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FEASIBILITY OF USING SEWAGE SLUDGE IN HIGHWAY EMBANKMENT CONSTRUCTION

A. Kawam, L.M. Smith, et al.

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16. Abstract

A laboratory evaluation of the feasibility of utilizing sewage sludge in construction of a highway embankment was conducted. Mixtures composed of lime, fly ash, waste calcium sulfate and up to 17 percent sewage sludge were evaluated. The effect of lime type, fly ash source and the relative proportions of lime, fly ash and waste calcium sulfate on compressive strength of compacted specimens was measured. Using the criterion that the 28-day compressive strength should be 50 p.s.i. (345 kN/m^2) greater than that of uncured specimens, over 75 percent of the formulations examined passed this test. Two soils, one sandy and the other clayey, were used to replace 30, 50 and 70 percent of the fly ash in selected formulations. All samples with the soil replacement exceeded the minimum strength gain criterion.

Selected formulations were further evaluated for volume change, durability, permeability and leachability. Both freeze-thaw resistance and wet-dry stability were measured and determined to be marginal. The permeability was found to be low, of the order of 10^{-6} cm/sec. Analysis of the leachate from the permeability tests indicated that the heavy metals present in the sewage sludge--cadmium, chromium, mercury and zinc--were retained in the mixture. However, lime and gypsum did increase the pH and calcium and sulfate ion concentrations in the leachate.

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PREFACE

The authors express their thanks to C. DeWitt, who assisted in many phases of the experimental work and M. S. Whitcraft for her technical assistance. Valuable discussions and consultations with Dr. Della M. Roy are also acknowledged.

The sulfate waste was obtained through the courtesy and aid of Mr. K. E. Martin, E. I. DuPont DeNemours and Company, LaPorte, Texas.

The use of mixtures of waste sulfate, fly ash, lime, and digested sewage sludge as possible highway construction materials has been studied by I. U. Conversion Systems, Inc. of Philadelphia, Pennsylvania. Background information which they developed by means of a small scale field demonstration in August 1973, provided impetus for the present study.

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INTRODUCTION

For reasons of decreased availability of raw materials for highway construction caused by reduced crude oil fraction allocations, higher energy costs and aggregate shortages, for example, it has become necessary to examine other potential building materials. With a trend towards conservation of our natural resources, the idea of materials recycling and waste utilization becomes increasingly important. Some success has been realized in this area, as exemplified by the use of fly ash, a by-product from coal burning power plants.

The present study was initiated in order to gain information on the possible use of sewage sludge in combination with other by-products and wastes. The planned route of I-95 through Philadelphia traverses the storage area of the Southwest Sewage Treatment Plant. The material in these ponds must either be moved to a new location or hopefully utilized in the construction. Its utilization in combination with lime, fly ash and waste calcium sulfate as embankment material is a possibility. This will serve two purposes. First, it will be a method of aesthetically disposing of the sludge in a useful manner. Secondly, it will mean that large quantities of fill soil will not have to be imported for embankments, bridge approaches, etc.

Lime-fly ash-soil-water mixtures have been used previously for stabilized bases, embankments, etc. Lime-fly ash-water mixtures have also been used in a compacted state as a subbase or base material (1). More recently, gypsum (anhydrite), or calcium sulfate, added to lime-fly ash-water mixtures (2, 3) has produced a base course material with improved properties. The addition of calcium sulfate causes improvement in the compressive strength and lowers the permeability of the resultant product. By-products of certain processes can be used as the source of calcium sulfate. Sources of waste gypsum identified (3) as being particularly well suited for enhancing pozzolanic mixtures were titangypsum, gas scrubber waste from power plants with lime or limestone injection for SO_2 removal, and by-product from hydrofluoric acid production.

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[1] Hollon, G. W. and Marks, B. A., "A Correlation of Published Data on Lime-Pozzolan-Aggregate Mixtures for Highway Base Course Construction," Illinois University Engineering Experimental Station Circular No. 72, 1962.

[2] Minnick, L. J., Webster, W. C. and Hilton, R. G., "Technical Control of Sulfate Waste Materials at the Transpo '72 Site," Final Report, Contract DOT-FH-11-7879, Federal Highway Administration, February 1973.

[3] Kawam, A. and Smith, L. M., "Technology for Using Sulfate Waste in Road Construction," Quarterly Reports for Contract DOT-FH-11-8122, 1974.

Organic matter is known to retard the hydration reactions which form the cementitious compounds (4). Therefore, the sewage sludge would be detrimental to the strength gains of lime-fly ash-sulfate-water mixtures. However, mixtures prepared by replacing water with sewage sludge could still have possible use as embankment or fill material. It was for this purpose that mixtures of lime-fly ash-sulfate waste-sewage sludge were evaluated.

EXPERIMENTAL

Materials

Three limes, one waste sulfate, two fly ashes, one sample of digested sewage sludge and two soils were used in this study. The sources of all these materials and their shorthand designation that will be used for identification are shown in Table 1.

Table 1. Material sources and designations.

L-LIME	
L_C	National Gypsum Company #26 Chemical Hydrated Lime Manufactured at Bellefonte, Pennsylvania
L_D	Pfizer Minerals, Pigments & Metals Division Nelco™ Dolomitic Chemical Lime
L_Q	Pfizer Minerals, Pigments & Metals Division Nelco™ Masons Quicklime
W-WASTE SULFATE	E. I. Dupont DeNemours & Company Hydrofluoric Acid Production
A-FLY ASH	
A_M	Amax Fly Ash Company, Mitchell Power Station
A_L	Albright Power Station
S-SOIL	
S_D	Danville, Virginia Clayey Soil
S_L	Ladysmith, Virginia Sandy Soil
SS-SEWAGE SLUDGE	Philadelphia's Southwest Water Pollution Control Plant Lagoon B

[4] Lea, F. M., The Chemistry of Cement and Concrete, Third Edition, Chemical Publishing Co., Inc., New York, 1971.

The two hydrated and one quicklime were obtained from commercial sources and used as received. Both monohydrated calcitic and dolomitic limes were included. The quicklime, a granulated mason's lime, was also calcitic. The properties of these materials are presented in Table 2.

Table 2. Chemical and physical analysis of lime.

CHEMICAL PROPERTIES	Lime		
	L_C	L_D	L_Q
CaO, percent	73.5	44.5	95.3
MgO, percent	0.7	26.3	0.4
SiO_2, percent	1.1	1.4	1.0
Fe_2O_3, percent	0.2	0.5	0.1
Al_2O_3, percent	0.3	0.2	0.4
PHYSICAL PROPERTIES			
Loss on Ignition, 110°C, percent	0.9	0.4	-
Loss on Ignition, 950°C, percent	24.0	28.0	-
Sieve Analysis:			
Retained #100, percent	-	-	100
Passing #100, percent	100	98	
Passing #200, percent	99	90	
Passing #325, percent	95	85	

The waste sulfate used was a by-product from hydrofluoric acid production. It was chosen based on its solids content and reactivity. It was received as a hard, lumpy solid and was broken up in a Wiley mill to pass a 0.5 mm screen. Being a dry material, this allowed all the water requirement of the mixture to be satisfied by the sewage sludge. Also, from our previous studies of lime-fly ash-sulfate mixtures, it was judged to be one of the better materials, approaching the reactivity of pure calcium sulfate. X-ray diffraction patterns indicated the presence of anhydrous calcium sulfate with small amounts of calcium fluoride and gypsum. Analysis of this material is presented in Table 3.

Table 3. Chemical and physical analysis of waste sulfate (Hydrofluoric Acid Production).

Appearance	White, lumpy solid
Solids Content, percent	84
Loss on Ignition, percent	16
pH	12.1
Free water, percent	0
Combined water, percent	15
SiO_2 and insolubles, percent	3
Fe_2O_3 & Al_2O_3, percent	2
CaO, percent	54
SO_3, percent	43

Two low carbon fly ashes were included in the program. One of them was from the Mitchell Power Station, Courtney, Pennsylvania, of the West Penn Power Company and marketed through the Amax Fly Ash Corporation. The other was from the Albright Power Station, Albright, West Virginia, of the Allegheny Power Service Corporation. The chemical and physical analyses of the ashes are presented in Table 4. Both these fly ashes were extensively examined in our previous experimental program of lime-fly ash-sulfate-water mixtures. They represent the best (Amax) and the worst (Albright) of all the ashes we examined based on strength development.

The digested sewage sludge examined was from lagoon B of Philadelphia's Southwest sewage treatment plant. A typical analysis of the material from that lagoon is presented in Table 5. This particular pond was filled in the early 1950's. We removed about 60 lbs. (27 kg) from borings at a depth of approximately five feet. The top few inches were crusty and dry while underneath the water content was higher. The material obtained from the borings were combined and mixed to give a uniform sample mixture. It was this material that was used, and had a solids content of 33 percent.

Two soils, one clayey and the other sandy, were included in part of the study. These two types were examined as being representative of the main soil types in the area where the sewage sludge is located. Philadelphia is located on or near the boundary between two large physiographic provinces, the Piedmont Province and the Coastal Plain Province.

Table 4. Analysis of fly ash.

	Amax (A_M)	Albright (A_L)
Al_2O_3, percent	23.6	27.4
SiO_2, percent	45.6	53.6
Fe_2O_3, percent	14.3	10.4
CaO, percent	6.0	1.3
MgO, percent	1.2	0.7
K_2O, percent	1.8	2.1
Na_2O, percent	1.0	0.3
SO_3, percent	0.2	< 0.1
P_2O_5, percent	0.7	0.4
Loss on Ignition, 110°C, percent	6.4	0.1
Loss on Ignition, 950°C, percent	5.7	2.0
pH	10.7	10.9
Specific Gravity	2.43	2.12
Blaine Fineness, cm^2/gm	4,339	1,980
Surface Area, cm^2/cm^3	10,540	4,198
Residue on #325-wet, percent	10.4	18.9
Sieve analysis, percent		
Retained on #4	< 0.1	< 0.1
Retained on #8	< 0.1	< 0.1
Retained on #20	< 0.1	< 0.1
Retained on #50	0.8	0.4
Retained on #100	7.0	4.7
Retained on #200	8.4	21.9
Passing #200	83.8	73.0

Table 5. Chemical analysis of sewage sludge from lagoon B, Philadelphia, Pennsylvania[a]

Solids, percent	23.45
Ash, percent	13.58
Volatile Solid, percent	41.61
Heat of Combustion, Cal/Gr	1,995
Oil & Grease, g/kg	55.38
Zn, ppm Zn^{2+}	2,637
Cu, ppm Cu^{2+}	809
Cr, ppm Cr(VI)	1,458
Pb, ppm Pb^{2+}	1,713
Cd, ppm Cd^{2+}	22
Hg, ppm Hg^{2+}	196

[a]United States Department of Agriculture, Agricultural Research Center, Beltsville, Md., January 29, 1973.

The Piedmont Province stretches from Central Alabama to the Hudson River. The bedrocks of the Piedmont Province are quite old and have a long and complicated history. Time, temperature and pressure have changed what were once shales, sandstones and limestones of sedimentary origin and granites, lava flows, etc., of igneous origin into hard crystalline metamorphic rocks such as schists, phyllites, gneisses, etc. Since the Piedmont Province has been above water and exposed to the weathering processes for millions and millions of years, those hard crystalline rocks have weathered quite deeply. Though soils vary considerably throughout the Piedmont Province, they frequently are found to be micaceous sandy silts with minor amounts of clay.

The rocks of the Coastal Plain Province are usually partially consolidated sedimentary deposits of sands, gravels, silts and clays. A soil type commonly associated with these deposits in a clayey silty sand.

The site of the sewage sludge ponds and the proposed project is located less than a mile to the south and west of the confluence of the Delaware and Schuylkill Rivers. It lies in what appears to be the flood plain of these rivers. The area is flat, low lying and marshy. Soil borings from the site were not available to us but the soils are believed to be alluvial deposits composed of lenses, layers and pockets of organic silts, sands, gravels and clay. It appeared to us that, other than soil from the dike of the sludge lagoons, materials for constructing the I-95 approach fills for the Schuylkill River bridge would need to be obtained offsite.

