Alternative Materials for The Modification and Stabilization of Unstable Subgrade Soils

Laboratory Testing

Physical Research Report No. 125

May 1997

Illinois Department of Transportation
Bureau of Materials and Physical Research

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
IL/PRR-125		

4. Title and Subtitle	5. Report Date
ALTERNATIVE MATERIALS FOR THE MODIFICATION AND STABILIZATION OF UNSTABLE SUBGRADE SOILS	MAY 1997
	6. Performing Organization Code
7. Author(s) GREG HECKEL	8. Performing Organization Report No. Physical Research No. 125
9. Performing Organization Name and Address Illinois Department of Transportation Bureau of Materials and Physical Research 126 East Ash Street Springfield, Illinois 62704-4766	10. Work Unit (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Materials and Physical Research 126 East Ash Street Springfield, Illinois 62704-4766	13. Type of Report and Period Covered Laboratory Testing January 1995 to December 1996 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This study examines two lime by-products and two fly ashes for treatment of unstable (CBR<6) subgrade soils. The treatment methods include both modification and stabilization. Modification is temporarily enhancing subgrade stability to improve constructability. Stabilization is the construction of a permanent, high strength base material which is considered a part of the pavement structure. The alternative materials include a dried lime kiln sludge (DLKS), a hydrated lime by-product (HLB), an ASTM C 618 Type C fly ash (TCFA), and a fly ash (FA) that does not meet the requirements of ASTM C 618. The performance of soils treated with these materials was compared to that of the corresponding soils treated with the control material, a high calcium lime kiln dust (LKD). Test results presented in this study include the moisture-density relationships, bearing values, compressive strengths, swell potential, and plasticity index for treated soils and untreated soils. The results do not provide enough data to comprehensively evaluate the performance of FA. However, the results do indicate that the suitability of DLKS, HLB, and TCFA depends on soil type, moisture contents, and expected performance.

17. Key Words	18. Distribution Statement
lime, fly ash, stabilization, modification, subgrade, waste utilization	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page	21. No. of Pages	22. Price
Unclassified	Unclassified	37	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ALTERNATIVE MATERIALS FOR THE MODIFICATION AND STABILIZATION OF UNSTABLE SUBGRADE SOILS

Laboratory Testing Report

By
Greg Heckel
Soils Field Engineer

May 1997

Illinois Department of Transportation
Bureau of Materials and Physical Research
Springfield, Illinois

ACKNOWLEDGMENTS

This study was supported and conducted at IDOT's Bureau of Materials and Physical Research Soils Lab, Springfield, Illinois. Discussions with Professor Marshall Thompson of the University of Illinois, Urbana, IL, and Riyad Wahab, Geotechnical Engineer at the Bureau of Materials and Physical Research, are greatly appreciated.

COVER

IDOT's first subgrade modification test section on Interstate 55 near Dwight. Photographed by R.J. Little prior to the addition of "Polyhydrate" by-product lime. July 1979.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Since around 1980, the Illinois Department of Transportation (IDOT) has accepted the use of high calcium lime kiln dust (LKD) as a low cost construction expedient on soft subgrades. In 1994, a major supplier of LKD announced that they would no longer reclaim material from mine storage. Consequently, only the LKD resulting directly from current production was available from that source. Since that time, the price of LKD has risen from $6 per ton in 1992 to $13 per ton in 1996. The demand for LKD has also caused supply difficulties for some contractors in central and southern Illinois. These events have made other cost-effective alternative materials more attractive.

The manufacture of various commercial lime products results in the production of by-products other than LKD. Also, coal combustion waste materials, such as fly ash, are often the first options considered as substitutes for lime. In Illinois, extensive laboratory research by Marshall Thompson (1966) at the University of Illinois, along with IDOT field tests (Little, 1983), and many years of construction experience form a confident base for IDOT's lime treatment specifications.

The use of coal combustion wastes for subgrade soil treatment does not have as rich a history in Illinois as lime. IDOT's experience with highly variable bed ash and fly ash from ADM in Decatur yielded mixed results. A laboratory study conducted by Dhamrait (1991) using TCFA and two low plasticity soils concluded that fly ash could not effectively compete with LKD. McManis (1989) came to the same conclusion, while others reported competitive results (Ferguson and Zey, 1990). TCFA, alone or with lime, has been used successfully in other parts of the country as a soil stabilizer. In Illinois, TCFA is primarily used by the concrete industry as a cement replacement. However, there are several sources of high CaO ashes that do not meet the specifications in ASTM C 618, but may be effective for soil modification.

This study was initiated to examine alternative lime by-products and fly ashes. The study concentrates on materials that, based on their chemical composition, show a potential for similar performance to the currently accepted LKD.

MATERIALS AND SAMPLE PREPARATION

Lime By-Products and Fly Ashes

The DLKS is produced from a wet kiln exhaust effluent which is currently ponded as an inert sludge. The effluent is collected, press-dried, and then further dried by activating it with 15% CaO (quicklime). The HLB, commonly called "hydrator tailings," is a coarse material that results from the production of a commercial, high grade hydrated lime. HLB should not be confused with "hydrated by-product lime" which is a hydrated, low calcium LKD activated with quicklime. The FA is a type C fly ash that does not meet the requirements of ASTM C 618. The TCFA included in this study is commonly used as a cement replacement in concrete. Table 1 presents the physical and chemical properties of the DLKS, HLB, FA, TCFA, and the control LKD. Figure 1 illustrates the production of lime by-products.

Table 1: Physical and Chemical Properties of the Alternative Materials.

	LKD	DLKS	HLB	FA	TCFA
CaO + MgO, %	81	87	94	23	27
$Ca(OH)_2$[a], % (Rapid Sugar)	43	31	83	4	2
Loss on Ignition (LOI), %	19.0	32.0	19.0	14.4[c]	0.5
Free Water, %	0.1	10.0[b]	0.0	0.8	0.0
+ 4.75 mm, %	0	0	0	0	0
+ 600 μm, %	4.2	0.0	4.0	0.0	4.2
+ 150 μm, %	11.7	5.0	54.0[b]	10.0	13.6
Specific Gravity (G)	2.91	2.46	2.46	2.51	2.67
SO_3, %	-	-	-	7.7[c]	1.7
SiO_2, %	-	-	-	21.4	35.2
Al_2O_3, %	-	-	-	14.3	20.5
Fe_2O_3, %	-	-	-	5.8	5.6
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	-	-	-	41.5[c]	61.3
Trade Name	Code L	85-15	Code H	-	TCFA
Source	Mississippi Lime Co. St. Genevieve			Will County Silo #1	Louisa Station

[a] Does not include equivalent MgO.
[b] Does not meet current IDOT by-product lime specification.
[c] Does not meet the requirements of ASTM C 618.
- Data not required by IDOT specifications and was not obtained.

Table 1 shows that the DLKS and LKD have similar chemical properties, except for the free water and LOI. The high LOI of the DLKS could be due to excess water from the drying methods used. The HLB could be considered a coarse hydrated lime because of its high $Ca(OH)_2$ content. The amount of material retained on the

150 micron sieve causes some concern. The coarse particles could take a longer time to completely hydrate, causing excess soil drying if a sufficient quantity of water is not available.

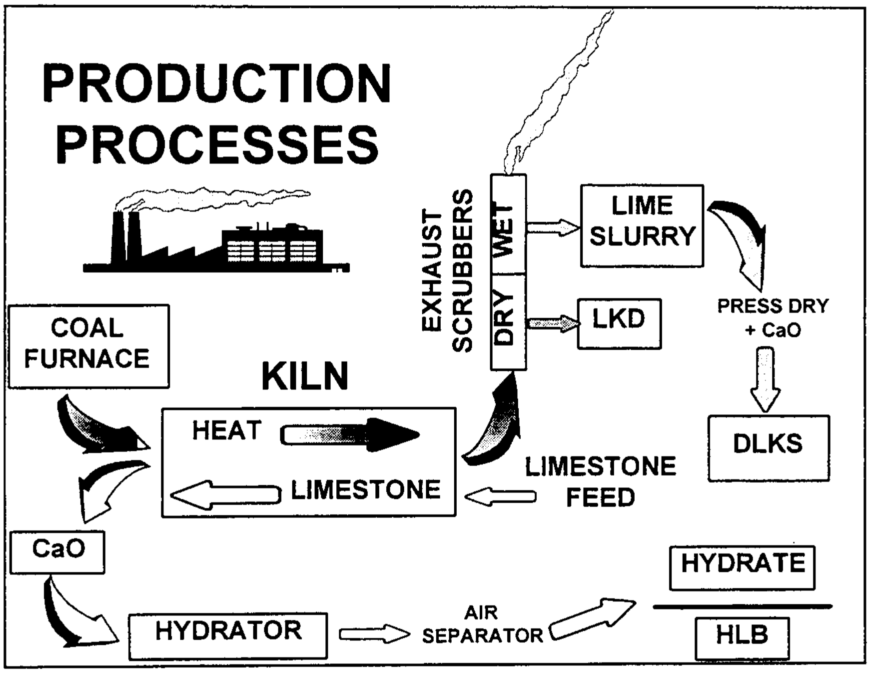


Figure 1: The Production of Lime By-Products.

The FA has high LOI and sulfate contents, compared to the TCFA. An LOI above 10% has been reported as being detrimental to the pozzolanic reaction in fly ash-treated soils (Glogowski, 1992). There are also concerns about the long term swell potential associated with sulfate contents above 10% (Ferguson, 1993). The literature does not specifically address the use of FA as a soil treatment, and there is limited information concerning projects that have used ashes with sulfate contents between 5 and 8 percent (Ferguson, 1996). Based on this limited information, the sulfate content of the FA is high enough to warrant caution against sulfate induced heave in treated soils.

Soils

Three typical Illinois soils were treated with the DLKS, HLB and LKD. A commercially available, dry-milled Fire Clay was treated, individually, with each lime by-product and fly ash. Hanson Engineers, Inc. (1996) independently performed laboratory tests on two of the three Illinois soils treated with TCFA. Their data will be presented and referenced where applicable. The Fire Clay was used as a readily available, uniform reference soil. Table 2 presents the properties of the untreated soils. Soil classification tests were performed according to AASHTO T 88, T 89, T 90, and T 100. Soils were classified based on AASHTO M 145 and the IDOT textural classification chart.

Table 2: Physical Properties of the Untreated Soil.

IDOT Classification	Clay	Silty Clay Loam (SiCL)	Clay Loam (CL)	Silty Clay (SC)
AASHTO M 145 Classification	A-6(9)	A-4(8)	A-6(6)	A-7-6(15)
Liquid Limit, LL, %	33.0	33.8	24.9	48.4
Plasticity Index, PI, %	13.4	8.5	10.8	24.6
- 0.075 mm, %	98.1	96.1	67.9	99.2
Sand Content, %	1.9	3.9	32.1	0.8
Silt Content, %	41.7	73.9	43.4	57.9
Clay Content, %	56.4	22.2	24.5	41.3
Specific Gravity, G	2.68	2.71	2.72	2.74
Source	AP Green / Dry Milled	Christian County	Macon County	Franklin County

Sample Preparation

The soils were treated with 5% of each lime by-product based on the dry weight of soil. The Clay was treated with 10% of each fly ash based on the dry weight of soil. Mixing was done according to ASTM D 3551. The ASTM D 3551 mixing time, after addition of water, for the fly ash-treated soils was reduced by 50% because the set time of the fly ash was not known. If the fly ashes hydrate quickly, test preparation would break up cemented fly ash particles. The shorter mixing time was used in an effort to avoid this possibility. The fly ash-treated soil was tested immediately after mixing.

