Class C Fly Ash as a Full or Partial Replacement for Portland Cement or Lime

KENNETH L. MCMANIS AND ARA ARMAN

A study was undertaken to evaluate the stabilization or modification of sands and clays using ASTM Class C fly ash as a full or partial replacement for hydraulic cement or hydrated lime. Strength and durability tests demonstrated that the Class C fly ashes of the study could be substituted for cement in some sands. Improvement of the sands was provided by the matrix formed with fly ash acting as a filler and as a cementing agent. The test results indicate the importance of the gradation characteristics of the materials and the effects on matrix quality due to the presence of fines in the natural sands. Also, improvements in the plastic properties and gains in soil support with the addition of fly ash and/or lime were evaluated for two clays. However, test results and analyses demonstrated that the Class C fly ash does not effectively compete as a substitute for lime in the treatment of clays.

Electrical power plants in Louisiana use western coals and are producing ASTM Class C fly ash. In addition to being pozzolanic, many Class C fly ashes have been shown to exhibit cementitious properties similar to portland cement. In recent years, an increasing number of stabilization projects has been performed using Class C fly ash alone (*1*). Class C fly ash with calcium oxide contents of 20 percent or more has reportedly adequately stabilized fine-grained plastic soils, as well as coarse-grained soils, without the use of lime (*1–4*). The objectives of this research were (a) to evaluate ASTM Class C fly ash as a lone or partial replacement for portland cement in sands and lime in clays and (b) to identify the manner in which improvements to the soils occur and the important characteristics of the materials.

TEST METHODOLOGY

The testing program included two sands commonly used in base construction and two clays: a nonplastic A-3-0 sand, a slightly plastic A-2-4 silty sand (liquid limit = 21, plastic index = 7), an A-6(9) silty clay, and an A-7-6(20) clay. Table 1 gives the engineering properties of the natural soils.

Three fly ashes produced in Louisiana's Big Cajun, Nelson, and Rodemacher power plants were included in the testing program. The physical and chemical properties were analyzed according to ASTM C 311 (Table 2). All the fly ashes were ASTM Class C. The calcium oxide content ranged from 21.5 percent to 27.2 percent. A hydrated, high-calcium lime (ASTM Designation C 207, Type N) and a Type I portland cement (AASHTO Designation M85) were used in the study.

K. L. McManis, Civil Engineering Department, University of New Orleans, New Orleans, La. 70148. A. Arman, Louisiana Transportation Research Center, Louisiana State University, 4101 Gourrier, Baton Rouge, La. 70804-9245.

A base or subbase material is usually evaluated with respect to its strength and durability. Louisiana Department of Transportation and Development (DOTD) criteria (TR 432-82) were used to evaluate the performance of the sand specimens (i.e., sand plus fly ash alone, sand plus fly ash and lime, sand plus fly ash and cement, and sand plus cement alone). This specification required the minimum cement content to correspond to a strength of 250 psi with a 7-day curing period at a temperature of 73° ± 3° F. The strength and durability of the specimens were tested using ASTM C 593 procedures, except that the curing temperature was modified to agree with DOTD TR 432-82.

Class C fly ash used as a clay modifier was also studied. Both clays were evaluated with respect to changes in their plastic properties, strength index, and curing time. Atterberg limit tests were conducted on the clays to evaluate the effects of the additives on the soil plasticity. *R*-value tests were performed to measure resistance to deformation and change in soil support values.

The standard Proctor (ASTM D 698) procedure was used in molding the mixtures into sets of three specimens. In compacting the specimens, moisture contents were not allowed to vary beyond ±1 percent of optimum; and dry densities were maintained to within ±3 lb of the theoretical dry weight density. Those specimens not meeting these criteria were remolded.

The molded specimens were extruded and cured for 7, 28, and 56 days at a temperature of 73° ± 3° F and at a relative humidity of 90 percent or greater. At the end of each curing period, the mixtures were tested for compressive strength and durability. The average compressive strength of the three specimen groups was used for comparison purposes. The coefficient of variance of the individual group test values was computed and compared as a measure of the relative test dispersion. The coefficient of variance ranged from 5 to 14 percent with an overall value of 9 percent.

DOTD TR 433-81 criteria for lime treatment of soils used in Louisiana highways were used to determine the minimum amount of lime required. This requires that the liquid limit (LL) and plastic index (PI) after lime treatment cannot exceed 40 and 10, respectively, for soils used as a base course and 40 and 15, respectively, when soils are used as a subbase. These criteria were also applied when fly ash was evaluated as a replacement for lime with the clays. Both the A-3 sand and the A-2-4 silty sand met this requirement without treatment.

TABLE 1 SOIL PROPERTIES

Variable	Soil A-3	A-2-4	A-7-6(20)	A-6(9)
Coarse sand (Ret #40) (%)	40	3	0	1
Fine sand (Ret #200) (%)	52	62	14	3
Clay and colloids (%)	3	17	55	34
Liquid limit (%)	NP	21	60	31
Plastic index (%)	NP	7	40	13
Max. dry wt. den. (pcf)	109.7	119.7	98.8	104.9
Optimum moisture (%)	13.0	12.1	23.1	19.0
R-value			<5	30

NOTE: NP = nonplastic.

TABLE 2 CHEMICAL AND PHYSICAL ANALYSES OF FLY ASHES

Variable	Fly Ash Source Cajun	Rodemacher	Nelson
Retained #325 (%)	9.2–7.6	12.0–11.0	13.9–18.3
Loss on ignition (%)	1.3–0.5	0.5–1.9	0.7–1.0
Total oxides[a] (%)	65.8–66.5	62.3–64.7	51.5–62.9
Calcium oxide (%)	21.5–24.5	27.20–24.0	25.2–25.8
Magnesium oxide (%)	4.4–4.7	4.9–4.5	4.9–2.9
Sulfur trioxide (%)	2.8–2.8	2.7–2.9	3.1–3.3
Alkalies (%)	1.34–0.66	1.49–1.06	1.45–1.74

NOTE: Materials were tested according to ASTM Designation C 311.
[a]$SiO_2 + Al_2O_3 + Fe_2O_3$.

As a measure of performance of the two treated clays in an embankment or subbase, the *R*-value test (resistance value—ASTM D 2844) was used. A few specimen sets were subjected to an *R*-value retest with an additional 7 days to observe any increase that may have occurred.

EVALUATION OF TEST RESULTS WITH SANDS

To satisfy the stated acceptance criteria (250 psi compressive strength with a 7-day cure), the following minimum proportions of stabilizing agents were required with the sands:

Stabilizing Agent	*A-3 Sand (%)*	*A-2-4 Silty Sand*
Fly ash	20–25	None meeting criteria
Lime + fly ash	4–6 lime + 15 fly ash	None meeting criteria
Cement + fly ash	All proportions acceptable except 4 cement + 5 fly ash	All acceptable
Cement	8	All acceptable

The test results were evaluated in an attempt to identify or explain the behavior of the fly ash mixtures.

Moisture Density

The density of the mixture has a major effect on the strength and durability of cement- and lime-fly ash stabilized materials (*5,6*). The curves for maximum dry density and optimum moisture content versus the percent fly ash additive for both sands are shown in Figure 1. All three fly ashes gave similar results. The addition of fly ash to the A-3 sand significantly increased the maximum dry density and decreased the optimum moisture content throughout the range of fly ash percentages tested. The reduction in optimum moisture content is attributed to the spherical shape of the fly ash particles in the sand voids, which lubricates the mix and aids in the densification efforts.

The addition of the fly ash to the A-2-4 silty sand produced a small increase in dry density between 3.3 and 6.9 pcf with the different fly ashes. The maximum density occurred at fly ash percentages of 15 to 20 percent for all three fly ashes. Additional fly ash beyond 20 percent produced a decrease in density. The fly ash percentage corresponding to the maximum density of the A-2-4 silty sand also seemed to coincide with the minimum value of the optimum moisture content.

