Fly Ash and Sodium Carbonate as Additives To Soil-Cement Mixtures

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Although the use of fly ash in mass concrete and in lime stabilization has been extensively investigated, there has been relatively little work done on its use in soil-cement stabilization. Apparently there is no published material available on the use of sodium carbonate in soil-cement-fly ash mixtures.

In this investigation, three soils (a dune sand, a friable loess, and an artificial sand-loess mixture) were studied. Three fly ashes from three different sources were used. The cement was Type I and the sodium carbonate was reagent grade.

It was found that fly ash could be used as an additive to, or as a replacement for, cement in friable soil-cement mixtures. The smaller the loss on ignition and the finer the particle size of the fly ash, the more useful it is as an additive or replacement; however these criteria are not in themselves sufficient to fully differentiate between the varying qualities of the fly ashes. For each fly ash there appears to be an optimum ratio of cement to fly ash. The advantages of fly ash are mainly reflected in long-term strengths. The addition of fly ash tends to retard the setting-up of soil-cement mixtures, thus allowing more time for mixing and compacting. The beneficial effects of the addition of sodium carbonate are most noticeable after short curing periods. Sodium carbonate can be detrimental over a long period of time to soil-cement and soil-cement-fly ash mixtures containing low cement contents.

•SOIL-CEMENT, where properly designed and constructed, has an enviable record as a reliable base course material. Nevertheless, as with all materials of construction, there is still some room for improvement in its properties and in its economy of use. A reduction in the cement requirement, without sacrificing needed strength and durability, is desirable from many view points.

The main objective, therefore, was to explore the possibility of benefiting soil-cement stabilization by using fly ash as an additive to, or as a replacement for, the cement. In addition, selected mixes were treated with a trace chemical (sodium carbonate) to determine its effect on the strength properties of soil-cement and soil-cement-fly ash.

BACKGROUND

Fly ash is the fine, gray, dust-like ash collected in power plants that burn powdered coal. As the finely divided pulverized coal is burned, particles of the ash are suspended in the gas stream and collected on the plates of electrostatic or on mechanical precipitators. Fly ash is available in vast quantities at some industrial centers, and because it is a waste product, it is low in cost.

Because of its low cost and its known pozzolanic behavior, fly ash has been widely used in concrete construction as a partial replacement for the more expensive cement (1). A pozzolanic material is one that, in the presence of moisture, will react with lime to form a cementitious compound (2). Calcium hydroxide (lime) is liberated by hydrating portland cement. This compound is believed to contribute little to the strength of the cementing action in concrete and it may in fact be leached out by percolating waters. It has been suggested, therefore, that if fly ash is present when cement is hydrating, then the fly ash will react with the liberated lime to produce supplemental cementitious compounds (1).

Although the use of fly ash in mass concrete (1, 3, 4, 5) and in lime stabilization (6, 7) has been extensively investigated, there is little published material available on its use in soil-cement stabilization. Brennan (8), working with a fine-grained soil and one fly ash, reported that a mixture containing 3 percent cement and 3 percent fly ash gave good strength improvement. Lilley (9) reported that a fly ash did not contribute to the strengths of cement stabilized cohesive soils. Davidson et al. (10) concluded that the addition of a fly ash appeared to be most beneficial with coarse-grained, poorly graded soils where strength improvements were due to improved soil gradation—resulting in more surface contact areas—and to complementary cementation from pozzolanic reaction products. The fly ash was observed to reduce shrinkage cracking during curing of a cement stabilized clay soil. Mateos and Davidson (11) found that the addition of a fly ash to mixtures of silt and cement increased strengths to a minor extent. Wright and Ray (12) added a fly ash to mixtures of three different soils and cement and concluded that fly ash can replace some of the cement.

Sodium carbonate has been found to accelerate the hardening of soil-lime-fly ash mixtures (6, 7, 11, 13, 14) and soil-cement mixtures (11, 15). Hence, it is not unreasonable to believe that it should therefore benefit the strengths of soil-cement-fly ash mixtures.

MATERIALS AND PROCEDURES

Soils

Two soils were extensively used in this investigation. One was a well-graded, high density sand-loess mix which was sampled from the blended material used in the soil-cement base of Iowa 117, north of Colfax. Because this soil was quite well graded, it was felt that any additional fly ash would not be considered as a filler material, but would instead displace soil particles. Hence, any strength increases that might occur could possibly be attributed to the supposed pozzolanic reaction. The other extensively investigated soil was a more poorly graded friable loess which is typical of that found in eastern Iowa.

In addition, a typical eastern Iowa dune sand was used in a preliminary evaluation of the effects of fly ash and sodium carbonate in soil-cement stabilization. A field description and some physical and chemical properties of each soil are given in Table 1.

Cement and Fly Ashes

Type I portland cement, which is the type commonly used in soil-cement construction, was used in this investigation. According to Davis (3), a larger replacement of cement by a pozzolan can be made when Type I or Type II cement is used instead of Type IV. The tricalcium silicate content of a cement is believed to be directly related to the amount of lime liberated during the cement hydration, and Types I and II cements contain more tricalcium silicate than Type IV. The analysis of the portland cement is given in Table 2.

Because fly ashes differ greatly with respect to their physical and pozzolanic properties, three different types of fly ash from three different sources were selected for this study. Their properties and descriptions are given in Table 3. The choice of the fly ashes was made on the basis of a previous study on the reactivity of different fly

TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF TEST SOILS

Property	Sand-Loess (Colfax mix)	Friable Loess (100-8)	Dune Sand (S-6-2)
Geological description	Mix of approximately 82% waste sand from hydraulic gravel dredging operations and 18% Wisconsin-age loess, oxidized, calcareous, medium plastic	Wisconsin-age loess oxidized, calcareous, friable	Wisconsin-age eolian sand, fine-grained, oxidized
Source (Iowa)	Jasper Co.	Scott Co.	Benton Co.
Soil series	Tama (loess)	Fayette	Carrington
Horizon	C (loess)	C	C
Sampling depth (ft)	Stock pile (sand), borrow pit (loess)	25-25 1/2	6-11
Textural composition (%):			
Gravel (<2mm)	0.0	0.0	0.0
Sand (2.0-0.074 mm)	70.7	2.8	94.4
Silt (0.074-0.005 mm)	22.3	85.2	1.6
Clay (<0.005mm)	7.0	12.0	4.0
Colloids (<0.0001 mm)	6.0	8.9	3.5
Predominant clay mineral	Montmorillonite, vermiculite	Montmorillonite	Montmorillonite, illite
Chemical properties:			
Cation exchange cap.[a] (meq/100 g)	11.0	3.8	--
Carbonates (%)	11.6	20.0	0
pH[b]	8.0	--	6.5
Organic matter (%)	0.2	0.2	0.1
Physical properties:			
Liquid limit (%)	19	27	N. P.
Plastic limit (%)	16	20	N. P.
Plasticity index	3	7	N. P.
Classification:			
Textural[c]	Sandy loam	Silty loam	Sand
Engineering (AASHO)	A-2-4	A-4(8)	A-3(0)

