshall	Luton	Carrington
Horizon	C	C	A-C	C
Sampling depth	39 - 40 ft	4 - 5 ft	0 - 3 ft	1½ - 16½ ft

quantities from the smoke in power plants burning powdered coal. Being a waste product flyash is cheap, which explains the widespread interest in utilizing it in concrete, especially as a partial replacement for the more expensive portland cement. Flyash contributes to strength in concrete by reacting with the lime and alkalies liberated by the hydrating cement to produce a gel, perhaps similar to the gel formed by the hydration of portland cement. Since the pozzolanic cementation develops more slowly than cementation from portland cement hydration, 28 days or longer may be required to compensate for the initial strength loss in concrete due to replacing part of the cement with flyash; the strength eventually may exceed that of concrete without flyash (3, 4). According to published reports (3, 4, 5, 6) the following benefits to properties of concrete, particularly mass concrete, may be obtained when flyash is used to replace a portion of either the cement or sand: improved durability, workability and resistance to sulfate attack; decreased permeability, shrinkage, bleeding, evolution of heat and segregation of aggregates; reduced expansion from the reaction between alkalies of the cement and certain types of aggregates. Some of these benefits are desirable for soil-cement.

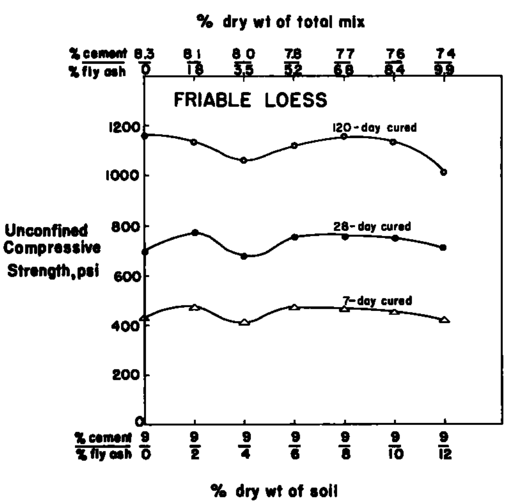

Figure 1. Effect of flyash additives to friable loess-cement on immersed unconfined compressive strength, when the portland cement content is near the minimum requirement for soil-cement.

Purpose of Investigation

Although the use of flyash in portland cement concrete has been extensively investigated, there is little published material available on its use in soil-cement other than the brief report by Baker (7) on the limited studies made by the West Virginia State Road Commission. The purpose of the present laboratory investigation was to explore the possibility of benefiting portland cement stabilization of sandy, silty and clayey soils by using flyash either as a partial replacement for portland cement or as an additive to the soil-cement mixture. Unconfined compressive strength and resistance to freezing and thawing were used as the principal criteria of improvement.

MATERIALS USED

Soils

A description and the properties of the

Cement (2) as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

TABLE 2

PROPERTIES OF SOILS USED

	Friable loess	Plastic loess	Alluvial clay	Dune sand
Textural composition, %[a]				
Gravel (>2.0 mm)	0	0	0	0
Sand (2.0 - 0.074 mm)	0.4	0.2	1.5	95.8
Silt (74 - 5μ)	82.6	58.0	24.2	1.2
Clay (<5μ)	17.0	41.8	74.3	3.0
Colloids (<1μ)	12.3	31.0	55.1	2.9
Predominant clay mineral[b]	Montmorillonite and illite	Montmorillonite and illite	Montmorillonite and illite	Montmorillonite and illite
Probable predominant exchangeable cation	Calcium	Calcium	Calcium	Calcium
Specific gravity, 25 C/4 C	2.68	2.72	2.65	2.65
Chemical properties				
Cat. ex. cap., m.e./100 gm[c]	13.4	28.2	39.4	1.5
Carbonates,[d] %	10.2	0.8	2.3	1.4
pH	7.8	6.2	7.3	7.4
Organic matter, %	0.2	0.5	1.7	0.17
Physical properties				
Liquid limit, %	32.9	53.1	71.0	91.0
Plastic limit, %	21.1	25.7	24.5	-
Plasticity index	11.8	27.4	46.5	N.P.
Shrinkage limit, %	28.3	19.9	10.2	-
Centrifuge moist. equiv., %	15.2	21.3	38.4	-
Classification				
Textural[e]	Silty clay loam	Silty clay	Clay	Sand
Engineering (AASHO)	A-4(8)	A-7-6(18)	A-7-6(20)	A-3(0)