Other mix combinations of cement plus fly ash and lime plus fly ash with the A-3 sand also produced gains in density. Both lime and cement increased the density at different percentage levels. The resulting increase or decrease varied among the different fly ashes. This was not the case for the A-2-4 silty sand. A decrease in density, below that of the raw soil, occurred with the addition of lime and was attributed to the effects of the fines present.

The aggregate gradation had a significant effect on the density, strength, and durability of the mix (*2,6*). Using Talbot's relationship for computing the ideal gradation necessary for maximum density, a grain size analysis was made for each sand.

$$P = (d/D)^{0.5} \quad (1)$$

where

P = percent finer by weight for grain size,
d = grain size being considered, and
D = maximum grain size.

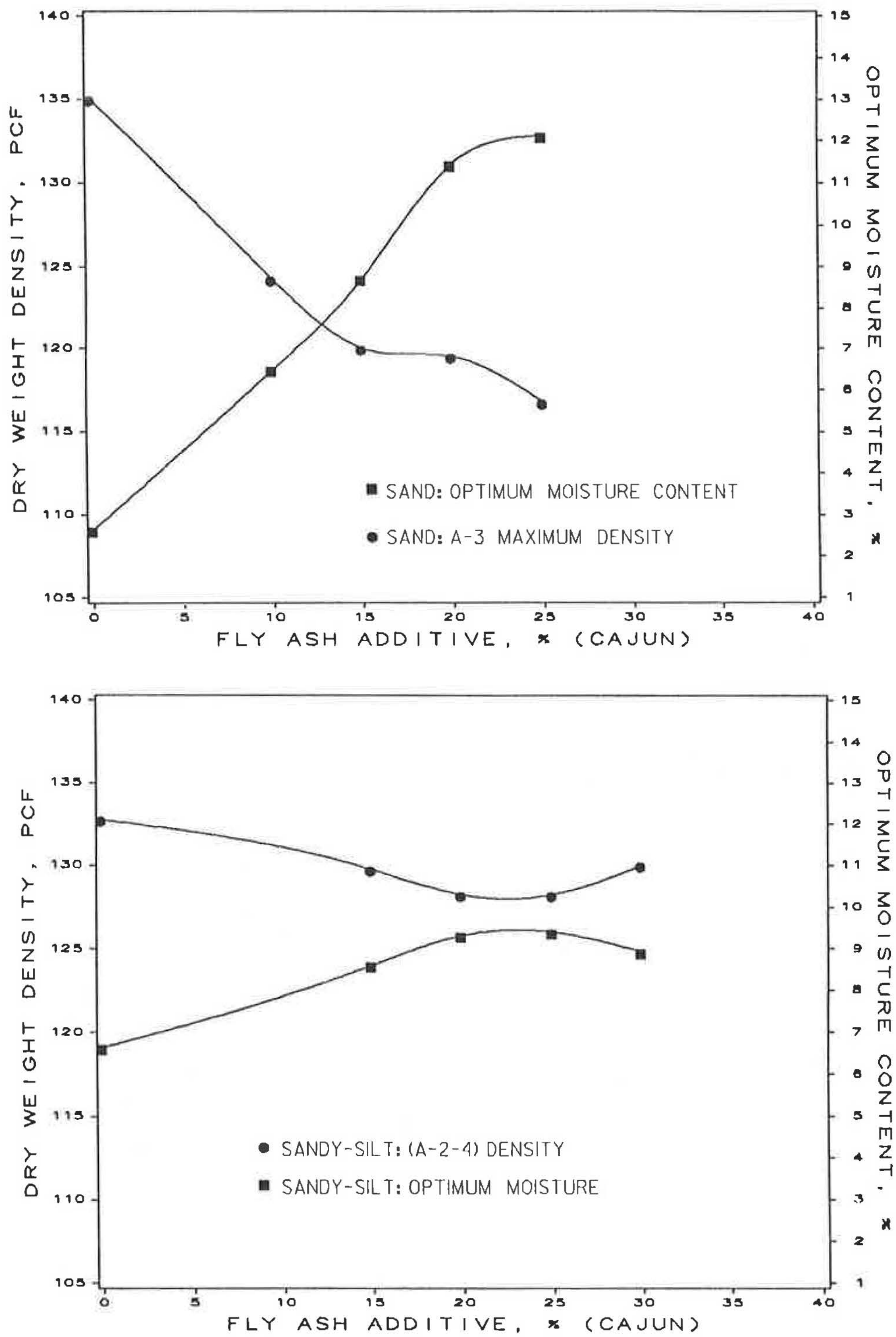


FIGURE 1 Dry density/optimum moisture content versus fly ash additive.

Figure 2 shows the original gradation curves for Rodemacher fly ash, the two sands, and the resulting gradation curves for the soils blended with different percentages of Rodemacher fly ash. Note that the additional fly ash brings the resulting gradation curves closer to the ideal curve for maximum density of the A-3 sand (i.e., maximum density is achieved at 25 percent fly ash). With the absence of fines in the A-3 sand, the addition of the silt-size fly ash fills the voids, providing a matrix for the sand particles. The maximum dry density was increased from 109.1 to 132.8 pcf with 25 percent fly ash.

Figure 2 indicates that the addition of approximately 15 percent fly ash would maximize the dry density of the A-2-4 silty sand compacted with the Rodemacher fly ash. Test results demonstrated that 20 percent fly ash actually provided the maximum dry density. The increase in maximum dry density