Soils treated with LKD and DLKS were allowed to mellow or “slake” for one hour prior to compaction. The HLB treated soils were allowed to mellow for 24 hours to ensure a more thorough hydration of the coarse HLB particles. Studies by Thompson (1995) and Baker (1995) revealed that the HLB treated soil specimens compacted after only a one hour mellowing period deteriorated when subjected to accelerated curing at 48.9°C. The deterioration of the specimens was attributed to the expansion of the HLB particles and excessive soil drying as the HLB continued to hydrate during curing. However, tests indicated the lab mellowing period, beyond one hour, does not affect the moisture-density-immediate bearing value relationship of lime treated soils. Refer to the section on Compressive Strength and Table 10 for a discussion of accelerated curing.

MOISTURE - DENSITY RELATIONSHIP

Moisture-density relationships of treated and untreated soils were determined according to AASHTO T 99. A fresh mixture was used for each point on the moisture-density curve. Test results, summarized in Tables 3 and 4, show the maximum dry density (ρ_{dmax}) of a lime-treated soil was lower than the untreated soil, with the latter also having a lower optimum moisture content (OMC). Ferguson (1985) reports that the effect of fly ash treatment on soils is not consistent, and it depends on the characteristics of the soil and the fly ash.

Table 3: The Maximum Dry Density of Untreated and Treated Soils.

	Clay ρ_{dmax} kg/m^3	SiCL ρ_{dmax} kg/m^3	CL ρ_{dmax} kg/m^3	SC ρ_{dmax} kg/m^3
Untreated	1817	1661	1988	1650
5% LKD	1737	1640	1854	1517
5% DLKS	1767	1612	1878	1573
5% HLB	1680	1597	1786	1458
3% HLB	1761	1611	1854	1536
10% TCFA	1853	1682[a]	1890[a]	-
10% FA	1767	-	-	-

[a] Data from Hanson Engineers, Inc. (1996).

Table 4: The OMC of Untreated and Treated Soils.

	Clay OMC, %	SiCL OMC, %	CL OMC, %	SC OMC, %
Untreated	14.8	18.3	11.5	19.9
5% LKD	14.5	19.0	14.6	21.0
5% DLKS	15.3	20.0	13.7	22.2
5% HLB	17.0	21.0	15.1	22.5
3% HLB	15.8	20.0	14.1	22.9
10% TCFA	12.9	18.2[a]	13.7[a]	-
10% FA	14.5	-	-	-

[a] Data from Hanson Engineers, Inc. (1996).

Tables 3 and 4 show that the HLB, compared to the other by-products, had the largest effect in reducing ρ_{dmax} and increasing the OMC for all soils. The reduction in ρ_{dmax} is generally attributed to the flocculation and agglomeration of the clay particles within the soil matrix. The HLB reduces ρ_{dmax}, possibly, because of a high $Ca(OH)_2$ content fueling the cation exchange necessary for the "clumping" of clay particles (TRB, 1987). With the exception of CL, the increase in OMC for soils treated with LKD, DLKS, and HLB appears to be associated with the increase in CaO content. According to

Herrin and Mitchell (1961), an increase in the percentage of CaO would increase the amount of H_2O needed to form $Ca(OH)_2$.

Also, Tables 3 and 4 show the 10% FA did not affect the OMC, and it reduced ρ_{dmax} for the Clay by an amount similar to the 5% DLKS. However, the 10% TCFA unexpectedly reduced the OMC, while it increased ρ_{dmax} for the Clay and SiCL. Ferguson (1996) used the same TCFA and Clay that were used in this study, and also observed this effect. He attributed it to the slower reaction characteristics of the particular TCFA used in both studies. However, this does not explain the reduction of ρ_{dmax} and increase of OMC observed in the TCFA treated CL.

IDOT's past experience with LKD indicates that the ρ_{dmax} and OMC is consistent within a treatment range of 3% to 7%. Therefore, additional moisture-density relationships were not determined for soils treated with 3% LKD and DLKS. However, moisture-density relationships were determined for soils treated with 3% HLB because of its higher $Ca(OH)_2$ content. Those results are also shown in Tables 3 and 4. A comparison between the ρ_{dmax} and OMC of soils treated with 3% and 5% HLB shows a variation greater than AASHTO's repeatability statement. That variation indicates that incremental changes in HLB content can affect moisture-density relationships.

IMMEDIATE BEARING VALUE (IBV)

The IBV penetration tests, using a standard CBR piston, were conducted immediately after compacting the moisture-density specimens, prior to their extraction from the mold. Therefore, each point on the moisture-density curve has a corresponding IBV value as recommended by Thompson, et al. (1977). The IBV value gives an indication of the subgrade soil stability, during construction, immediately after compaction. IDOT's Lime-Soil Mix Design Procedures for lime modification identifies the required percent of lime as that percentage which will result in an IBV of 10 to 12 percent. Table 5 shows the IBV, at OMC, for the treated and untreated soils.

Table 5: The IBV at OMC.

	Clay IBV, %	SiCL IBV, %	CL IBV, %	SC IBV, %
Untreated	15	13	9	14
5% LKD	25	27	28	20
5% DLKS	22	19	24	20
5% HLB	28	26	23	29
10% TCFA	18	16[a]	10[a]	-
10% FA	24	-	-	-

[a] Data from Hanson Engineers, Inc. (1996).

Table 5 shows that there is no one by-product that consistently outperformed the other by-products. However, the data appears to indicate that the HLB performed better than the other products in the clayey soils, and the LKD performed better in the silty and sandy soils. The data presented for the Clay treated with 10% FA was not sufficient to arrive at a conclusion concerning its performance with other soil types. However, with the Clay, the performance of FA was similar to that of LKD and is better than that of the TCFA. TCFA added to the SiCL and CL does not appear to have a significant effect on the immediate bearing value. Some explanation for this can be found in the Hanson Engineers report which shows a slightly different IBV vs. moisture content relationship for the untreated soils than that determined by IDOT testing. In general, the data in Table 5 shows that performance depends on both the soil type and the by-product used.

IDOT's standard specifications allow the field moisture content to be up to 120% of OMC. The IBV values at a moisture content 120% of OMC are summarized in Table 6.

Table 6: IBV at 120% of OMC.

	Clay IBV, %	SiCL IBV, %	CL IBV, %	SC IBV, %
Untreated	4	2	2	6
5% LKD	19	5	8	14
5% DLKS	11	5	11	8
5% HLB	19	3	7	19
10% TCFA	10	6[a]	4[a]	-
10% FA	15	-	-	-

[a] Data from Hanson Engineers, Inc. (1996).

Table 6 shows that an increase in moisture content above OMC had a significant effect on the performance of each product. Again, there is no one by-product that consistently outperformed the others. At 120% of OMC, the HLB still performed well with clayey soils, but the DLKS performed as well as or better than the LKD with silty and sandy soils.

The 10% FA performed better than the 5% DLKS, but not as well as the 5% LKD or HLB. The 10% TCFA yields results similar to the 5% DLKS in Clay. The SiCL treated with 10% TCFA shows the greatest improvement when compared to all of the lime by-products. The CL treated with TCFA is not as promising. IDOT's Subgrade Stability Manual states that a subgrade with at least a CBR of 6% may not require additional remedial measures and, thus, may be considered stable. The data shows that, except for the SiCL soil with the lime by-products and the CL with TCFA, at these treatment levels, all treated soils would perform satisfactorily, at 120% of OMC, in terms of the field subgrade stability.

Each soil was also treated with 3% of each lime by-product to determine if treatment level, like moisture content, had a significant effect on performance. A moisture content of 120% of OMC was selected for comparison because it represents the worst field condition allowed. Table 7 shows the IBV at 120% of OMC of each soil treated with 3% of each lime by-product.

Table 7: IBV at 120% of OMC at a 3% Treatment Level.

	Clay IBV, %	SiCL IBV, %	CL IBV, %	SC IBV, %
Untreated	4	2	2	6
3% LKD	10	3.5	9	4
3% DLKS	10	2.5	14.5	4
3% HLB	8	2	5	14

The data presented in Table 7 verifies that treatment level significantly affects the performance of these materials at high moisture contents. One can determine, from Tables 4 through 7, that the performance of each lime by-product is dependent on the soil type, moisture content, and treatment level. Even though the fly ash was not tested at another treatment level, other researchers have come to the same conclusion. In addition to these factors, the source of the fly ash would also play a role in performance characteristics (McManis, 1988).

A good example of the effects of these factors on performance can be observed by examining the data for SC treated with HLB in Tables 6 and 7. The data shows that, at 120% of OMC, a 5% treatment rate of LKD performs as well as a 3% treatment rate for HLB. This information shows a significant potential for cost savings if both materials are tested in the mix design process. In general, the IBV data shows a thorough mix design process is essential to obtaining optimal performance.

COMPRESSIVE STRENGTH

Unconfined compressive strength, q_u, tests were performed according to AASHTO T 208. Soil-lime and soil-fly ash mixtures were compacted into 50.8 mm x 101.6 mm cylinders in three equal layers with scarification between each layer. The cylinders were then sealed into plastic bags to prevent moisture loss during curing. For each soil-additive mix, four specimens were compacted and the average strength is presented herein. All specimens tested were compacted between 95% and 108% of their respective ρ_{dmax} and OMC. Individual sample information and test results can be found in the appendix.

The uncured compressive strength results indicate how effectively the by-products react with some soils to enhance immediate strength. Table 8 shows the average q_u values, from four identical tests, for untreated and treated soils. Each uncured sample was tested within 30 minutes of compaction. The coefficient of variation, for every four tests, ranged from 4% to 12%.

Table 8: Uncured q_u of Untreated and Treated Soils.

	Clay q_u (kPa)	SiCL q_u (kPa)	CL q_u (kPa)	SC q_u (kPa)
Untreated	385	256	338	434
5% LKD	795	447	454	459
5% DLKS	509	243	303	379
5% HLB	440	237	350	480
10% TCFA	499	-	-	-
10% FA	650	-	-	-

The IBV values at OMC, shown in Table 5, indicate that the HLB performed as well as or better than LKD with the Clay, the SiCL or the SC. On the other hand, the q_u values in Table 8 indicate that HLB performed poorly compared to the LKD with any of these three soils. The DLKS also performed poorly with all soils when compared to the LKD. With lime-treated soils, the immediate effects on the soil strength is generally attributed to cation exchange and the flocculation and agglomeration of the soil particles, not to the pozzolanic reaction (TRB, 1987).

The Clay treated with FA performed nearly as well as the LKD and outperformed the HLB, DLKS and TCFA. The immediate strength gain in fly ash can be attributed to the reaction of tricalcium aluminate (Ferguson 1985) and the portion of CaO existing as tricalcium silicates (McManis 1988), similar to portland cement. Like the IBV, uncured q_u data is an indicator of the suitability of the mixture for use as a construction expedient. In general, considering all soil types, the alternative lime by-products are not as consistent at improving uncured q_u as the LKD.

The effects of curing on soils treated with each by-product was also explored. Four specimens for each curing condition were compacted from each soil-additive combination and their average strengths are shown herein. All specimens tested were between 95% and 108% of ρ_{dmax} and OMC at the time of compaction. Treated soils were tested after curing for 7 days at 23.9°C. Additional tests were also conducted on the lime-treated soils which were cured for 48 hours at 48.9°C, and on the fly ash-treated Clay which was cured for 28 days at 23.9°C.

The 7-day curing period was chosen because it corresponds to IDOT's current procedure for construction of lime stabilized subgrades. According to IDOT's procedure, the compacted, treated soil is allowed to cure for 7 days in the field before final paving. Curing has different effects in lime-treated soils than in fly ash-treated soils. The 7-day strength gain in lime-treated soils can be attributed to the cation exchange, flocculation and agglomeration of the clay particles, and the soil-lime pozzolanic reaction. The 7-day strength gain in fly ash, like the immediate strength gain, can be attributed to the reaction of tricalcium aluminate (Ferguson 1985) and the portion of CaO existing as tricalcium silicates (McManis 1988) similar to portland cement. Table 9 shows the average q_u, of four tests, for treated soils cured for 7 days at 23.9°C. The untreated, uncured soil data is provided for comparison. The coefficient of variation (COV), for each set of four tests, ranged between 0% and 13% for all data in Table 9, except for the CL and SC treated with 5% HLB. These two treated soils showed COVs of 28% and 27%, respectively.