In an attempt to obtain soils which might be representative of potential borrow areas in the Philadelphia area two materials were chosen. One soil chosen was a silty clay obtained from the B horizon of the Madison soil from near Danville, Virginia. This material is representative of many of the soils found in the Piedmont Province of Virginia, North Carolina, Maryland and Pennsylvania. The engineering properties of this soil are shown in Table 6. The second soil was a very silty sand obtained from the Coastal Plain Province near Ladysmith, Virginia. This soil is rather typical of many of the Coastal Plain deposits along the east coast. Its engineering properties, pedological classification, etc., are also shown in Table 6.

Procedures

Compaction - Samples of a compactible consistency were prepared with a modified Harvard Miniature Compaction Apparatus as developed by the Virginia Highway Research Council (5). This apparatus was used to simulate the compactive effort of AASHO T-180-731, Moisture Density Relations of Soils Using a 10-lb. Rammer and an 18-in. Drop. Five layers were used with the number of blows per layer adjusted to obtain the same density as a regular mold and hammer on test samples.

Sample Preparation - Specimens for moisture-density relationship and strength tests were prepared identically. The dry ingredients (fly ash, lime, sulfate waste and soil, when used) were placed in the mixing bowl of a Hobart Model N-50 Mixer. Dry blending at low speed proceeded for one minute. Then, the digested sewage sludge was added and mixing continued for another two minutes. For the samples prepared with quicklime, the mixture was allowed to sit in the covered bowl for one hour prior to final mixing. The material was then transferred to jars and two moisture samples were taken. Moisture-density relationships were obtained according to the procedure listed in the compaction section. Strength specimens were also prepared in this manner, weighed, wrapped in Saran Wrap and sealed. They were then cured for 28 days at 73 ± 3°F (22.8 ± 1.7°C).

At the end of the curing period the specimens were unwrapped and weighed to determine if any moisture had been lost. They were then tested for unconfined compressive strength on an Instron Model TT-D Universal Testing Instrument, at a constant loading rate of 0.2 cm/min (0.08 in/min). All 28-day strength measurements were the average of three specimens prepared from the same formulation.

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[5] Anday, M. D., "Curing of Lime-Stabilized Soils," Highway Research Board Record No. 29, 13-26, 1963.

Table 6. Index properties and mineralogical data of the soils

Property	Sandy Soil (Ladysmith)	Clayey Soil (Danville)
Specific Gravity of Solids	2.65	2.77
Liquid Limit	16	63.7
Plastic Limit	15	42.4
Plasticity Index	1	21.3
Shrinkage Limit	13	39
Maximum dry unit wt. AASHO T99	117.0 p.c.f. ($1874\ kg/m^3$)	94.0 p.c.f. ($1506\ kg/m^3$)
Optimum moisture content AASHO T99	15.0 percent	28.5 percent
Maximum dry unit wt. AASHO T180	127.6 p.c.f. ($2044\ kg/m^3$)	109.0 p.c.f. ($1746\ kg/m^3$)
Optimum moisture content AASHO T180	10.2 percent	20.9 percent
Percent Passing Sieve No.		
10	100	100
20	98.2	76.7
40	90.0	47.3
60	63.5	29.5
140	30.0	13.5
200	16.5	9.5
Pedological Classification	Sassafras	Madison
Mineralogical Composition	Approx.	The whole soil consists largely of Kaolinite and mica with a little mica and a trace of gibbsite. The clay fraction consists principally of Kaolinite with some Mica-Vermiculite-chlorite. About 10 percent gibbsite was observed and small amounts of goethite and hematite were also present.
Kaolinite	70	
Illite-Vermiculite	20	
Hematite	-	
Goethite	5-10	
Halloysite	Minor	
Quartz	Minor	
Feldspar	-	
Mica	-	

Engineering Properties - Selected mixtures were evaluated for durability by freeze-thaw resistance and wet-dry stability, volume change and permeability including chemical analysis of the leachate. Standard ASTM procedures used were: D560-71, Freezing and Thawing Tests of Compacted Soil-Cement Mixtures; D559-71, Wetting and Drying Tests of Compacted Soil-Cement Mixtures. Permeability was measured using the falling head technique.

Leachate Analysis - Run-off from the permeability tests was collected for analysis of pH, "P" alkalinity, "T" alkalinity, calcium hardness, total hardness, sulfate, fluoride, and the metal ions of copper, mercury, zinc, chromium, cadmium and sodium.

The pH of the samples were measured with a glass electrode. Alkalinity, which has little or no relation to pH, refers to the amount of various alkalies in the water which are capable of neutralizing acids. "P" alkalinity was determined by titrating with a standard acid solution using phenolphthalein indicator. The titration end point was at pH 8.3. This procedure measures the hydroxide content and half the carbonate present. "T" alkalinity or total alkalinity from hydroxides, carbonate bicarbonates, etc., was obtained by titrating with the standard acid solution to the methyl orange end point at pH 4.5 to 5.1.

Calcium hardness is a measure of the calcium ion concentration present. Total hardness indicates the combined calcium and magnesium ion content. Both were determined by complexiometric titration, using different indicators. Sulfate ion was determined by the turbidimetric method. The only source of sulfate in the leachate was the waste sulfate in the mixtures, so this value gave us a measure of the reactivity of the mixture. Fluoride was determined using a fluoride sensitive electrode. It was included since the sulfate waste was from hydrofluoric acid production, and some residual calcium fluoride was known to be in the waste. The metal ions, copper, mercury, zinc, chromium, cadmium and sodium were analyzed by atomic absorption spectrophotometry.

RESULTS

Formulation

Based on previous knowledge of the lime-fly ash-sulfate-water system, proportions of the various constituents were chosen that would give a satisfactory and economical embankment material. A lime/sulfate ratio of 0.5 was used in this work based on previous experiments which showed that the 28-day compressive strength was constant at 1200 p.s.i. (8274 kN/m^2) when the lime/sulfate ratio was varied from 0.38 to 0.67 at a constant lime level and with Amax fly ash. Over this range the 7-day compressive strength varied from 490 p.s.i. to 360 p.s.i. (3378 to 2482 kN/m^2).

Lime additions of 3, 5 and 8 weight percent were felt to be adequate for these mixtures. The 1200 p.s.i. (8274 kN/m^2) compressive strength cited above was with three percent lime. Since it was not known to what extent the organics in the sewage sludge would lower the strength gain, the higher lime levels, five and eight percent, were included.

The last of the three dry ingredients, fly ash, comprised the rest of the dry mixture. Therefore, the three formulations examined for this stage of the program were:

Formulation A:	3% lime;	6% sulfate;	91% fly ash
Formulation B:	5% lime;	10% sulfate;	85% fly ash
Formulation C:	8% lime;	16% sulfate;	76% fly ash

Sewage sludge was handled as water and used at a ratio of sludge to dry ingredients that gave a maximum dry density.

Moisture-Density Determination

To determine the optimum sewage sludge content, the moisture-density relationship was investigated. The intermediate lime addition level, five percent, was examined for both fly ashes. In addition, formulation B and C were examined with quicklime. This was done since this lime was granular as compared to the very fine particle size of the other two lime types. From Figures 1 and 2, the following optimum moisture contents were obtained:

	Optimum Moisture Content (percent)
L_C (5%) WA_L	19
L_C (5%) WA_M	20
L_Q (5%) WA_L	22
L_Q (5%) WA_M	23
L_Q (8%) WA_L	22

Some difficulty was encountered in preparing these as well as all other specimens, caused by the non-homogeneous nature of the sewage sludge. Though care was taken to remove large pieces of debris, there were still pieces or chunks of rubber, twigs, cigarette butts, etc., that were compacted into the samples.

When using water instead of sewage sludge, the optimum moisture content for similar mixtures with Albright fly ash was 20 percent and for Amax fly ash was 24 percent.

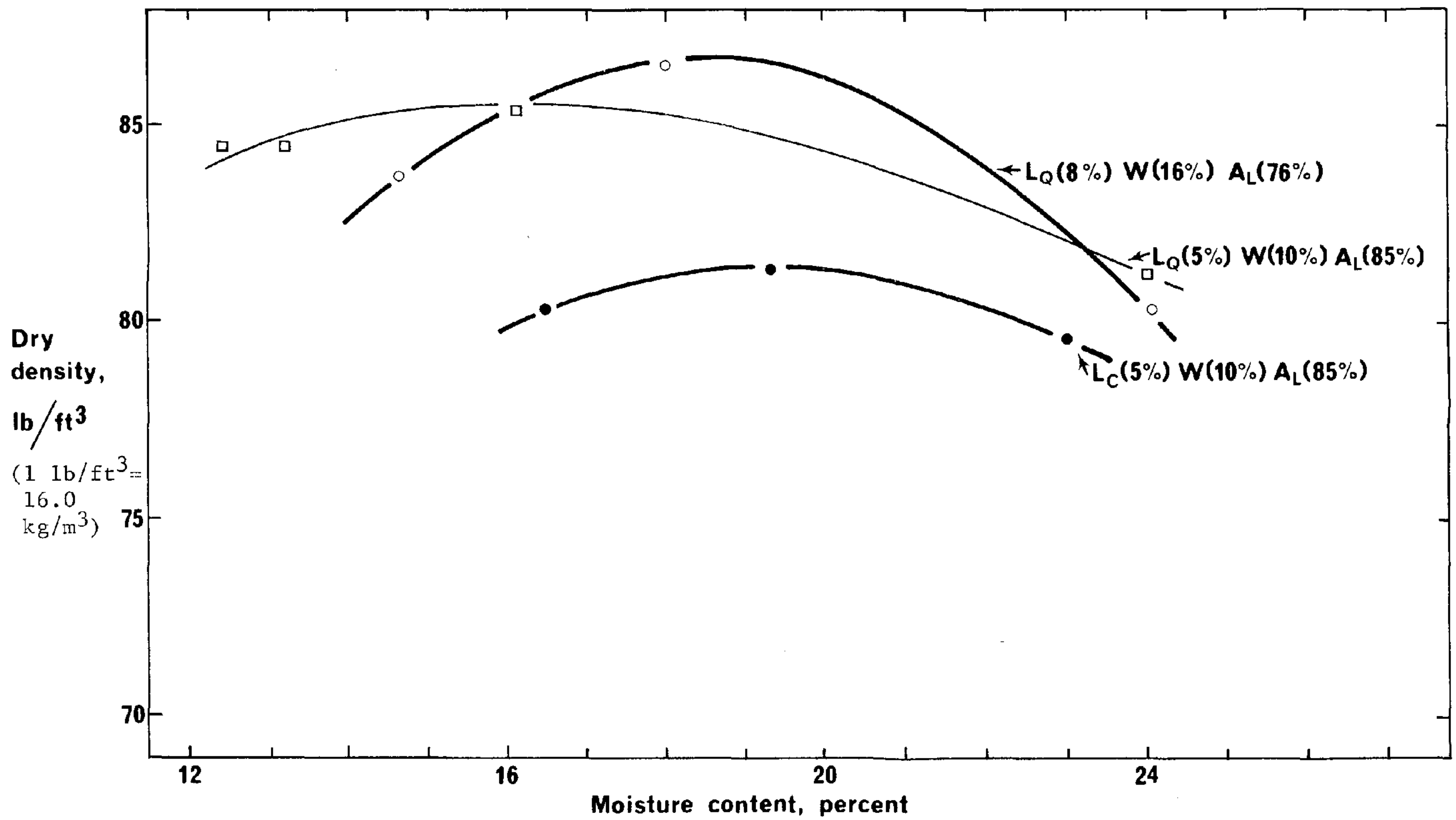

Figure 1. Moisture-density relationship with Albright fly ash.

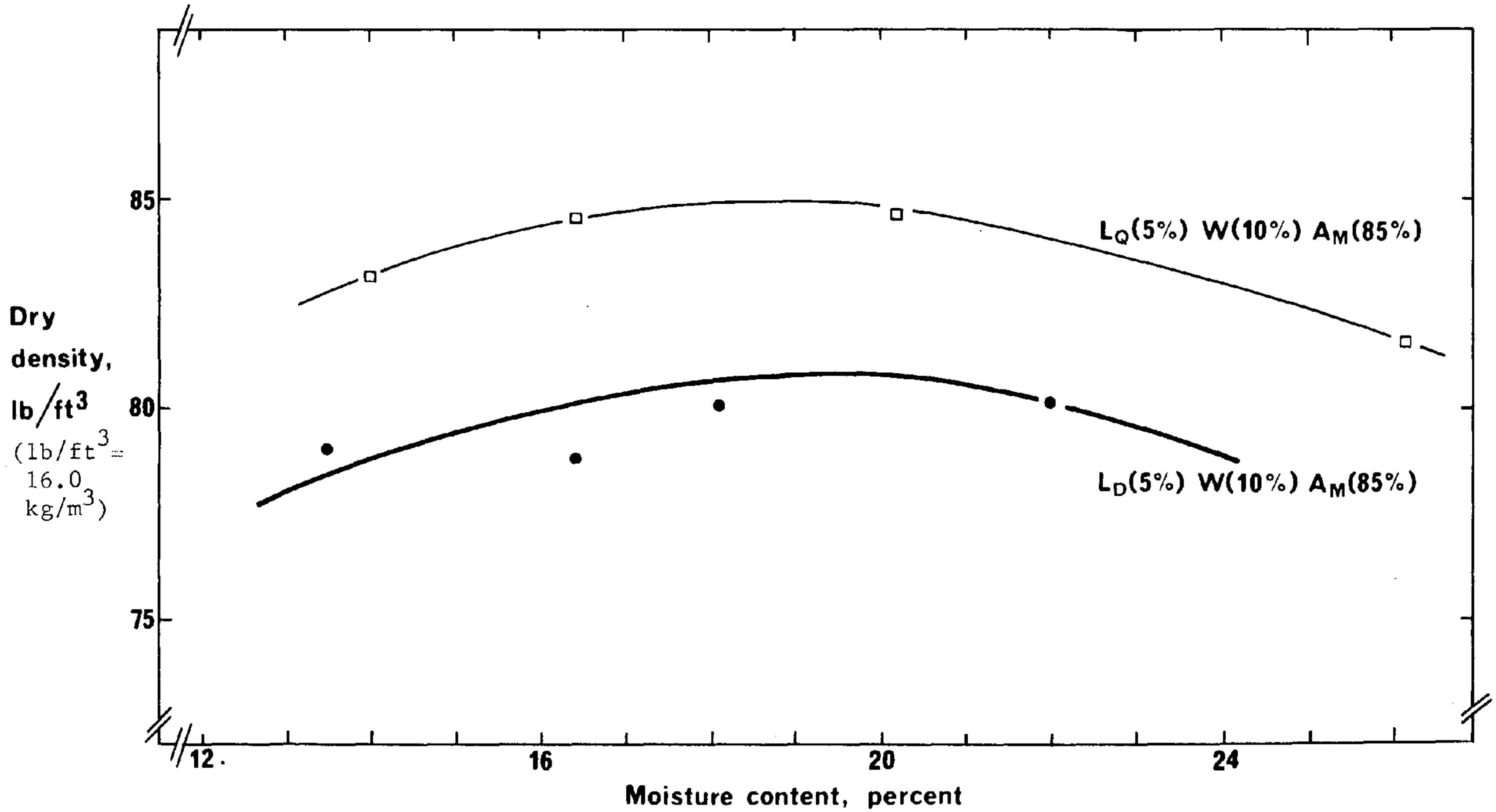

Figure 2. Moisture-density relationship with Amax fly ash.

Strength Development

A complete factorial experimental design was utilized for the first phase of the strength development studies. Specimens from formulations A, B and C for each of the three lime types were compacted for testing at zero and 28 days. Tables 7 through 9 present the dry density and compressive strength for all these combinations. Figure 3 gives a visual presentation of the data.

Table 7. Density and strength of samples from formulation A[a] using sewage sludge.

Sample	Lime[d]	Fly Ash[d]	Dry Density, p.c.f.[e]	Compressive Strength, p.s.i.[f]	
				uncured	cured 28 days
A-0[b,c]	L_D	A_M	85.3	-	690
A-1[c]	L_C	A_M	82.9	55	1085
A-2	L_C	A_M	76.3	25	195
A-3	L_C	A_L	67.7	15	65
A-4	L_D	A_M	77.4	20	80
A-5	L_D	A_L	80.2	15	80
A-6	L_Q	A_M	85.0	35	140
A-7	L_Q	A_L	84.4	15	20

[a] 3 percent lime, 6 percent sulfate waste, and 91 percent fly ash.

[b] 3 percent lime, 97 percent fly ash.

[c] Prepared using only distilled water.

[d] See Table 1 for designations.

[e] 1 p.c.f. = 16.0 kg/m^3.

[f] 1 p.s.i. = 6.89 x 10^3 N/m^2.

Table 8. Density and strength of samples from formulation B[a] using sewage sludge.

Sample	Lime[(c)]	Fly Ash[(c)]	Dry Density, p.c.f.[(d)]	Compressive Strength, p.s.i.[(e)] uncured	cured 28 days
B-1[(b)]	L_D	A_L	86.0	20	860
B-2	L_C	A_M	77.9	35	195
B-3	L_C	A_L	80.5	20	60
B-4	L_D	A_M	79.7	35	200
B-5	L_D	A_L	83.0	20	90
B-6	L_Q	A_M	85.7	30	150
B-7	L_Q	A_L	87.1	20	25

[a]5 percent lime, 10 percent sulfate waste and 85 percent fly ash.

[b]Prepared using only distilled water.

[c]See Table 1 for designations.

[d]1 p.c.f. = 16.0 kg/m^3.

[e]1 p.s.i. = 6.89×10^3 N/m^2.

Table 9. Density and strength of samples from formulation C[a] using sewage sludge.

Sample	Lime[c]	Fly Ash[c]	Dry Density, p.c.f.[d]	Compressive Strength, p.s.i.[e]	
				uncured	cured 28 days
C-1[b]	L_C	A_M	89.5	60	1725
C-2	L_C	A_M	81.1	40	325
C-3	L_C	A_L	86.4	25	140
C-4	L_D	A_M	80.6	30	255
C-5	L_D	A_L	85.0	30	120
C-6	L_Q	A_M	88.1	55	355
C-7	L_Q	A_L	90.4	20	30

[a] 8 percent lime, 16 percent sulfate waste, 76 percent fly ash.

[b] Prepared using only distilled water.

[c] See Table 1 for designations.

[d] 1 p.c.f. = 16.0 kg/m^3.

[e] 1 p.s.i. = 6.89×10^3 N/m^2.

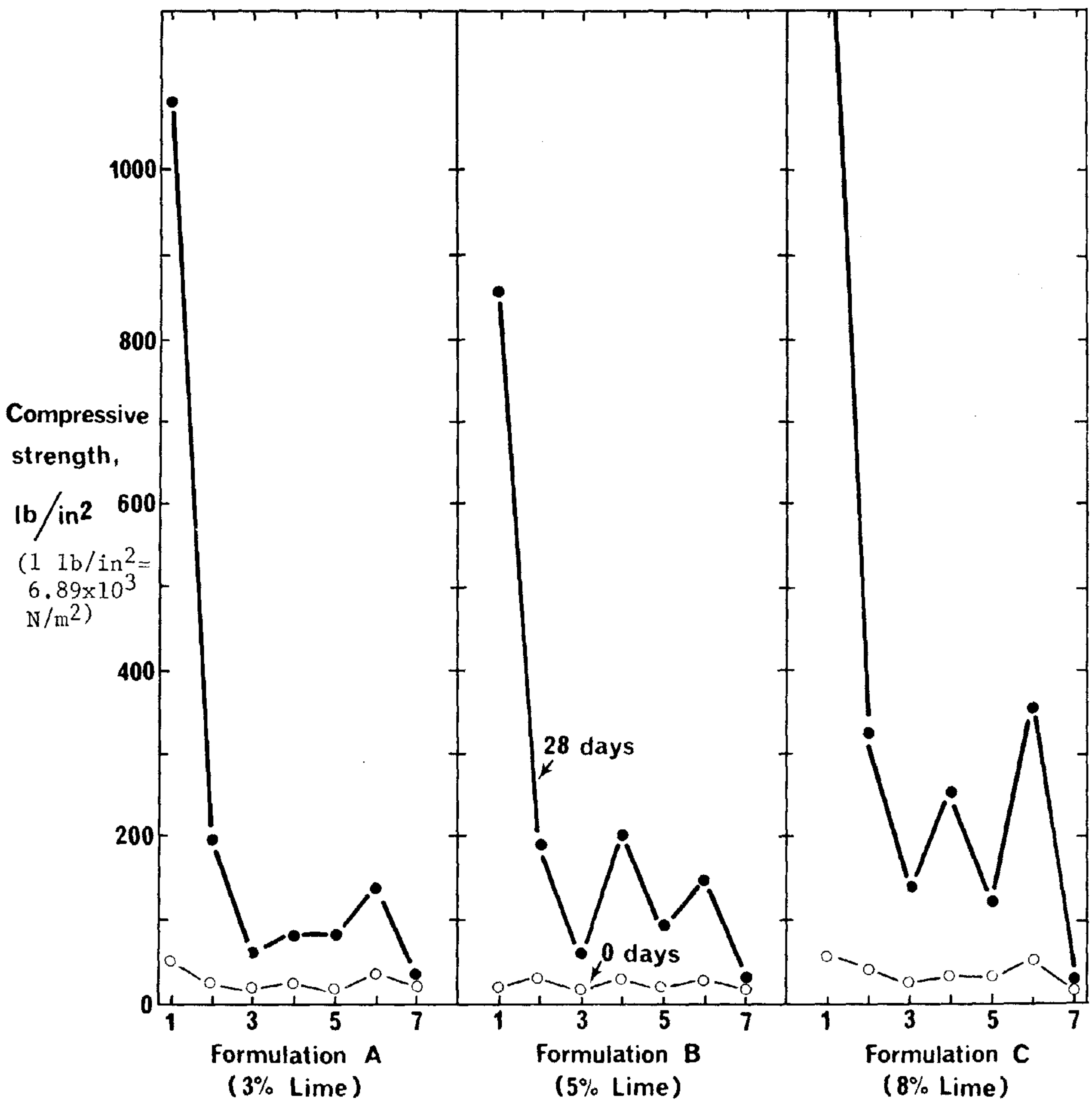

Figure 3. Compressive strength at zero and 28 days.

Samples designated as A-1, B-1 and C-1 were prepared with water instead of sewage sludge and represent the highest strength that would be expected from these mixtures. These 28-day values were in the range of 860 to 1725 p.s.i. (5929-11,893 kN/m^2). The uncured strengths, in the range of 20 to 60 p.s.i. (138 to 414 kN/m^2) were not much different from the results when sewage sludge was used. This was expected since no cementing reactions had taken place in this time period. Formulation A-0 was examined using no sulfate waste and pure water, to give an indication of the effect the sulfate played on strength development.

The criterion for acceptability of these mixtures for use in an embankment was that the unconfined compressive strength of the compacted specimens should be 50 p.s.i. (345 kN/m^3) greater after 28 days of curing than uncured specimens of the same composition. Of the 18 formulations examined, only four failed to develop 50 p.s.i. (345 kN/m^2) strength over the uncured strength by 28 days. Three of these were the Albright fly ash in combination with quicklime. The other one that failed this criterion also used Albright fly ash. Three other Albright formulations using hydrated lime exhibited strength gains of the order of 50 to 70 p.s.i. (345 to 483 kN/m^2).

For mixtures incorporating Amax fly ash, all the formulations were found acceptable by the 50 p.s.i. (345 kN/m^2) strength gain after 28 days criterion. A lime level as low as three weight percent was found to be adequate when used in combination with Amax fly ash. These results indicated the importance of the fly ash variable in strength development.

The statistical tool used to evaluate the results of the compressive strength data was the analysis of variance, which is ideally suited for factorial design. The purpose of the analysis was to supply criteria for determining whether a given variable or factor was influencing the results. The significance of factors or variables was tested by applying the F ratios first between the interaction of factors, then main factors and the pooled term or the mean square error term. The mean square error term represents the experimental error. When the F ratio shows significance for the factor, the levels or component parts of it can be analyzed several ways. One way is to plot population means versus factors. This is called a simple effects profile of factors. These profiles show main effects and interaction effects readily.

Another way of differentiating between levels of factors is to apply the $Tukey_{HSD}$ (honestly significant difference) test. The Tukey procedure has the general property that all tests on differences between pairs have a significance which is at most equal to α. It is calculated from the formula

$$HSD = q_{\alpha}\sqrt{\frac{\hat{s}_w^2}{n}}$$

where $\hat{s}_w^2$ is the within group variance estimate, q_α is the given α level distribution of the Studentized range statistic and n is the number of means.

The compressive strength data were analyzed using three separate two-way analyses of variance, one for each lime level (or formulation). Before analysis it was necessary to convert the values to logarithmic form. This was necessary from the observations of our previous work on lime-fly ash-sulfate-water systems that the range of replicates divided by their means was approximately constant.

In the analyses of the data the F-ratios showed the factors and their interactions did influence the strengths. This is dramatically shown in Table 10 where the experimental F-ratios and the F-ratios at 0.95 and 0.99 significance levels are presented. This means that the choice of each individual material, lime, sulfate waste and fly ash was important in determining the strength.

Table 10. F-ratio test for the compressive strength data.

Formulation	Factor[a]	Degrees of Freedom	Mean Squares	F-Ratio	F-Statistic .05	F-Statistic .01
	LA	2	0.35205	154.91	3.89	6.93
A - 3%	A	1	0.78814	346.81	4.75	9.33
lime level	L	2	0.17419	76.65	3.89	6.93
	MSE	12	0.00227	-	-	-
	LA	2	0.09161	24.44	3.89	6.93
B - 5%	A	1	1.34789	358.40	4.75	9.33
lime level	L	2	0.21962	58.61	3.89	6.93
	MSE	12	0.00375	-	-	-
	LA	2	0.23594	90.80	3.89	6.93
C - 8%	A	1	1.49939	577.05	4.75	9.33
lime level	L	2	0.17271	66.47	3.89	6.93
	MSE	12	0.00260	-	-	-

[a]A-fly ash, L-lime, MSE-mean square error.

To better illustrate the results obtained, profiles of simple effects for the three formulations are presented in Figures 4 to 6. In all three figures it was seen that Amax fly ash performed better than Albright fly ash. With regard to lime, the Amax fly ash consistently gave the highest strengths when paired with hydrated calcitic lime. With Albright fly ash, the dolomitic monohydrated lime was better. Quicklime always was poor in combination with Albright fly ash, but did not show a definite trend with the better, Amax fly ash.

In order to quantify these observations, the Tukey test was used to compare the mean strength values. Table 11 presents these results. They indicated that the dolomitic lime was the superior lime when only the Albright fly ash was considered, and was the poorest of the three limes when examined in combination with only the Amax fly ash. The ranking of the limes was consistent with Albright fly ash at the three addition levels. With Amax fly ash, the five percent lime by weight addition showed no significance for the lime factor. For the other two addition levels, only the quicklime and the hydrated calcitic lime changed rankings.

The effect of the amount of lime on these various combinations can best be seen in Figure 7. Here the strength was plotted as a function of the lime weight percent. Again, it was obvious from this plot that formulations prepared with Amax ash were better than those prepared with Albright ash. It also showed that for combinations incorporating Amax fly ash, the greatest percent strength gain for the high calcium limes was when they were increased from five to eight percent. The increase from three to five percent did not produce as large an increase in strength except for the dolomitic lime. For the Albright fly ash, a greater strength increase was experienced with the larger hydrated lime additions than with the quicklime addition.

The quicklime did not perform as well as the hydrated limes when compared using calcium oxide equivalents rather than a weight basis. This was felt to arise from the different properties of the limes. The quicklime was granular, with almost 100 percent retained on a 100 mesh sieve, while the hydrated limes had over 85 percent pass a 325 mesh sieve. Therefore, the distribution of the quicklime throughout the mixture especially at these low addition levels was not as thorough or as intimate as with the hydrated limes. Alexander, Smith and Sherman (6) found the coarser quicklime to be better than the finer, hydrated limes for soil stabilization. However, their procedure called for loose curing of the mixture for 24 hours. This would allow for hydration of the lime and time for dissolution before compaction. Our procedure was to loose cure for an hour before sample compaction. The effect of longer times of mellowing was not examined.

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[6] Alexander, M. L., Smith, R. E. and Sherman, G. B., "The Relative Stabilizing Effect of Various Limes on Clayey Soil," State of California, Division of Highways Materials and Research Department, Research Report 633101, December 1971.

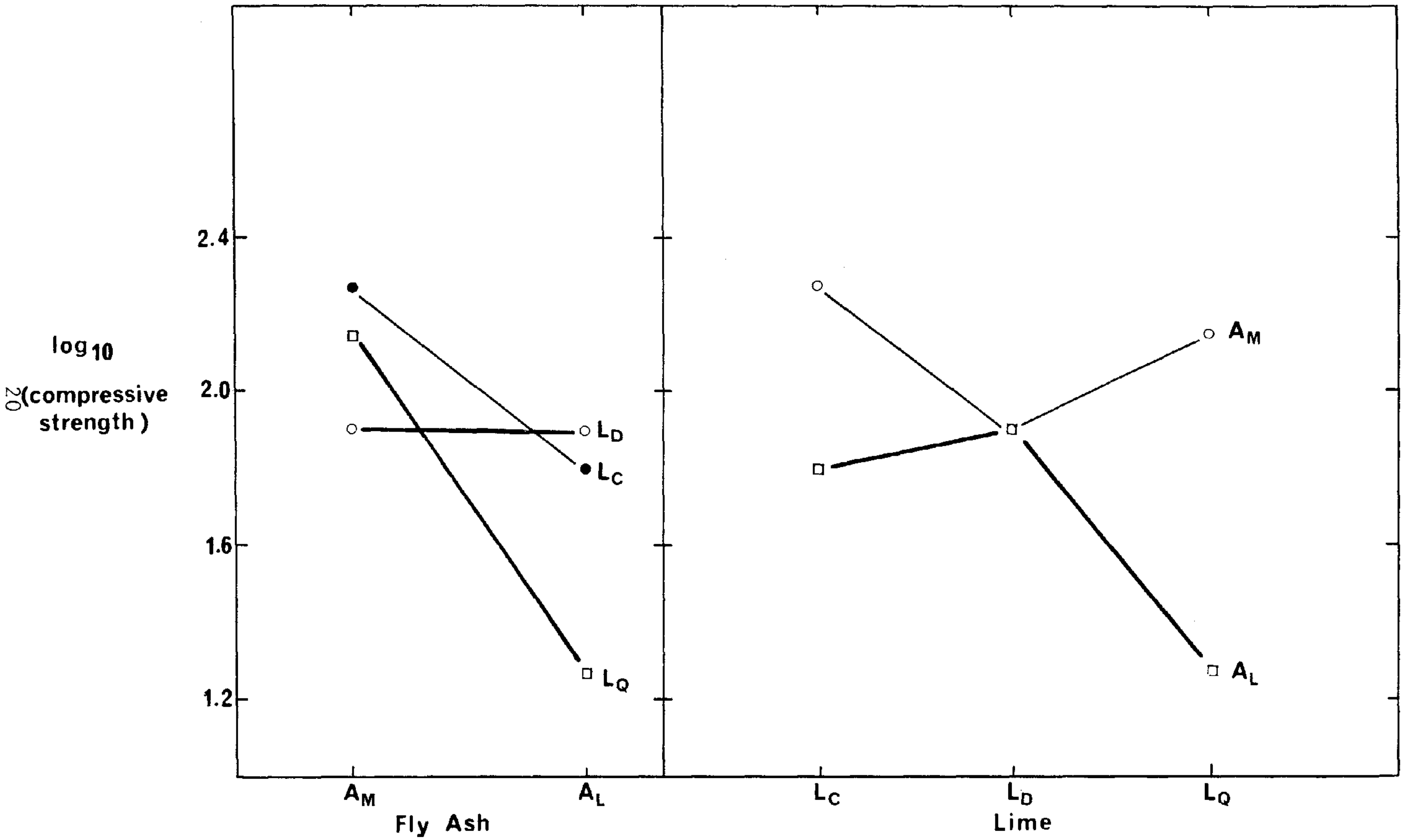

Figure 4. Simple effects profiles for formulation A (3 percent lime addition).

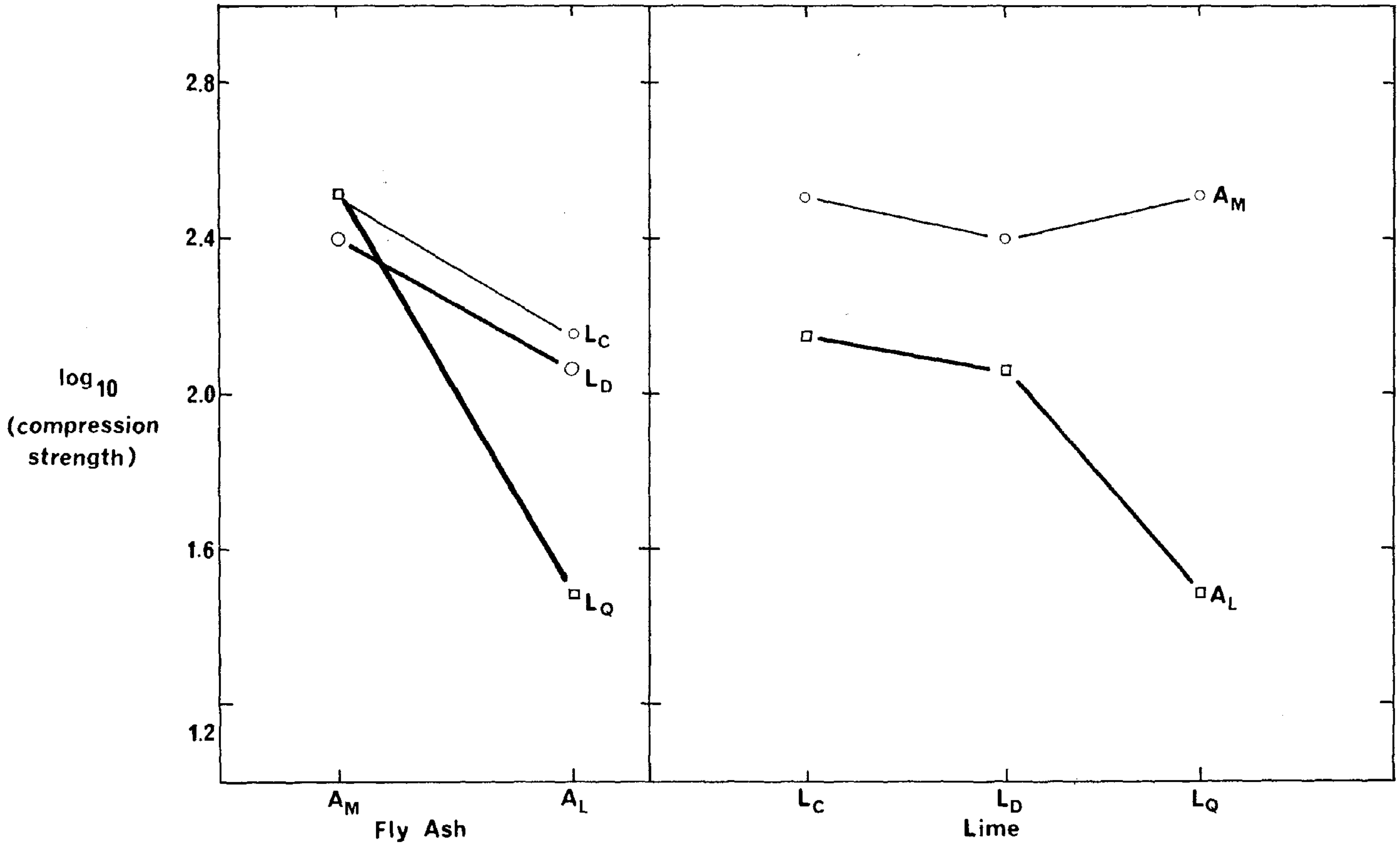

Figure 5. Simple effects profiles for formulation B
(5 percent lime addition).

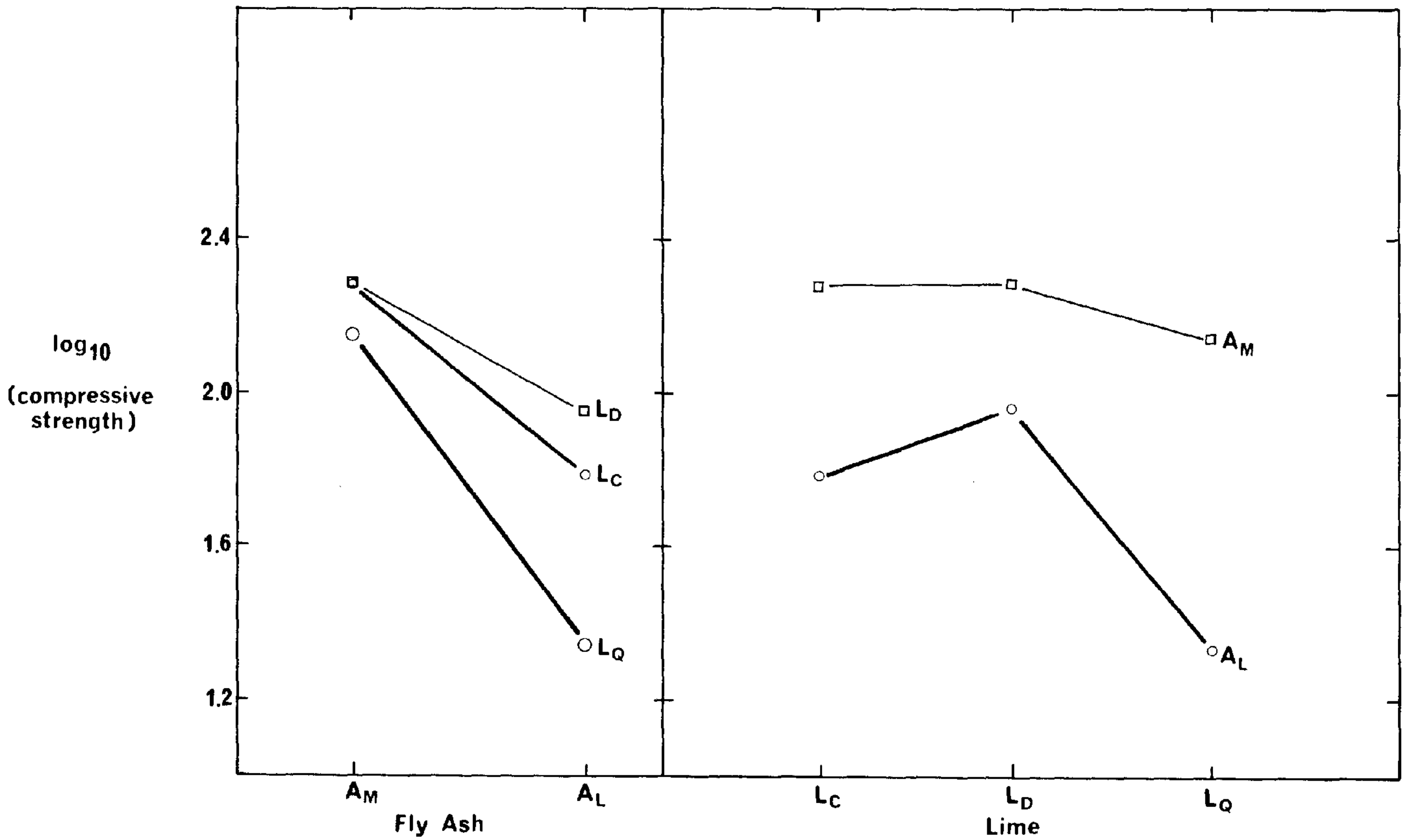

Figure 6. Simple effects profiles for formulation C (8 percent lime addition).

Table 11. Comparison of means by the $Tukey_{HSD}$ test[a].

Fly Ash	Ranking[b] of Limes		
FORMULATION A - 3 percent lime addition, HSD = 0.104			
	1	2	3
A_M	L_C 2.277 (195)	L_Q 2.141 (140)	L_D 1.903 (80)
A_L	L_D 1.904 (80)	L_C 1.799 (65)	L_Q 1.271 (20)
FORMULATION B - 5 percent lime addition, HSD = 0.134			
	1	2	3
A_M	L_D 2.290 (200)	L_C 2.284 (195)	L_Q 2.166 (150)
A_L	L_D 1.959 (90)	L_C 1.792 (62)	L_Q 1.350 (25)
FORMULATION C - 8 percent lime addition, HSD = 0.111			
	1	2	3
A_M	L_Q 2.519 (355)	L_C 2.512 (325)	L_D 2.401 (255)
A_L	L_C 2.149 (140)	L_D 2.070 (120)	L_Q 1.484 (30)

[a]Data converted to logarithmic form. Values in parenthesis are the means.
[b]Underlined values were not significantly different.

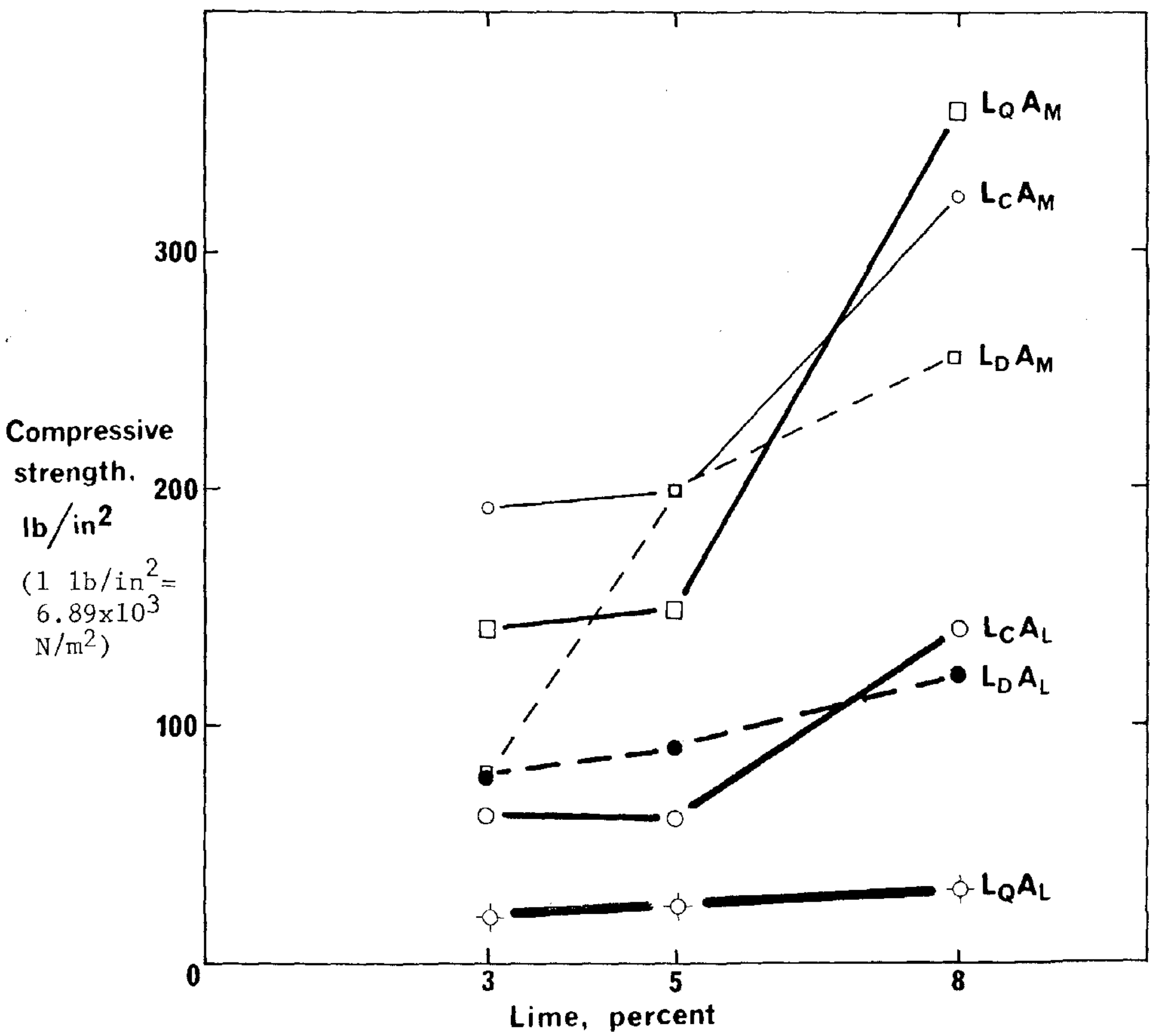

Figure 7. Compressive strength at various lime addition levels.

Engineering Properties

In an endeavor to further evaluate selected combination of lime, fly ash, sulfate, and on site sewage sludge for potential use as general fill material, several engineering tests were conducted in the Soil Mechanics Laboratories at the University of Virginia. These studies involved 1) durability (freeze-thaw and wet-dry) tests, 2) permeability tests including chemical analysis of the leachate, 3) volume change, and 4) strength tests. Two formulations representing promising formulations were chosen. They were:

C-3:	8 percent L_D;	16 percent sulfate waste;	76 percent A_M
B-2:	5 percent L_C;	10 percent sulfate waste;	85 percent A_L

The first formulation represents an acceptable mixture based on strength development. It had a compressive strength of 255 p.s.i. (1758 kN/m^2) at 28 days. The other formulation was chosen to represent a borderline case, having a 28-day strength of only 65 p.s.i. (448 kN/m^2).

Table 12 presents the results from this battery of tests. Freeze-thaw resistance was measured by two methods. In one case the samples were put through twelve cycles of freezing and thawing and then tested for compressive strength. Another set of specimens were treated according to the method of the standard specification used and brushed after each cycle. A large effect from the freezing and thawing was noted for both tests.

The wet-dry stability results were interesting. For the better mixture, C-3, the samples gained in strength, though being subjected to alternate cycles of wetting and drying. This meant that the hydration reactions responsible for strength proceeded whenever there was moisture present. For the poorer formulation, no strength gain was noted.

The coefficient of permeability was measured only on the better formulation. The B-2 combination specimens cracked during saturation. For C-3, a coefficient of 3.7×10^{-5} cm/sec was measured. This value was quite low and was indicative of a fairly impermeable material.

The leachate analysis indicated that some of the starting materials were being washed out of the sample. The analyses presented in Table 12 were performed on the solution phase of the material leached from the specimens. Results from formulation B-2 were suspect since the specimen cracked sometime during the permeability test. In all cases a small amount of white precipitate was present in the sample. With both formulations the pH was quite high and indicative of loss of calcium hydroxide. The calcium and sulfate ion content were also appreciable. Therefore, both lime and sulfate waste were being lost from the specimens. The fluoride was measured at 1 p.p.m. This was double the amount that was in the water run through the permeability apparatus. No heavy metals

Table 12. Engineering properties of selected mixtures.

	Formulation[a]	
	C-3	B-2
Freeze-Thaw Resistance		
Strength:		
7-day moist cured	65 p.s.i. (448 kN/m^2)	30 p.s.i. (207 kN/m^2)
unbrushed after 12 cycles	broke on 10th cycle	10 p.s.i. (69 kN/m^2)
Weight Loss on Brushing	36.8%	63.4%
Maximum Moisture	-	46.2% (11th cycle)
Maximum Volume Change[b]	18% (9th cycle)	16.8% (11th cycle)
Curing Volume Change[c]	-	0.6%
Wet-Dry Stability		
Strength:		
7-day moist cured	65 p.s.i. (448 kN/m^2)	30 p.s.i. (207 kN/m^2)
after 12 cycles	120 p.s.i. (827 kN/m^2)	20 p.s.i. (138 kN/m^2)
Maximum Moisture	35.6% (12th cycle)	31.3% (12th cycle)
Maximum Volume Change	3.3% (7th cycle)	0.9% (2nd cycle)
Permeability		
Coefficient of Permeability	3.7×10^{-5} cm/sec	samples cracked during saturation
Leachate Analysis		
pH	12.5	11.9
"P" Alkalinity, ppm Ca^{2+}	584	160
"T" Alkalinity, ppm Ca^{2+}	712	196
Calcium Hardness, ppm Ca^{2+}	1120	348
Total Hardness, ppm Ca^{2+}	1152	400
Sulfate, ppm $SO_4^{=}$	1460	280
Sodium Fluoride, ppm F^-	1	1
Copper, ppm Cu^{2+}	< 0.1	2
Mercury, ppm Hg_2^{2+}	< 0.5	< 0.5
Zinc, ppm Zn^{2+}	< 0.05	< 0.05
Chromium, ppm Cr(VI)	< 0.15	< 0.15
Cadmium, ppm Cd^{2+}	< 0.05	< 0.05

[a]Formulation C-3 was 8 percent lime, 16 percent sulfate waste and 76 percent fly ash.
Formulation B-2 was 5 percent lime, 10 percent sulfate waste and 85 percent fly ash.

[b]Increase in volume during freeze-thaw test based upon the volume of the molded sample.

[c]Increase in volume during the 7-day curing period based upon the volume of the molded sample.

were found in the effluent, except for copper in one instance. These metals were present in the sewage sludge. At the high pH of the effluents, these metals would be precipitated as the metal hydroxides or oxides. The solubility product for these compounds have been reported and are:

$$Cd(OH)_2 - 2 \times 10^{-14};\ Cr(OH)_3 - 1 \times 10^{-17};\ Cu(OH)_2 - 2 \times 10^{-19};$$

$$HgO - 3 \times 10^{-26};\ \text{and}\ Zn(OH)_2 - 2 \times 10^{-17}.$$

Therefore, it would not be expected that these precipitates would add to the total ion content of the leachate.

Soil Addition

The effect of replacing part of the fly ash with soil in the dry mixture was examined using the two formulations chosen for detailed evaluation. Soil substitution levels of 30, 50 and 70 percent of the fly ash were used. It was felt that these levels would be necessary to understand the effect of soil on the system. Also, the knowledge gained would be useful for the utilization of sewage sludge in areas where acceptable soil was scarce as well as where it was abundant.

The first necessity was to create the moisture-density curves since the soils had different water requirements than the fly ashes. The results are presented in Figures 8 and 9. Again, the use of sewage sludge instead of water, and the variability of that material produced scatter in the moisture-density curves.

The results of strength studies are presented in Tables 13 and 14. It can be seen from the data that the acceptable formulation, C-3, was improved by addition of the clayey soil while the sandy soil was detrimental. For the borderline formulation, B-2, dramatic strength increases were obtained with both soils and at all replacement levels. This can best be seen from the profiles of simple effects presented in Figures 10 and 11. The profile also shows that the clayey soil performed better than the sandy soil when gauged by strength development. Substitution of soil for part of the fly ash resulted in a material with strengths which are adequate for embankment construction.

In statistically handling the data from Tables 13 and 14, a slightly different procedure than before was used due to the additional comparison of the control formulation incorporated into this analysis. Four, one-way analyses of variance were performed and the results are presented in Table 15. In all cases except one, the F-ratios showed that the factors influenced the strength. The one case where significance was not found was in the formulation with the better fly ash, Amax, in combination with the sandy soil.

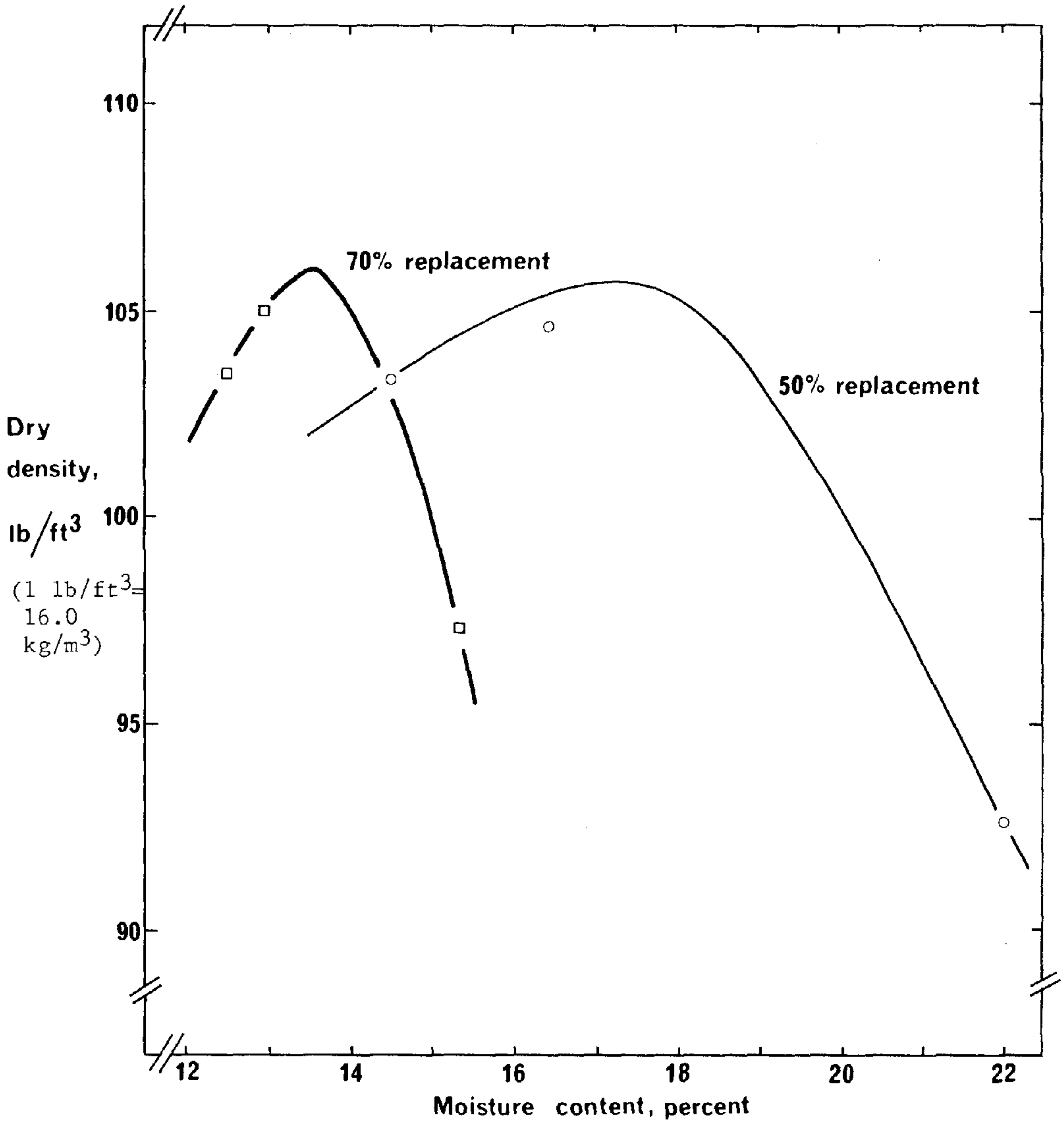

Figure 8. Moisture-density relationship when replacing fly ash by Danville B soil.

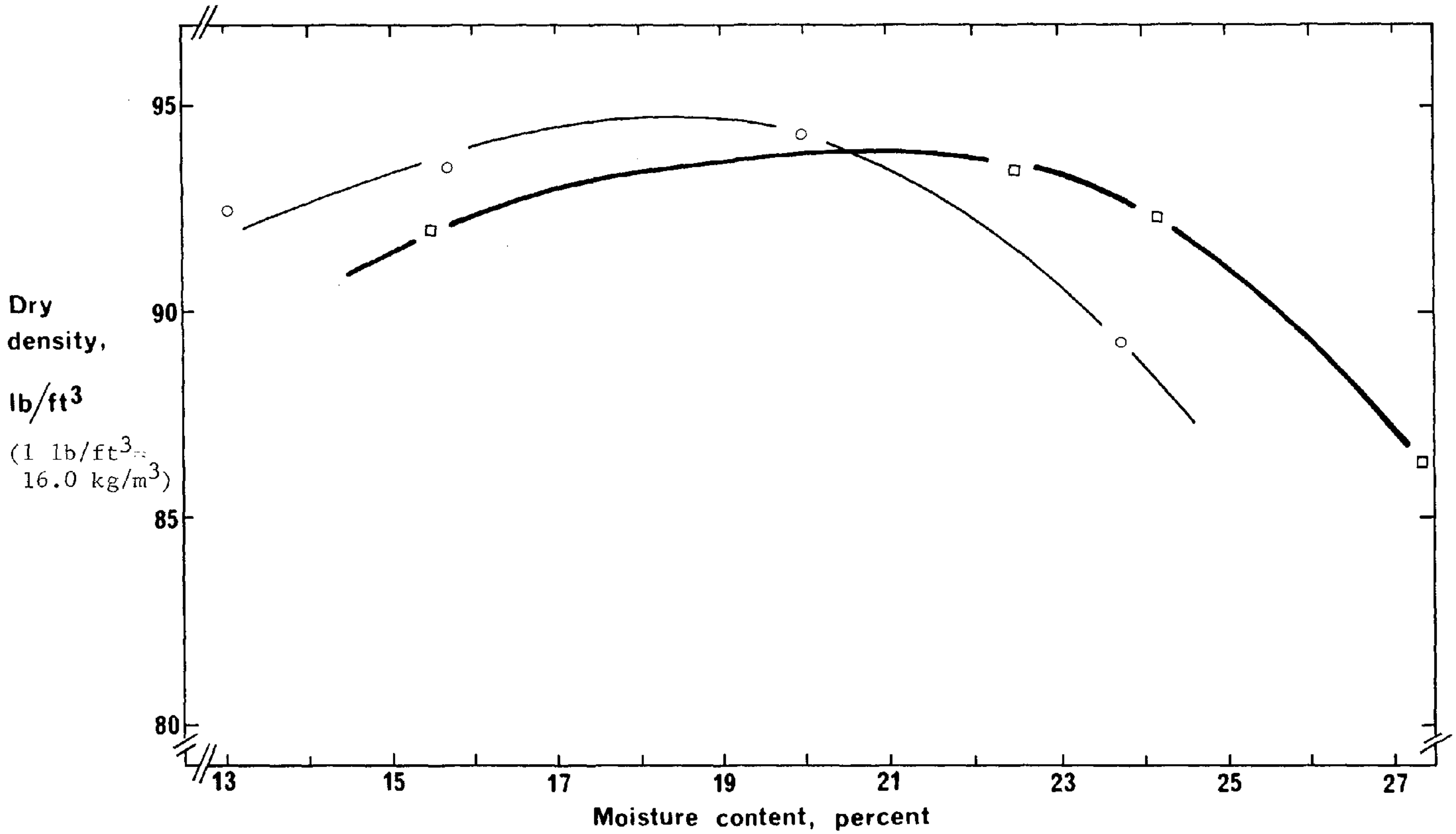

Figure 9. Moisture-density relationship when replacing fly ash by Ladysmith Soil.

Table 13. Soil replacement in formulation C-3[a].

Soil[b] Type	Soil Replacement,[c] percent	Dry Density, p.c.f.[(d)]	Compressive Strength, p.s.i.[(e)]	
			uncured	cured 28 days
-	-	80.4	30	255
S_D	30	95.8	70	550
S_D	50	102.5	90	695
S_D	70	106.5	75	350
S_L	30	90.3	70	175
S_L	50	93.4	90	250
S_L	70	96.5	95	215

[a]Formulation C-3: 8 percent Dolomitic lime, 16 percent Sulfate waste, 76 percent Amax fly ash.

[b]S_D - Danville, clayey soil; S_L - Ladysmith, sandy soil.

[c]Percentage of fly ash replaced.

[d]1 p.c.f. = 16.0 kg/m^3.

[e]1 p.s.i. = 6.89 x 10^3 N/m^2.

Table 14. Soil replacement in formulation B-2[a].

Soil[b] Type	Soil Replacement,[c] percent	Dry Density, p.c.f.[(d)]	Compressive Strength, p.s.i.[(e)] uncured	Compressive Strength, p.s.i.[(e)] cured 28 days
-	-	80.5	20	60
S_D	30	96.5	30	325
S_D	50	102.2	45	260
S_D	70	113.6	60	330
S_L	30	91.5	45	125
S_L	50	94.9	85	200
S_L	70	96.2	-	260

[a]Formulation B-2: 5 percent Calcitic lime, 10 percent Sulfate waste, 85 percent Albright fly ash.

[b]S_D - Danville, clayey soil; S_L - Ladysmith, sandy soil.

[c]Percentage of fly ash replaced.

[d]1 p.c.f. = 16.0 kg/m^3.

[e]1 p.s.i. = 6.89 x 10^3 N/m^2.

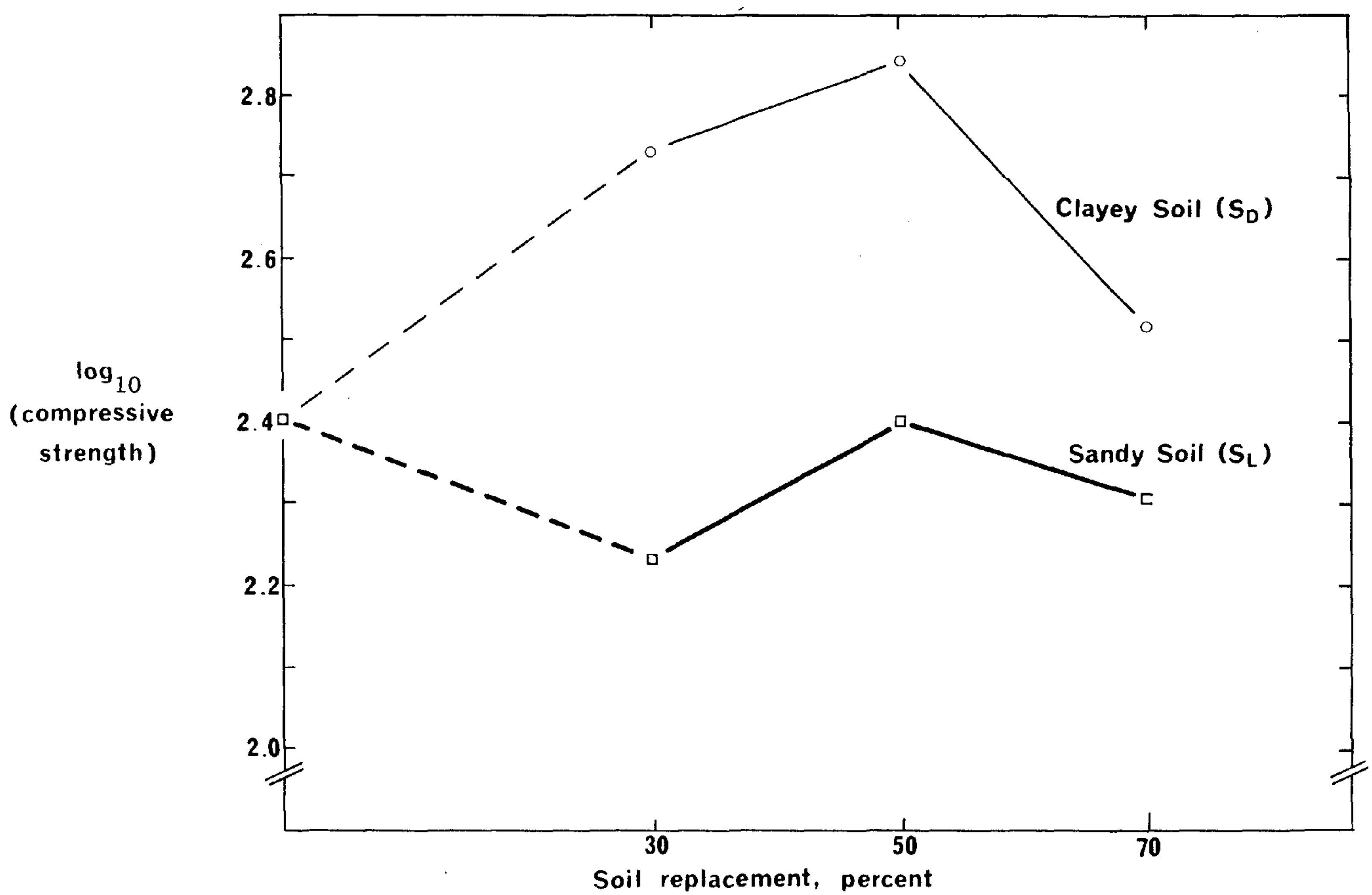

Figure 10. Simple effects profile of soil replacement on formulation C-3.

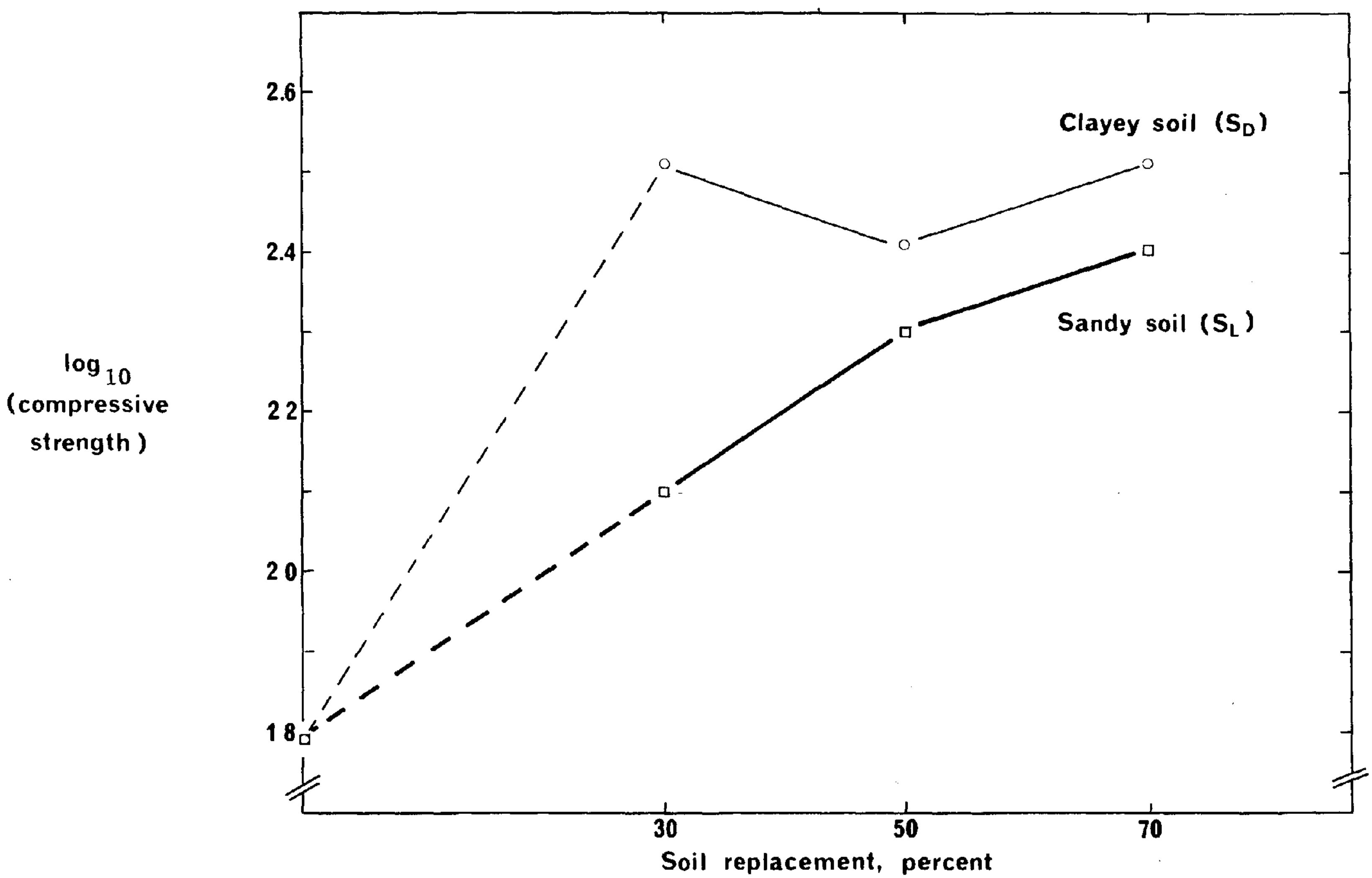

Figure 11. Simple effects profile of soil replacement on formulation B-2.

Table 15. F-ratio test for soil replacement series.

Formulation	Factor[a]	Degrees of Freedom	Mean Squares	F-Ratio	F-Statistic	
					.05	.01
B-2 S_D	S_D	3	0.36036	1590.59	4.07	7.59
	MSE	8	0.00023	-	-	-
B-2 S_L	S_L	3	0.21850	62.69	4.07	7.59
	MSE	8	0.00349	-	-	-
C-3 S_D	S_D	3	0.11876	109.27	4.07	7.59
	MSE	8	0.00109	-	-	-
C-3 S_L	S_L	3	0.02104	1.68	4.07	7.59
	MSE	8	0.01253	-	-	-

[a] S_D - Danville soil; S_L - Ladysmith soil; MSE - Mean square error.

The means of the factors were analyzed using the $Tukey_{HSD}$ test and are shown in Table 16. It shows that the poorer formulation was more improved by the higher soil additions.

Table 16. Comparison of specific means of soil replacement series by the Tukey test.

Fly Ash	Soil	HSD	Ranking[a]			
			1	2	3	4
A_M	S_D	0.078	50% (2.841)	30% (2.737)	70% (2.521)	0 (2.404)
A_M	S_L	0.263	0 (2.404)	50% (2.399)	70% (2.310)	30% (2.227)
A_L	S_D	0.004	70% (2.515)	30% (2.510)	50% (2.412)	0 (1.792)
A_L	S_L	0.120	70% (2.405)	50% (2.299)	30% (2.100)	0 (1.792)

[a]Listed in percent soil replacement. Values in parenthesis are the logarithmic means of the strength data. The underlined values were not significantly different.

Due to the marked strength gains exhibited by soil replacement, the engineering properties of these formulations were examined. The same tests--freeze-thaw, wet-dry, permeability and leachate analysis--were performed.

Table 17 shows the results of freeze-thaw and strength tests which were run on the B-2 formulation combined with various percentages of the Danville and Ladysmith soils. The results shown in Table 17 indicated that the 7-day moist cured specimens had greater strengths when the standard formulation B-2 was combined with either the sandy (Ladysmith) or clayey (Danville) soils. Strength decreased with increasing percentage of soil in the case of the sandy soil while the change in strength did not show a clear trend for the clayey soil.

The strength of compacted samples (B-2 formulation) which had been cured for 7-days and then subjected to 12 cycles of freezing and thawing was considerably lower than the unfrozen samples in the case of both sandy and clayey soils.

Table 17. Results of freeze-thaw tests on formulation B-2[a]

Formulation[b]	Strength, p.s.i.[c]		Maximum Volume Change, percent		Maximum Moisture Content, percent	Remarks
	7-day	unbrushed after 12 cycles	on Curing	Freeze-Thaw		
B-2-0	30	10	0.6	16.8 on 11th cycle	46 on 11th cycle	
B-2-30 S_D	60	0	14.2	66.5 on 7th cycle	99 on 7th cycle	Sample fell apart after 12 cycles.
B-2-50 S_D	50	2	10.5	66 on 10th cycle	86 on 10th cycle	
B-2-70 S_D	140	-	13.4	45 on 3rd cycle	-	Sample broke on 3rd cycle.
B-2-30 S_L	45	15	2.0	12.3 on 10th cycle	36 on 10th cycle	Soft outer crust after 12 cycles.
B-2-50 S_L	35	20	3.1	15.2 on 12th cycle	28 on 12th cycle	
B-2-70 S_L	30	15	2.3	1.4 on 2nd cycle	26 on 2nd cycle	Volume measurements stopped after 2nd cycle.