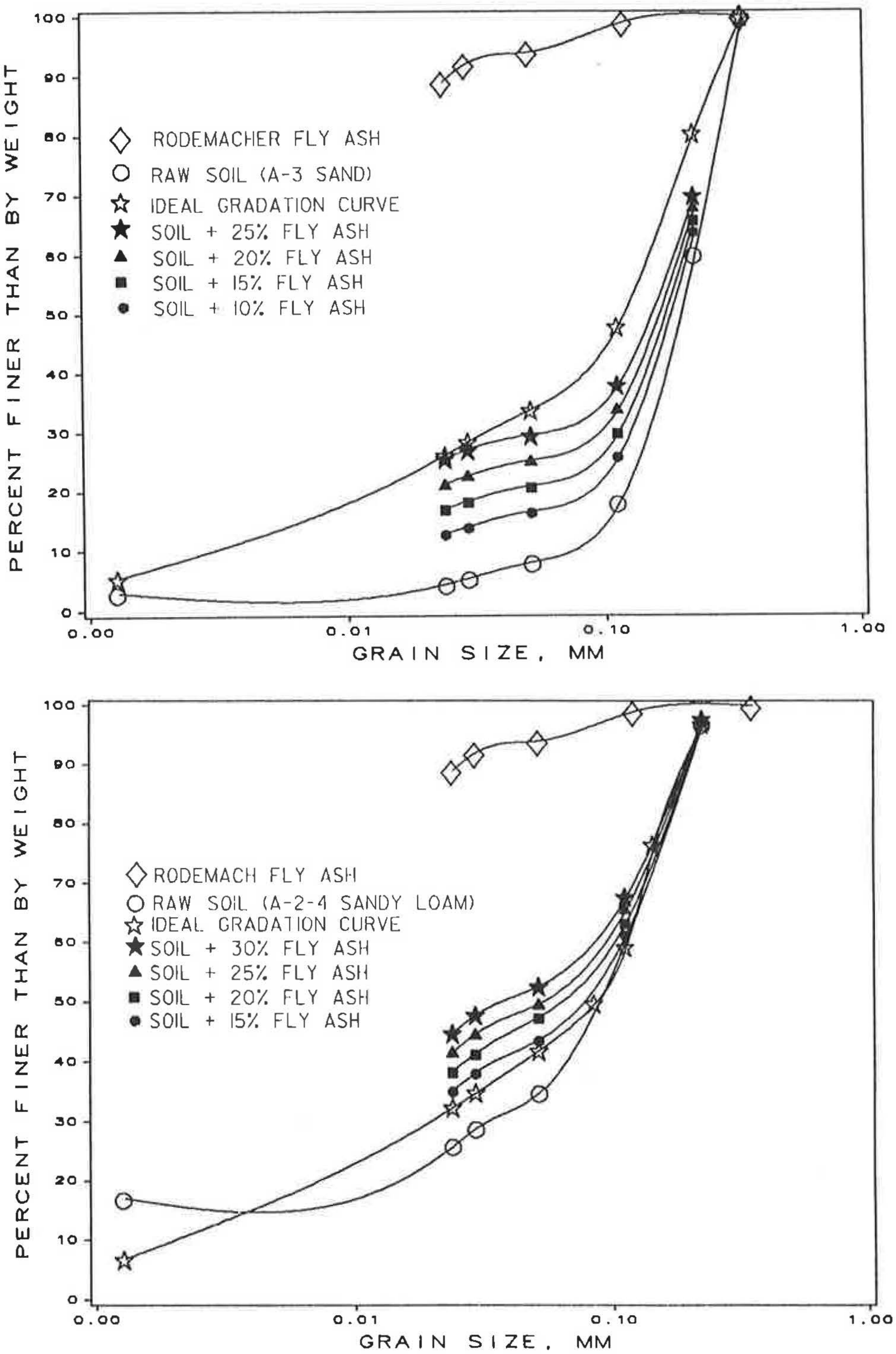


FIGURE 2 Comparison of the gradation curves for the A-3 and A-2-4 sands with and without Rodemacher fly ash.

with the addition of fly ash was modest—increasing from 119.1 pcf to values ranging from 120.5 pcf to 124.8 pcf for the different fly ashes. The A-2-4 silty sand contained 35 percent fines (18 percent silt size and 17 percent clay size) for the natural soil. The addition of 20 percent fly ash to the natural silt and clay constituents of the A-2-4 soil gives 48 percent fines. It would appear that the small gain in density occurs with a suspension of the sand particles in a matrix consisting of a secondary structure of silt and fly ash with clay particles between.

Unconfined Compressive Strength

Strength variation with increasing fly ash reflects the changes observed in density for both of the sands (Figure 3). Large

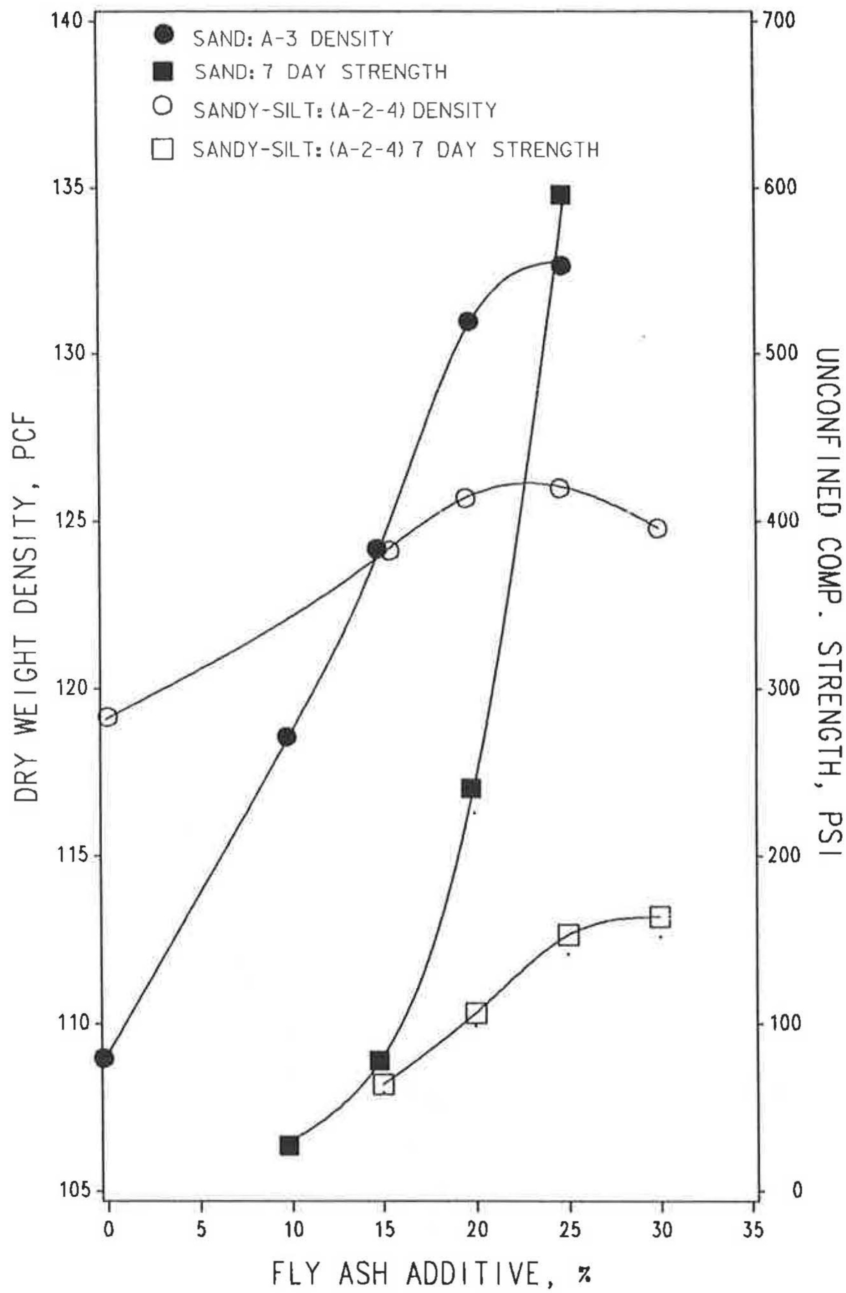


FIGURE 3 Strength/dry density versus percent Cajun fly ash additive.

gains in strengths were developed in the A-3 sand with each increment of increased fly ash. The strength variation of the A-2-4 silty sand with fly ash also paralleled that of its variation in dry density. The fly ashes contained approximately 25 percent calcium oxide (Table 2). Several investigators (*7–10*) have shown that much of the CaO in some Class C fly ash is combined with silicates and aluminates similar to that found in portland cement. In comparing the performance of the A-3 sand and the A-2-4 silty sand with the addition of 20 percent fly ash, the maximum cementing CaO constituents possibly available would be 5 percent of the total mixture (25 percent CaO content × 20 percent fly ash). This would be true for both sands. However, the A-3 sand would have a 25 percent CaO concentration in its fly ash matrix as opposed to 10.4 percent for the A-2-4 silty sand matrix of fly ash, silt, and clay (25 percent CaO content × 20 percent fly ash/48 percent fly ash, silt, and clay). The performance of the stabilized sands, as measured by their strength and durability tests, is closely related to the quality of the cementitious matrix of the mixture. In comparing the strength gain between mixtures of fly ash and the A-3 sand and A-2-4 silty sand, the difference can be seen.