Table 9: Unconfined Compressive Strength of Treated Soils Cured for 7 Days at 23.9°C.

	Clay q_u (kPa)	SiCL q_u (kPa)	CL q_u (kPa)	SC q_u (kPa)
Untreated	385	256	338	434
5% LKD	1719	936	1403	549
5% DLKS	582	224	474	349
5% HLB	592	273	468	568
10% TCFA	1056	290[a]	620[a]	-
10% FA	1311	-	-	-

[a] Data from Hanson Engineers, Inc. (1996).

Table 9 shows higher q_u values for the LKD when compared to the DLKS and HLB, with the exception of HLB treated SC. The Clay, SiCL, and CL treated with either 10% FA or 10% TCFA, outperformed the 5% DLKS and 5% HLB. The DLKS, though similar in chemical composition to the LKD, did not perform as well as the LKD. The high LOI in the DLKS may have slowed the pozzolanic reaction. The LOI effect may be similar to that reported by Glogowski (1992) for high LOI fly ashes. The performance of HLB was not consistent, possibly because of its coarse gradation. The coarse particles appear to require more time to completely hydrate. Therefore, during curing, some of the CaO may not have been readily available for reaction. Based on the strength gain observed for the Clay and CL treated with 10% TCFA, treated SiCL should have shown a higher strength. This would seem to indicate that, even though TCFA is self cementing, the soil type can affect the strength gain. For the fly ash, the reaction of tricalcium aluminate and silicates is usually complete after 7 days (Ferguson, 1985). Any strength gain in the fly ash-treated soils after 7 days is attributed to a pozzolanic reaction.

The lime-treated soils were also cured for 48 hours at 48.9°C. This elevated temperature curing is required by IDOT's lime stabilization design procedure. Curing lime-treated soils under these conditions has been correlated with 28-day curing under ambient temperatures (Illinois Division of Highways, 1970). The fly ash-treated soils were not subjected to elevated temperature curing conditions. There is some debate in the literature (McManis, 1988) concerning reactions that take place at elevated temperatures and the variability of data obtained using fly ash from different sources. The FA and TCFA treated Clay were cured at 23.9°C for 28 days to provide an approximate comparison with the strengths of lime-treated soils cured for 48 hours at 48.9°C. Table 10 shows the average q_u values of lime-treated soils after curing for 48 hours at 48.9°C, and fly ash-treated Clay after curing for 28 days at 23.9°C. The COV for each set of four tests ranged from 3% to 18% for all data in Table 10, except for the Clay and CL treated with 5% HLB. These two treated soils showed COVs of 22% and 26%, respectively.

Table 10: Unconfined Compressive Strength of Lime-Treated Soils Cured for 48 Hours at 48.9°C and Fly Ash-Treated Clay Cured for 28 Days at 23.9°C.

	Clay q_u (kPa)	SiCL q_u (kPa)	CL q_u (kPa)	SC q_u (kPa)
Untreated	385	256	338	434
48 hours at 48.9°C				
5% LKD	2820	1059	2076	857
5% DLKS	1062	277[a]	680[a]	447[a]
5% HLB	1121	333[a]	818	1599
28 days at 23.9°C				
10% TCFA	1456	-	-	-
10% FA	1619	-	-	-

[a] Does not meet IDOT's 690 kPa minimum strength requirement for soil stabilization.

Table 10 shows that the DLKS performed well with the Clay. However, the DLKS did not produce a significant strength gain with either the SiCL, CL or the SC. The soils treated with DLKS may be affected by a high LOI. The HLB performed well with all the soils except for the SiCL. No deterioration was observed on the HLB treated specimens which were mellowed for 24 hours prior to compaction. The cured q_u values in Table 10 reflect the level of reactivity between the by-products and the soils. The reactivity is affected by the clay mineral content of the soils, in conjunction with the different chemical and physical properties of each lime by-product. Higher treatment levels may be required when using DLKS or HLB, depending on the specific soil type. A job-specific mix design program should be conducted to identify the percentage of DLKS or HLB needed to achieve design requirements. The Clay, treated with 10% of either FA or TCFA, performed well compared to the Clay treated with 5% of the lime by-products.

ILLINOIS BEARING RATIO (IBR)

The IBR test was also performed on uncured, treated soils according to IDOT's Method of Determining the Bearing Ratio of Soils and Aggregates. After compaction, the specimens were soaked for 96 hours prior to penetration. During the soaking period, the amount of swell was monitored. Table 11 summarizes the IBR values for treated and untreated soils.

Table 11: IBR for Untreated and Treated Soils.

	Clay IBR, %	SiCL IBR, %	CL IBR, %	SC IBR, %
Untreated	1.1	3.8	3.6	3.6
5% LKD	7.2	70.3	37.0	16.1
5% DLKS	5.7	14.6	23.9	6.5
5% HLB	11.8	21.0	15.1	31.4
10% TCFA	7.2	-	-	-
10% FA	2.4	-	-	-

Table 11 shows there was no one by-product that consistently outperformed the others. The HLB performed better than the LKD with the Clay and SC. The Clay treated with 10% TCFA performed the same as the 5% LKD. A slight increase in the IBR value was observed with the 10% FA.

PLASTICITY INDEX (PI)

A reduction in the PI is often used to determine the effectiveness of lime treatment on a particular soil. Atterberg limit tests were conducted according to AASHTO T 89 and AASHTO T 90. For lime-treated soils, the soil was dry mixed with the lime by-product and allowed to mellow prior to initiating the test. The fly ash-treated Clay was tested immediately after mixing. The PI values for treated and untreated soils are summarized in Table 12.

Table 12: PI of Untreated and Treated Soils.

	Clay PI, %	SiCL PI, %	CL PI, %	SC PI, %
Untreated	13.4	8.5	10.8	24.6
5% LKD	11.4	6.1	7.1	19.4
5% DLKS	10.8	7.9	5.9	13
5% HLB	9.2	6.6	7.5	11.7
10% TCFA	18.4	-	-	-
10% FA	20.5	-	-	-

Table 12 shows that all lime by-products reduced the PI as anticipated. This reduction in PI is caused by the flocculation and agglomeration of clay particles in the presence of CaO (Herrin and Mitchell). Similar to the bearing value data, not one lime by-product seemed to give uniformly superior performance, in terms of reducing the PI, for all soil types. Both fly ashes increased the PI instead of reducing it. McManis (1988) indicated that the CaO contained in fly ash is combined with other compounds and is not free to react with clay particles in the same manner as lime. It is believed by others (Ferguson, 1985) that fly ash contains enough free CaO to initiate flocculation and agglomeration in the fly ash-treated soils. The results here appear to indicate that the fly ash is not contributing to any flocculation, agglomeration, or cation exchange in the treated Clay. McManis (1988) also reports a slight increase in PI for a similar A-6 soil. An in depth determination of the availability of free lime in fly ash is beyond the scope of this study.

SWELL

Due to the tendency of the coarse HLB particles to expand during hydration and the high percentage of sulfates in the FA, the potential for excess swell could not be overlooked. Swell was monitored according to AASHTO T 193. The results indicated the potential for swell should not be a concern with any of the lime-treated soils. The lime-treated soils had one-dimensional swells ranging from 0.1% to 3.1%. The results of individual tests can be found in the appendix.

A modified soaking procedure was also used for further evaluation of the HLB treated soils. The procedure called for a one-hour mellowing period prior to compaction, followed by immediate soaking for 4 days at 48.9°C. The elevated temperature was used to increase the rate of hydration. The results from this test indicated a slight increase in swell values, but they were still insignificant with the highest swell being 1.9% for the HLB treated CL.

The amount of swell observed with the uncured FA treated Clay was 14%, compared to the 4% observed for the TCFA treated Clay. The untreated Clay showed a swell of 1.7%. A duplicate test was conducted on the FA treated Clay for verification and for monitoring the rate of swell. The second test revealed a swell of 15%. In all cases, most of the swell occurred within the first 24 hours, and thereafter remained constant at 15%. Figure 2 shows the rate of swell for FA treated Clay.

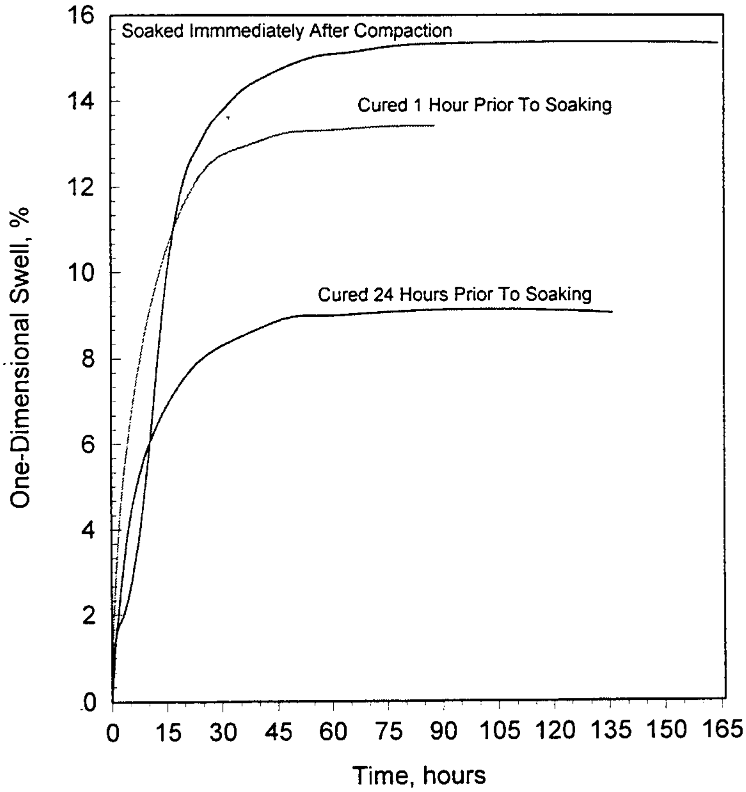


Figure 2: Rate of Swell of FA Treated Clay.

Additional tests were performed with TCFA and FA treated specimens cured at room temperature for one hour and 24 hours prior to soaking. The one-hour curing period did not significantly change the swell or the IBR value. The 24-hour curing reduced the swell to 9% and increased the IBR to 3.4%. The IBR value for the uncured FA treated Clay (Table 7) was low, possibly due to the 14% swell. Excessive swell appears to break down the cementitious bond in the fly ash.

Clay treated with 10% FA and SiCL treated with 10% TCFA were also subjected to further swell testing to evaluate the potential for long-term swell. The specimens were allowed to cure for 7 days at room temperature, after compaction, before being submersed in water for 67 days. The swell was monitored during soaking, and again, most of the swell occurred within the first 24 hours. The TCFA treated SiCL showed negligible swell while the FA treated Clay swell was reduced to 4.0%.

The high initial swell observed for the FA treated Clay may be due to the hydration of tricalcium aluminate in the presence of sulfate. The same reaction occurs during the hydration of portland cement (Mindess and Young, 1981). The low aluminum oxide content combined with the high sulfate content of the FA may have reacted, in the presence of water, to form significant amounts of ettringite. This ettringite-forming reaction can be completed within 24 hours, which is consistent with the data shown in Figure 2. The expansion pressure of the growing ettringite crystals probably forced the uncured Clay to swell. Curing FA treated soils may allow the hydration of calcium silicates and aluminates to harden the compacted soil-ash mixture which resists the expansion pressures of the ettringite crystals.

The formation of ettringite is dependent on the concentration of sulfate ions in the fly ash. If the concentration of sulfate is too low, ettringite will not form (Mindess and Young, 1981). This may explain why the TCFA treated Clay did not experience the same high swell as the FA treated clay. Additionally, if there are not enough sulfate ions to completely react with the aluminate ions, monosulfoaluminate forms. When monosulfoaluminate comes into contact with another external source of sulfate, ettringite can form again (Mindess and Young, 1981).

The factors influencing the amount of swell can include fly ash chemical properties, soil properties, lab testing conditions, and external factors, like acid rain, encountered in the field. Because of these findings and the lack of reference material concerning its use, treating soil with fly ash should be approached with caution.

CONCLUSIONS

(1) Test results indicate that the DLKS and HLB reduced the maximum dry density and plasticity index. They also increased the optimum moisture contents, the compressive strengths, immediate bearing values, and the Illinois Bearing Ratio. The immediate bearing value test results indicated that DLKS and HLB would perform well as soil modifiers. The compressive strength increase using DLKS and HLB was not as high as that observed with the LKD in all soils. As a result, higher treatment levels of either DLKS or HLB may be required to obtain acceptable stabilization results for a given soil type.

(2) The HLB treated soils should be allowed to mellow, at or above optimum moisture content, for at least 24 hours prior to compaction to allow for a more complete hydration of the coarse HLB particles. This condition does not apply to laboratory moisture-density-immediate bearing value testing.

(3) The Clay treated with 10% FA and 10% TCFA experienced an increase in the bearing ratios and compressive strengths along with an increase in plasticity index. The FA treated Clay data alone is not a sufficient indicator of the suitability of FA as a construction expedient or stabilizer with other soils. A thorough mix design process should be performed to evaluate the performance of FA with a given soil.

(4) The FA treated Clay swelled up to 15% during the first 24 hours of soaking, and thereafter, remained constant at 15%. A 7-day curing period, at room temperature prior to soaking for 67 days, reduced the swell to 4% and increased the Illinois Bearing Ratio from 2.4% to 11.0%.

(5) Additional research is needed to identify the effects of different combinations of the chemical constituents in fly ash on the behavior of treated soils.

(6) DLKS, HLB, and TCFA are recommended to be evaluated as subgrade modifiers during field testing.

REFERENCES

Baker, T. (1995). Unpublished Test Data. IDOT District 5, Paris.

Dhamrait, J.S. (1991). "Modification and Stabilization of Pavement Subgrade with Class C Fly Ash." Unpublished IDOT Bureau of Materials and Physical Research Report.

Ferguson, G. (1985). "Fly Ash Stabilization of Soils." Proceedings of the Seventh International Ash Utilization Symposium and Exposition - Volume 2. Orlando, FL. pp. 560-574.

Ferguson, G and Zey, J.J. (1990). "Stabilization of Pavement Subgrade with Class C Fly Ash." Proceedings of the Ninth International Coal Ash Utilization Symposium. Orlando, FL. pp. 42-1 to 42-14.

Ferguson, G. (1993) "Use of Self-Cementing Fly Ashes as a Soil Stabilization Agent." Fly Ash for Soil Improvement. ASCE Geotechnical Special Publication No. 36. New York, NY.

Ferguson, G. (1996). "Evaluation of Class "C" Fly Ash for Soil Stabilization Applications - American Fly Ash Company." Unpublished Report. Geosystems Engineering, Inc. Lenexa, Kansas.

Glogowski, P.E., Kelly, J.M., McLaren, R.J. and Burns, D.L. (1992). Fly Ash Design Manual for Road and Site Applications. Volume 1. Electric Power Research Institute. Palo Alto, CA. EPRI Report No. TR-100472.

Hanson Engineers Incorporated, (1996). "Laboratory Study -- Modification of Illinois Soils with Self-Cementing Fly Ash." Unpublished report prepared for American Fly Ash Company. Springfield, IL.

Heckel, G. and Wahab, R. (1996). "Soil Stabilization Utilizing Alternative Waste Materials." Materials for the New Millennium. Proceedings of the Fourth Materials Engineering Conference, Washington, D.C., Vol. 1. ASCE, New York. pp. 318-327.

Herrin, M. and Mitchell, H. (1961). "Lime-Soil Mixtures." Highway Research Board Bulletin 304. Washington D.C. pp. 99-138.

Illinois Division of Highways, (1970). "Design Coefficients for Lime-Soil Mixtures." Research and Development Report No. 22. Springfield, IL.

Little, R.J. (1983). "Lime-Modified Soil to Increase Subgrade Stability." IDOT Bureau of Materials and Physical Research Report No. 97. FHWA/IL/PR-097. Springfield, IL.

McManis, K.L. (1988). "Laboratory Evaluation of Fly Ash Treated Embankment and Base Materials." FHWA/LA-87/204. Louisiana Transportation Research Center, Baton Rouge.

McManis, K.L. and Arman, A. (1989). "Class C Fly Ash as a Full or Partial Replacement for Portland Cement or Lime." Transportation Research Record 1219. Transportation Research Board. Washington D.C. pp. 68-81.

Mindess, S. and Young, J.F. (1981). Concrete. Prentice-Hall, Inc. Englewood Cliffs, NJ.

Thompson, M.R. (1966). "Lime Reactivity of Illinois Soils." Journal of the Soil Mechanics and Foundations Division. American Society of Civil Engineers. Vol. 92 No. SM5 pp. 67-92

Thompson, M.R., Kinney, T.C., Traylor, M.L., Bullard, J.R. and Figueroa, J.L. (1977). "Subgrade Stability." (FHWA-IL-UI-169). Transportation Engineering Studies No. 18. University of Illinois, Urbana.

Thompson, M.R. (1995). Unpublished Test Data. University of Illinois, Urbana.

Transportation Research Board (1987). "Lime Stabilization." State of the Art Report 5. Washington D.C.

APPENDIX

Results of Individual Unconfined Compressive Strength Tests

SOIL TYPE	TREATMENT	CURING	q_u, kPa	ε_u, % [a]	Dry Density, kg/m^3	MC, %	% of ρ_{dmax}	% of OMC
Clay	None	-	410	8.3	1863	14.9	102.6	100.7
			401	8.5	1873	14.5	103.1	98.0
			342	6.5	1789	14.7	98.5	99.3
SiCL	None	-	240	4.0	1636	18.7	98.5	102.2
			278	3.8	1672	17.5	100.7	95.6
			249	3.0	1650	18.5	99.3	101.1
CL	None	-	316	15.0	1983	12.4	99.8	107.8
			335	15.0	2011	11.7	101.1	101.7
			347	14.5	2014	11.5	101.3	100.0
			354	13.1	2025	11.6	101.9	100.9
SC	None	-	417	4.5	1605	19.3	97.3	97.0
			451	5.8	1644	19.5	99.6	98.0
			416	5.4	1655	19.6	100.3	98.5
			453	5.5	1663	19.6	100.8	98.5
Clay	5% LKD	-	689	2.6	1850	13.9	106.5	95.9
			804	3.1	1886	13.8	108.6	95.2
			871	4.0	1865	14.0	107.4	96.6
			814	3.0	1862	13.9	107.2	95.9
Clay	5% DLKS	-	575	4.8	1862	15.1	105.3	98.7
			511	3.8	1804	15.0	102.1	98.0
			445	3.8	1783	15.5	100.9	101.3
			505	4.0	1793	15.4	101.5	100.7
Clay	5% HLB	-	481	2.5	1698	17.4	1.10.	102.4
			426	1.9	1669	17.4	99.3	102.4
			484	2.0	1684	17.8	100.2	104.7
			373	1.6	1650	17.6	98.2	103.5
Clay	10% FA	-	642	1.9	1754	14.2	99.3	97.9
			597	2.3	1714	14.0	97.0	96.6
			655	2.5	1773	14.4	100.4	99.3
			707	2.6	1786	14.3	101.1	98.6
Clay	10% TCFA	-	500	2.8	1860	12.7	100.3	98.4
			557	3.6	1890	13	102.0	100.8
			524	2.9	1842	12.4	100.4	96.1
			416	4.1	1831	12.6	98.8	97.7
Clay	10% FA	24hr@23.9°C	1075	2.6	1753	14.0	99.2	96.6
			1714	2.5	1757	14.2	99.5	97.9
			1773	3.1	1821	14.3	103.1	98.6
			1786	2.1	1705	14.1	96.5	97.2
Clay	10% TCFA	24hr@23.9°C	795	2.1	1876	12.9	101.2	100.0
			779	1.9	1860	13.2	100.3	102.3
			684	2.7	1804	12.9	97.3	100.0
			759	1.9	1842	12.6	99.4	97.7
Clay	5% LKD	7days@23.9°C	1839	3.8	1881	13.5	108.3	93.1
			1570	2.5	1862	13.9	107.2	95.9
			1810	2.8	1871	13.9	107.7	95.9
			1657	2.6	1852	13.8	106.6	95.2
Clay	5% DLKS	7days@23.9°C	600	2.8	1807	15.3	102.3	100.0
			589	2.8	1797	14.8	101.7	96.7
			561	2.5	1794	15.5	101.5	101.3
			579	2.7	1778	15.2	100.6	99.3

[a] Strain at Ultimate

Results of Individual Unconfined Compressive Strength Tests (cont.)

SOIL TYPE	TREATMENT	CURING	q_u, kPa	ε_u, %	Dry Density, kg/m^3	MC, %	% of ρ_{dmax}	% of OMC
Clay	5% HLB	7days@23.9°C	540	1.7	1714	17.0	102.0	100.0
			569	1.7	1672	17.1	99.5	100.6
			495	1.8	1671	17.0	99.4	100.0
			663	1.8	1670	17.3	101.1	101.8
Clay	10% FA	7days@23.9°C	1163	2.1	1724	13.9	97.6	95.9
			1472	2.6	1807	13.8	102.3	95.2
			1256	2.2	1740	14.4	98.5	99.3
			1353	2.4	1762	14.0	99.7	96.6
Clay	10% TCFA	7days@23.9°C	1239	2.3	1916	12.8	103.4	99.2
			1142	2.1	1876	12.8	101.2	99.2
			872	1.6	1821	12.4	98.3	96.1
			969	1.5	1836	13.2	99.0	102.3
Clay	5% LKD	7days@4.4°C	768	2.3	1745	14.3	100.5	98.6
			737	2.1	1749	14.3	100.7	98.6
			802	2.4	1764	14.4	101.6	99.3
			729	2.5	1738	14.1	100.1	97.2
Clay	5% HLB	7days@4.4°C	376	1.5	1679	17.0	99.9	100.0
			426	1.8	1672	17.4	99.5	102.4
			447	1.5	1663	17.5	99.0	102.9
			368	1.6	1628	17.8	96.9	104.7
Clay	5% LKD	48hrs@48.9°C	2930	4.1	1894[b]	12.8	109.0	88.3
			2557	3.5	1868[b]	13.0	107.6	89.7
			2940	4.2	1874[b]	13.2	107.9	91.0
			2854	4.0	1879[b]	12.9	108.2	89.0
Clay	5% DLKS	48hrs@48.9°C	1054	2.1	1772[b]	14.2	100.3	92.8
			1227	2.8	1815[b]	14.4	102.7	94.1
			1067	2.6	1780[b]	14.7	100.7	96.1
			901	2.3	1815[b]	14.3	102.7	93.5
Clay	5% HLB	48hrs@48.9°C	798	1.6	1658[b]	16.6	98.7	97.6
			1331	1.9	1679[b]	16.3	99.9	95.9
			1044	2.0	1653[b]	16.6	98.4	97.6
			1312	1.9	1642[b]	16.2	97.7	95.3
Clay	10% FA	28days@28.9°C	1841	3.1	1833	15.0	103.7	103.4
			1645	2.5	1778	14.9	100.6	102.8
			1576	2.2	1719	14.9	97.3	102.8
			1412	2.2	1725	14.7	97.6	101.4
Clay	10% TCFA	28days@28.9°C	1634	2.7	1930	12.9	104.1	100.0
			1542	2.6	1914	13.1	103.3	101.6
			1342	2.5	1881	12.8	101.5	99.2
			1308	2.5	1852	13.3	99.9	103.1
SiCL	5% LKD	-	407	2.0	1636	18.0	99.7	94.7
			450	2.1	1660	17.8	101.2	93.7
			468	3.0	1650	18.1	100.6	95.3
			463	3.0	1645	18.2	100.3	95.8
SiCL	5% DLKS	-	265	2.8	1626	21.1	100.9	105.5
			224	2.3	1600	20.9	99.3	104.5
			248	2.9	1591	21.0	98.7	105.0
			267	2.4	1604	20.7	99.5	103.5
SiCL	5% HLB	-	223	2.2	1581	21.5	99.0	102.4
			217	2.5	1583	21.4	99.1	101.9
			262	2.7	1602	21.7	100.3	103.3
			246	2.6	1599	21.4	100.1	101.9

[b] Calculated using the average batch MC because of moisture loss during curing.

Results of Individual Unconfined Compressive Strength Tests (cont.)

SOIL TYPE	TREATMENT	CURING	q_u, kPa	ε_u, %	Dry Density, kg/m³	MC, %	% of ρ_{dmax}	% of OMC
SiCL	5% LKD	48hrs@48.9°C	1131	2.2	1644[b]	16.6	100.2	87.4
			873	2.0	1640[b]	16.7	100.0	87.9
			1127	2.3	1645[b]	17.0	100.3	89.5
			1106	2.3	1650[b]	16.9	100.6	88.9
SiCL	5% DLKS	48hrs@48.9°C	282	2.7	1596[b]	19.3	99.0	96.5
			322	2.1	1604[b]	19.5	99.5	97.5
			276	2.1	1605[b]	20.6	99.6	103.0
			227	1.8	1600[b]	20.0	99.3	100.0
SiCL	5% HLB	48hrs@48.9°C	268	2.2	1583[b]	19.8	99.1	94.3
			318	2.7	1602[b]	19.9	100.3	94.8
			342	2.8	1589[b]	19.7	99.5	93.8
			405	2.4	1613[b]	19.7	101.0	93.8
SiCL	5% LKD	7days@23.9°C	992	2.1	1645	17.9	100.3	94.2
			1029	2.7	1642	17.9	100.1	94.2
			872	2.1	1650	17.9	100.6	94.2
			847	1.9	1654	17.8	100.9	93.7
SiCL	5% DLKS	7days@23.9°C	233	2.1	1597	21.2	99.1	106.0
			224	1.8	1586	21.4	98.4	107.0
			228	1.9	1597	21.2	99.1	106.0
			213	2.1	1583	21.4	98.2	107.0
SiCL	5% HLB	7days@23.9°C	272	2.0	1612	20.7	100.9	98.6
			284	2.0	1597	20.9	100.0	99.5
			253	2.1	1597	21.5	100.0	102.4
			281	2.3	1597	21.2	100.0	101.0
SiCL	5% LKD	7days@4.4°C	711	2.0	1663	17.8	101.4	93.7
			712	2.1	1644	17.7	100.2	93.2
			745	2.1	1642	17.9	100.1	94.2
			660	1.9	1642	18.2	100.1	95.8
SiCL	5% HLB	7days@4.4°C	212	1.8	1600	20.6	100.2	98.1
			267	2.6	1591	21.0	99.6	100.0
			276	2.7	1605	21.4	100.5	101.9
			242	2.3	1591	21.3	99.6	101.4
CL	5% LKD	-	446	2.3	1850	14.1	99.8	96.6
			435	1.9	1842	14.1	99.4	96.6
			482	2.3	1852	14.3	99.9	97.9
			454	1.8	1846	14.1	99.6	96.6
CL	5% DLKS	-	349	3.8	1886	14.9	100.4	108.8
			269	4.2	1870	14.7	99.6	107.3
			281	3.5	1874	14.7	99.8	107.3
			311	3.9	1870	14.7	99.6	107.3
CL	5% HLB	-	391	2.0	1821	15.1	102.0	100.0
			352	2.1	1793	15.3	100.4	101.3
			350	2.5	1813	15.4	101.5	102.0
			306	2.1	1797	15.3	100.6	101.3
CL	5% LKD	48hrs@48.9°C	2097	3.1	1863[b]	13.0	100.5	89.0
			2155	3.1	1855[b]	12.8	100.1	87.7
			2011	3.5	1854[b]	12.7	100.0	87.0
			2040	3.4	1854[b]	13.1	100.0	89.7
CL	5% DLKS	48hrs@48.9°C	824	2.4	1900[b]	14.0	101.2	102.2
			523	1.6	1823[b]	14.1	97.1	102.9
			679	2.2	1889[b]	14.0	100.6	102.2
			693	1.8	1870[b]	13.9	99.6	101.5
CL	5% HLB	48hrs@48.9°C	675	2.0	1815[b]	14.1	101.6	93.4
			718	2.4	1857[b]	14.4	103.9	95.4
			977	1.4	1791[b]	14.2	100.3	94.0
			900	2.6	1783[b]	14.4	99.8	95.4

Results of Individual Unconfined Compressive Strength Tests (cont.)

SOIL TYPE	TREATMENT	CURING	q_u, kPa	ε_u, %	Dry Density, kg/m³	MC, %	% of ρ_{dmax}	% of OMC
CL	5% LKD	7days@23.9°C	1369	2.2	1855	14.3	100.1	97.9
			1369	2.3	1852	14.3	99.9	97.9
			1408	2.4	1862	14.2	100.4	97.3
			1465	2.3	1860	14.0	100.3	95.9
CL	5% DLKS	7days@23.9°C	489	2.6	1895	14.5	100.9	105.8
			518	1.6	1887	14.3	100.5	104.4
			439	2.0	1874	14.7	99.8	107.3
			449	1.7	1870	14.7	99.6	107.3
CL	5% HLB	7days@23.9°C	339	1.3	1759	15.8	98.5	104.6
			383	2.1	1772	14.7	99.2	97.4
			626	1.8	1817	14.4	101.7	95.4
			523	1.5	1769	14.7	99.0	97.4
CL	5% LKD	7days@4.4°C	878	3.0	1905	14.2	102.8	97.3
			791	2.4	1874	14.4	101.1	98.6
			616	1.9	1855	14.3	100.1	97.9
CL	5% HLB	7days@4.4°C	286	1.5	1812	15.2	101.4	100.7
			312	2.0	1772	15.8	99.2	104.6
			400	2.4	1812	15.5	101.4	102.6
			342	1.9	1797	15.3	100.6	101.3
SC	5% LKD	-	442	2.2	1511	20.6	99.6	102.9
			520	2.5	1517	21.4	100.0	101.9
			457	2.5	1507	21.3	99.4	101.4
			415	1.9	1509	21.5	99.5	102.4
SC	5% DLKS	-	423	4.5	1610	22.9	102.3	103.2
			343	3.4	1552	23.1	98.7	104.1
			376	3.0	1578	22.7	100.3	102.3
			374	2.9	1557	23.4	99.0	105.4
SC	5% HLB	-	427	0.7	1453	21.4	99.7	95.1
			504	0.9	1474	21.3	101.1	94.7
			499	1.2	1469	21.7	100.8	96.4
			489	1.4	1474	21.3	101.1	94.7
SC	5% LKD	48hrs@48.9°C	869	2.1	1522	21.7	100.3	103.3
			1053	1.6	1506	21.7	99.3	103.3
			748	1.0	1517	21.5	100.0	102.4
			757	1.5	1517	21.2	100.0	101.0
SC	5% DLKS	48hrs@48.9°C	468	1.3	1580	22.8	100.4	102.7
			448	1.8	1560	23.4	99.2	105.4
			462	1.5	1554	23.3	98.8	105
			409	2.1	1556	22.9	98.9	103.2
SC	5% HLB	48hrs@48.9°C	1695	1.4	1477	21.1	101.3	93.8
			1551	1.8	1477	22.1	101.3	98.2
			1551	2.0	1475	21.1	101.2	93.8
SC	5% LKD	7days@23.9°C	501	2.4	1507	21.9	99.4	104.3
			599	2.7	1532	21.9	101.0	104.3
			469	1.3	1528	21.2	100.7	101.0
			626	1.5	1522	21.0	100.3	100.0
SC	5% DLKS	7days@23.9°C	386	2.0	1546	23.9	98.3	107.7
			314	1.6	1552	21.4	98.7	108.6
			350	1.7	1557	24.0	99.0	108.1
			345	1.6	1546	23.6	98.3	106.3
SC	5% HLB	7days@23.9°C	766	1.3	1483	21.9	101.8	97.3
			517	0.7	1469	21.7	100.8	96.4
			404	1.3	1459	22.5	100.1	100.0
			584	0.9	1467	21.5	100.7	95.6

Results of Illinois Bearing Ratio Tests

Soil Type	Treatment	Test[c]	IBR[d]	Swell, %	Molded Dry Density, kg/m^3	Molded MC, %	Molded S_r, %	Soaked Dry Density, kg/m^3	Soaked MC, %	Soaked S_r, %
Clay	None	S	0.9	1.4	1794	16.2	88.0	1765	19.1	98.9
			1.3	1.9	1801	16.2	89.0	1717	21.8	100.0
Clay	5% LKD	S	6.0	1.9	1729	15.8	77.0	1724	19.1	92.4
			8.4	4.2	1735	14.9	73.4	1645	22.5	96.2
Clay	5% DLKS	S	5.4	1.6	1727	16.1	78.3	1684	20.6	93.4
			5.9	1.6	1727	15.6	75.8	1679	20.9	94.0
Clay	5% HLB	S24	12.2	0.9	1697	17.0	78.7	1677	20.5	92.0
			11.3	0.9	1677	17.3	77.6	1663	20.6	90.3
Clay	5% HLB	MT	25.0	1.4	1689	17.3	79.0	1661	20.3	88.8
			25.7	1.2	1692	17.1	78.5	1661	20.3	88.8
Clay	5% HLB	S	11.8	1.2	1677	17.1	76.7	1664	20.5	90.1
			11.7	1.2	1677	17.0	76.3	1669	20.0	88.6
Clay	10% FA	S0	2.5	13.9	1764	15.8	81.6	1495	30.7	100.0
			2.3	14.0	1761	15.7	80.7	1498	30.0	100.0
Clay	10% FA	MS	2.2	*	1778	13.8	73.0	1543	26.3	95.7
			2.2	*	1783	13.8	73.6	1567	24.3	91.7
Clay	10% FA	SC1	2.2	*	1756	14.1	71.9	1556	25.7	95.4
Clay	10% FA	MS C24	3.4	*	1756	14.0	71.4	1612	23.5	95.1
Clay	10% TCFA	S0	7.3	3.9	1849	14.0	83.5	1745	19.9	99.6
			7.0	4.0	1857	13.6	82.3	1749	19.5	98.3
Clay	10% FA	C7S67	11.0	4.0	1767	14.2	73.7	1761	21.3	100.0
SiCL	None	S	3.1	2.0	1658	19.4	84.4	1632	21.0	87.8
			4.5	1.4	1645	19.5	83.2	1624	21.5	88.8
SiCL	5% LKD	S	71.0	0.5	1650	19.1	82.1	1644	20.9	88.9
			69.6	0.5	1640	19.1	80.8	1636	21.5	90.3
SiCL	5% DLKS	S	15.2	0.1	1610	20.5	82.7	1599	22.5	89.2
			14.0	0.0	1588	21.5	83.8	1591	23.1	90.5
SiCL	5% HLB	S24	22.6	0.1	1591	21.6	84.6	1597	22.5	89.0
			19.4	0.2	1588	21.8	85.0	1596	22.8	90.0
SiCL	5% HLB	MT	23.0	0.6	1607	21.4	85.9	1591	23.0	90.1
			20.9	0.5	1596	21.2	83.7	1583	23.2	89.8
SiCL	5% HLB	S	22.5	0.4	1594	21.0	82.7	1597	23.1	91.4
SiCL	10% TCFA	C7S67	27.4	0.0	1666	19.2	83.1	1676	20.6	90.5
CL	None	S	3.6	1.2	1985	12.4	93.1	1962	13.2	95.0
			3.6	1.3	1978	12.1	89.7	1958	13.2	94.1
CL	5% LKD	S	38.0	1.2	1855	14.9	88.4	1837	16.6	95.6
			36.0	1.3	1852	14.7	86.8	1829	16.9	96.0
CL	5% DLKS	S	23.5	0.1	1881	14.1	87.5	1878	15.2	93.8
			24.3	0.0	1881	13.8	85.6	1870	15.4	93.7
CL	5% HLB	S24	15.1	0.3	1786	15.0	79.3	1796	16.8	90.2
			15.1	0.2	1804	14.7	80.0	1810	16.9	92.9
CL	5% HLB	MT	34.3	1.9	1785	15.8	83.3	1721	20.4	96.8
			34.0	1.9	1785	16.1	84.8	1730	20.0	96.4
CL	5% HLB	S	14.7	1.4	1780	14.6	76.3	1770	17.7	91.1

[c] Test Designations: S=Standard S0=Standard test/no compaction delay S24=Standard test/24 hour mellow MT=Modified soak temperature:48.9°C MS=Modified soak time:7 days _C1=Cured for 1 hour prior to soaking _C24=Cured for 24 hours prior to soaking C7S67=Cured for 7 days prior to soaking for 67 days

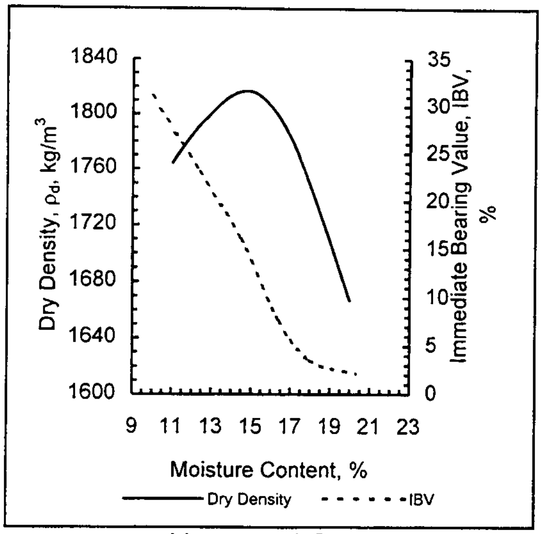
[d] IBR = Illinois Bearing Ratio

* See Figure 2

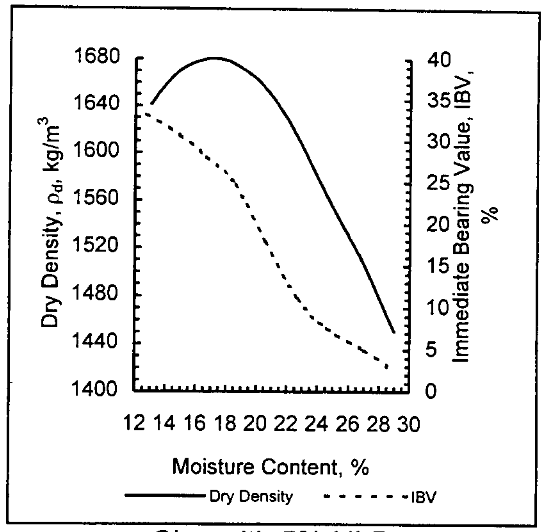
Results of Illinois Bearing Ratio Tests (cont.)

Soil Type	Treatment	Test[c]	IBR[d]	Swell, %	Molded Dry Density, kg/m^3	Molded MC, %	Molded S_r, %	Soaked Dry Density, kg/m^3	Soaked MC, %	Soaked S_r, %
SC	None	S	4.5	2.8	1656	21.1	90.5	1608	24.5	97.6
			2.7	3.9	1621	21.5	87.3	1554	27.0	98.9
SC	5% LKD	S	16.6	1.8	1514	21.3	73.5	1507	26.1	89.2
			15.5	1.9	1515	21.0	72.6	1513	26.3	90.5
SC	5% DLKS	S	6.5	1.0	1552	24.3	88.8	1548	26.1	94.7
			6.5	1.0	1565	23.9	89.1	1549	26.3	95.7
SC	5% HLB	S24	29.8	0.1	1440	23.3	72.0	1490	25.4	84.5
			32.9	0.1	1451	23.2	72.9	1519	23.7	82.3
SC	5% HLB	MT	94.1	0.2	1461	21.5	68.5	1467	27.9	89.8
			94.2	0.4	1458	21.6	68.5	1453	28.5	89.7

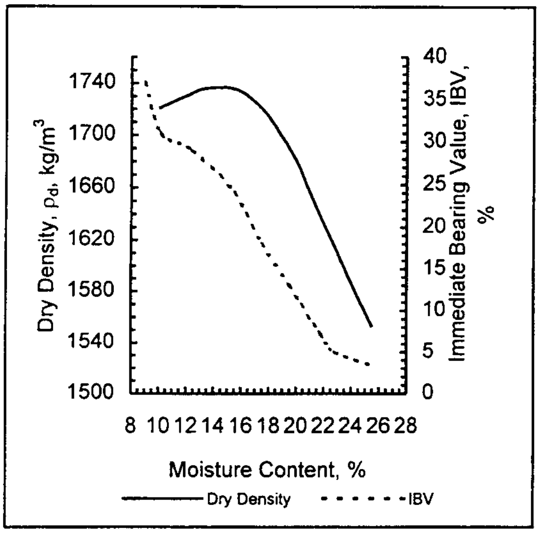
MOISTURE-DENSITY-IBV RELATIONS FOR TREATED AND UNTREATED CLAY



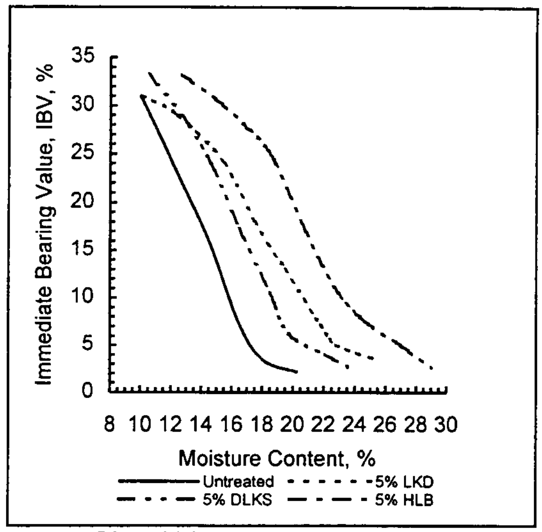
Untreated Clay



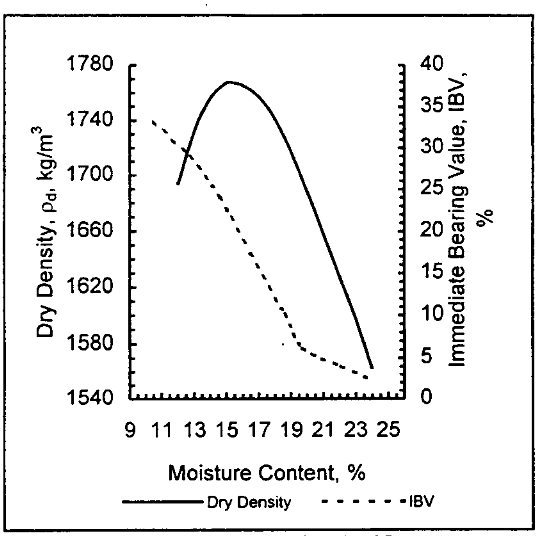
Clay with 5% HLB



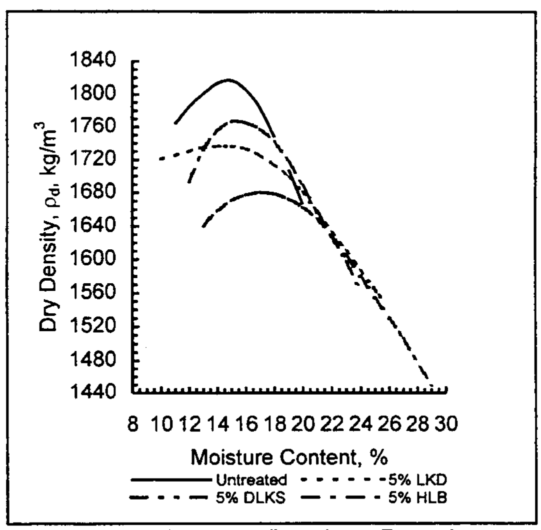
Clay with 5% LKD



Clay / Lime By-Product IBV

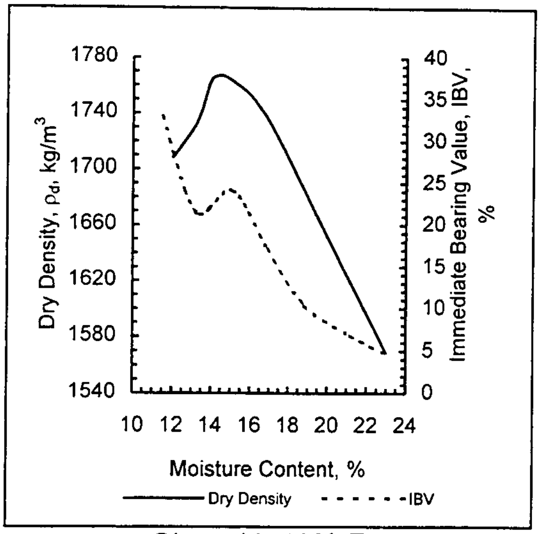


Clay with 5% DLKS

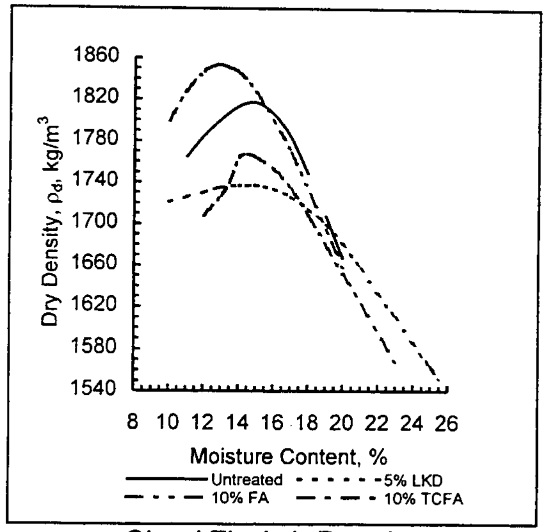


Clay / Lime By-Product Density

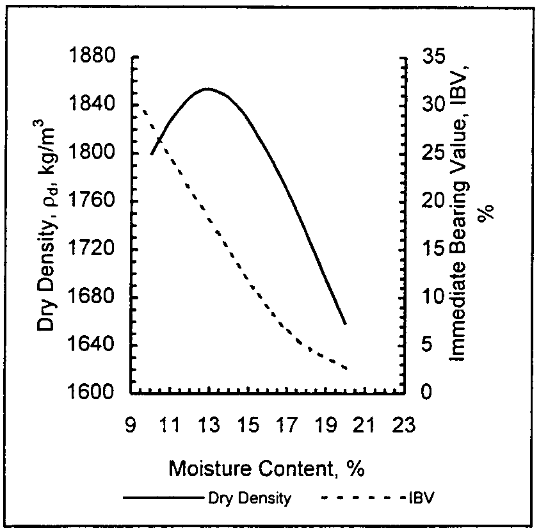
MOISTURE-DENSITY-IBV RELATIONS FOR TREATED AND UNTREATED CLAY



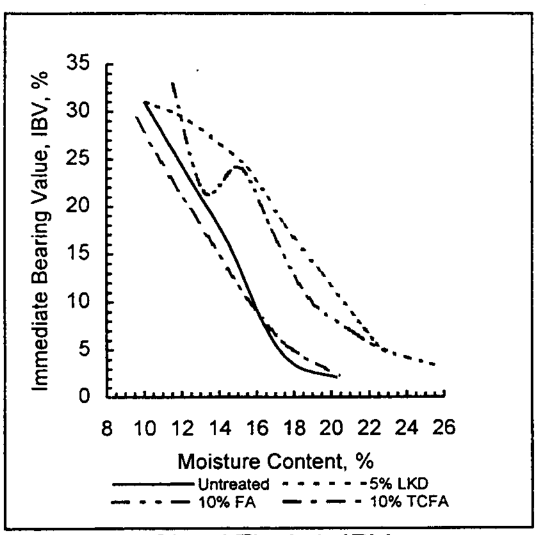
Clay with 10% FA



Clay / Fly Ash Density

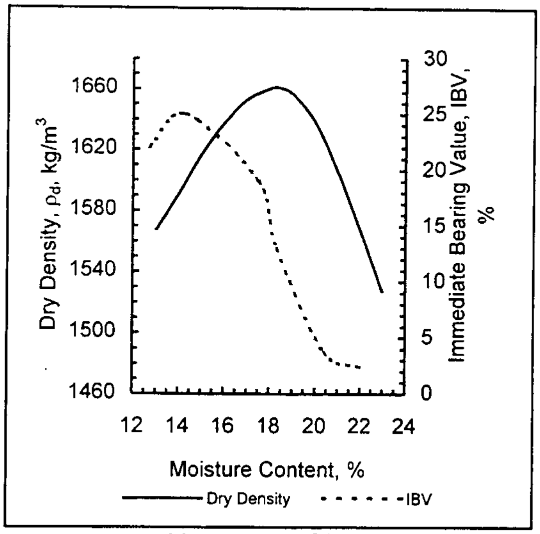


Clay with 10% TCFA

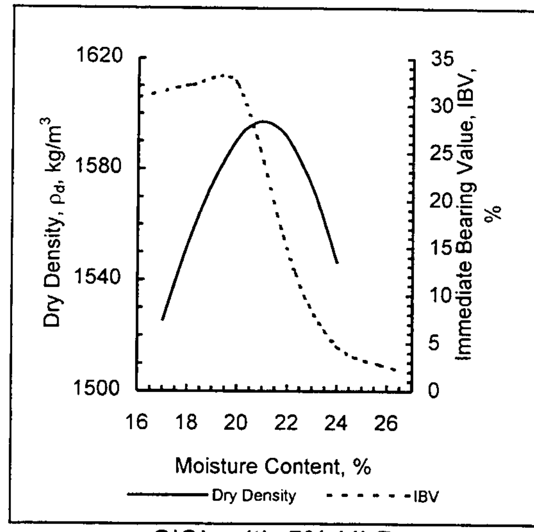


Clay / Fly Ash IBV

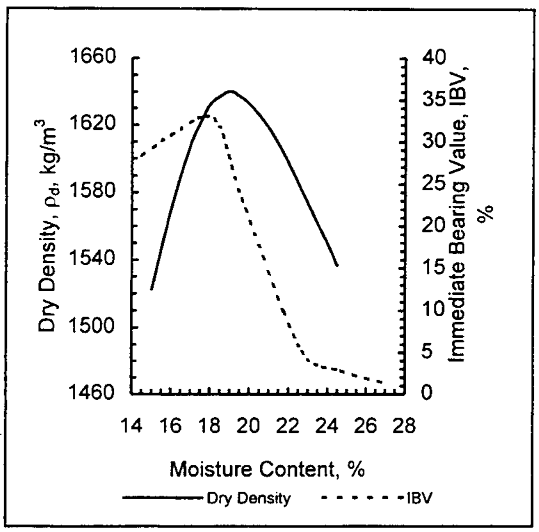
MOISTURE-DENSITY-IBV RELATIONS FOR TREATED AND UNTREATED SiCL



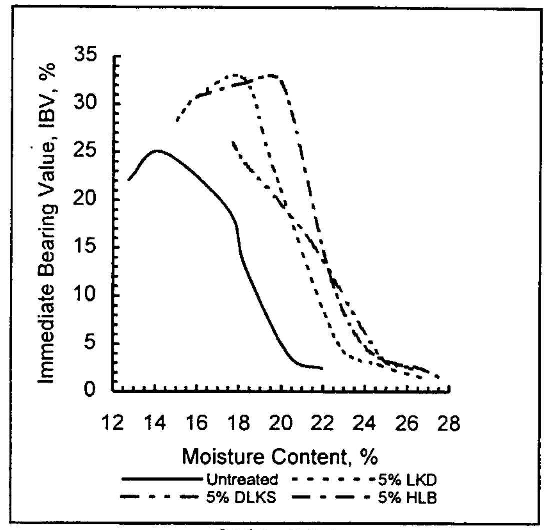
Untreated SiCL



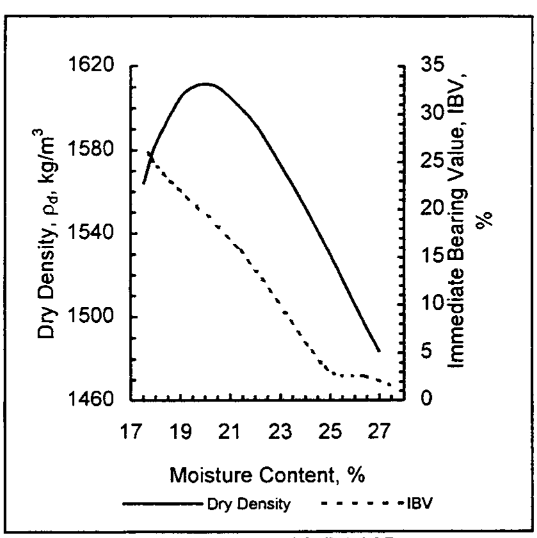
SiCL with 5% HLB



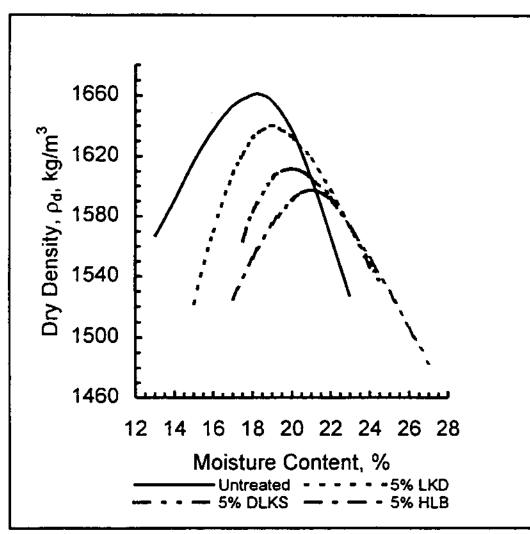
SiCL with 5% LKD



SiCL IBV

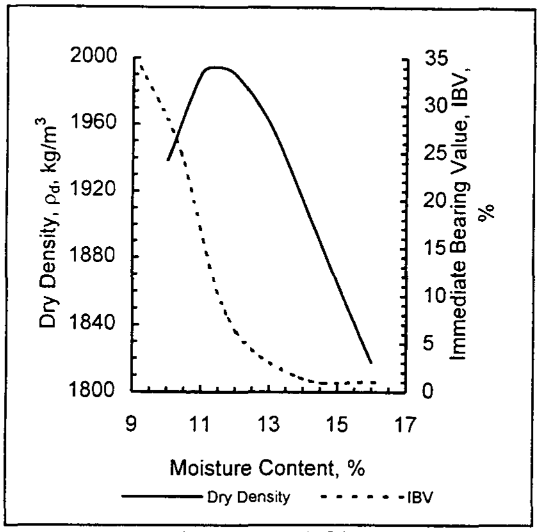


SiCL with 5% DLKS

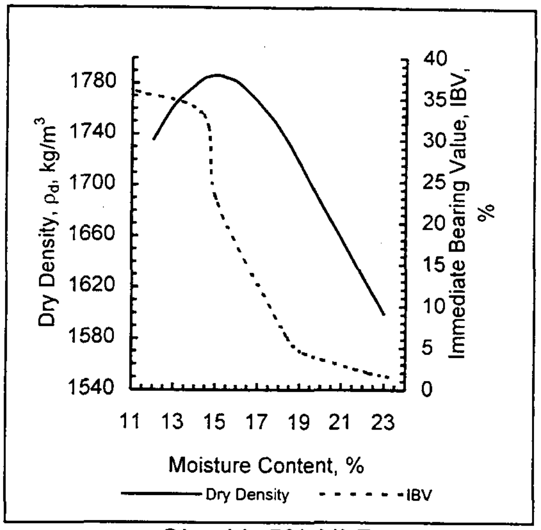


SiCL Density

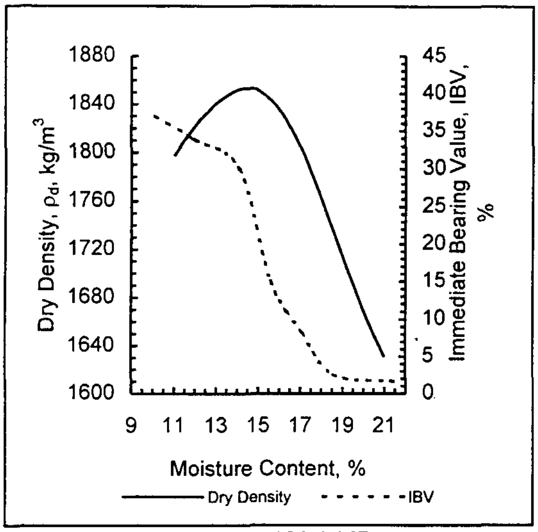
MOISTURE-DENSITY-IBV RELATIONS FOR TREATED AND UNTREATED CL



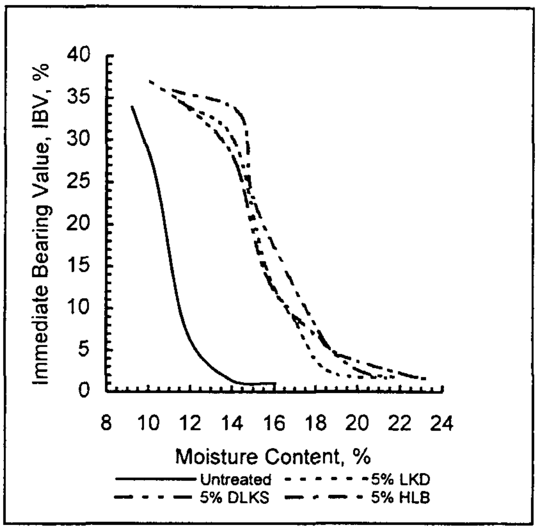
Untreated CL



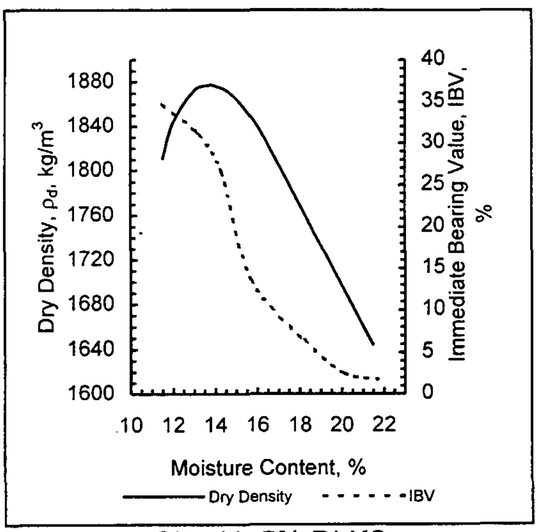
CL with 5% HLB



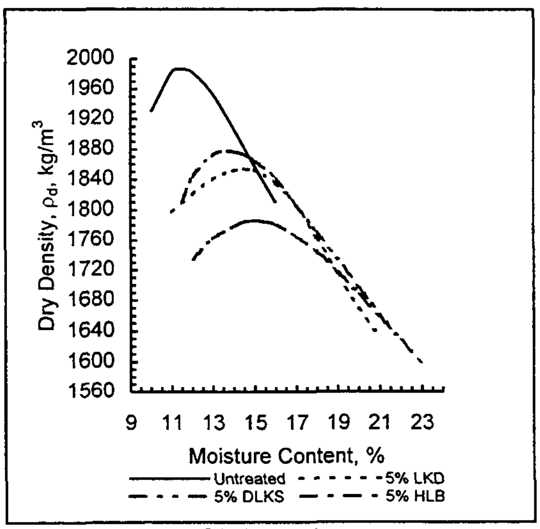
CL with 5% LKD



CL IBV

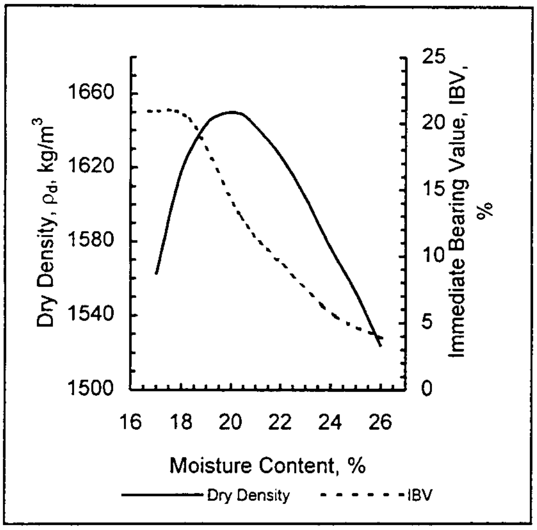


CL with 5% DLKS

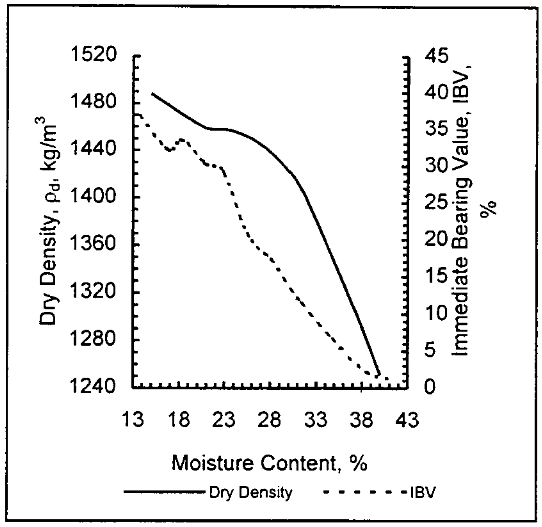


CL Density

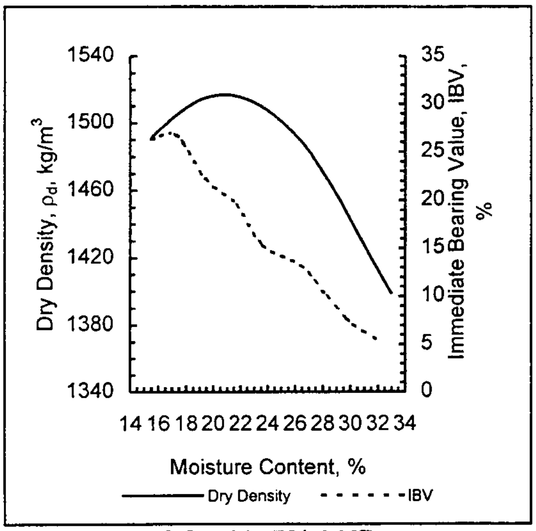
MOISTURE-DENSITY-IBV RELATIONS FOR TREATED AND UNTREATED SC



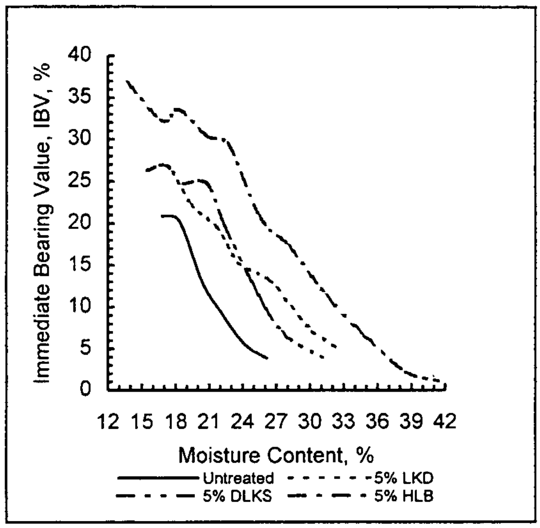
Untreated SC



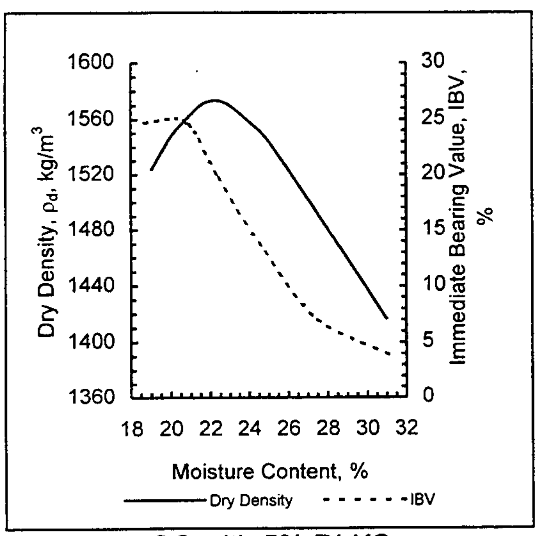
SC with 5% HLB



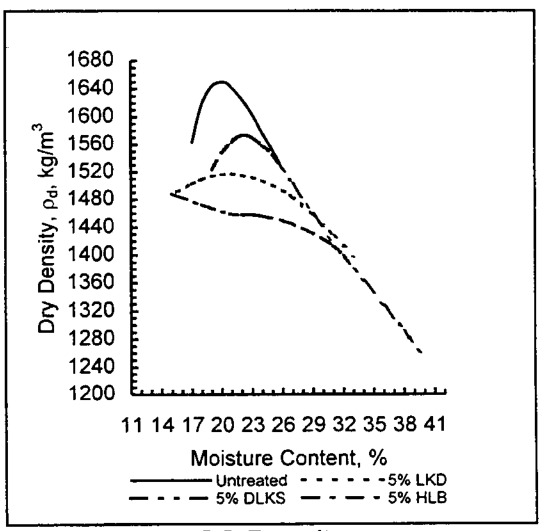
SC with 5% LKD



SC IBV

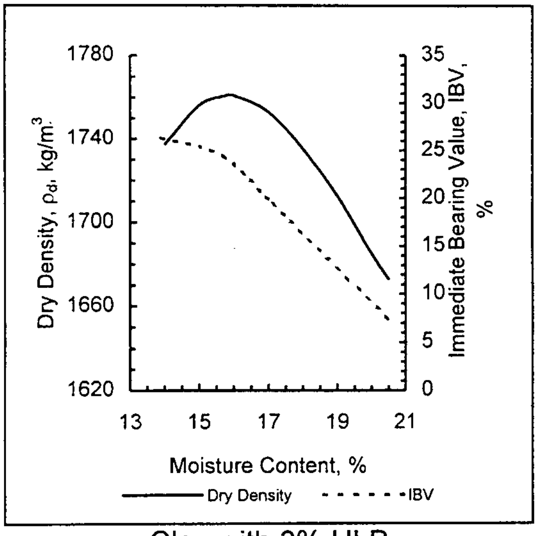


SC with 5% DLKS

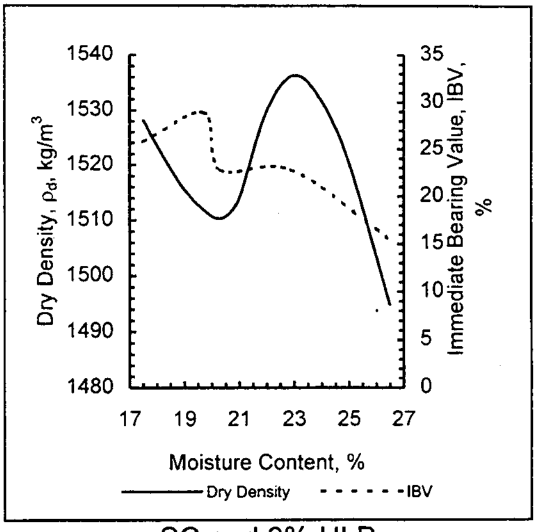


SC Density

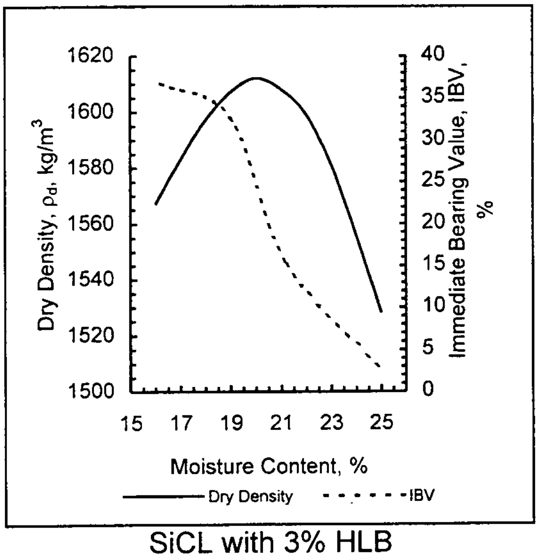
MOISTURE-DENSITY-IBV RELATIONS FOR SOILS TREATED WITH 3% HLB



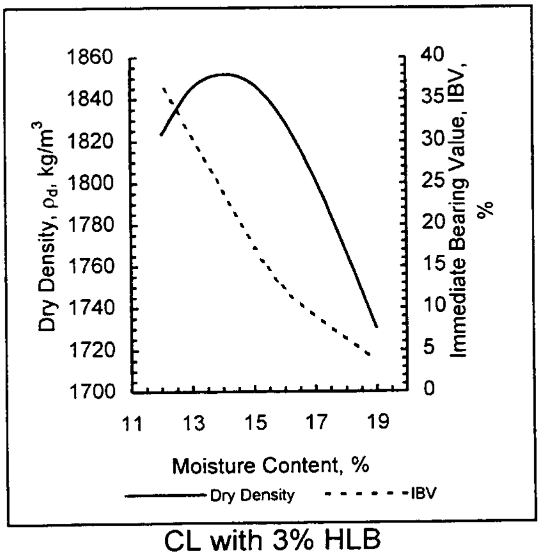
Clay with 3% HLB



SC and 3% HLB



SiCL with 3% HLB



CL with 3% HLB