[a] Dispersed by air-jet with sodium metaphosphate dispersing agent
[b] From differential thermal analysis of fraction passing No. 200 sieve.
[c] Fraction passing No. 40 sieve.
[d] From differential thermal analysis.
[e] Textural classification is based on former Bureau of Public Roads system (8, p. 18) except that sand and silt sizes are separated on No. 200 sieve (0.074 mm).

four soils used in the investigation are given in Tables 1 and 2. The samples are typical of major fine-grained soil types in Iowa. The most detailed studies were with the friable loess; the plastic loess, alluvial clay and dune sand were used to obtain some test results with different textural types.

Portland Cement and Flyash

Fresh samples of portland cement and flyash were used. Chemical composition and physical property data are given in Table 3.

Portland Cement. The cement was marketed as Type I, the type commonly employed in soil-cement construction. It may be classed as medium-alkali cement (equiv. Na_2O = 0.49%); the tricalcium silicate content of the cement was 53 percent. Tricalcium silicate content is related to the amount of lime liberated during cement hydration, the more tricalcium silicate the more lime that should be available to react with a pozzolan. Type I and Type II cements contain more tricalcium silicate than Type IV. According to Davis (9) a larger replacement of cement by a pozzolan may be made when Type I or Type II cement is used than when Type IV is used. Brink and Halstead (6), working with cement-flyash mortars, found evidence that the alkali in the cement accelerates the pozzolanic reaction at earlier ages, whereas at later ages the amount of tricalcium silicate in the cement governs the benefits derived from the addition of flyash to the mortar.

Flyash. The most reliable criteria for judging the quality of flyash for use as a pozzolan in concrete appear to be the loss on ignition[2] of the flyash and the fineness

[2] Approximately equal to carbon content.

TABLE 3

CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF THE PORTLAND CEMENT AND FLYASH

	Portland Cement[a] (Type I)	Flyash[b]
Chemical composition, %		
Silicon dioxide	21.8	41.9
Aluminum oxide	4.9	22.5
Ferric oxide	2.7	25.8
Calcium oxide	64.3	2.7
Magnesium oxide	2.2	1.0
Sulfur trioxide	2.2	0.8
Loss on ignition	1.0	3.6
Sodium oxide	0.21	0.3
Potassium oxide	0.41	-
Total equiv. alkalies as Na_2O	0.49	-
Insoluble residue	0.3	-
Free calcium oxide	1.0	-
Computed compound composition, %		
Tricalcium silicate	53.0	-
Dicalcium silicate	-	-
Tricalcium aluminate	8.3	-
Physical properties		
Specific gravity	-	2.61
Specific surface (Wagner), sq cm/g	1816	-
Specific surface (Blaine), sq cm/g	-	2720
Passing No. 325 sieve, %	-	88.7
Autoclave expansion, %	0.114	-
Time of setting (Gillmore test)		
Initial, hr	3.0	-
Final, hr	6.5	-
Compressive strength (1.2.75 mortar)		
At 3 days, psi	1815	-
At 7 days, psi	2525	-
At 28 days, psi	4000	-
Mortar air content, %	5.0	-

[a] Hawkeye Portland Cement Company, Des Moines, Iowa.
[b] Detroit Edison Company, St. Clair Power Plant, Detroit (St. Clair), Michigan.

of the flyash as measured by the amount passing the No. 325 sieve (6). The St. Clair Power Plant flyash is representative of what presently is considered good quality flyash.

METHODS USED

Cement Requirement

The minimum percentage of portland cement required for each of the soils to meet PCA criteria for soil-cement was determined by the ASTM standard test procedures (ASTM Designations: D558-44, D559-44, D560-44).

Mixing and Molding

Soil-cement-flyash mixes were proportioned and mixed dry; then optimum water content for maximum standard Proctor density was added and the materials were machine-mixed for 4 minutes.

Two-inch diameter by 2-in. high specimens for unconfined compressive strength tests were prepared at approximate standard Proctor density with a double plunger drop-hammer molding apparatus. Four-inch diameter by 4.6-in. high specimens for freezing and thawing tests were prepared with the standard Proctor compaction apparatus.