[a]For fraction passing No. 40 sieve.
[b]For fraction passing No. 10 sieve.
[c]Textural classification is from triangular chart developed by U. S. Bureau of Public Roads. Sand and silt sizes are separated on No. 200 sieve (0.074 mm).

TABLE 2

PROPERTIES OF TYPE I PORTLAND CEMENT

Property	Value
Chemical composition (% by wt.):	
Silicon dioxide	21.62
Aluminum oxide	5.05
Ferric oxide	2.97
Calcium oxide	64.05
Magnesium oxide	2.90
Sulfur trioxide	2.26
Loss on ignition	0.58
Insoluble residue	0.16
Physical properties:	
Specific surface (Wagner) (sq cm/g)	1,855
Air Permeability (Blaine)(sq cm/g)	3,395
Setting time (Gillmore test) (hr):	
Initial	3.15
Final	5.15
Autoclave expansion (%)	0.120
Compressive strength (1:2.75 G.O.S.)(psi):	
At 3 days	2,269
At 7 days	3,721
At 28 days	5,625

TABLE 3

ANALYSIS OF FLY ASHES

Property	Fly Ash 1	Fly Ash 3	Fly Ash 4
Source	St. Clair, Mich.	Louisville, Ky.	C. Rapids, Iowa
Loss on ignition (%)	3.9	2.6	18.6
Specific surface, Blaine (sq cm/g)	2,820	3,226	4,550
Specific gravity	2.58	2.60	2.37
Fineness (% passing No. 325 sieve)	91.8	86.1	54.9
Chemical composition (% by wt.):			
Silicon dioxide (SiO_2)	43.5	42.5	36.2
Magnesium oxide (MgO)	0.2	0.8	0.9
Calcium oxide (CaO)	2.9	5.7	8.3
Aluminum oxide (Al_2O_3)	23.2	23.4	15.8
Iron oxide (Fe_2O_3)	24.8	20.0	16.7
Sulfur trioxide (SO_3)	0.8	2.3	1.5

ashes with lime (6). In that study fly ash 3 proved to be of very good quality, fly ash 1 of good, and fly ash 4 of poor quality when used in lime and fly ash mixtures.

Often used criteria for judging the quality of a fly ash are the loss on ignition (which is approximately equal to the carbon content) and the fineness of the fly ash as measured by the amount passing the No. 325 sieve. Using these criteria, fly ashes 3 and 1 could be considered to be of good quality and 4 to be of rather poor quality.

Trace Chemical

Although a number of chemicals are known to act as accelerators for pozzolanic reactions, sodium carbonate is believed to be one of the better, safer and more economical to use (14, 15). Sodium carbonate, reagent grade, was used in this investigation.

Mixture Proportions

In this investigation the percentages of cement, fly ash, and soil are expressed as percentages of the total dry weight of the soil, cement, and fly ash in the mix. The amount of sodium carbonate is expressed as a percentage of the total dry weight of soil, cement, and fly ash in the mixture under consideration.

In a preliminary study, specimens were first prepared which contained dune sand, 11 percent cement, and 0, 3, 6 and 9 percent fly ash 1. Specimens were also prepared that contained varying amounts of cement and fly ash but in all of these additional specimens, the total cement and fly ash content was 11 percent. All specimens were then duplicated except that ½ percent sodium carbonate was added.

Three cement contents (5, 8, and 11 percent) were used in the main studies. It was felt that these percentages would well enclose the cement requirement to meet the criteria for soil-cement. Soil-cement mixtures were first prepared without fly ash and then with fly ash contents of 3, 6, and 9 percent of each of the different fly ashes. Extra mixtures were then prepared in which ½ percent sodium carbonate was added in powder form to all soil, cement and fly ash combinations containing 5 percent cement.

Mixing and Molding

All soils were air dried, and ground with mortar and pestle to pass through the No. 10 sieve before any mixing took place. Mixing of batches was done in a Hobart kitchen mixer, model C-100, at low speed in the following sequence of operation: the dry ingredients were mixed for 30 sec, the required amount of distilled water was then added, and the batch was then mixed for 1 min. The mixture was then hand mixed for about 30 sec so as to clean the side of the mixing bowl and the paddle, after which the mixture was machine mixed for another minute. After mixing was completed, a damp cloth was placed over the bowl so as to prevent drying of the mixture during molding.

Molding of test specimens was started as soon as possible after completion of mixing. Test specimens, 2 in. in diameter by 2 ± 0.05 in. high, were compacted with the Iowa State compaction apparatus (6, 7, 10, 11, 13, 14, 16). Maximum densities obtained using this apparatus have been very closely correlated with those maximum densities obtained using the standard Proctor apparatus (16).

Numbers of Specimens

The average of three specimens was used to obtain each point on the moisture-density and moisture-strength relationship curves. When the optimum moisture content for maximum density was obtained for each soil-cement-fly ash combination, four specimens were molded at this moisture content for each curing condition. The average of these four strength values is reported.

Curing

Specimens for the main study were cured for 7, 28, and 90 days and for 7, 28, and 120 days for the preliminary investigation. The curing room was maintained at a temperature of 71 ± 3 F and a relative humidity of greater than 90 percent. To maintain the moisture in the specimens better and to reduce absorption of carbon dioxide from the air, they were wrapped in wax paper and sealed with cellophane tape before being placed in the humid room.