There was an additional gain in strength corresponding to the addition of lime or portland cement with fly ash and the two sands. The strength gain with the addition of lime was not as significant in the A-2-4 silty sand as that occurring in the A-3 sand. Also, the A-2-4 soil seemed to produce more erratic test measurements than did the A-3 sand. The clay and silt-size fraction of the A-2-4 sand did not appear to have strong pozzolanic characteristics. The fines of the natural soil

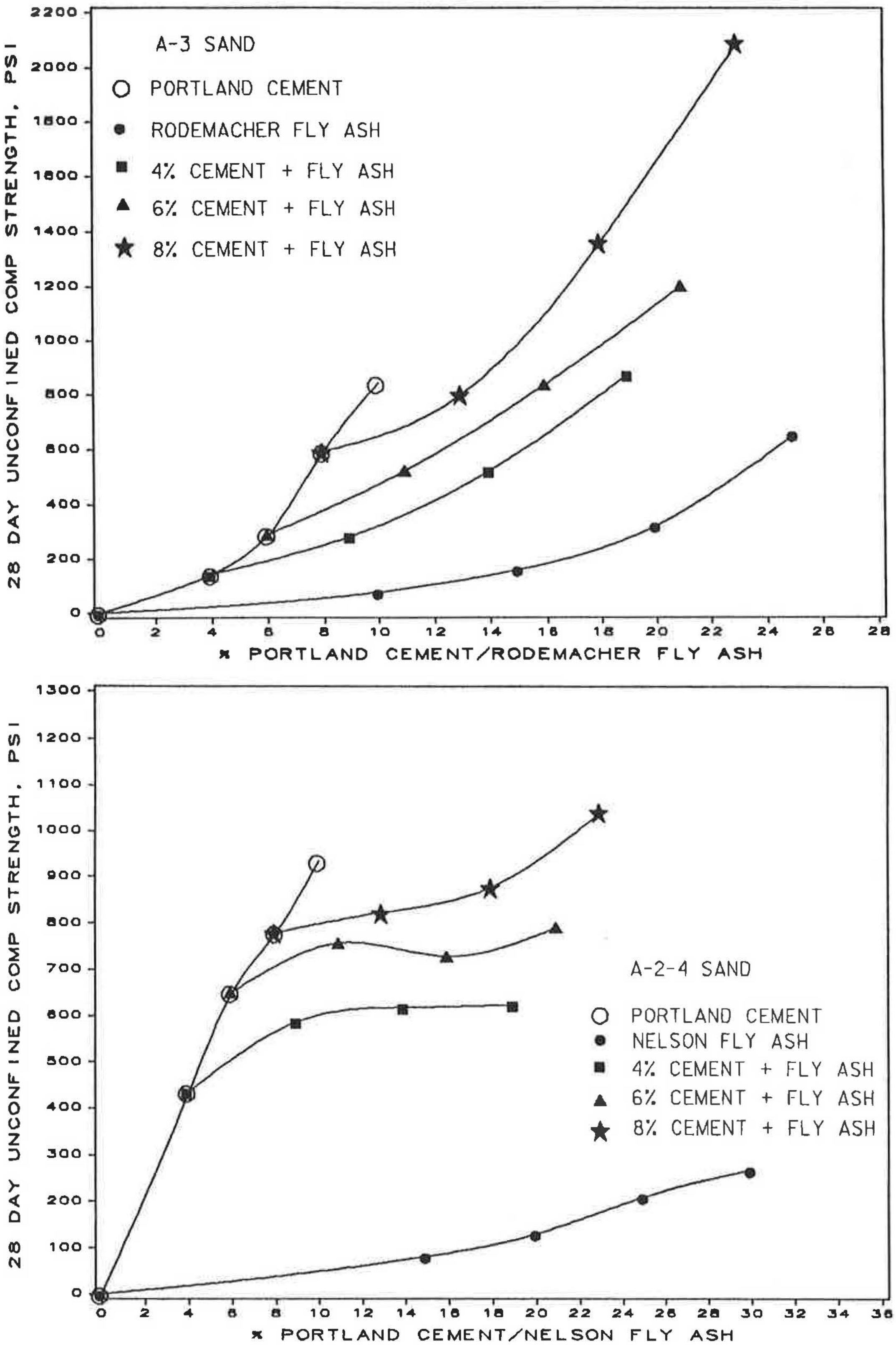


FIGURE 4 Unconfined compressive strength versus percent portland cement/fly ash.

may interfere with and produce discontinuities in the cement formed within the matrix by the fly ash and fly ash combinations of additives. In the A-3 sand, the density (i.e., increased percentages of fly ash) seemed to be more critical for strength gain than did the added lime.

A plot of the relationship between the 28-day strength and the additives for the cement–fly ash combinations appears to take the shape formed by shifting and combining the strength curves for cement and fly ash used alone (Figure 4). The cement–fly-ash strength of the A-3 sand demonstrates that combining portland cement and fly ash contributes significantly to the cementing properties of the matrix. Similar trends

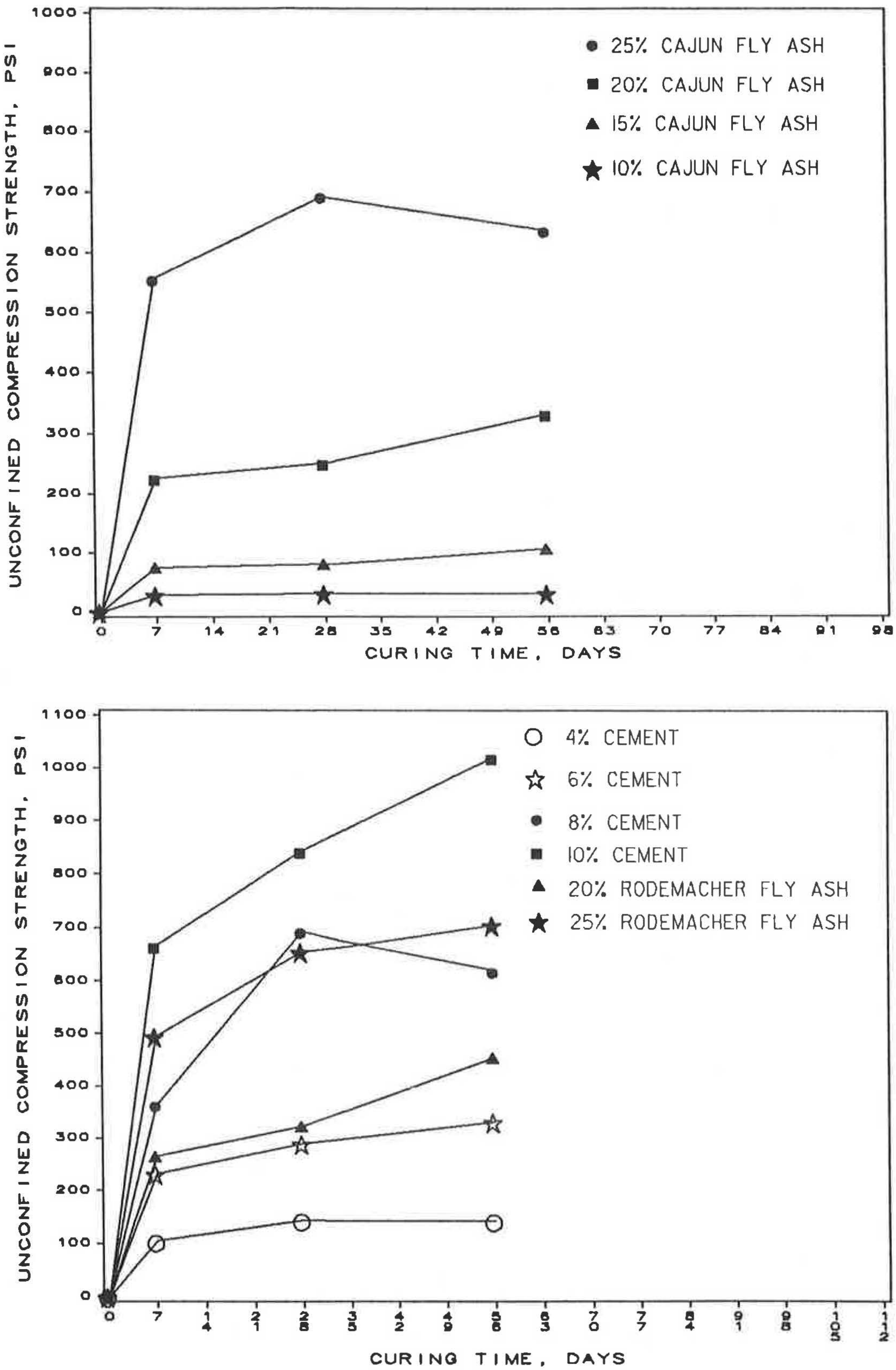


FIGURE 5 Strength gain versus curing time for the A-3 sand with fly ash and cement.

occurred in the cement–fly-ash mixtures of the A-2-4 silty sand. However, the magnitude of the strength gain with additional fly ash was much less, and the values were more erratic.