Curing

The specimens were double wrapped in waxed paper and aluminum foil to better preserve moisture and to prevent entry of carbon dioxide from the air. Curing for periods of 7, 28 and 120 days was done in a moist curing room at 70±3 F and a relative humidity of not less than 90 percent.

Unconfined Compressive Strength Test

At the end of the 7, 28 or 120-day curing periods, 2-in. by 2-in. specimens were unwrapped, immersed in distilled water for 24 hours and then tested for unconfined compressive strength using a load travel rate of 0.10 in. per minute. Tests were run in triplicate and average strengths reported in psi; no correction was made for the ht/diam ratio which was one.

Freezing and Thawing Test

Seven and 28-day cured 4-in. by 4.6-in. specimens were used in the freezing and thawing test which was conducted according to the ASTM standard procedure (ASTM Designation: D560-44) with the following modification: duplicate specimens were used for the loss on brushing measurements, and volume change was not determined.

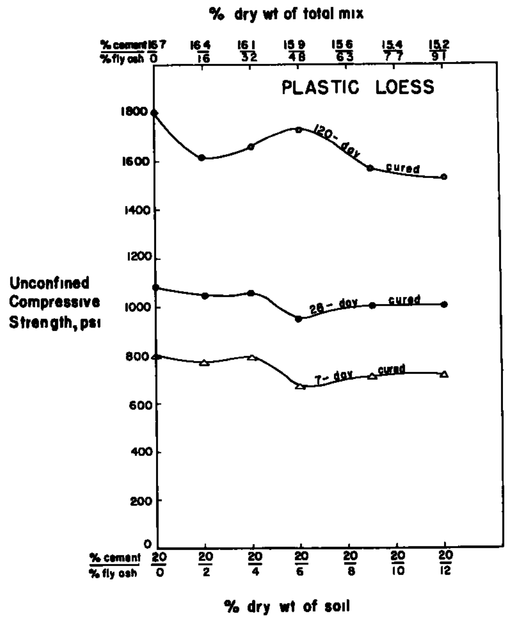

Figure 2. Effect of flyash additives to plastic loess-cement on immersed unconfined compressive strength, when the portland cement content is near the minimum requirement for soil-cement.

FLYASH AS AN ADDITIVE TO SOIL-CEMENT

As an additive to soil-cement, flyash in the amounts used may be considered mainly a replacement for the soil, with the cement content remaining nearly constant. The extent to which this is true is shown by the upper abscissa scales in Figures 1, 2, 3 and 4, where on a total mix dry weight basis the maximum replacements of cement by flyash are only 0.8 percent (friable loess) to 1.6 percent (alluvial clay). Thus the lower abscissa scales, where both cement and flyash contents are expressed as percentages of the soil dry weight, can be used to obtain an indication of the effect on strength and durability of varying flyash as an additive when the portland cement content is the minimum requirement for soil-cement. The minimum cement requirements were 9 percent for the friable loess, 20 percent for the plastic loess, 21 percent for the alluvial clay and 11 percent for the dune sand, all percentages being of the soil dry weight.

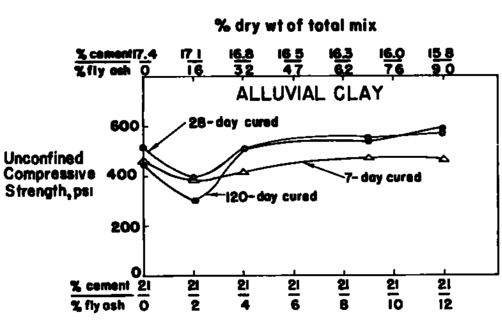

Figure 3. Effect of flyash additives to alluvial clay-cement on immersed unconfined compressive strength, when the portland cement content is near the minimum requirement for soil-cement.

Effect on Unconfined Compressive Strength

Friable Loess. Adding flyash to friable loess-cement resulted in strength gains of about 10 percent after 7 and 28 days curing, but no gain due to flyash was apparent at 120 days (Fig. 1). No additional benefit to strength was obtained with more than 2 percent flyash. The reason for the strength decrease with 4 percent flyash, which occurred at all ages, is not known;

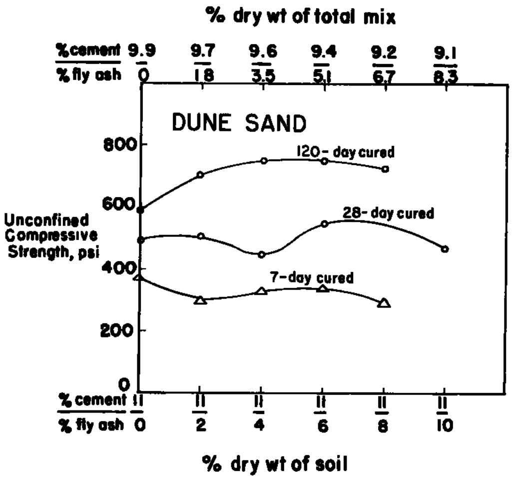

Figure 4. Effect of flyash additives to dune sand-cement on immersed unconfined compressive strength, when the portland cement content is near the minimum requirement for soil-cement.

but the decreases with 10 percent and 12 percent flyash probably reflect decreas- in portland cement content (see upper abscissa scale).

The strength gains are attributed to cementation products resulting from the pozzolanic reactions between the flyash and the lime and alkalies liberated by the hydrating portland cement, as discussed previously. With friable loess and the amount of cement used, evidently only a small amount of flyash (about 2 percent) is needed to obtain maximum strength gain from pozzolanic reactions. No other benefits to friable loess-cement from the use of flyash as an additive were observed. Compacted density was not significantly changed by the amounts of flyash used.

Plastic Loess. There was no indication of pozzolanic action in the plastic loess-cement-flyash mixes at 7, 28 or 120 days (Fig. 2). The slight decrease of 7- and 28-day strengths with increasing flyash content may be due either to the lubricating action of the predominantly spherical flyash particles or to the decreasing cement content (see upper abscissa scale) or to both effects. The 120-day strength data generally show the same trend as the 7- and 28-day, but the decrease in strength is considerably

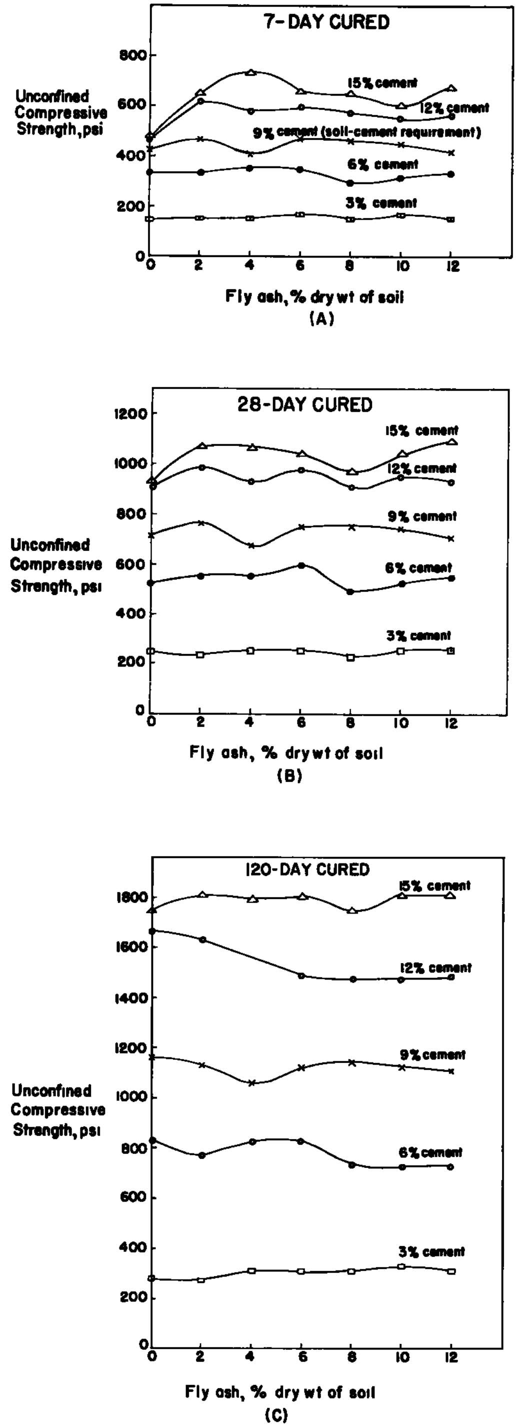

Figure 5. Effect of flyash additives to friable loess-cement on immersed unconfined compressive strength, when the portland cement content is above and below the minimum requirement for soil-cement.