[a] 5 percent Calcitic lime, 10 percent Sulfate waste, 85 percent Albright fly ash.

[b] Represents formulation, soil replacement level and soil type.

[c] 1 p.s.i. = 6.89×10^3 N/m^2.

Table 17 also shows the increases in volume of the B-2 formulation samples after both a 7-day cure period and also subsequent to several (up to 12) cycles of freezing and thawing.

Table 18 shows the results of freeze-thaw tests on the C-3 formulation combined with the sandy (Ladysmith) as well as the clayey (Danville) soil. The strength of samples which had moist cured for 7 days at 73°F (22.8°C) is shown as is the strength of 7-day cured specimens which were subsequently subjected to several (up to 12) cycles of freezing and thawing with no brushing. Volume changes after both 7-day curing and freeze-thaw cycles are also shown.

Tables 19 and 20 show the results of wet-dry tests for the B-2 and C-3 formulations, respectively.

Table 21 shows the results of falling head permeability tests performed on compacted samples which were cured for 7 days at 73°F (22.8°C).

The results shown in Table 21 indicated that all mixes were quite impervious, the sandy (Ladysmith) soil being less pervious than the clayey soil. This difference in permeability between the two soils was most certainly due to the larger volume change (expansion) which took place in the clayey soil specimens during both curing and subsequent saturation.

Calculations have shown that it would take over 4 days for water, under a head of 2 feet, to move one foot through the most pervious mix tested and shown in Table 21. This is believed to represent a very extreme field condition and indicates that movement of water through a fill composed of these materials would be most difficult.

Leachate samples obtained during the permeability tests were chemically analyzed as previously mentioned. These results are presented in Tables 22 and 23. Though not specifically analyzed for organic content, the leachate samples all had a distinctive sewage sludge odor. In some cases droplets of an oily substance were observed on the surface. The results again were similar to what has previously been mentioned. The unreacted lime and the gypsum were being washed out of the specimens. The C-3 formulation, having more lime and gypsum than the B-2 formulation, exhibited larger amounts of calcium, sulfate and alkalinity in the effluent. In addition to the results reported, analyses were performed on leachate water collected after the permeability tests were completed. These tests showed that the alkalinity, calcium and sulfate content had decreased by around 90 percent. This would indicate that the first water through the specimens removed mainly unreacted or free lime and gypsum. Therefore, the leachate concentrations reported in Tables 23 and 24 would not reflect the long-term leachability of these formulations. Also, if more time for reaction were permitted by longer curing, these leachates might also be of different concentrations.

Table 18. Results of freeze-thaw tests on formulation C-3[a].

Formulation[b]	Strength, p.s.i.[c] 7-day	Strength, p.s.i.[c] unbrushed sample after 12 cycles	Maximum Volume Change, percent on Curing	Maximum Volume Change, percent Freeze-Thaw	Maximum Moisture Content, percent	Remarks
C-3-0	65	Broke on 10th cycle.	-	18 on 9th cycle		
C-3-30 S_D	60	5	16.5	60 on 8th cycle	43 on 5th cycle	Stopped after 8 cycles.
C-3-50 S_D	50	Broke on 3rd cycle.	14.5	35 on 3rd cycle		
C-3-70 S_D	110	Broke on 3rd cycle.	7.8	20 on 1st-3rd cycles		
C-3-30 S_L	80	165	6.7	44 on 6th cycle	40 on 4th cycle	
C-3-50 S_L	80	225	1.7	24 on 11th cycle	29 on 4th cycle	Volume measurements stopped after 11 cycles.
C-3-70 S_L	60	-	5.1	12 on 5th cycle		Large chunk fell out at end of 5th cycle.

[a] 8 percent Dolomitic lime, 16 percent Sulfate waste, 76 percent Amax fly ash.

[b] Represents formulation, soil replacement level and soil type.

[c] 1 p.s.i. = 6.89×10^3 N/m^2.

Table 19. Results of wet-dry tests on formulation B-2[a].

Formulation[b]	Strength, p.s.i.[c]		Weight Loss, percent	Volume Change, percent		Maximum Volume Change, percent
	7-day	After 12 cycles		Curing	Wet-Dry	
B-2-0	30	20	63.4-12 cycles	0.6	0.9-2nd cycle	31.3-12th cycle
B-2-30 S_D	60	0	100-3 cycles	13.6	47-3rd cycle	
B-2-50 S_D	50	0	100-2 cycles	9.5	30-1st cycle	
B-2-70 S_D	140	0	100-2 cycles	15.0	30-1st cycle	
B-2-30 S_L	45	70	62.1-12 cycles	5.7	5.6-1st cycle	20.5-1st cycle
B-2-50 S_L	35	120	29.9-12 cycles	5.7	4.0-1st cycle	21.9-1st cycle
B-2-70 S_L	30	60	29.9-12 cycles	2.0	-6-8th cycle +2-1st cycle	24-1st cycle

[a]5 percent Calcitic lime, 10 percent Sulfate waste, 85 percent Albright fly ash.

[b]Represents formulation, soil replacement level and soil type.

[c]1 p.s.i. = 6.89×10^3 N/m^2.

Table 20. Results of wet-dry tests on formulation C-2[a].

Formulation[b]	Strength, p.s.i.[c]		Weight Loss, percent	Volume Change, percent		Maximum Volume Change, percent
	7-day	After 12 cycles		Curing	Wet-Dry	
C-3-0	65	120	36.8-12 cycles	-	3.3-7th cycle	35.6-12th cycle
C-3-30 S_D	60	0	100-2 cycles	15.0	21.5-1st cycle	
C-3-50 S_D	50	145	100-2 cycles	14.5	21.0-2nd cycle	34.6-2nd cycle
C-3-70 S_D	110	0	100-3 cycles	6.6	30.9-2nd cycle	
C-3-30 S_L	80	50	17.1-12 cycles	4.3	5.1-3rd cycle	11.6-12th cycle
C-3-50 S_L	80	70	20.6-12 cycles	1.7	1.9-1st cycle	40.6-12th cycle
C-3-70 S_L	60	135	84.2-12 cycles	2.9	3.4-1st cycle	23.3-1st cycle

[a] 8 percent Dolomitic lime, 16 percent Sulfate waste, 76 percent Amax fly ash.

[b] Represents formulation, soil replacement level and soil type.

[c] 1 p.s.i. = 6.89×10^3 N/m^2.

Table 21. Results of permeability tests.

No. of Samples	Formulation[a]	Coefficient of Permeability after seven-day cure (20 C) (cm/sec)
1	C-3-0	3.70×10^{-5}
2	C-3-30 S_D	3.37×10^{-5}
2	C-3-50 S_D	3.58×10^{-5}
1	C-3-70 S_D	1.13×10^{-5}
1	C-3-30 S_L	1.84×10^{-6}
	C-3-50 S_L	So impervious was unable to get water through sample.
1	C-3-70 S_L	6.89×10^{-8}
2	B-2-0	Both samples cracked during saturation - no test.
1	B-2-30 S_D	4.23×10^{-5}
1	B-2-50 S_D	Sample cracked during curing - no test.
	B-2-70 S_D	Sample cracked during curing - no test.
1	B-2-30 S_L	1.27×10^{-6}
1	B-2-50 S_L	5.88×10^{-8}
1	B-2-80 S_L	4.30×10^{-6}

[a]C-3 formulation: 8 percent Dolomitic lime, 16 percent Sulfate waste, 76 percent Amax fly ash.

B-2 formulation: 5 percent Calcitic lime; 10 percent Sulfate waste, 85 percent Albright fly ash.

Table 22. Chemical analysis of leachate from soil replacement series with formulation C-3[a].

Soil Replacement	pH	Alkalinity, ppm Ca^{2+}		Hardness, ppm Ca^{2+}		Sulfate, ppm	Fluoride, ppm	Cu, ppm	Hg, ppm	Zn, ppm	Cr, ppm	Cd, ppm
		"P"	"T"	Calcium	Total							
0	12.5	756	908	1120	1152	1460	1	0[b]	0[b]	0[b]	0[b]	0[b]
30% S_L	12.4	584	712	1160	1152	1280	2	3	0	0	0	0
50% S_L			IMPERMEABLE									
70% S_L	11.8	136	272	808	880	1160	1	7	0	0	0	0
30% S_D	10.6	205	309	900	917	2106	3	1	0	0	0	0
50% S_D	11.8	208	312	888	928	1453	1	2	0	0	0	0
70% S_D	12.1	264	368	2480	2480	1060	1	6	1	0	0	0

[a]C-3: 8 percent Dolomitic lime, 16 percent Sulfate waste, 76 percent Amax fly ash.

[b]See Table 12 for limits of detection.

Table 23. Chemical analysis of leachate from soil replacement series with formulation B-2[a].

Soil Replacement	pH	Alkalinity, ppm Ca^{2+} "P"	Alkalinity, ppm Ca^{2+} "T"	Hardness, ppm Ca^{2+} Calcium	Hardness, ppm Ca^{2+} Total	Sulfate, ppm	Fluoride, ppm	Cu, ppm	Hg, ppm	Zn, ppm	Cr, ppm	Cd, ppm
0[b]	11.9	160	196	348	400	280	1	2	0[c]	0[c]	0[c]	0[c]
30% S_L	12.2	432	600	960	992	960	2	5	3	1	0	0
50% S_L	12.2	456	680	1460	1464	1400	2	5	1	1	0	0
70% S_L	11.8	128	160	176	184	< 10	1	1	0	0	0	0
30% S_D	12.3	552	704	1336	1400	1960	2	3	1	0	1	0
50% S_D[(b)]	11.7	96	120	332	332	400	1	0	0	0	0	0
70% S_D[(b)]	11.7	80	104	168	168	< 10	0	0	0	0	0	0

[a]B-2: 5 percent Calcitic lime, 10 percent Sulfate waste, 85 percent Albright fly ash.

[b]Sample cracked during permeability test.

[c]See Table 12 for limits of detection.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of these engineering tests and for the soils employed, it is our opinion that small quantities of on-site sewage sludge can be mixed with soil, lime, fly ash and waste sulfate to produce a material which will be suitable for use in highway embankments. Since the sewage sludge is primarily water, the amount which can be used with a given mix will be governed by the optimum moisture content and natural moisture content of the soil employed. The mix must not be too wet or dry (of optimum moisture content) and must be workable.

For the soils employed, we observed a rather serious breakup of the mixes in the freeze-thaw and/or wet-dry tests. We therefore recommend that the embankments be so zoned during construction that the sewage sludge treated materials be buried at least 3 feet (0.9 m) below any exposed (top or side) surfaces of the fill. This precaution should eliminate the possibility of freeze-thaw or wet-dry breakup of the material and its movement into adjacent ground or surface water by erosion.

For actual construction operations on I-95 in Philadelphia using this sewage sludge, if tests show that the soils which are finally chosen for use produce a more permeable product when mixed with lime, fly ash, waste sulfate and sewage sludge, it may be necessary to employ a 3-4 foot (0.9-1.2 m) impervious blanket of another soil at the base of the fill. This would isolate the sewage sludge treated soil from the local ground water. Isolation of the sludge from ground or surface water should be, at least, as good as that which is now present in and around the existing sludge lagoons.

Consideration should be given to odor and health safety matters in the removal, application, mixing, spreading and rolling of the sewage sludge mixes. This will be necessary no matter what the method of removal and disposition of the sewage sludge may be. The potential problem of odors during construction should be mitigated somewhat due to the odors associated with the existing plant in this neighborhood.

Finally, it must be understood that additional testing of mix designs will be required once the actual soil borrow areas to be used have been selected and the soils to be used are available.