Strength Testing

At the end of a specified curing period, the specimens were unwrapped, immersed in distilled water for 24 ± 3 hr and then tested for unconfined compressive strength

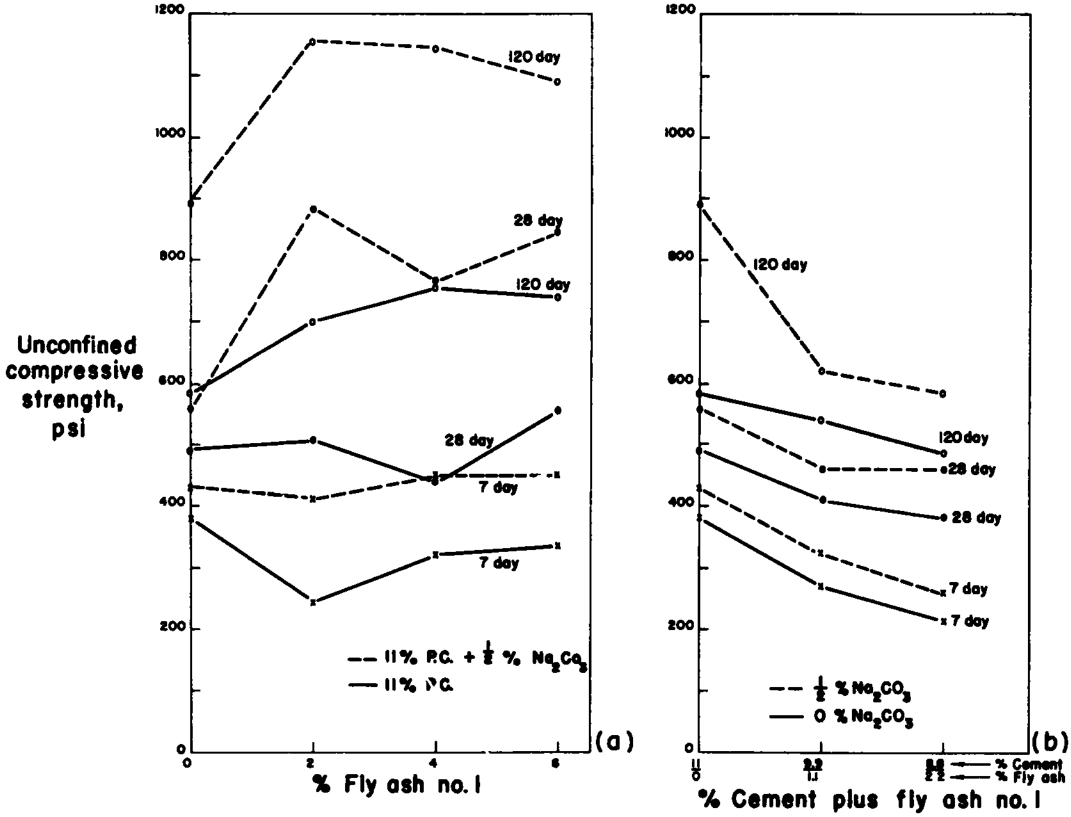

Figure 1. (a) Fly ash 1 without cement; (b) fly ash 1 with cement.

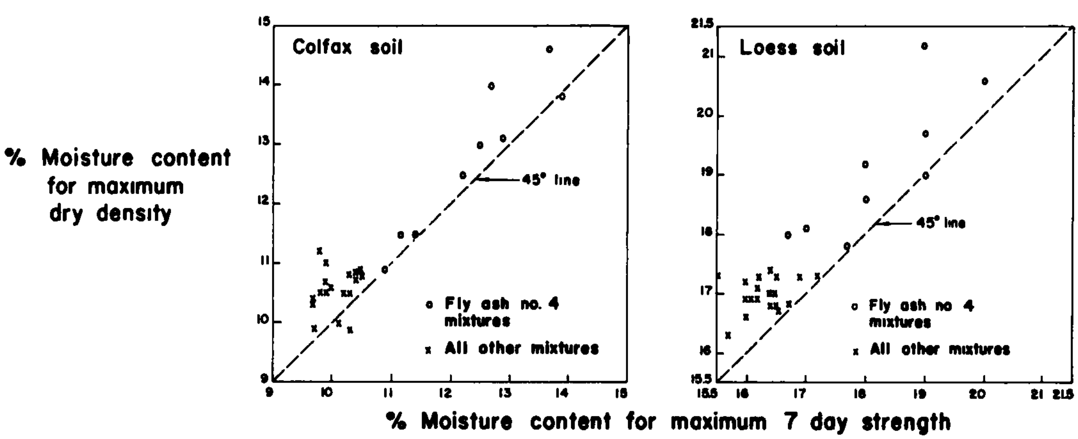

Figure 2. Comparison of optimum moisture contents for maximum densities with optimum moisture contents for maximum strengths.

using a load travel rate of 0.1 in. per min. Strength values were evaluated for reliability in a statistical manner (17) and any values which were then disqualified were not considered in determining average compressive strengths.

PRELIMINARY INVESTIGATION

Before the main study, the effect of fly ash and sodium carbonate on poorly graded dune sand-cement mixtures was investigated. In testing for the effect of fly ash as an additive, only one cement content, 11 percent, and fly ash 1 were used. Mixtures were also prepared at two lower cement contents and fly ash added until the total cement and fly ash content totaled 11 percent. All of these mixtures were then duplicated except that 0.5 percent sodium carbonate was added to each before dry mixing. Specimens were cured for 7, 28, and 120 days before testing for unconfined compressive strength.

The results obtained are shown in Figure 1 . The addition of fly ash to 11 percent cement causes decreasing strengths at 7 days (Fig 1a). At 28 days, there is perhaps a slight strength increase. After 120 days the addition of fly ash is seen to be most beneficial, the addition of 4 percent fly ash causing a 25 percent increase in strength. When 0.5 percent sodium carbonate was added to these mixtures, great increases in strength were noted. For the soil-cement mixes, increases amounted to 16 percent at 7 and 28 days and 33 percent at 120 days. Best results were obtained with 11 percent cement, 2 percent fly ash, and 0.5 percent sodium carbonate. At 7 days there was a negligible gain in strength over those mixtures containing cement alone. However, after 28 and 120 days these mixtures gave strengths that were 82 percent and 95 percent, respectively, greater than the soil-cement strengths.