Curing Time

In Figure 5, the initial slope of the strength-time curve is indicative of the early self-hardening characteristics of the fly ashes. The initial set times of Class C fly ash have been reported to occur very rapidly in other studies (*8,11*). Laboratory tests conducted with slurries of sand mixed with Cajun, Nelson, and Rodemacher fly ashes measured short initial set times ranging from 21 min to 3 hr 20 min. Thus, to get the full advantage of Class C fly ash, the soil should be quickly mixed and compacted (*11*).

Comparisons of the A-3 sand with cement alone and with the Rodemacher fly ash alone are shown in Figure 5. The 25 percent fly ash mixture compared well with the 8 percent cement and provided a denser mixture that may be more durable. Using the current Louisiana DOTD strength/curing criteria and using the current local costs of cement and fly ash, the fly ash appeared to be competitive as a replacement for cement in a clean sand.

Durability

Specimens were conditioned in a vacuum saturation chamber and tested for compressive strength according to ASTM C 593 specifications, with the exception that they were cured in a humidity room at 73° ± 3° F rather than the 100° F specified in the ASTM procedure. A comparison of the differences in strength between specimens subjected to this procedure and those not subjected provided a relative measure or indication of the durability of all sand mixtures (Figure 6). There did not seem to be any consistent loss of strength with the A-3 sand beyond what might be expected as experimental variation. However, the A-2-4 silty sand demonstrated a consistent loss in strength in the vacuum saturation test.

EVALUATION OF TEST RESULTS WITH CLAYS

DOTD TR 433-81 was used as the criterion to evaluate attempts to modify the clay's plasticity (i.e., maximum LL of 40 and maximum PI of 10 and 15 for bases and subbases, respectively). The Atterberg limits of the untreated A-6(9) silty clay satisfied the subbase criteria. The results of modification efforts on the plasticity of both soils produced the following proportions:

Stabilizing Agent	*A-6(9) Clay (%)*	*A-7-6(20) Clay (%)*
Fly ash	20 (base requirements)	30 (base criteria, Rodemacher only) 25–30 (subbase criteria)
Lime	2	3 (base and subbase criteria)
Lime + fly ash	<2 lime + fly ash	Varies, approximately 2 lime with 10 fly ash

Some reports have indicated that a portion of the calcium oxide in some fly ashes exists as free lime, making it possible for flocculation and agglomeration of clay minerals to occur and reduce the soil's plasticity (*1,4*). However, other investigators (*7–10*) report that the CaO (lime) present in the Class C fly ash is not in a free (available) state and, as a soil stabilizing agent, will not modify the plastic behavior of fine-grained soils. The tests performed on the two clays in this study were reviewed and analyzed in an attempt to examine the role of the CaO in the fly ash.

Soil Plasticity

The Atterberg test results for the two clays, treated and untreated, are shown in Figure 7. Lime added to the A-7-6 clay reduced the liquid limit and greatly increased the plastic limit—resulting in a much-reduced plastic index. The lime fixation for this soil (i.e., the amount of lime required to produce a constant value of the plastic index) is 4 percent lime. This corresponds to a PI of 4 (raw soil PI = 40) and a liquid limit of 38 (raw soil LL = 60). The A-6 clay was somewhat lime-reactive, and modifications to the plastic properties of the soil occurred with the addition of lime. The PI was reduced from 13 to 7 with 2 percent lime and to 4 with 5 percent lime.

Adding fly ash to the clays also produced changes in the plasticity. These changes were greater in the A-7-6 clay (Figure 8). However, these changes occurring in the plastic properties can be attributed to the effects of diluting the clay constituents with a nonplastic material (i.e., the fly ash). Theoretical relationships between the liquid and plastic limits and the clay content were developed by Seed et al. (*12*). It was shown that the variation of the liquid limit with the clay content can be expressed as

$$w_{LL} = (C/100)\, w_{CLL} \qquad (2)$$

where

w_{LL} = liquid limit of the soil mixture,
w_{CLL} = liquid limit of clay fraction, and
C = percent of clay particles.

A similar relationship for the plastic limit (*14*) is

$$w_{PL} = (C/100)\, w_{CPL} \qquad (3)$$

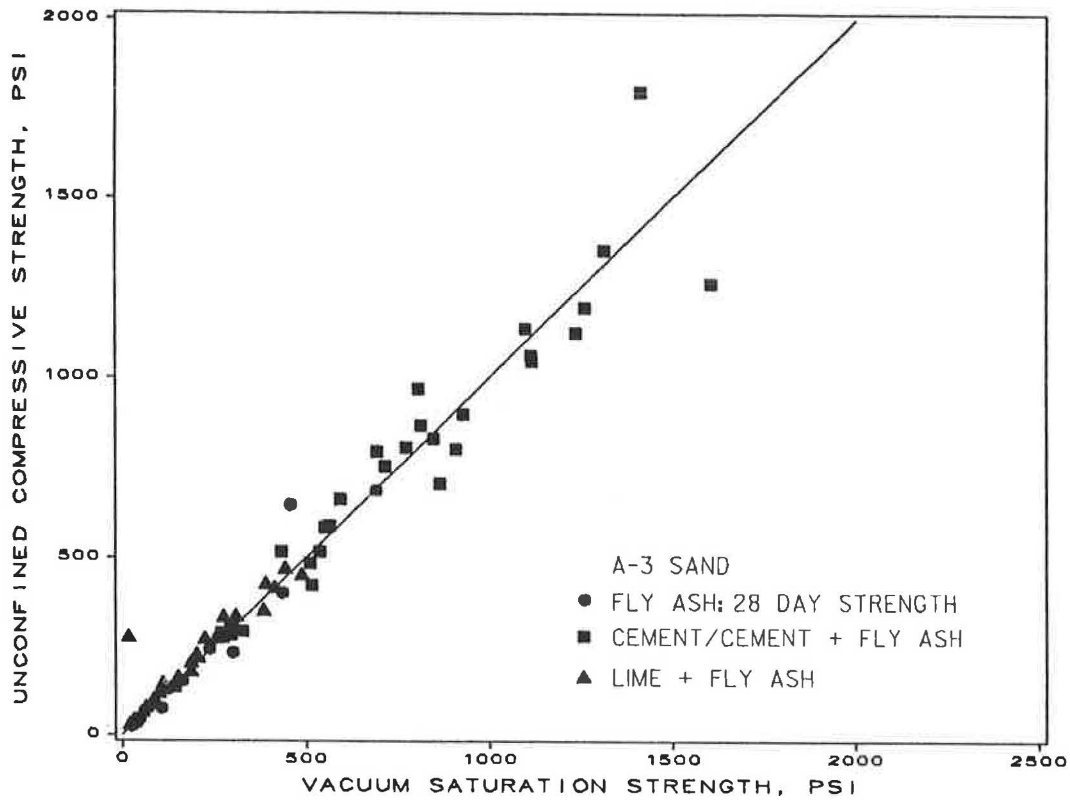
where w_{PL} is the plastic limit of soil mixture, and w_{CPL} is plastic limit of clay fraction; or $w_{PL} = 0.5C$ (for $C > 40$).