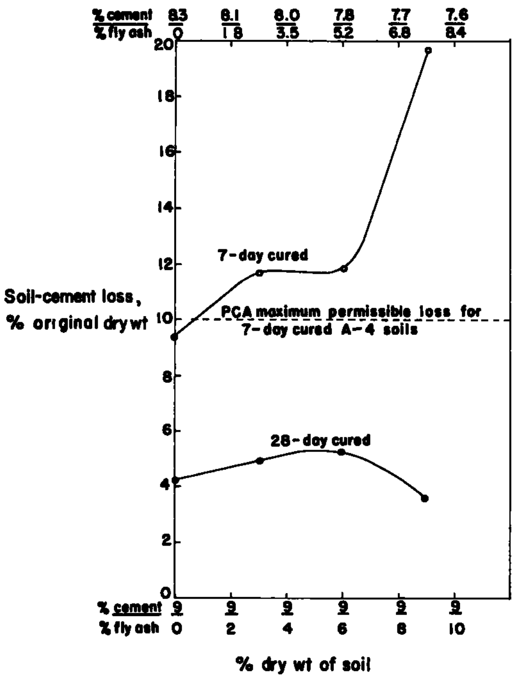

Figure 6. Effect of flyash additives to friable loess-cement on 12-cycle freeze-thaw resistance, when portland cement content is near the minimum requirement for soil-cement.

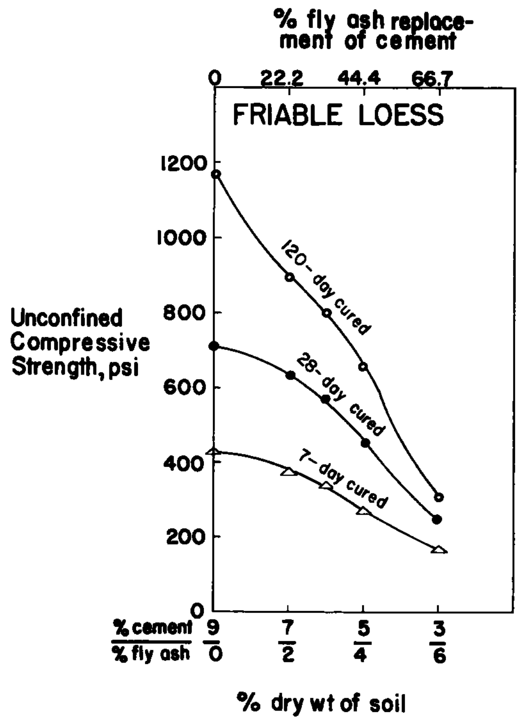

Figure 7. Effect on immersed unconfined compressive strength of partially replacing portland cement with flyash in friable loess-cement.

greater. The reason for the apparent irregularities in the curves is not known; they are not due to variation in compacted density, which was very slight.

Alluvial Clay. The strength gains attributable to flyash additives to alluvial clay-cement are mainly due to reduction of shrinkage during curing (Fig. 3). This benefit was especially evident for 120-day cured specimens; those containing no flyash were badly cracked, which is the reason the zero flyash strength is lower at 120 days than at 7 and 28 days. Four percent or more of flyash reduced cracking of 120-day cured specimens, and those containing 9 percent and 12 percent flyash showed no surface cracks. As in the case of friable loess and plastic loess, the flyash additives to alluvial clay-cement did not cause significant variation in compacted density.

Dune Sand. The most encouraging results with flyash as an additive were obtained with dune sand-cement (Fig. 4). At 120 days the strength with 4 percent to 6 percent flyash was about 28 percent greater than the strength without flyash. The beneficial effects of flyash in the dune sand-cement are attributed to two related factors: first, the flyash acted as a filler —6 percent increased the compacted density from 114.9 to 117.2 pcf; second, the flyash acted as a pozzolan and the resulting cementation was made more effective by the improvement in grain contact areas. At 7 days the lubricating quality of the flyash evidently overshadowed the beneficial effects, resulting in a net decrease in strength, but at 28 days the benefits appear and continue to increase up to 120 days.

Comparison of Benefits. The different results obtained with the four soils indicate that soil texture has an important effect on the benefits from flyash as an additive in soil-cement. Although this investigation was not extensive enough to obtain a correlation between beneficial pozzolanic activity and the clay content of soil, there is

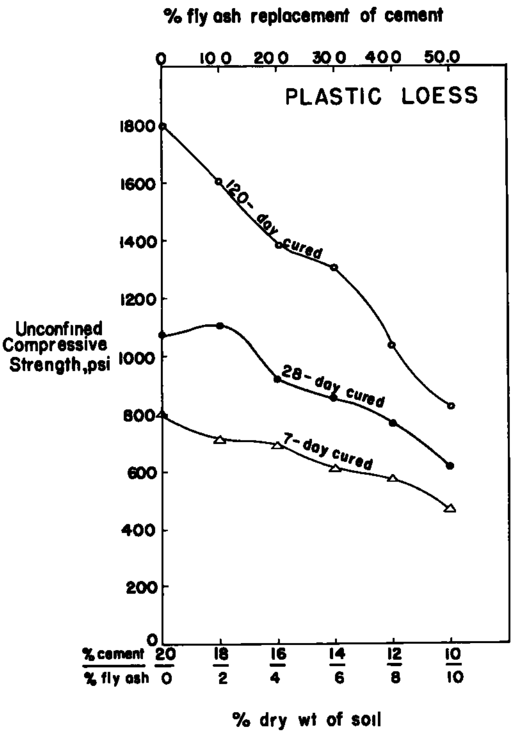

Figure 8. Effect on immersed unconfined compressive strength of partially replacing portland cement with flyash in plastic loess-cement.

evidence that such a relationship exists. In the two high clay content soils, plastic loess (41.8 percent 5 micron clay) and alluvial clay (74.3 percent 5 micron clay), there was no sign of beneficial pozzolanic reactions between flyash and hydration products of portland cement, presumably because of clay coatings on the flyash or fixation of lime by clay or a combination of both effects. In the friable loess (17 percent 5 micron clay) and in the dune sand (3 percent 5 micron clay), sufficient lime and alkalies from the hydrating portland cement were available to react with from 2 to 6 percent flyash; the best strength gains to pozzolanic reactions were obtained with the dune sand, probably because of its low clay content.

The other beneficial effects of flyash additives in soil-cement, reduction of shrinkage cracking in the alluvial clay mixes and improvement of gradation in the dune sand mixes, are also important, particularly to ultimate strength.

Influence of Cement Content. The friable loess was used to check on the beneficial effect of flyash additives when the portland cement content is above and below that required for soil-cement, in this case 9 percent. As shown in Figure 5A, at 7 days there is definite indication of increased pozzolanic action for cement contents higher than 9 percent: for 15 percent cement the strength gain due to flyash reached a maximum of 53 percent with 4 percent flyash, as compared to the 40 percent gain for 12 percent cement with 2 percent flyash, and the 10 percent gain for 9 percent cement with 2 percent flyash. For cement contents less than 9 percent there was little or no indication of pozzolanic activity. Thus it appears that with the friable loess and the Type I portland cement used, at least 9 percent cement is needed to provid sufficient lime and alkalies for significant pozzolanic reactions with flyash at 7 days. The use of larger amounts of cement resulted in the formation of more reaction products as evidenced by the greater strength gains.

The 28-day strength curves (Fig. 5B) generally display the same trends as the 7-day curves, but the strength gains from pozzolanic action are less. At 120 days (Fig. 5C) there is little or no remaining evidence of benefit to strength from pozzolanic action. The apparent decrease of pozzolanic activity with increased curing time is contrary to expectations; it will be recalled that the opposite trend was obtained in the experiments with dune sand. It may be that there was no re-

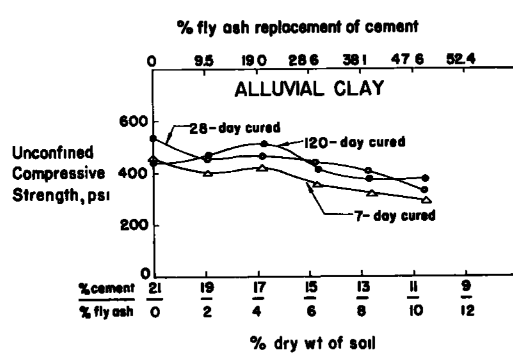

Figure 9. Effect on immersed unconfined compressive strength of partially replacing portland cement with flyash in alluvial clay-cement.

duction of pozzolanic activity at 28 and 120 days, as would appear from the data, but rather that there was interference of some sort with the normal portland cement hydration process. This of course is just a guess.

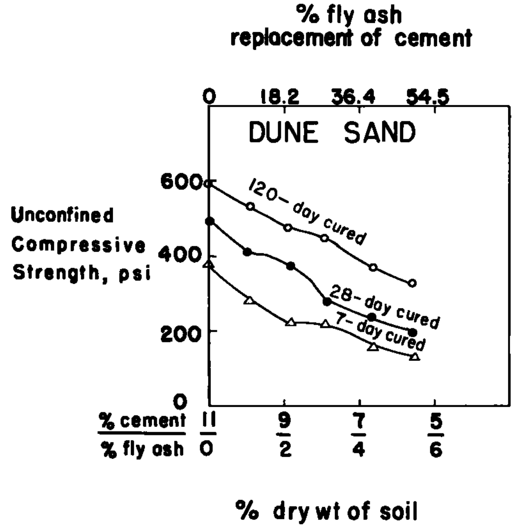

Figure 10. Effect on immersed unconfined compressive strength of partially replacing portland cement with flyash in dune sand-cement.

Effect on Freeze-Thaw Resistance

Although it is known that a relationship exists between the unconfined compressive strength and freeze-thaw resistance of soil-cement, there is always the possibility that an additive to soil-cement, such as flyash, will produce unexpected results. As a check on this, the effect of flyash on the freeze-thaw resistance of soil-cement was studied with the friable loess. To save on testing time, only the soil-cement weight-loss-with-brushing part of the standard freeze-thaw test procedure was conducted.

According to the PCA criteria for soil-cement, the maximum permissible friable loess-cement loss in weight during 12 cycles of freezing and thawing, with brushing after each cycle, is 10 percent of the original dry weight of the test specimen. As shown in Figure 6, the addition of flyash to friable loess-cement increased the 12-cycle weight losses of 7-day cured specimens to above the maximum permissible value; flyash contents greater than 6 percent appear especially detrimental, probably because of the lubricating action of the flyash and the consequent lowered resistance to brushing.

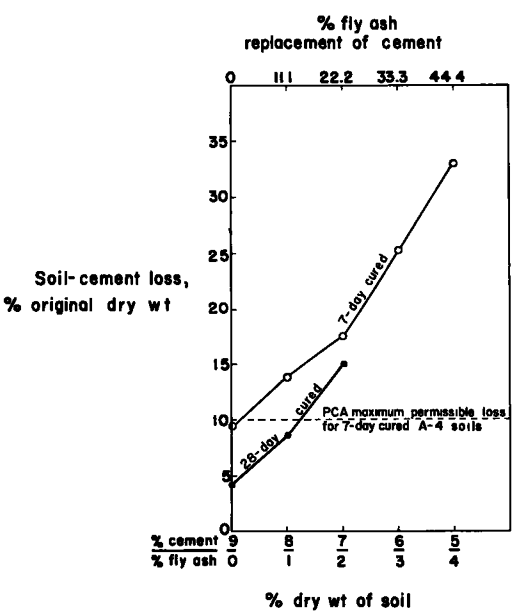

Figure 11. Effect on 12-cycle freeze-thaw resistance of partially replacing portland cement with flyash in friable loess-cement.

If the interpretation of a lubrication effect is correct, it would mean that the brushing test is relatively more severe for soil-cement-flyash than for pure soil-cement, and the results should be weighed accordingly. Brushing of course does not correspond to any expected field usage of soil-cement-flyash in base course construction, since resistance to abrasion is not required.

The weight losses of 28-day cured specimens, both with and without flyash, were considerably lower than the 7-day maximum allowable loss. Also, on the basis of the 28-day data, flyash additives to friable loess-cement appear to be much less detrimental to freeze-thaw resistance, possibly because the increased pozzolanic activity with longer curing compensated for some of the flyash lubrication effects.

FLYASH AS A PARTIAL REPLACEMENT FOR PORTLAND CEMENT

This part of the investigation was made to determine the feasibility of using flyash as a partial replacement or substitute for portland cement in soil-cement. The replacement of cement with flyash is expressed in two different ways in Figures 7, 8, 9, 10 and 11. The bottom abscissa scales show the relative percentages of cement and flyash on the basis of the dry weight of the soil; the top scales express the flyash replacement of cement as a percentage of the cement requirement for soil-cement.

Effect on Unconfined Compressive Strength

Even a cursory examination of the data trends in Figures 7, 8, 9 and 10 shows that cementation from pozzolanic reaction products does not compensate for that lost due to the reduction of portland cement content. Apparently not enough lime and alkalies are available for beneficial pozzolanic reactions with flyash when the cement content is below that for soil-cement; this conclusion is also supported by the previously discussed data in Figure 5. It is possible that replacements smaller than those tried might cause only slight loss of strength, but this possibility is of little practical interest, since it seems doubtful that flyash would be used in the field in quantities less than 2 percent of the dry soil weight.

The only definite benefit from flyash as a replacement for portland cement was observed with the 120-day cured alluvial clay-cement-flyash specimens which showed an increase in strength due to less shrinkage cracking (Fig. 9).

Effect on Freeze-Thaw Resistance

The question naturally arises, how strong does soil-cement have to be? Maybe some strength reduction is permissible providing resistance to freezing and thawing is satisfactory.

The answer for one soil, the friable loess, is evident from Figure 11. Freeze-thaw resistance at both 7 and 28 days is drastically decreased by even small replacements of cement by flyash.

CONCLUSION

In conclusion it would seem that for use in soil stabilization with portland cement, flyash is more promising as an additive than as a replacement for part of the portland cement.

The greatest benefits from flyash as an additive in soil-cement appear to be obtainable with poorly graded, low clay content soils such as dune sand, in which improvement in strength is the result of more surface contact areas and complimentary cementation from pozzolanic reaction products.

Flyash, both as an additive and as a partial replacement for cement, was observed to reduce shrinkage cracking during curing of portland cement stabilized highly plastic clay soil. Whether sand or other relatively inert material would have been equally effective was not determined.

ACKNOWLEDGMENT

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Discussion

L. T. NORLING, Soil-Cement Bureau, Portland Cement Association, Chicago — Davidson's paper adds much needed information on the effect of adding flyash to soil-cement mixtures.

It is significant that no beneficial pozzolanic reaction due to addition of flyash as an admixture was obtained for the plastic loess and alluvial clay, and only slight benefit was obtained in some instances for the friable loess soil. Similar results were reported by A. A. Lilley in the Cement and Concrete Association, London, England, Technical Report TRA/158, October, 1954. Lilley reports that flyash does not contribute to the strength of a cohesive soil or soil-cement mixture. The compressive strengths were proportional to the percentage of cement in the mixture.

Some increase in compressive strength, particularly after 120-day cure, was obtained by Davidson for a dune sand soil. As he points out, the benefit is due to the flyash acting as a filler and possibly to some pozzolanic action. It may be pointed out that the addition of a friable silty or clayey soil to the dune sand would also act as a filler and may increase the compressive strength to the same degree as the flyash admixture did. On most soil-cement projects the friable borrow soil could be obtained at less cost than the flyash.

The reduced resistance of the friable loess to freezing-and-thawing reported by Davidson is particularly significant. Exploratory tests run in the Portland Cement Association Soil-Cement Laboratory gave similar results. For example, the addition of 6.2 percent flyash by weight of soil to a clay soil-cement mixture (PCA Soil No. 5787) almost doubled the losses due to freezing and thawing. In similar tests on a gravelly soil-cement mixture (PCA Soil No. 5773), losses were doubled by the addition of 2.5 percent flyash by weight of soil. In both these instances the higher losses were due to softening of the specimen and not to abrasion of the brush.

Davidson's paper shows the detrimental effects of adding flyash as a partial replacement for cement in soil-cement work. Compressive strengths were lowered appreciably for each of the four soils tested and the resistance of the friable loess to freezing and thawing was decreased drastically. (Freeze-thaw tests were not run on the other three soils.) This is in agreement with the work reported by Lilley and with exploratory tests run in the Portland Cement Association's Soil-Cement Laboratory.

In summary, the data in Davidson's paper show that flyash cannot be used as a partial replacement for cement in soil-cement. Compressive strengths were lowered and the resistance to freezing and thawing was reduced drastically. The data show that the addition of flyash as an admixture may be practical or economical in soil-cement work where a filler is beneficial such as in the case of dune sands. However, benefit may also be obtained by adding a friable silty or clayey soil as a filler or by adding a small additional amount of cement.