Figure 1b shows quite clearly that the substitution of fly ash 1 for an equal amount of cement is not beneficial. However, this limited study indicated that there might be some ratio of cement to fly ash, with or without sodium carbonate, that might allow some economical substitution.

MAIN STUDY RESULTS

A moisture-density relationship was run for each combination of soil, cement, and fly ash. Five points were obtained on each curve, each point being the average of three specimens. After tabulation of the moisture-density data, the specimens were placed in the humid room, cured for 7 days and then tested under unconfined compression. Moisture-strength curves were then drawn for each of the soil-cement-fly ash combinations.

The optimum moisture contents for both density and strength increased as the amount of fly ash in a particular mix increased. The effect of the different types of fly ash on these optimum moisture contents is noteworthy. For a particular soil, the mixes containing fly ashes 1 and 3 had their optimum moisture contents all contained within 1.3 percentage points and this spread contained these required for the cement and soil alone (Fig. 2). On the other hand, the mixtures containing the coarsest and highest carbon content fly ash (No. 4) had a spread of 4.5 percentage points.

The optimum moisture contents for maximum 7-day strengths were consistently on the dry side of the optimum moisture content for maximum density for both the Colfax and loess soils. The reason for this is not exactly known. An interesting conjecture reasons that the difference is related to soil texture. The surfaces of such sands and silts are relatively inactive and hence little of the lubricating water is adsorbed onto the soil particles. As a result most of the water that has been added to ensure maximum density is also available for cement hydration purposes. This amount of free water may be over and above the amount required for cement hydration. In concrete work, the lower the water to cement ratio, the higher the strength. Therefore, it may be that the optimum moisture content for obtaining maximum density for a soil-cement-fly ash or soil-cement mixture is greater than the water requirements to satisfy the cementitious reaction. As a result, the optimum moisture content for maximum strength will be on the dry side of the optimum moisture content for maximum density.

In general, densities decreased as the amount of fly ash in a mixture increased. Again the different fly ashes had different effects on densities. For fly ashes 1 and 3, density decreases ranged from 1 to 4 pcf depending on the amount of fly ash used. With fly ash 4 density decreases were as much as 12 pcf. This is due to the low unit weight of this fly ash.

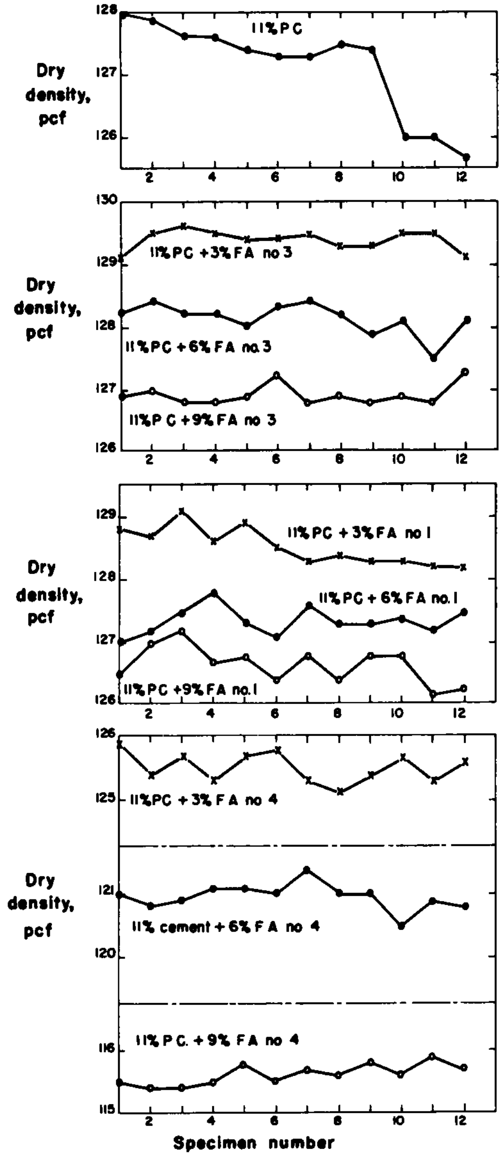

Figure 3. Effect of fly ash as a retarding agent on setting up of Colfax soil-cement mixtures—typical data.

After the optimum moisture content for maximum density was obtained for a particular mix, 12 specimens were molded at that moisture content. The strength results obtained from these specimens are discussed later. However, the effect of time on the specimen densities within a particular batch (Fig. 3) is noteworthy. The time from when moisture was first added to the dry mix until the end of the compacting of the last specimen varied from 17 to 24 min. The time from the beginning of compaction of the first specimen until the end of the last varied from 14 to 21 min. Soil mixtures containing only cement and sodium carbonate or cement alone showed definite decreasing density trends as compaction time progressed. On the other hand, the addition of fly ashes 3 and 4 apparently had the effect of retarding the setting-up of the soil-cement. The medium type fly ash (No. 1) had less of a retarding effect.

UNCONFINED COMPRESSIVE STRENGTH RESULTS

Fly Ash as Additive to Soil Cement

As mentioned earlier, 12 specimens were molded at the optimum moisture content for maximum density for each combination of cement, soil, and fly ash. After being cured in the humid room, 4 specimens were tested after 7 days, 4 after 28 days, and the remaining 4 after 90 days. The 4 specimens tested at a particular time were selected statistically to minimize differences in the time and space. The average strength results obtained are shown in Figures 4 and 5.

As expected, both the soil-cement and the soil-cement-fly ash mixtures increased in strength as curing time progressed. However, the manner in which the different fly ashes affected these strength increases was very significant.

Fly Ash 3.—This fly ash appears to be the most beneficial of the three. The 7-day strengths show the addition of the fly ash to have relatively little effect on both soils. However at 28 days, fly ash is seen to be most beneficial. Best results are obtained with the Colfax soil where the addition of 9 percent fly ash to 11 percent cement shows a strength increase of 46 percent at 28 days and of 37 percent after 90 days. With the more poorly graded loess soil, the results were not so striking, the maximum strength gains being in the range of 25 to 34 percent.