Assuming that the fly ash consists of particle sizes in the fine sand-to-silt range (*2*) (Table 2) and that the only source of clay-size particles is from the A-7-6 clay alone, then

$$C = [1 - (FA/100)]\ (\%\ \text{clay in raw soil}) \qquad (4)$$

where FA equals percent fly ash.

Table 3 compares the liquid and plastic limits measured in laboratory tests using the three fly ashes with those limits predicted on the basis of variations in the clay content as shown above. Average values of the percent clay in the raw soil were assumed to vary between 55 and 60 percent, and the mean values tested for the liquid and plastic limits of the raw soil were used. The outcome of the laboratory Atterberg tests did not vary greatly from what would be expected by blending a fine-grained, nonplastic soil with the A-7-6 clay.



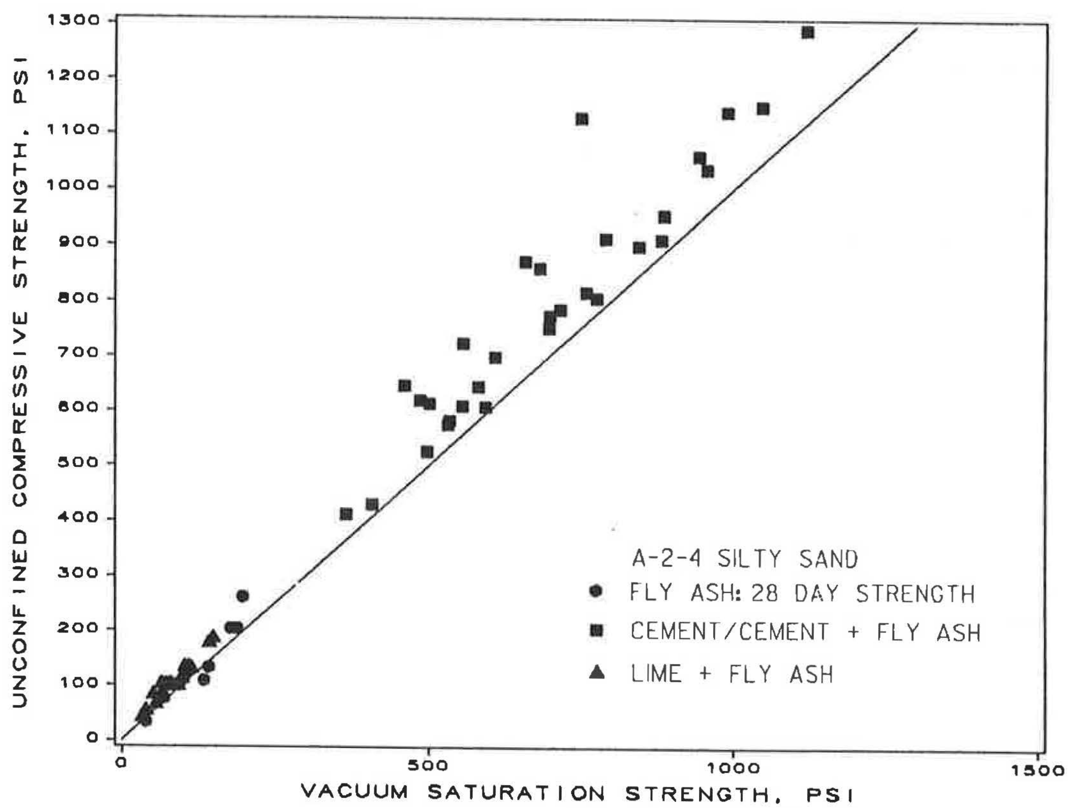


FIGURE 6 Unconfined versus vacuum-saturated strength for the A-3 and A-2-4 sands.

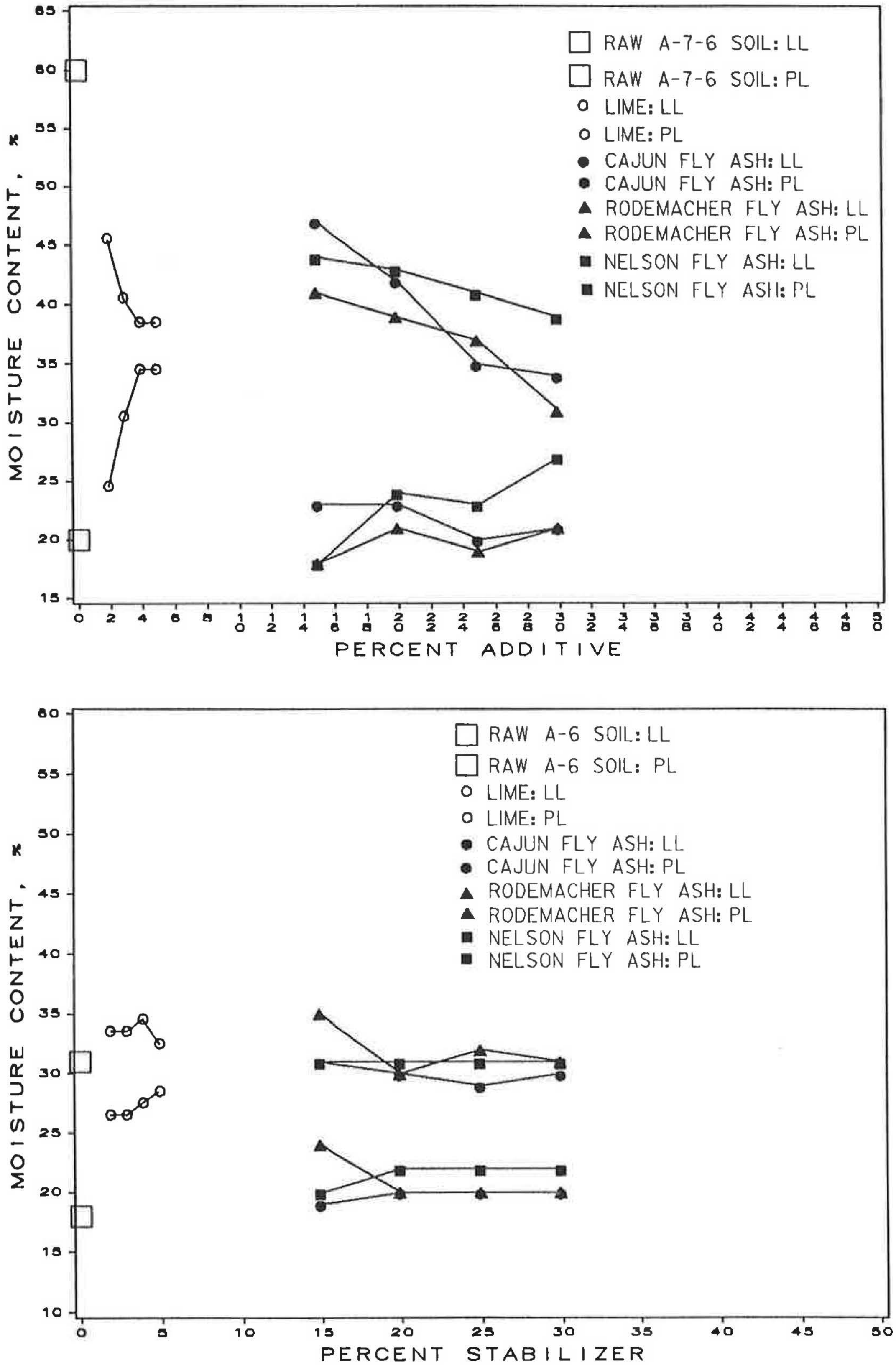


FIGURE 7 Atterberg tests versus percent additive for the A-7-6 and A-6 clays.