Fly Ash 1.—Again the 7-day strengths are relatively nonsignificant. Actually, for the loess soil there is a tendency towards a slight strength loss. Again at 28 days, the loess soil-cement mixtures tend to be slightly hurt by the addition of this fly ash. However, at 90 days slight strength increases of up to 15 percent are recorded as fly ash

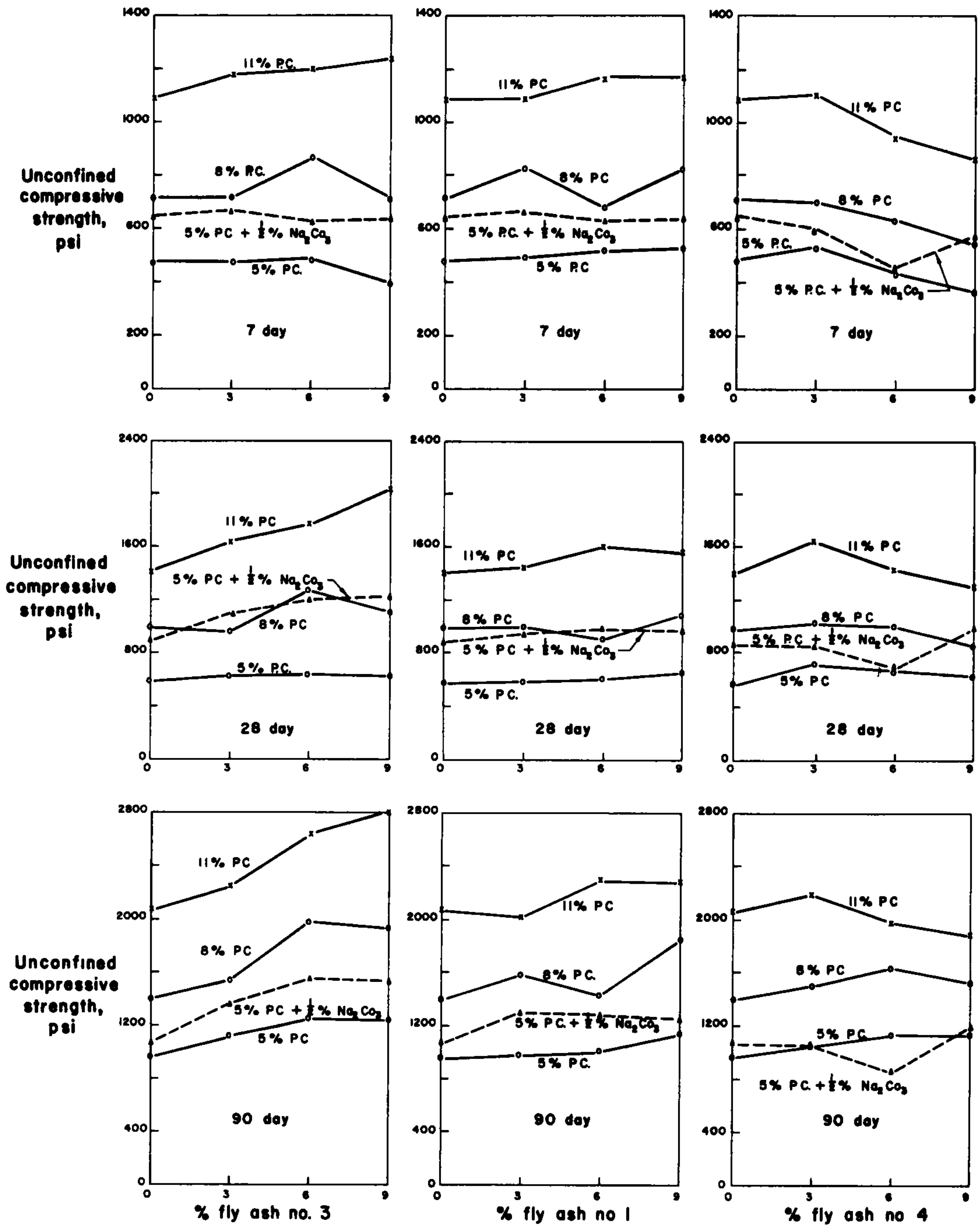

Figure 4. Strengths obtained by Colfax soil-cement mixtures containing fly ash and sodium carbonate after varying curing periods.

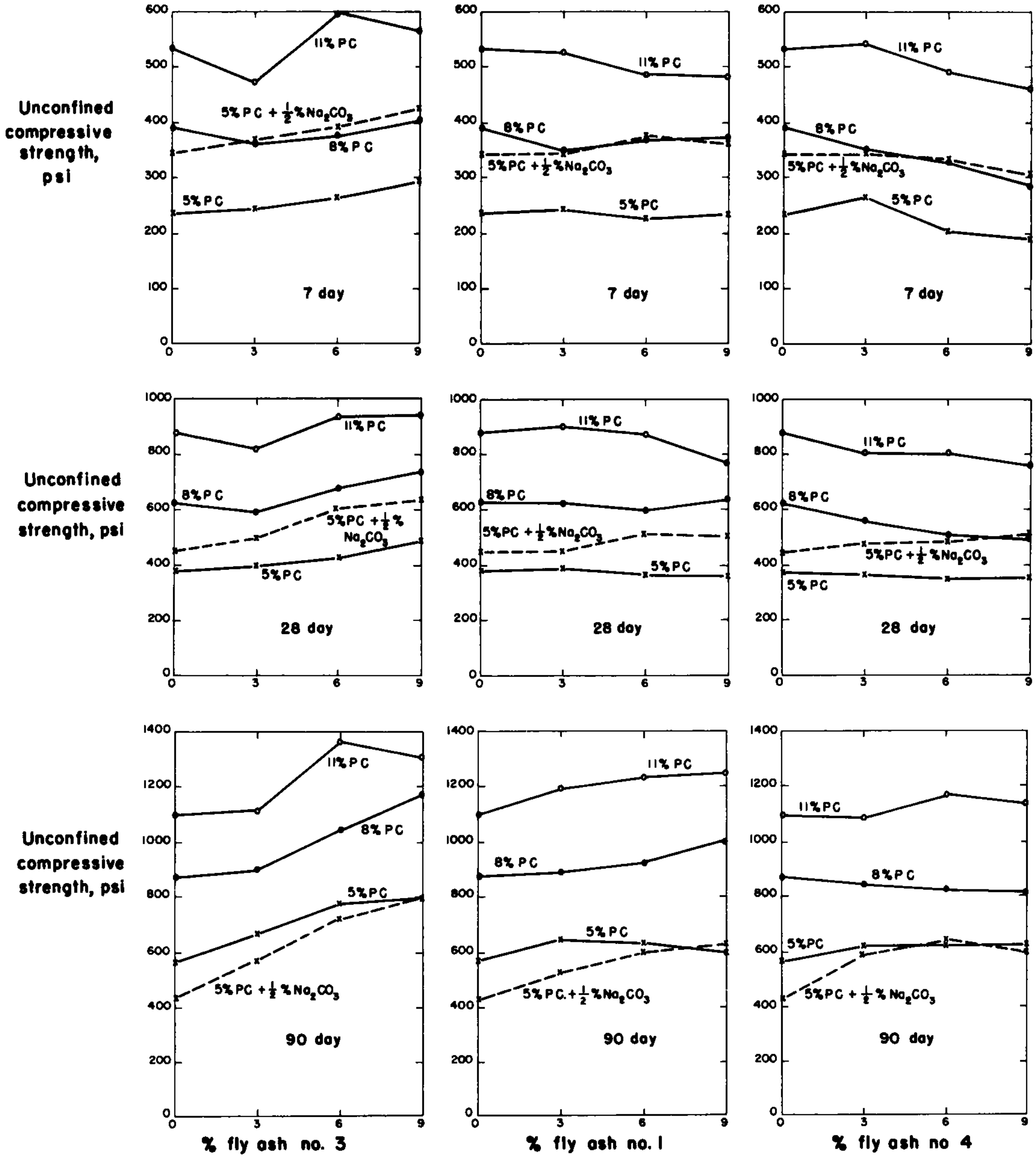

Figure 5. Strengths obtained by loess soil-cement mixtures containing fly ash and sodium carbonate after varying curing periods.

is added to the loess-cement. The Colfax mixtures show minor strength increases after 28 days. The beneficial effects of the fly ash are most noticeable after 90 days where the addition of 9 percent fly ash to 8 percent cement caused a strength increase of 31 percent. Also, fly ash 1 was sampled from the same source as that used by Davidson et al. (10) in their investigation.

Fly Ash 4.—The effects of fly ash 4 on soil-cement mixtures are very clear. Strengths at 7 days indicate quite strongly that the addition of more than 3 percent fly ash to either of the soils causes a definite decrease in strength. The 28- and 90-day strength results

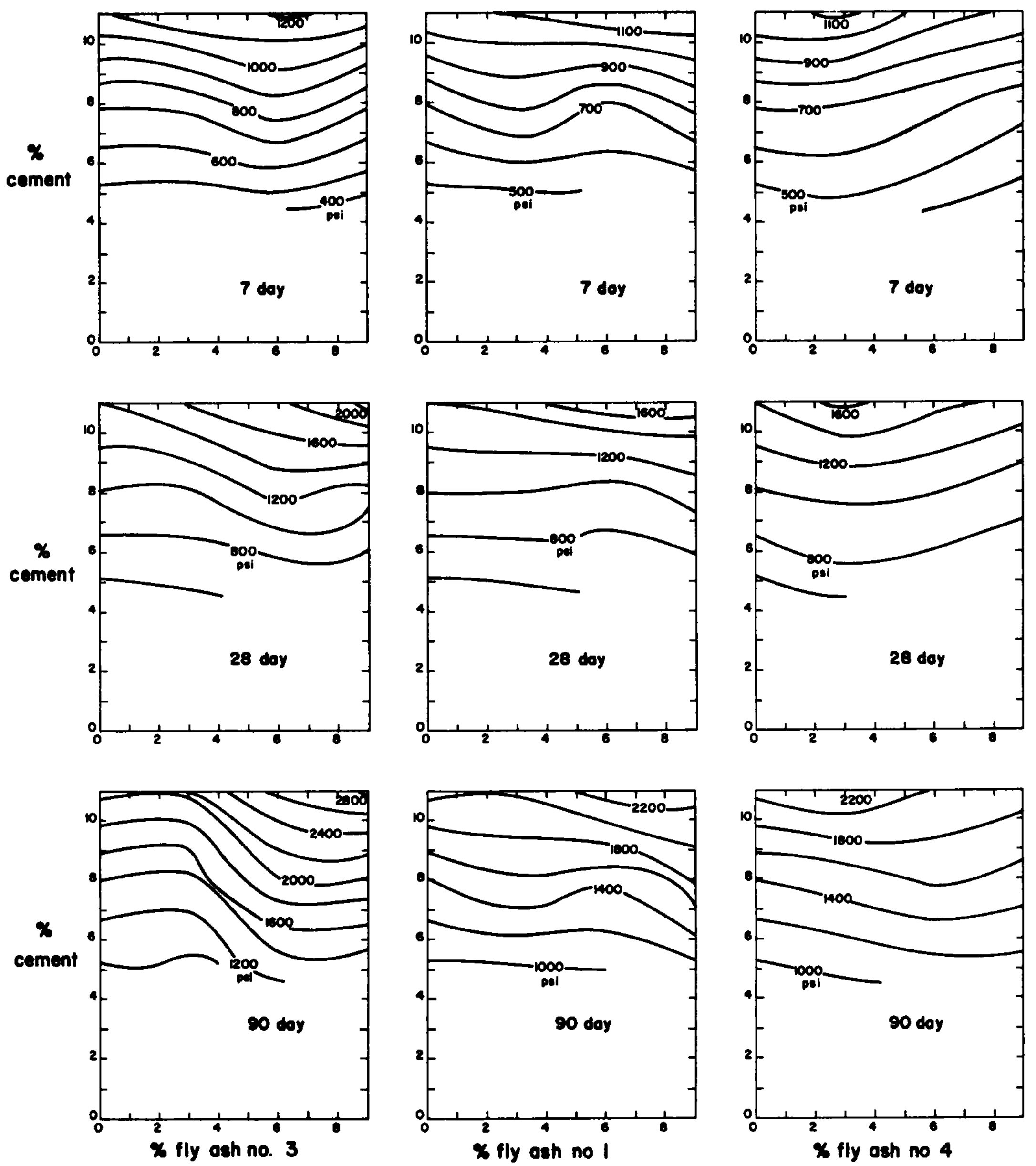

Figure 6. Iso-strength contour graphs for Colfax soil-cement mixtures containing fly ash after varying curing periods.

indicate that the addition of this fly ash to the loess-cement mixtures can be a disadvantage. With the Colfax soil, 3 to 6 percent would seem to be about optimum for beneficial results.

In summary, the addition of fly ash can be beneficial to soil-cement mixes. However, its helpfulness depends on the type of fly ash used. The smaller the loss on ignition and the finer the particle size of the fly ash, the more useful it is as an additive. Poor quality fly ash can be a detriment in soil-cement mixtures. The manner in which the different fly ashes react would seem to support the liberated lime-pozzolan reaction theory (1) because it is known that the pozzolanic activity of fly ash is dependent on its particle size and the loss on ignition.

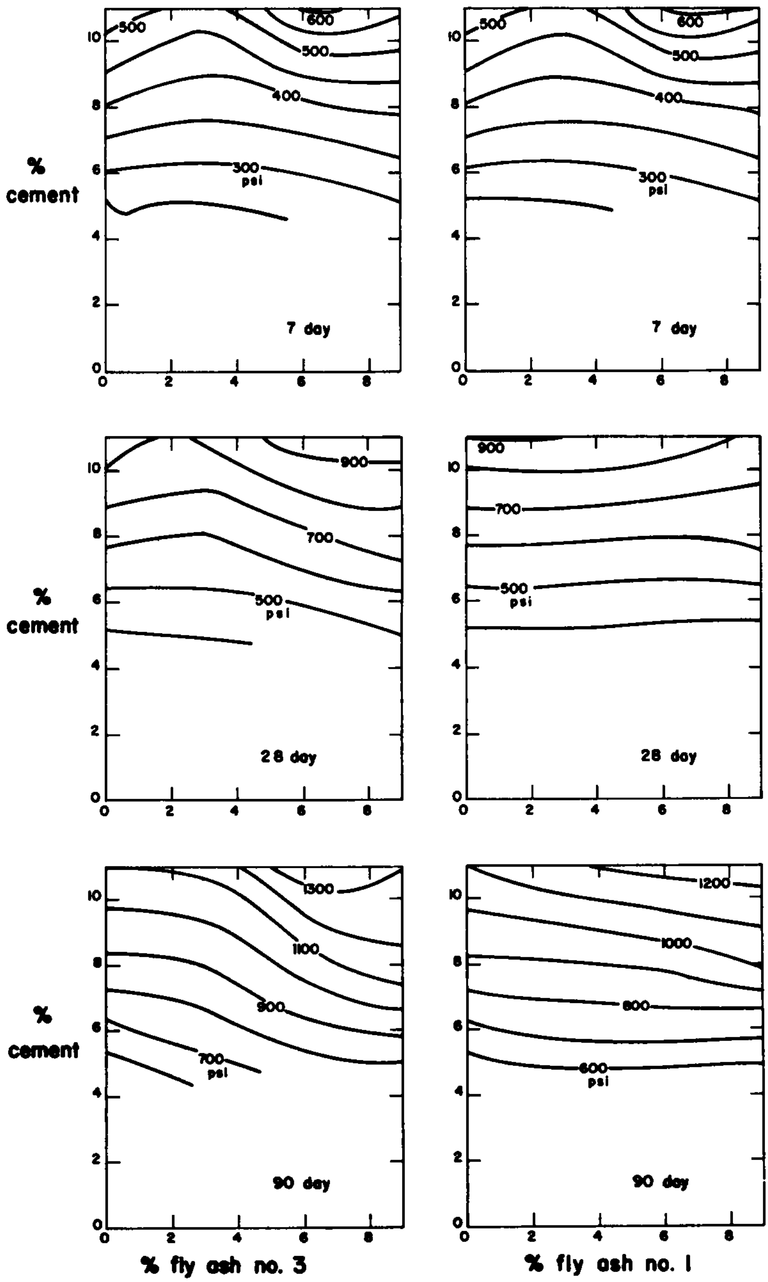

Figure 7. Iso-strength contour graphs for loess soil-cement mixtures containing fly ash after varying curing periods.

Fly Ash as Replacement for Cement

Contour graphs for the different soil, cement, and fly ash mixtures, based on the preceding strength values, are shown in Figures 6 and 7. An examination of these indicates some interesting trends.

Fly Ash 3.—For both soils a ratio of cement to fly ash of about 3:2 is optimum at 7 days. After 28 days and 90 days, and again for both soils, the best ratio is about 11 cement to 9 fly ash.

Fly Ash 1.—With the Colfax mixtures a ratio of 11 parts cement to 9 parts fly ash might again be taken as optimum for 7, 28, and 90 days. For the loess soil mixtures the results are rather inconclusive. At 7 days, a ratio of 3 parts cement to 2 parts fly ash appears best. At 28 days, a ratio of 11 parts cement to 1 part fly ash would seem to be about optimum, but the ratio again changes to 11:9 after 90 days.

Fly Ash 4.—For 7-day strengths a ratio of 4 parts cement to 1 part fly ash might be deemed optimum for the Colfax mixtures. After 28 and 90 days, the effect of the fly ash is more noticeable giving an optimum ratio of 3 parts cement to 1 part fly ash for both curing periods. Contours for the loess-cement mixtures containing this fly ash are not shown here as it is apparent from Figure 5 that the addition of this fly ash generally has a detrimental effect.

In summary, fly ash can be used to replace cement in soil-cement mixtures. Table 4 gives the amounts of cement and a particular fly ash that can be used to attain the same strength at a given time as that obtained by, for instance, 11 percent cement alone. The amount of fly ash required to replace cement to get a certain strength at a given time is variable, depending mainly on the type of fly ash, and on the soil.

Effect of Sodium Carbonate

As already indicated, optimum moisture contents for maximum density were obtained for all combinations of cement, soil, and fly ash. To all the mixtures that contained 5 percent cement and to the mixtures containing 8 and 11 percent cement but without any fly ash, 0.5 percent of sodium carbonate was added in powder form. The mixtures were then compacted at the same moisture contents as those mixtures without sodium carbonate. Unconfined compressive strengths obtained from the mixtures containing only soil, cement, and sodium carbonate are given in Table 5, and those containing soil, 5 percent cement, fly ash, and sodium carbonate are shown in Figures 4 and 5.

As can be clearly seen, the addition of sodium carbonate has varying effects on the strengths of the soil-cement and soil-cement-fly ash mixtures.

Colfax mixtures containing only cement show increases in strength of up to 32 percent after 7 days, 65 percent after 28 days, and 10 percent after 90 days when sodium carbonate is added. The loess soil-cement mixtures show increases of 44 percent after 7 days and 18.5 percent after 28 days and a decrease of about 30 percent after 90 days.

The effectiveness of the addition of sodium carbonate to soil-cement-fly ash mixtures is dependent on the type of fly ash used. The best results are obtained with fly ash 3. For instance, with the 5 percent cement-Colfax soil mixtures, the addition of 9 percent of this fly ash and 0.5 percent sodium carbonate gives a 28-day strength that is 38 percent greater than that obtained by adding only 0.5 percent sodium carbonate and 133 percent greater than with just 5 percent cement. The corresponding 90-day values are 17 and 30 percent. With the loess soil mixtures (Fig. 5) it is clearly seen that the more fly ash in the mix, the more effective is the addition of sodium carbonate. For example, when 0.5 percent is added to the mixture containing 5 percent cement and 9 percent fly ash 3, the 28-day strength is increased by 17 percent over that obtained by adding sodium carbonate to the mixture containing 5 percent cement and no fly ash, and by 68 percent over that obtained when the mixture contains no fly ash and no sodium carbonate. Again at 90 days, sodium carbonate is most effective with the mixtures containing high fly ash contents. For instance, the mixture of loess, cement, 9 percent fly ash 3, and sodium carbonate gives a strength that is 54 percent greater than that obtained by omitting the fly ash entirely. However, with this soil the addition of sodium carbonate appears to be detrimental to long-term strengths. Figure 5 shows the loess mixtures containing sodium carbonate tend to give lower strengths after 90 days than the mixtures without any sodium carbonate. The reason for this is not fully understood.

TABLE 4

AMOUNTS OF CEMENT AND FLY ASH GIVING SAME STRENGTHS AS 11 PERCENT CEMENT AFTER A GIVEN CURING PERIOD

Soil	Length of Curing (days)	Type of Fly Ash (no.)	Ratio of Cement to Fly Ash	Amount of Cement and Fly Ash to Replace 11 Percent Cement	
				% Cement	% Fly Ash
Colfax	7	3	3:2	9.9	6.6
	28		11:9	8.8	7.2
	90		11:9	8.2	6.8
	7	1	11:9	10.2	8.3
	28		11:9	9.8	8.0
	90		11:9	9.6	7.9
	7	4	4:1	10:6	2.6
	28		3:1	9.8	3.3
	90		3:1	9.6	3.5
Loess	7	3	3:2	10.2	6.8
	28		11:9	9.9	8.1
	90		11:9	8.2	6.8
	7	1	3:2	10.2	6.8
	28		11:1	10.9	0.9
	90		11:9	9.4	7.6
	7	4	--	--	--
	28		--	--	--
	90		5:3	10.4	6.2

TABLE 5

UNCONFINED COMPRESSIVE STRENGTHS OBTAINED FOR SOIL-CEMENT AND SOIL-CEMENT-SODIUM CARBONATE MIXTURES

Soil	Additive		Unconfined Compressive Strength (psi)		
	% Cement	% Sodium Carbonate	7-Day	28-Day	90-Day
Colfax	5	0	480	580	964
		1/2	645	885	1,077
	8	0	714	996	1,400
		1/2	765	1,064	1,447
	11	0	1,085	1,408	2,072
		1/2	1,262	1,857	2,465
Loess	5	0	239	381	572
		1/2	344	447	431
	8	0	396	627	879
		1/2	481	708	893
	11	0	538	880	1,097
		1/2	654	927	1,213

In summary, the addition of 0.5 percent sodium carbonate can cause great strength increases or decreases in soil-cement and soil-cement-fly ash mixtures. In certain situations, the cement requirement for soil-cement can perhaps be lowered by the substitution of a small amount of sodium carbonate. The cement requirement can be further reduced by the addition of fly ash. The type of fly ash to be used is most important. Of course, for these substitutions to be made, special attention should be paid to the design criteria, especially the length of curing time in which the desired strength must be attained.

Cost Data

If fly ash and/or sodium carbonate are to be used to the greatest advantage, it must be on a sound economical basis. Cement costs approximately $20 per ton on the site. Fly ash, being a waste product, is very low in cost, approximately $1 per ton at source. Cost of transportation of fly ash varies with job location but an average value of $4 to $5 per ton might be used. Cost of spreading and mixing the fly ash with the cement and soil will vary, depending on the amount of fly ash to be used and the equipment on the job site. Because the cost of transportation is perhaps the most prohibitive, it would seem that fly ash could be most economically used in locales near the fly ash source.

Sodium carbonate costs about $35 to $65 per ton at its source. Although this cost is relatively high, it should be kept in mind that very small amounts are required. For this reason, the cost of transportation, spreading and mixing should be very small. Sodium carbonate would seem to be used to its greatest advantage when high early strengths are required.

CONCLUSIONS

Fly ash can be used either as an additive to, or as a replacement for, cement in friable soil-cement mixtures. The smaller the loss on ignition and the finer the particle size of the fly ash, the more useful it is as an additive or replacement; however, these criteria are not sufficient in themselves to differentiate fully between the varying qualities of fly ashes. For each fly ash there appears to be an optimum ratio of cement to fly ash. The advantages of fly ash are mainly reflected in long-term strengths. The addition of fly ash tends to retard the setting-up of soil-cement mixtures, thus allowing more time for mixing and compacting. Moisture contents for maximum densities tend to the wet side of moisture contents for maximum 7-day strengths for all combinations of mixtures. The manner in which the different fly ashes reacted would seem to support the liberated lime-pozzolan reaction theory. The beneficial effects of the addition of 0.5 percent sodium-carbonate are most noticeable after short curing periods. Sodium carbonate can be detrimental over a long period of time to soil-cement and soil-cement-fly ash mixtures containing low cement contents. In certain cases, the cement requirement for soil-cement can be reduced by the addition of small amounts of the trace chemical.

The usefulness of fly ash and/or sodium carbonate as an additive to, or as a replacement for, cement in soil-cement is dependent on the available curing time in which the design strength is to be attained and on the availability and cost of the materials at the site.

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