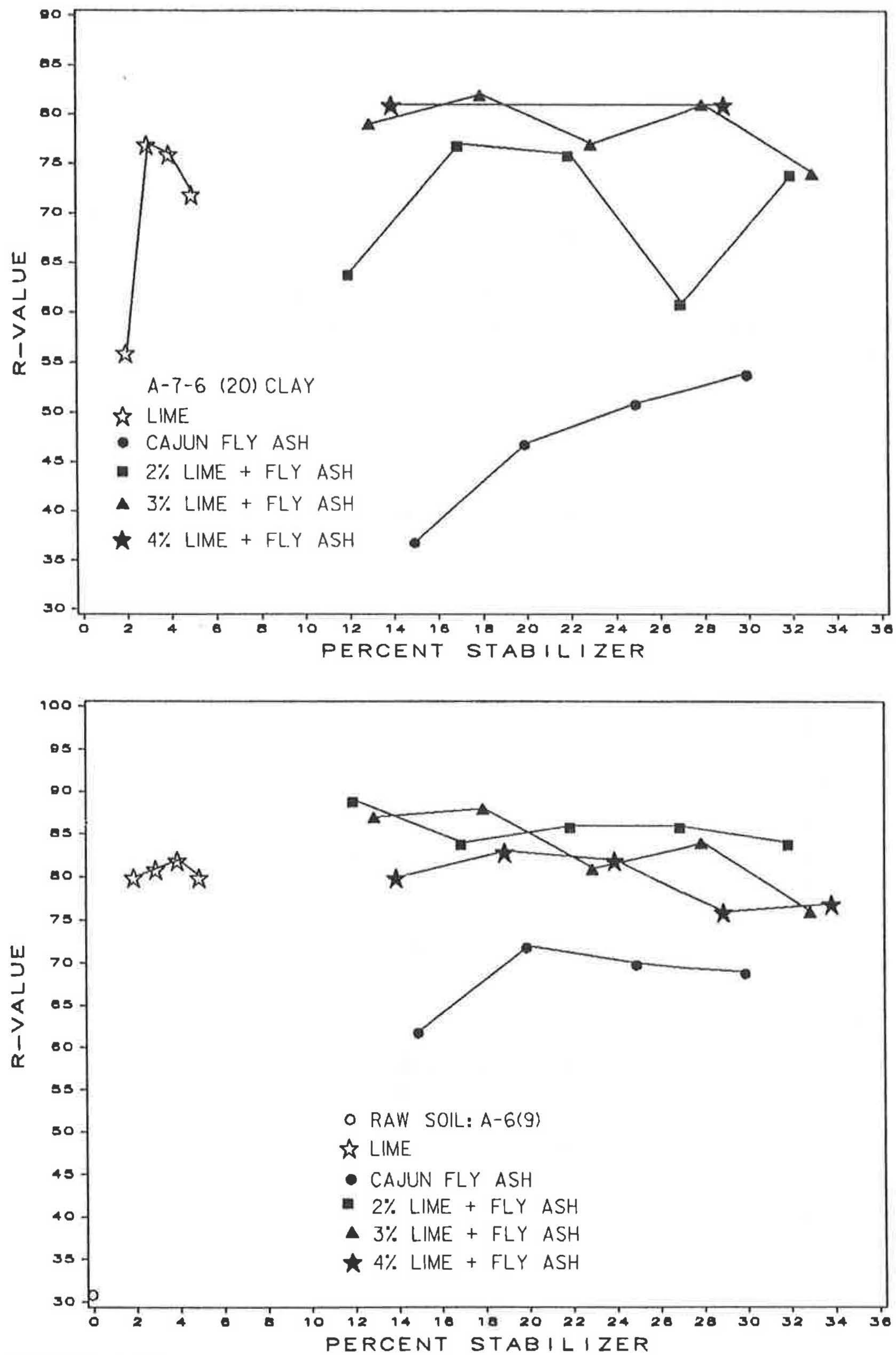


FIGURE 8 Stabilometer tests for A-7-6 and A-6 clays.

TABLE 3 ATTERBERG LIMITS: PREDICTED AND OBSERVED

Percent FA	Percent C	A-7-6 Raw Soil	Fly Ash Cajun	Fly Ash Nelson	Fly Ash Rodemacher	Predicted
			Liquid Limit			
0	55	60				
15	47		47	44	41	47-51
20	44		42	43	39	44-47
25	41		35	41	37	41-44
30	39		34	39	31	39-43
			Plastic Limit			
0	55	20				
15	47		23	18	18	16-24
20	44		23	24	21	15-22
25	41		20	23	19	14-21
30	39		21	27	21	13-20

FA - fly ash percentage

C - clay fraction percentage

Thus, it appeared that the changes in plastic properties of the fly ash-soil mixtures for these Class C fly ashes could be credited more to a decrease in the clay fraction than to chemical alteration of the clays. This is not to say that there was not some effect or change due to whatever percentage of free lime was available. However, there did not appear to be enough free lime to provide substantial changes.

Dry Density

As expected, the addition of lime to the compacted clays produced a density less than that for the raw soil. Although the fly ash-soil density values varied, they seemed to produce densities that were approximately equal to those obtained with the untreated soil. However, combining the lime and fly ash with the A-6 soil further reduced the density of the mix. The pronounced effect that the addition of lime had on the density of both clays, with and without fly ash, and the lack of change (reduction) in density with the soil plus fly ash are further indications of the absence of free lime in the fly ash.

Soil Support Resistance Value

The resistance or *R*-values of the A-7-6 and A-6 silty clays were greatly improved with additions of lime, fly ash, and lime-fly ash combination (Figure 8). However, the addition of lime or lime in combination with fly ash produced the greatest gain in the measured *R*-values for both soils.

The testing procedure should be considered in evaluating the results. In this procedure, the test specimens were compacted after being mixed with the stabilizing agents and slaked with water for a 72-hr period. Within the ensuing 24 hr, they were tested for exudation pressure followed by determination of expansion pressures. The *R*-values were measured approximately 24 hr after compaction or 4 days after being initially mixed with the stabilizing agents and slaking water. This is not enough time to assess the pozzolanic gain in strength. There are also the effects of the slaking period on the Class C fly ashes. Mixing the fly ash, soil, and water with the 72-hr slake period in the *R*-value test procedure is probably counterproductive with respect to the fast initial set of the Class C fly ashes.

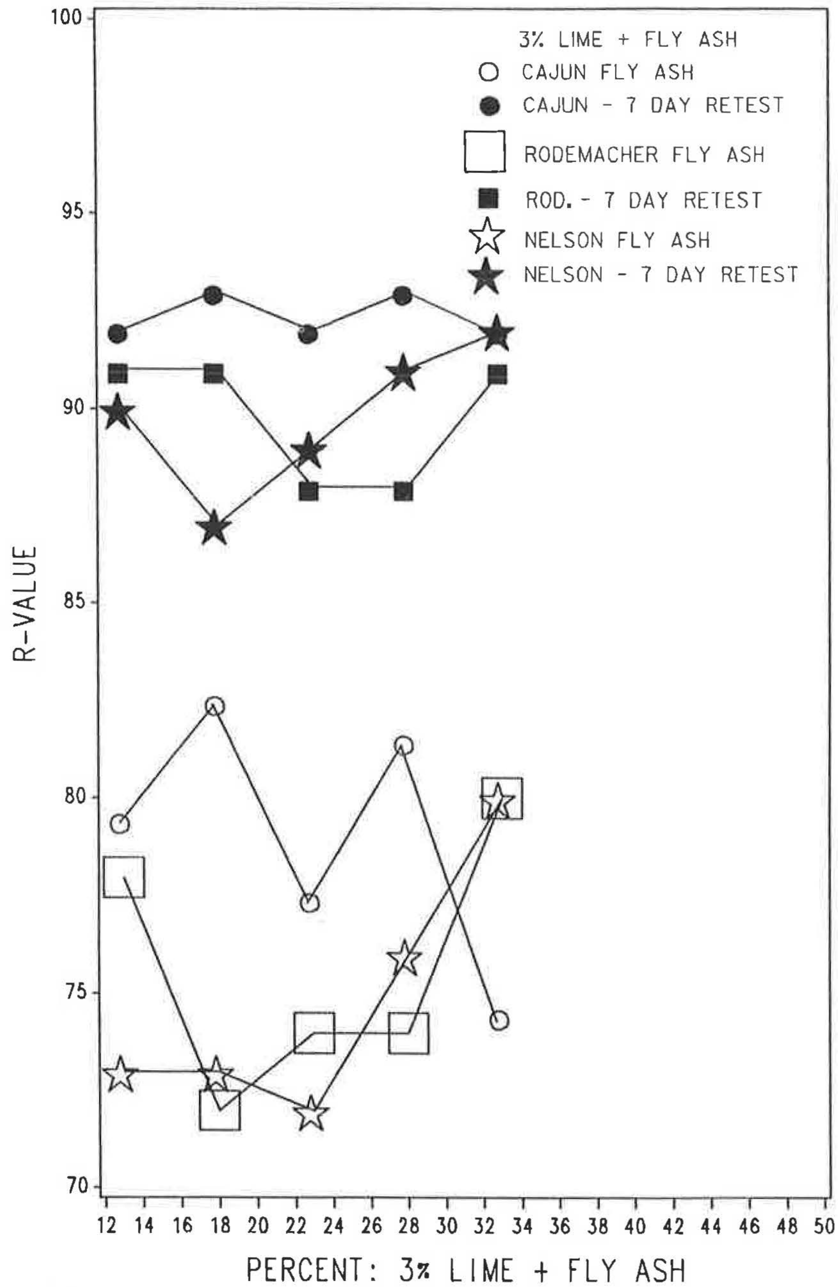


FIGURE 9 ***R*-value gain with 7-day retests of A-7-6 clay with lime plus fly ash.**

The uncured lime-soil and fly ash-soil mixtures immediately improved the strength and deformation properties of both soils, with the most dramatic gain occurring in the A-7-6 clay (Figure 8). Treating the A-7-6 soil with the lime or with the lime-fly ash produced final *R*-values almost as high as those of the treated A-6 silty clay (*R*-values of 77 versus 85)—the A-7-6 being the most lime-reactive of the two soils. Lime was the most effective stabilizing agent, although some small gains in the *R*-values were achieved in some cases by combining the lime and fly ash. Large quantities (30 percent) of fly ash added to the lime showed no improvement over the smaller proportions (10 percent).

Some of the A-7-6 specimens were retested for their *R*-values after an additional 7-day curing period. Figure 9 shows the test results of one set. The results varied but consistently showed a significant gain in a relatively short time. Because these test specimens were previously subjected to loading in the stabilometer in the initial *R*-value test, the second *R*-value determined at the end of an additional 7-day curing included some autogeneous healing in addition to further development of their pozzolanic strength.

CONCLUSIONS

The test results of this study demonstrate that ASTM Class C fly ash could be used as a lone or partial replacement of portland cement in sands, depending on their gradation characteristics. The improvement of the sands with the Class C fly ash tested is credited to its dual role as a matrix filler and cementing agent. The engineering and physical properties of the sand–fly-ash mixtures varied with changes in the fly ash source. However, the general behavior was consistent for all.

Proportioning the A-3 sand and fly ash for maximum density produced a correspondingly large gain in strength. However, large quantities of fly ash (20 to 25 percent) were required to maximize the density. Fly ash alone and the A-2-4 silty sand did not fare well. Success in stabilizing a silty sand or sandy silt with Class C fly ash will depend on the quantity and reactive properties of the fine-grained material (< #200 sieve), that is, the matrix quality. The importance of the matrix materials with respect to durability was also reflected in a greater loss of strength for the A-2-4 silty sand in the vacuum saturation tests.

Alterations of the plastic properties of the clays with the Class C fly ashes used alone are attributed to an overall reduction in the percentage of clay content corresponding to the high percentages of fly ash used. The amount of free lime available in the fly ashes for cation exchange and flocculation-agglomeration reactions is insufficient to compete effectively as a lime substitute.

The soil support resistance of both clays as measured by the stabilometer test was greatly improved with the addition of lime or fly ash, or both. The greatest improvements occurred in the poorest soil [the A-7-6(20) clay]. As a lone additive, lime provided the greatest improvement in soil support. A small gain in the *R*-values resulted when fly ash was added to the lime. However, lime alone performed almost as well without the fly ash. Unless proven economical to do so, there does not appear to be any advantage to using a Class C fly ash over lime in the treatment of clays.

ACKNOWLEDGMENTS

This study was sponsored by and conducted in cooperation with the Louisiana Department of Transportation and Development and the Federal Highway Administration, U.S. Department of Transportation. The testing program was performed by the Louisiana Transportation Research Center.

REFERENCES

1. A. M. Digiola, R. J. McLaren, D. L. Burns, and D. E. Miller. *Fly Ash Design Manual for Road and Site Applications, Volume 1: Dry or Conditioned Placement.* Electric Power Research Institute, Palo Alto, Calif., Feb. 1986.
2. R. Pachowski et al. *Brown Coal Fly Ash in Soil Stabilization.* Interim Report FHWA/RD-84/072. U.S. Department of Transportation, Federal Highway Administration, Oct. 1984.
3. M. Mateos. Stabilization of Soils with Fly Ash Alone. *Highway Research Record 52*, HRB, National Research Council, Washington, D.C., 1964.
4. R. C. Joshi, D. M. Duncan, and H. McMaster. New and Conventional Engineering Uses of Fly Ash. *Transportation Engineering Journal,* ASCE, Vol. 101, No. TE4, Nov. 1975.
5. B. J. Dempsey and M. R. Thompson. Vacuum Saturation Method for Predicting Freeze-Thaw Durability of Stabilized Materials. *Highway Research Record 442*, HRB, National Research Council, Washington, D.C., 1973.
6. R. Andres, R. Giballa, and E. J. Barenberg. Some Factors Affecting the Durability of Lime-Fly Ash-Aggregate Mixtures. In *Transportation Research Record 560*, TRB, National Research Council, Washington, D.C., 1976.
7. W. C. McKerall, W. B. Ledbetter, and D. J. Teague. *Analysis of Fly Ashes Produced in Texas.* Research Report 240-1. Texas Transportation Research Institute, Texas A&M University, Jan. 1981.
8. W. B. Ledbetter. *Is Lime in Fly Ash Available for Soil Stabilization?* Civil Engineering Department, Texas A&M University, April 1981.
9. M. L. Mings, S. M. Schlorholtz, J. M. Pitt, and T. Demirel. Characterization of Fly Ash by X-Ray Analysis Methods. In *Transportation Research Record 941*, TRB, National Research Council, Washington, D.C., 1983, pp. 5–11.
10. J. M. Pitt, M. L. Mings, and T. Demirel. Characterization and Techniques for Rapid Evaluation of Iowa Fly Ashes. In *Transportation Research Record 941*, TRB, National Research Council, Washington, D.C., 1983, pp. 12–17.
11. S. I. Thornton and D. G. Parker. *Self-Hardening Fly Ash.* AHTD Report H-52. Arkansas Highway and Transportation Department, Little Rock, Oct. 1975.
12. H. B. Seed, R. J. Woodward, and R. Lundgren. Fundamental Aspects of the Atterberg Limits. *Journal of the Soil Mechanics and Foundation Division,* ASCE, Vol. 90, No. SM6, Nov. 1974.

Publication of this paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization.