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PROPERTY CHANGES IN LIME TREATED EXPANSIVE CLAYS UNDER CONTINUOUS LEACHING

by

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This report is the result of a study to determine what effects continuous water leaching has on the engineering, physical, and chemical properties of three lime treated expansive clays in north central Texas. Seventy laboratory prepared lime treated clay samples were subjected to continuous accelerated leaching for 45 and 90 days in large diameter, flexible wall leach cylinders. Constants during the leach testing were types of soil used, flow pressure, curing conditions, and compaction effort. Variables were lime content, initial moisture content, and duration of the leach cycle.

The soil's physical and chemical properties were measured before and after leaching then graphically and statistically compared. Physical properties tested included permeability, Atterberg limits, linear shrinkage, swell properties, unconfined compression strength, and differential thermal analysis properties. Chemical properties measured were soil pH, porewater cation extractions, and exchange complex cation extractions. Extractions were tested

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for calcium, sodium, magnesium, and potassium cations. Additionally, the leachate passing
through the soil was collected and monitored for changes in pH and cation concentrations.

Results indicate that leaching does have a detrimental impact on the properties of lime
treated expansive clay. The changes in the soil's physical and chemical properties are related
to lime content and moisture content during compaction. The permeability of all samples tested
increased dramatically with the addition of lime, and it is speculated that permeability plays
a key function in determining the amount of physical and chemical change that occurs during
leaching. Maximum detrimental changes generally occurred at lime contents at or less than the
lime modification optimum. At lime contents at or above the lime stabilization optimum, the
detrimental effects were minimized.

An estimation technique to correlate laboratory leach results to field predictions of
calcium removal and soil pH declination is presented. Field samples of known lime
specifications were used to validate the technique with limited success.

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PREFACE

This report presents the final results of a two-year research project to determine what effects continuous water leaching has on the physical and chemical properties of lime treated expansive clays in north central Texas. Seventy laboratory prepared lime treated clay samples were subjected to continuous accelerated leaching for 45 and 90 days in larger diameter, flexible wall leach cylinders. The soil's physical and chemical properties were measured before leaching and graphically and statistically compared after leaching. An estimation technique to correlate laboratory leach results to field predictions of calcium removal is presented.

The research project was started in June 1988, and was completed in March 1990. It was conducted in the Geotechnical Research Laboratory, Civil Engineering Department, The University of Texas at Arlington (UTA).

The research was conducted by CPT Larry D. McCallister, Ph.D., P. E., US Army Corps of Engineers, as partial fulfillment of the requirements for the degree of Doctor of Philosophy. Dr. Thomas M. Petry, P. E., Associate Professor of Civil Engineering at UTA, provided primary technical advice. Drs. Clyde Armstrong, Jim Williams, R. C. Baker, Steve Collins, and the late Arthur Poor provided advice and served on the advisory committee. CPT McCallister wrote this report with assistance by Dr. Petry.

Various organizations and personnel provided assistance during the research. Soil was obtained from three locations. Soil from two of those locations was obtained from the Dallas/Fort Worth (D/FW) International Airport by authorization of the D/FW Airport Planning, Engineering, and Construction Division. Mr. Doug Showers was Senior Construction Engineer for the Division. Soil from the third site was obtained from a development

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Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

To convert from	To	Multiply by
in	mm	2.540
ft	m	0.3048
in^2	mm^2	645.160
ft^2	m^2	0.0929
ft^3	m^3	0.0283
quart (U.S. liquid)	liter	0.9464
kg (force or mass)	N	9.8067
lb (mass)	g	453.592
kips (1000 lbs)	kN	4.4482
kip/ft	kN/m	14.5939
lb/ft	kg/m	1.4882
lb/ft^2	N/m^2 (pascal)	47.8803
kg/cm^2	kN/m^2 (kPa)	98.0665
kip/ft^2 (ksf)	kPa	47.8803
lb/in^2 (psi)	kPa	6.8948
kip-ft	kN-m	1.3558
lb/ft3 (pcf)	kg/m^3	16.0185
kip/ft^3	kN/m^3	157.0875
g/cm^3	kN/m^3	9.8067

Temperatures can be converted by using the following equations:

$$°C = 5/9 \ (°F - 32) \tag{a}$$
$$°F = 9/5 \ (°C + 32) \tag{b}$$

PROPERTY CHANGES IN LIME TREATED EXPANSIVE CLAYS UNDER CONTINUOUS LEACHING

Final Report

PART I. INTRODUCTION

Damage Caused by Expansive Clays

1. Expansive clays are those clays that exhibit high potential for volume change, i.e., shrink-swell, due to changes in soil moisture. They cause extensive damage each year to foundations, pavements and other rigid structures. Jones and Jones (1987) estimates that the total annual damage just to U. S. homes exceeds $1 billion and over $9 billion for other facilities built on expansive clays. Boynton and Blacklock (1986) estimates that the total annual structural damage exceeds $5 billion. This damage is more than the estimated damage caused by earthquakes, floods, and other natural disasters. The U. S. Army Corps of Engineers (Department of the Army 1983) considers the primary causes of foundation damage due to heave or settlement, i.e., expansive clay phenomena, to be a result of soil moisture changes affected by changes in the natural environment (e.g., rainfall changes) or manmade environment (e.g., construction or water usage changes).

2. Expansive soils are found throughout the world but are limited primarily in the continental United States to some southwestern and north central states. Texas, South Dakota, and Montana appear to have the most significant occurrences of expansive clays (Department of the Army 1983).

3. Damage due to expansive clays can occur in the form of pavements exhibiting center or dome heaving, edge heaving, cyclic heaving (seasonal rise and fall), and as lateral heaving of retaining structures, or any combinations of these. Expansive soil movement causes masonry walls to crack, floor slabs to shift and

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crack, grade beams to break, slopes to slide, and pavements and runways to become hazardous and frequently unusable (Boynton and Blacklock 1986; Department of the Army 1983; Byer 1980).

Control of Expansive Clays

4. Whenever expansive soils are encountered, the design engineer usually considers three options, namely: (1) use the soil and make appropriate changes to the structural requirements, (2) remove the questionable soil and replace with non-expansive soil, or (3) modify the expansive soil (Ingels and Metcalf 1973; Boynton and Blacklock 1986). Modification is generally the preferred choice for large projects.

5. Expansive clays have been successfully modified using chemical, mechanical, and other methods. Mechanical or physical methods include presoaking, water injection, preloading, compaction, de-watering, isolation by membranes, and electro-osmosis. These methods attempt to control the flow of water in the soil mass by modifying the rate of moisture change. Some of these methods are relatively inexpensive and reliable, but generally all are time consuming to apply. With each method, water movement still occurs, although at a reduced rate.

6. Physicochemical modification alters the behavior of the expansive clay particles within the soil mass, resulting in improved soil workability and reduction in shrink-swell potential. Various chemicals and additives have been used including salts, asphaltic material, nonorganic chemicals such as sodium silicate, and polymers such as aniline-furfural, epoxies, latex and calcium acrylate. Most are not in wide use because of expense, ineffectiveness and safety considerations (Marks and Haliburton 1970; Davidson, Mateos, and Barnes 1960; Ingels and Metcalf

1973). One of the most common and effective physicochemical treatments is the addition of lime, in the form of calcium hydroxide ($Ca(OH)_2$) or quicklime (CaO), to expansive clays.

7. Lime treatment of expansive clays has been widely used for many years. It has been used by more than 40 states as the primary stabilization in roads, runways, buildings and parking lots (Anonymous 1953; Goldberg and Klein 1952; Clare and Cruchley 1957; Boynton 1976; Terrel et al. 1979). Lime has been the subject of numerous research investigations to explain the physical phenomena of the lime-soil reactions (Ladd et al. 1960; Hilt and Davidson 1960; Ho and Handy 1963; Diamond and Kinter 1965; Townsend and Kylm 1966; Thompson 1966; Eades, Nichols, and Grim 1962; Johnson 1948). However, little work has been done to study what effect leaching will have on the achieved beneficial properties of lime-soil mixtures.

Scope of Investigation

8. It was the intent of this research to thoroughly study the long-term effects of continuous leaching on lime modified expansive clays. This was accomplished by studying the leaching effects on laboratory prepared samples, analyzing the changes of the soil's physical and chemical properties after leaching, and comparing the results to changes that have occurred over time to lime treated clays in the field.

Field Sites

9. In order to attempt a correlation between laboratory sample changes after leaching to actual field data, three sites were selected in the Dallas/Fort Worth (DFW) Metroplex. At each site there is a concrete pavement constructed over a lime modified expansive clay subgrade. The lime treated subgrade extends past the

concrete by at least 18 inches with minimum top-soil covering. The construction specifications of the lime treatment and time since construction for each site are known. Engineering and chemical tests were conducted on these extended subbases to determine any changes of modified properties since they were first constructed. The three lime treated construction projects are 3, 8, and 16 years old. In-situ, non-treated soil from these three areas was used for preparing laboratory samples for leaching.

Laboratory Testing

10. Laboratory compacted samples of various soil-lime mixtures were leached with distilled/demineralized water in specially designed, large diameter, flexible wall leach cells for periods of 45 and 90 days. By subjecting each soil-lime sample to numerous physical and chemical tests prior to the start of the leach process and repeating at the end of leaching, any change in the soil's physical and chemical properties were readily noted. Control or reference data was used by testing and leaching the same soil with no lime added.

11. Variables investigated included changes in lime content, changes in initial compaction moisture content, and leaching duration. Constants maintained throughout the investigation included compactive effort, cure conditions, flow pressure, and type of soil used.

12. Laboratory testing was conducted in three phases. Each phase was essentially identical except for the percentages of lime used (which is based on individual soil behavior) and soil type. During each phase only the soil from one of the three selected sites was used. Laboratory and field testing were completed and the results analyzed prior to proceeding to the next phase. By repeating the testing three times, with three different expansive clays (although they are all from the

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same geologic formation), repeatability and conformation of results were significantly enhanced.

Correlation

13. Based on comparisons of changes obtained in laboratory leach tests to changes in field modified soils caused by rainfall percolation, it was speculated that a correlation could be developed. If such a correlation exists, then a method of estimating soil-lime mixture longevity would be possible, thus eliminating much of the conservatism that is presently used in construction for estimating the quantity of lime required for proper subgrade modification.

Statistical Analysis

14. A statistical analysis was conducted on each site's data to determine the significance of changes in results before leaching versus after leach tests. All statistical tests were conducted at an $\alpha = 0.05$ level of significance using the student's t test to test the difference between the means.

PART II. LITERATURE REVIEW

Longevity of Lime Treated Soils

15. It has been widely accepted that once lime is applied to a lime reactive soil, the physical changes occurring within the soil-lime mass remain fairly permanent with time. Eades and Grim (1960) questioned the permanency of lime in soil and conducted experiments with lime in pure clay minerals. They speculated that if stabilization was due to only flocculation or ion exchange, percolation of ground water could replace calcium. Although their studies did not include any percolation or leach tests, they concluded that based on distinct structural changes in the clay minerals, i.e., formation of crystalline silicate hydrates, the "reaction products" would be permanent and not susceptible to leaching.

16. Kennedy (1988) recently commented that once a soil is physically altered by extensive calcium silicate hydrate (CSH I and II) formation, the silicates are permanent and cannot be reversed. Since these silicate formations are pozzolanic in nature and similar to the reaction in Portland cement concrete, Kennedy (1988) stated soil-lime mixtures would be resistant to weathering to the same degree that a weak concrete resists weathering. However, the percentage of lime added must be sufficient enough to generate the long-term pozzolanic reactions and large calcium silicate formations. Therefore, this does not dispute the possibility of reversal or degeneration of soil-lime effects for areas where smaller quantities of lime have been added than that necessary for complete soil stabilization.

17. Gutschick (1978) presented arguments for the permanency of lime stabilization in his paper by discussing the success of several lime stabilized water retention projects. He stated that the mixing of clays with lime will form complex calcium and aluminum silicate reactions that make the treated layer hydrophobic,

i.e., non-sensitive to waters. Examples of successful projects sighted included the Friant-Kern Canal in California, a Mississippi River levee in Arkansas and earth dams in Oklahoma, Mississippi, Texas, Tennessee, Arizona, and New Mexico. All projects were built in the 1960's and 1970's and were performing adequately at the time of his paper.

Durability of Lime Stabilized Construction Projects

18. An extensive field investigation was undertaken in 1977 to determine the long-term effectiveness of lime stabilized roads (Kelley 1977). During the late 1940's, the Fourth Army (now the Fifth Army Command) at Fort Sam Houston, Texas, initiated a lime stabilization program at several military posts throughout Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. The projects were to repair the posts' road networks that had badly deteriorated since their hasty construction during World War II. Lime was chosen as the primary stabilizer in order to save gravel cost and because a large portion of the road failures were caused by highly expansive clay subgrades (plasticity indices of 12 to over 50). Since lime stabilization was a very new construction procedure, the Fourth Army engineers arbitrarily chose the percentages of lime to use, ranging from three to eight percent with the majority in the three to four percent range. The typical stabilized layer was six inches* thick with a thin asphaltic cement overlay.

19. On all posts investigated, the lime stabilized pavements were performing satisfactorily after more than 25 years of use. In terms of low maintenance requirements, the lime stabilized roads offered good alternatives to concrete pavement overlaying thickened gravel bases and cement stabilized subgrades.

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*A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 25.

There was a significant increase in strength gain for lime stabilized bases. For example, at Fort Polk, Louisiana, lime stabilized bases increased from a 100 CBR* in 1952 to over 139 CBR in 1975. At Fort Chaffee, Arkansas, base strength increased from 325 psi to 1820 psi. In fact, Kelley (1977) suggests that the strength gain caused detrimental cracking of the pavements and could have been prevented if only approximately two-thirds of the lime had been used.

20. The Friant-Kern Canal in California was experiencing cracking, sliding, and sloughing in areas of highly expansive clays after only three years of operations (Byers 1980). In the early 1970's, it was decided to remove portions of the canal lining, flatten the side slopes and recompact the lining using lime stabilization. The clay had a liquid limit of up to 70 and plasticity indices of up to 46. Four percent quicklime (CaO) was used during construction. The canal goes through cyclic submerged and dry conditions on a yearly basis and for two months of the year the canal is completely empty.

21. After construction of one modified section in 1972, the lining was monitored for changes. Tests showed that after seven years, the effective lime content decreased slightly by approximately one percent. However, the dry density remained fairly constant and the unconfined compressive strength increased slightly. Erosion measurement showed that after six years, maximum erosion was four inches with the majority of the canal averaging about two inches of erosion (Byers 1980).

22. Since 1969, the Soil Conservation Service has used lime, alum, and gypsum to treat over 50 dams constructed of dispersed clays (McElroy 1982, 1987). These soils contain high concentrations of dissolved sodium in their porewater making them highly erosive. The sodium cations increase the repulsive

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* A list of abbreviations and notations is given in Appendix G.

forces between the clay minerals, thereby increasing the potential for the minerals to go into suspension in water (McElroy 1987). Furthermore, these clays tend to contain appreciable amounts of active clay minerals which exhibit shrink-swell characteristics, particularly large cracks upon drying. A maximum of three percent hydrated lime ($Ca(OH)_2$) was used at each dam site.

23. The effectiveness of the lime treatment was monitored in the field and studied in the laboratory using dispersion tests. After 15 years of testing and monitoring, it was noted that there was "an indication that some of the lime-treated soils were behaving in a dispersed manner" when tested in the laboratory, but no evidence existed in the field to indicate erosion of piping (McElroy 1982). It was also noted that the pH of the soil decreased with time. After 12 to 20 months, the soil pH had dropped to a level that allowed vegetation to grow once again. A general equation was developed to predict the soil pH with time;

$$pH = 10.340 - 1.553 \log_{10}(months) \tag{1}$$

with an error of plus or minus 0.937.

24. In September 1973, the largest lime treated subgrade construction project in the world was dedicated. This was the Dallas/Fort Worth International Airport. Approximately 2,400,000 square yards of runways and taxiways were constructed over lime treated subgrade material. A minimum of six percent lime was required for treatment of subgrade material. Nine inches of lime treated soil were specified beneath taxiways and runways while beneath terminal aprons, 18 inches of lime treated subgrade was required. A seal coat was applied to the lime treated soil and allowed to remain in place 75 days prior to construction of the concrete (Dallaire 1973; Long 1989). According to DFW maintenance and engineering personnel, the airport has provided 15 years of continuous service

without major maintenance, and appears that it will continue to provide satisfactory service well beyond its 20 year design life (Long 1989).

Leaching Effects on Untreated and Lime Treated Clays

25. The vast majority of testing clay soils under leaching conditions has been conducted by engineers interested in determining the long-term effects of hazardous fluids or industrial wastes on clay-lined holding points (Yong et al. 1985, 1986; Gordon and Forrest 1981; Darcel 1983; Simon and Reuter 1985; Haji-Djafarii and Wright 1983; Hansen and Shrestha 1981; Hansen et al. 1983; Miner et al. 1986; Wright and Iyengar 1982). Although this area of research deals mainly with toxic or hazardous permeants, the clay structure modifications due to fluid leaching are directly correlated to groundwater leaching or percolation. Therefore, a review of this important field of research in conjunction with water leaching will contribute to a better understanding of the leaching process of lime stabilized clays.

Weathering of Clays

26. One of the most detrimental effects to any clay mass is prolonged exposure to water above that necessary to balance charge deficiencies. Water molecules will surround the negatively charged clay particles and react with the clay minerals by the dipolar water molecules attaching to the negatively charged clay surface, the dipolar water molecules attaching to cations on the clay surface, hydrogen sharing (bonding) of the water molecules and clay surface, hydration of potential exchangeable cations in the soil-water system, or combinations of these various reactions (Das 1983).

27. Leaching of a permeant through a soil mass will generally produce one of three behaviors, namely:

a. The permeant will proceed through the soil with no noticeable change to soil-water system.

b. The permeant will react with the soil to effectively alter the soil system by either dissolution of the chemical bonds or enhancing the chemical bonding by cation exchange or other processes.

c. The permeant itself will be changed by the soil chemistry (Gordon and Forrest 1981).

The leaching process is predominantly chemical in nature for fine grained soils, although it can involve some physical reactions such as washing away fines, e.g., piping failures in earth embankments. Generally, however, physical reactions occur only after the chemical processes have taken place.

28. The long-term effects of subjecting a soil to a leachate can be termed "weathering" in a generic sense as weathering of a soil usually includes all environmental influences and not just liquid changes. Yong, Elmonayeri, and Chong (1985) attributed long-term weather effects to be by one or two methods, i.e., a loss of shear strength due to mechanical breakdown of cementation bonds during construction processing and/or changing of the chemical system within the soil structure. They stated that since most of the mechanical properties of the clay soils are closely related to the water-retention characteristics of the soil, any changes in pore fluid chemistry by leaching may result in a chemical breakdown of the system, thereby affecting the entire soil mass integrity and eventually its stability.

29. Thompson (1966) stated that soil weathering is affected directly by soil drainage and influences such items as soil pH, percentage base saturation and

calcium/magnesium ratios. Thompson observed that there appears to be decreasing soil-lime reactivity in areas of better drainage. In poorly drained soils, the removal of soil "constituents" are slowed and leaching effects are minimized, thereby maintaining the calcium/magnesium ratio and higher soil pH (Thompson 1966; Joffe 1949). Also, soils with poor drainage will have a higher source of silica and/or alumina for pozzolanic reactions. Thompson's (1966) research showed that the deeper soils (horizons B and C) showed better lime reactivity than horizon A soils. However, Thompson also discussed how the presence of organics in upper levels also is detrimental to lime reactivity.

30. Frenkel, Amrhein, and Jurinak (1983) conducted leach tests on soil samples by washing calcium, magnesium and sodium chloride through the samples and testing the mineral weathering effects. They concluded that mineral weathering is found to be dependent on soil-to-water ratio, exchangeable cations, and type of dominant minerals present in the soil. In general, as the rate of weathering was enhanced, the amount of exchangeable sodium increased. They also found that the total amount of calcium and magnesium leached due to weathering increases as the amount of exchangeable sodium increases in the soil (Suarez and Frenkell 1981).

Strength Changes

31. Yong, Elmonayeri, and Chong (1985) postulated that any "weathering" effects to a clay will have a long-term effect on its stability. All soils are initially at an energy equilibrium level that is disrupted by the inflow of cations from a permeant (water or other fluid) and the soil-fluid system will attempt to rearrange its structure to reach a new equilibrium level. This process will not be immediate,

in most cases, but will develop over a long period of time, contributing to a "creep deformation process" of the soil's stability.

32. In their work, Yong, Elmonayeri, and Chong (1985) subjected clay soil samples to accelerated leaching tests for up to 69 days using modified triaxial permeability tests. Various chemical solutions were tested as the permeant, including distilled water and a calcium hydroxide solution. Incremental stress-strain, drained creep tests were run on the leached samples. All samples were tested first using only water as a control then leached using the various permeants. In order for the soil system to be temporarily stable, the new equilibrium energy level must be obtained. This energy level is maintained by a balance of the net attractive and repulsive forces within the clay minerals. When this happens, "fabric reinforcement" and "fabric degradation" are equally maintained.

33. Yong, Elmonayeri, and Chong (1985) showed that when the natural clay was leached with only distilled water, the shear strength decreased slightly. They suggested that this was caused by the net increase in particle repulsion due to a decrease in electrolyte concentration in the soil mass. This is in agreement with work done by Olson and Daniels (1981) who postulated that "leaching a sample with distilled water may cause expansion of the diffused cloud of absorbed cations around the clay particles," thereby decreasing the natural shear strength of the clay.

34. Yong, Elmonayeri, and Chong (1985) also showed that strength increased when leaching with a calcium hydroxide solution. The clays exhibit a reduction of repulsive forces due to cation exchange reaction, increase in electrolyte concentration, small amount of pozzolanic reaction with time and other strength gaining phenomena as researched by Eades and Grim (1960), Diamond and Kinter (1960), and Thompson (1966).

35. Thompson (1968) conducted a series of compression tests on completely immersed lime stabilized clay samples and compared them to original samples. He showed that prolonged exposure to water reduces the compressive strength of the samples only slightly. Ratios of soaked to original compressive strength ranged from 0.7 to 0.85 for Illinois soils. This was in general agreement with research reported by others (Transportation Research Board 1976, 1987; Terrel et al. 1979).

36. Biswas (1972) conducted strength tests on immersed Texas soil samples at varying cure times and lime contents. He found that a soil that indicates a good reactivity for lime (as determined by Thompson (1966) such that unconfined compression strength of lime stabilized soils increase by at least 50 psi over non-stabilized soils) does not always produce good durability for weathering or immersion. Ratios of soaked to original strength lime reactive clays ranged from 0.13 for 4.5 percent lime to 0.28 for 8.5 percent lime, after only one day of immersion. Kennedy and Tahmoressi (1987) also showed that for certain clays, the ratio of soaked to original strength was significantly less than those indicated by Thompson (1968). Kennedy and Tahmoressi (1987) also showed that for increased compactive effort, there was no significant increase in the soaked compressive strength.

Ion Sorption Studies

37. From studies by Yong, Elmonayeri, and Chong (1985) and Frenkel, Amrhein, and Jarinak (1983), it has been shown that calcium and magnesium ions exhibit a lesser rate of replacement than sodium ions. Frenkel, et al. (1983) concluded that the higher the initial sodium content in the soil, the greater amount of calcium and magnesium released during the leaching process. This implies that

clays with a high sodium content will be more receptive to cation exchange but will have more potential for leaching calcium ions.

38. Yong, Warith, and Boonsimuk (1986) conducted a series of leach tests to monitor the attenuation of ions through a clay. The leach apparatus was 3.9 in. in diameter by 3.9 in. high and the leach fluid was high in calcium, potassium, magnesium, and sodium salts. According to the report, these cations tend to attenuate mainly through cation exchange.

39. It was shown that the higher concentrations of these cations remained in the upper soil layer, as expected. The reduction of cation concentration was shown to change with the water content at which the soil was compacted, i.e., the lower the water content, the less likely the cations were absorbed in the soil. All of the cations were absorbed to some degree, but the sodium showed some negative attenuation or elution as the leachate passed through the soil. The soil was very high in sodium content before leaching which may help to explain the higher sodium concentration of the effluent than the influent.

40. Preliminary leach tests were conducted by Simons and Reuter (1985) utilizing distilled water and various organic and inorganic leachates on illite and kaolinite clays. Their tests indicated that the "washout" rate (percent difference between parameter ions in solution before and after leaching) for most leachates was comparatively higher for kaolinite than illite. Alkaline test liquids provided the greatest "washout" rate.

Lime Treated Soil Studies

41. Only limited data exists for studying the effects of leaching lime treated soils with water. Barenberg (1970) conducted a series of leach test on lime-cement-flyash aggregate (LCFAA) mixtures to study the migration of lime and cement

under pavements. Various mixtures of aggregate, flyash, cement and lime were used as shown in Table 1. Leach tubes, two feet long by four inches in diameter were filled with 18 inches of Mix B at optimum moisture and vibrated to desired density. The samples were allowed to cure for 48 hours at 70° F then leached with water at a rate comparable to rainfall during a 10-day period at the Newark, New Jersey, airport. Field samples of the LCFAA mixture shown in Table 1 were then removed from the Newark airport and compared to the laboratory leach tests.

TABLE 1

MIX DESIGNS USED AT NEWARK AIRPORT, NEW JERSEY

Item	Mix Designation		
	A	B	C
Mix proportions (dry weight basis)			
Coarse aggregate (%)	30.0	0.0	0.0
Sand (%)	52.5	83.0	83.5
Flyash (%)	13.0	13.0	13.0
Lime (%)	3.6	3.2	2.8
Portland cement (%)	0.9	0.8	0.7
Optimum Moisture Content (%)	6.4	9.0	9.0
Maximum dry density, pcf	137.2	125.6	125.6

Source: Barenberg, J. 1970. "Evaluation of Remolded Field Samples of Lime-Cement-Flyash-Aggregate Mixture," Highway Research Record No. 315, Highway Research Board, Washington, D. C., p 133.

42. Field samples tested for lime plus cement concentration with depth showed that generally the percentages of lime plus cement were lower than those specified for construction. As curing time increased, the lime plus cement content decreased. In the laboratory leach tests, less than 0.1 percent of the approximately 4.0 percent original lime plus cement content had percolated through the soil sample after ten days. However, it should be noted that the titration method of

extracting calcium from the effluent used only two to five minutes of stirring to "wash" the cation from the samples with ammonium chloride. There is a strong indication from the results that this was not adequate time to completely dissolve the calcium from the solution. Additionally, the water percolated through the soil for only ten days on a noncontinuous bases in small volume increments.

43. Plaster and Noble (1970) conducted leach testing on several 1 to 1 solids-to-liquid ratio mixtures of minus No. 230 U. S. Standard sieve fractions of soils combined with 40 percent Portland cement by dry weight. The samples were cured for 2, 21 and 56 days at room temperature, then leached with distilled water. The leachate was analyzed for calcium oxide concentration. It was hoped that the calcium leached would indicate the amount of calcium hydroxide present in the soil-cement mixtures. This measurement would ultimately serve as a measure of mixture hydration. The percentage of potential calcium hydroxide determined was based on the estimate that calcium hydroxide was 25 percent of fully hydrated cement.

44. The results of Plaster and Noble (1970) varied widely for three soils tested but, in general, they concluded that the reaction of calcium hydroxide within the soils constituents was proportional to the amount of clay size fractions present. For soils with high montmorillinite content, the amount of calcium hydroxide leached increased with curing time increases, whereas soils with high kaolinite content experienced a decrease in calcium hydroxide leaching with curing time increases. Plaster and Noble (1970) concluded that the "rate of calcium hydroxide consumption ... exceeded the rate of production."

45. Stocker (1972) theorized that the clay surface remains active throughout time and that if any cementatous material is removed, it must be removed by dissolution from percolating water. In his experiments, small amounts of water

were allowed to percolate through lime and cement treated samples. He was mostly interested in the diffusion effects of the water-lime front through the samples. Small amounts of dissolution did occur in his tests but he states that the likelihood of substantial cementation reduction to be minimal. He presented a theoretical example to show that in order to reduce the amount of lime by one percent, at a 26 percent moisture content and a lime-silica ratio of 0.8, it would require 100 complete changes of porewater.

Permeability Changes

46. The studies of permeability changes in an untreated clay and lime treated clay sample are widely varied. Increases in permeability can be caused by three mechanisms. The first of these is mineral dissolution, especially of clay minerals in extremely high at low pH—extremely basic solutions usually produce a permeability increase due to high solubility of amorphous silica in alkaline solutions (D'Appolonia 1980). The second mechanism is ion exchange reactions, similar to those discussed with regards to strength changes that cause a collapse of the clay system. The third is clay desiccation due to displacement of water by highly organic fluids (Gordon and Forrest 1981).

47. Decreases in the hydraulic conductivity can be caused by precipitation of the minerals, such as calcium sulfate. Additionally, ion exchange reactions that will result in expansion of the clay minerals, e.g., distilled water has been shown to increase the diffused cloud of ions surrounding the clay particles, thereby decreasing the permeability (Olson and Daniels 1981), and entrap-ment of gas from dissolution will decrease permeability (Haji-Djafari and Wright 1983).

48. Townsend and Klym (1966) hypothesized that lime stabilized soils would increase the pore volume due to flocculation which would enable more fluid flow

through the clay soils. Their test data showed a general increase in permeability of heavy clays after the addition of lime. Ranganatham (1961) showed a ten-fold increase in permeability after the addition of lime to expansive clay. In another study, Fossenberg (1965) showed a reduction in permeability after treating a clay with lime. However, Fossenberg compacted his samples immediately after mixing with lime and this may have not allowed flocculation to occur (Townsend and Klym 1966).

49. Malone and May (1987) report that the addition of five percent lime to a sandy loam material, then leached with uranium tailings, showed a remarkable decrease in permeability compared to untreated material. It was speculated that the contaminant in the fluid precipitated into the intergranular soil spaces. Malone and May (1987) also commented on the ability of lime treated clay to reduce the flow of water through small earth dams and irrigation canals. Gutschick (1978) presented a paper for the National Lime Association showing that the permeability of a lime-flyash-aggregate liner for irrigation channels initially increased in permeability above natural material. However, with time the permeability decreased to a flow rate comparable with natural clay.

50. In his in-depth studies, Stocker (1972) noted that for strong, very advanced stages of lime modification in a soil mass, the permeability tended to decrease. However, for less modified soils, there "may be an apparent reduction in permeability, due to prohibition by cementation, or swelling during the permeability test." But as previously noted, no satisfactory data has been published to study the permeability of clays with small percentages of lime added.

Summary

51. Much research has been conducted over the past 30 years in order to understand the complex interactions between lime and lime-reactive clays. A great deal is known about how an expansive clay will react when mixed with lime, although there is some disagreement as to the exact causes of the changes. Relatively simple tests have been developed to determine whether certain clays are lime-reactive and, if reactive, to what degree. Innumerable construction projects have been and are being built on lime treated clays and have used lime as the primary means to control expansive clay's shrink/swell characteristics. The longevity of many of these projects (some of which are 40 to 50 years old) have been cited in studies and literature to verify the durability and long-term success of lime treated clays.

52. However, limited research has been conducted to determine what changes have occurred in the lime treated clay layers over time due to the presence of percolating rainfall. Furthermore, it would be useful to know if the physical changes (if any) that occur due to rainfall would be offset by the lime content, compactive moisture content or other means that can be readily controlled at the time of construction. If percolating rainfall is detrimental to lime treated clay layers, then some method to estimate the longevity of a given soil-lime layer may be possible.

53. In the research that follows, an attempt has been made to answer some of the questions concerning the changes that occur when leaching lime treated expansive clays. The research is an initial approach to determine if leaching is detrimental and, if so, does the soil's lime content and moisture content influence the leaching effects. The study does not attempt to answer all soil-lime mixture

longevity questions. Rather, it presents some interesting and useful analyses on leaching effects which will further the field of knowledge in this complex area of geotechnical engineering.

PART III: MATERIAL, EQUIPMENT, AND PROCEDURES

Introduction

54. This study incorporated a multi-phased, sequential sampling, testing, and evaluation process. Soil sites were selected based on predetermined criteria and tested for lime reactivity prior to laboratory testing. Laboratory testing included an extensive array of chemical and physical property tests. Once the basic soil properties were established, duplicate leach tests for each soil-lime mixture chosen were conducted in specially designed and fabricated flexible-wall column leach cells. Sampling and testing of the leachate continued throughout the leach tests. After a designated period of leaching, the leached samples were broken down and analyzed using the same physical and chemical tests as previously conducted prior to leaching. Comparisons of before leaching and after leaching test data were then possible.

55. A field sampling program of in-situ lime treated soil was undertaken simultaneously as the laboratory leach testing. The same physical and chemical property tests were conducted on these samples as were done on laboratory prepared samples.

Material Selection

Location of Test Materials

56. At the onset of this research, it was deemed desirable to investigate the longevity of lime treated expansive clays on locally available material. The Dallas/Fort Worth Metroplex is well known for its highly plastic clays, especially those clays located in the Irving/Los Colinas area.

57. In order to test the correlation between laboratory and field conditions, sites of known construction standards, i.e., percentage of lime, compaction effort, time of construction, curing time, and moisture content used during construction were selected. Each site was selected such that the lime treated soil is not covered by pavement or a structure but may be covered with up to 14 in. of top-soil. Additionally, in order to compare time effects of field and laboratory leaching, the three sites range in age of construction completion from 3 to 16 years. Bulk samples of untreated soil were obtained using a six inch auger boring machine, drilling up to three feet. All untreated bulk material was gathered within 25 ft of the in-situ lime treated material. All locations were in cut sections of the construction project to insure only natural soil was obtained. Figure 1 shows the location of all three sites. These locations will be referred to as Sites No. 1, 2, and 3.

Description of Geologic Formation

58. The soils from these three sites are primarily weathered clay shale outcrops from the Eagle Ford geologic formation. This formation dips to the east and is overlain by the Austin Chalk formation then the Taylor Marl formation in the city of Dallas, Texas. The Eagle Ford Shale formation is underlain by the Woodbine formation (Norton, 1965).

59. The Eagle Ford shale formation is divided into three members, the Arcadia Park, Britton, and Tarrant. The material from Sites No. 1 and 3 are from the Britton member. This is described by Powell (1968) as shale weathering to a dark grey to bluish-grey clay with a few thin discontinuous beds of brownish-grey calcareous siltstones. Site No. 2 is considered to be from the Tarrant Member

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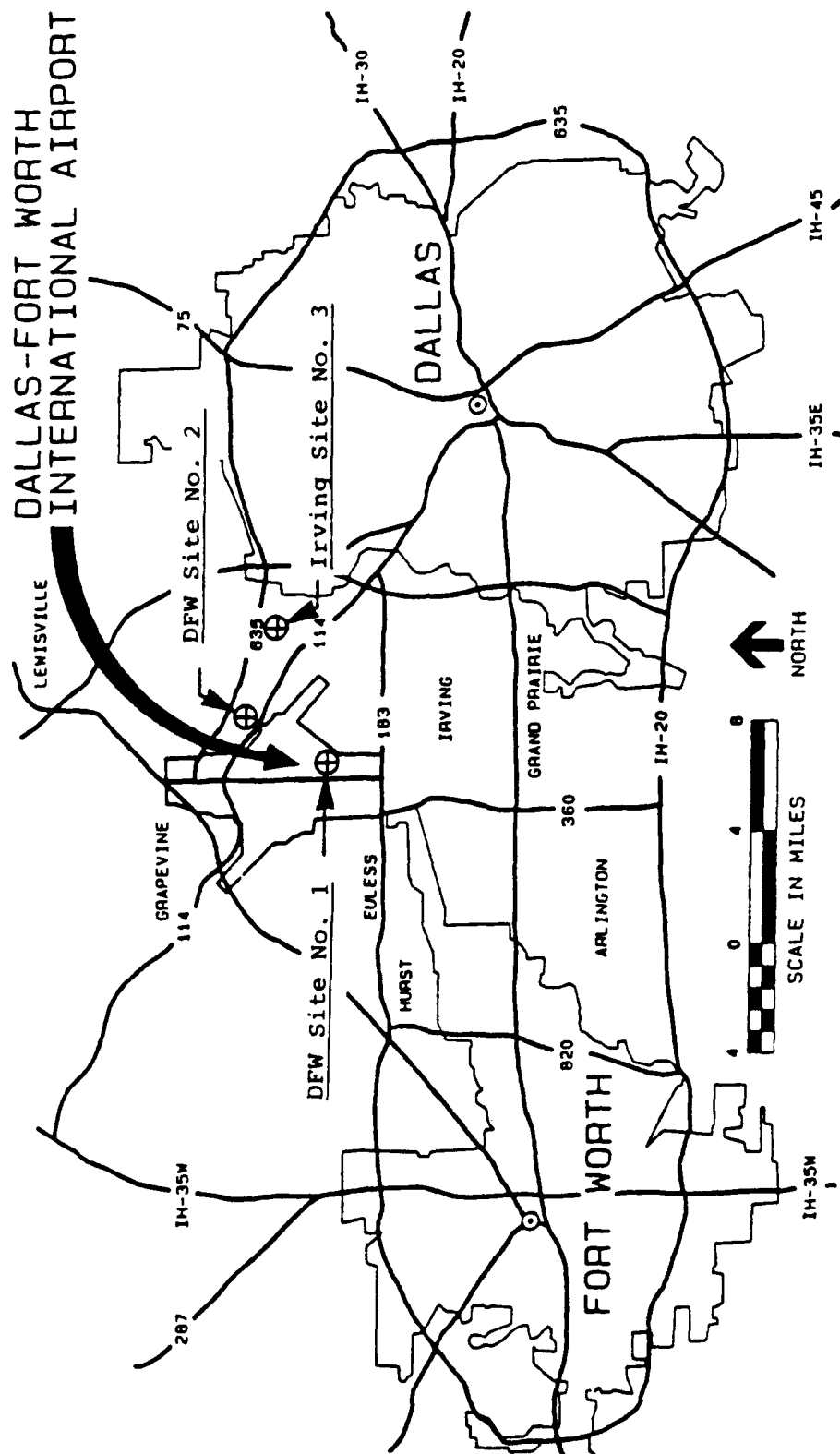
Figure 1. Material site locations.

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which is described by Powell (1968) as light yellowish-brown clay and clay shale, gysiferous with small fragments of lignite.

60. Borings taken at the beginning of construction (1970) for the Dallas/Fort Worth International Airport (DFW Airport) showed that in the immediate vicinity of Site No. 1, the Eagle Ford clay-shale is at least 15 ft thick with the top two to three feet of soil consisting of brown to yellow, highly plastic clay with the underlying clay tan to grey in color. The clay is generally known to range from 20 to 30 ft thick in this area, with increasing thickness to the south and east of the airport.

61. At Site No. 2, previous soil borings by DFW airport engineers showed the soil to consist of at least 15 ft of light tan to medium yellow brown highly plastic clay. The clay is known to range from 15 to 25 ft thick in this area.

62. Borings near Site No. 3 showed stiff to very stiff brown to olive brown clays. The clays exhibited slickensided structure, often with fissures filled with gypsum. Average thickness of these clays was approximately 36 ft.

Physical and Chemical Properties

63. **Site No. 1.** Site No. 1 material is a light to medium grey clay with occasional white calcareous nodules. The material is a high plasticity clay (CH) with high volume change potential and relatively high dry strength. Swelling pressures on remolded samples averaged 1 ksf with free swell on remolded samples ranging from 1.1 to 5.4 percent (although they averaged only 1.80 percent swell). Unconfined compression strength test results for remolded samples averaged 10.9 ksf.

64. **Site No. 2.** Site No. 2 material is a light yellow brown clay with some silty texture but maintaining a high plasticity structure. This soil also exhibited

high volume change potential with swell pressures exceeding 1.1 ksf and free swelling characteristics on laboratory remolded samples exceeding 3.2 percent. Unconfined compression strength was approximately equal to that of Site No. 1 material (10 ksf).

65. Site No. 3. Site No. 3 soil displayed the highest potential for massive volume change. This area is located in the Irving/Los Colinas area, well known for its construction difficulties on Eagle Ford Clay (Hansen and Abrams 1988; Long 1989). Swelling pressures have been measured to exceed 10 ksf (Hansen and Abrams 1988) although during this research project, swell pressures rarely exceed 2.2 ksf on remolded samples. Volumetric swell ranged from 5 to 13 percent, averaging approximately 12 percent. Liquid limits exceeded 75 percent and plasticity indices ranged from 45 to 100 percent. Unconfined compressive strengths were similar to that of soils from Site No. 3 as from Sites No. 1 and 2. A summary of the physical and chemical soil data is shown in Table 2.

66. Grain size distribution plots for soils from all sites are shown in Figure 2. Hydrometer analyses show that the clay size portion (less than 0.002 mm) is approximately 35 percent for Site No. 1, approximately 12 percent for Site No. 2, and approximately 60 percent for Site No. 3. The percent of silt and clay material (minus 0.07 mm) is 85 percent for Site No. 1, 90 percent for Site No. 2, and 98 percent for Site No. 3.

Clay Mineralogy

67. X-Ray Diffraction. The Soil Conservation Service, South National Technical Center in Fort Worth, Texas, conducted x-ray diffraction analysis on the total clay portion of soils from Sites No. 1 and 2. Site No. 3 was not available in time for x-ray diffraction to be done.

TABLE 2

SITES NO. 1, 2 AND 3 SOIL PROPERTIES

Property*	Data		
	Site 1	Site 2	Site 3
Physical Data			
Specific gravity	2.74	2.71	2.73
Maximum dry density (pcf)	103.5	101.0	100.0
Optimum moisture (%)	22.5	22.5	24.5
Liquid limit (%)	63	60	76
Plastic limit (%)	33	27	31
Plasticity index (%)	30	33	45
Linear shrinkage (%)	22.0	17.7	24.4
Swell pressure (psf)	977.6	1104.7	2117.9
Free swell (%)	1.80	3.21	11.97
Strength** (ksf)	10.92	10.04	9.24
Permeability[†] (cm/sec x 10^{-9})	5.3	23.0	6.9
Chemical Data			
pH	8.40	8.40	8.71
Porewater Cations (meg/l)			
Calcium	15.17	2.47	6.69
Sodium	4.66	0.57	14.85
Magnesium	0.80	0.16	2.08
Potassium	0.32	0.10	0.23
Exchangeable Cations (meq/100 gm)			
Calcium	34.46	19.84	21.21
Sodium	1.08	0.08	3.68
Magnesium	0.99	0.31	2.39
Potassium	0.78	0.28	0.54
Cation Exchange Capacity (meq/100 gm)[††]	35.5	18.8	37.0

*   All results are the average of three or more tests on remolded samples. All engineering property tests conducted on samples compacted at optimum moisture content.

** Strength is measured using unconfined compression strength tests.

[†]   Average permeability is for 90 day continuous permeability tests.

[††] Sites No. 1 and 2 CEC (Calcium) were determined by the Soil Conservation Service, South National Technical Center, Fort Worth, Texas. Site No. 3 CEC was provided by Albert H. Halft Associates, Inc., Dallas, Texas.

Grain Size Distribution
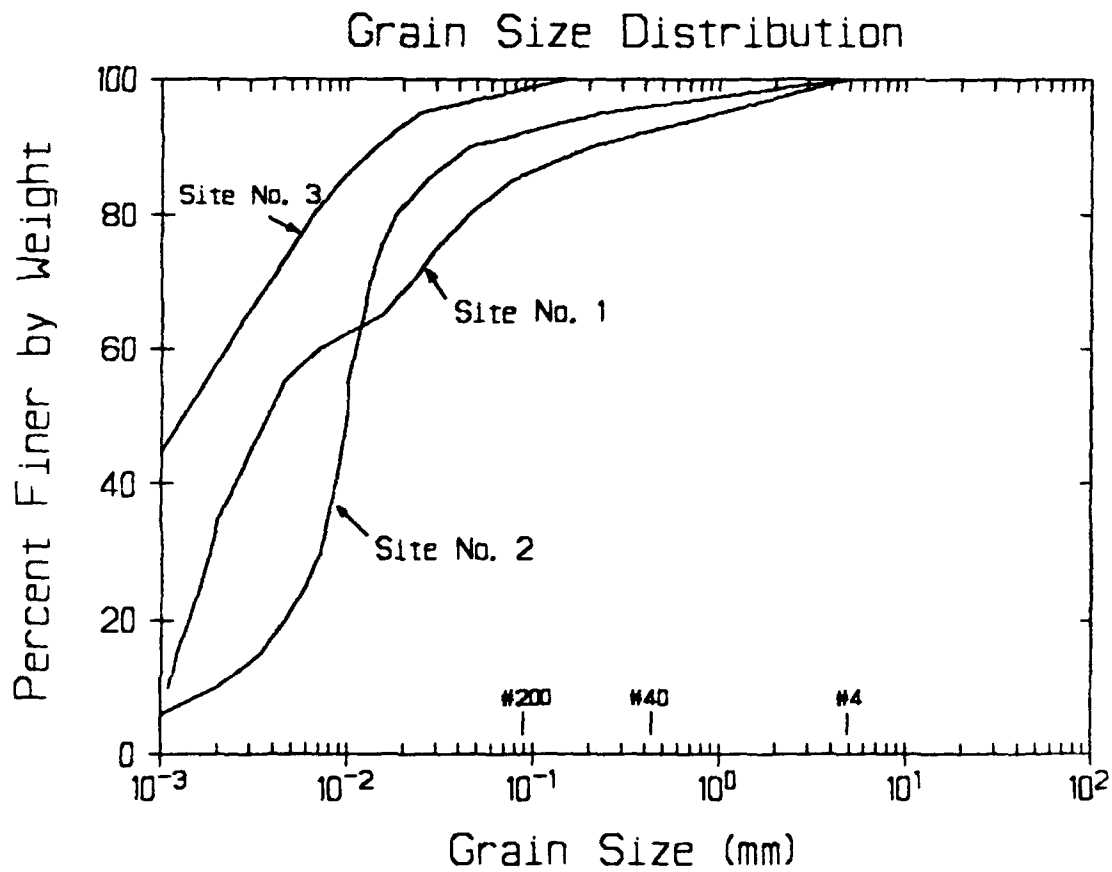
Figure 2. Grain size distribution curves for Sites No. 1, 2, and 3.

68. Site No. 1 material showed the clay fraction to be predominantly calcite with equal and significant portions of montmorillonite and kaolinite minerals. Some vermiculite and mica are also present in small amounts.

69. Site No. 2 material also contains a very large amount of calcite with medium portions of montmorillonite. Kaolinite and lepidocrocite are also present in small portions, with geothite and mica present in very small percentages.

70. Site No. 1 soil contains 18.0 percent Al_2O_3 and 7.0 percent Fe_2O_3. Site No. 2 soil contains 14.0 percent Al_2O_3 and 5.6 percent Fe_2O_3.

71. <u>Differential Thermal Analysis</u>. Differential thermal analysis (DTA) were run on the natural clays in an attempt to verify the clay minerals within the samples. All material tested was minus No. 40 sieved and air dried. Samples were tested using a Perkin-Elmer 1700 DTA furnace controlled by a Model 3600 computer data station. Samples were tested up to a maximum temperature of 1100 °C at a heating rate of 40 °C per minute, and using nitrogen gas as the atmosphere.

72. Since these are not pure clays, there was a considerable number of small or "shoulder" peaks that could not be readily identifiable. Significant endothermic peaks for Site No. 1 occurred at temperatures of 165, 568 and 869 °C, while significant exothermic peaks occurred at 475, 646 and 924 °C. From reference clay mineral data presented by Olphen and Fripiat (1979) and from clay minerals tested in the laboratory, predominate minerals appear to be montmorillonite (860-880 °C; 920-950 °C) and illite (560-580 °C). This agrees well with the x-ray diffraction analysis. Calcite minerals (900-930 °C) were identified in the x-ray tests but were not readily identified in the DTA tests. The lowest endothermic peak is due to desorption of absorbed water.

73. Site No. 2 endothermic peaks occurred at 566, 901 and a small one at 1015 °C. Maximum peaks occurred at 486, 638 and 999 °C. The predominate

mineral is most likely calcite (900-930 °C) with some amounts of kaolinite (980-1000 °C) and montmorillonite. This agrees exceptionally well with x-ray diffraction results.

74. Significant endothermic peaks for Site No. 3 soil occurred at 579 and 812 °C with exothermic peaks at 425, 668 and 841 °C. The predominate minerals appear to be illite (570-585 °C) and montmorillonite (small peak at 560-580 °C). Some kaolinite might be present but this would have to be verified by x-ray analysis.

Test Procedures

75. All physical testing was done in accordance with U. S. Army Corps of Engineers, Engineer Manual (EM) 1110-2-1906 dated 1970 with change 2 (Department of the Army 1986), except for some modification to the swell pressure and free swell tests. Swell tests were run based on procedures developed at The University of Texas at Arlington. The Texas Highway Department Test Method Tex-107-E was used to determine linear shrinkage. Chemical tests were conducted for measurement of pH, exchangeable complex cations, and porewater cations. Titration tests to determine percent lime for Site No. 1 material were based on ASTM D3155-83, Standard Test Methods. All non-standard chemical and physical testing are described in appendix A.

76. All material tested was slaked through a No. 40 sieve,* air dried at 120° F in an oven, then lightly crushed prior to any physical or chemical tests. All physical testing was conducted on remolded samples.

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* All references to sieves are for U. S. Standarad Sieves.

Leach Test Program

Leaching Apparatus

77. In order to model the effects of prolonged leaching on lime treated clays in a laboratory, nine large diameter, flexible-wall leaching cells or columns were designed and built. These leach cells are housed in the research geotechnical laboratory in the New Engineering Building (NEB) at The University of Texas at Arlington (UTA). The leaching cells are constructed of 7 in. diameter by 1/4 in. thick pexiglas cylinders, 8 in. in height. One inch thick plexiglas sheets serve as the top and bottom plates with recessed slots for the cylinder. A rubber membrane is on the inside of the cylinder which allows an air confining pressure to be applied to the sample to prevent side leakage. The membrane extends the full length of the cylinder and is held in place by stretching it over the outside of the cylinder and securing with two 9 in. diameter hose clamps. Water was leached through the sample from the top and dispersed by flowing over a porous stone through the sample. A porous stone is also on the bottom of the sample to prevent soil wash-out. Figure 3 shows a detail drawing of a test cylinder and Figure 4 shows a disassembled leach apparatus.

78. Since multiple leach testing was necessary due to the nature of the research, nine leaching cylinders were constructed and assembled for simultaneous leach testings. Figure 5 shows a schematic diagram of the complete system. Each cylinder is independently controlled at the main control panel by quick connections and positive (zero-flow) shut off valves. Therefore, separate tests can be assembled or disassembled without affecting the other leach tests (Figures 6 and 7).

79. Water was leached through the samples under pressure from a 141 liter tank which regulated air pressure applied to it. The inside of the tank had been acid

TOP AND BOTTOM VIEW

PLAN VIEW

Figure 3. Details of leach test cell.

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Figure 4. Disassembled test cell.
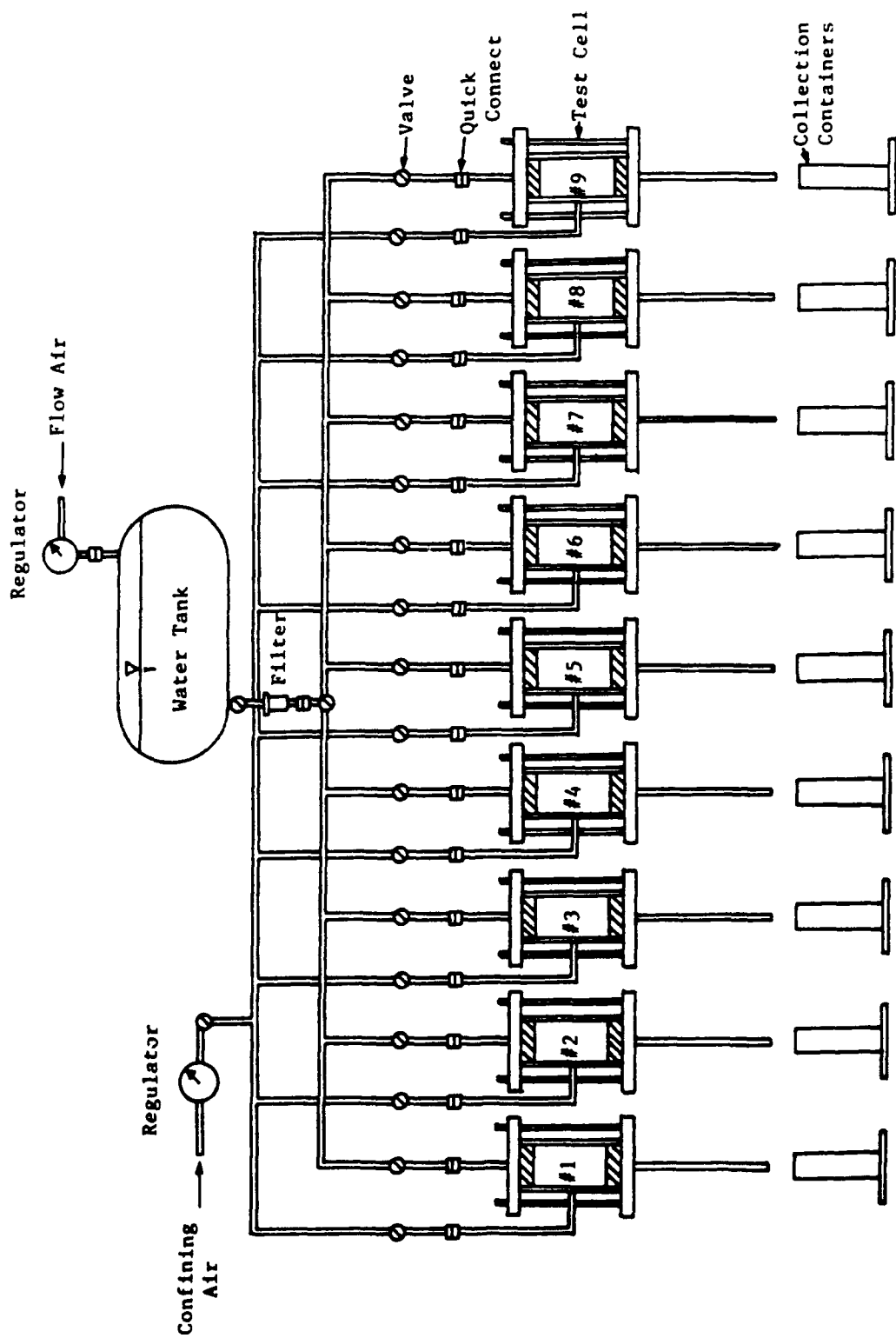
Figure 5. Schematic diagram of multiple test cell operation.

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Figure 6.   Test cells with control panel.
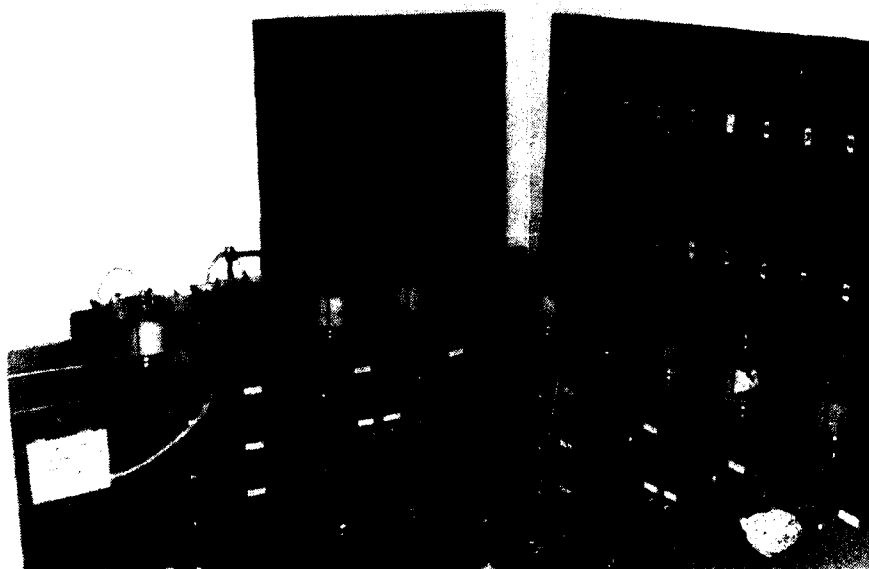
Figure 7.   Complete multiple leach cell operation.

cleaned then coated with contact rubber cement. The water was distilled water that had passed through a Barnstead Ultrapure water filter. Demineralized-distilled water was used in order to have consistently mineral free leach fluid containing no outside cations that could possibly influence the soil's leaching behavior. Upon exiting the tank, the water also passed through a charcoal filter before distribution to the samples, to catch any impurities that may have been left in the tank. Water pressure was monitored both at the air regulator and by a pressure gauge on the tank (Figure 8). The water flow pressure for all nine samples was the same and controlled at a central regulator.

80. Water passed from the tank, through the charcoal filter, through the distribution panel to the samples. The leachate was collected as it passed through the samples into 20 liter glass or plastic carboys (Figure 9).

Testing Procedures

81. <u>Preliminary Tests</u>. The soil was thoroughly investigated for its lime reactivity prior to any leach tests. This data would serve two purposes; to identify the range of lime treated samples that must be tested and to present the soil conditions prior to leaching (the "Before" data).

82. Of particular initial importance was determination of the optimum moisture content and maximum dry density (unit weight) of the soil-lime mixtures. Hydrated lime was added to the soil (based on percent dry weight) and compacted with the Harvard miniature device. Only Standard Proctor (ASTM D698) densities were considered in this research. Trial work showed that compacting in the miniature device with 4 layers and 25 blows per layer (40 pound-force on the Harvard tamper) approximated Standard Proctor densities, particularly for soils

Figure 8. Portable pressurized
water reservoir with filter.
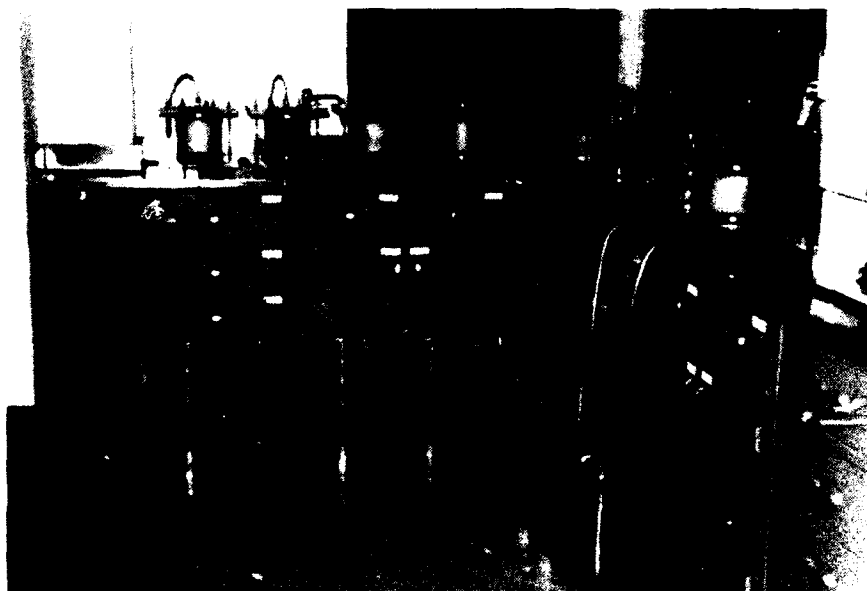
Figure 9.   Leachate collection carboys (20 liter).

with over two percent lime. Table 3 shows the optimum moisture-maximum density relationships for the various line contents for all three soil sites.

83. Lime contents chosen for testings were based on preliminary lime reaction tests and the amount of lime that was used in the field constructions at each site. The lime percentages chosen for Site No. 1 were one, two, three, four, six, and eight percent. For Site No. 2, one, two, three, five and seven percent lime were tested, although nine percent was initially used during preliminary physical property testing but not for leach testing. For Site No. 3, one, two, three, five, seven and nine percent lime were chosen for all testing. Compaction curves for soil from these sites at various lime contents are shown in Appendix B. Soils from all sites showed similar compaction reaction to lime, i.e., decreasing dry density and increasing optimum moisture with increased lime content. All test samples (leach, strength, swell, etc.) were compacted at optimum moisture contents with a goal of achieving 95 percent of maximum dry density. Only slaked, air dried, minus No. 40 sieve material was used for all preliminary soil-lime tests. The remaining soil-lime reactivity data is discussed in Part IV and presented graphically in Appendix B.

84. Before Leaching Preparations. Bulk quantities of all natural soils were air dried at 120° F in an oven for a minimum of five days. The soils were then passed through a No. 4 sieve to remove any rocks or organic material. Material not passing the No. 4 sieve was crushed using a Bico Pulverizer. Each portion of the soil (plus and minus No. 4) was mixed together and stored for testing. Final air-dried moisture contents were between two and three percent for all soils.

85. Each leach sample required approximately 5300 g of air dried soil. Knowing the present water content and the desired moisture content, a percentage of hydrated lime was added to the soil based on the dry weight of the soil Figure

TABLE 3

MOISTURE-DENSITY RELATIONSHIPS

Soil Site	Lime Content (%)	Maximum Dry Density (pcf)	Optimum Moisture Content (%)
Site No. 1	0	103.5	22.5
	1	96.5	25.5
	2	93.0	26.5
	3	90.5	28.0
	4	88.5	28.5
	6	87.5	29.5
	8	86.5	29.5
Site No. 2	0	101.0	22.5
	1	97.5	24.0
	2	94.5	26.0
	3	94.5	26.5
	5	94.0	27.0
	7	93.6	27.5
Site No. 3	0	100.0	24.5
	1	98.0	25.0
	2	95.0	26.5
	3	94.0	27.5
	5	91.0	28.0
	7	90.5	28.5
	9	90.0	28.5

10). While mixing with a Blakeslee rotary mixer, moisture was added to bring the soil-lime mixture to the desired level. The mixture was covered with plastic and sealed for 24 hours. This was the "mellowing period" used for all leach tests (Figure 11).

86. The mellowed soil-lime mixture was compacted in a six inch diameter compaction mold. A one-eighth inch spacer was placed in the mold to yield a final height of 6.875 in. and a volume of 0.1125 cu ft. In order to yield the equivalent compactive effort for a Standard Proctor (ASTM D698) four inch mold [12,375 ft-lb(f)/ft^3], it was calculated that four layers, each compacted with 65 blows per

Figure 10. Lime added to prepared soil.

Figure 11. Soil-lime mixture sealed for mellow period.

layer, would be required. This yields a compactive effort of 12,711 ft-lb(f)/ft³ for each 1.72 in. layer. Calculations for the compacted samples included percentage of maximum dry density, percent plus or minus optimum moisture content, degree of saturation, and pore volume (Figure 12). Unused soil-lime mixture was placed in air-tight, plastic storage bags for chemical analysis at the completion of the leaching cycle (45 or 90 days).

87. The compacted samples were wrapped twice in cellophane, c. ated with wax, then placed in an oven for 48 hours at 120° F. The excess bagged samples were cured under the same conditions. This accelerated curing method was chosen as the standard for all lime treated samples as it is routinely used to simulate 28 days curing at 70° F for soil-lime mixtures (Biswas 1972; Transportation Research Board 1987).

88. Some investigation was conducted on accelerated curing conditions for Site No. 1 material at the conclusion of all sites leach testing. This very preliminary work showed that curing conditions of approximately 72 hours at 105° F resulted in strengths of -3 to +20 percent of 28 day cure strength. Samples cured for 48 hours at 120° F generally yielded strength results of 20 to 30 percent higher than 28 day strength. This was in general agreement with work done by Lockett and Moore (1982) for soils in the South. However, as the 48 hour condition is still the most widely used, and gives consistently conservative results, it was chosen as the cure condition for all tests.

89. Figure 13 shows three samples after curing. Moisture content checks after curing showed minimal change, generally less than one percent.

90. Figures 14 through 18 show the process of assembling a leach apparatus for testing. The compacted sample was placed on the bottom plate between two 1/2-in. thick porous stones. Grade 362 qualitative filter paper was placed between the

Figure 12. Compaction of soil-lime mixture in six inch mold.
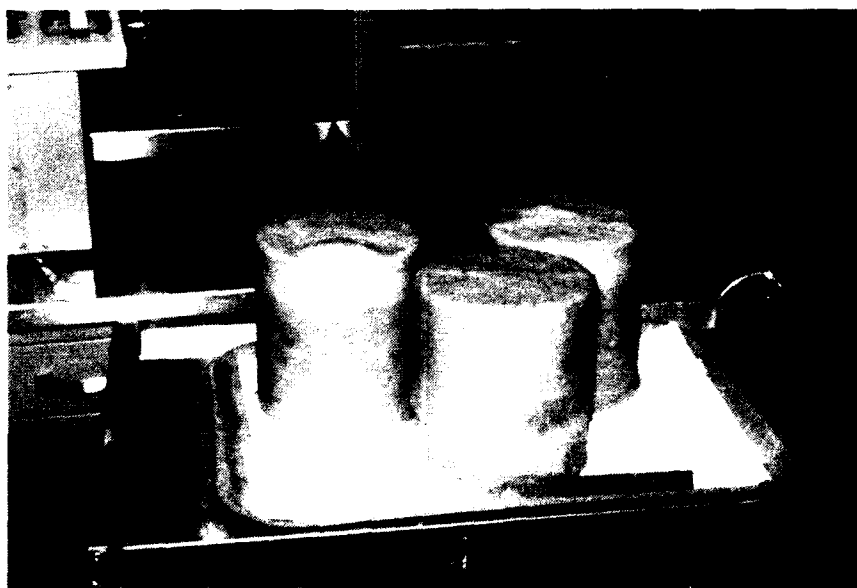
Figure 13. Wax coated samples after curing period.
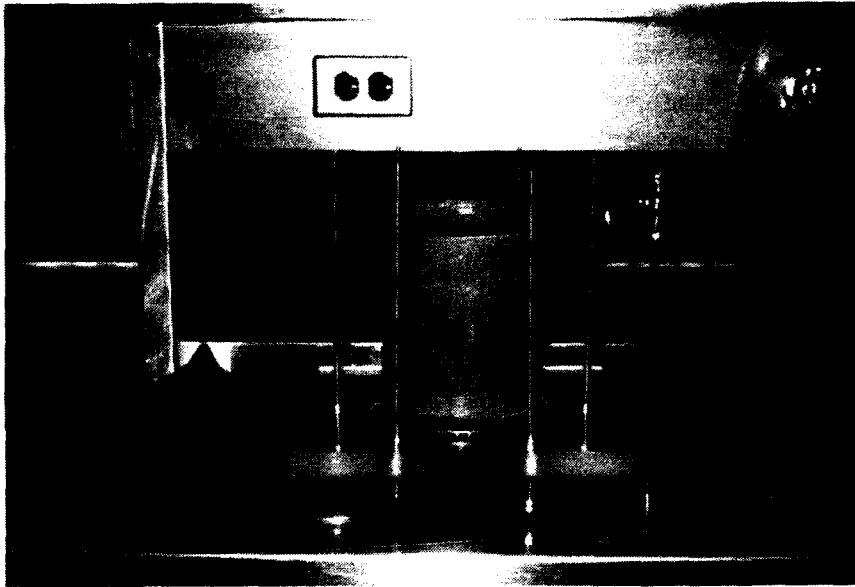
Figure 14. Porous stones and filter paper placed on top and bottom of sample.

Figure 15. Metal band placed on bottom of sample.
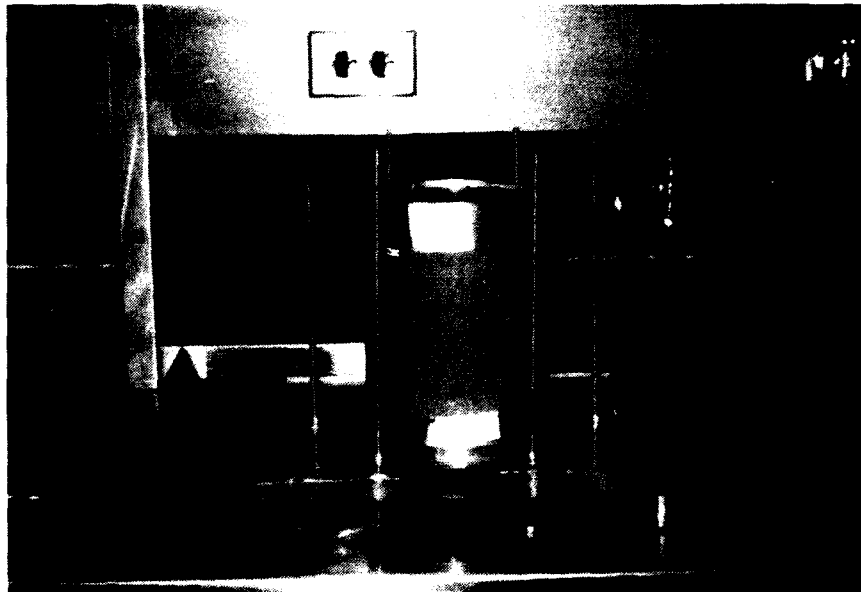
Figure 16. Metal bands place on top of sample.
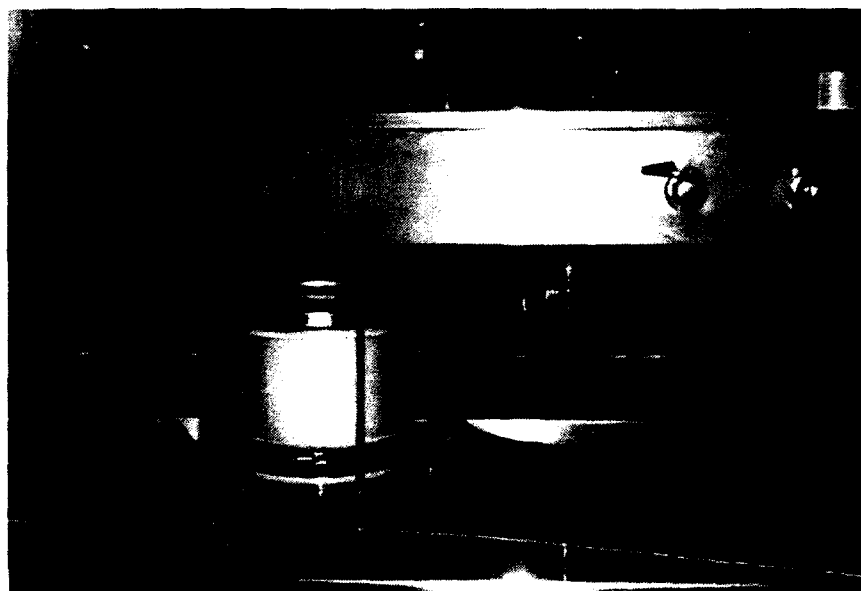
Figure 17. Vacuum applied to cylinder for place-
ment over sample.
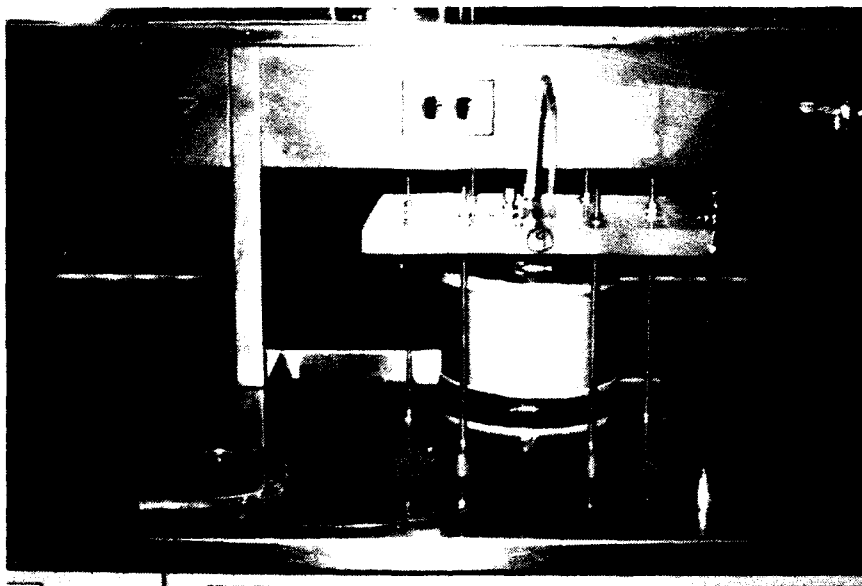
Figure 18. Assembled test cell with sample.

stones and the sample to prevent clogging of the stones. One inch wide, thin, galvanized metal strips were secured at the top and bottom of the sample to prevent puncturing of the membranes by the porous stone while applying the confining pressure. A vacuum was applied to the cylinder to draw the membrane tight, then the cylinder was lowered over the sample. Vacuum grease was spread on the top and bottom plates beneath the cylinder to insure an adequate seal. The top plate was bolted in place and the apparatus was ready for leach testing.

91. _During Leach Testing_. A confining pressure of between 5 to 10 psi greater than the flow pressure was desired. The confining pressure used for all tests was 20 psi. The leach samples were connected to the control panel (refer to Figure 6) and the confining pressure slowly applied. Once the system was checked for leaks, the air release valves on top of the cylinders and the control panel water valves were opened. The cells were designed such that a small water pocket would be provided at the top of the cylinders to allow for entrapped air to collect during saturation. Any trapped air could be easily bled off daily with the air release or "bleeder" valve (see Figure 3).

92. The samples were leached under a small flow pressure that remained constant during the entire testing sequence. The majority of tests were leached with 10 psi flow pressure, but for samples compacted significantly wet of optimum moisture, 15 psi was required to generate sufficient leachate. The small flow pressure was chosen based on trial and error to minimize disturbance to the test specimen yet allow the water sufficient time to migrate through and interact with soil-lime mixture. This was in accordance with research by others on hazardous wastes permeants that have indicated that one pore volume change (specimen free pore space volume) in 24 hours should be the maximum flow rate goal and one pore

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volume change in 168 hours (7 days) to be the minimum goal (Haji-Djafari and Wright 1983; Miner, Maltby and Dell 1986).

93. The leachate was continuously collected in 20 liter carboys and periodically (initially within the first 24 hours then approximately every 100 hours thereafter) measured and recorded. Samples of the leachate were collected in clean graduated cylinders and placed in thoroughly washed 60 ml polyethylene bottles. The pH of the leachate was measured using an Orior Model 601A digital pH meter. Prior to storage, the samples were acidified by adding approximately one-half percent by volume concentrated nitric acid to lower the pH to less than 2.0. This prevents the suspended salts from plating to the sides of the polyethylene sample bottles. Samples of the water coming directly out of the tank were also taken for analysis in order to establish a reference concentration of cations, i.e., pure water cation concentrations.

94. The leachate samples were analyzed for cation concentration (calcium, sodium, magnesium and potassium) using inductively coupled plasma (ICP) spectrophotometry analysis. This analysis was conducted at the U. S. Army Corps of Engineers, Southwestern Division Testing Laboratory in Dallas, Texas. The ICP spectrophotometer was an Applied Research Laboratories (ARL) Model 3410 with mini torch, using argon gas.

95. Leaching was continuous for periods of 45 and 90 days. When it became necessary to refill the water tank (approximately once a week), the main control flow valve was shut off and the tank disconnected by quick-connects (see Figure 8). No pressure loss occurred throughout the system due to the positive shut-off valves and low volume change quick-connectors. Refilling the tank took approximately one hour. This filling time was excluded from the total leach times.

96. <u>After Leaching Testing</u>. At the completion of the leach test, the leach cell was disconnected from the main control panel and disassembled. The soil sample was inspected for discoloration, cracks or other irregularities. The soil sample was split in half, through the width of the sample, to make a top and bottom sample. A moisture content sample and a 100 g pH test sample were obtained from each half (additionally, a 300.0 g titration sample was obtained from Site No. 1 leach tests; see Part IV). The leach sample halves were wrapped in a double layer of cellophane until ready for complete testing (always within two days).

97. Each half of a leached sample was subjected to identical tests and recorded as information for the "Top" and "Bottom". The results for both halves were averaged. Additionally, since each leach test was duplicated, a total of four samples were tested after leaching with all results averaged. Extensive physical and chemical tests were conducted on each half. Those tests* included:

    <u>a</u>. Physical Tests — Atterberg limits, linear shrinkage, swell pressure (trimmed and reworked), free swell (trimmed and reworked), unconfined compression strength (trimmed and reworked).

    <u>b</u>. Chemical Tests — pH, porewater cation extraction, exchange complex cation extraction, titration to determine percent lime remaining (Site No. 1 only).

Also, differential thermal analyses (DTA) were conducted on selected samples before and after leaching.

98. <u>Trimmed Samples</u>. The cellophane wrapped sample halves were trimmed for unconfined compression strength tests using a Soil-test Model P-400 soil lathe (Figure 19). Each trimmed sample was 3.5 cm in diameter by 7.0 cm in height. Additionally, free swell and swell pressure test samples were trimmed to fit

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* A complete description of all testing procedures is located in Appendix A.

Figure 19.   Trimming an unconfined
compression specimen.

consolidometer rings such that trimmed sample dimensions were 4.9 cm in diameter by 3.2 cm in height (Figure 20).

99. All testing after leaching was to be conducted at optimum moisture content as a standard of control. All trimmed samples exceeded the optimum moisture content after leaching. Therefore, the trimmed samples were left in the open for up to six hours. The samples were weighed periodically to determine weight loss due to drying. Once a predetermined weight was reached based on the optimum moisture content (within five grams), the trimmed samples were double wrapped in cellophane and allowed to equilibrate for a minimum of 7 days but not to exceed 10 days before testing.

100. Unconfined compression strengths were determined using a Karol-Warner Model 507 loading frame (Figure 21) and a Geotest Model S2014 loading frame (Figure 22). The strain rate used for all testing was 0.5 percent per minute. Testing stopped at compressive failure or at 10 percent strain, whichever came first.

101. Swell pressure and free swell tests were determined using consolidation load frames(Figure 23). Swell pressure tests were continuous for 24 hours while free swell tests were conducted for a minimum of 48 hours. Both tests used only a seating load of 32.6 psf (pressure from cap and ball) as overburden since this research was interested in only surface material behavior.

102. <u>Reworked Samples</u>. After extracting trimmed samples from the leach test soil halves, the remaining material was oven dried at 120° F for a period of five days. The soil was lightly crushed and separated with a No. 40 sieve. Air dried material passing the No. 40 sieve was used for the remainder of physical and chemical tests, i.e., Atterberg limits, linear shrinkage, swell pressure, free swell,
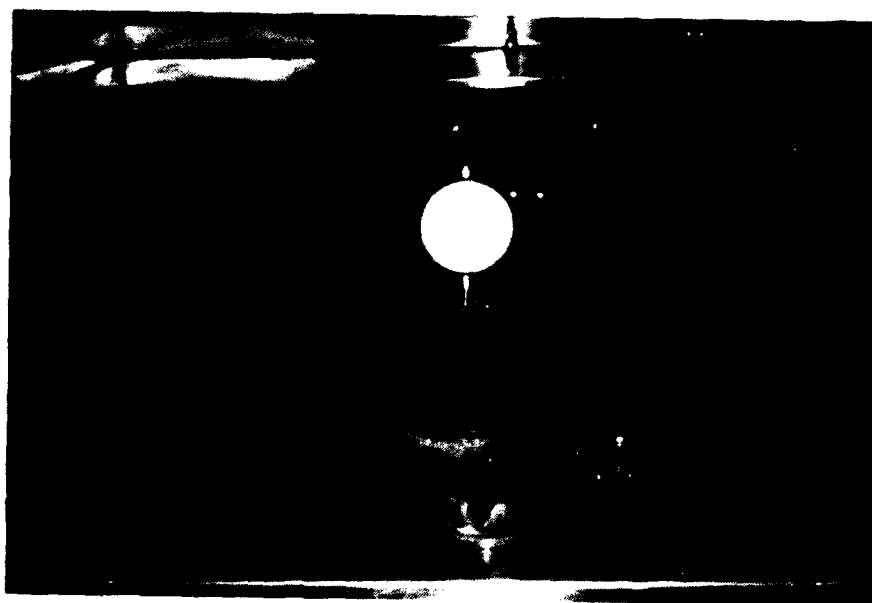
Figure 20.   Swell test mold and ring.
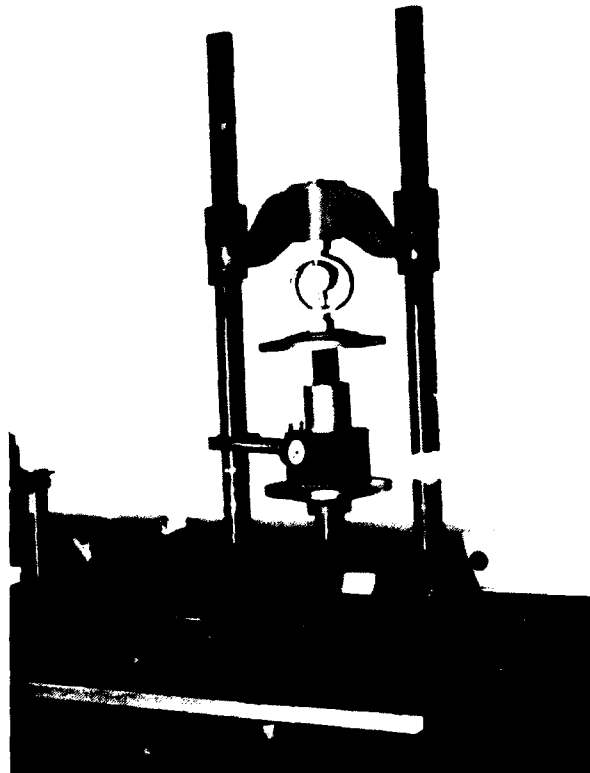
Figure 21. Unconfined compression
testing using a Karol-Warner load-
ing frame.
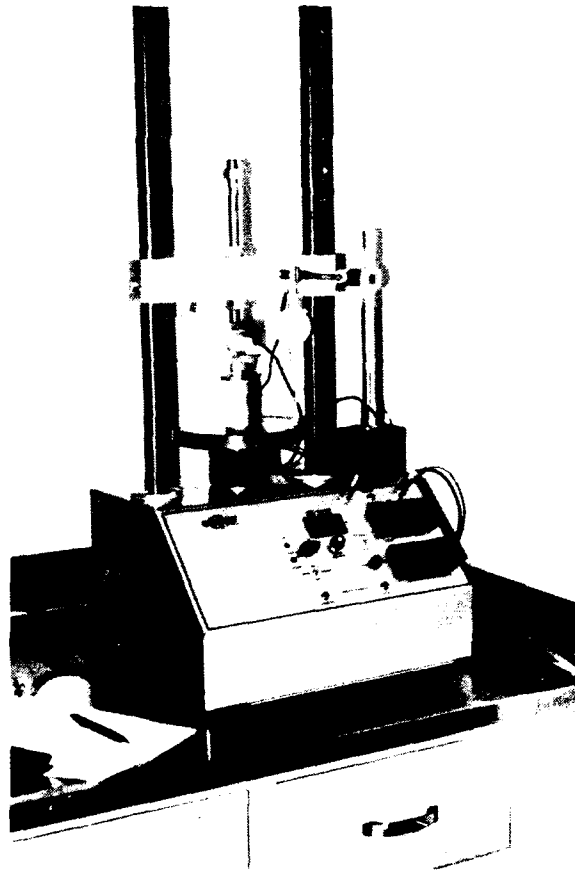
Figure 22.   Unconfined compression
testing using a Geotest loading
frame.
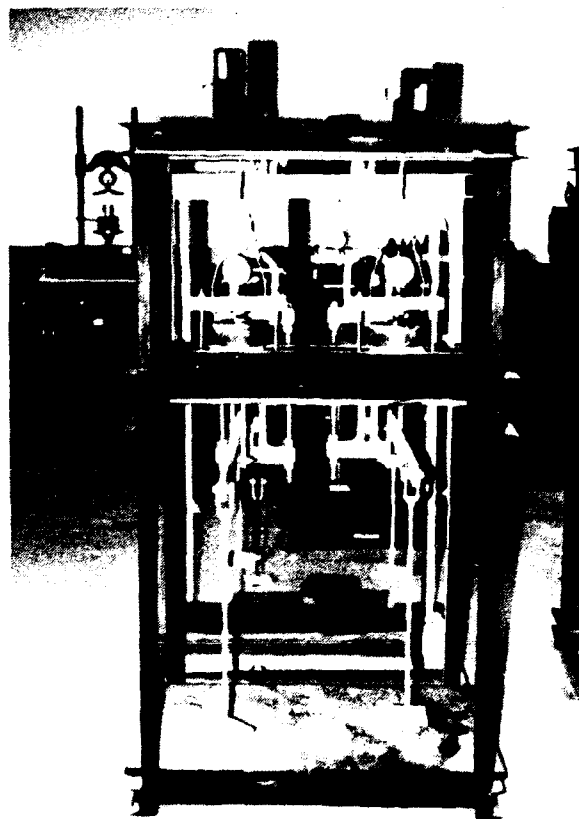
Figure 23. Swell test loading frame.

unconfined compression strength, porewater extractions, and exchangeable cations extraction tests.

103. This material is called reworked as it has been previously remolded for the leach tests. Therefore, any further remolding must be termed reworking the soil.

104. Unconfined compression, free swell, and swell pressure test samples were brought to optimum moisture content prior to compaction. After moisture was added, the samples were allowed to mellow overnight. The unconfined compression tests were made in the Harvard miniature devices with 4 layers at 25 blows per layer, as previously discussed. The unconfined compression test samples were then double wrapped in plastic, coated with wax then cured at 120° F for 48 hours.

105. Free swell and swell pressure test samples were compacted in previously described consolidation rings and compacted with a Harvard miniature tamper using 3 layers at 40 blows per layer. This approximates the same compactive effort and layer thickness as for the unconfined compression samples. Dry unit weights were similar in both cases.

106. Control Tests. In order to correlate before and after leaching data, control tests were established. Physical property changes after leaching (Atterberg limits, shrinkage, strength, swell and permeability) were compared directly to the tests run prior to leaching under the same moisture, compaction and curing condition used in preparing the leaching tests. This comparison method is fairly straightforward as strength, swell, and other physical property changes can be reliably measured with good repeatability.

107. However, due to the complex nature of the soil-lime structure, the chemical property changes required tighter control measures. Curing conditions

(time, temperature, moisture) were considered the primary factors that must be duplicated for before and after leaching tests. Therefore, "before" leaching material was prepared by placing the excess soil for each leach test preparation in air tight plastic bags, curing for 48 hours at 120° F, and storing for the duration of the leach tests (45 to 90 days). These samples were then air dried, lightly crushed, and separated with a No. 40 sieve. Material passing the No. 40 sieve was used for porewater and exchangeable cations extraction. This duplicated the exact conditions of testing the leached soil samples.

108. To measure the cation washout during leaching for soil with no lime added, high pressure, long-term leaching tests were run using two Soiltest Model K-670, miniature permeameters (Figure 24). Non-treated soil was compacted at optimum moisture into the molds (3.3 cm diameter by 7.1 cm high) using a Harvard miniature compaction tamper to achieve 95 percent of maximum dry density (Standard Proctor). The samples were leached with distilled/demineralized water for 45 and 90 days with leachate samples taken periodically for cation concentration measurements. At the completion of the leach tests, the samples were air dried, lightly crushed and set aside for porewater extractions and exchangeable cations extractions.

In-Situ Test Program

Site Description

109. As previously discussed, the soil used in this research was chosen due to its expansive nature and its proximity to a controlled lime treated section of a construction project. Site No. 1 is adjacent to a section of pavement that was constructed in 1972 as part of the Dallas/Fort Worth International Airport complex. The soil beneath the pavement and cement treated base coarse was treated
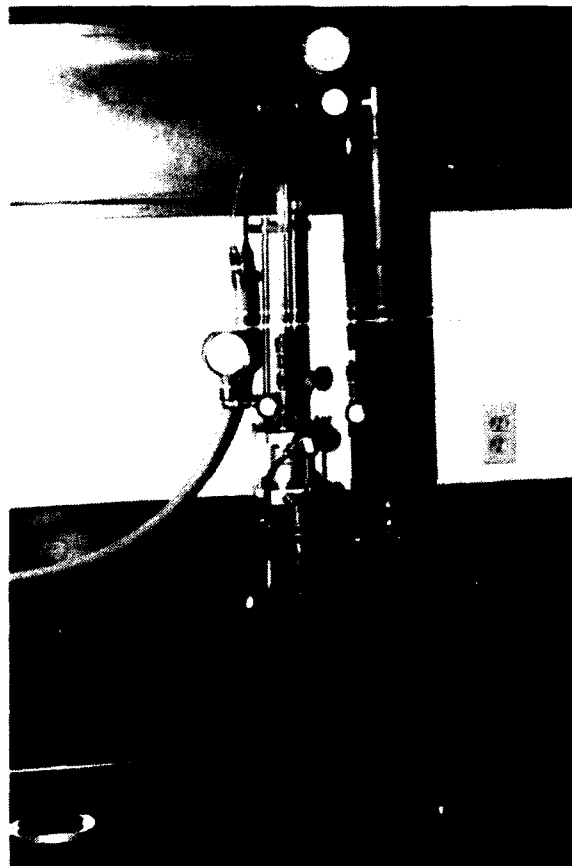
Figure 24. Soil test high pressure
miniature permeameter.

with six percent lime for six inches then with three percent lime for 18 in. The treated material extends 12 in. beyond the back of the curb.

110. Site No. 2 is located near a concrete road that was constructed in the North Foreign Trade Zone in 1980. The subgrade for this concrete road is a six inch, seven percent lime treated material that extends beyond the back of the curb by approximately 12 in. According to the construction specifica-tions, all lime treated material at Sites No. 1 and 2 were compacted at optimum moisture to 95 percent Standard Proctor density then cured for a minimum of seven days prior to allowing traffic on it.

111. Site No. 3 is located near a concrete road in a future industrial area in north Irving, Texas. The concrete road is constructed over eight inches of nine percent lime treated subgrade. The lime treated subgrade extends two feet beyond the edge of the curb. The lime-soil subgrade was compacted to 95 percent of Standard Proctor density at optimum moisture. However, after approximately 27 days, lime treated soil was removed and stockpiled in order to lower the grade. After final grading, the stockpiled material was replaced and recompacted to original specifications. The pavement was placed in 1986. Figure 25 shows the cross-sections of these three sites.

Testing the Material

112. Initially, samples of the lime treated subgrade material were obtained using two inch diameter Shelby tubes. However, this proved to be unreliable. Therefore, bag samples were obtained using a two inch diameter hand auger to bypass the top soil and soil-cement layer, and a 1-1/2 in. hand auger was used to gather the lime treated soil.

Site No. 1

Site No. 2

Site No. 3
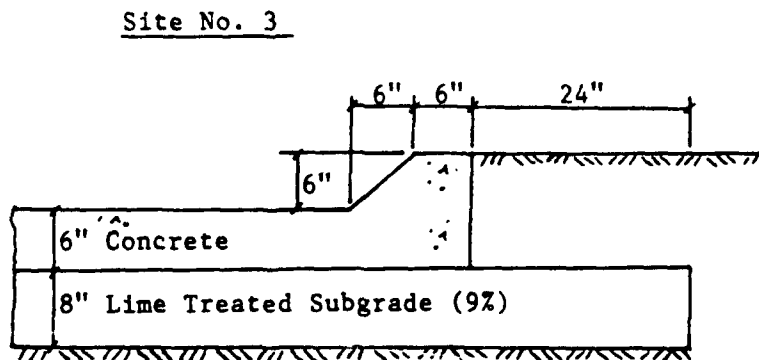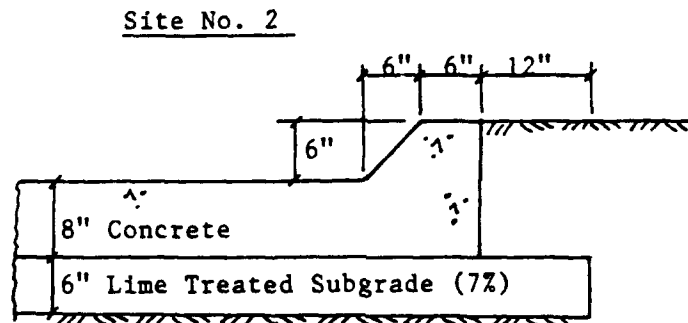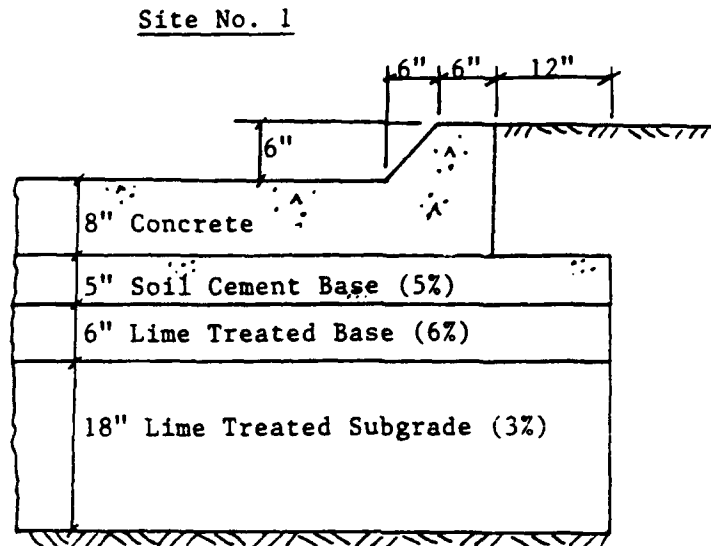
Figure 25. Cross-sections of Sites No. 1, 2, and 3 pavement and subgrade.

113. Testing of the material included all physical and chemical tests as previously discussed for leached samples. All compacted samples were remolded samples. All soil was slaked through a No. 40 sieve and air dried prior to any testing.

PART IV: RESULTS AND DISCUSSION

Introduction

114. Thirty-one, twenty-five and fourteen leach tests were completed using material from Sites No. 1, 2 and 3, respectively, for a total of 70 leach tests. Factors held constant during the leach testing were compactive effort (all samples compacted to meet a minimum of 95 percent Standard Proctor density for each individual soil-lime compaction curve for samples compacted at or near optimum moisture), curing conditions (all samples waxed and cured for 48 hours at 120 °F), and water flow pressure (10 psi except for Site No. 1 samples compacted wet of optimum where 15 psi was required). Variables used included compaction moisture content, lime percent additions and time of leaching (45 and 90 days). The 90 day leach tests were only used on samples intended to simulate field conditions. Therefore, 90 day tests were only run on samples to which field percentage of lime was added as well as samples mixed at their lime modification optimum.

115. Three compactive moisture content ranges were used: (1) plus or minus three percent around optimum moisture content, OMC, (-3% < OMC < +3%); (2) minus eight to minus three percent below optimum, -OMC; and (3) plus three to eight percent above optimum, +OMC. The same compactive effort was used for all three moisture ranges.

116. The average moisture content deviations from optimum moisture for +OMC, OMC, and -OMC leach tests were +5.3, +0.4, and -5.6 percent, respectively, for Site No. 1. For Site No. 2, average moisture content deviations were +5.2, -0.3, and -5.1 percent for +OMC, OMC, and -OMC leach tests, respectively. For Site No. 3, only optimum moisture tests were conducted which

averaged 0.5 percent above optimum. The goals were to average +5.0, ±1.0, and -5.0 percent for the respective moisture tests.

117. Average percents of maximum dry density (Standard Proctor) for +OMC, OMC, and -OMC specimens were 93.6, 97.6 and 95.7 percent, respectively, for Site No. 1. Percents of maximum dry density for soils from Site No. 2 were 92.6, 96.4 and 93.8 percent for +OMC, OMC, and -OMC leach tests, respectively. Site No. 3 leach test samples averaged 94.5 percent of maximum dry density. The goal was to achieve 95 percent for OMC samples only. Samples compacted above or below optimum moisture were compacted using the same effort as for samples compacted at optimum moisture. Their resulting compacted unit weights were recorded in order to note the decrease in density with widely varied moisture contents. Table 4 gives a summary of the leach tests conducted.

Laboratory Soil-Lime Reactivity

118. Prior to any leach testing, the untreated bulk soil from each site was subjected to numerous physical and chemical tests to determine its reactivity to various lime contents. Hydrated lime was added to the soil samples at a given percentage, based on the sample's dry weight. All test results are based on compaction to 95 percent Standard Proctor density at optimum moisture content.

Lime Modification Optimum

119. The lime modification optimum (LMO), as was used in this research, is the minimum percentage of lime added to a lime reactive clay that reduces the soil's plasticity to a minimum. The Eades and Grim (1966) pH test method was initially

TABLE 4

SUMMARY OF VARIABLES USED DURING
LEACH TESTING FOR ALL SOIL SITES

Soil	Variables					
	Percent	Time of Leaching		Moisture Content (%)[*]		
Site	Lime (%)	45 Days	90 days[**]	-OMC	OMC	+OMC
1	0	X	X		X	
	1	X		X	X	X
	2	X			X	
	3	X	X	X	X	X
	4	X		X	X	X
	6	X	X	X	X	X
	8	X			X	
2	0	X	X		X	
	1	X		X	X	X
	2	X		X	X	X
	3	X	X	X	X	X
	5	X		X	X	X
	7	X	X	X	X	X
3	0	X	X		X	
	1	X			X	
	2	X			X	
	3	X	X		X	
	5	X			X	
	7	X			X	
	9	X	X		X	

[*] -OMC = -8% to -3% below OMC; OMC = -3% < OMC < +3%; +OMC = +3% to +8% above OMC

[**] Ninety day tests were compacted at OMC only.

used to estimate the LMO and Atterberg limits were used to verify it. Both tests gave identical results for soils from all three soil sites. The LMO was determined to be 4.0 percent for Site No. 1 and 3.0 percent for Sites No. 2 and 3. Knowing the modification optimum, the leach tests were established such that at least two percentages below and above LMO were utilized. Additionally, the field lime

percentages were to be included in the leach tests, particularly for 90 day tests. Graphical representations of the LMO tests, using pH as a measure, are shown in Appendix B.

Physical and Chemical Changes with Lime

120. Site No. 1 Physical Data. Even when only a small amount of lime is added to Site No. 1 Eagle Ford clay, dramatic changes in the soil's in-situ characteristics occur. At four percent lime, the plasticity index drops from 30 to 10 percent (66.7 percent decrease), linear shrinkage drops from 22.0 to 7.1 percent (66.7 percent decrease), swelling pressure drops from approximately 1000 psf to 197 psf (80.3 percent decrease), and vertical swelling reduces from approximately 2.0 percent to 0.2 percent (90.0 percent reduction). Furthermore, strength gains at the LMO show a 425 percent strength increase over that of in-situ soil.

121. Site No. 2 Physical Data. At the LMO for Site No. 2 (three percent), the soil's plasticity index decreased from 33 to 13 percent (60.6 percent decrease), linear shrinkage dropped from 17.7 to 3.1 percent (82.5 percent decrease), swelling pressure dropped from 1105 psf to 301.3 psf (72.7 percent decrease), and vertical swelling decreased from 3.2 to 0.2 percent (93.8 percent reduction). Strength gains on remolded samples (not reworked) showed an increase from 10.04 ksf to 25.47 ksf (153.7 percent increase) at three percent lime.

122. Site No. 3 Physical Data. For Site No. 3 material tested at the LMO (three percent), the plasticity index dropped from 45 to 11 percent (75.6 percent decrease), linear shrinkage decreased from 24.4 to 4.7 percent (80.7 percent decrease), swelling pressure dropped from 2117.9 psf to 588.7 psf (72.2 percent decrease), and vertical swelling decreased from 12.0 to 0.5 percent (95.8 percent

reduction). Strength gains at three percent lime increased 200.0 percent above that of original in-situ soil. Graphical presentation of Atterberg limits, linear shrinkage, swelling pressure, and free swell characteristics for soils from all three sites are shown in Appendix B. All site's data are shown on single graphs (except Atterberg limits) for each test in order to provide a visual comparison of the similarities of each soil site. The lime reactive data for all three sites is consistent with research by others on similar expansive clays in Texas, particularly Eagle Ford clay in the Dallas/Fort Worth area (Biswas 1979; Tsai 1979; Petry, Armstrong and Chang 1982).

123. Lime Stabilization Optimum. The lime stabilization optimum (LSO), or the lime percentage point at which maximum shear strength occurs, appears to be approximately six percent lime for Site No. 1 material, six to seven percent for soil from Site No. 2, and six percent lime for Site No. 3 material. This is shown graphically in Figure 26. Also shown in Figure 26 is the reworked strength. The procedure for determining the reworked strength was described in Part III. Figure 26 clearly shows that if a lime treated soil is exceptionally disturbed and allowed to dry after its curing period is complete, it will exhibit an extremely large decrease in strength when recompacted, even when allowed to recure under the same initial conditions.

124. This is an important consideration when stabilizing a subgrade for a pavement. Final grade must be established before stabilization occurs. If cut and fill operations are undertaken on the cured subgrade, dramatic changes on stabilization properties are possible.

125. Chemical Data. Porewater cations and exchange complex cations were extracted from lime treated soil after curing all samples for 48 hours at 120 °F then for an additional 45 or 90 days at 70° (room temperature). This parallels the same
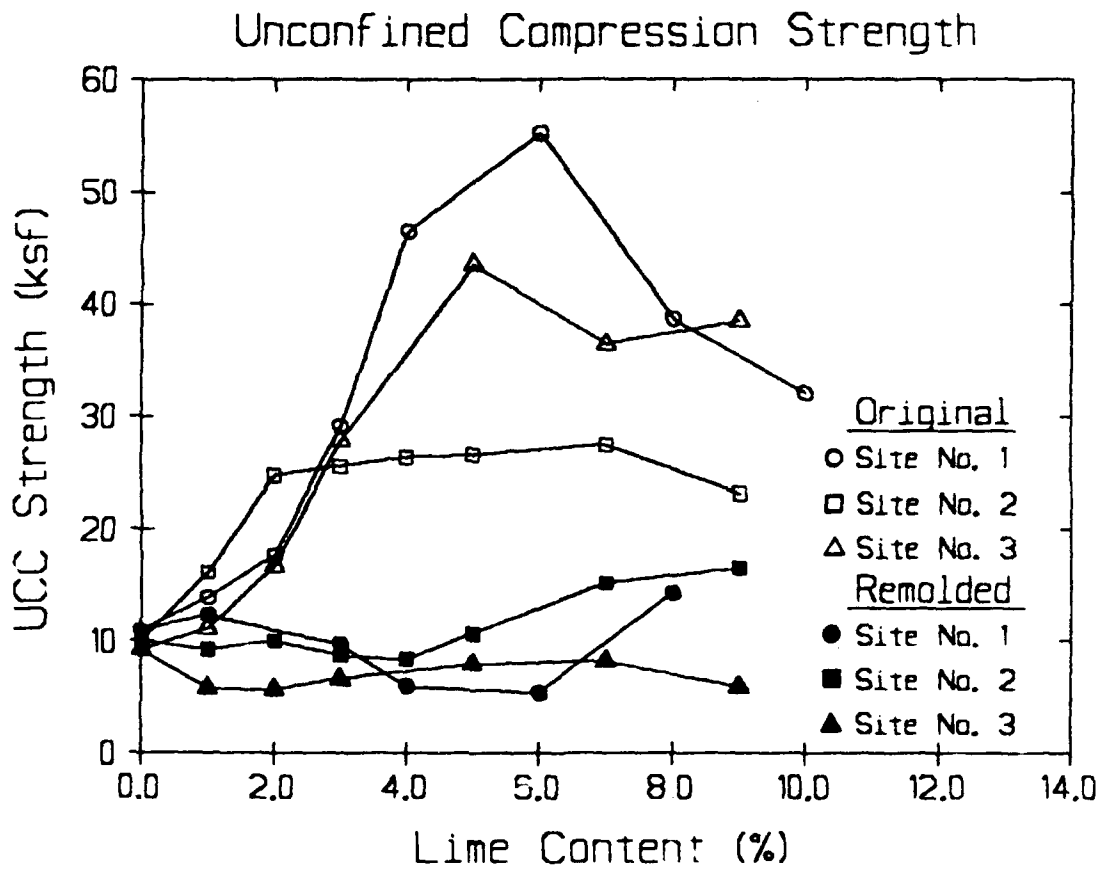
Figure 26. A comparison of strength data for various lime contents on Sites No. 1, 2, and 3.

testing conditions as for the leached samples except there was no leaching. This represents the "Before" conditions for the testing. Figures 27 and 28 show the porewater extraction curves of calcium and sodium for the 45 day cure tests, taken from samples mixed at optimum moisture. Figures 29 and 30 show the exchange complex extractions for the same cations. Magnesium and potassium cations are discussed later in this chapter.

126. Of particular importance is the change in the calcium concentrations with the addition of lime. Figure 27 shows a general decrease in the porewater concentration with the addition of lime while Figure 29 shows an increase in the exchange complex concentration. This suggests that with the increase in lime, pozzolanic reactions are taking the lime out of the excess in the porewater and using it in the exchange complex. This follows general lime reactivity theory that says increasing calcium concentration increases the formation of calcium silicate hydrates (CSH I and II) within the soil-lime structure (Diamond and Kinter 1965; Ingles and Metcalf 1973), therefore, increasing the pozzolanic reaction. The soil porewater gives up its calcium cations rapidly at first to satisfy the initial pozzolanic and cation exchange requirements, but the loss diminishes as the amount of calcium is increased in the system. Figure 29 also shows all sites are naturally high in calcium which is typical of montmorillonitic clays in the Southwest (Johnson, Cady and James 1962; Diamond and Kinter 1965).

127. Figures 28 and 30 show that soils from Site No. 3 had a much larger concentration of sodium in its natural state than the soils from the other two sites. Site No. 3 material also had the largest plasticity index (PI) and swelling properties. The large concentration of sodium in the soil's porewater would explain, to some degree, the larger PI and swelling properties of Site No. 3 soil. Expansive clay minerals are known to be negatively charged with large surface areas, thereby
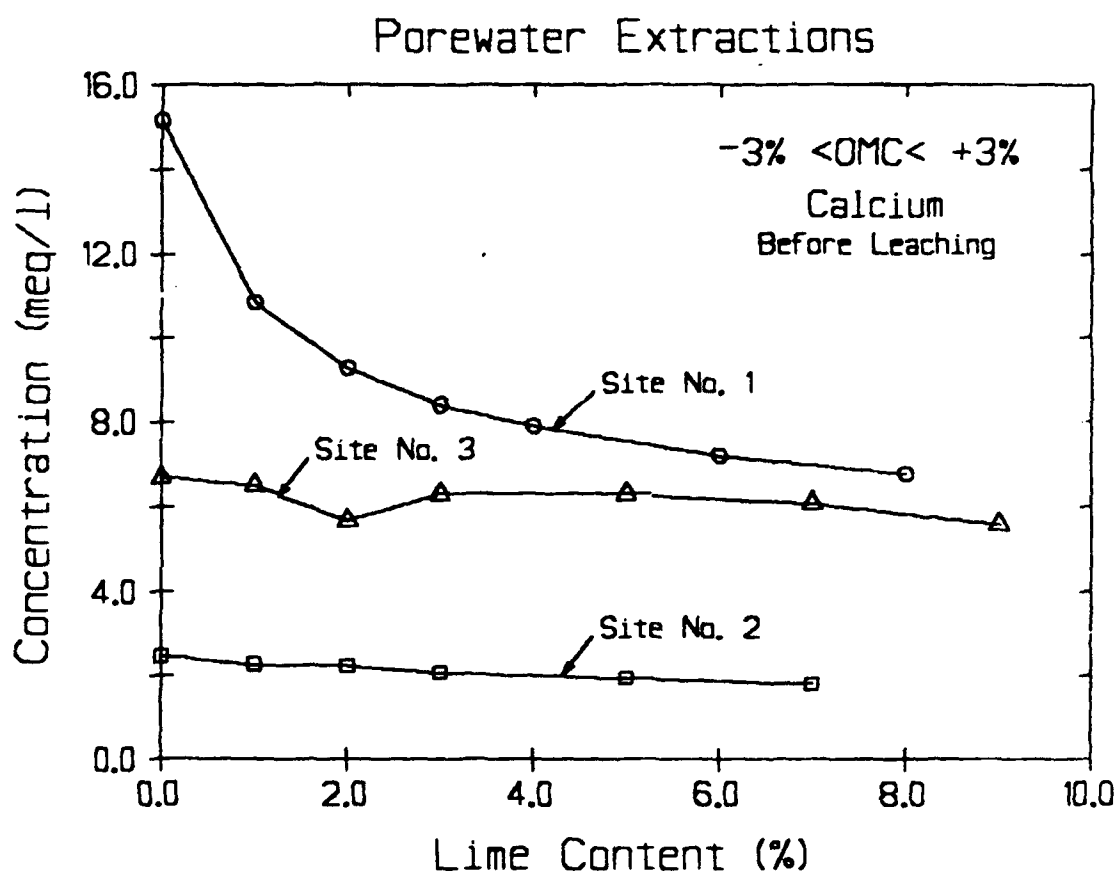
Figure 27. Porewater extractions of calcium before leaching.
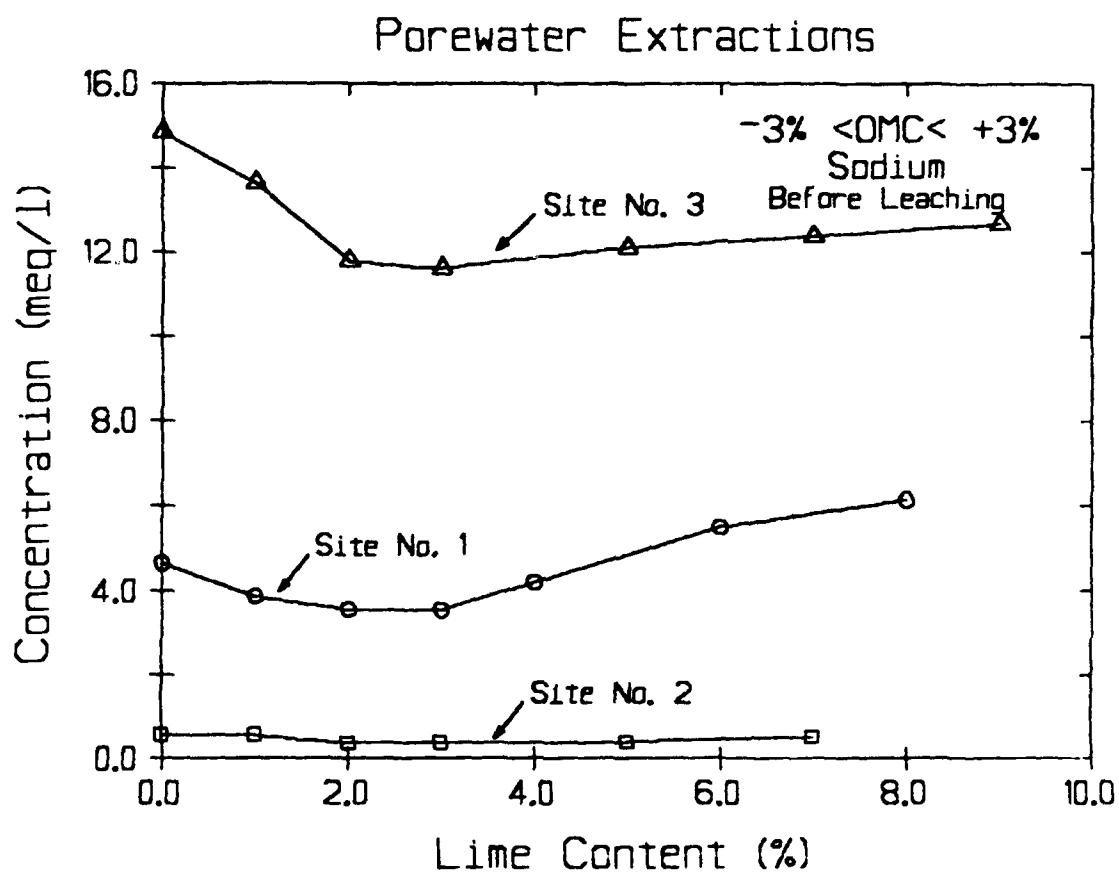
Figure 28. Porewater extractions of sodium before leaching.

Exchangeable Cations

-3% <OMC< +3%
Calcium
Before Leaching

Site No. 1

Site No. 3

Site No. 2
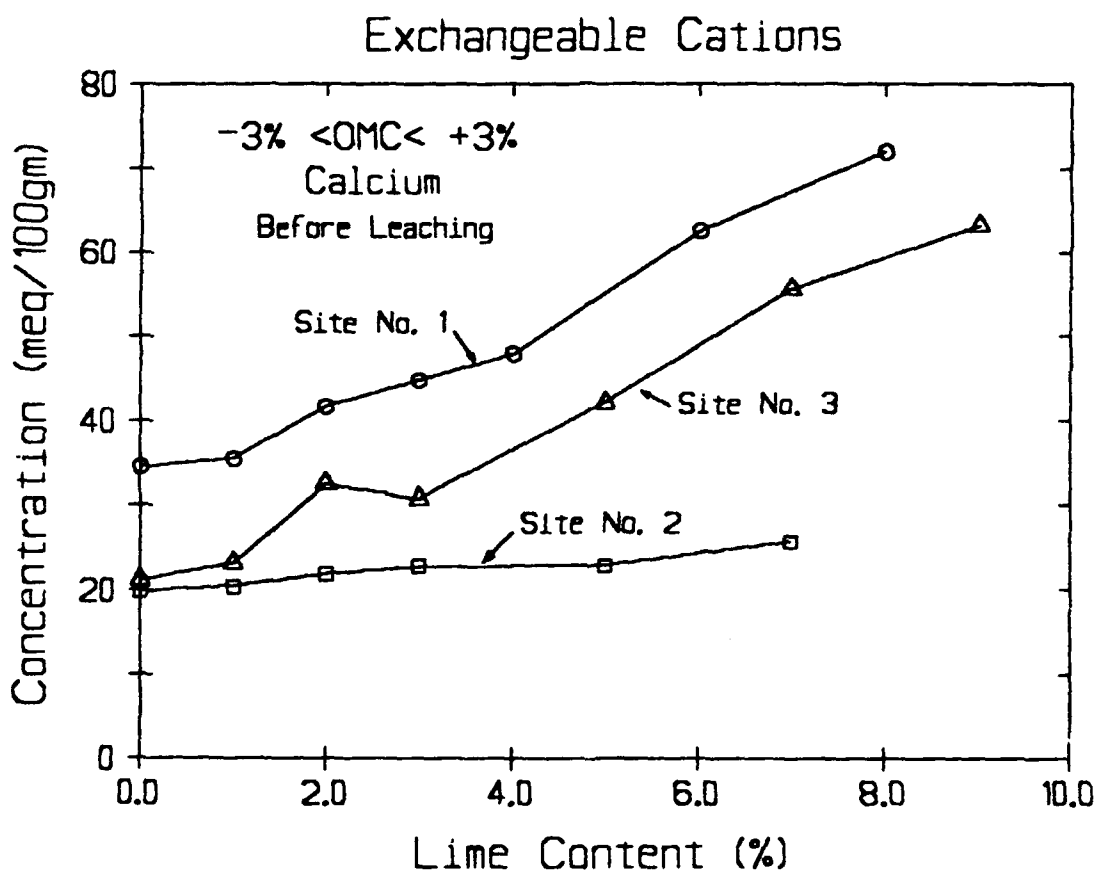
Figure 29. Exchange complex extractions of calcium before leaching.

96
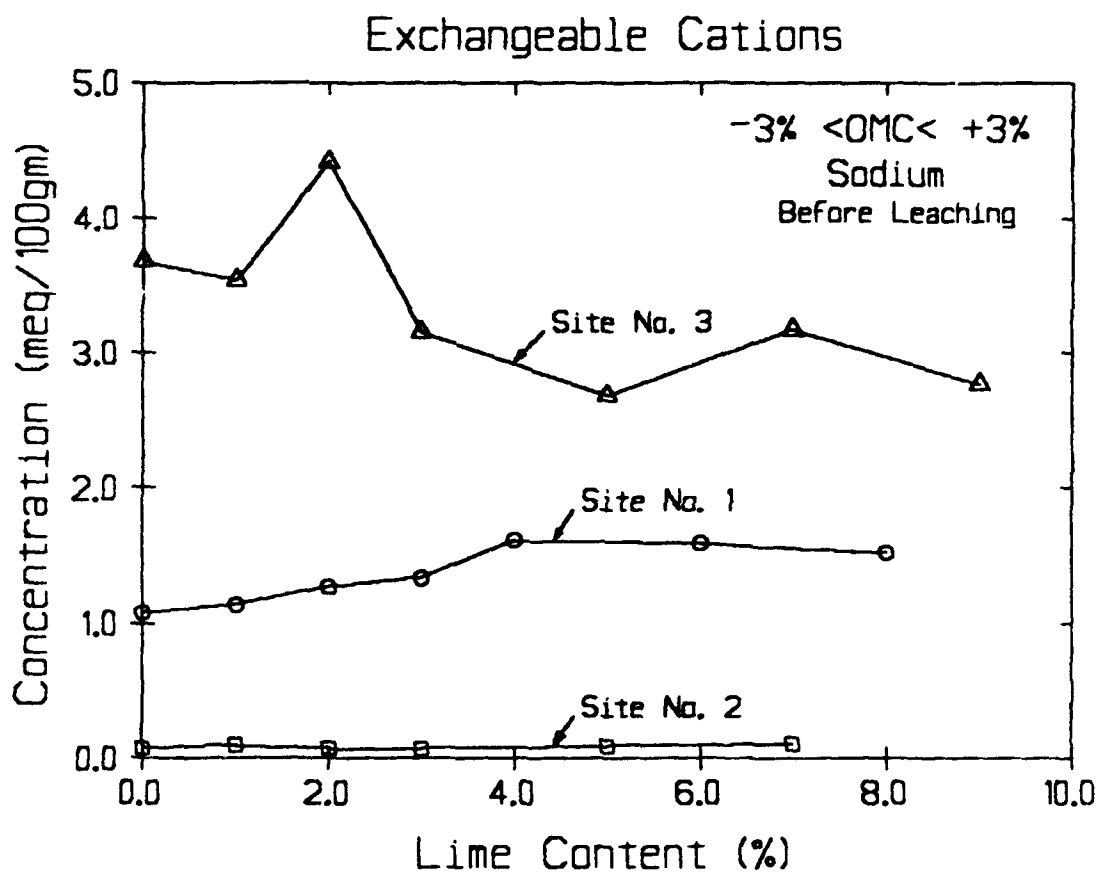
Figure 30. Exchange complex extraction of sodium before leaching.

attracting large quantities of positive ions in an attempt to balance their change deficiency (Das 1983; Grim 1968; Mitchell 1976). Monovalent sodium ions are easily replaced along the clay surface as water enters the area between the minerals and then become diffused away from the clay surface. This allows more water to attach itself to the clay particles, as well as to the sodium ions, resulting in a diffused layer surrounding each clay mineral. This diffused layer is comprised of water held by hydrogen bonding and a diffused layer of cations, some of which are attached to dipolar water molecules and some which are weakly attached to the clay surface (Little 1987). For a much more in depth study of expansive clay behavior, the reader is referred to excellent work by Mitchell (1976) and Lambe and Whitman (1969).

128. Tables 5, 6 and 7 give the chemical and physical data for the various percentages of lime used to test soils from Sites No. 1, 2 and 3, respectively. All samples were prepared and cured as previously discussed in Part III. Note that all strength tests are unconfined compression tests and all chemical tests are conducted on samples cured for 48 hours at 120 °F then for 45 days at 70 °F (room temperatures).

Leach Tests—Leachate Analysis

129. Sampling of the water as it exited the leaching cells occurred approximately every 100 hours. Using ICP spectrophotometry, the leachate was analyzed for concentrations (parts per million, ppm, or mg/l) of calcium, sodium, magnesium and potassium. Additionally, the leachate pH was monitored.

TABLE 5

SITE NO. 1, LIME REACTIVITY BEFORE LEACHING
(-3% < OMC < +3%)

Property	Lime Content						
	0%	1%	2%	3%	4%	6%	8%
Liquid Limit (%)	63	62	62	60	56	59	59
Plastic Limit (%)	33	40	48	47	46	46	47
Plasticity Index (%)	30	22	14	13	10	13	12
Linear Shrinkage (%)	22.0	18.1	16.5	9.1	7.1	8.7	8.7
Swell Presure (psf)	977.4	389.2	301.2	197.6	197.0	154.1	141.1
Free Swell (%)	1.80	0.74	0.80	0.34	0.20	0.14	0.28
Shear Strength (ksf)							
Remolded	10.92	13.47	17.67	29.08	46.50	55.26	38.69
Reworked	10.92	12.32	--	9.71	6.01	5.40	14.30
Porewater Cations (meq/l)							
Calcium	15.17	10.85	9.28	8.29	7.90	7.20	6.76
Sodium	4.66	3.86	3.55	3.54	4.20	5.50	6.13
Magnesium	0.30	0.09	0.11	0.12	0.11	0.06	0.01
Potassium	0.32	0.21	0.23	0.24	0.26	0.30	0.36
Exchange Complex Cations (meq/100 g)							
Calcium	34.56	35.42	41.66	44.73	47.89	62.52	72.05
Sodium	1.08	1.14	1.27	1.34	1.62	1.60	1.53
Magnesium	0.99	0.48	0.71	1.03	1.37	1.71	1.27
Potassium	0.78	0.77	0.71	0.73	0.74	0.83	0.94
Soil pH	8.40	11.47	12.31	12.40	12.44	12.45	12.50

TABLE 6

SITE NO. 2, LIME REACTIVITY BEFORE LEACHING
(-3% < OMC < +3%)

Property	0%	1%	2%	3%	5%	7%
				Lime Content		
Liquid Limit (%)	60	49	48	45	48	47
Plastic Limit (%)	27	33	32	32	34	34
Plasticity Index (%)	33	16	16	13	14	13
Linear Shrinkage (%)	17.7	5.9	4.7	3.1	5.5	5.5
Swell Presure (psf)	1104.7	458.4	315.0	301.3	258.5	232.4
Free Swell (%)	3.21	1.82	0.30	0.17	0.17	0.11
Shear Strength (ksf)						
Remolded	10.04	16.12	24.68	25.47	26.51	27.41
Reworked	10.04	9.21	10.01	8.78	10.67	15.20
Porewater Cations (meq/l)						
Calcium	2.47	2.26	2.23	2.07	1.94	1.80
Sodium	0.57	0.57	0.37	0.38	0.39	0.52
Magnesium	0.16	0.17	0.16	0.17	0.13	0.07
Potassium	0.10	0.13	0.11	0.10	0.10	0.14
Exchange Complex Cations (meq/100 g)						
Calcium	19.84	20.42	21.86	22.75	22.91	25.73
Sodium	0.08	0.10	0.08	0.07	0.09	0.11
Magnesium	0.31	0.41	0.50	0.65	0.67	0.94
Potassium	0.28	0.26	0.27	0.28	0.22	0.31
Soil pH	8.40	11.36	11.99	12.20	12.62	12.63

TABLE 7

SITE NO. 3, LIME REACTIVITY BEFORE LEACHING
(-3% < OMC < +3%)

Property	Lime Content						
	0%	1%	2%	3%	5%	7%	9%
Liquid Limit (%)	76	70	61	56	57	53	55
Plastic Limit (%)	31	38	45	45	45	42	43
Plasticity Index (%)	45	32	16	11	12	11	12
Linear Shrinkage (%)	24.4	14.9	7.9	4.7	3.9	3.9	2.4
Swell Presure (psf)	2117.9	1179.6	662.6	588.7	362.5	306.3	301.9
Free Swell (%)	11.97	3.10	1.57	0.50	0.19	0.19	0.19
Shear Strength (ksf)							
Remolded	9.24	11.09	16.72	27.79	43.45	36.40	38.43
Reworked	9.24	5.78	5.68	6.65	7.92	8.22	5.93
Porewater Cations (meq/l)							
Calcium	6.69	6.50	5.68	6.30	6.30	6.09	5.60
Sodium	14.85	13.64	11.78	11.60	12.09	12.36	12.67
Magnesium	2.08	0.27	0.19	0.14	0.11	0.02	0.01
Potassium	0.23	0.20	0.17	0.16	0.20	0.20	0.25
Exchange Complex Cations (meq/100 g)							
Calcium	21.21	24.38	32.46	30.74	42.13	55.63	63.26
Sodium	3.68	3.54	4.42	3.15	2.68	3.17	2.77
Magnesium	2.39	1.37	1.69	1.96	1.58	2.00	1.74
Potassium	0.54	0.48	0.58	0.44	0.53	0.65	0.64
Soil pH	8.71	11.18	11.48	12.02	12.53	12.61	12.63

Changes in Leachate pH

130. <u>Site No. 1 Leachate pH</u>. Figure 31 shows the leachate pH for Site No. 1 leach samples compacted at OMC. As expected, the figure shows that with an increase in lime content, the leachate pH increases. However, after approximately the LMO (four percent) has been reached, increases in lime content have minimum effect on pH. For six and eight percent lime contents, the pH remained essentially identical after the first 100 hours of leaching.

131. For all lime contents, the leachate pH decreased with leaching time. The decrease in pH is slight for most percentages of lime, but appears to be larger for percentages greater than the LMO. For example, total decreases in pH for 45 day tests were 0.01, 0.18, 0.30, and 0.59 for one, two, three, and four percent lime, respectively. Decreases in pH for six and eight percent lime were 0.35 and 0.95, respectively, with eight percent dropping rapidly after approximately 700 hours.

132. <u>Site No. 2 Leachate pH</u>. Leachate pH for Site No. 2 leach tests compacted at OMC are shown in Figure 32. As with Site No. 1, the general trend was for the pH to increase with increases in lime content. Above the LMO (three percent), however, the pH of the leachate samples were virtually identical. This correlates well with Eades and Grim pH tests (LMO test) that shows that after the LMO the increase in pH is minimal.

133. As with Site No. 1 tests, the pH of all tests decrease with leaching time, except for zero percent lime, which shows a slight tendency to increase. The total decrease is larger for samples below the LMO and extremely small for samples above the LMO. For example, at one percent lime, the total decrease in pH is 0.43 after 45 days, whereas the total decrease for five percent lime is 0.20 after 45 days of leaching.
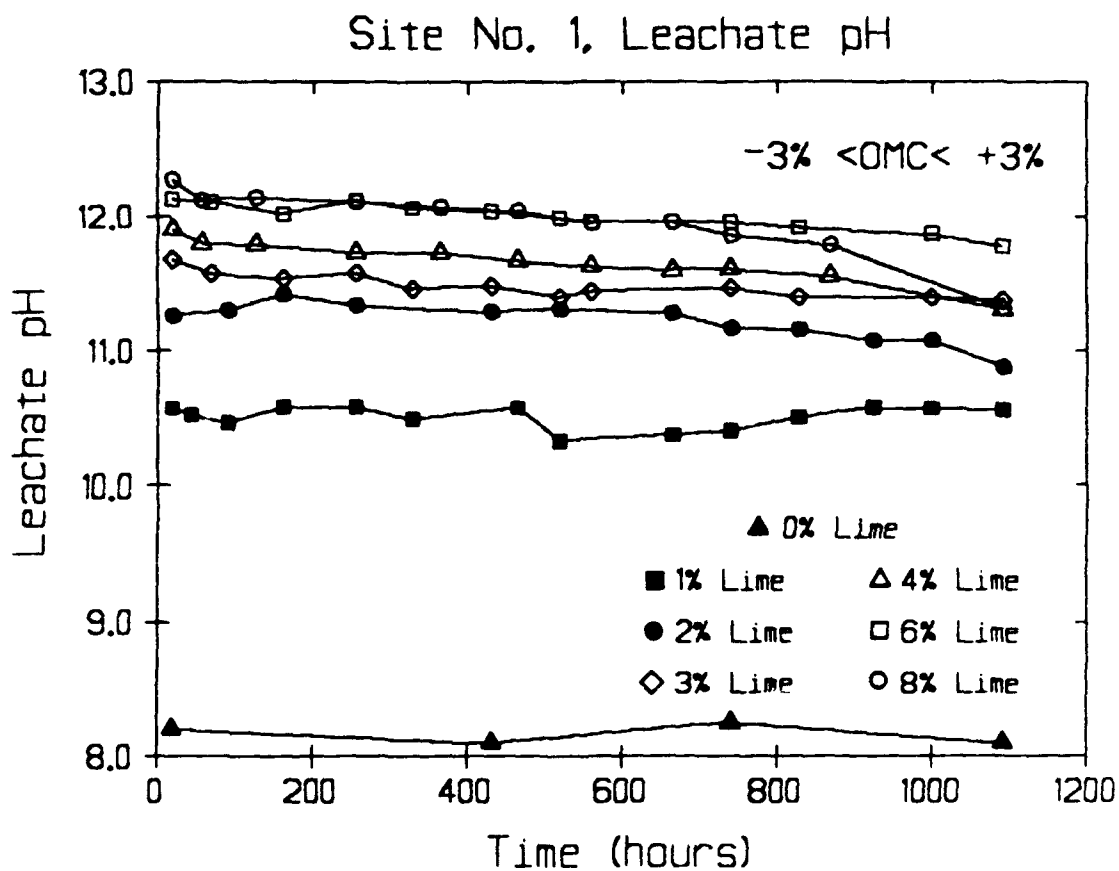
Figure 31. Leachate pH during 45 days of leaching for Site No. 1 material.
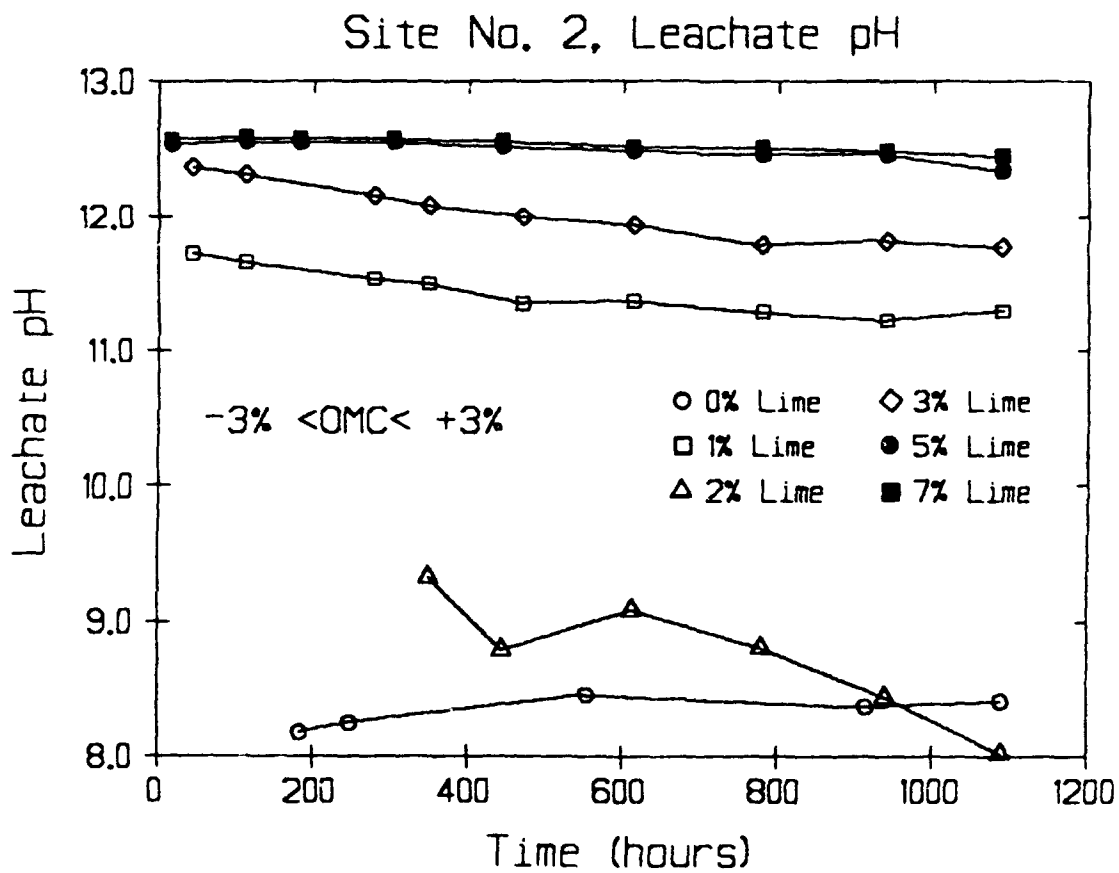
Figure 32. Leachate pH during 45 days of leaching
for Site No. 2 material.

134. <u>Site No. 3 Leachate pH</u>. Figure 33 shows the leachate pH for Site No. 3 leach samples compacted at OMC. With increases in lime content, the leachate pH increases as with Sites No. 1 and 2 leachate. Also, all leachate pH curves tend to decrease with leaching time, as was found with Sites No. 1 and 2 materials. The exception is that leachate from samples treated with one percent lime had pHs slightly increasing with leaching time. However, since the pH of the one percent lime leachate approximates the natural sample's leachate, and since the permeability of the one percent lime sample was extremely small, the cations could have become plated to the container during the time it took to collect enough sample to measure the pH.

135. Decreases in the pH appear to be largest for samples compacted with lime contents below the LMO (three percent). The decrease in total pH for leachate from samples treated with three percent lime was 0.45, and for samples with nine percent lime, the leachate pH dropped by 0.35. This is the same general trend as was noted in Site No. 2 leachate tests but the opposite of Site No. 1 tests.

136. <u>Linearity of Leachate pH</u>. Figures 34, 35, and 36 show the linearity of the leachate pH for the 90 day leach tests for Sites No. 1, 2 and 3, respectively. The natural (zero percent) soil sample's leachate pH remained essentially the same for all three sites with some degree of scatter during the 90 days of leaching. This can be partially attributed to the extremely small amount of leachate obtained and tested during the leaching process as only a Harvard miniature sample could be tested under the pressures necessary to generate a flow of water through the Eagle Ford clays (refer to Part III). Linear regression analysis of the data from samples yielded the equations and correlation coefficients, r, shown in Table 8.

137. Since there exists strong evidence that the leachate pH is linear with time, this suggests that the "washout" effects of the soil's alkalinity may be
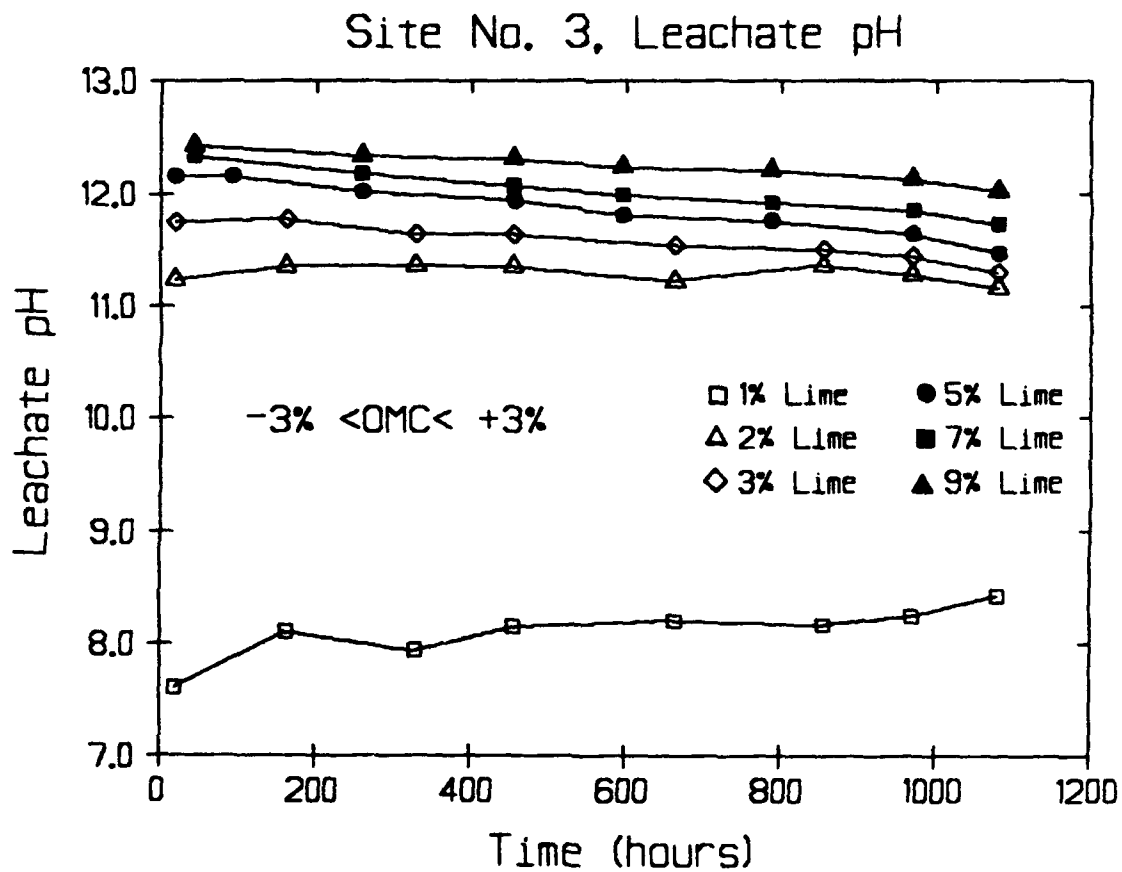
Figure 33. Leachate pH during 45 days of leaching for Site No. 3 material.
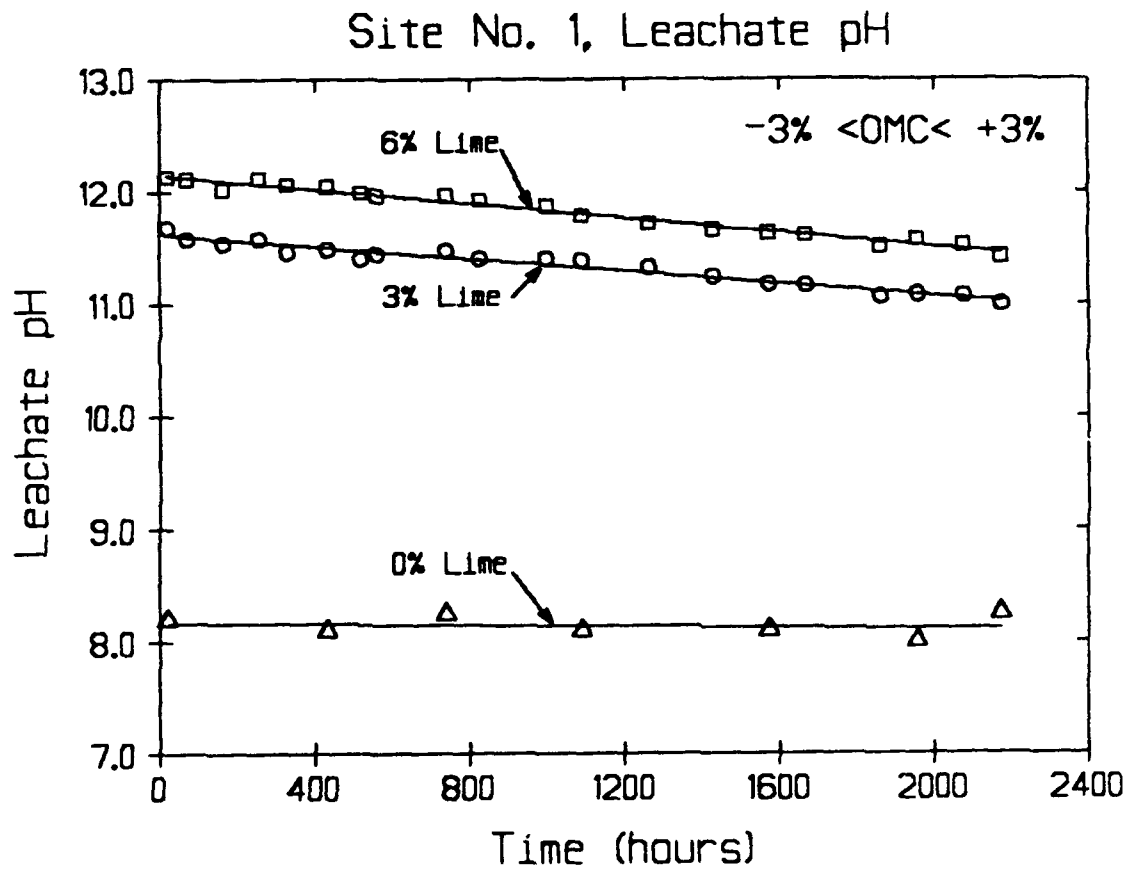
Figure 34. Leachate pH during 90 days of leaching of Site No. 1 material.
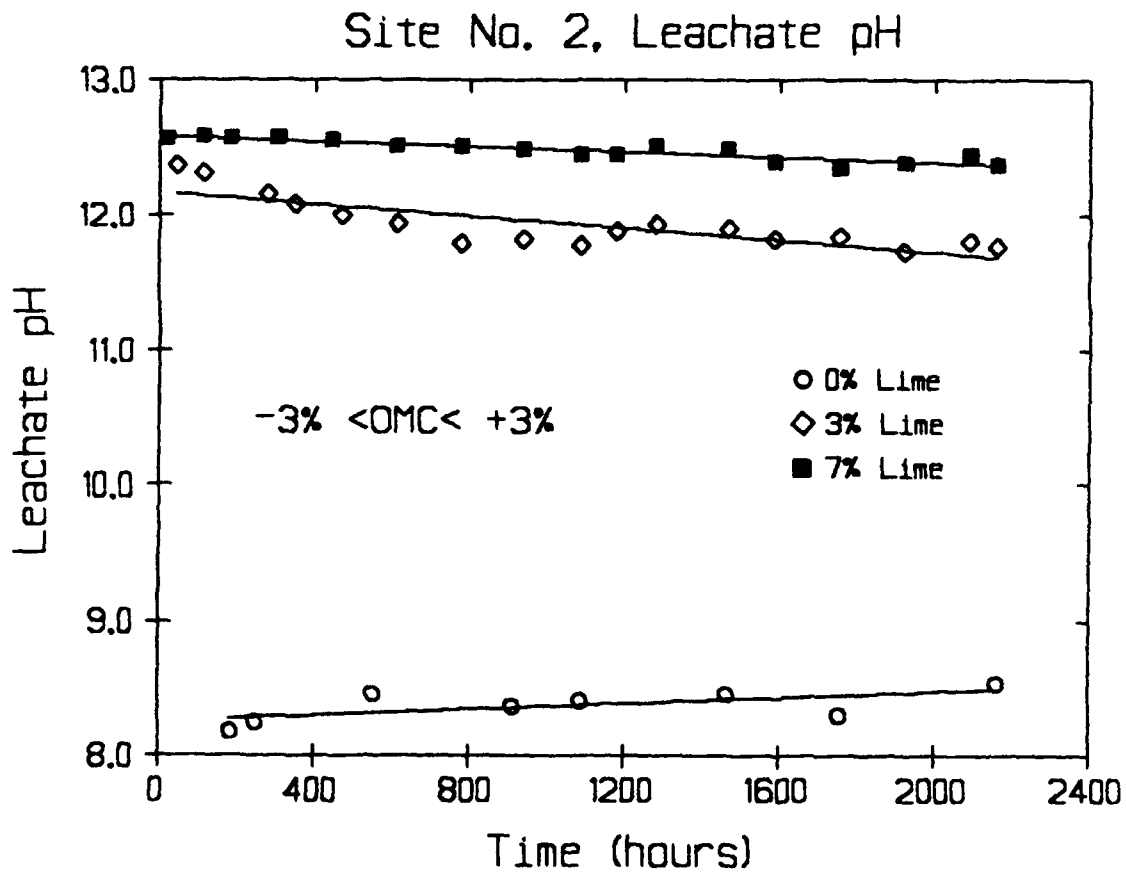
Figure 35.   Leachate pH during 90 days of leaching
of Site No. 2 material.
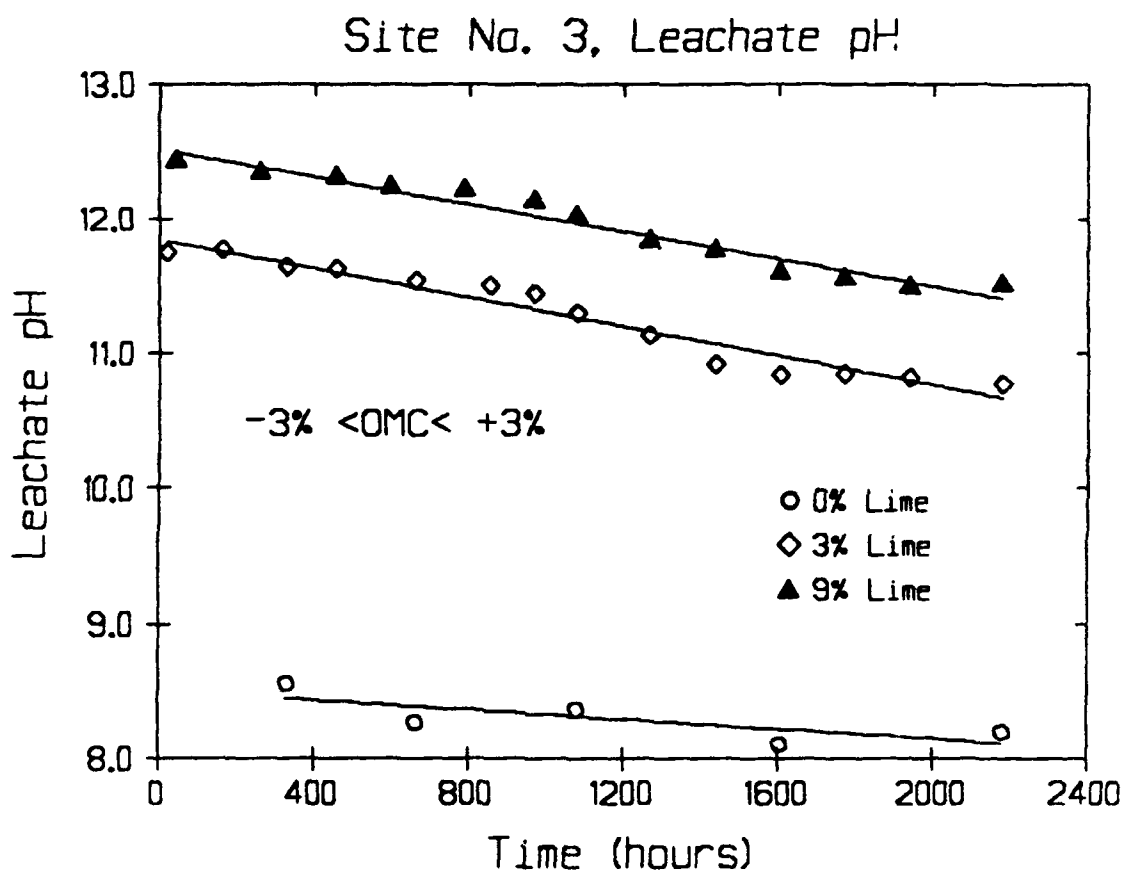
Figure 36. Leachate pH during 90 days of leaching
of Site No. 3 material.

predictable. Since alkalinity is an indirect measurement of lime concentration in the soil (although not limited to only lime, but other complex hydrogen ions as well), leachate pH could possibly be used to

TABLE 8

LINEARITY OF LEACHATE PH
(3% < OMC < -3%)

Site No.	Lime Content (%)	Intercept, A*	Slope, B	Correlation Coefficient, r
1	3	11.62	-2.74×10^{-4}	-0.98
	6	12.15	-3.22×10^{-4}	-0.99
2	3	12.13	-1.96×10^{-4}	-0.86
	7	12.59	-9.75×10^{-5}	-0.90
3	3	11.85	-5.39×10^{-4}	-0.97
	9	12.52	-5.10×10^{-4}	-0.98

* General equation is pH = A + (B x hours)

monitor detrimental effects of leaching in lime treated soils. However, permeability would be the governing consideration and must be considered before any generalizations can be made.

138. It should be noted that in most tests, the most rapid decrease in leachate pH occurred at lime contents below the established LMO. At very low lime contents the pH was very unpredictable, whereas at contents above the LMO, the decrease in pH with time was fairly uniform.

139. Moisture Effects on Leachate pH. Leachate pH for the leach tests compacted wet and dry of optimum moisture were also measured for Sites No. 1 and 2 and are presented in Appendix C. Similar results were obtained for wet and dry samples as was obtained for samples compacted at OMC, i.e., increase in

leachate pH with increase in lime contents. The leachate pH of samples compacted wet (+OMC) tended to be much lower than samples compacted at OMC, especially at lime contents above the LMO. At the higher lime contents, samples compacted at OMC had leachate pH's that were slightly higher than samples compacted below optimum. For lime contents below the LMO, the leachate pH of samples compacted dry (-OMC) were approximately equal to the pH of samples at OMC. This tends to suggest that the lowest leachate pH may be obtained by compacting wet of optimum.

140. For samples treated with one percent lime and compacted wet of optimum, both sites showed extremely low leachate pH. This is possibly due to the extremely low permeability of these samples, allowing the cations time to plate to the collection containers.

Cation Concentrations in the Leachate

141. Calcium Concentrations in Site No. 1 Leachage. Calcium concentrations in the leachate for 45 and 90 day leached samples are shown in Figures 37 and 38, respectively. The sample with one percent lime had the greatest concentration initially but this concentration rapidly dropped during leaching. Samples with six percent lime showed the second highest concentration during leaching. From Figure 37, it would appear that the least amount of calcium "washout" would occur with the addition of two or three percent lime, whereas the most "washout" takes place in samples with one or six percent. Figure 38 shows that the calcium washout is fairly linear with time. This will be investigated later in this chapter.

142. Figure 39 shows a typical graph comparing the calcium concentration for samples compacted wet, dry and at optimum moisture. All remaining graphical comparisons of leachate cations (calcium, sodium, magnesium, and potassium) for samples initially compacted wet or dry of optimum are shown in Appendix C.

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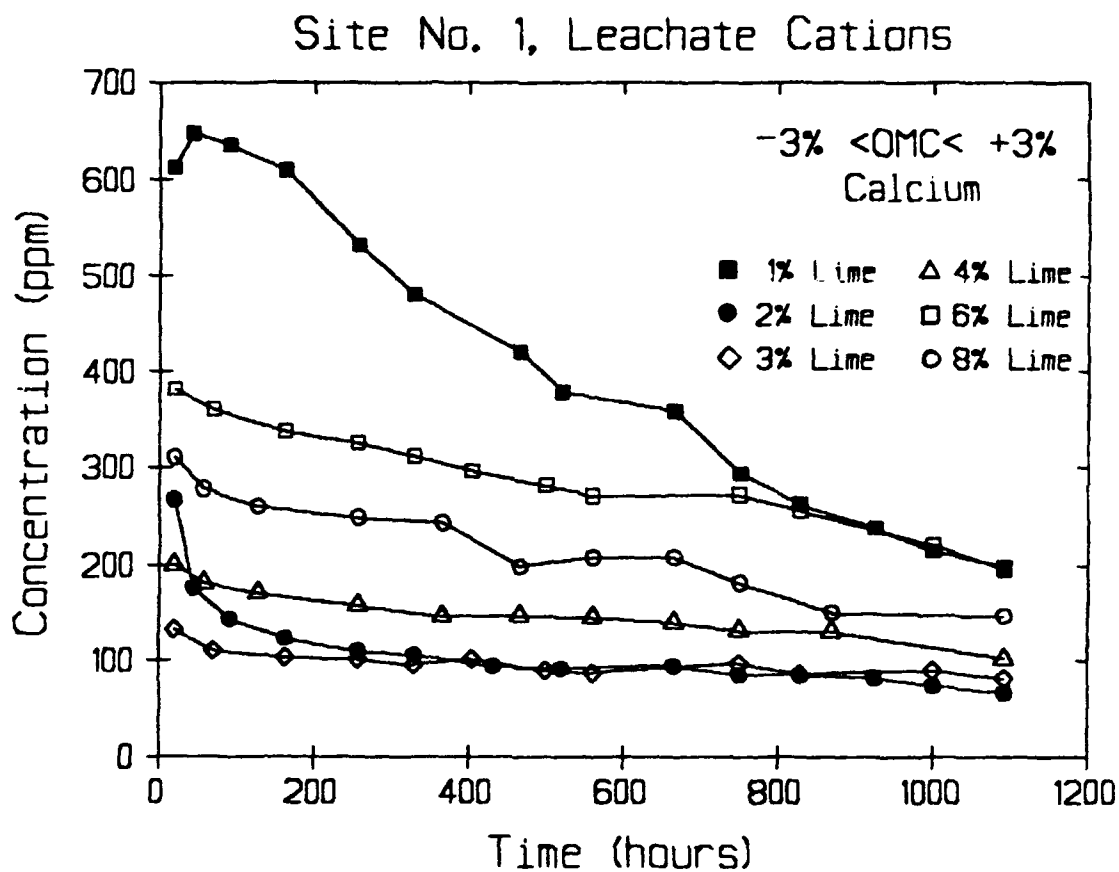
Figure 37. Calcium concentrations in Site No. 1
leachates during 45 days of leaching.
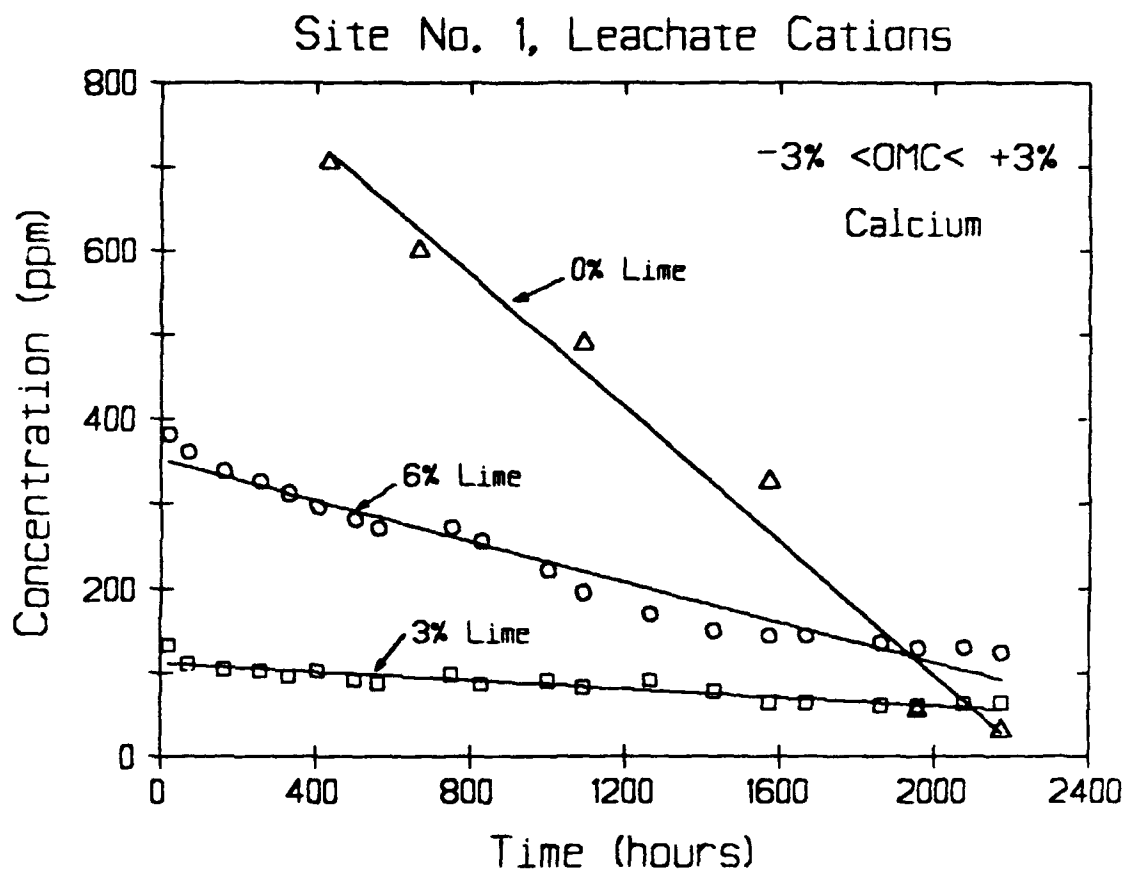
Figure 38. Calcium concentrations in Site No. 1
leachates during 90 days of leaching.
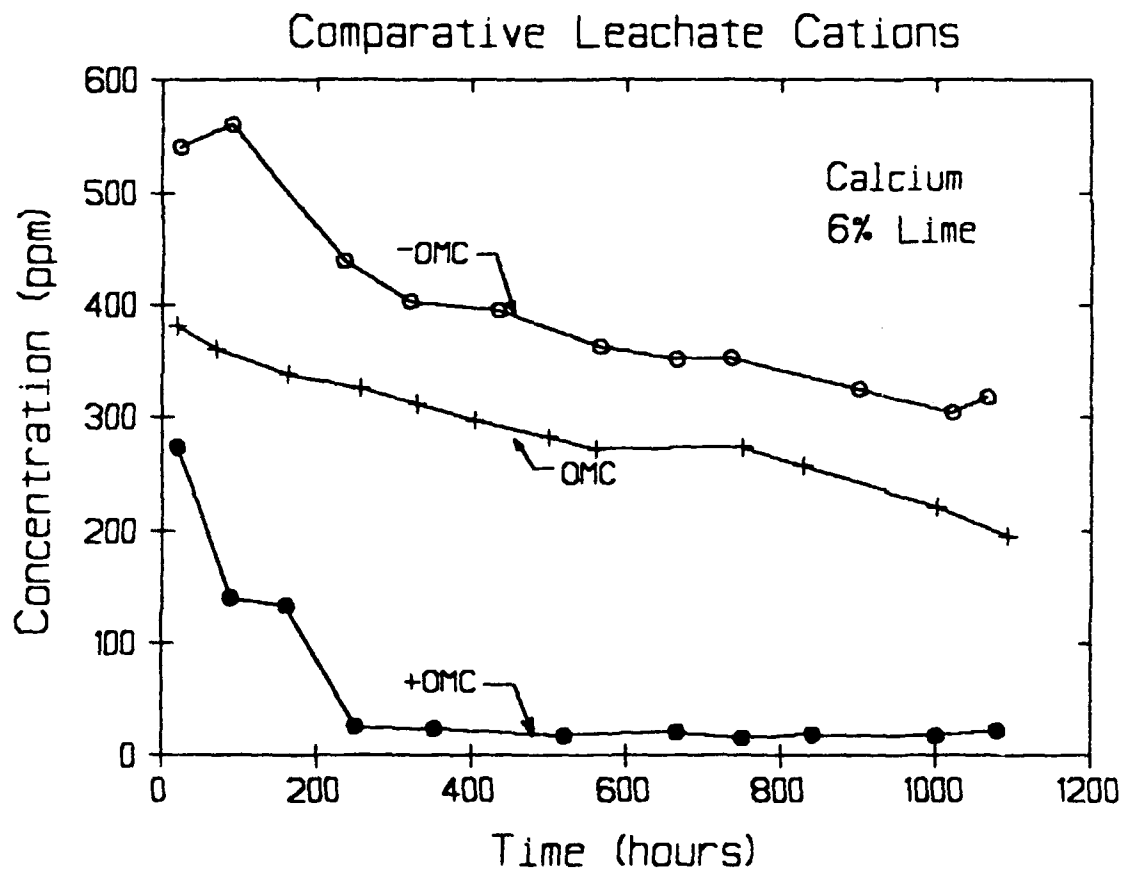
Figure 39. Typical data presentation for moisture content effects on calcium in Site No. 1 leachate at 6% lime.

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Figures C5 through C7 in Appendix C show the calcium concentrations for Site No. 1 samples compacted wet, dry and at optimum moisture for various lime contents.

143. *Minimum calcium concentrations* appear in samples treated with three percent lime and compacted wet or dry, and with six percent lime compacted wet (only after approximately 200 hours of leaching). As a general analysis, samples compacted wet of optimum (except for those with one percent lime), appear to have the lowest concentrations of calcium in their leachate. Additionally, the concentrations in those samples treated with three percent lime appear to change the least regardless of moisture conditions at time of compaction.

144. Figures 40 and 41 show the calcium concentrations in Site No. 2 leachates during 45 and 90 days of leaching, respectively. The highest concentration of calcium in the leachate occurred in samples with five and seven ercent lime. The least amount of calcium in the leachate would appear to occur in samples compacted with one percent lime. This follows the general trend in that the highest calcium "washout" occurred at lime contents greater than the LMO. From Figure 40, it can be seen that the difference between concentrations in samples with lime contents below the LMO and samples compacted above the LMO is considerable. Samples with five and seven percent lime contain two to four times as much calcium as three percent lime and below samples.

145. Figure 41 shows that some linearity exists for the calcium removal although it is not as linear as seen in the case of Site No. 1 material. This will be discussed more later.

146. Figures C8 through C11 in Appendix C show the comparison of various calcium removal in the leachates from *Site No. 2 samples compacted wet, dry and at optimum moisture.* Minimum calcium concentration removal appeared to be in samples compacted wet of optimum at lime contents of three, five or seven percent.

115
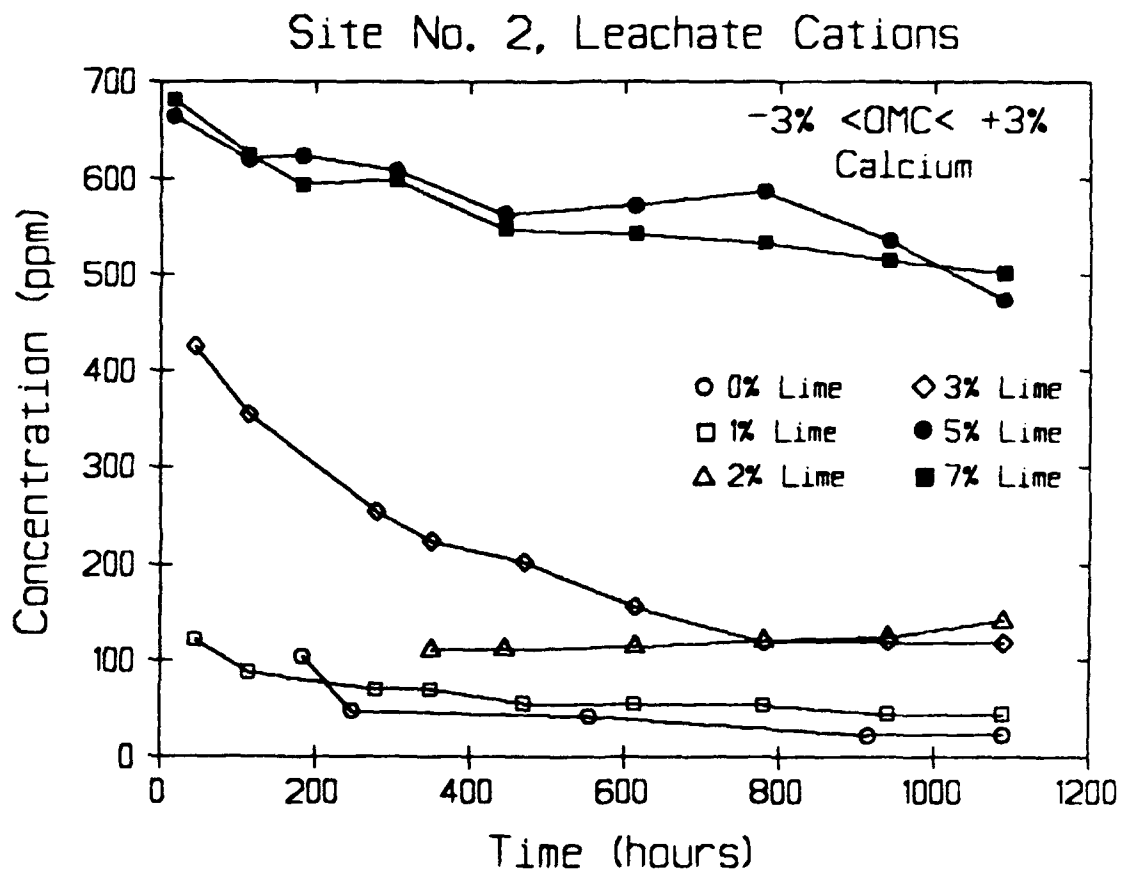
Figure 40. Calcium concentrations in Site No. 2 leachates during 45 days of leaching.
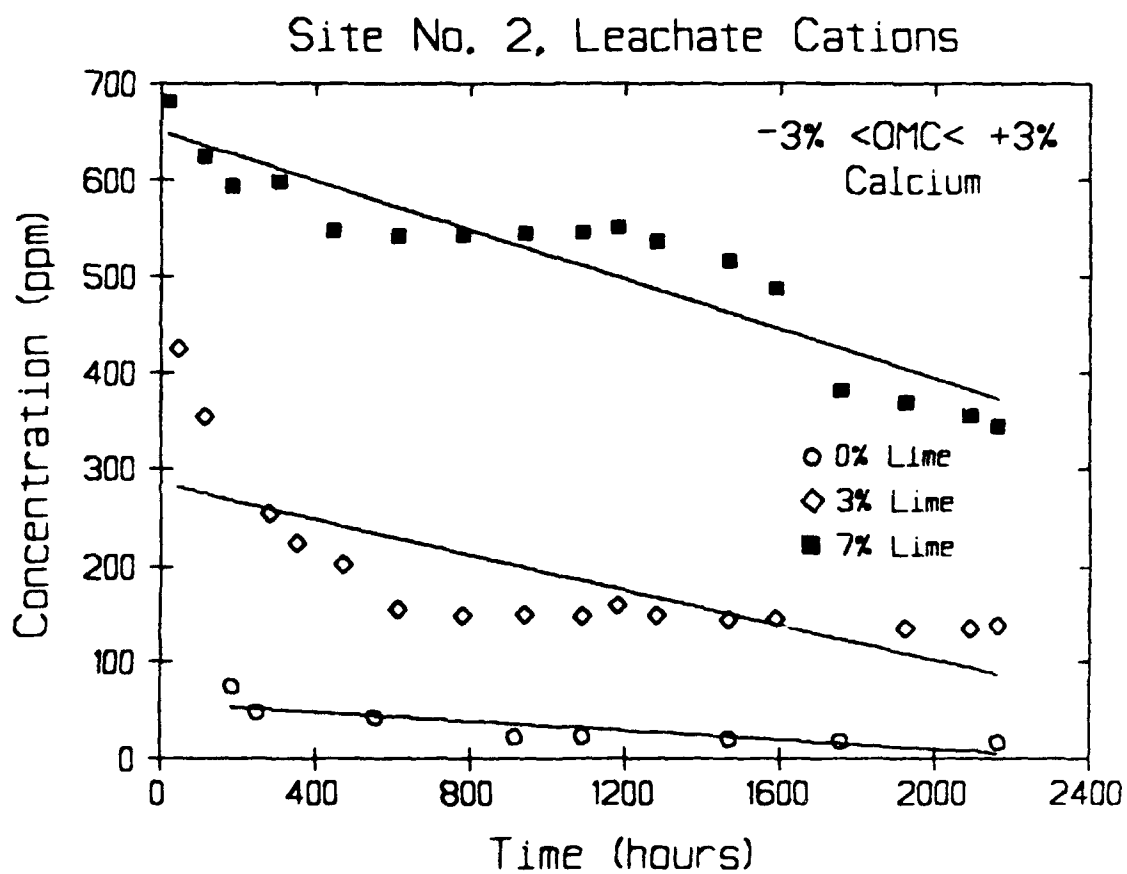
Figure 41. Calcium concentrations in Site No. 2
leachates during 90 days of leaching.

Maximum removal occurred in samples compacted at optimum moisture. As with Site No. 1, samples compacted with three percent lime appear to have relatively low calcium concentration conditions at all moisture contents, particularly after approximately 700 hours of leaching.

147. Calcium concentrations in Site No. 3 leachates for 45 and 90 day leach tests are shown in Figures 42 and 43, respectively. Figure 42 shows the highest concentration of calcium to have occurred in the leachate of samples treated with one percent lime, as with Site No. 1. The lowest concentrations occurred at very low lime contents (except for the one percent lime samples) and increased with increasing lime contents. Therefore, the lowest calcium removal occurred in samples compacted with two or three percent lime and the highest removal would most likely occur at lime contents of one percent or nine percent. Figure 43 also shows that the leachate calcium removal was relatively linear with time under constant flow pressure.

148. It was shown in Figure 27 that soils from Sites No. 1 and 3 have a naturally high calcium content in their porewater extractions. This is verified by Figures 38 and 43 which also show high calcium contents in their natural states. Site No. 2 soil displayed only a small concentration of calcium in its natural state. Additionally, calcium is more readily removed by leaching from Sites No. 1 and 3 soil in their natural state than it is from Site No. 2 soil. This may be because there were excess calcium cations present in the porewater before leaching began for soil from Sites No. 1 and 3 (see Figure 27). These cations would be diffused away from the clay's surface, thus allowing them to be more readily removed by excess water.

149. All soil sites tend to exhibit identical leachate properties during leaching. One possible explanation of the calcium leachate phenomena is that the addition of lime in the clay soil increases the calcium concentration which
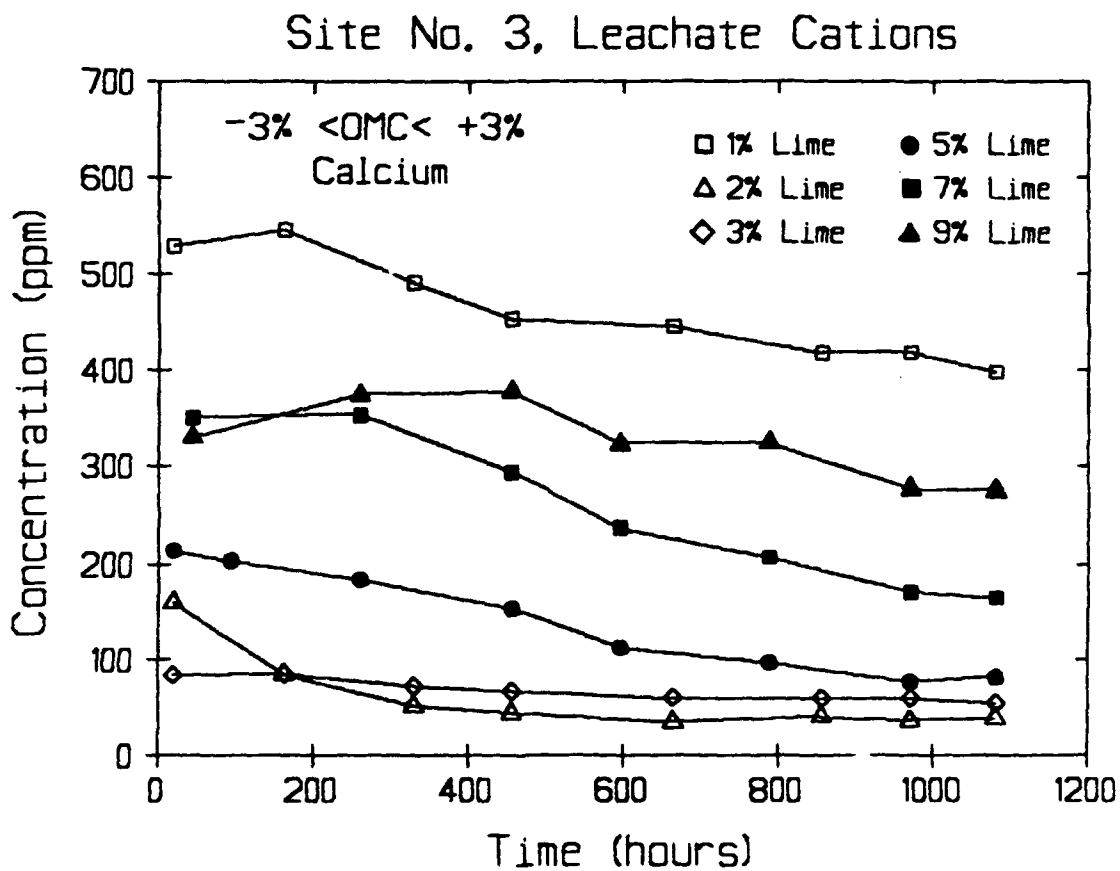
Figure 42. Calcium concentrations in Site No. 3
leachates during 45 days of leaching.
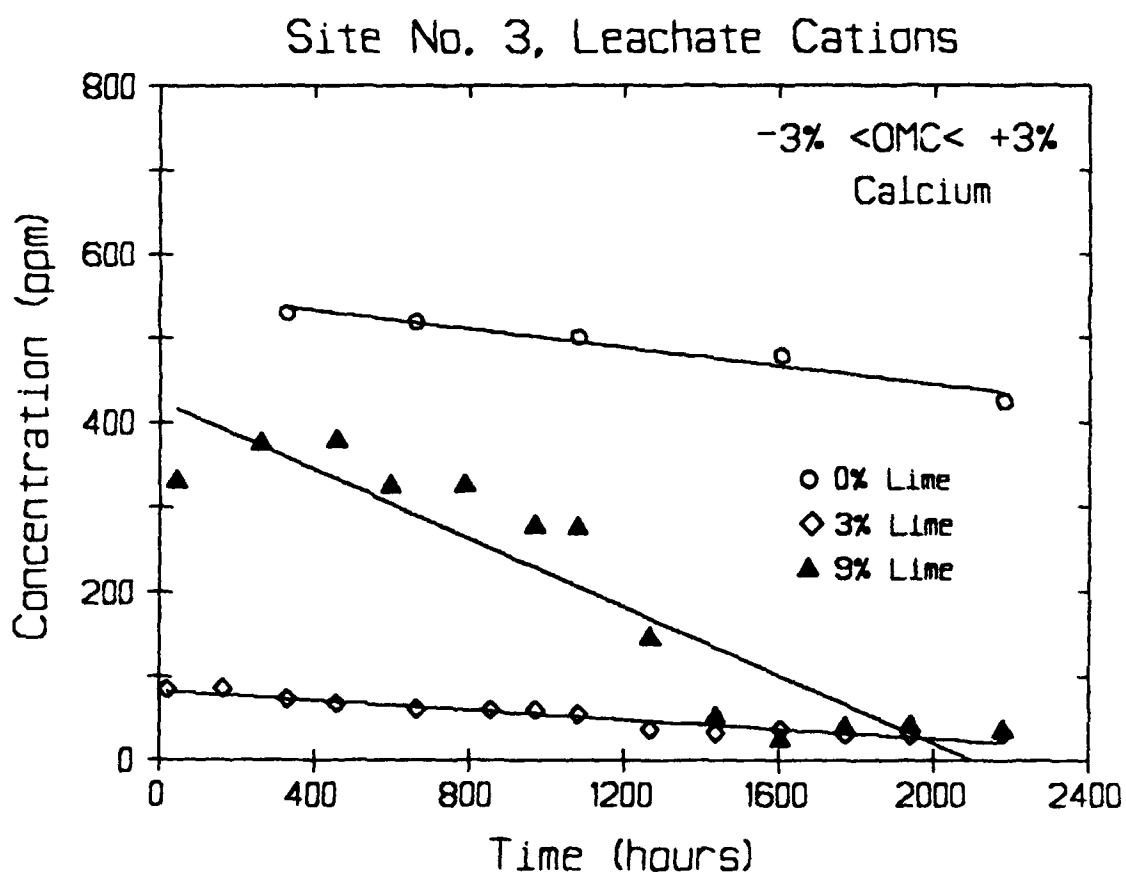
Figure 43. Calcium concentrations in Site No. 3 leachates during 90 days of leaching.

contributes to cation crowding along the clay surface and flocculation of the clay particles. These excess cations could be easily washed away except that with enough calcium, the pH is raised sufficiently that significant pozzolanic reactions start to occur, using up much of the calcium. At a certain lime content, the amount of calcium removed by leaching would be thereby minimized. This "balance" point appears to be at two or three percent lime or approximately the LMO for all three sites. Any additional lime may further the pozzolanic reaction and, in fact, does increase the strength properties (see Figure 26), but also increases the calcium leaching. What effect this has on the long-term stability of the soil must be considered in conjunction with permeability and internal soil-lime interaction.

150. Sodium Concentrations in the Leachate. The concentrations of sodium cations in the leachate for Site No. 1 tests are shown in Figures 44 and 45 for 45 and 90 days of leaching, respectively. Maximum concentration (and maximum decrease in concentration with leaching time) occurred in the samples treated with eight percent lime, and the minimum concentrations were found in those samples compacted with three and four percent lime.

151. Figures C12 through C15 in Appendix C show the effect of compaction moisture on the sodium concentration in Site No. 1 leachates for various lime contents. Minimum sodium removal occurred at samples compacted dry of optimum, and maximum sodium concentration in the leachate occurred in samples compacted wet. Three and four percent lime samples displayed the most non-moisture affected and uniformly lowest sodium concentration in the leachate for all ranges of compaction moisture.

152. Figures 46 and 47 show the sodium concentration in Site No. 2 leachate tests during 45 and 90 days of leaching, respectively. Minimum concentrations of sodium appear in the leachate of samples compacted with one and three percent lime
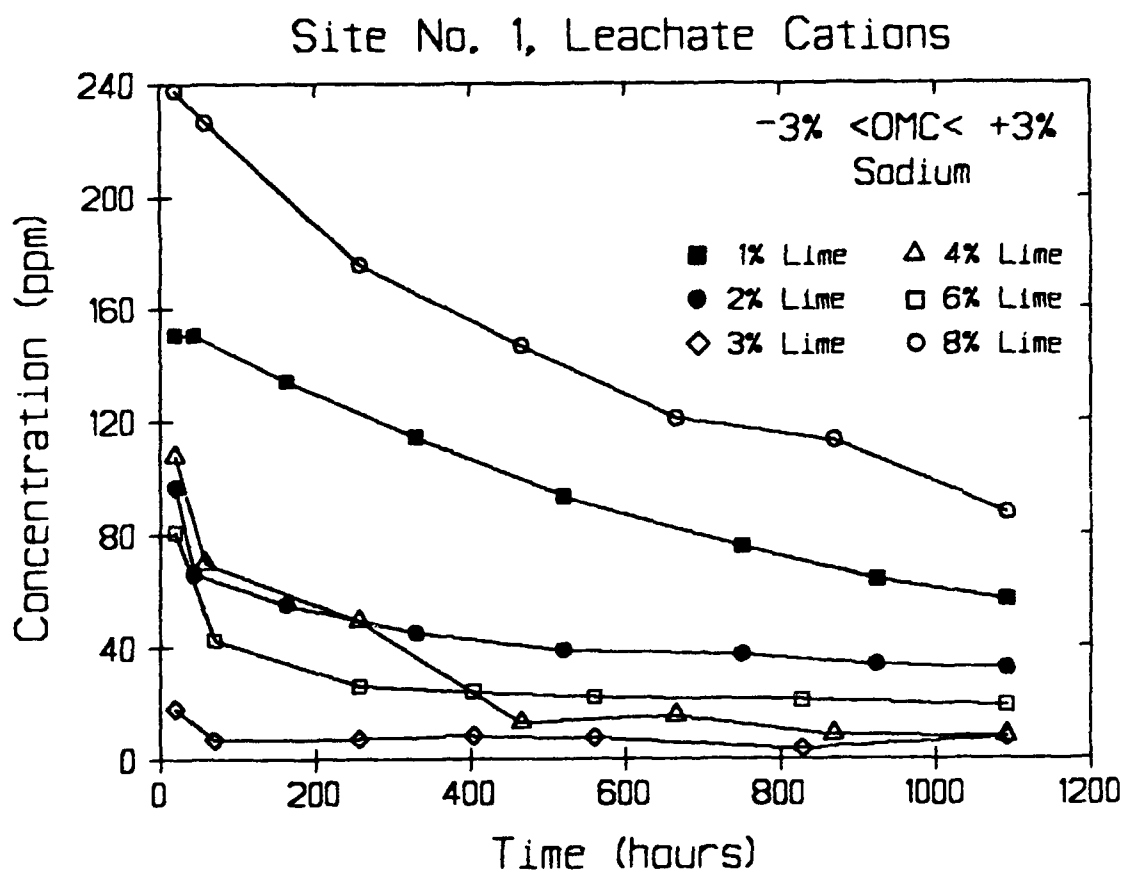
Figure 44. Sodium concentrations in Site No. 1
leachates during 45 days of leaching.
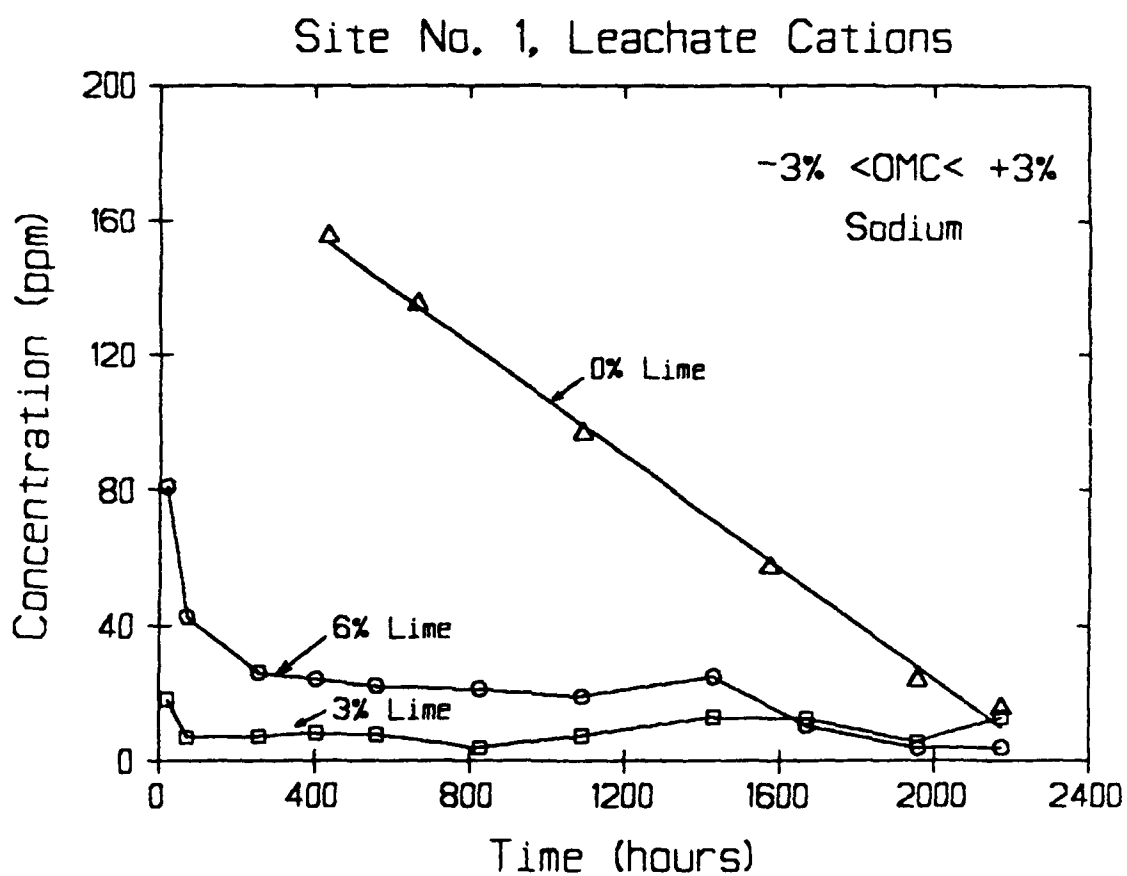
Figure 45. Sodium concentrations in Site No. 1 leachates during 90 days of leaching.

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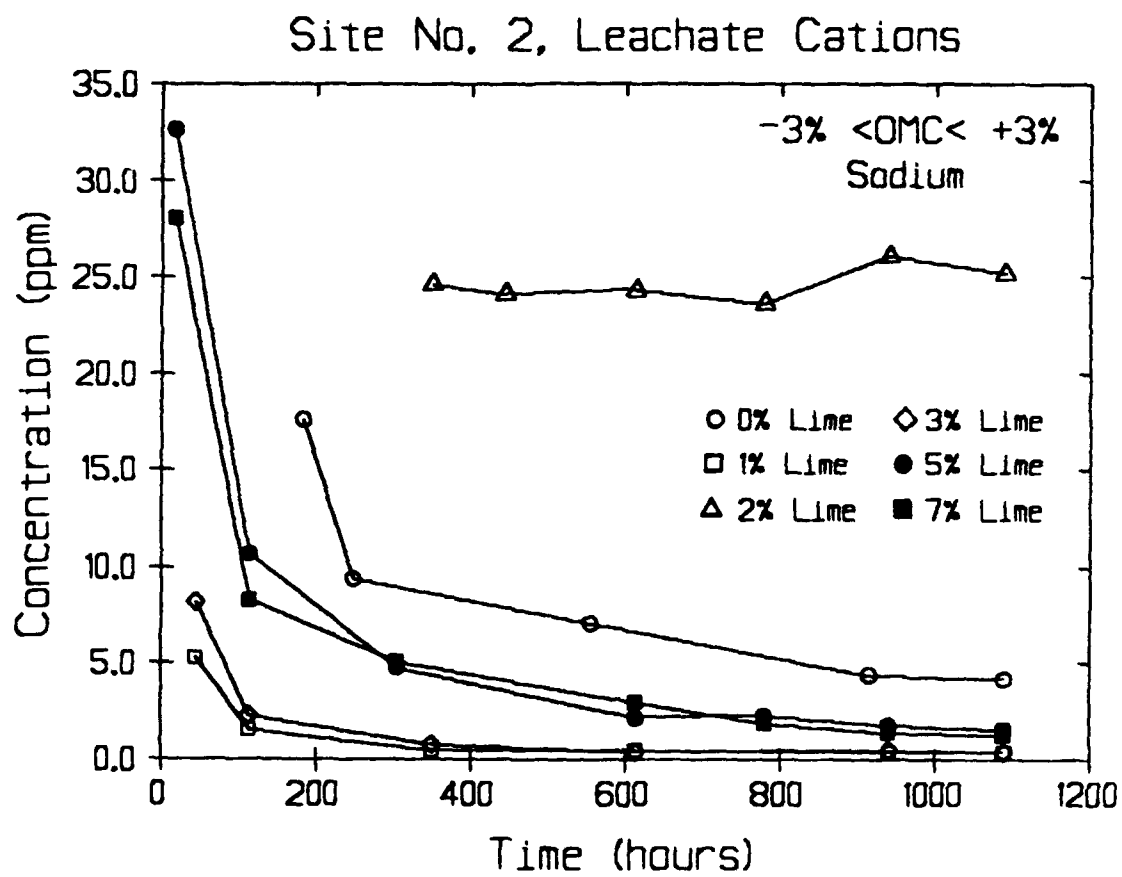
Figure 46. Sodium concentrations in Site No. 2 leachates during 45 days of leaching.
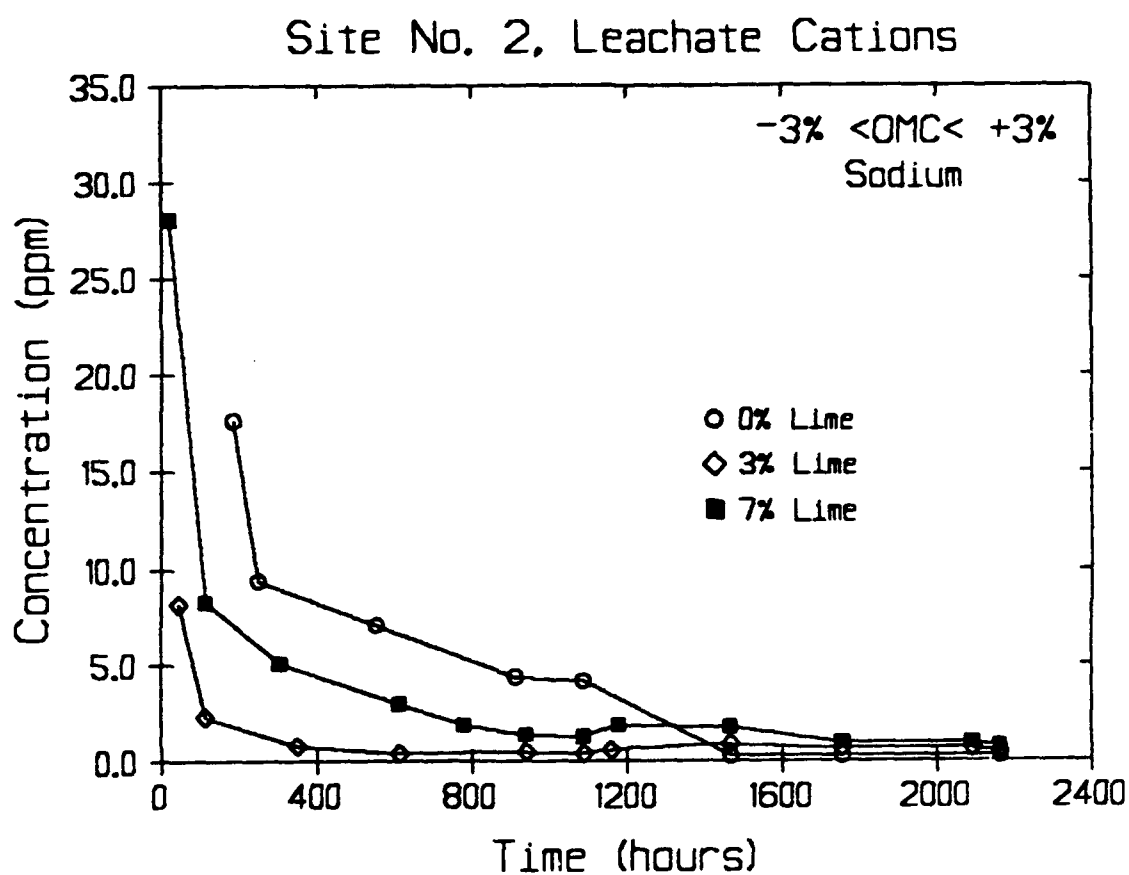
Figure 47. Sodium concentrations in Site No. 2
leachates during 90 days of leaching.

while maximum concentrations are present in two percent lime samples. All samples, except those treated with two percent lime, showed rapid decreases in sodium concentration in the leachate with continuous leaching, particularly at the higher lime contents.

153. The effects of compaction moisture on sodium removal in Site No. 2 leachates are shown in Figures C16 through C19 in Appendix C. Samples compacted wet of optimum displayed much larger concentrations of sodium in the leachate than was present in samples compacted dry or at optimum moisture content. Samples compacted wet tended to have sodium leachate concentra-tions that increased with leaching. This could possibly be as a result of the extremely low permeability of samples compacted wet of optimum, thereby causing longer periods of time required to collect the leachate, thus allowing some plating of sodium on the collectors.

154. Figure 48 and 49 show the sodium concentration in leachate from Site No. 3 leach tests during 45 and 90 days of leaching, respectively. As with Sites No. 1 and 2, sodium concentration in the leachate rapidly decreased with time for all lime contents, with the minimum amount of sodium lost occurring in samples compacted with three percent lime. Maximum leachate sodium concentrations occurred in samples treated with one percent lime.

155. Figures 45, 47 and 49 show that all three soils contain a large concentration of sodium in their natural condition (the zero percent lime curves). Natural leachate sodium concentrations for Site No. 3 were extremely high, containing approximately 2000 ppm at the start of the leach cycle. However, with each soil site, the sodium content rapidly decreased in concentration with continuous leaching.
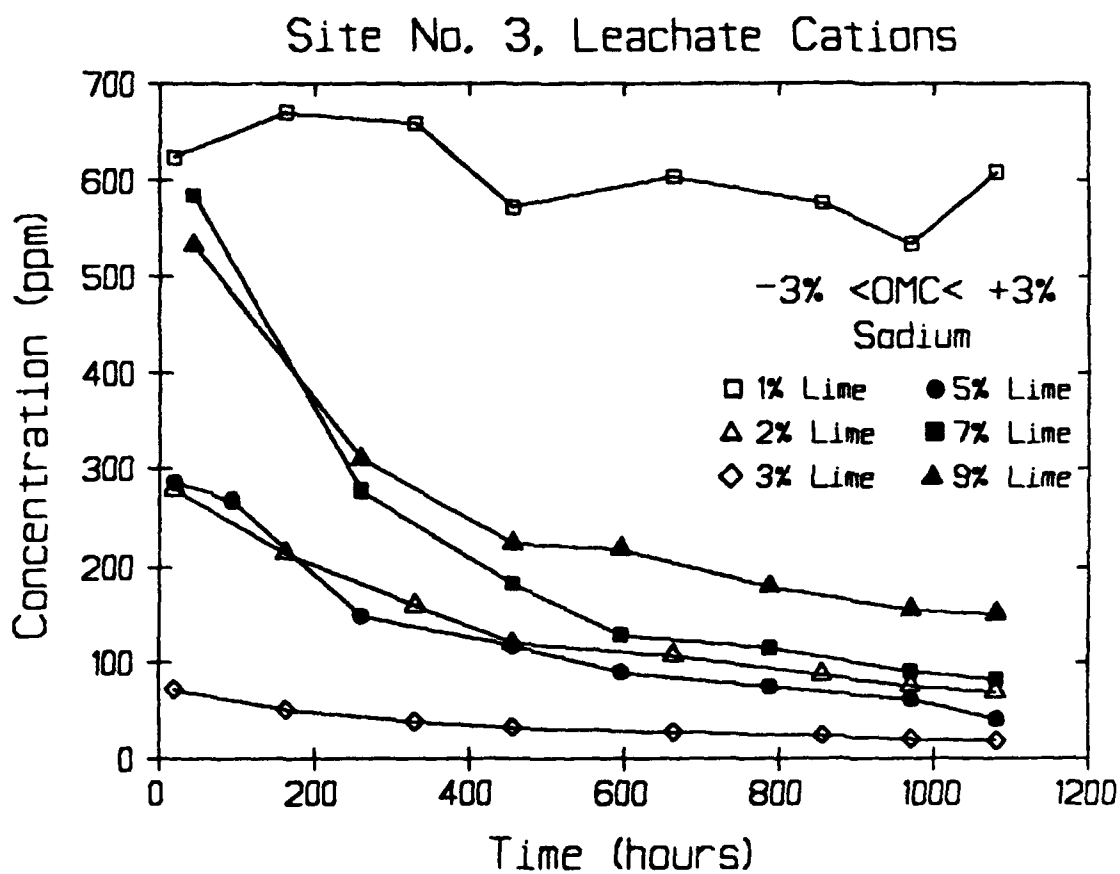
Figure 48. Sodium concentrations in Site No. 3
leachates during 45 days of leaching.

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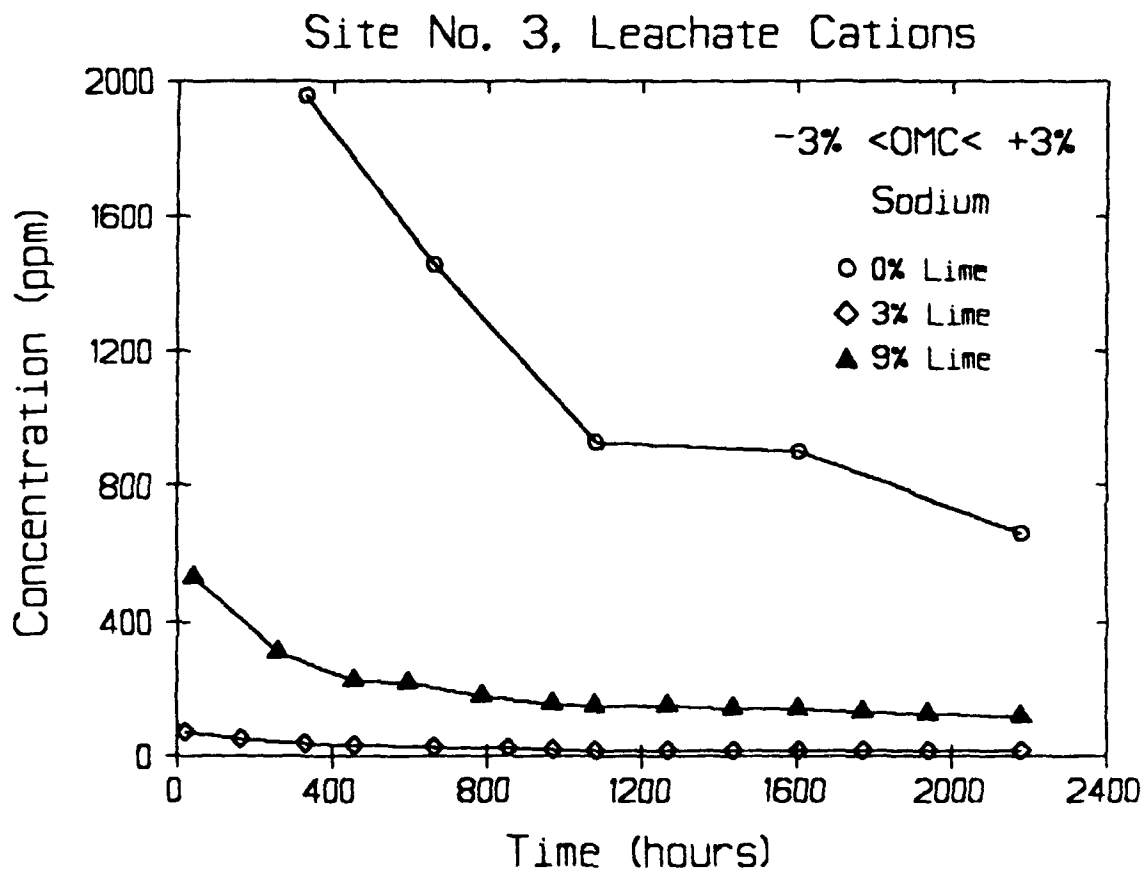
Figure 49. Sodium concentrations in Site No. 3 leachates during 90 days of leaching.

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156. In all soils, the minimum concentration of sodium in the leachate appeared at lime contents of two to four percent lime, i.e., approximately the LMO. Maximum washout of sodium occurred at generally very low lime contents, one or two percent, or very high lime contents, eight or nine percent lime. This may be directly related to permeability as will be discussed later.

157. Potassium Concentrations in the Leachate. Figures 50 and 51 show the potassium concentrations in the leachate for Site No. 1 leach tests. The minimum potassium concentrations appeared in the samples treated with three percent lime with the maximum concentration in those treated with eight percent for samples compacted at optimum moisture. At lime contents above three percent, increases in lime directly increased the potassium in the leachate. Comparisons of +OMC, OMC and -OMC for Site No. 1 samples show no pattern or relationship for minimum or maximum potassium concentration in the leachate (Figures C20 through C23 in Appendix C).

158. Site No. 2 leachate potassium concentrations are shown in Figures 52 and 53 for 45 and 90 day leach tests, respectively. The lowest concentrations of potassium occurred in samples made with one and three percent lime, while maximum concentrations occurred in samples with five and seven percent lime.

159. Figures C24 through C27 in Appendix C show that, generally, Site No. 2 samples compacted dry of optimum had the least amount of potassium in their leachate, whereas samples compacted wet had the highest concentrations. Samples compacted wet of optimum also tended to have increased concentrations during the leach cycle. All other samples showed a gradual decrease in leachate potassium during leaching.

160. Figures 54 and 55 show the leachate potassium concentrations for Site No. 3 tests during 45 and 90 days of leaching, respectively. Minimum concentrations in the leachate occurred in samples compacted with two and three
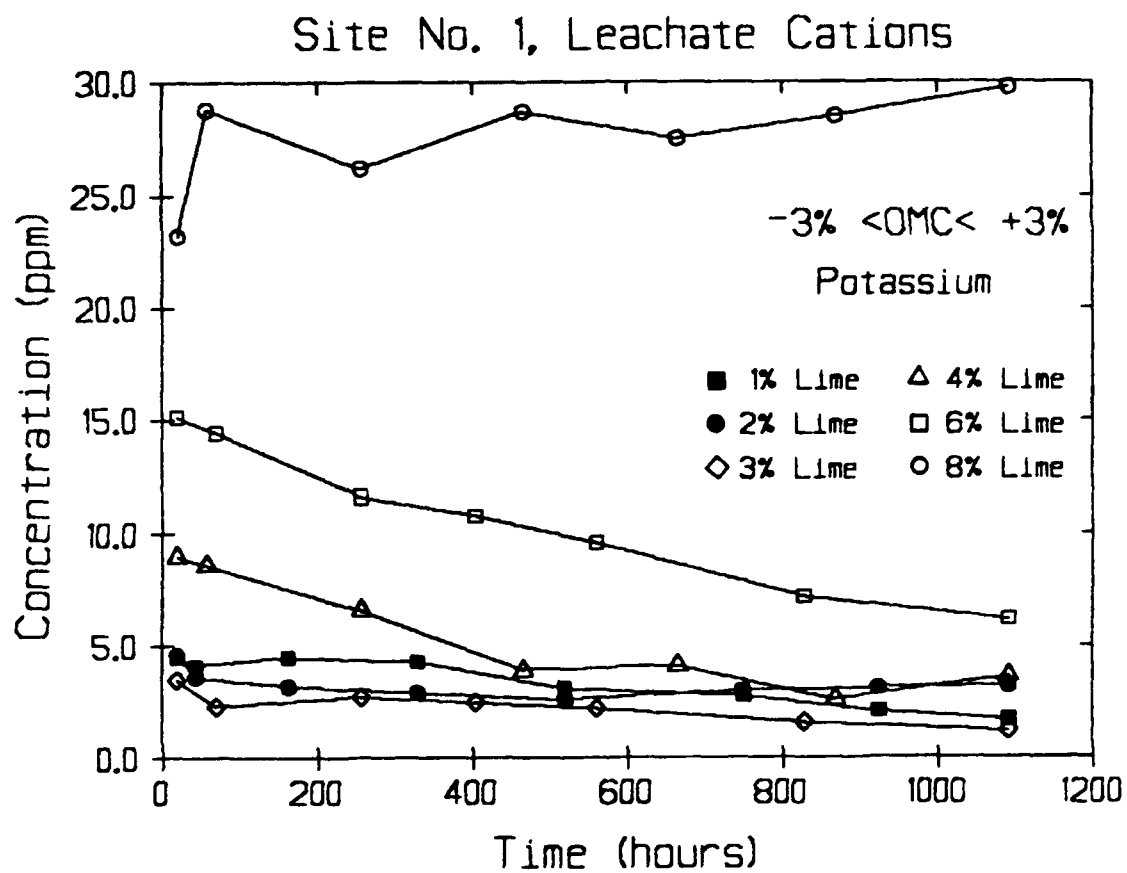
Figure 50. Potassium concentrations in Site No. 1 leachates during 45 days of leaching.
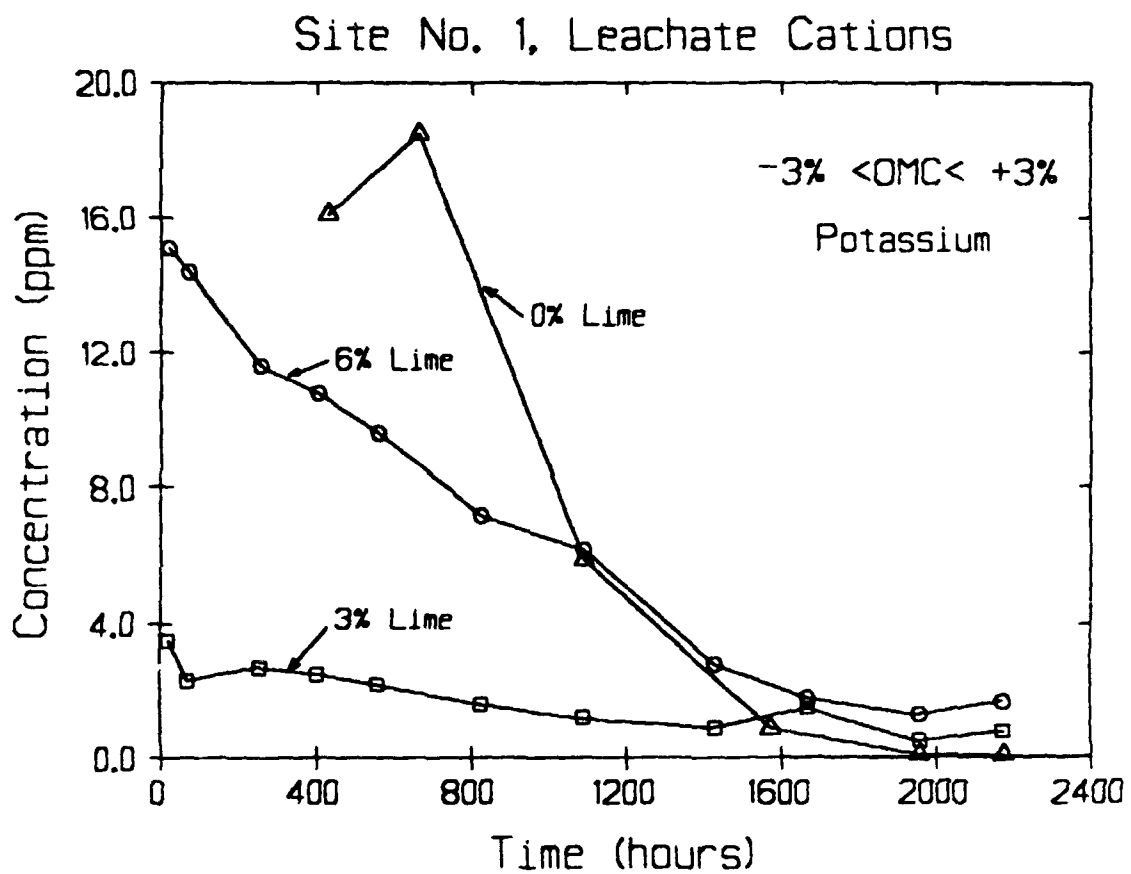
Figure 51.   Potassium concentrations in Site No. 1
leachates during 90 days of leaching.
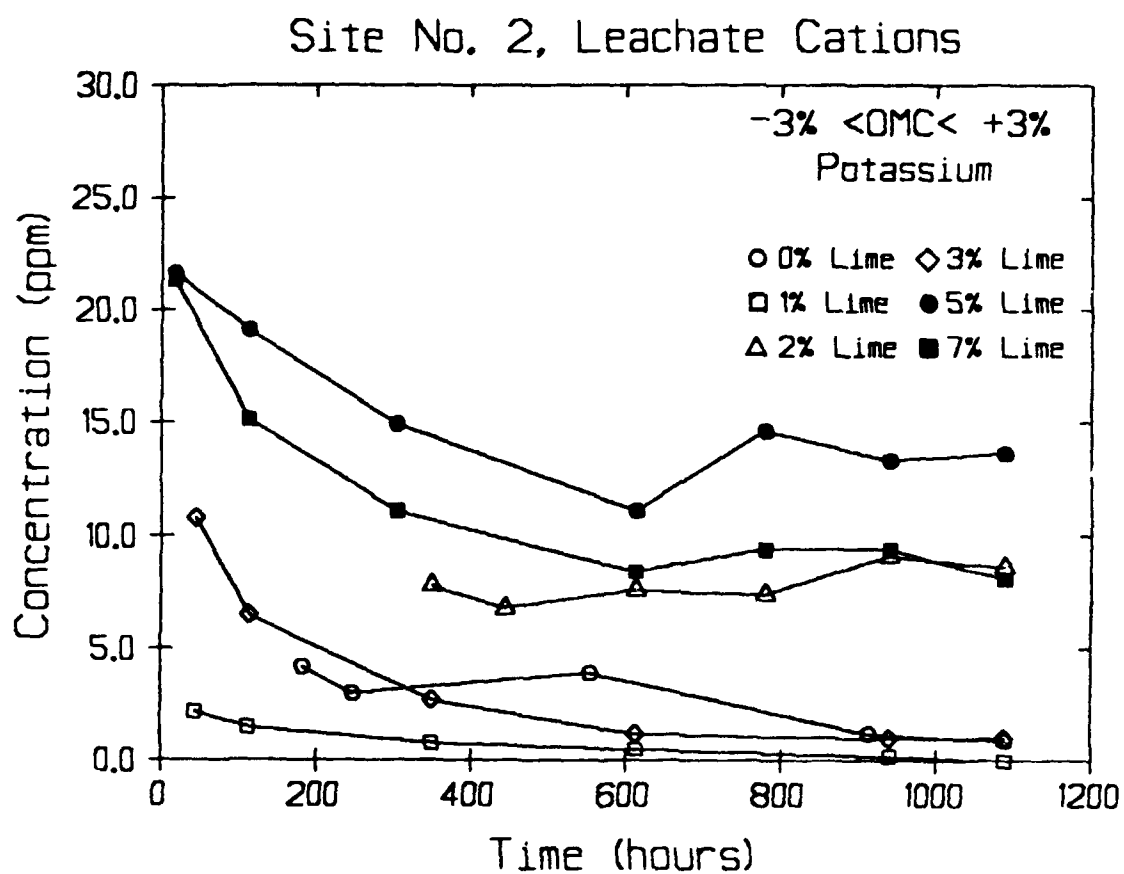
Figure 52.   Potassium concentrations in Site No. 2
leachates during 45 days of leaching.
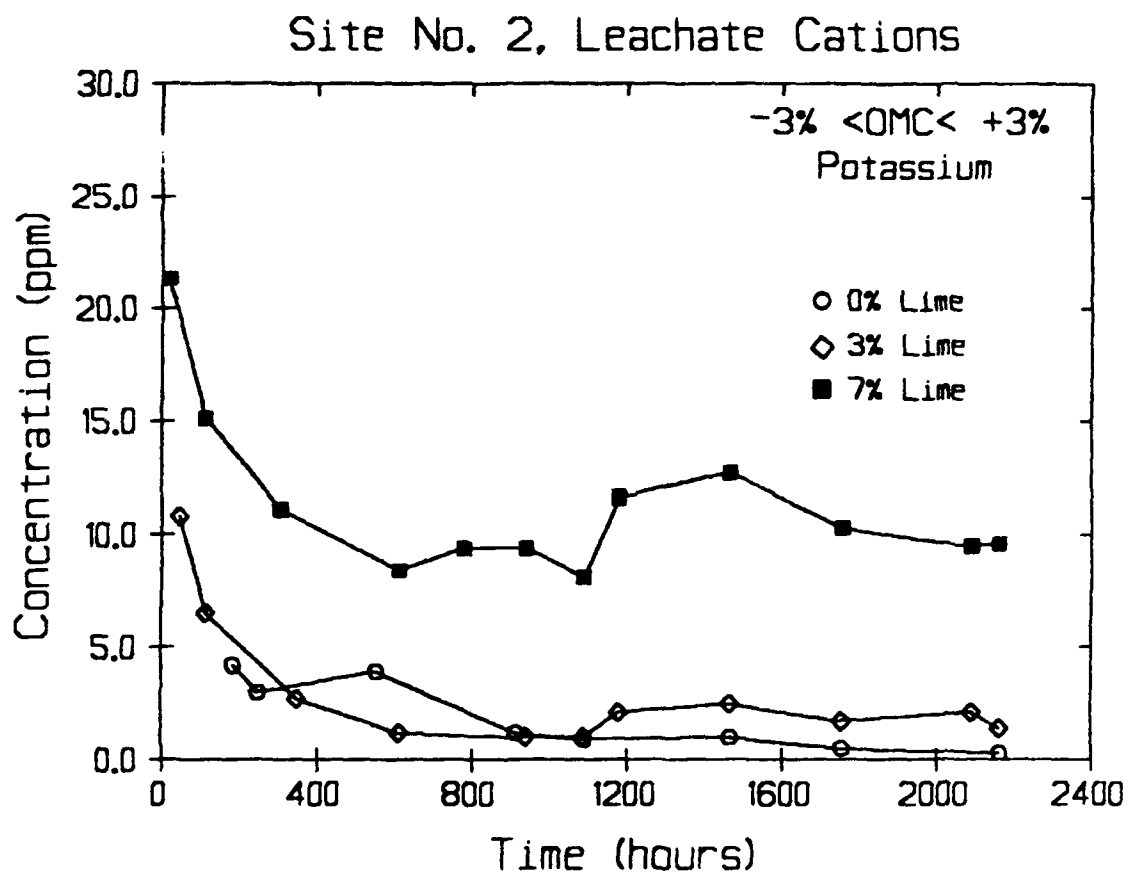
Figure 53. Potassium concentrations in Site No. 2 leachates during 90 days of leaching.
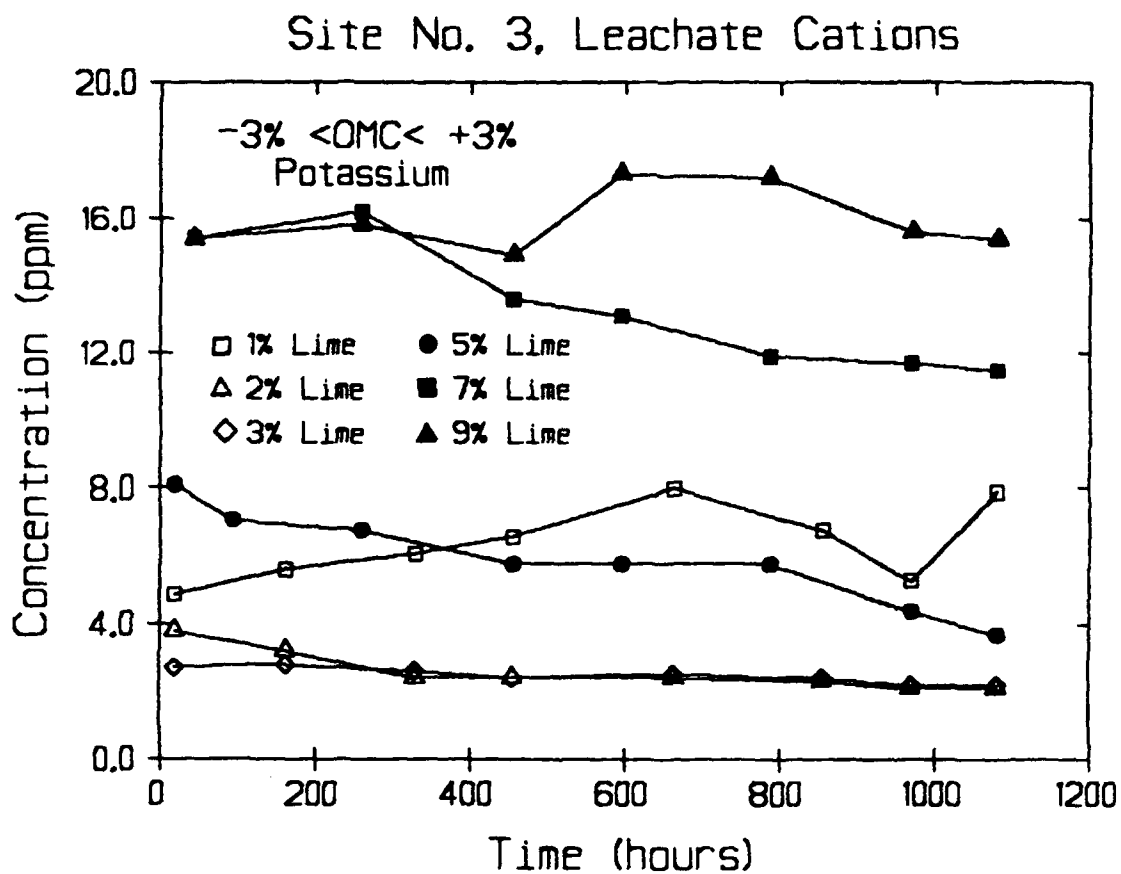
Figure 54. Potassium concentrations in Site No. 3 leachates during 45 days of leaching.
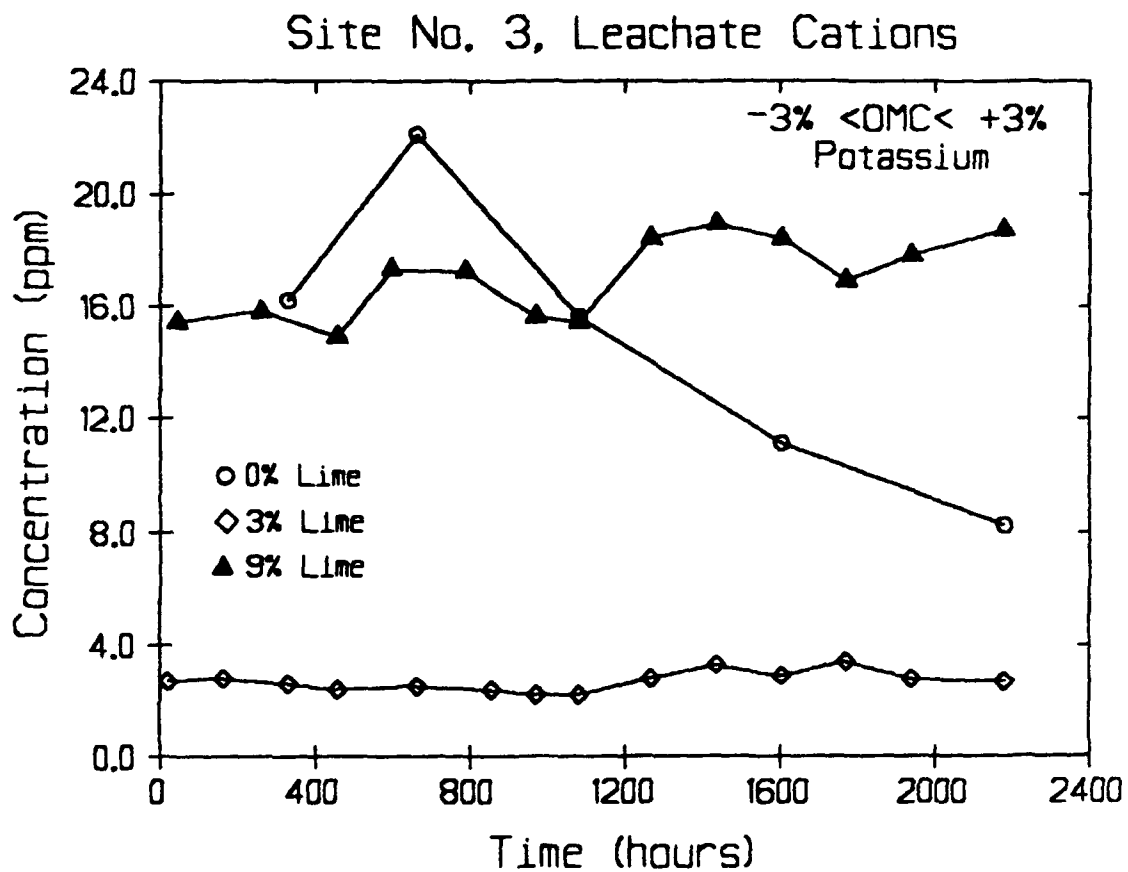
Figure 55. Potassium concentrations in Site No. 3
leachates during 90 days of leaching.

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percent lime and maximum concentrations were in samples with nine percent lime. All leachate concentrations tended to decrease with leach time, except for the samples mixed with nine percent lime which showed a slight increase with time.

161. The soils from all sites displayed identical trends in potassium washout. All three soils showed that minimum potassium concentrations occurred at a lime content of three percent (approximately the LMO). Maximum concentrations were at lime contents of eight and nine percent. All soils showed a general decrease in potassium concentration with leaching.

162. Natural soils from Sites No. 1 and 3 showed relatively high concentrations of potassium that were rapidly reduced with leaching. Site No. 2 soil showed a low potassium concentration in the leachate for the natural soil.

163. Magnesium Concentrations in the Leachate. Only trace amounts (less than 0.7 ppm) of magnesium were found in all leachate samples. Therefore, analyses of magnesium in the leachates are omitted.

164. Linear Regression Analysis. It was noted that most of the leachate cation concentrations in the 90 day leach tests followed fairly linear patterns of decreasing concentrations with time. Site No. 1 leachate displayed the highest degree of linearity while Site No. 2 leachate displayed the lowest. Linear regression analyses of the data for the 90 day leached samples compacted at optimum moisture are presented in Table 9. Particularly good linearity exists for calcium concentrations and for all cations leached out of the natural soil. As previously viewed, Figure 38 shows a typical linear plot for Site No. 1 calcium concentrations in the leachate during 90 days of leaching.

165. The general trend found for all three sites was that at lime contents approximately equal to their respective LMO, minimum amounts of all cations are present in the leachate. In most instances, this was in samples with three percent

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TABLE 9

LINEAR REGRESSION ANALYSIS OF LEACHATE
(-3% < OMC < +3%)

Site No.	Cation	Lime Content (%)	Intercept, A[*]	Slope, B	Correlation Coefficient, r
1	Calcium	0	887.8	- 0.38	-0.99
		3	111.9	-2.54×10^{-2}	-0.92
		6	351.5	-0.12	-0.98
	Sodium	0	188.9	-8.15×10^{-2}	-0.99
		3	9.2	2.74×10^{-4}	0.55
		6	45.7	-2.11×10^{-2}	-0.76
	Potassium	0	21.4	-1.10×10^{-2}	-0.93
		3	2.8	-1.09×10^{-3}	-0.91
		6	13.7	-6.56×10^{-3}	-0.97
2	Calcium	0	58.5	-2.39×10^{-2}	-0.84
		3	284.9	-8.95×10^{-2}	-0.75
		7	651.2	-0.13	-0.93
	Sodium	0	13.1	-7.27×10^{-3}	-0.87
		3	3.25	-1.66×10^{-3}	-0.54
		7	11.57	-6.67×10^{-3}	-0.62
	Potassium	0	3.92	-1.95×10^{-3}	-0.88
		3	5.68	-2.50×10^{-3}	-0.62
		7	14.2	-2.72×10^{-3}	-0.53
3	Calcium	0	555.3	-5.48×10^{-2}	-0.98
		3	83.3	-2.80×10^{-2}	-0.96
		9	425.1	-0.20	-0.92
	Sodium	0	1941.4	-0.65	-0.92
		3	48.6	-1.90×10^{-2}	-0.81
		9	348.9	-0.14	-0.79
	Potassium	0	21.7	-6.03×10^{-3}	-0.84
		3	2.47	2.13×10^{-4}	0.41
		9	15.3	1.52×10^{-3}	0.71

[*] General equation is PPM = A + (B x hours)

lime. For samples with no lime or very low lime contents (e.g., one percent), and samples with very high lime contents (e.g., seven, eight or nine percent), the maximum amount of cation concentrations occurred in the leachate.

166. These phenomena seem to indicate that at very low lime contents, the cations in the clay porewater exist in a greatly diffused state or are weakly attached to the clay mineral. These cations can be easily removed by leaching. At very large concentrations of lime, sodium and potassium appear to be replaced by calcium, yet there is now excess calcium in the porewater. These cations are also easy to remove by leaching. For samples with lime contents at approximately the LMO (three or four percent), calcium is replacing some monovalent cations and some bonding to the clay minerals is occurring. However, since the sodium and potassium ions in the leachate are now fewer than they were at lower lime contents, they must still be in the clay structure, possibly even aiding the calcium in flocculation/agglomeration of the soil.

167. Of course, permeability will be the primary factor in determining the amount of cation washed from a lime treated soil over a given time. This will be discussed in the next section.

Leach Tests—Physical Property Changes

168. The results of physical and engineering analyses of before leaching and after leaching test data are compiled and presented in Table 10 for Site No. 1 leach test samples, Table 11 for Site No. 2 leach test samples, and in Table 12 for Site No. 3 leach test samples. Tables 10, 11 and 12 contain the results from samples compacted at optimum moisture content before leaching testing. Tabulation of results for samples compacted wet of optimum and dry of optimum from Sites No. 1 and 2 are presented in Appendix D (Tables D1 through D4). All data is presented

TABLE 10

SITE NO. 1, PHYSICAL PROPERTY CHANGES
(-3% < OMC < +3%)

Physical Property	0% Lime			1% Lime		2% Lime		3% Lime			4% Lime		6% Lime			8% Lime	
	B*	A45	A90	B	A45	B	A45	B	A45	B90	B	A45	B	A45	A90	B	A45
Dry Unit Weight (pcf)	98.0	--	--	89.6	--	88.5	--	86.3	--	--	85.0	--	84.2	--	--	86.5	--
Percent Max. Weight (%)	94.7	--	--	92.8	--	95.2	--	95.0	--	--	96.0	--	96.2	--	--	100.0	--
Moisture Content (%)	22.2	31.3	33.0	26.1	31.7	26.5	35.3	28.6	37.3	34.3	29.8	39.9	28.4	36.4	39.6	30.3	35.3
Percent OMC (%)	-0.3	+8.8	+10.5	+0.6	+6.2	0	+8.8	+0.6	+9.3	+6.3	+1.3	+11.4	-0.1	+6.9	+10.1	+0.8	+5.8
Degree of Saturation (%)	81.3	+100.0	+100.0	78.4	95.2	77.9	95.2	79.2	97.9	97.5	80.5	+100.0	76.3	95.1	96.3	85.2	99.0
Liquid Limit (%)	63	--	--	62	62	62	55	60	55	54	56	53	59	51	52	59	52
Plastic Limit (%)	33	--	--	40	31	48	36	47	39	34	46	39	46	38	39	47	43
Plasticity Index (%)	30	--	--	22	31	14	19	13	16	20	10	14	13	13	13	12	9
Linear Shrinkage (%)	22.0	--	--	18.1	15.8	16.5	13.8	9.1	12.6	8.9	7.1	8.1	8.7	5.1	4.9	8.7	2.2
Trimmed Samples																	
Swell Pressure (psf)	977.4	--	--	389.2	434.5	301.2	334.0	197.6	271.7	274.8	197.0	279.2	154.1	304.1	179.2	141.1	202.1
Free Swell (%)	1.80	--	--	0.74	1.14	0.52	0.54	0.34	0.38	0.53	0.20	0.43	0.14	0.35	0.27	0.23	0.28
Shear Strength (ksf)	10.92	--	--	13.47	3.13	17.67	17.70	29.08	34.07	26.26	46.50	41.46	55.26	39.42	40.71	38.69	70.85
Failure Strain (%)	5.03	--	--	2.07	2.34	2.32	2.27	1.57	2.15	1.76	1.80	1.93	1.96	2.18	1.41	1.35	2.39
Reworked Samples																	
Swell Pressure (psf)	977.4	--	--	--	597.5	--	456.3	--	486.9	349.8	--	347.6	--	195.6	265.1	--	171.7
Free Swell (%)	1.80	--	--	--	1.67	--	0.90	--	0.99	0.87	--	0.65	--	0.38	0.54	--	0.19
Shear Strength (ksf)	10.92	--	--	12.32	10.97	11.10	11.49	9.71	10.23	11.10	6.01	10.73	5.40	8.03	9.04	14.30	5.74
Failure Strain (%)	5.03	--	--	2.46	2.70	2.36	2.04	2.16	1.82	1.53	3.60	1.42	1.66	1.17	0.99	1.38	1.22

* B = Before leaching; A45 = After 45 days leaching; A90 = After 90 days leaching

TABLE 11

SITE NO. 2, PHYSICAL PROPERTY CHANGES
(-3% < OMC < +3%)

Physical Property	0% Lime			1% Lime		2% Lime		3% Lime			5% Lime		7% Lime		
	B*	A45	A90	B	A45	B	A45	B	A45	B90	B	A45	B	A45	A90
Dry Unit Weight (pcf)	103.4	--	--	89.1	--	92.9	--	90.1	--	--	90.3	--	88.9	--	--
Percent Max. Weight (%)	102.4	--	--	91.4	--	98.3	--	95.3	--	--	96.1	--	94.9	--	--
Moisture Content (%)	21.8	25.2	26.0	25.5	31.9	26.8	30.4	24.8	35.0	33.4	26.3	32.7	26.5	33.5	32.5
Percent OMC (%)	-0.7	+2.7	+3.5	+1.5	+7.9	+0.8	+4.4	-1.7	+8.5	+6.9	-0.7	+5.7	-1.0	+6.0	+5.0
Degree of Saturation (%)	75.6	+100.0	+100.0	71.2	89.0	88.5	+100.0	76.4	+100.0	+100.0	81.5	+100.0	79.4	94.0	97.6
Liquid Limit (%)	60	--	--	49	47	48	49	45	45	45	48	44	47	40	47
Plastic Limit (%)	27	--	--	33	25	32	30	32	31	31	34	32	34	30	35
Plasticity Index (%)	33	--	--	16	22	16	19	13	16	14	14	12	13	10	12
Linear Shrinkage (%)	17.7	--	--	5.9	11.9	4.7	11.4	3.1	8.5	5.6	5.5	6.1	5.5	3.3	2.4
Trimmed Samples															
Swell Pressure (psf)	1104.7	--	--	458.4	393.2	315.0	271.6	301.3	208.6	249.9	258.5	1269.4	232.4	202.1	189.0
Free Swell (%)	3.21	--	--	1.82	0.37	0.30	0.20	0.17	0.18	0.18	0.17	0.16	0.11	0.19	0.13
Shear Strength (ksf)	10.04	--	--	16.12	12.42	24.68	23.49	25.47	28.88	30.20	26.51	30.50	27.41	30.73	32.01
Failure Strain (%)	3.78	--	--	1.08	1.84	1.44	2.48	1.17	1.84	1.83	1.32	2.15	1.51	2.00	1.73
Reworked Samples															
Swell Pressure (psf)	1104.7	--	--	--	462.7	--	388.9	--	319.4	406.3	--	375.8	--	258.6	219.4
Free Swell (%)	3.21	--	--	--	1.01	--	0.97	--	0.65	0.44	--	0.42	--	0.25	0.22
Shear Strength (ksf)	10.04	--	--	9.21	6.35	10.01	7.92	8.73	7.25	6.21	10.67	6.53	15.20	5.92	5.93
Failure Strain (%)	3.78	--	--	2.16	5.01	3.60	2.33	2.16	3.76	3.40	1.35	1.94	1.40	1.78	1.78

* B = Before leaching; A45 = After 45 days leaching; A90 = After 90 days leaching

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TABLE 12

SITE NO. 3, PHYSICAL PROPERTY CHANGES
(-3% < OMC < +3%)

Physical Property	0% Lime			1% Lime		2% Lime		3% Lime			5% Lime		7% Lime		9% Lime		
	B*	A45	A90	B	A45	B	A45	B	A45	B90	B	A45	B	A45	B	A45	A90
Dry Unit Weight (pcf)	99.3	--	--	88.5	--	87.6	--	87.0	--	--	86.7	--	86.6	--	86.7	--	--
Percent Max. Weight (%)	99.3	--	--	90.4	--	92.2	--	92.5	--	--	95.2	--	95.6	--	96.3	--	--
Moisture Content (%)	25.1	29.5	35.0	28.0	35.7	29.2	33.5	26.9	38.2	38.7	27.7	41.3	27.3	38.8	28.5	39.9	43.3
Percent OMC (%)	+0.6	+5.0	+11.3	+3.0	+10.7	+1.7	+7.0	-0.6	+9.7	+11.2	-0.3	+13.3	-1.2	+10.3	0.0	+11.4	+14.8
Degree of Saturation (%)	77.2	+100.0	+100.0	85.5	+100.0	81.5	96.3	76.8	+100.0	+100.0	78.1	+100.0	78.2	+100.0	80.5	+100.0	+100.0
Liquid Limit (%)	76	--	--	70	66	61	71	56	66	57	57	54	53	51	55	54	55
Plastic Limit (%)	31	--	--	38	36	45	35	45	35	40	45	39	42	45	43	44	44
Plasticity Index (%)	45	--	--	32	30	16	36	11	31	17	12	15	11	6	12	10	11
Linear Shrinkage (%)	24.4	--	--	14.9	17.6	7.9	19.6	4.7	17.7	10.2	3.9	6.6	3.9	3.7	2.4	3.7	4.7
Trimmed Samples																	
Swell Pressure (psf)	2117.9	--	--	1179.6	962.5	662.6	853.7	588.7	892.8	871.1	362.8	491.7	306.3	401.3	301.9	341.1	280.3
Free Swell (%)	11.97	--	--	3.10	4.03	1.57	1.89	0.50	2.20	1.14	0.19	0.39	0.19	0.46	0.19	0.29	0.28
Shear Strength (ksf)	9.24	--	--	11.09	13.89	16.72	9.78	27.79	12.83	14.96	43.45	24.11	36.40	33.07	38.43	38.05	40.66
Failure Strain (%)	3.22	--	--	1.81	2.18	1.35	2.46	1.43	1.65	1.67	1.38	2.31	1.68	2.14	1.16	1.65	2.47
Reworked Samples																	
Swell Pressure (psf)	2117.9	--	--	--	1640.1	--	1335.9	--	1116.6	840.6	--	825.5	--	480.1	--	377.6	315.0
Free Swell (%)	11.97	--	--	--	5.77	--	5.78	--	4.75	2.85	--	0.97	--	0.56	--	0.44	0.36
Shear Strength (ksf)	9.24	--	--	5.78	8.43	5.68	8.13	6.65	8.23	15.75	7.92	9.11	8.22	9.44	5.93	12.82	8.22
Failure Strain (%)	3.22	--	--	3.22	2.33	3.22	2.69	2.86	3.14	1.98	2.86	1.77	3.04	1.67	2.50	1.98	1.52

* B = Before leaching; A45 = After 45 days leaching; A90 = After 90 days leaching

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graphically to show relationships between before and after leach data, and the influence, if any, of the initial compacted moisture content.

Permeability

169. <u>Site No. 1 Permeability</u>. The permeability of all samples increased significantly with the addition of lime, regardless of the moisture content at compaction (Figures 56 and 57). Natural permeability of Site No. 1 clay averaged 5.26×10^{-9} cm/sec. The addition of lime increased the range of permeabilities from approximately 1.35×10^{-7} cm/sec (27 fold increase) for eight percent lime to approximately 1.80×10^{-6} cm/sec (342 fold increase) for three percent lime (average permeabilities after 600 hours of leaching for samples compacted at optimum moisture). For samples compacted at optimum moisture, the order of permeability increases (from smallest increase to largest increase after 600 hours of leaching) occurred in samples compacted with eight, one, two, four, six and three percent lime, respectively.

170. Figure 58 is a typical graph showing comparisons of permeabilities for samples compacted wet, dry and at optimum moisture. The remaining graphs for showing permeability comparisons at various moisture contents are shown in Appendix E. These graphs are for Sites No. 1 and 2 only, as Site No. 3 was tested only at optimum moisture. Figures E1 through E5 in Appendix E show the permeabilities of wet, dry and optimum moisture samples for Site No. 1.

171. Minimum permeabilities occurred in all samples compacted wet of optimum. Those samples treated with one percent lime showed permeabilities close to the natural material. Maximum permeabilities occurred in samples compacted dry of optimum, except for those with six percent lime where approximately equal permeabilities were noted for OMC and -OMC samples. Maximum permeabilities,
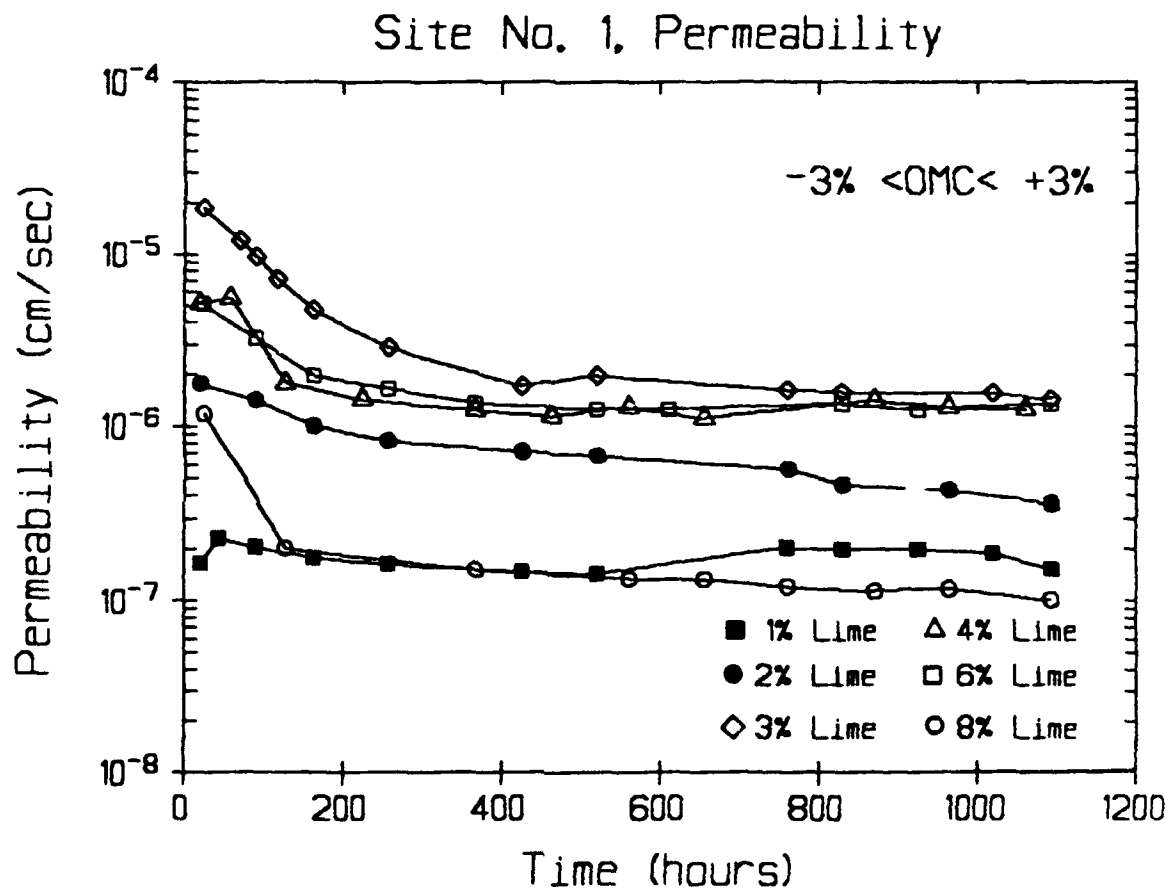
Figure 56.   Permeability changes for Site No. 1
samples during 45 days of leaching.
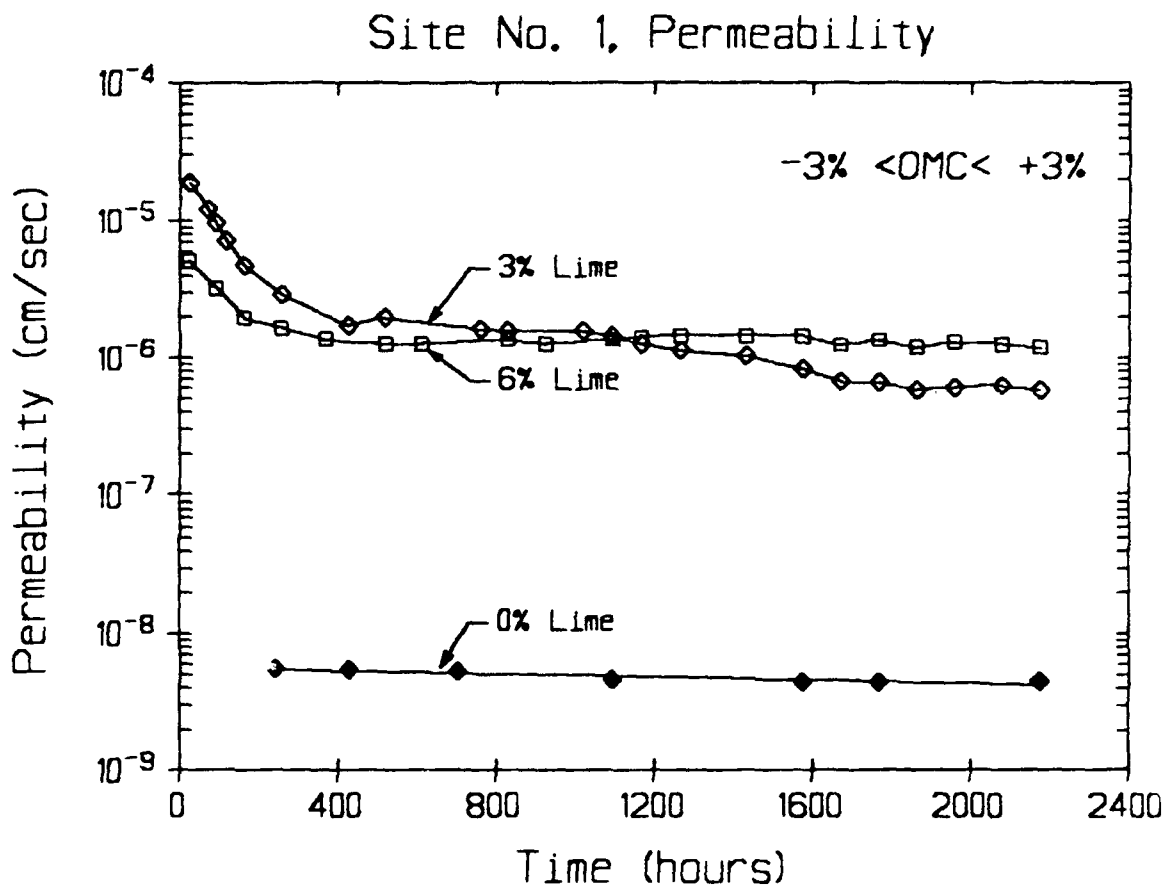
Figure 57. Permeability changes for Site No. 1
samples during 90 days of leaching.

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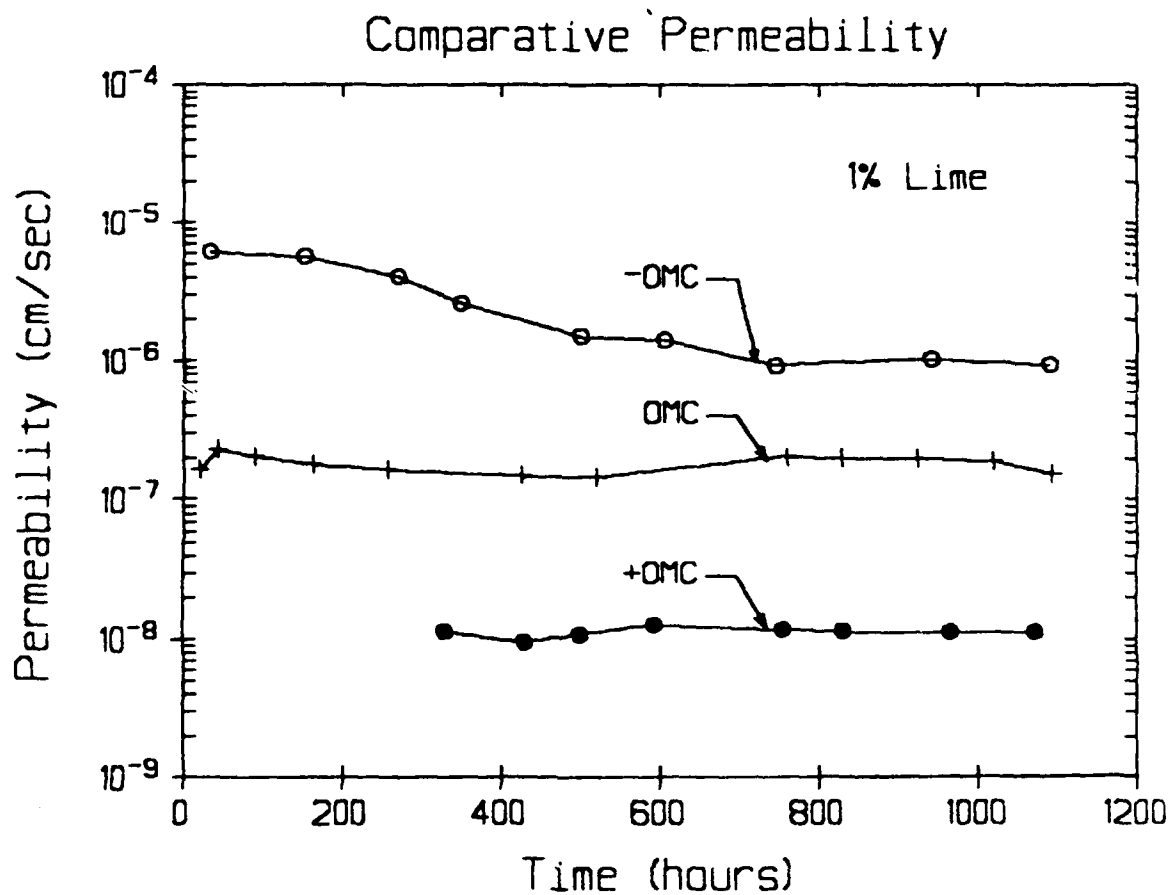
Figure 58. Typical graphical presentation of permeabilities showing moisture content effects on Site No. 1 material using 1% lime.

whether dry or wet, still occurred in samples made with three percent lime. Additionally, the same trend as seen in Figure 56 was established to show that very low or very high lime contents displayed minimum permeabilities, both for wet and dry samples.

172. <u>Site No. 2 Permeability</u>. Figures 59 and 60 show the permeabilities of Site No. 2 samples leached for 45 and 90 days, respectively, compacted at optimum moisture. As with Site No. 1 material, all samples displayed a gradual decrease in permeability with time. The natural material showed an average permeability of 2.30×10^{-8} cm/sec. With the addition of lime, permeabilities greatly increased with a minimum increase to 9.46×10^{-7} cm/sec (41 fold increase) for seven percent lime samples to a maximum increase to 3.16×10^{-6} cm/sec (137 fold increase) for three percent lime (average permeabilities after 600 hours of continuous leachings. Only at two percent lime was there a decrease in permeability, but it its believed that this was due to a partially clogged porous stones on one of the leached samples.

173. Figures E6 through E11 in Appendix E show the comparisons of permeabilities of Site No. 2 material compacted at various moisture and lime contents. These figures clearly show that samples compacted wet of optimum maintain the lowest permeabilities during leaching, while those compacted dry displayed the highest permeabilities, regardless of lime content. Figure E10 in Appendix E shows that three percent lime still caused the highest permeability for samples compacted dry. Samples compacted wet, however, tended to have similar permeabilities (approximately 1.50×10^{-8} cm/sec) for all lime contents tested.

174. <u>Site No. 3 Permeability</u>. Permeabilities are shown in Figures 61 and 62 for Site No. 3 test samples during 45 and 90 days of leaching, respectively. As with Sites No. 1 and 2, permeabilities increased with lime content and decreased with continuous leaching. The natural clay's permeability averaged 6.86×10^{-9} cm/sec
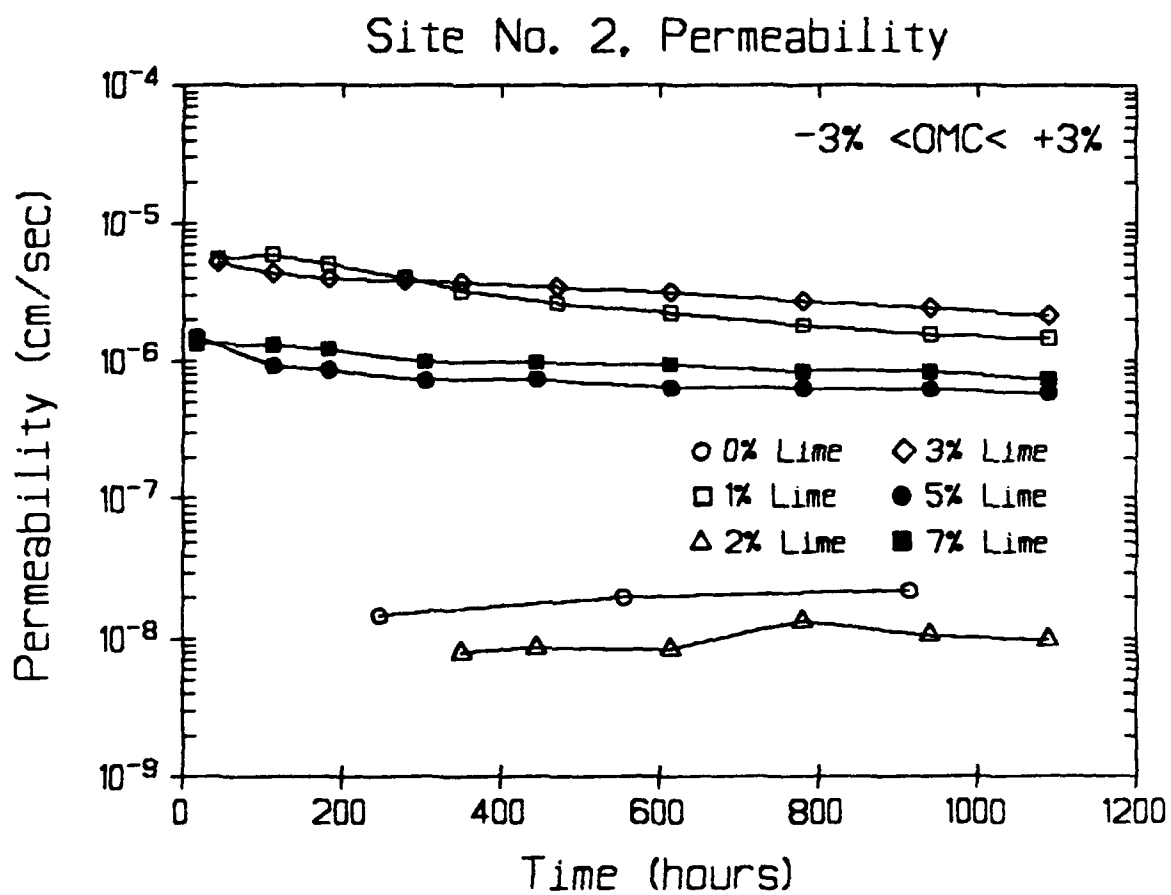
Figure 59.   Permeability changes for Site No. 2
samples during 45 days of leaching.
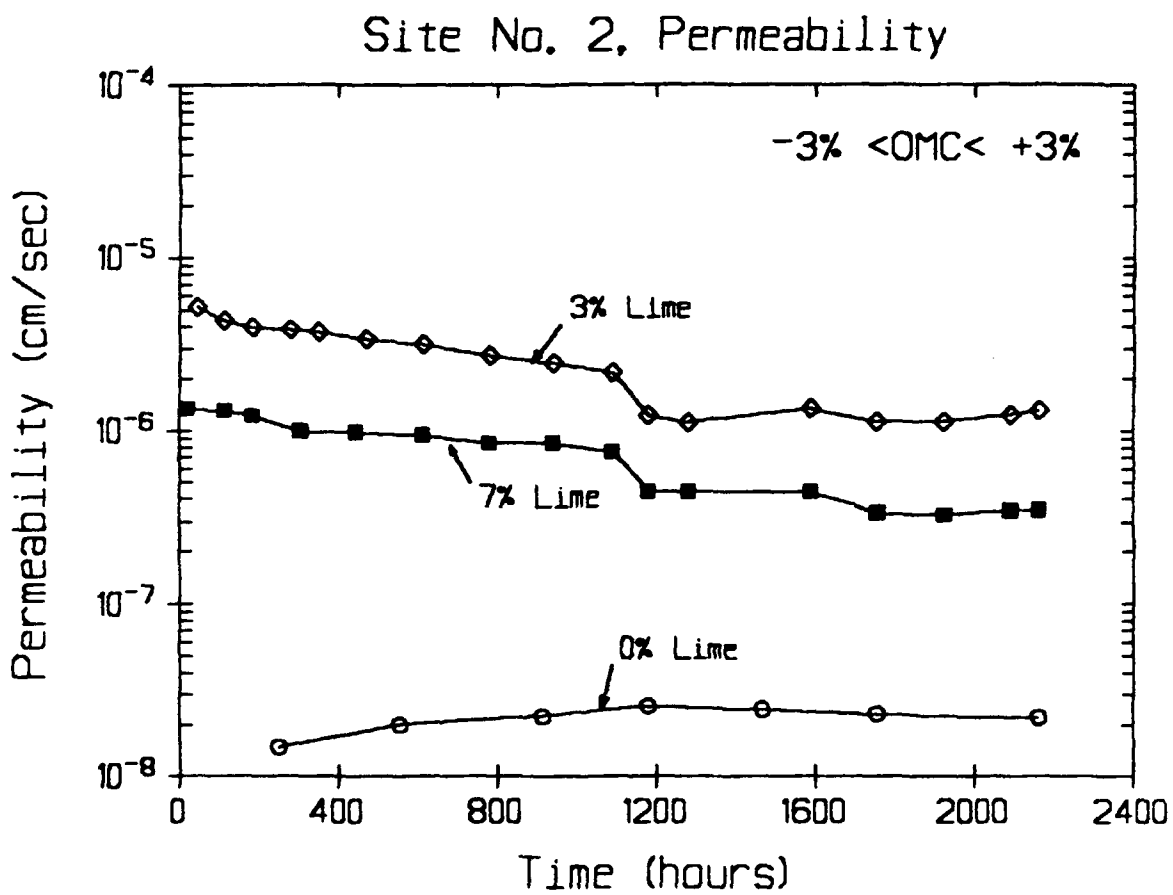
Figure 60. Permeability changes for Site No. 2
samples during 90 days of leaching.
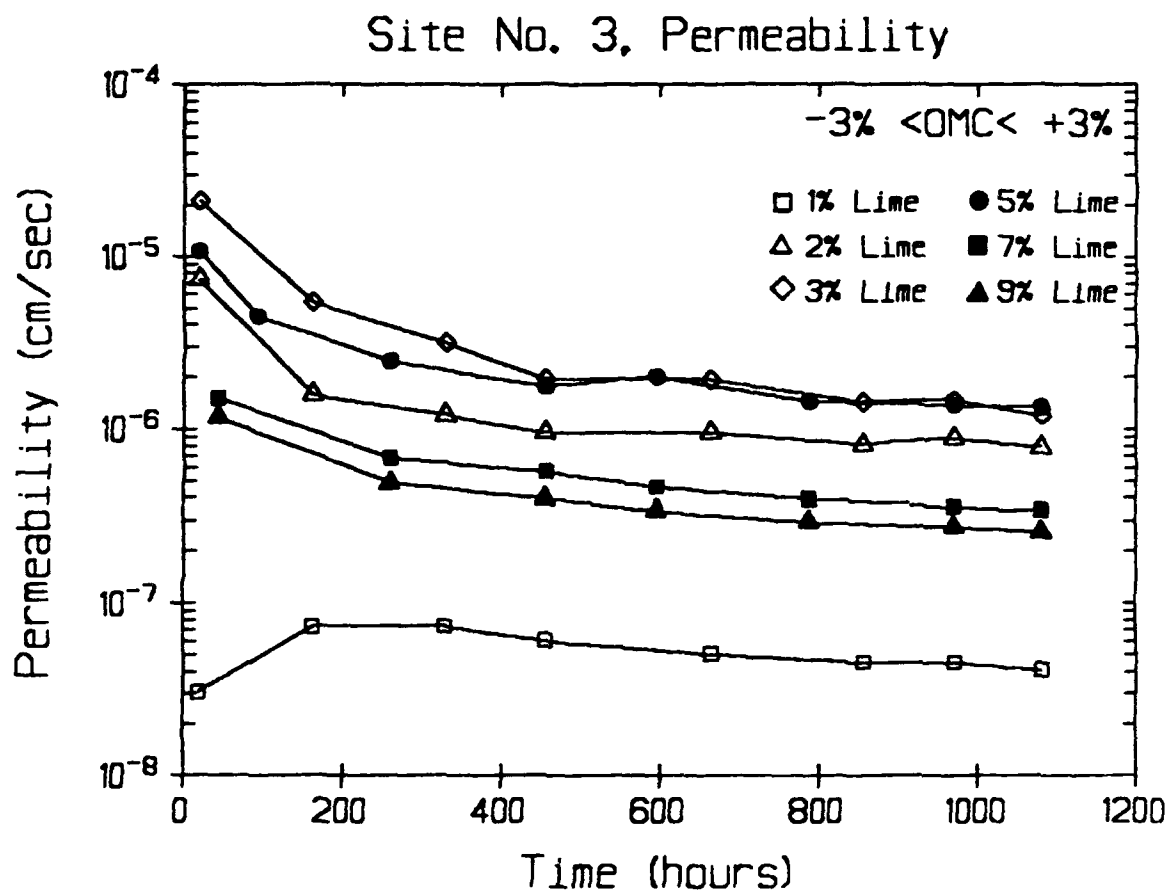
Figure 61. Permeability changes for Site No. 3 samples during 45 days of leaching.
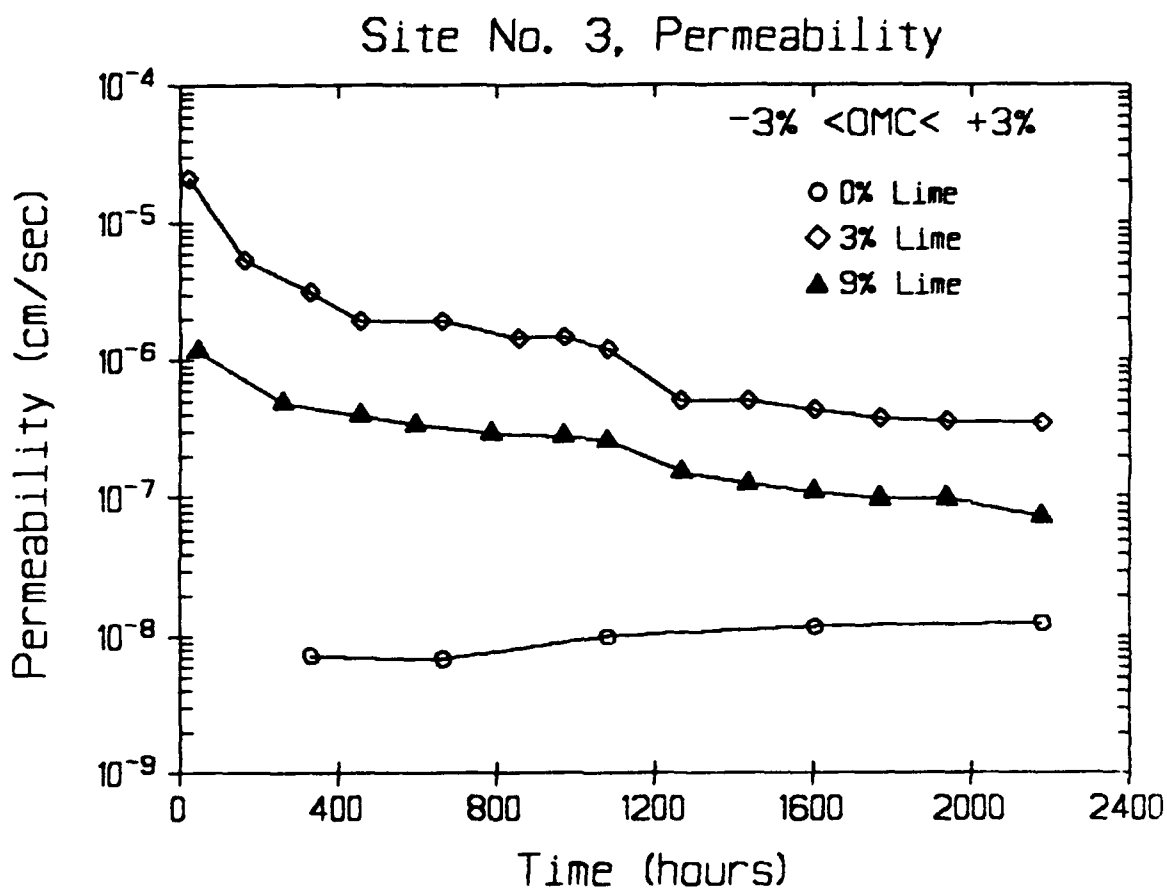
Figure 62. Permeability changes for Site No. 3 samples during 90 days of leaching.

after 600 hours of leaching, although it did tend to increase slightly with time. Increases in permeability with the addition of lime ranged from a minimum of 5.06 x 10^{-8} cm/sec (a seven fold increase) for one percent lime samples to a maximum of 1.92 x 10^{-6} cm/sec (a 280 fold increase) for samples mixed with three percent lime.

175. For all three soil sites, the permeabilities of the lime treated clay decreased during leaching after an initially high permeability at the start of each test. This is consistent with research by others (Gutschick 1978). It appears that after some short leaching time, the soil's permeability reached a point where it was still decreasing but at a much slower rate. The long-term leaching diagrams indicate that this point occurred for most soil-lime mixtures after approximately 300 hours (12.5 days). This leveling phenomena was also noted when soils were leached with industrial fluids (Haji-Djafari and Wright 1983).

176. It is speculated that this "leveling" of the permeabilities is due to the sample becoming saturated with time. Since the samples are not saturated at the start of the testing (samples compacted at optimum moisture had an average initial saturation of 79.4 percent), their permeabilities will be erratic, not laminar, as water flows through voids filling them with fluid. Darcy's Law for saturated flow is not strictly valid for determining the unsaturated flow rate for these early leach measurements. However, by using Darcy's flow equations for all measurements and since the test cells are, in effect, constant head, flexible wall permeameters, continuous, although not exact, measurements of the flow rate are possible at the start of each test. Once the samples become saturated, the flow rate becomes relatively steady, though slowly decreasing with continuous leaching. However, this was not unique for lime treated samples as fully saturated samples with no lime added displayed permeability decreases by 22 percent over 90 days for Site No. 1 material.

177. The change in permeabilities with the addition of lime varied considerably with the amount of lime added. In all tests, however, the permeability increased over that of the natural soil (with the sole exception of Site No. 2 material with two percent lime, as was previously discussed). That increase is directly related to the lime content, and possibly, to the soil-lime reaction as measured by the LMO test. Figure 63 shows that for all three soils, permeabilities increasd with increasing amounts of lime up to a maximum permeability at three percent lime. With additional lime, the permeabilities started to decline but never reduced to the permeabilities of the natural clay, even with up to nine percent lime. Three percent lime is the established LMO for Sites No. 2 and 3 soils and approximately the LMO of Site No. 1 soil.

178. For Sites No. 1 and 2 material, minimum permeabilities occurred in soils compacted wet of optimum. Maximum permeabilities took place in samples compacted dry of optimum.

179. Changes in permeability by adding lime are, therefore, speculated to be directly related to the ion complex within the clay soil. With the addition of small amounts of lime (less than the LMO) the soil particles flocculate to some degree and pozzolanic reaction has not occurred on a large scale, resulting in small increases in permeability. At lime contents near the LMO, larger amounts of flocculation and agglomeration are occurring, opening up larger channels of flow and increasing permeability dramatically. The pH of the soil has not been increased to the point where silica hydrates are forming sufficiently to produce massive crystalline structures. However, at lime contents above the LMO, pozzolanic formation becomes the predominant reaction, forming complex silica and alumina crystals within the soil mass, blocking flow channels and reducing water flow, although the
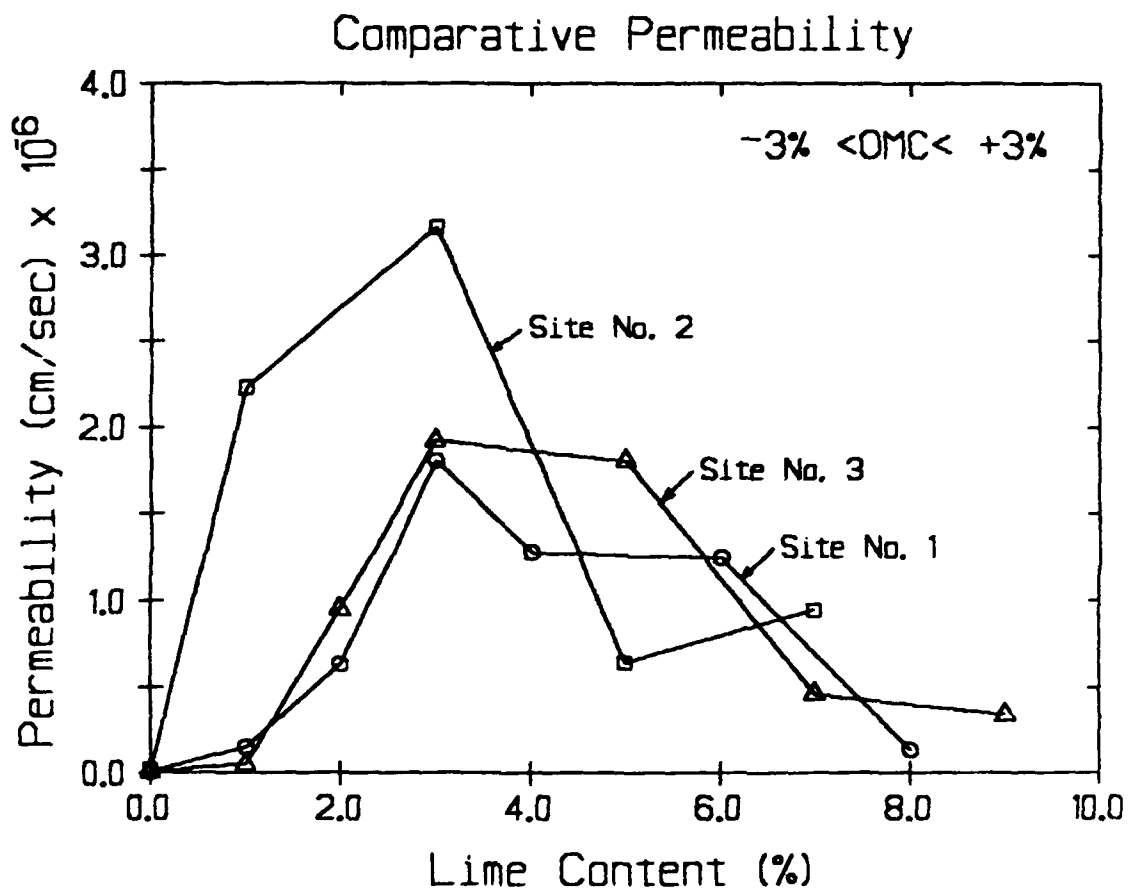
Figure 63. The effects of lime content on permeability after 600 hours of continuous leaching.

permeability is still significantly above natural permeability (Diamond and Kinter 1965; Ingles and Metcalf 1973).

180. The results of this research differ significantly from works by others that have used lime primarily for the purpose of decreasing the soil's permeability (refer to Part II, Permeability Changes). Gutschick (1978), for example, stated that lime has been mixed with earth dam core material (presumably highly plastic clay) to minimize leakage. In most projects, however, the clay involved tended to be dispersive. Lime, in fact, has been shown by the U. S. Army Corps of Engineers and the Soil Conservation Service to be very beneficial at reducing dispersive clay permeability and dispersive characteristics (Gutschick 1978; McElroy 1987). Lime-fly ash-aggregate mixture also appear to work well after sufficient curing to minimize water flow through liners. But for highly expansive clays with no dispersive properties and containing a significant quantity of silt size or large particles, this research showed that the permeabilities of expansive clays would most likely be substantially increased with the addition of lime in any amount up to those tested.

181. Permeability is perhaps the most significant tool necessary for estimating the long-term effectiveness of lime treated clays. It is possible that property changes in the field may be estimated for a given time knowing the permeabilities of the soil with and without lime and the property changes of a laboratory leach test. This will be further discussed later in this chapter.

Linear Shrinkage

182. Site No. 1 Linear Shrinkage. The amount of linear shrinkage for samples leached 45 and 90 days is shown in Figure 64. Samples leached 90 days tended to have lower linear shrinkages than samples leached 45 days, although the
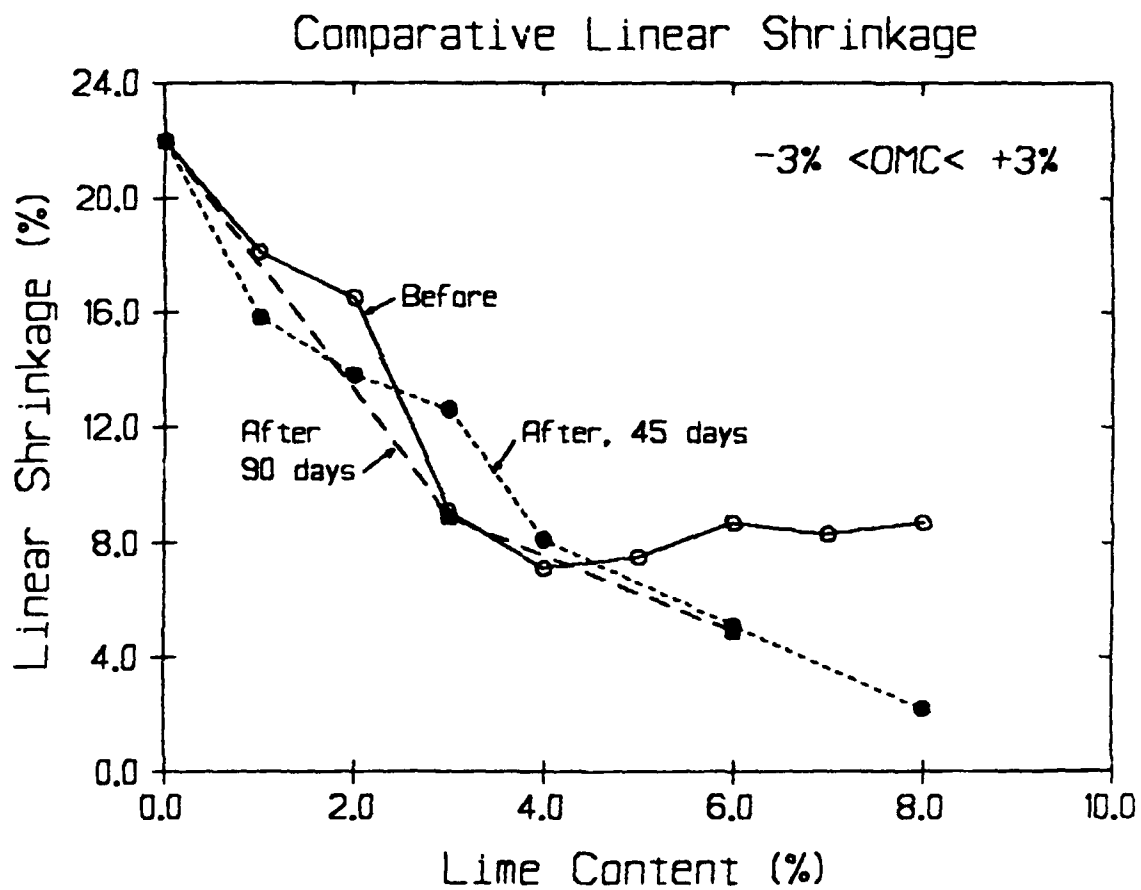
Figure 64.   Linear shrinkage changes in Site No. 1
samples after leaching.

difference was extremely small at six percent lime. Samples mixed with three and four percent lime showed larger linear shrinkage after leaching. Samples with more than five percent lime displayed linear shrinkage that was less after leaching than before leaching. Figure 65 indicates that there was only a slight difference in linear shrinkage for samples compacted wet, dry or at optimum moisture after leaching 45 days. Minimum shrinkage appears to have occurred for samples compacted wet of optimum. In all cases, shrinkage continued to decrease with increasing lime content at a fairly constant rate for all leached samples. Figure 65 is a typical graph comparing the physical property changes after leaching 45 days for samples initially compacted wet, dry and at optimum moisture. All "Before" curves on these graphs represent samples tested at OMC. All remaining physical property comparative graphs for moisture content variations will be placed in Appendix E for clarity of reading the main report.

183. Site No. 2 Linear Shrinkage. The effects of leaching for 45 and 90 days on Site No. 2 soil are shown in Figure 66. Samples mixed with less than five percent lime showed considerable increase in linear shrinkage after leaching. For example, samples with two percent lime displayed a 143 percent increase in linear shrinkage after leaching 45 days. Samples with greater than five percent lime displayed a lower linear shrinkage after leaching than before, similar to Site No. 1 results.

184. Figure E12 in Appendix E compares the linear shrinkage of samples compact wet, dry and at optimum moisture for Site No. 2 samples. Minimum shrinkage appears to have occurred in samples compacted wet of optimum with maximum after leach linear shrinkage occurring in samples compacted dry.

185. Site No. 3 Linear Shrinkage. Figure 67 compares the linear shrinkage of Site No. 3 samples compacted at optimum moisture and leached 45 and 90 days.
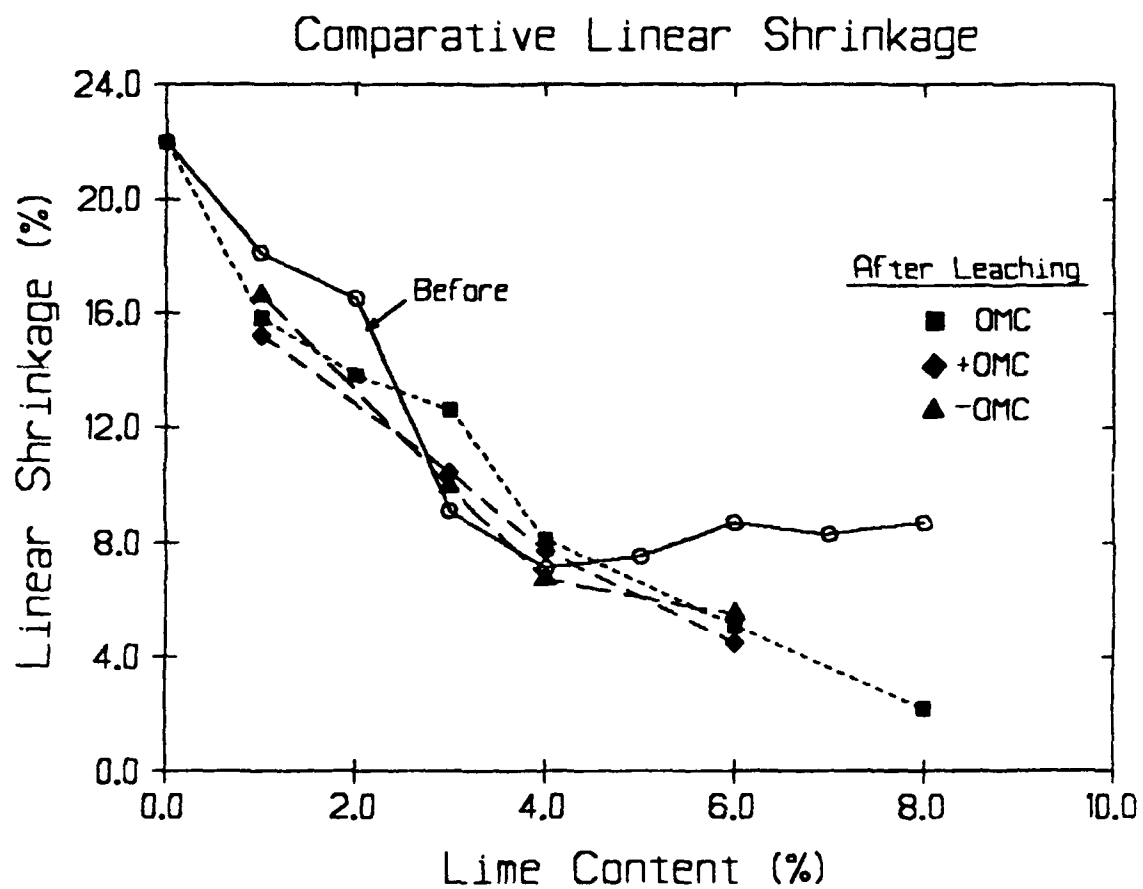
Figure 65. Moisture content effects on linear shrinkage for Site No. 1 samples after 45 days of leaching.
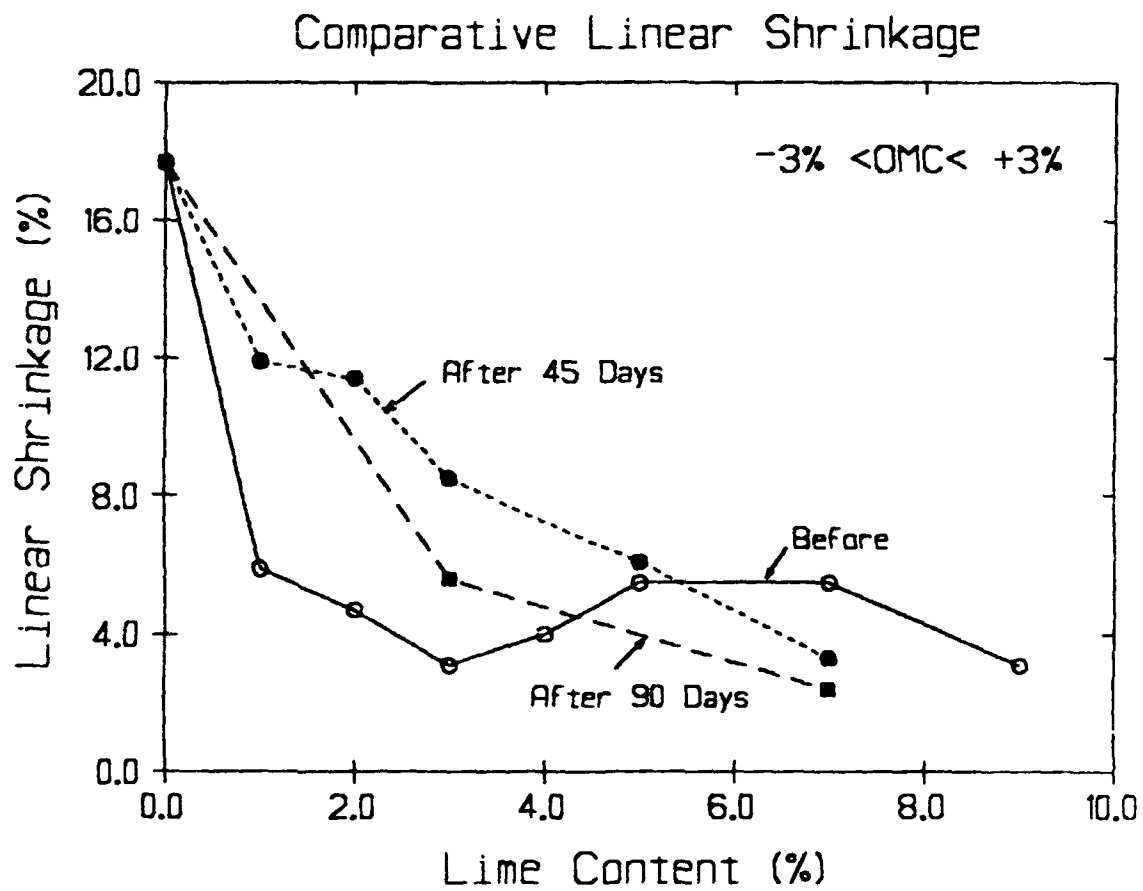
Figure 66. Linear shrinkage changes in Site No. 2
samples after leaching.
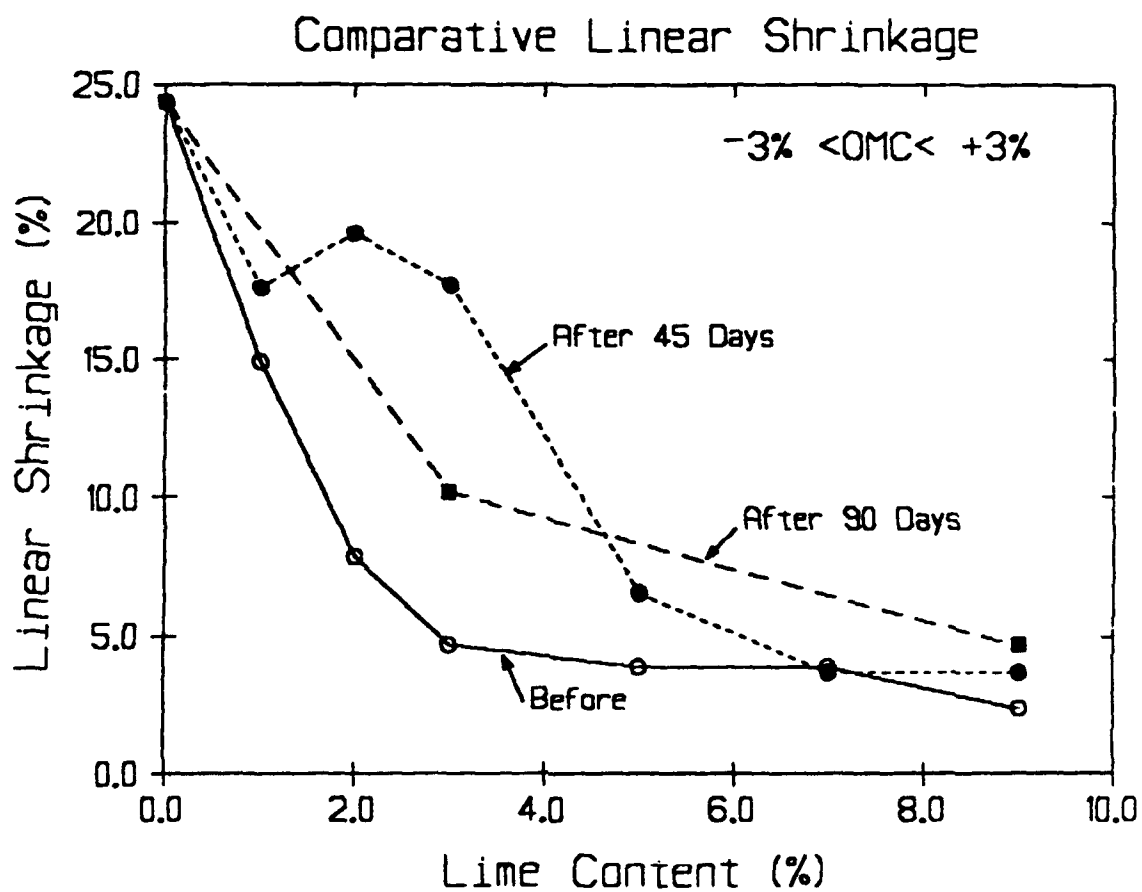
Figure 67. Linear shrinkage changes in Site No. 3 samples after leaching.

For lime contents below seven percent, leached samples displayed an increase in linear shrinkage.

186. Maximum increase occurred in samples compacted with three percent lime, a 276 percent increase after 45 days of leaching. At lime contents of seven and nine percent, linear shrinkages after leaching did not change significantly.

187. All three sites displayed the same characteristics after leaching. Linear shrinkage was higher after leaching than it was before leaching, but at a specific lime content, the differences became insignificant. This minimum shrinkage point appears to be at five percent lime for Sites No. 1 and 2 and six percent lime for Site No. 3. These lime contents are slightly more than the LMO but slightly less than the LSO, except for Site No. 3 where six percent lime is the LSO. Beyond these lime contents, the linear shrinkage results were not detrimentally affected by leaching.

188. Non-leached samples for all sites displayed similar reactions. The addition of lime to all three soils decreased the linear shrinkage until approximately four percent lime was added, after which the decrease in linear shrinkage was minimal or nonexisting. One possible explanation is that for non-leached samples, after the LMO has been reached, the soil is essentially calcium saturated. Additional lime increases the pozzolanic reactions (more calcium-silica and calcium-alumina products), but does not increase flocculation or further reduce the thickness of the hydrated water layers surrounding the clay particles since the amount of moisture in the system is finite.

189. When samples are completely saturated (during leaching), additional porewater may aide in the pozzolanic reaction, generating more calcium-silica products thereby using up or "fixing" more potential swelling clay minerals. However, if the amount of calcium present is less than the amount necessary to balance the excess water molecules now surrounding the clay minerals, the

absorbed water layer increases and the linear shrinkage increases above pre-leached results. Once additional lime is added, cation exchange, flocculation and pozzolanic reactions are increased, which further reduces the shrinkage potential.

190. One interesting note is that in all three sites, the material mixed with three percent lime then leached 90 days showed lower linear shrinkage results after leaching than did samples leached 45 days. The additional contact with water may aide in the pozzolanic reaction as discussed above, reducing the shrinkage potential of the lime treated sample. With the addition of lime to or past the LSO, the soils from all sites showed linear shrinkage results approximately equal after 45 and 90 days of leaching.

191. For Sites No. 1 and 2, minimum increases in linear shrinkage occurred in samples compacted wet of optimum. Samples compacted dry of optimum displayed the highest linear shrinkage after leaching.

Atterberg Limits

192. Site No. 1 Atterberg Limits. For samples compacted at optimum moisture then leached 45 days, substantial changes took place in their Atterberg limits. As shown in Figure 68, the soil's plastic limit and liquid limit decreased after leaching. The result was a general increase in plasticity index (PI) after leaching. The largest increase for samples compacted at optimum moisture was for samples treated with one percent lime where the PI increased from 22 to 31, which is approximately the PI of the natural soil. The maximum percentage increase in PI above pre-leached measurements, for those compacted at optimum moisture, were those treated with one and four percent lime after leaching 45 days which showed increases of 40.9 and 40.0 percent, respectively. Minimum PI changes were noted for samples treated with six and ` ght percent lime which showed changes in PI of

161
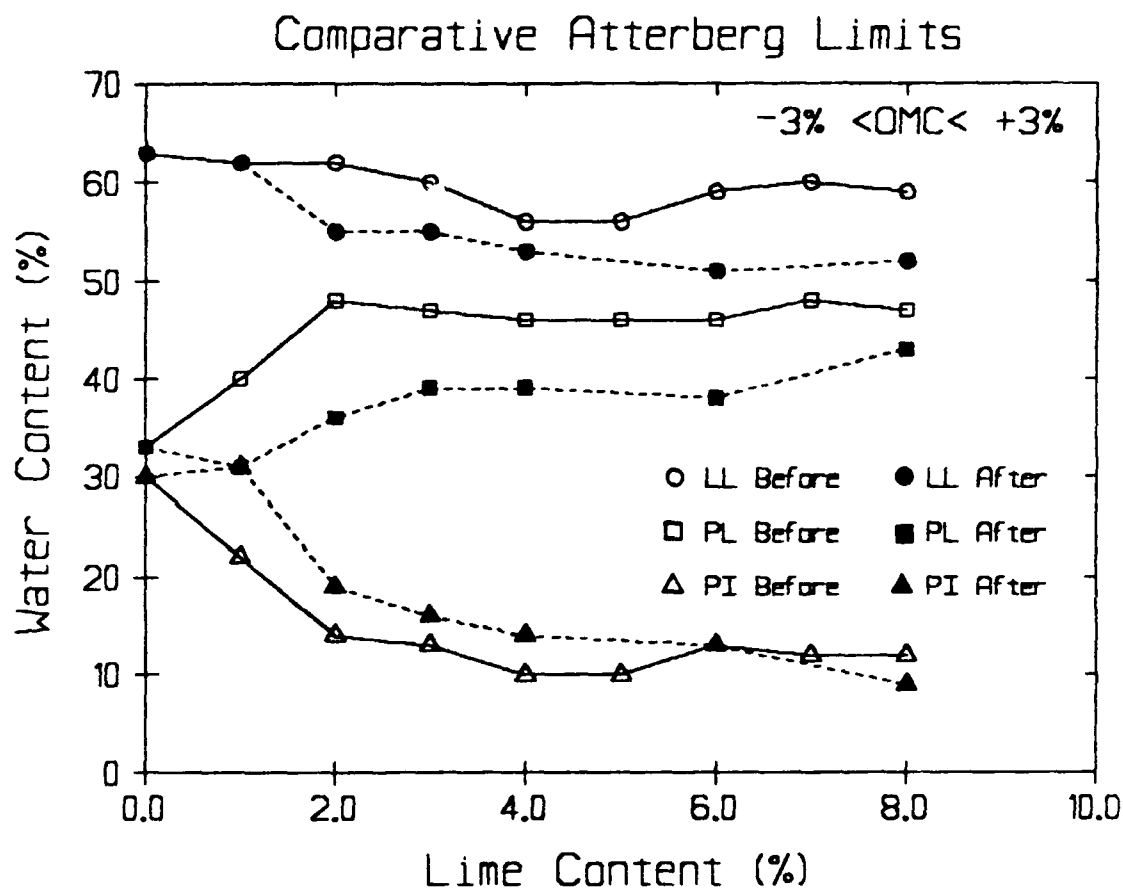
Figure 68. Atterberg limits changes in Site No. 1
samples after leaching 45 days.

zero and 25.0 percent decrease, respectively. Samples leached 90 days showed an even larger increase in PI at three percent lime (53.8 percent) but again, no change at six percent lime (Figure 69).

193. Samples compacted wet of optimum showed the largest increase in PI after leaching, and samples compacted at optimum moisture showed the smallest increase. When treated with four percent lime, the PI increased from 10 to 18 for wet of optimum samples, an 80.0 percent increase. At six percent lime, the soils from all sites showed similar PI regardless of compaction moisture (Figure E13 in Appendix E).

194. Site No. 2 Atterberg Limits. Figure 70 shows the results of Atterberg limits tests on Site No. 2 material after leaching 45 days. As seen in Site No. 1 tests (Figure 68), liquid limits and plastic limits tend to be lower after leaching while the soil's PI increased. The largest increase occurred in samples treated with one percent lime where the PI increased from 16 to 22 (a 37.5 percent increase), but the plasticity increase diminished as more lime was added to the samples. At five percent lime, the soil's PI was less after leaching than before leaching and continued to decrease when seven percent lime samples were leached. This compares well with Site No. 1 results. Samples leached 90 days showed lower increases in PI than samples leached 45 days with three percent lime, but at seven percent lime, the PI was less after leaching (figure 71).

195. Figure E14 in Appendix E shows that there is very little difference in PI after leaching for samples compacted wet, dry or at optimum moisture. Samples compacted wet tended to have slightly higher after leach plasticity than those compacted at other moisture contents, and samples compacted dry displayed the lowest increase in PI after leaching. At five percent lime, all samples had plasticity

163
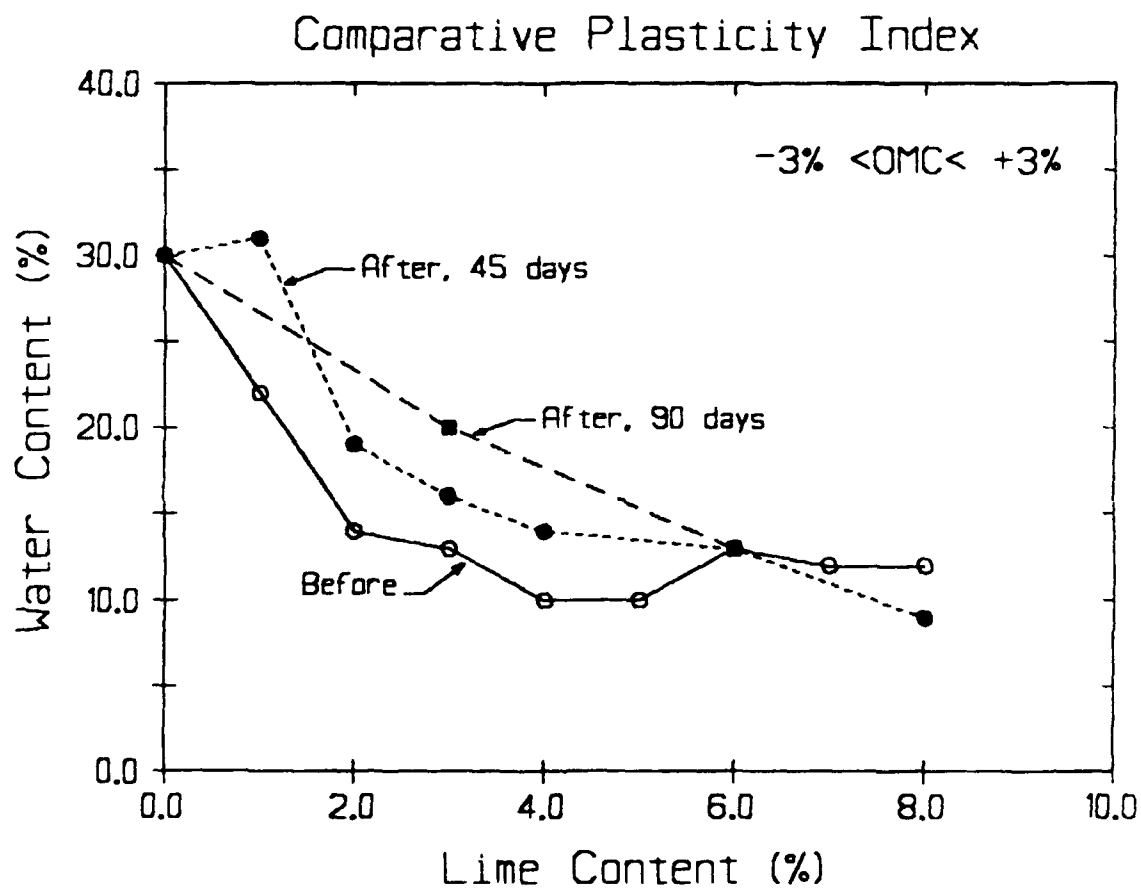
Figure 69. Plasticity index changes in Site No. 1 samples after leaching.

164
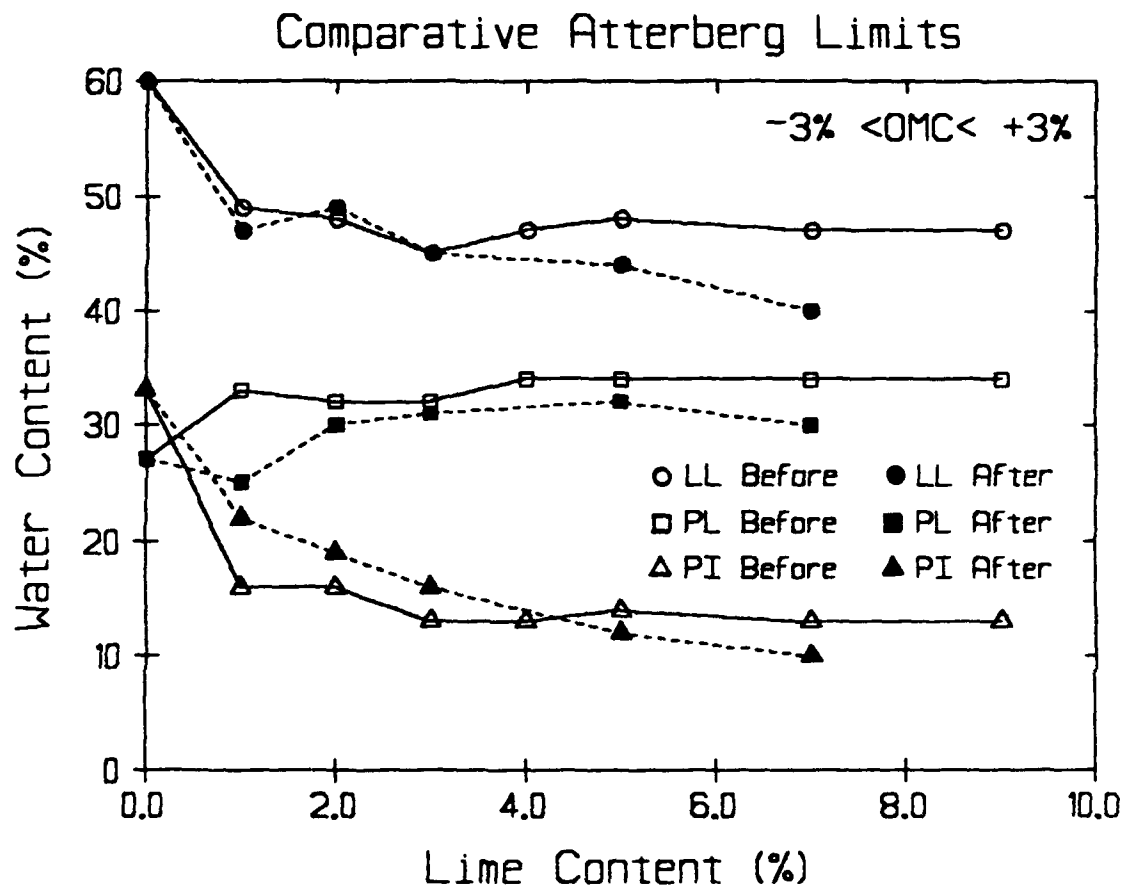
Figure 70. Atterberg limits changes in Site No. 2
samples after leaching 45 days.
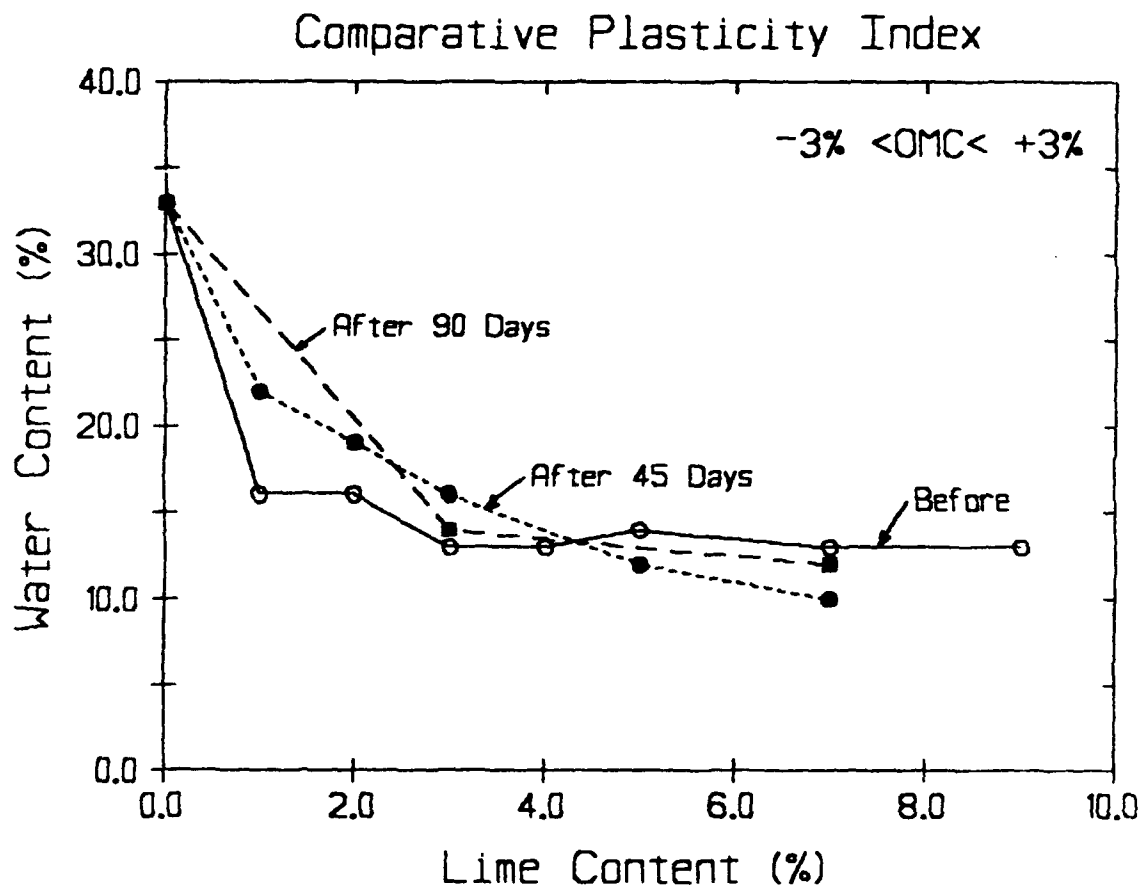
Figure 71. Plasticity index changes in Site No. 2 samples after leaching.

indices after leaching that were less than or equal to those before leaching. Again, these results compare well with Site No. 1 tests.

196. <u>Site No. 3 Atterberg Limits</u>. Site No. 3 material's Atterberg limits, after leaching 45 days, are shown in Figure 72. As with Sites No. 1 and 2, the plastic limits decreased and the plasticity indexes increased after leaching. The liquid limit results were slightly different from the other two site's tests in that they increased after leaching for lime contents at two and three percent. For all remaining lime contents, the liquid limits decreased after leaching.

197. The largest increase in PI occurred in samples treated with three percent lime where it increased from 11 to 31 (a 181 percent increase). The difference between before and after leach PI results decreased until at approximately six percent lime the results were approximately equal. The PI of the soil after leaching continued to drop with the addition of more lime so that after six percent lime was added, the PI after leaching was less than it was before leaching. At three percent lime, samples leached 90 days showed plasticity indexes less than those after 45 days of leaching but greater than the results shown before leaching. At nine percent lime, there was minimum difference in the test's plasticity indexes (Figure 73).

198. Soil from all three sites showed similar reactions after leaching. Maximum increases in plasticity indexes occurred at lime contents of one, one and three percent for Sites No. 1, 2 and 3, respectively. All increases in plasticity after leaching steadily decreased with the addition of lime such that at approximately six percent lime for all three sites, the PI after leaching was equal to or less than the PI before leaching. Sites No. 1 and 2 soils showed maximum increases in PI after leaching when compacted wet of optimum and minimum increases when compacted dry.
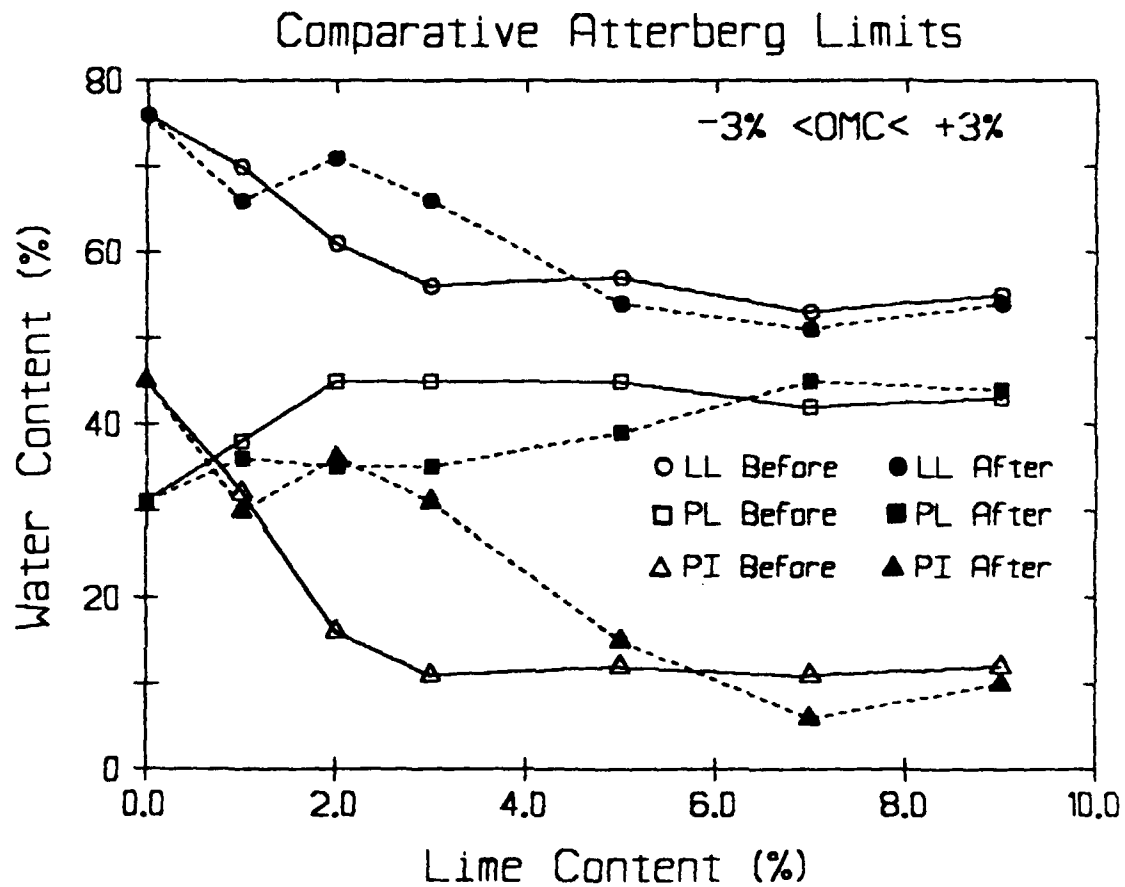
Figure 72. Atterberg limits changes in Site No. 3
samples after leaching 45 days.
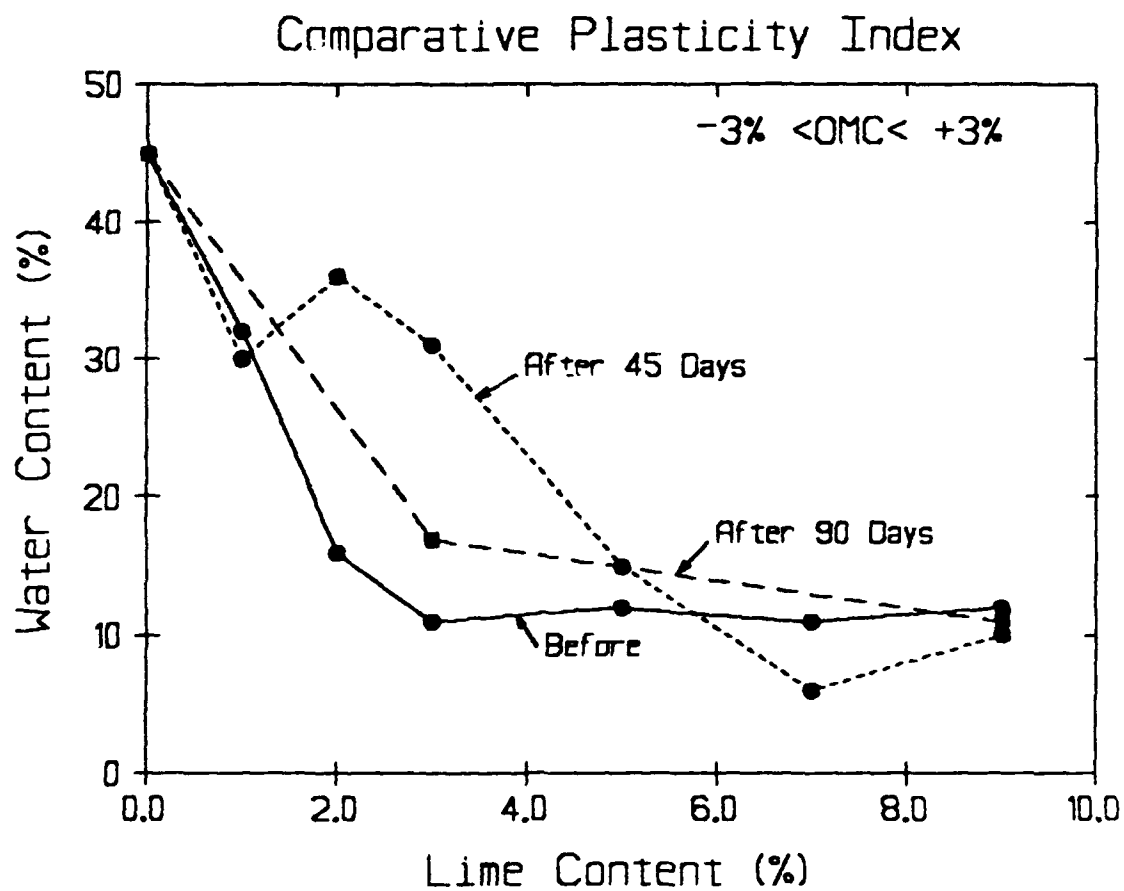
Figure 73. Plasticity index changes in Site No. 3
samples after leaching.

Swelling Tests

199. <u>Free Swelling Tests</u>. Figure 74 shows that Site No. 1 samples trimmed from the leach test specimens had increases in free swell percentages after leaching. The maximum percent increase for trimmed samples compacted at optimum moisture occurred in samples compacted with four and six percent lime (increases of 115.0 and 150.0 percent, respectively). The minimum increase was for samples with two percent lime (3.8 percent increase). Site No. 1 samples leached 90 days showed a larger percent increase in free swell at three percent lime but a lesser increase at six percent when compared to 45 day leach tests. Samples compacted wet of optimum generally exhibited the largest increase in free swell after leaching (Figure E15 in Appendix E). Samples compacted dry of optimum showed similar free swell characteristics after leaching as those before leaching, except for those with one percent lime (an increase of 47.3 percent) and three percent lime (a decrease of 47.1 percent).

200. Figure 75 shows the effects of leaching on free swell results for Site No. 2 samples compacted at optimum moisture. There appears to be very little difference in before and after leach data. Maximum change occurred at one percent lime where free swell decreased 79.0 percent after leaching. Those samples leached 90 days displayed similar swell results as those samples not leached.

201. Figure E16 in Appendix E shows that Site No. 2 samples compacted wet have the largest increase in swell after leaching. For example, samples at three percent showed a 94.0 percent increase in free swell. However, after approximately five percent lime was added to the soil, the changes in free swell with leaching were negligible.

202. Free swell results for soil from Site No. 3 showed similar results after leaching as shown by Site No. 1 material (Figure 76). All lime contents tested

170

Figure 74. Free swell changes in Site No. 1
samples after leaching (trimmed samples).

171

Figure 75. Free swell changes in Site No. 2
samples after leaching (trimmed samples).

172

Figure 76. Free swell changes in Site No. 3
samples after leaching (trimmed samples).

173

showed an increase of swell after leaching 45 and 90 days with the maximum increase occurring in samples compacted with three percent lime (from 0.5 to 2.2 percent or 340.0 percent increase). The minimum increase occurred in samples with nine percent lime (from 0.2 percent to 0.3 percent or a 50.0 percent increase). Samples leached 90 days showed smaller swell increases than samples leached 45 days at three percent lime but had approximately equal changes when treated with nine percent lime.

203. Sites No. 1 and 3 material showed similar reactions after leaching. All samples tested showed an increase in free swell after leaching with the maximum increases occurring at three or four percent lime contents. After six percent lime had been added, the swell increase after leaching had been significantly reduced although there was still some small increase in free swell with leaching. Maximum swelling occurred when samples from all sites were compacted wet. Samples compacted dry displayed slightly lower free swell after leaching, but the differences between those samples compacted dry and those compacted at optimum moisture were minimal.

204. Swell Pressure Tests. Figure 77 shows a comparison of swell pressure tests for Site No. 1 samples compacted at optimum moisture before and after leaching 45 and 90 days. All samples compacted at optimum moisture and leached 45 days showed increases in swell pressure after leaching. Six percent lime samples leached 90 days showed a much lower increase in swell pressure after 90 days than those subjected to 45 days of leaching. The maximum increase in trimmed, after leach, optimum moisture swell pressure results occurred in soils treated with six percent lime after 45 days of leaching. Swell pressures increased from 153.8 psf to 304.1 psf, an increase of 97.7 percent. However, these swell pressures are still relatively small overall compared to those of the natural soil.

174
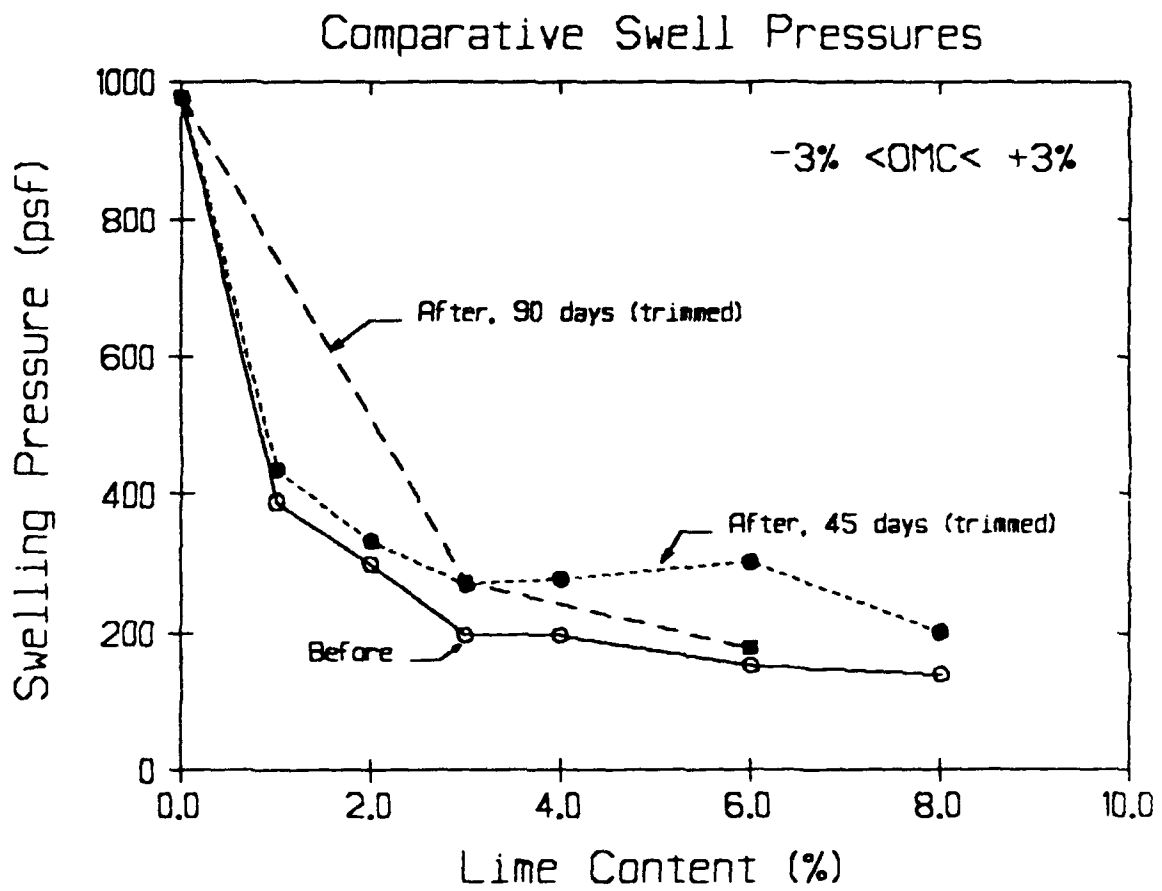
Figure 77.   Swell pressure changes in Site No. 1
samples after leaching (trimmed samples).

205. Site No. 1 samples compacted wet of optimum showed the largest percentages in swell pressure increase after leaching, except for those samples compacted with six percent lime (Figure E17 in Appendix E). Samples compacted dry showed similar swell pressures before and after leaching except for those samples with one percent lime which showed a 30.0 percent increase.

206. Site No. 2 tests displayed unusual swell results as all after leach swell pressures were slightly less than swell pressures before leaching (Figure 78). This was true for both 45 and 90 day leach tests. In samples with seven percent lime there was little difference between the before and after leach swell pressure results. Samples compacted wet displayed the highest swell pressures after leaching 45 days, but they were still equal to or slightly less than the swell pressures before leaching. Samples compacted dry displayed swell percentages approximately equal to those compacted at optimum moisture (Figure E18 in Appendix E).

207. Figure 79 shows that after leaching 45 and 90 days, the swelling pressures from Site No. 3 material have increased significantly. These results agreed well with Site No. 1 swell pressure test results. Maximum increase in swell pressure occurred in samples with three percent lime (an increase of 51.7 percent) while minimum increases occurred in samples with nine percent lime (an increase of 12.9 percent). The swell pressures of those samples leached 90 days were approximately equal to those leached 45 days.

208. As with free swell tests, Site's No. 1 and 3 material behaved similarly in swell pressure tests after leaching. Samples from these two sites showed increases in swell pressure after leaching with the maximum increases occurring in samples treated with between three and six percent lime. For all three soil sites, after the lime content had reached greater than seven percent, the swell pressure after leaching was approximately equal to the swell pressures before leaching.
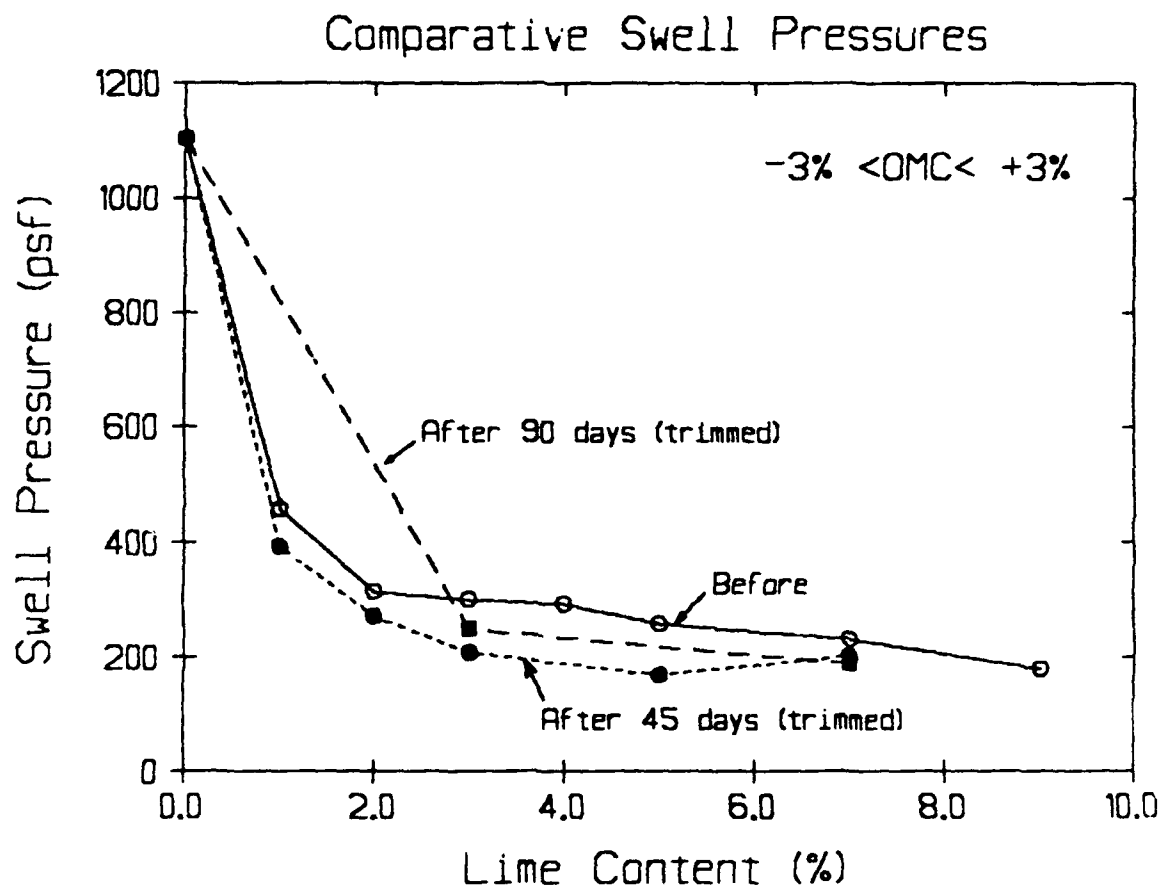
Figure 78. Swell pressure changes in Site No. 2
samples after leaching (trimmed samples).
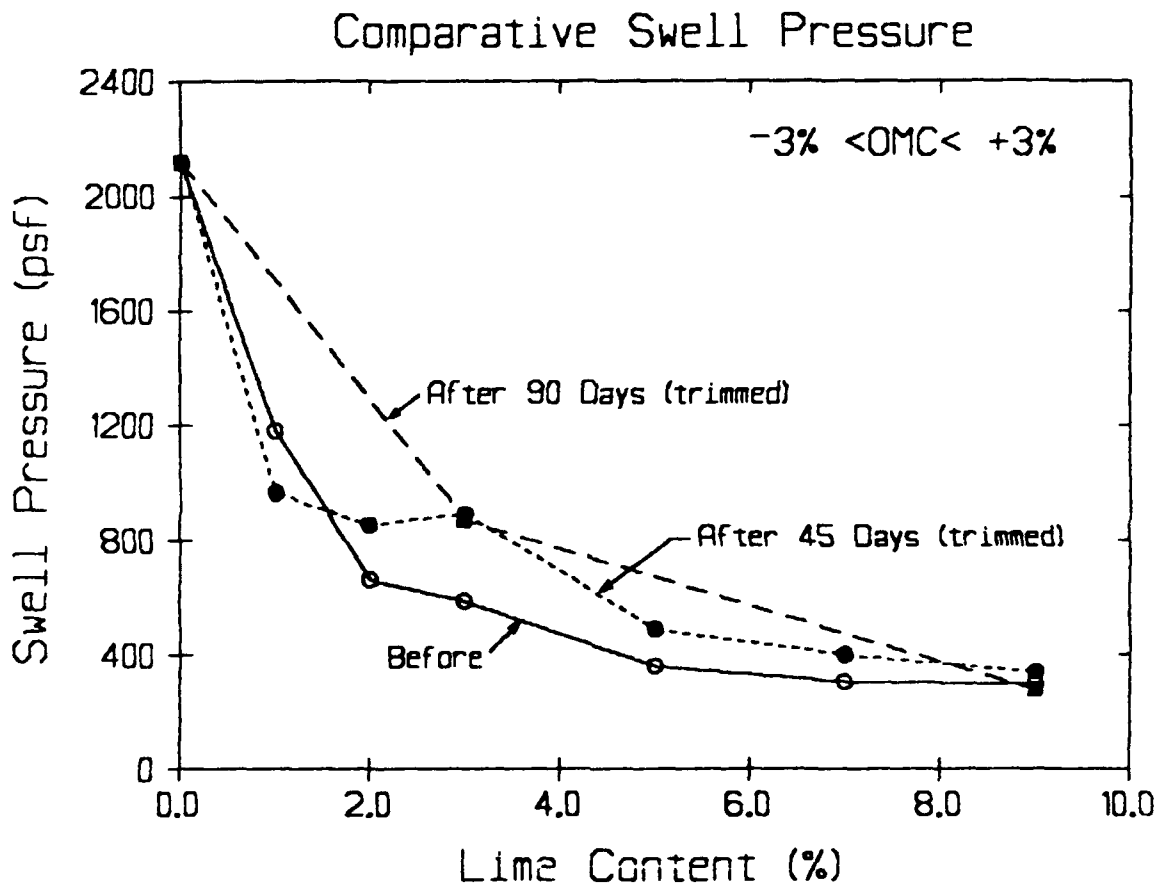
Figure 79. Swell pressure changes in Site No. 3 samples after leaching (trimmed samples).

Maximum swell pressure increases occurred in samples compacted wet. Sites No. 1 and 2 samples compacted dry of optimum showed swell pressures after leaching that were approximately equal to the swell pressures measured when compacted at optimum moisture.

209. <u>Reworked vs. Trimmed</u>. Reworked samples, as defined in Part III, displayed much larger increases in free swell percentages after leaching 45 days than samples trimmed from the leached samples (Figures 80 through 82). The largest increases in reworked free swell occurred at the lower lime contents. For example, at three percent lime, Site No. 3 soil increased from 0.5 to 4.8 percent swell for reworked samples compared to an increase of 0.5 to 2.2 percent swell for trimmed samples. With larger lime contents the differences between trimmed and reworked free swell decreases to a point at about seven percent lime for all three soil sites where reworked and trimmed after leach swell data were approximately equal to their before leach swell results.

210. Samples compacted dry of optimum then reworked generally displayed the largest increase in free swell for Sites No. 1 and 2 material. Maximum increase in swell occurred in soil from Site No. 2 at three percent lime (a 605.9 percent increase) for samples compacted dry of optimum. No really clear pattern develops for Site No. 1 reworked samples (dry or wet) except that both reworked dry and wet samples exceed optimum moisture samples free swell percentages after leaching.

211. Reworked samples showed much larger increases in swelling pressures after leaching than trimmed samples displayed for all three sites (Figures 83 through 85). Maximum increases in reworked swell pressure occurred at two percent lime for Site No. 3 material (a 101.6 percent increase), five percent lime for Site No. 2 material (a 45.4 percent increase), and at three percent lime for Site
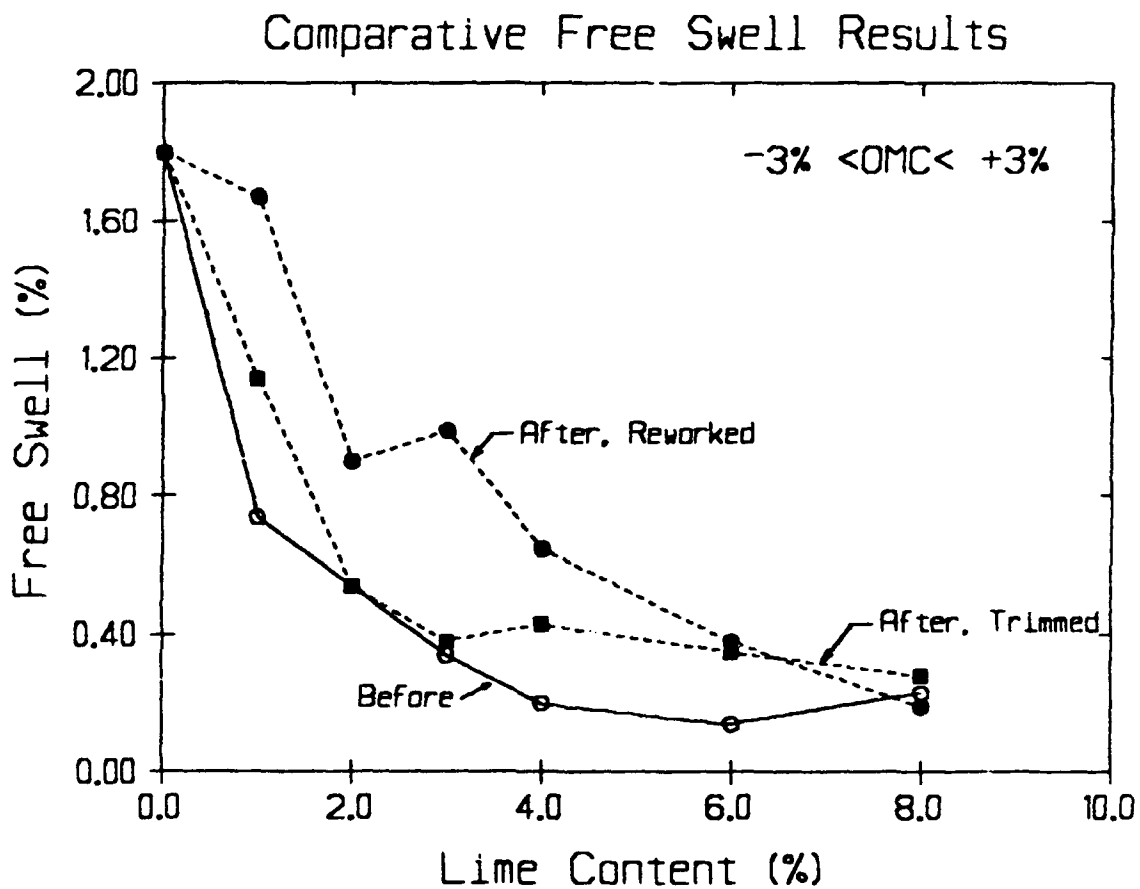
Figure 80. Comparison of free swell changes in
Site No. 1 samples after leaching (trimmed vs
reworked).
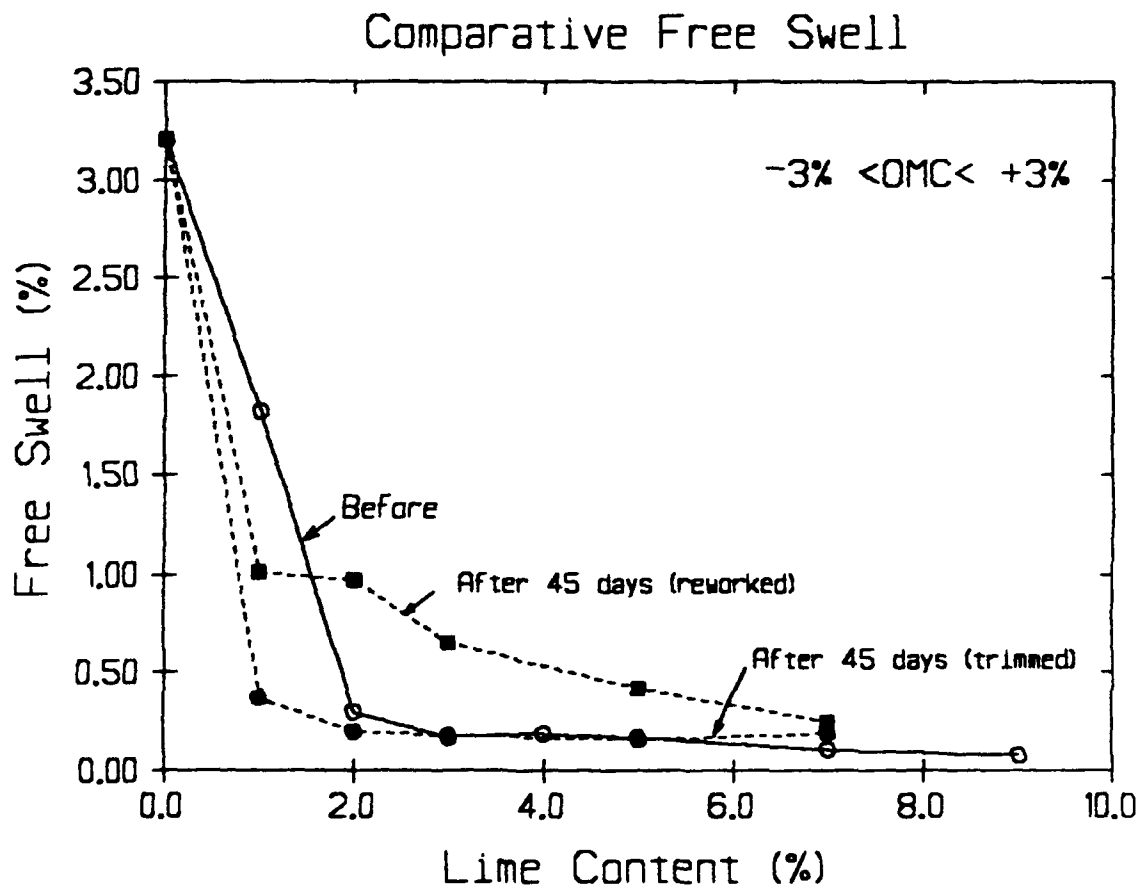
Figure 81. Comparison of free swell changes in
Site No. 2 samples after leaching (trimmed vs
reworked).
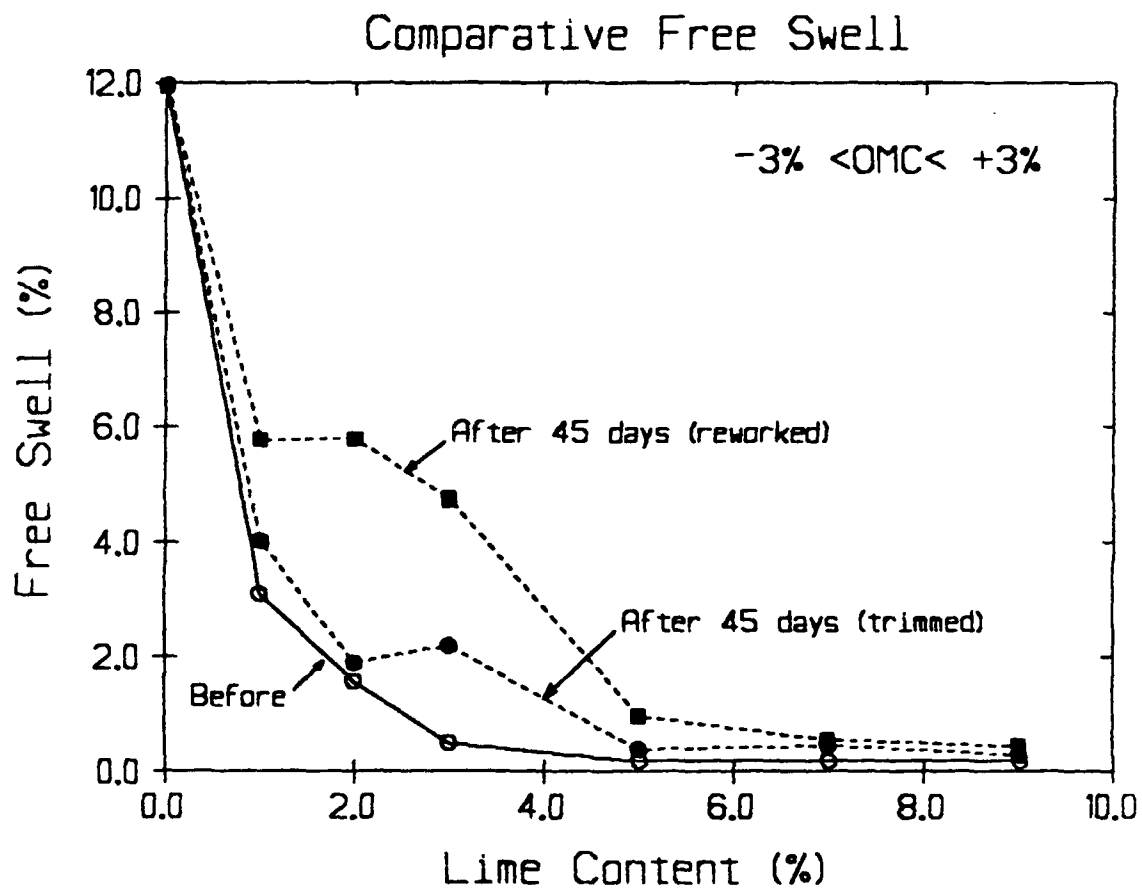
Figure 82.   Comparison of free swell changes in
Site No. 3 samples after leaching (trimmed vs
reworked).
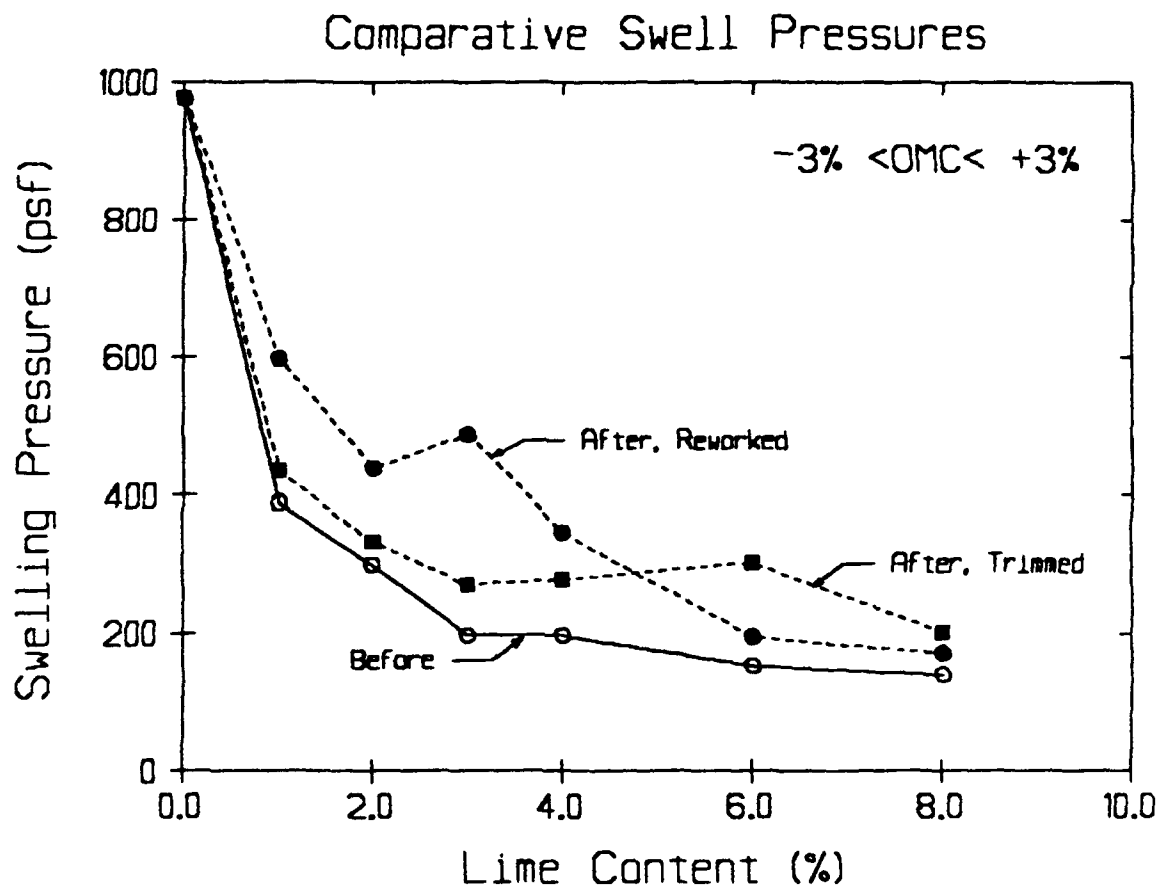
Figure 83. Comparison of swell pressure changes in Site No. 1 samples after leaching (trimmed vs reworked).
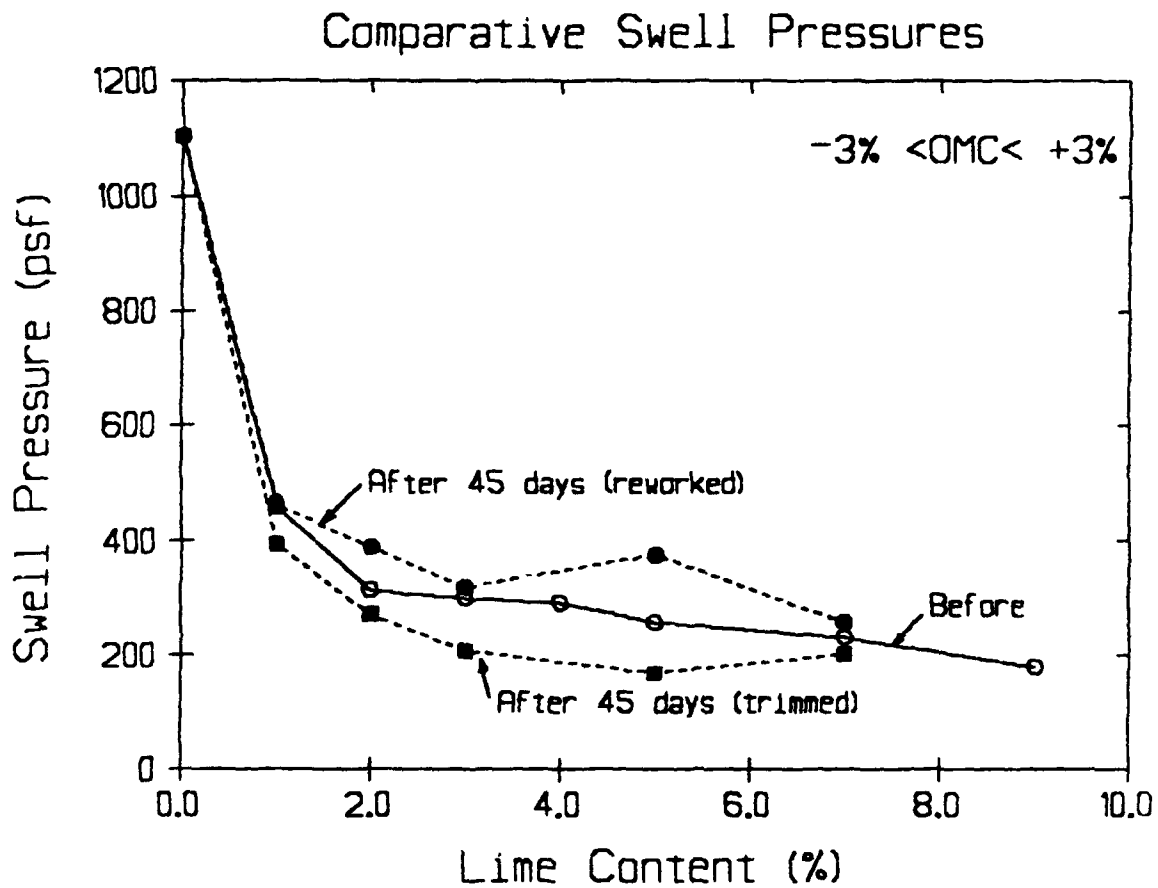
Figure 84. Comparison of swell pressure changes in
Site No. 2 samples after leaching (trimmed vs
reworked).
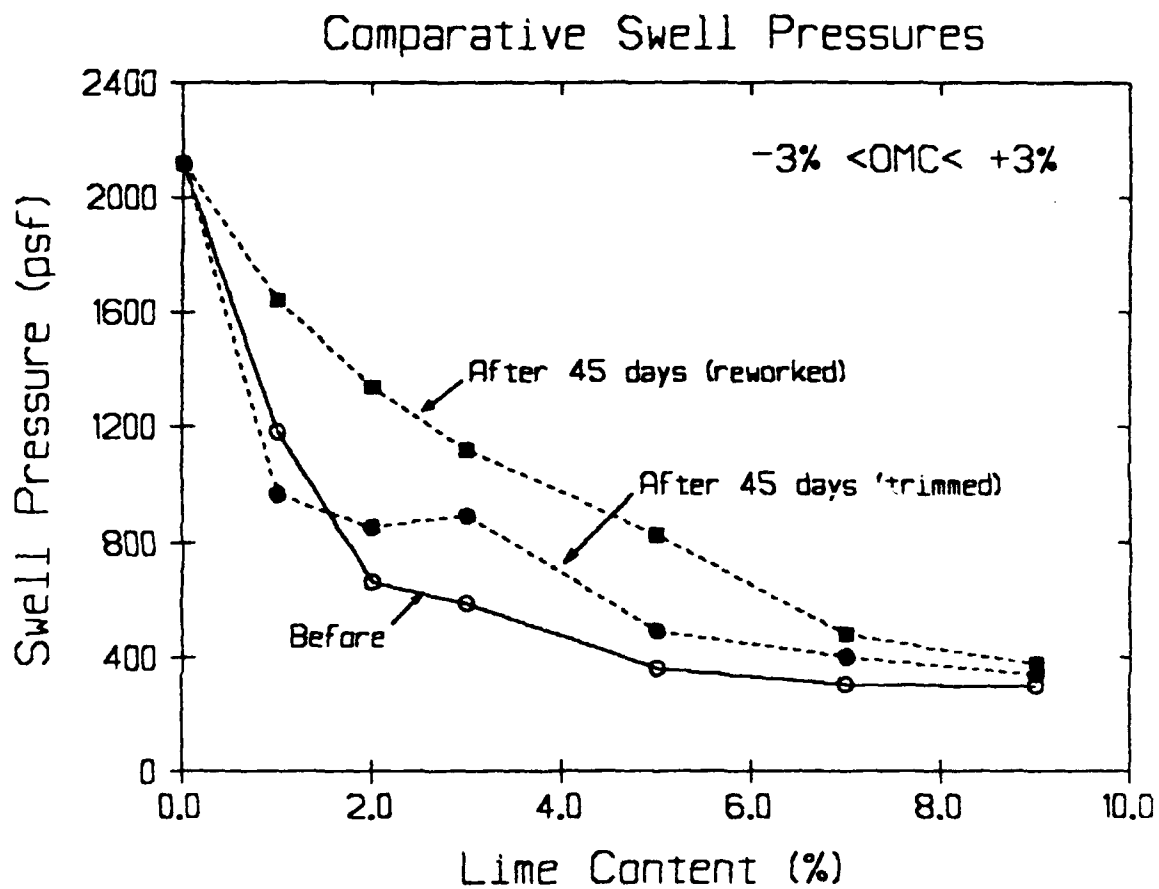
Figure 85.   Comparison of swell pressure changes in
Site No. 3 samples after leaching (trimmed vs
reworked).

No. 1 material (a 146.4 percent increase), for soils compacted at optimum moisture. After approximately seven percent lime was added to all soils, the swell pressure increases after leaching were approximately equal to the swelling pressures before leaching, for both trimmed and reworked specimens.

212. For material from Sites No. 1 and 2, reworked samples compacted wet generally displayed the largest increase in swell pressures after leaching for lime contents below six percent. After approximately seven percent lime was added to the samples, the differences between swell pressure results for reworked, trimmed, wet, dry, or optimum moisture samples became negligible.

Strength Tests

213. Site No. 1 Strength. After 45 and 90 days of continuous leaching, unconfined compression test results indicated that there was a wide variance in shear strength before and after leaching. Figure 86 shows that for samples compacted at optimum moisture, maximum strength decreases occurred in samples with one percent lime (a 76.9 percent decrease). Samples with two and three percent lime showed slight increases in strength after leaching, whereas samples with one, four and six percent lime showed considerable decrease in strength after leaching. Ninety day leached samples showed a small decrease in strength at three percent lime and a 26.3 percent decrease at six percent lime, which is essentially the same as found in the 45 day leach tests. Samples compacted wet of optimum showed slightly larger net strength increases after 45 days of leaching than those compacted at optimum moisture (although with diminishing gains with increasing lime contents). Samples compacted dry of optimum showed the largest overall decreases in strength after leaching (Figure E19 in Appendix E).
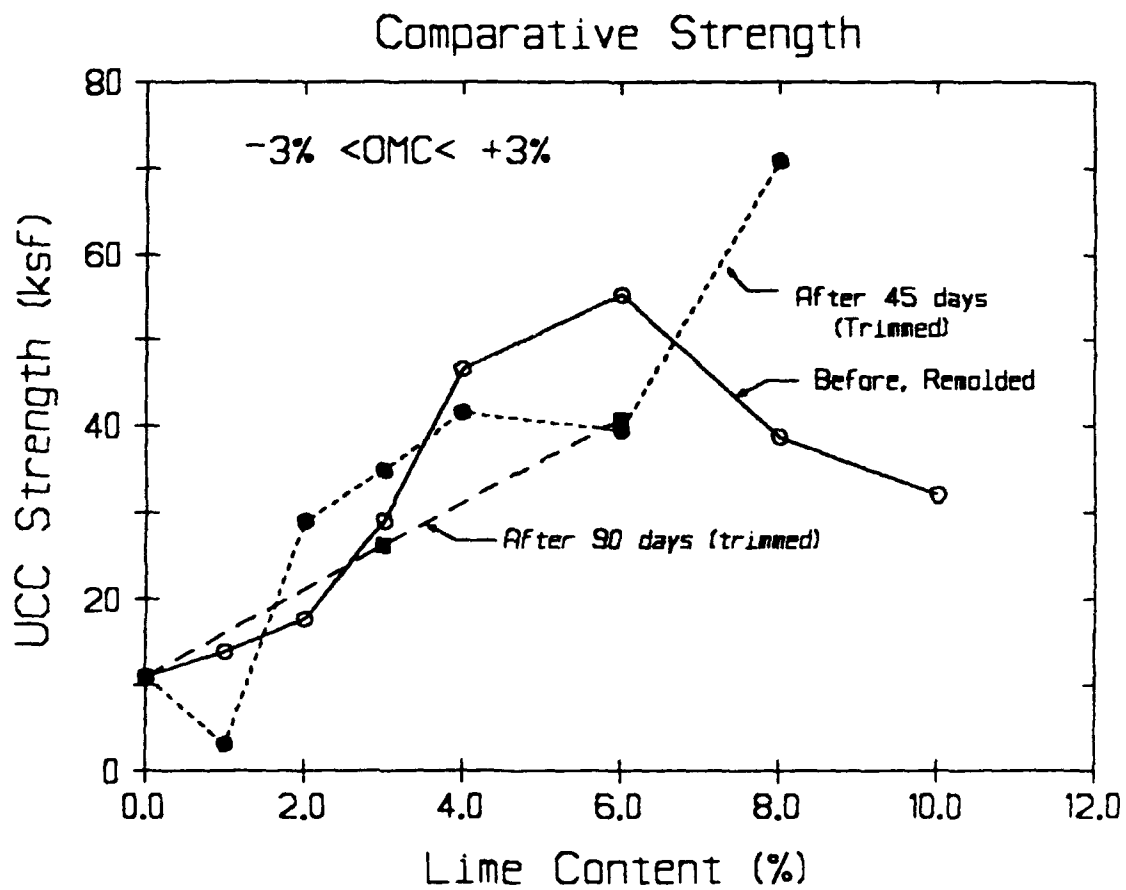
Figure 86. Strength changes in Site No. 1 samples after leaching (trimmed samples).

214. <u>Site No. 2 Strength</u>. Site No. 2 material showed small strength decreases after leaching for 45 days at lime contents of one and two percent (Figure 87). At lime contents above three percent, strength tests on trimmed samples leached 45 and 90 days showed increases in strength by as much as 15.1 percent for samples with five percent lime (45 days leaching) and 18.6 percent for samples with three percent lime (90 days leaching). Ninety day leach test results showed slightly larger strength gains than 45 day leach tests.

215. As seen in Figure E20 in Appendix E, samples compacted dry of optimum displayed enormous loss in strength after leaching. For example, at three percent lime, the shear strength in Site No. 2 soil decreased from 25.47 ksf to 4.83 ksf (an 81.0 percent drop). However, leached samples compacted at optimum moisture resulted in strengths near or larger than original strength.

216. <u>Site No. 3 Strength</u>. Figure 88 shows the strength changes after leaching Site No. 3 samples. This figure shows similar results as seen in Site No. 1 soils. There was a decrease in shear strength after leaching 45 and 90 days for all lime contents up to approximately eight percent lime. The maximum decrease in strength occurred in samples with three percent lime where strength dropped 53.8 percent. After approximately eight percent lime had been added to the soil, the strength after leaching was approximately equal to the strength before leaching. Strength tests on 90 day leached samples showed strengths approximately equal to those measured after 45 days of leaching.

217. The soil from all three sites displayed similar strength characteristics after leaching. There was an initial decrease in strength after leaching for the smaller percent lime contents. But after a specific lime content had been reached, the difference in strength between samples before and after leaching became negligible. This lime content was reached at approximately seven percent for

Comparative Strength
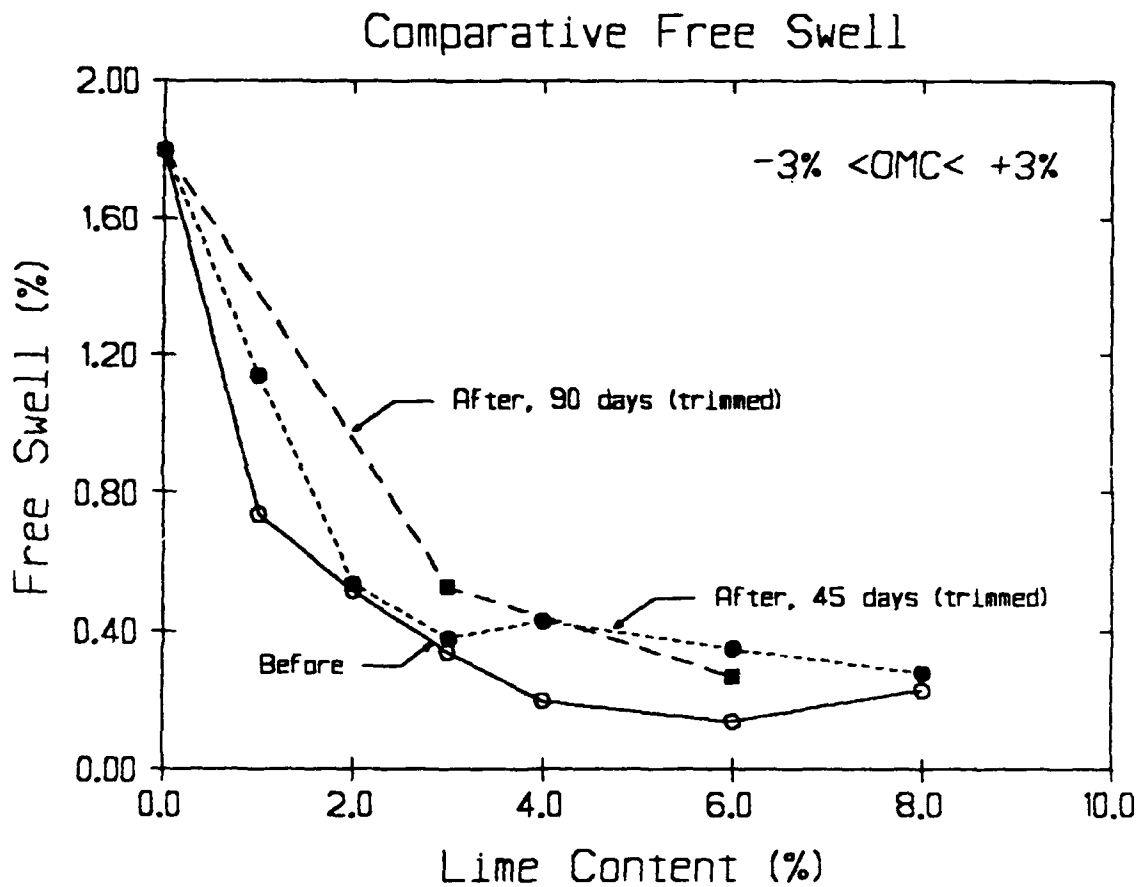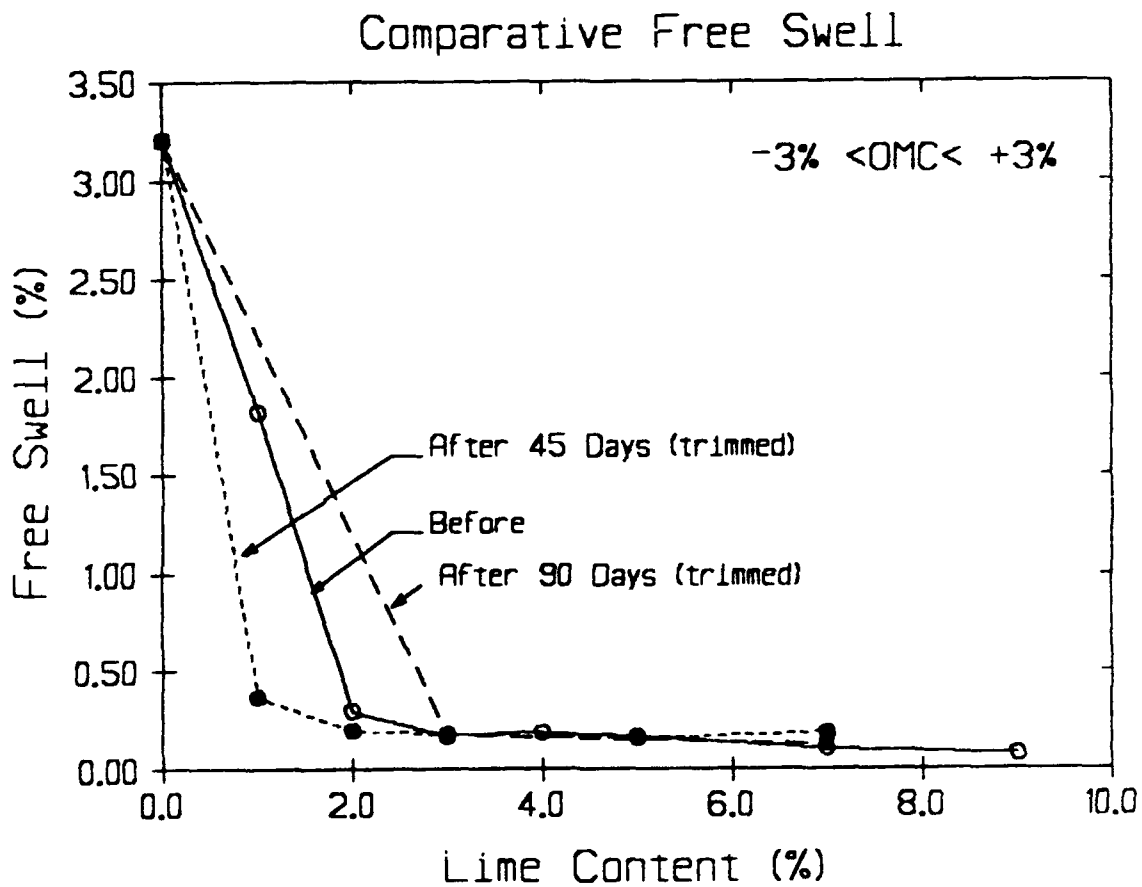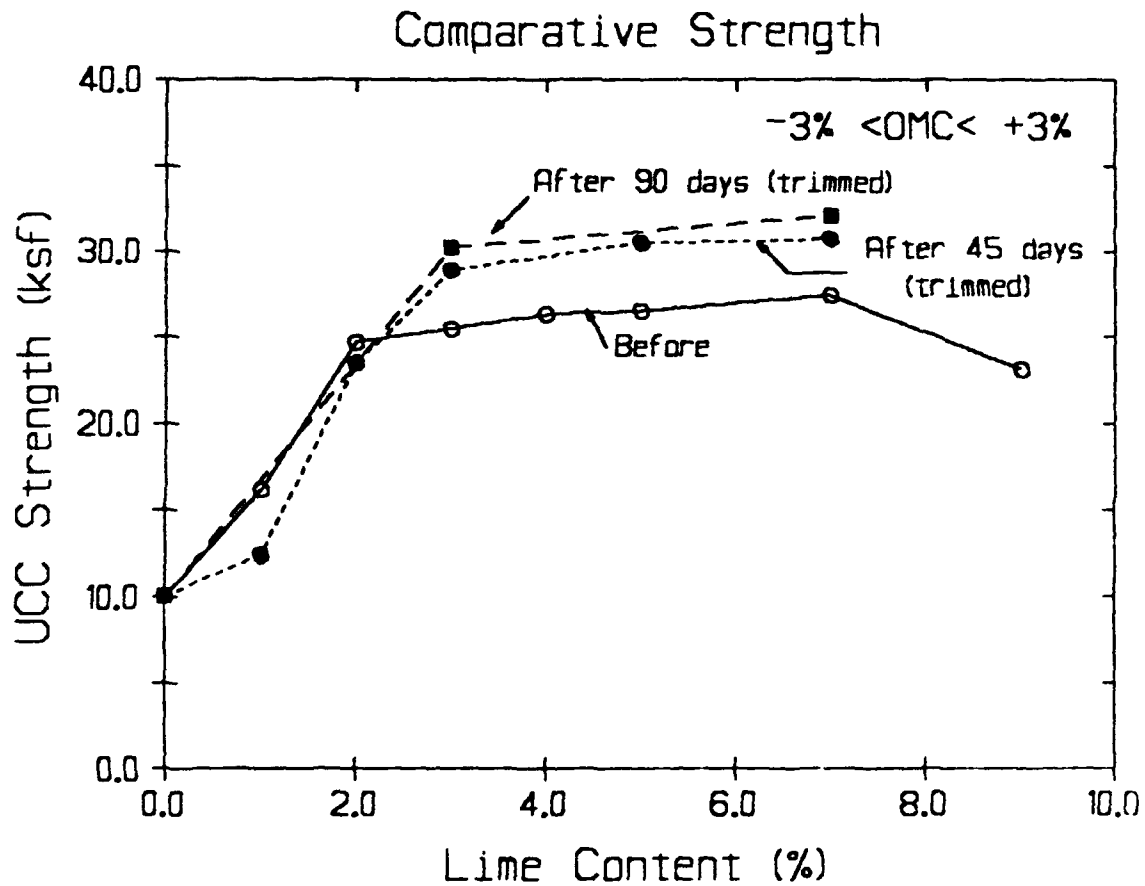

Figure 87. Strength changes in Site No. 2 samples after leaching (trimmed samples).

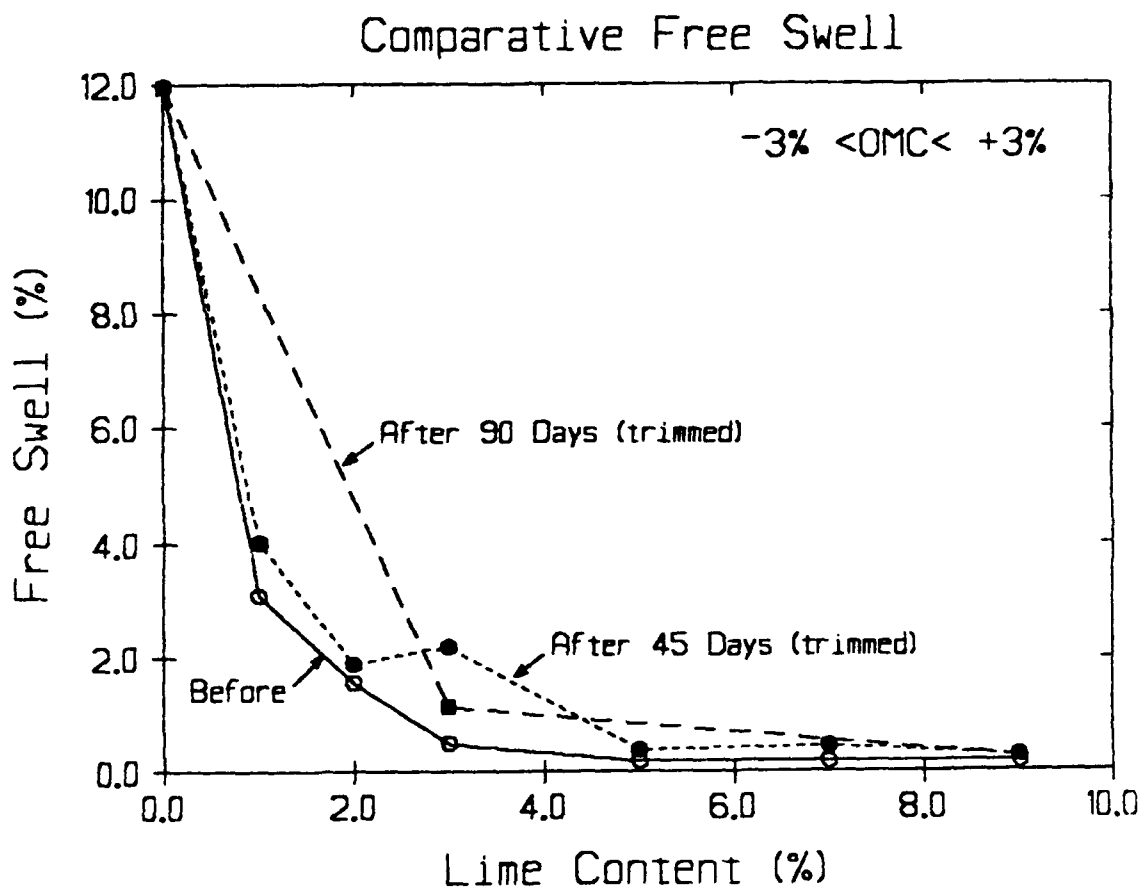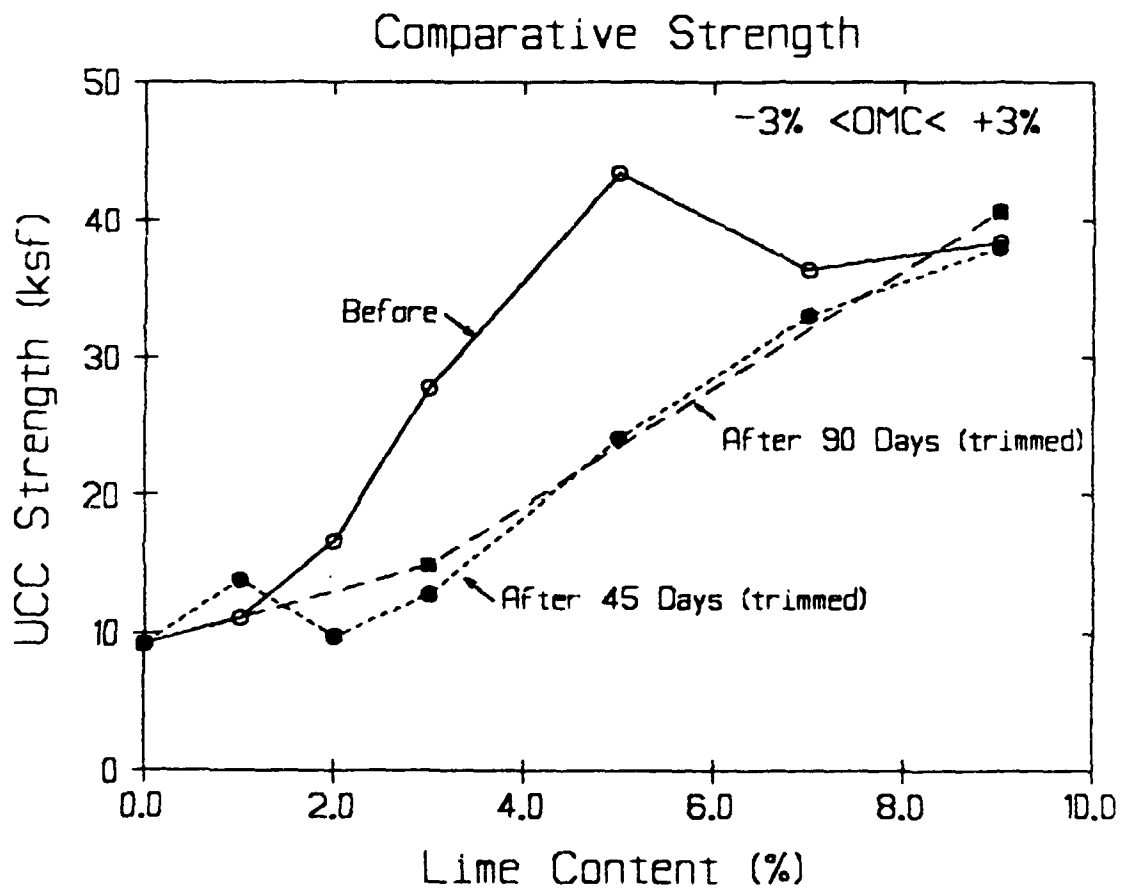Figure 88. Strength changes in Site No. 3 samples
after leaching (trimmed samples).

samples from Sites No. 1 and 3 and at approximately four percent for Site No. 2 material. At lime contents greater than these, the strengths results after leaching surpassed the strength before leaching.

218. Maximum st, ngth after leaching occurred in samples compacted at optimum moisture for Sites No. 1 and 2 material. Minimum strength after leaching took place in samples compacted dry of optimum.

219. The strain at failure for all three sites behave similarly. Failure strain decreased sharply as lime content increased for samples before leaching, which is typical of soil-cement or other brittle products (Thompson 1966; Biswas 1972). After leaching, the strain at failure increased for all lime contents but remained well below that of the natural soil.

220. Reworked vs. Trimmed. The soils from all sites displayed large decreases in reworked strength before leaching as was discussed previously in this chapter and shown in Figure 26. When samples were leached 45 days, broken down, recompacted and tested in unconfined compression tests, they displayed strengths approximately equal to their reworked strengths before leaching (Figures 89 through 91). In Site No. 2 samples, the reworked, after leach strengths were slightly less than before leach tests; Site No. 3 samples were slightly stronger after leaching than before leaching; and for Site No. 1 samples, before and after leach reworked strengths were approximately equal. This would indicate that once a lime treated soil is cured then broken down and recompacted, leaching has very little influence on strength as all reworked strengths have been severely reduced by reworking.
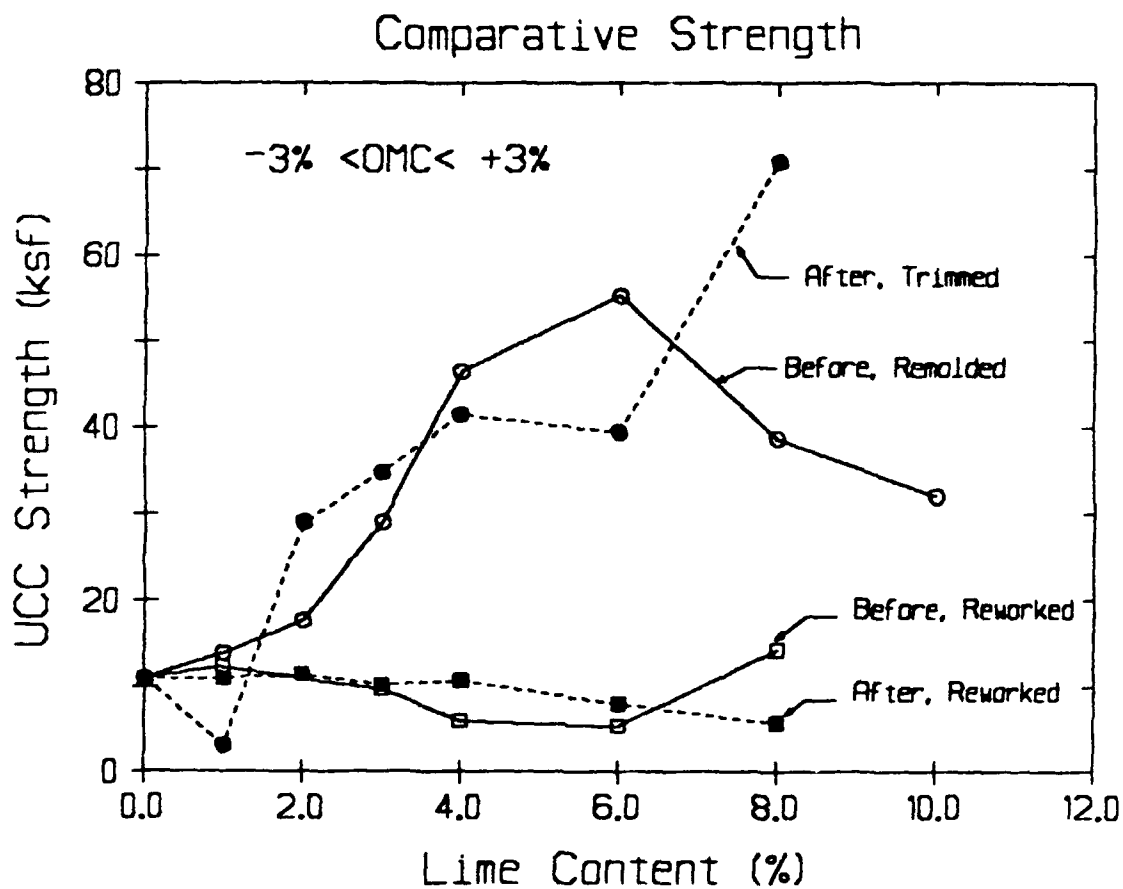
Figure 89. Comparison of strength changes in Site
No. 1 samples after leaching (trimmed vs reworked).
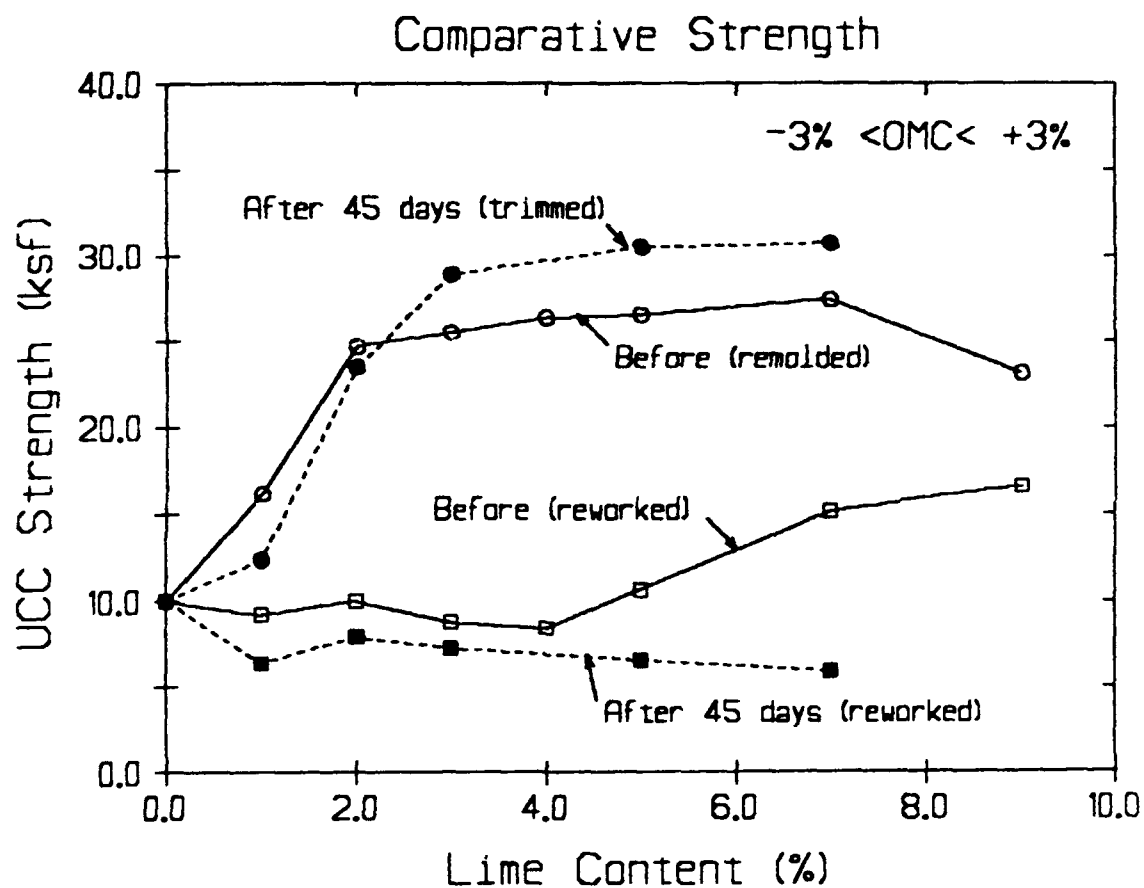
Figure 90. Comparison of strength changes in Site No. 2 samples after leaching (trimmed vs reworked).
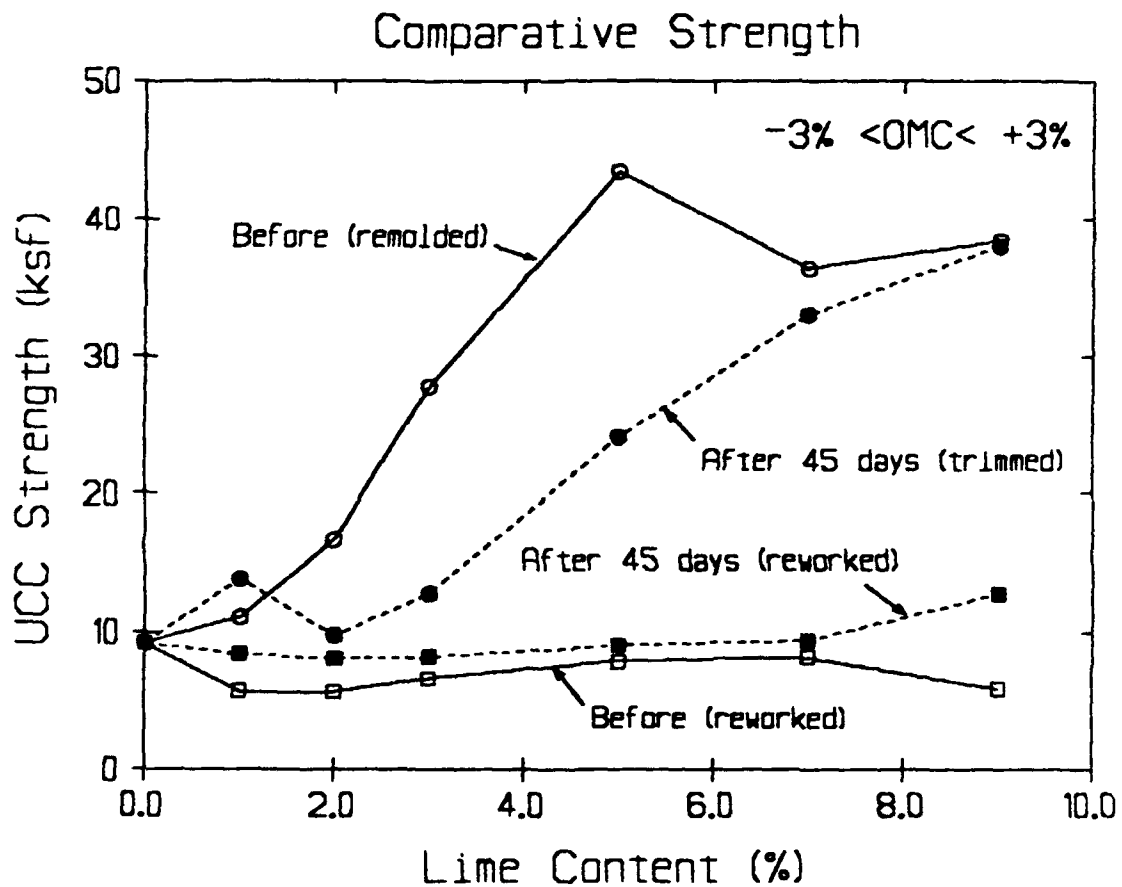
Figure 91. Comparison of strength changes in Site
No. 3 samples after leaching (trimmed vs reworked).

Analysis of Physical Property Changes

221. Tables 13, 14 and 15 present summaries of the percentage changes in physical properties after leaching 45 and 90 days for samples from Sites No. 1, 2 and 3, respectively. It is important to remember that while some of the percentage changes appear relatively large, they must be viewed with respect to their original or "before" leaching data. For example, a free swell percentage increase of 150 percent may initially seem significant, but considering that is only an increase from 0.14 to 0.35 percent, it may be statistically significant but most probably is not physically significant. However, other test result, though they exhibit smaller percentage changes, are possibly very physically significant, especially in the areas of strength and Atterberg limits.

222. For each physical property change tested for all three sites, there was a lime content determined beyond which the change in property measured after leaching was not significantly different from that measured before leaching. In fact, in most instances, after this lime content had been reached, properties measureds after leaching were actually improved. This "optimal" lime content varied slightly between physical tests. For example, for Atterberg limits and linear shrinkage, the "optimal" lime content was found to be between five and six percent, while for swelling properties, it varied between seven and eight percent. For strength measurements after leaching, it was found that minimal change occurred after leaching once a lime content of approximately seven percent had been added to the soils.

223. Therefore, all changes in physical properties during leaching tend to be minimized at the five to eight percent lime content. It turns out that this amount of lime is at or slightly above the amount necessary to alter the soil-lime reactions from primarily cation exchange, ion crowding, and flocculation/aggromeration to

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TABLE 13

SITE NO. 1, PERCENT CHANGES IN PHYSICAL PROPERTIES AFTER LEACHING

Percent Property Change (%)

Physical Property	1% Lime			2% Lime		3% Lime			4% Lime			6% Lime				8% Lime
	+OMC*	045	-OMC	045	+OMC	045	090	-OMC	+OMC	045	-OMC	+OMC	045	090	-OMC	045
Liquid Limit	+1.6	0.0	+1.6	-11.3	-1.6	-8.3	-10.0	-8.3	+3.6	-5.4	-3.6	-50.1	-13.6	-11.2	-8.5	-11.9
Plastic Limit	-17.5	-22.5	-17.5	-25.0	-17.0	-17.0	-27.7	-19.1	-13.0	-15.2	-17.4	-10.9	-17.4	-15.21	-13.0	-8.5
Plasticity Index	+36.4	+40.9	+36.4	+35.7	+53.8	+23.1	+52.8	+30.8	+80.0	+40.0	+60.0	+15.3	0.0	0.0	+7.7	-25.0
Linear Shrinkage	-16.0	-12.7	-8.3	-16.4	+14.3	+38.5	-2.2	+8.8	+8.5	+14.1	-5.6	-48.3	-41.4	-43.7	-36.8	-74.7
Trimmed Samples																
Swell Pressure	+41.1	+11.6	+30.0	+10.9	+33.0	+37.5	+39.0	+0.1	+48.9	+41.7	+2.5	+51.2	+97.7	+16.5	+13.0	+43.2
Free Swell	+24.3	+54.1	+47.3	+3.8	+52.9	+11.8	+55.9	-47.1	+145.0	+115.0	-15.0	+157.1	+150.0	+92.9	+42.9	+21.7
Shear Strength	-48.9	-76.8	-20.0	+0.2	+25.6	+19.3	+9.7	-60.3	-4.6	-10.8	-38.9	+5.7	-28.7	-26.3	-29.2	+83.1
Reworked Samples																
Swell Pressure	+82.0	+53.5	+39.5	+51.5	+167.2	+146.4	+77.0	+244.1	+274.9	+76.4	+46.7	+27.0	+27.2	+72.4	+76.7	+22.6
Free Swell	+162.2	+125.7	+79.2	+73.1	+126.5	+191.2	+155.9	+294.1	+420.0	+225.0	+225.0	+66.7	+171.4	+285.7	+157.1	-17.4
Shear Strength	-15.3	-10.9	-16.3	+3.5	+5.4	+5.4	+14.3	+7.0	+61.4	+78.5	+56.4	+41.5	+48.7	+67.4	+35.2	-59.9

* 045 = Optimum moisture, 45 day leaching; 090 = Optimum moisture, 90 day leaching; -OMC = Below optimum moisture, 45 day leaching; +OMC = Above optimum moisture, 45 day leaching.

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TABLE 14

SITE NO. 2, PERCENT CHANGES IN PHYSICAL PROPERTIES AFTER LEACHING

Percent Property Change (%)

Physical Property	1% Lime			2% Lime		3% Lime			5% Lime			7% Lime			
	OMC*	045	-OMC	045	+OMC	045	090	-OMC	+OMC	045	-OMC	+OMC	045	090	-OMC
Liquid Limit	0.0	-4.1	-18.4	+2.1	+6.6	0.0	0.0	-4.4	0.0	-8.3	0.0	-2.1	-14.9	0.0	+4.3
Plastic Limit	-18.2	-24.2	-36.4	-6.3	+3.1	-3.1	-3.1	-15.6	+2.9	-5.9	0.0	+5.9	-11.8	+2.9	-5.9
Plasticity Index	+37.5	+37.5	+18.8	+18.8	+15.4	+23.1	+7.7	+18.8	-7.1	-14.3	0.0	-23.1	-23.1	-7.7	+30.8
Linear Shrinkage	+140.7	+101.7	+116.9	+142.6	+109.7	+174.2	+80.6	+193.5	0.0	+10.9	+36.4	-36.3	-40.0	-56.4	+70.9
Trimmed Samples															
Swell Pressure	-13.7	-14.2	-54.0	-13.8	+2.4	-30.8	+17.1	-40.2	-20.2	-34.4	-20.2	+9.4	-13.0	-18.7	-7.4
Free Swell	-71.4	-79.7	-85.7	-33.3	+94.1	+5.9	+5.9	-11.8	0.0	-5.9	0.0	+136.4	+72.7	+18.2	+127.3
Shear Strength	-36.3	-22.9	-71.8	-4.8	-25.0	+13.4	+18.6	-81.0	+8.5	+15.1	-40.1	-7.5	+12.1	+16.8	-75.8
Reworked Samples															
Swell Pressure (psf)	-12.3	+0.1	-14.2	+23.5	+24.8	+6.0	+34.8	-3.9	-5.0	+45.4	+9.2	-3.7	+11.2	-5.6	+16.9
Free Swell (%)	-22.5	-44.5	-45.1	+223.3	+417.6	+282.4	+158.8	+605.9	+129.4	+147.1	+394.1	+90.9	+127.2	+100.0	+227.3
Shear Strength (ksf)	-40.1	-31.1	-50.9	-20.9	-1.4	-17.4	-29.3	-32.2	-33.7	-38.3	-39.6	-59.9	-61.1	-60.9	-60.5

* 045 = Optimum moisture, 45 day leaching; 090 = Optimum moisture, 90 day leaching; -OMC = Below optimum moisture, 45 day leaching; +OMC = Above optimum moisture, 45 day leaching

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TABLE 15

SITE NO. 3, PERCENT CHANGES IN PHYSICAL PROPERTIES AFTER LEACHING

Physical Property	Percent Property Change (%)							
	1% Lime	2% Lime	3% Lime		5% Lime	7% Lime	9% Lime	
	045*	045	045	090	045	045	045	090
Liquid Limit	-5.7	+16.4	+17.9	+1.8	-5.3	-3.8	-1.8	0.0
Plastic Limit	-5.3	-22.2	-22.2	-11.1	-13.3	+7.1	+2.3	+2.3
Plasticity Index	-6.3	+125.0	+181.8	+54.5	+25.0	-45.4	-16.7	-8.3
Linear Shrinkage	+18.1	+148.1	+276.6	+117.0	+69.2	-5.1	+54.2	+95.8
Trimmed Samples								
Swell Pressure	-18.4	+28.0	+51.7	+47.9	+20.4	+31.2	+12.9	-7.2
Free Swell	+30.0	+20.4	+340.0	+128.0	+105.3	+142.1	+52.6	+47.4
Shear Strength	+25.2	-41.5	-53.8	-46.2	-44.5	-9.1	-1.0	+5.8
Reworked Samples								
Swell Pressure	+39.0	+101.6	+89.7	+42.8	+35.5	+56.7	+25.1	+4.3
Free Swell	+86.1	+268.2	+850.0	+470.0	+410.5	+194.7	+131.6	+89.5
Shear Strength	+45.8	+43.1	+23.8	+136.8	+15.0	+14.8	+116.2	+38.6

* 045 = Optimum moisture, 45 day leaching; 090 = optimum moisture, 90 day leaching

pozzolanic reactions. It is possible that the same soil-lime interactions used to explain the changes in permeability with leaching and lime content variations may be useful in explaining changes in shrinkage, Atterberg limits, swelling and, to some degree, strength.

224. It is speculated that for soil-lime mixtures below approximately six percent lime for all three sites, calcium can be leached out of the system in sufficient quantity that the mixture loses some of its cation exchange and flocculation properties that it had gained in a static moisture (finite amount of moisture present in the system) environment. This is possibly due to the large quantity of water molecules suddenly introduced in the soil-water system during leaching. The increase in water molecule concentration will cause the system to attempt to diffuse any absorbed calcium cations on the clay surface (a large increase in dipolar water molecules versus no increase in calcium cations) and tend to increase the absorbed water layer surrounding the clay particles. The charge on the clay particle's surfaces will once again become largely negative and unbalanced. This will increase the soil's affinity for water, which would alter its plasticity index, shrinkage, and swelling characteristics.

225. Additionally, when the lime content is below optimum concentration for maximum pozzolanic reactions (pH < 12.45), the flocculation bonding is weak and could possibly be removed simply by flowing or leaching water as suggested by Diamond and Kinter (1965). This theory is supported by swell pressure diagrams from all three soil sites, by Sites No. 1 and 2 free swell diagrams, and by Site No. 1 plasticity graph, especially since samples leached 90 days showed larger increases in PI, free swell, and swell pressure than those leached 45 days. After enough lime is added to the soil, the increase in water molecules in the soil-lime system is offset by

the amount of calcium cations present, and the pH is sufficiently high that pozzolanic reaction products are permanently altering the soil-lime mixture.

226. It is known that pozzolanic reactions occur even with small additions of lime when added to lime reactive clays (Thompson 1966, 1970). These reactions depend highly on the clay mineralogy, water content and pH of the soil. Sufficient calcium silicate hydrates and calcium aluminate hydrates are generated in high pH environments to produce long-term strength gains (Little 1987). Porewater must be present at optimum levels to aide in the pozzolan formations, yet not interfere in the reactions. It is speculated that when additional water is added in such a large quantity, as during saturation and leaching, the additional water prevents adequate pozzolan formation until the amount of calcium present is sufficient to offset the disruptive nature of the water molecules. This may have a tendency to push the lime stabilization optimum (LSO) to the right, i.e., require slightly more lime to achieve maximum strength gains.

227. Before leaching, maximum pozzolanic reaction (or LSO) was shown to be between six and seven percent lime content based on strength gains for material from Sites No. 1, 2 and 3 (Figure 26). In general, strength gains after leaching 45 and 90 days tend to be less after leaching than before leaching, especially at the lower lime contents. The most dramatic losses occurred for all three sites when the soils were treated with only one to three percent lime. After approximately seven or eight percent lime had been added to the soils from Sites No. 1 and 3, the strength of samples after leaching were equal to or larger than those before leaching.

228. Although this study showed that the "optimal" lime content varied between five and eight percent, depending on what physical property is measured, it appears that a minimum of a one percent lime content above the normal LSO for all three site would minimize the changes in all physical properties caused by leaching.

Lime contents of seven to eight percent for soil from the three sites tested would most likely minimize leaching effects, to include strength loss, which appears to require the largest amount of lime to offset the detrimental phenomena of leaching.

229. Reworking samples probably breaks down much of the pozzolanic cementation that has occurred during curing, resulting in the material being much more susceptible to swelling and causing dramatic reductions in strength. This area of research suggests that these soil-lime mixtures may not exhibit as much autogenous healing, particularly after prolonged leaching, as they are generally believed to have (Thompson and Dempsey 1968; Transportation Research Board 1987). Perhaps longer curing time or additional moisture may improve strength gains after reworking, but that is beyond the scope of this research.

230. The amount of moisture added during compaction plays an important role in determining after leach changes. It is known that water content is critical to cation exchange, flocculation and pozzolanic reactions. It is speculated that too much or too little moisture sufficiently alters these processes during the curing phase, varying in degree with which engineering property is measured. Sites No. 1 and 2 samples compacted wet of optimum then leached, showed the highest increases in plasticity index, free swelling and swell pressure, but only slightly less strength. Beneficial results for wet of optimum samples were that they displayed the lowest permeabilities and linear shrinkage after leaching.

231. Leached samples that had been compacted and cured at moisture contents dry of optimum, displayed varied reactions after leaching. Samples compacted dry displayed smaller increases in swelling properties and plasticity indexes after leaching than those tested at optimum moisture. Dry samples also showed a slightly higher linear shrinkage after leaching than those compacted at other moisture contents. However, samples compacted dry exhibited the largest

permeabilities during testing and extremely large decreases in strength after leaching.

Leach Tests — Chemical Property Changes

232. The complete results for all chemical analyses are shown in Tables 16, 17, and 18 for Sites No. 1, 2 and 3 samples, respectively, for material compacted at optimum moisture. Test results are the averages of at least four tests (two leach tests split in half and tested independently). Samples were first cured 48 hours at 120 °F then an additional 45 or 90 days at 70 °F. Samples were tested before leaching and tested again after leaching 45 and 90 days. The chemical test results of samples compacted wet and dry of optimum moisture then leached 45 days are shown in Tables D5 through D8 in Appendix D for Sites No. 1 and 2 material. Site No. 3 samples were only tested at optimum moisture content.

Soil pH

233. <u>Site No. 1 Soil pH</u>. Figure 92 shows the change in Site No. 1 soil pH after 45 and 90 days of leaching for samples compacted at optimum moisture. Samples leached 90 days showed a larger reduction in pH than those leached 45 days. The pH reduction after 45 and 90 days at three percent lime was 1.20 and 2.23, respectively, while in samples with six percent lime, the reductions were 0.56 and 1.66, respectively. This is consistent with field studies that showed the soil-lime pH gradually reduces with time and approaches the natural soil's values (McElroy 1982). However, with more lime in the soil, the decrease in pH will take longer to reach its natural pH. This agrees well with the pH analyses of the leachate.

234. The changes in soil pH for samples compacted wet and dry of optimum are shown in Figure E21 in Appendix E. All samples were leached for 45 days

TABLE 16

SITE NO. 1, CHEMICAL PROPERTY CHANGES
(-3% < OMC < +3%)

Chemical Property	0% Lime			1% Lime		2% Lime		3% Lime				4% Lime		6% Lime				8% Lime	
	B45*	A45	A90	B45	A45	B45	A45	B45	B90	A45	A90	B45	A45	B45	B90	A45	A90	B45	A45
EDTA Titration (ml)	5.9	--	--	7.7	5.7	7.8	6.1	8.2	6.0	6.5	5.9	9.2	6.6	12.8	9.8	8.5	7.0	17.7	11.6
Soil pH	8.40	8.20	8.10	11.47	10.77	12.31	11.07	12.40	12.40	11.20	10.17	12.44	11.45	12.45	12.45	11.89	10.79	12.50	11.90
Porewater Cations (meq/1)																			
Calcium	15.17	6.22	4.75	10.85	8.41	9.28	9.39	8.29	10.50	6.95	6.04	7.90	8.95	7.20	7.82	9.21	8.52	6.76	6.11
Sodium	4.66	1.74	0.86	3.86	2.45	3.55	2.06	3.54	4.00	0.96	0.65	4.20	0.62	5.50	5.39	1.12	0.40	6.13	1.02
Magnesium	0.30	0.20	0.17	0.09	0.17	0.11	0.15	0.12	0.13	0.17	0.24	0.11	0.25	0.06	0.13	0.11	0.20	0.01	0.01
Potassium	0.32	0.27	0.17	0.21	0.27	0.23	0.27	0.24	0.27	0.29	0.17	0.26	0.24	0.30	0.37	0.31	0.19	0.36	0.33
Exchange Complex Cations (meq/100 g)																			
Calcium	34.56	35.00	33.15	36.45	34.72	39.90	38.55	44.46	36.09	36.75	39.04	49.80	38.53	61.49	53.39	44.78	42.68	72.29	57.01
Sodium	1.08	0.65	0.49	1.15	0.57	1.27	0.78	1.40	1.02	0.31	0.29	1.52	0.24	1.65	1.71	0.37	0.15	1.52	0.45
Magnesium	0.99	0.88	0.41	0.48	0.51	0.71	0.78	1.03	0.89	0.98	1.14	1.37	1.00	1.71	1.35	1.23	1.20	1.27	1.03
Potassium	0.78	1.00	0.98	0.77	0.69	0.71	0.71	0.73	0.71	0.69	0.67	0.74	0.62	0.83	0.86	0.76	0.64	0.94	0.79

* B45 = Before leaching, cured 45 days; B90 = Before leaching, cured 90 days; A45 = After leaching 45 days; A90 = After leaching 90 days

TABLE 17

SITE NO. 2, CHEMICAL PROPERTY CHANGES
(-3% < OMC < +3%)

Chemical Property	0% Lime			1% Lime		2% Lime		3% Lime				5% Lime		7% Lime			
	B45*	A45	A90	B45	A45	B45	A45	B45	B90	A45	A90	B45	A45	B45	B90	A45	A90
Soil pH	8.40	8.32	8.22	11.36	10.63	11.99	11.18	12.20	12.20	11.57	10.83	12.62	12.25	12.63	12.63	12.18	11.91
Porewater Cations (meq/l)																	
Calcium	2.47	1.57	1.44	2.26	2.16	2.23	2.07	2.07	1.76	1.97	2.07	1.94	1.83	1.80	1.62	2.32	3.04
Sodium	0.57	0.23	0.09	0.57	0.08	0.37	0.10	0.38	0.36	0.08	0.08	0.39	0.11	0.52	0.93	0.12	0.10
Magnesium	0.16	0.13	0.12	0.17	0.12	0.16	0.16	0.17	0.13	0.15	0.15	0.13	0.13	0.07	0.01	0.12	0.06
Potassium	0.10	0.14	0.11	0.13	0.07	0.11	0.09	0.10	0.09	0.07	0.07	0.10	0.07	0.14	0.17	0.08	0.10
Exchange Complex Cations (meq/100 g)																	
Calcium	19.84	18.88	19.09	20.42	19.85	21.86	20.96	22.75	25.31	21.73	23.77	22.91	24.66	25.73	28.39	27.81	31.41
Sodium	0.08	0.0	0.0	0.10	0.01	0.08	0.01	0.07	0.06	0.0	0.0	0.09	0.01	0.11	0.16	0.0	0.01
Magnesium	0.31	0.28	0.29	0.41	0.30	0.50	0.52	0.65	0.71	0.58	0.59	0.67	0.75	0.94	0.77	0.87	0.69
Potassium	0.28	0.31	0.26	0.26	0.24	0.27	0.23	0.28	0.28	0.22	0.21	0.27	0.27	0.31	0.32	0.26	0.24

* B45 = Before leaching, cured 45 days; B90 = Before leaching, cured 90 days; A45 = After leaching 45 days; A90 = After leaching 90 days

TABLE 18

SITE NO. 3, CHEMICAL PROPERTY CHANGES
(-3% < OMC < +3%)

Chemical Properties	0% Lime			1% Lime		2% Lime		3% Lime				5% Lime		7% Lime		9% Lime			
	B45*	A45	A90	B45	A45	B45	A45	B45	B90	A45	A90	B45	A45	B45	A45	B45	B90	A45	A90
Soil pH	8.71	8.57	8.98	11.18	10.20	11.45	10.98	12.03	12.02	11.30	10.96	12.53	11.86	12.61	12.10	12.63	12.65	12.11	11.92
Porewater Cations (meq/l)																			
Calcium	6.69	4.99	1.12	6.50	3.65	5.68	5.05	6.30	6.72	3.84	6.26	6.30	8.41	6.09	6.30	5.60	3.84	6.29	6.14
Sodium	14.85	9.2i	3.39	13.64	8.66	11.78	8.19	11.60	13.56	4.29	2.52	12.09	3.43	12.36	2.55	12.67	11.09	2.69	2.55
Magnesium	2.08	0.94	0.23	0.27	0.13	0.19	0.28	0.14	0.13	0.18	0.16	0.11	0.13	0.12	0.10	0.01	0.07	0.10	0.11
Potassium	0.23	0.28	0.17	0.20	0.10	0.17	0.17	0.16	0.25	0.13	0.19	0.20	0.21	0.20	0.22	0.25	0.22	0.21	0.20
Exchange Complex Cations (meq/100 g)																			
Calcium	21.21	24.00	23.15	24.38	28.11	32.46	28.59	30.74	36.69	23.41	33.22	42.13	35.61	55.63	45.74	63.26	49.42	46.75	45.84
Sodium	3.68	2.99	1.79	3.54	2.19	4.42	2.66	3.15	3.64	1.19	0.66	2.68	0.81	3.17	0.72	2.77	3.26	0.76	0.82
Magnesium	2.39	1.99	1.99	1.37	1.88	1.69	1.40	1.96	1.78	1.04	1.20	1.58	1.88	2.00	1.82	1.74	1.11	1.48	1.02
Potassium	0.54	0.89	0.89	0.48	0.41	0.58	0.57	0.44	0.70	0.38	0.69	0.53	0.53	0.65	0.71	0.64	0.64	0.70	0.73

* B45 = Before leaching, cured 45 days; B90 = Before leaching, cured 90 days; A45 = After leaching 45 days; A90 = After leaching 90 days

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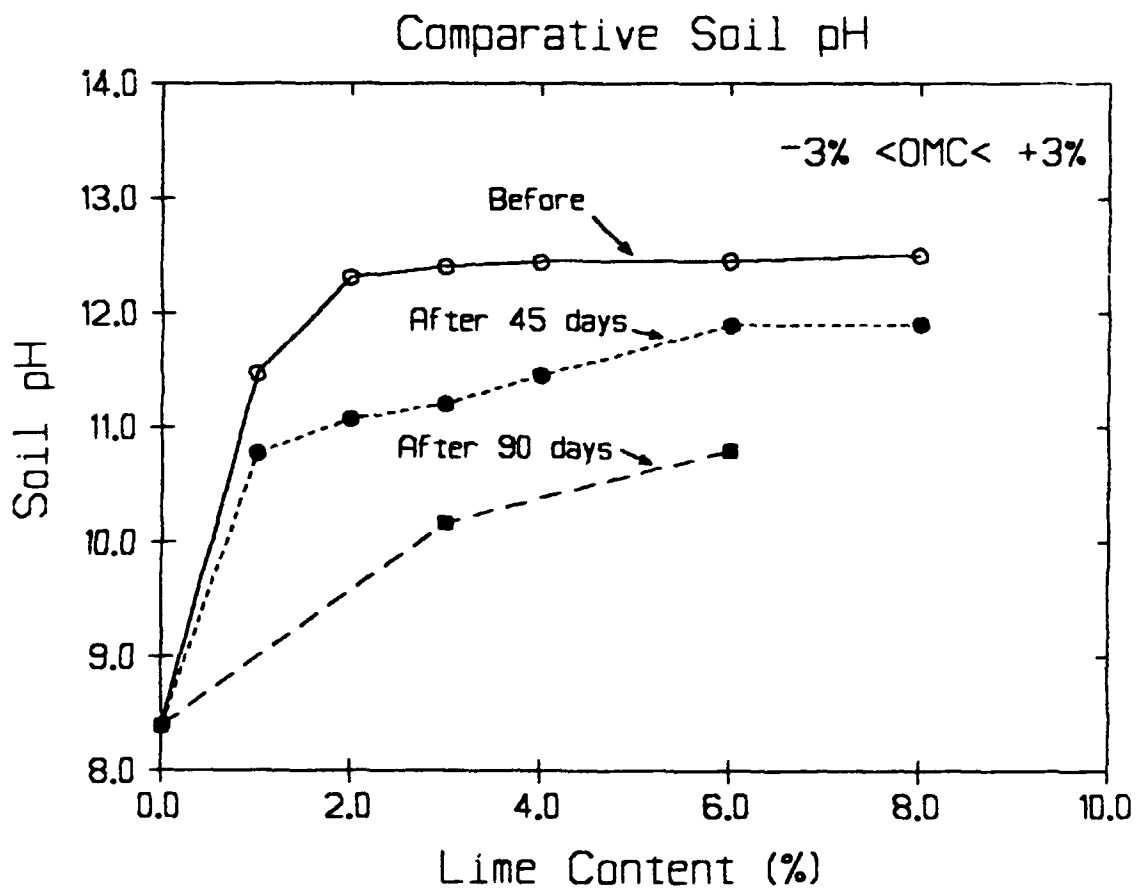
Figure 92. Soil pH changes in Site No. 1 samples after leaching.

only. Samples compacted wet and dry of optimum did not attain pH's as high as samples compacted at optimum moisture when tested before leaching. This trend continued after leaching as well, and dry samples displayed lower pH's than samples compacted at optimum. The largest drop in pH occurred for three percent lime treatment for dry samples (a decrease of 10.7 percent) while the smallest change in pH occurred for treatment with one percent lime for wet samples (an increase of 1.3 percent). Soils compacted wet tend to show the lowest change in pH after leaching, probably as a result of their lower permeabilities.

235. Site No. 2 Soil pH. Changes in Site No. 2 soil pHs after leaching 45 and 90 days are shown in Figure 93. This graph is similar to Figure 92 in that samples leached 90 days showed lower pH's than those leached 45 days and that the pH of leached samples were lower than samples not leached. Maximum decrease in pH occurred in samples compacted with three percent lime after 90 days of leaching (a 11.2 percent decline), with the smallest decrease recorded in samples with five percent lime (a 2.9 percent drop).

236. Figure E22 in Appendix E shows the effect that compacting wet or dry of optimum moisture will have on the soil's pH before and after leaching. All samples had approximately the same pH when tested before leaching regardless of the compaction moisture content. All samples displayed considerable decrease in pH after leaching with those compacted dry showing the largest drop in pH, the maximum occurring in samples treated with one and three percent lime (a 24.5 percent decline). Soils compacted wet or at optimum moisture showed similar pHs after leaching.

237. Site No. 3 Soil pH. Figure 94 shows the changes in Site No. 3 soil pHs after leaching 45 and 90 days, for samples compacted at optimum moisture. After 45 and 90 days of leaching, the pH of the soil had dropped significantly. The
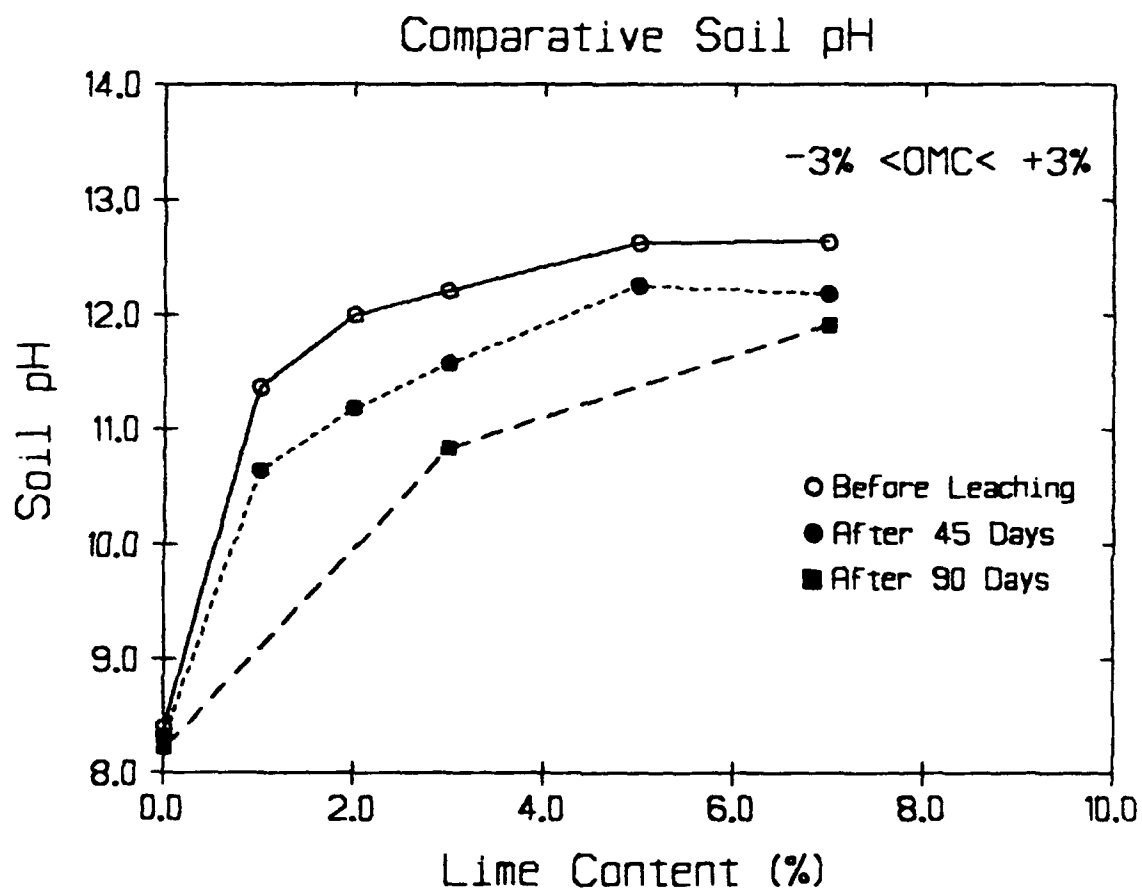
Figure 93. Soil pH changes in Site No. 2 samples after leaching.
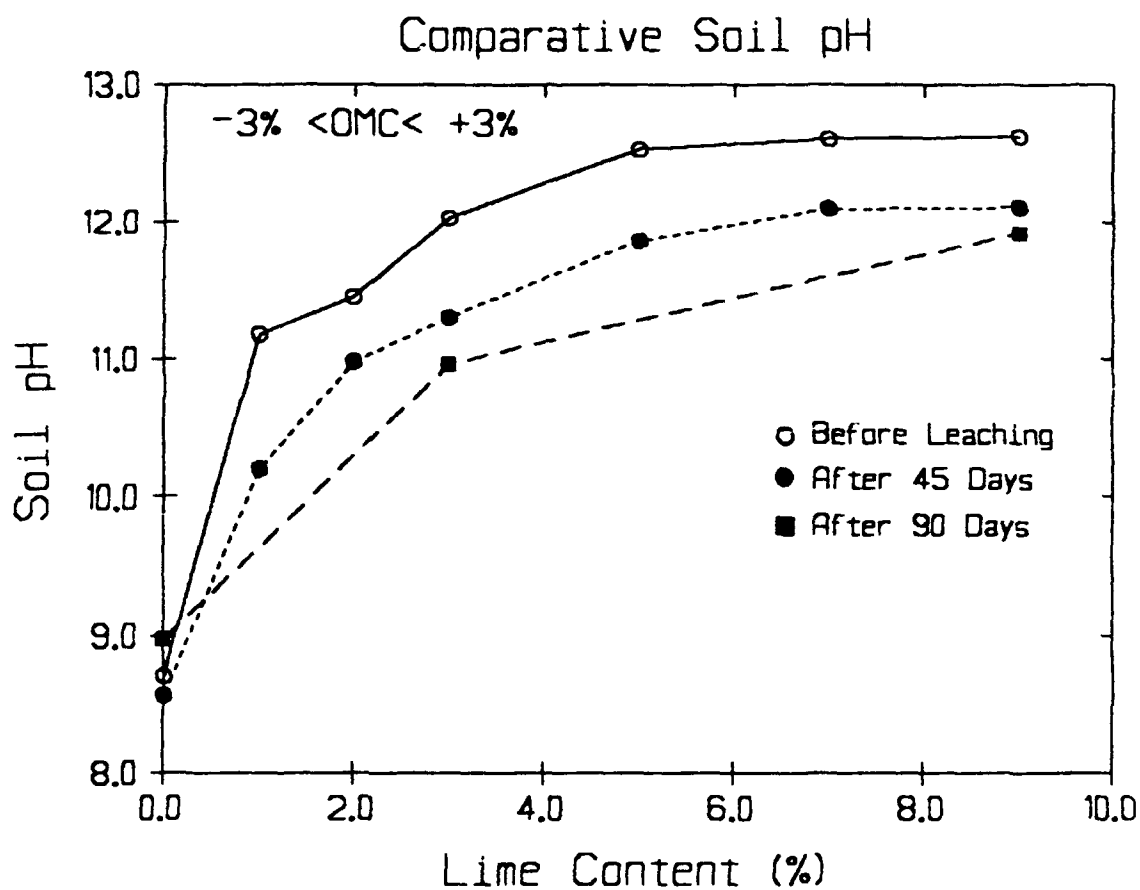
Figure 94. Soil pH changes in Site No. 3 samples after leaching.

maximum drop in pH was found in 90 day leached samples mixed with three percent lime and in 45 day leached samples with one percent lime (both with an 8.8 percent drop). The minimum decline occurred in samples with seven percent lime (a 4.0 percent decrease). The pH of samples leached 90 days showed lower pHs than those leached 45 days.

238. All sites showed similar pH phenomena before and after leaching. All sites showed that, before leaching, the soil's pH approached a maximum value after which the addition of more lime did not change the soil's pH significantly. For Site No. 1 soil, this maximum value was 12.44 at four percent lime; for Site No. 2 soil it was 12.62 at five percent lime; and for Site No. 3 soil it was 12.53 at five percent lime. After leaching 45 days, the pH of all three soils dropped but still approached a maximum value. These maximum values after leaching were 11.89 at six percent lime, 12.25 at five percent lime, and 12.10 at seven percent lime for the soil from Sites No. 1, 2 and 3, respectively. After these percentages of lime had been added to the soil, the change in pH after leaching remained fairly constant with the addition of more lime.

239. These reactions add support to the previously discussed theory that after the soil has approximately reached its lime stabilization optimum (LSO), pozzolanic reactions are predominant, and the soil-lime mixture is not as easily influenced by the addition of large amounts of water. Reduction in pH still occurs during leaching but at a slower rate than those tested below their LSO. For example, in Sites No. 2 and 3 samples mixed with seven and nine percent lime showed less reduction in pH after 90 days than those mixed with three percent lime.

Lime Content Estimations for Site No. 1

240. Measurement of the percentage lime left in Site No. 1 soil after leaching was attempted by using ASTM Standard Test D3155-84 to measure the amount calcium remaining in the samples. This test measures calcium concentration using a titration of 0.1 M EDTA (ethylenedinitrilo tetraacetate dihydrate) into aliquot of supernatant containing hydroxynaphthol blue indicator power. Ammonium chloride is used to extract the calcium from the soil sample. This test was designed for use on uncured samples (soil samples tested within eight hours of mixing with lime). However, provision was made in the test for longer (though unspecified) periods of mellowing as long as the calibration curve samples were mellowed the same period of time.

241. This procedure was first introduced by Rude (1965) as a quick method to determine the cement content in cement-treated base materials. He suggested that it was appropriate for lime stabilized materials, and that by increasing the stirring time, it was suitable for cement-treated materials up to six months old.

242. Figure 95 shows the results of testing samples after leaching 45 and 90 days and for samples mellowed for 45 and 90 days but not leached. It can be seen that, although the after leached curves are consistently less than the before leached curves (and approximately parallel in the case of the 45 day tests), the projected lime contents were unrealistic. In most cases, the estimated lime content after leaching was zero percent except for samples with six percent and eight percent lime which showed approximately 3.2 and 5.5 percent lime remaining in the samples. It is highly unlikely that three to four percent lime was leached out of the soil. The curves in Figure 95 are not corrected for EDTA titration at zero percent lime. This would only shift all four curves down with the projected differences remaining the same.
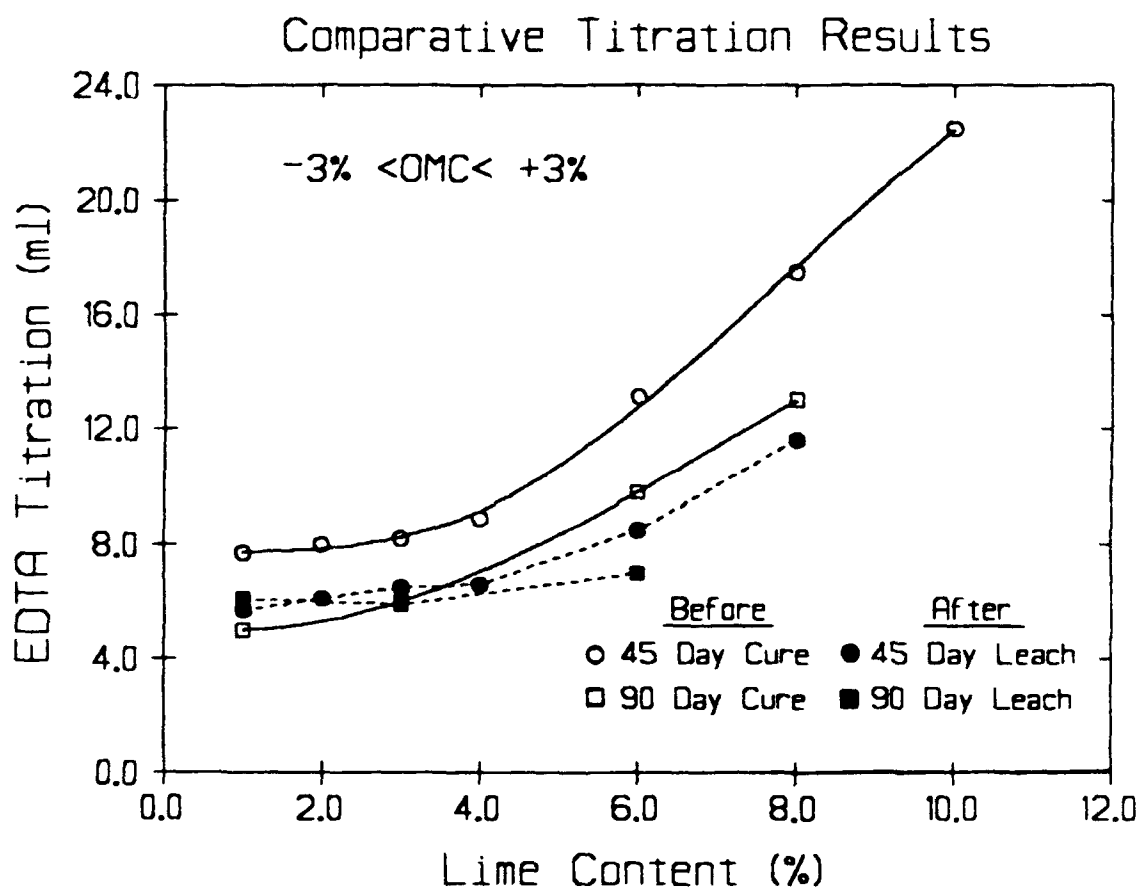
Figure 95. EDTA calcium titration before and
after leaching (Site No. 1).

243. It should be noted that traditional before leaching titration curves should be straight lines. Since these are not, it is speculated that the long curing periods (45 and 90 days) allow pozzolan formations which are very difficult to dissolve with one washing of ammonium chloride. With higher lime contents, the dissolution becomes even more difficult, increasing the differences between before and after leaching titration data.

244. It was decided that more washings were necessary with a stronger solution. The test for exchange complex cations uses a one normal (1N) solution of ammonium acetate with three washings to separate the cations (see Appendix A for test procedures). The calcium extracted was measured using ICP spectro-photometry with results converted from mg/l (ppm) to milliequivalents per 100 g (meq/100 g).

245. Figure 96 shows a plot of the average concentrations of calcium after 45 days of curing and compared to those after 45 days of leaching. In order to account for natural calcium found in the soil, a blank (zero percent lime) was run and subtracted from all data. Site No. 1 natural soil contained approximately 34.5 meq/100g of calcium. A straight line should theoretically go through the points starting at zero. Figure 96 shows that a linear regression analysis puts the straight line a little below zero (intercept at -2.99 meq/100 g) with a correlation coefficient, r, equal to 0.99.

246. Table 19 presents the predicted values of lime content after leaching 45 and 90 days based on Figure 96 using multiple washings of ammonium acetate. The results are also largely unrealistic. The tests showed post- leaching lime contents to have dropped to 1.4 percent lime for those initially with two percent lime to retaining only 2.7 percent lime after initially containing 6.0 percent lime. It is
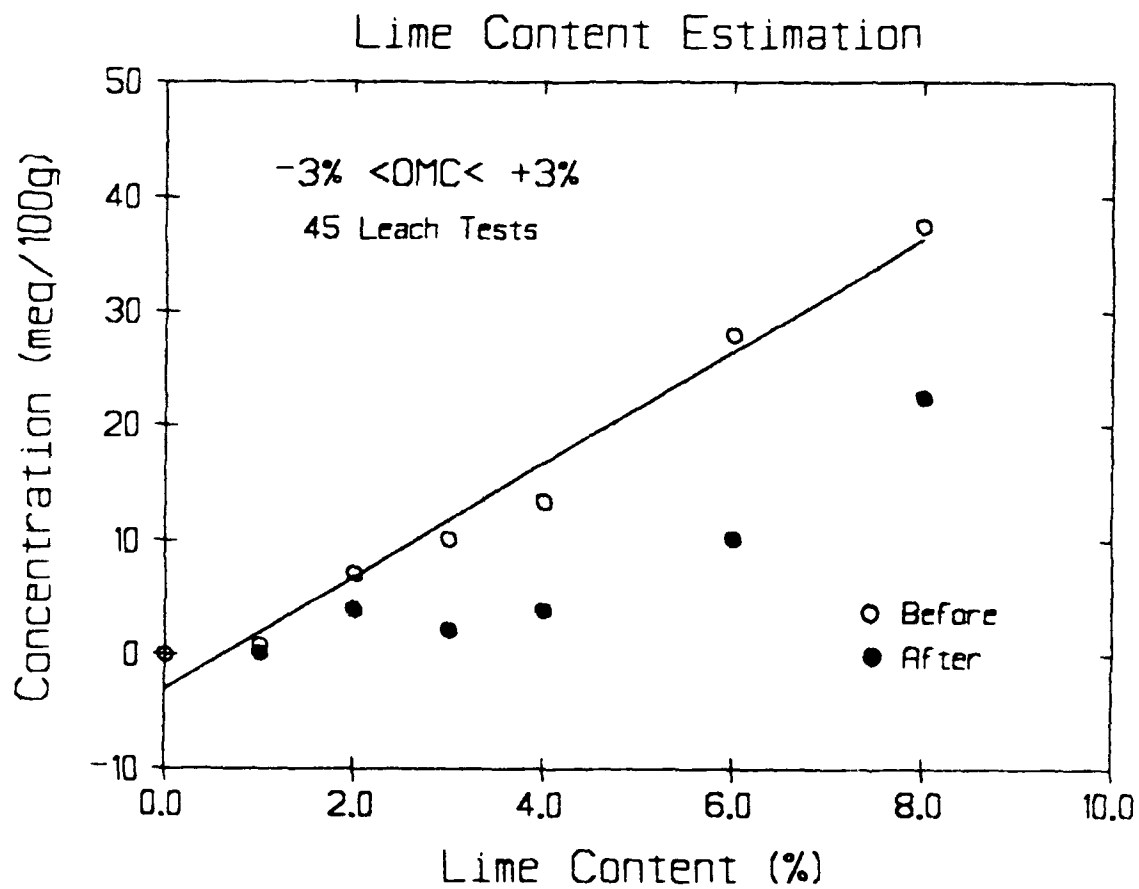
Figure 96. Calcium extractions used to determine lime content before and after leaching 45 days.

speculated that even with using three washings of ammonium acetate, the calcium complexes may not be totally dissociated.

TABLE 19

SITE NO. 1, LIME CONTENT ESTIMATION USING AMMONIUM ACETATE
(-3% < OMC < +3%)

Lime Content (%)	Calcium Concentration (meq/100 g)[*]				Projected Lime Content (%)	
	Before 45	After 45	Before 90	After 90	After 45[**]	After 90
1	0.86	0.16	--	--	0.6	--
2	7.10	3.99	--	--	1.4	--
3	10.17	2.19	1.53	4.48	1.1	3.5
4	13.33	3.97	--	--	1.4	--
6	27.96	10.22	18.83	8.12	2.7	2.6
8	37.49	22.45	--	--	5.2	--

[*] All data corrected for calcium content at 0% percent lime.
[**] Linear regression yields lime (%) = (conc. in meq/100 g + 2.99) / 4.91.

Porewater Cations

247. The cations in the porewater were extracted and measured for samples cured 45 and 90 days at 70 °F (plus 48 hours at 120 °F) and for those leached 45 and 90 days after during 48 hours at 120 °F. Calcium, sodium, magnesium and potassium concentrations were measured using ICP spectrophotometry. Results were converted from mg/l (ppm) to milliequivalents per liter (meq/l).

248. <u>Porewater Calcium</u>. Figure 97 shows the concentration of porewater calcium for Site No. 1 samples compacted at optimum moisture then leached for 45 and 90 days. Figure 97 indicates that there is a high initial concentration of calcium present in the soil, but it is easily removed after leaching if no lime is present. The longer the leach duration, the larger the decline of porewater calcium in the natural soil. Calcium was leached from the soil in significant amounts until approximately four percent lime had been added. Additional increase in lime content had no additional increase in the amount of calcium remaining in the porewater. There is a larger difference in before leaching versus after leaching concentrations after 90 days of leaching than after 45 days of leaching. At three percent lime there is a 16.2 percent decrease in before leaching concentrations after 45 days leaching and a 42.5 percent decrease after 90 days.

249. Figure 98 is a typical graph showing the comparisons of porewater concentrations for samples compacted wet, dry or at optimum moisture content. All remaining moisture compaction comparison graphs for porewater and exchangeable complex extractions are shown in Appendix E. Samples compacted dry of optimum displayed the largest reduction in porewater calcium at lime contents below four percent. Samples compacted wet produced similar calcium concentration reductions at all lime contents (averaged 15.8 percent) except for those samples treated with one percent lime, which showed a slight increase in calcium concentration after leaching (8.9 percent increase). Samples compacted at optimum moisture appeared to have the greatest ability to retain calcium after leaching, particularly for lime contents of four percent or greater.

250. Only a small quantity of calcium was present in Site No. 2 natural soil, but this small amount was readily removed by leaching (Figure 99). The longer the leach duration, the more calcium that was removed. Samples tested before leaching
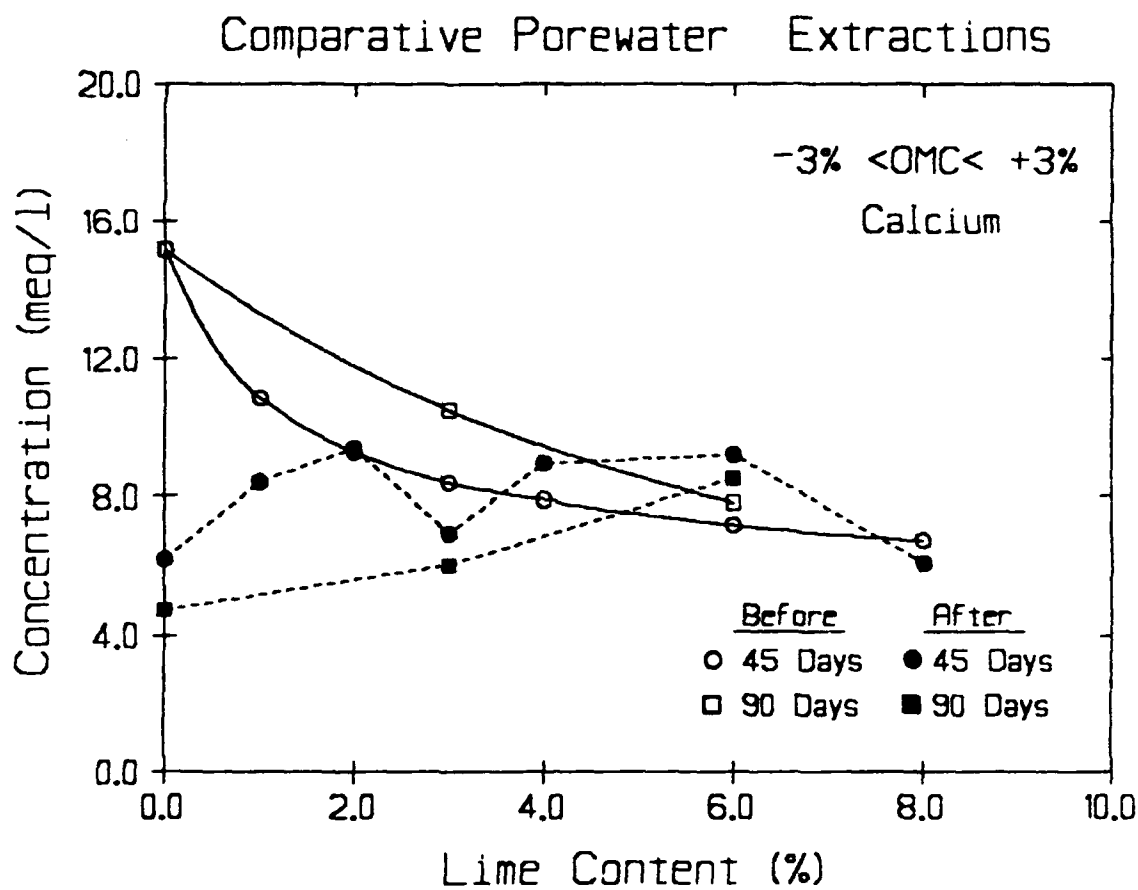
Figure 97. Calcium concentration in the porewater
of Site No. 1 samples after leaching.
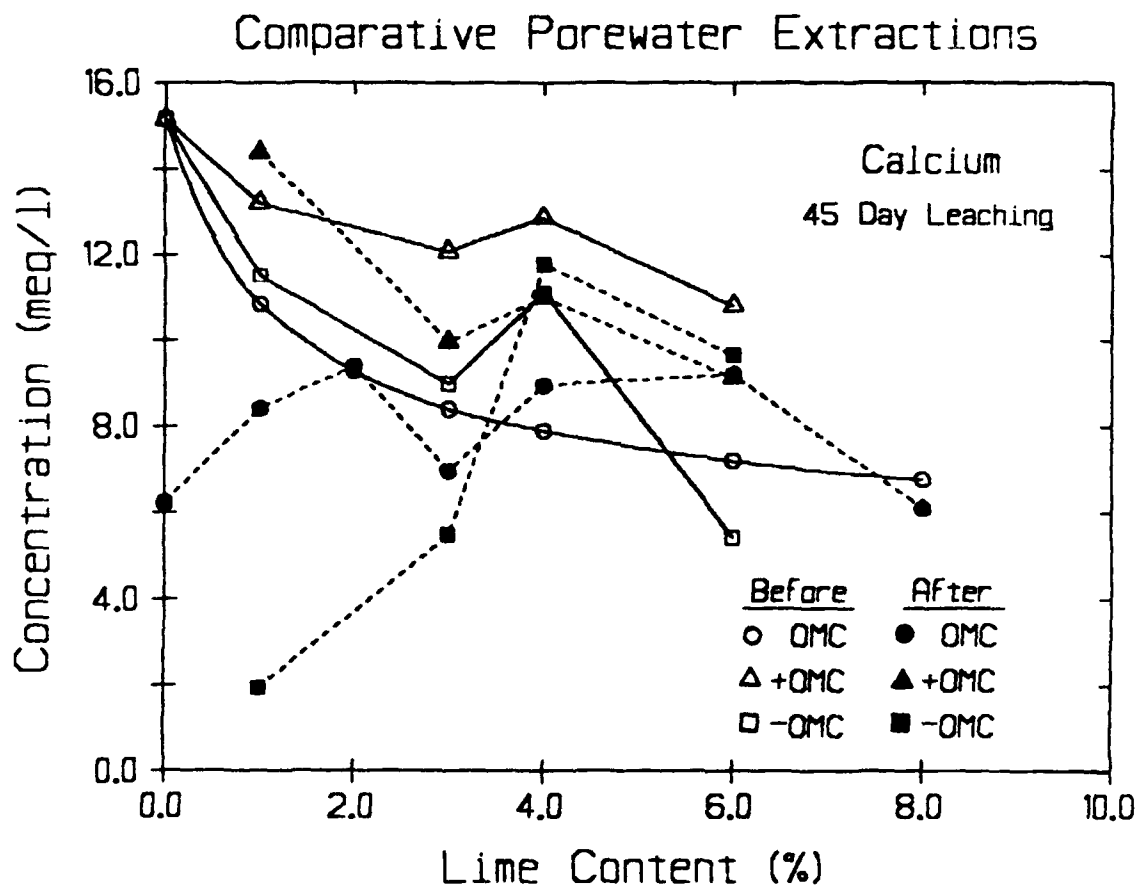
Figure 98. Moisture content effects on calcium in the porewater of Site No. 1 samples after leaching 45 days.
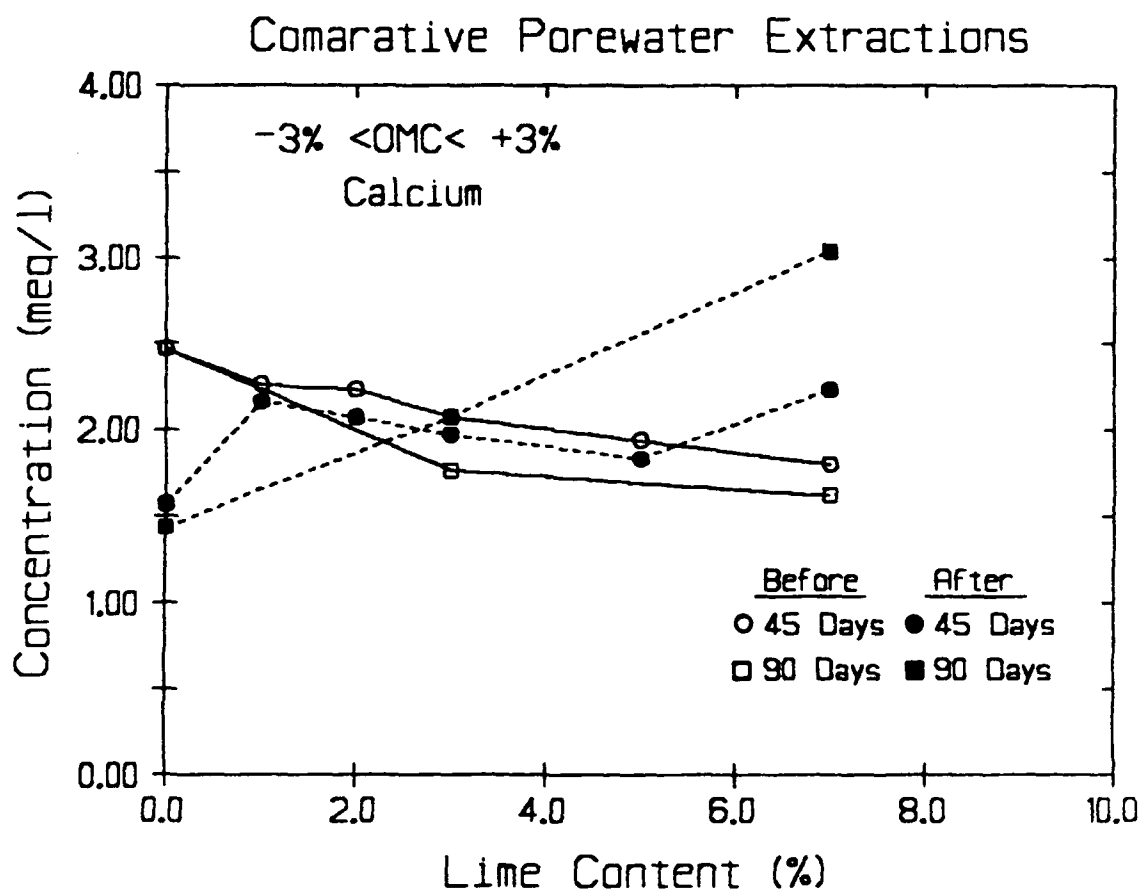
Figure 99. Calcium concentration in the porewater of Site No. 2 samples after leaching.

showed that the calcium in the porewater diminished as the amount of lime increased. After leaching, calcium concentrations in the porewater were less than they were before leaching, but with additional lime, the amount of washout reduces. After approximately five percent lime had been added, the amount of calcium present in the porewater was actually greater after leaching than before. These results are very similar to those discussed for Site No. 1 samples.

251. Site No. 2. Samples compacted dry displayed the smallest concentration of calcium in their porewater after leaching (Figure E23 in Appendix E). Samples compacted at optimum or wet were the least likely to lose excessive calcium during leaching, particularly at lime contents greater than five percent.

252. Site No. 3 natural samples contained significant amounts of calcium in their porewater that was readily removed by leaching with longer leach periods generating additional calcium removal (Figure 100). The addition of lime slightly lowered the amount of calcium in the porewater before leaching. After leaching, the calcium concentration in the porewater increased with the addition of lime such that after four percent lime had been added, the calcium concentrations after leaching were slightly higher than they were before leaching.

253. All three sites displayed similar porewater characteristics. All had calcium present in their natural soil that could be easily removed with leaching. With the addition of lime, their concentrations before leaching decreased and their concentrations after leaching increased until at certain lime contents, there was larger concentrations of calcium in the porewater after leaching than before. These lime contents were four percent for Sites No. 1 and 3 samples and five percent for Site No. 2 samples. Samples compacted dry had the largest reductions in concentrations after leaching. Samples compacted at optimum moisture or wet of
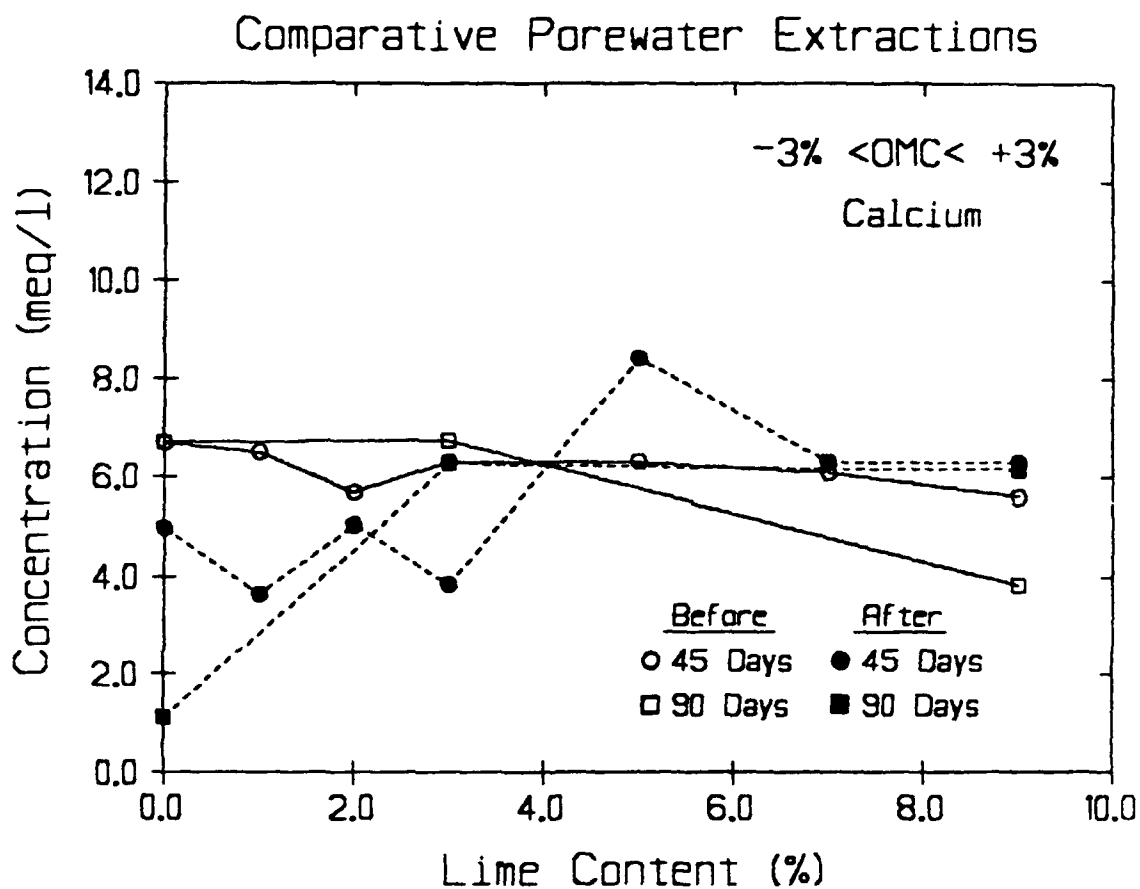
Figure 100. Calcium concentration in the porewater of Site No. 3 samples after leaching.

optimum displayed the least amount of calcium washout through porewater extractions.

254. Porewater Sodium. Sodium was significantly leached from all Site No. 1 samples, regardless of the compaction moisture content or lime content. Figure 101 shows that after 45 days of continuous leaching, the porewater sodium concentration decreased to an approximate level of 1.0 meq/l for samples compacted at optimum moisture. Ninety days of leaching decreased the levels further. Figure E24 in Appendix E demonstrates that samples compacted wet tend to have the least amount of sodium reduction whereas samples compacted dry have the greatest loss of sodium cations.

255. Site No. 2 soils did not contain much sodium in their natural state, less than 0.6 meq/l. As with Site No. 1, the sodium was readily removed by leaching. When lime was added to the soil, the amount of sodium in the porewater reduced (Figure 102). However, lime apparently had no influence on leaching effects as sodium concentrations continued to decline for all lime contents after leaching 45 and 90 days. Samples compacted dry showed the largest sodium reduction in the porewater after leaching while those compacted wet showed the lowest sodium removal (Figure E25 in Appendix E).

256. Site No. 3 soils contained the highest natural sodium concentration in their porewater but it was easily removed by leaching (Figure 103). Sodium was reduced 77.2 percent after leaching 90 days with no lime present. The addition of lime caused only a slight reduction in the sodium concentration of the porewater before leaching, but a significant drop in sodium content occurred after leaching.

257. All three sites displayed similar results. Sodium was present in some amount in all three natural soils (largest in Site No. 3 soil, smallest in Site No. 2 soil) and was easily removed by leaching. The longer the leach period, the more
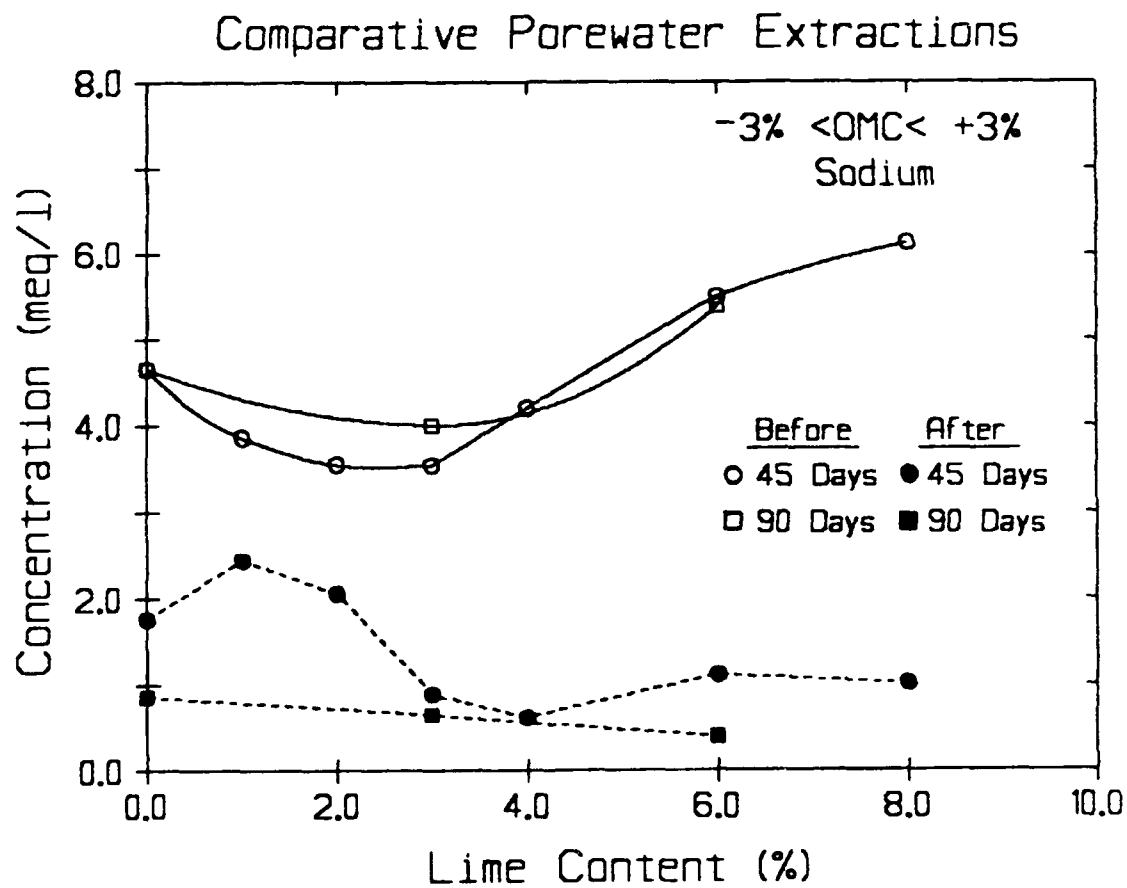
Figure 101. Sodium concentrations in the porewater of Site No. 1 samples after leaching.
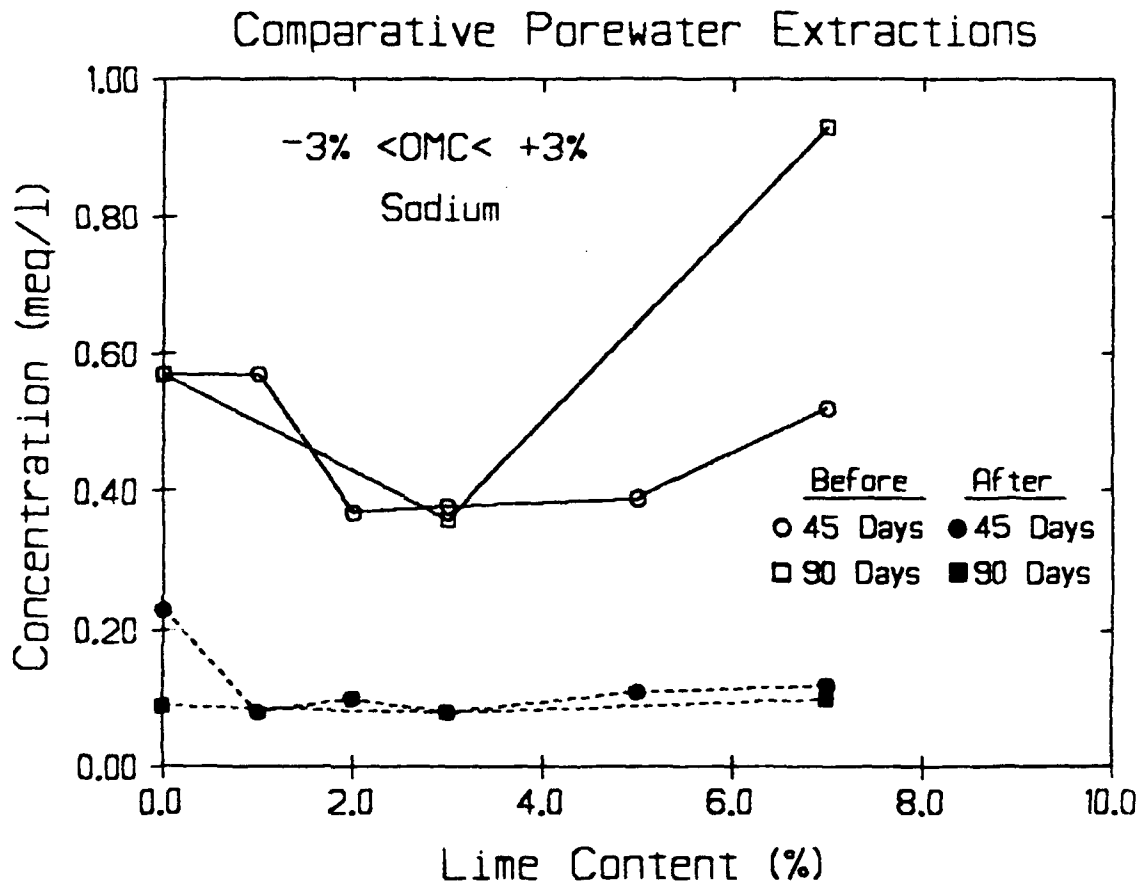
Figure 102. Sodium concentrations in the porewater of Site No. 2 samples after leaching.
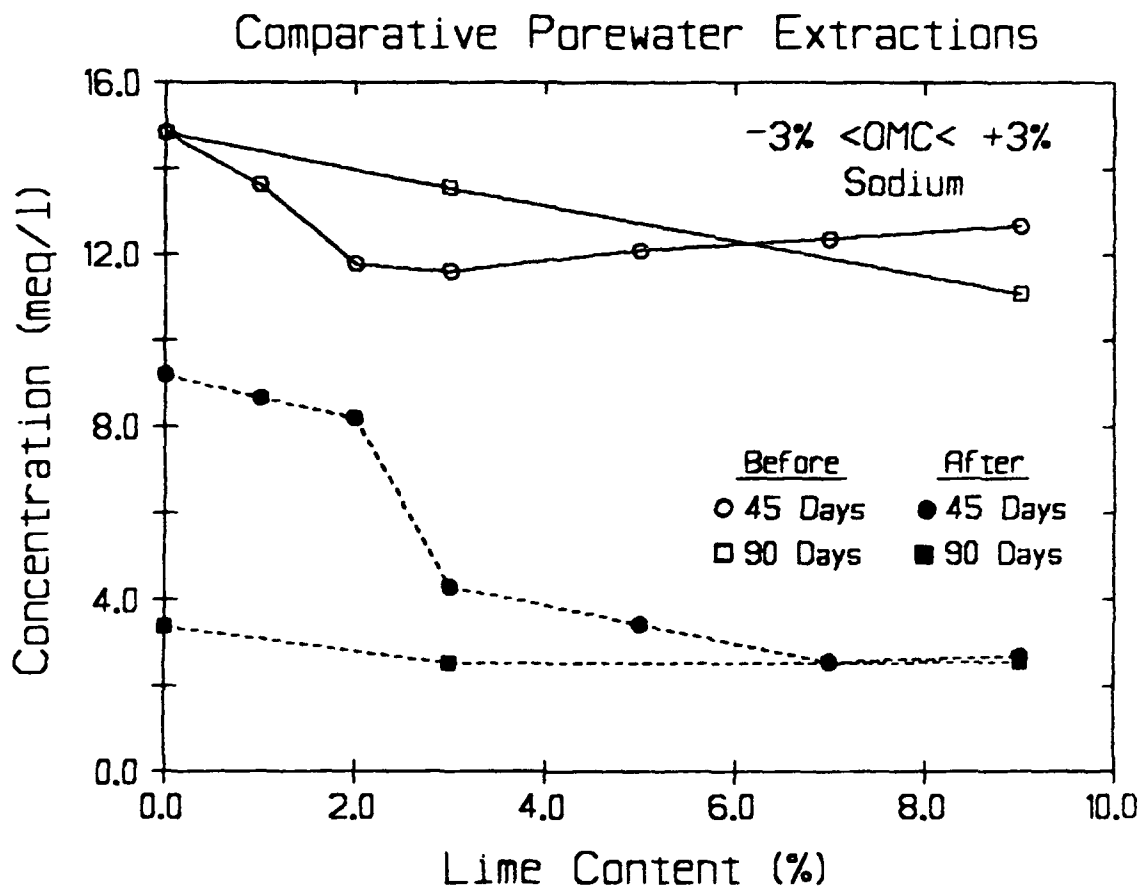
Figure 103. Sodium concentrations in the porewater of Site No. 3 samples after leaching.

sodium removed from the porewater. In samples not leached, the addition of lime to each soil initially reduced the amount of sodium present in the porewater. However, after lime contents of four, five and five percent for Sites No. 1, 2 and 3, respectively, have been added, the porewater sodium concentration in the samples before leaching increased.

258. The sodium present in the porewater of leached samples significantly decreased with the addition of lime for all three soil sites. This may indicate that as more lime is being added to the soil, more sodium is being exchanged with calcium in the clay complex, thereby forcing more sodium into the highly viscous water layer surrounding the clay particles which can then be readily leached out of the soil-lime mixture. Samples compacted dry displayed the largest decrease in porewater sodium while those compacted wet had the least amount of sodium leached.

259. Porewater Magnesium . Magnesium exists in the natural soils in very small concentrations and was easily removed by leaching. The longer the leach duration, the more magnesium that was removed for samples compacted at optimum moisture (Figures 104 through 106). With the addition of lime before leaching, the soil-lime mixtures lost magnesium in their porewater. After leaching, some of the magnesium was apparently replaced in the porewater. Ninety day leaching showed larger replacements than 45 day leach tests. However, the porewater magnesium concentration in all three sites after leaching was only slightly higher than it was before leaching. Porewater magnesium concentrations continued to decline in both before and after leach tests with increasing lime contents. For all sites, the porewater magnesium concentrations for all tests (except Site No. 3 samples at zero percent lime) were less than 0.3 meq/l (7 ppm).
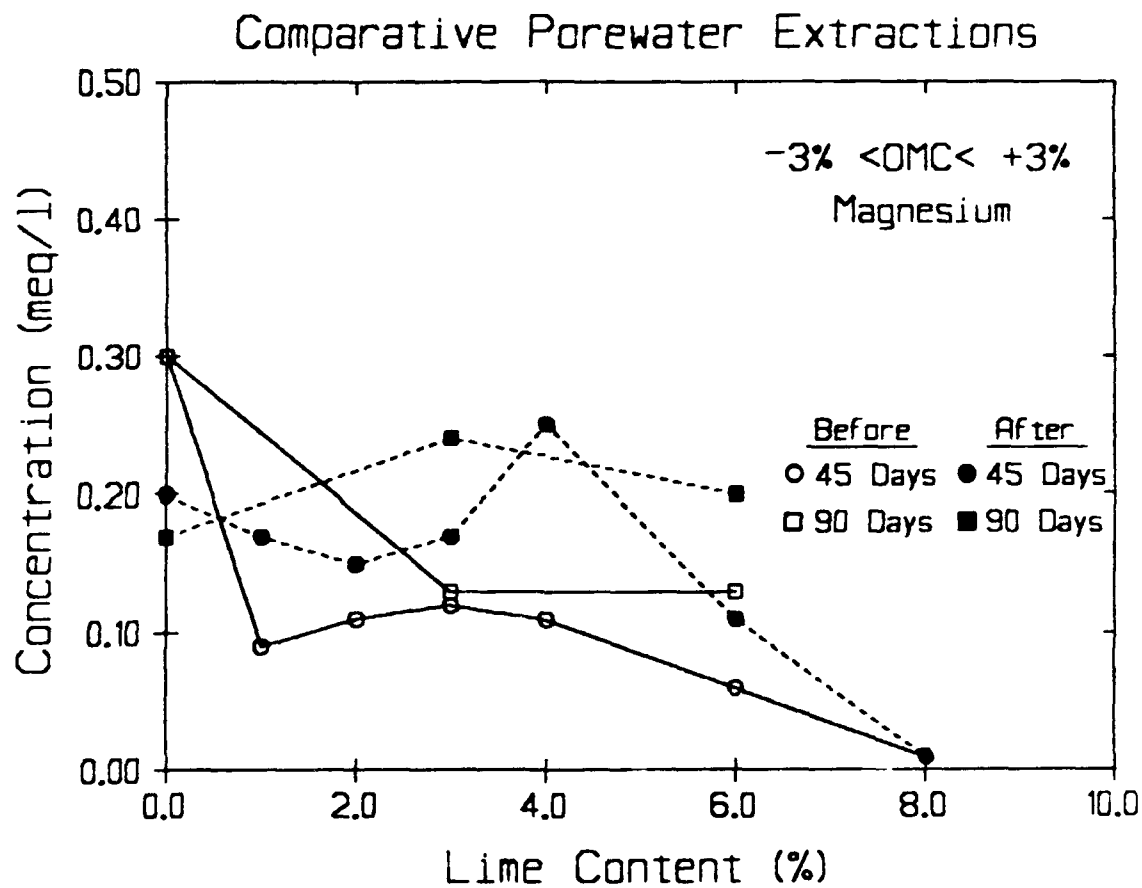
Figure 104. Magnesium concentrations in the pore-water of Site No. 1 samples after leaching.
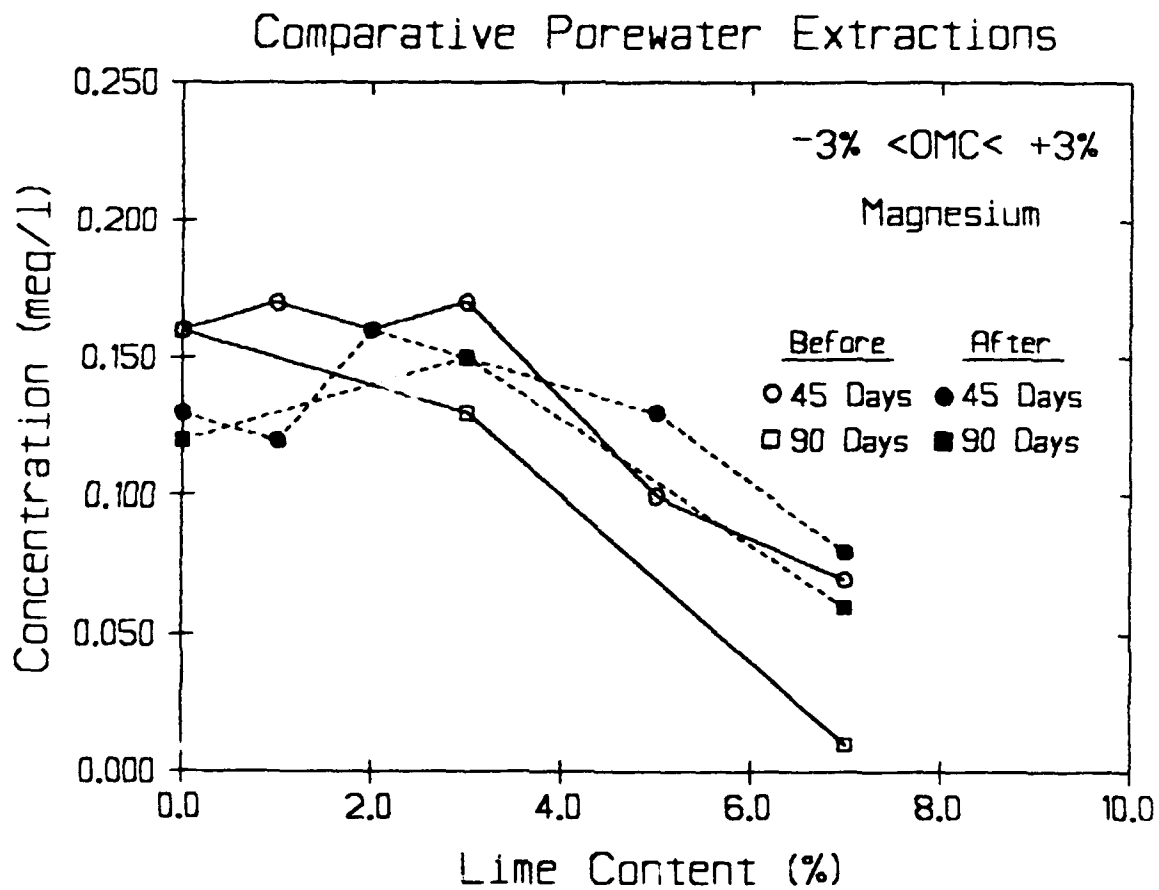
Figure 105.   Magnesium concentraᵢᵢcns in the pore-
water of Site No. 2 samples after leaching.
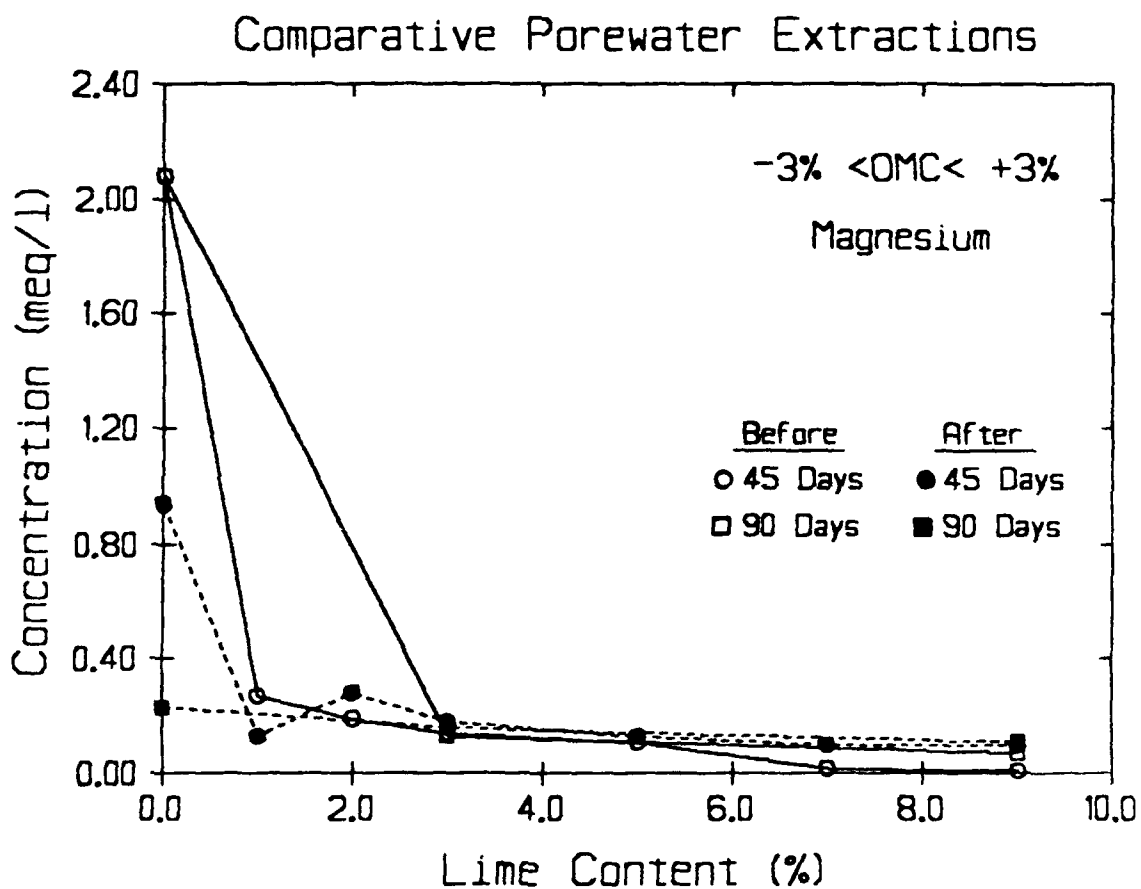
Figure 106. Magnesium concentrations in the pore-
water of Site No. 3 samples after leaching.

260. For Sites No. 1 and 2, samples compacted wet and dry of optimum moisture then leached 45 days displayed magnesium contents generally higher than those with no leaching. Samples compacted dry showed the largest increase in after leach concentrations (Figure E26 and E27 in Appendix E).

261. <u>Porewater Potassium</u>. Potassium in the porewater of all three site was only available in very small concentrations (less than 0.4 meq/l or 15 ppm). It, too, was easily eroded by leaching in a natural state with longer leaching periods producing more removal in all three natural soils (Figures 107 through 109).

262. Potassium concentrations in all soils after leaching 45 days averaged only slightly lower than those concentrations before leaching. Samples leached 90 days showed larger potassium losses after leaching than for samples leached 45 days for all sites, however, before and after leach tests showed a general trend to increase the potassium concentrations with increasing lime content.

263. Samples compacted dry of optimum moisture showed the largest drop in porewater potassium after leaching. Samples compacted wet generally displayed the least amount of potassium removal during leaching (Figures E28 and E29 in Appendix E).

Exchange Complex Cations

264. Cation concentrations in the exchanged complex include cations in the porewater, absorbed water layer, the highly viscous water surrounding the clay minerals and within the clay particles themselves. Since most of the cations within the latter three exchange sites are tightly held within the exchange sites, it requires saturation with a chemical solution to replace the calcium, sodium, magnesium and potassium in the exchange complex. An ammonia solution is most often used to accomplish this exchange. Three washings with a one normal (1N) ammonium
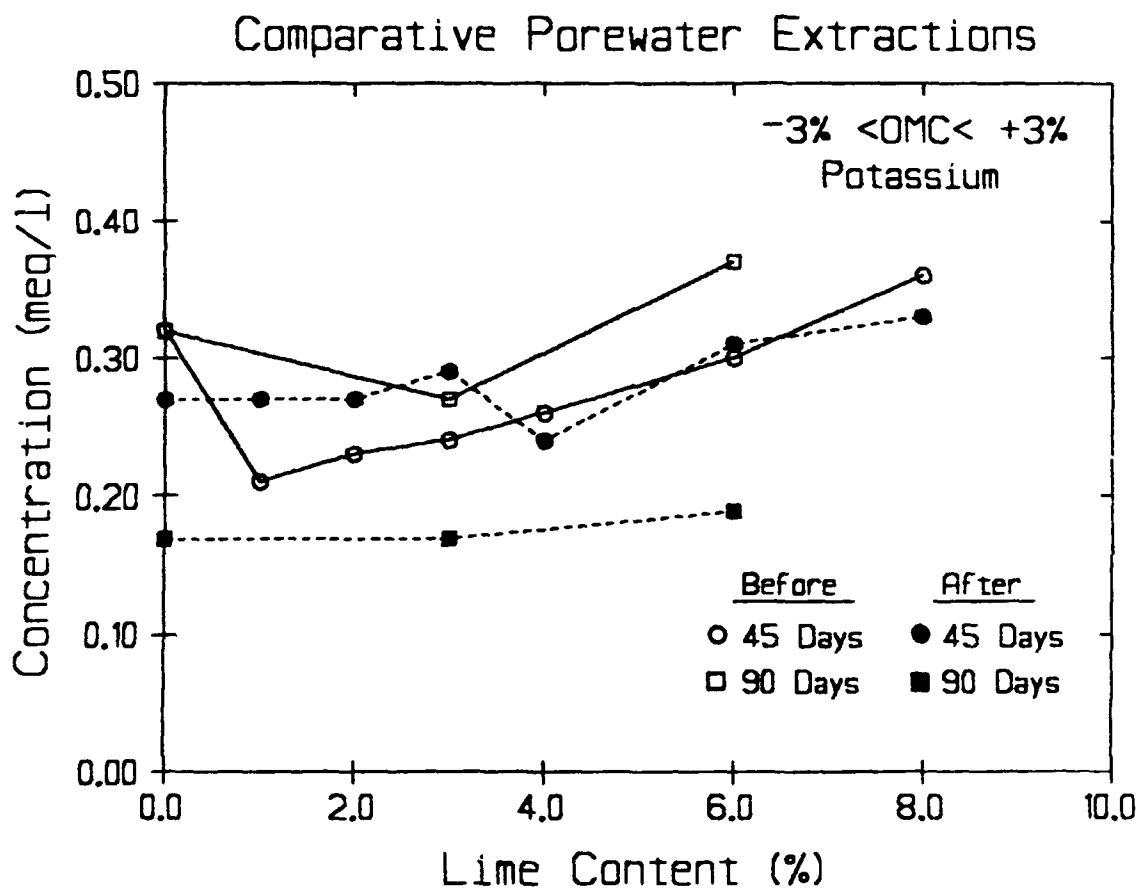
Figure 107. Potassium concentrations in the pore-water of Site No. 1 samples after leaching.
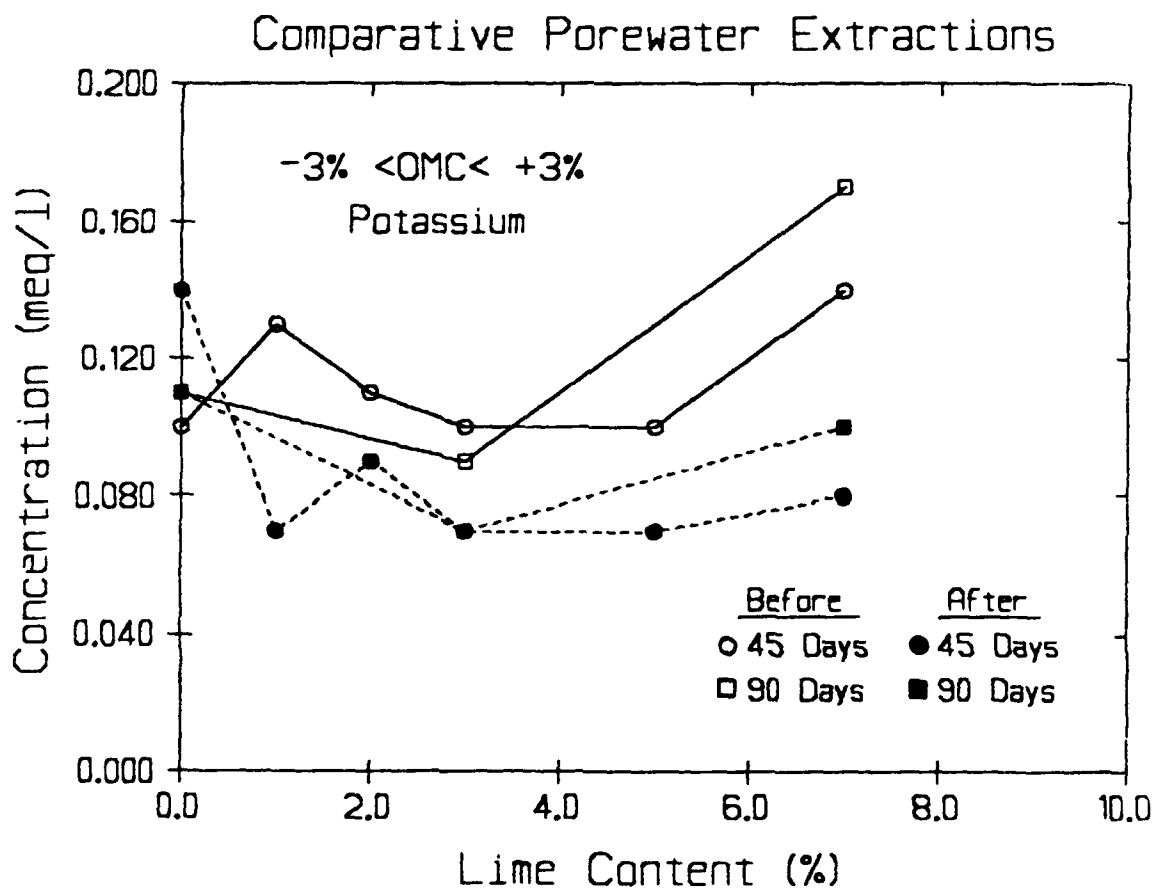
Figure 108. Potassium concentrations in the pore-
water of Site No. 2 samples after leaching.
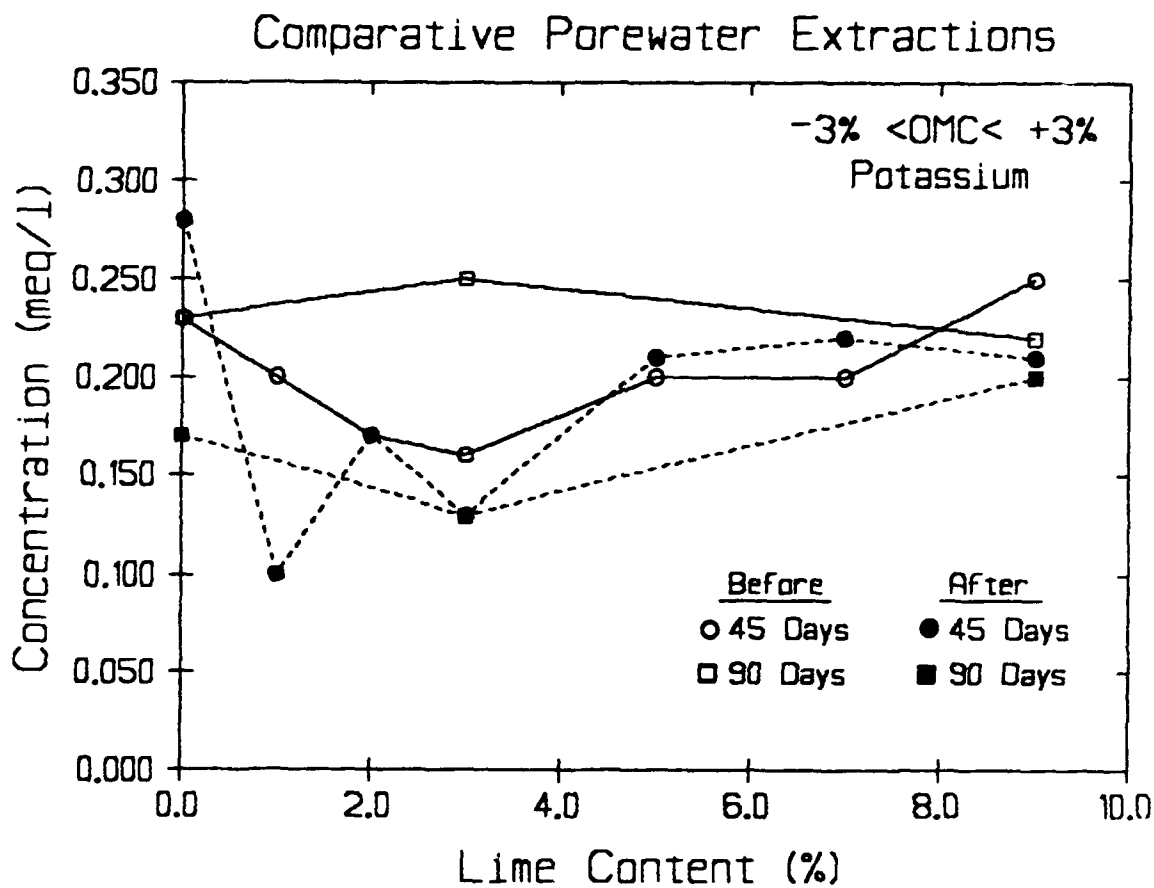
Figure 109. Potassium concentrations in the pore-water of Site No. 3 samples after leaching.

acetate solution were used to extract the cations with the concentrations (mg/l or ppm) converted to milliequivalents per 100 g (meq/100 g).

265. Exchange Complex Calcium . Figure 110 shows that the natural soil from Site No. 1 has a significant amount of calcium in its exchange complex. However, it cannot be significantly removed from the natural soil simply by leaching except what little was removed in the porewater (see previous discussion). The addition of lime increased linearly the amount of calcium exchanged and, with time, some of the calcium was removed by leaching. A comparison of 45 day and 90 day leach cycles suggests that the 90 day curing process allows more of the calcium to be absorbed, thus making it harder to be leached out. For samples with six percent lime, 45 day leaching caused a 27.2 percent decrease in exchange site calcium, whereas 90 day leaching caused only a 20.0 percent decrease. The gap between before and after leach concentrations of calcium in the exchange sites appeared to widen with the amount of lime added, ranging from a 4.7 percent to a 27.2 percent decrease in calcium for lime contents of one and six percent, respectively.

266. Figure E30 in Appendix E compares reductions in calcium concentrations for Site No. 1 samples compacted at, wet and dry of optimum moisture then leached 45 days. All samples displayed smaller concentrations in the exchange sites after leaching. Samples compacted wet of optimum showed the smallest decrease in calcium concentrations for all lime contents. Samples compacted at optimum moisture displayed the largest decrease in calcium concentrations after leaching.

267. Site No. 2 samples also displayed a uniformly increasing concentration of calcium in the exchange complex as the lime content increased for samples before leaching (Figure 111). Natural soil samples contained significant quantities of calcium, which could not be easily eroded away by leaching, even after 90 days.

Figure 110. Calcium concentration in the exchange complex of Site No. 1 samples after leaching.
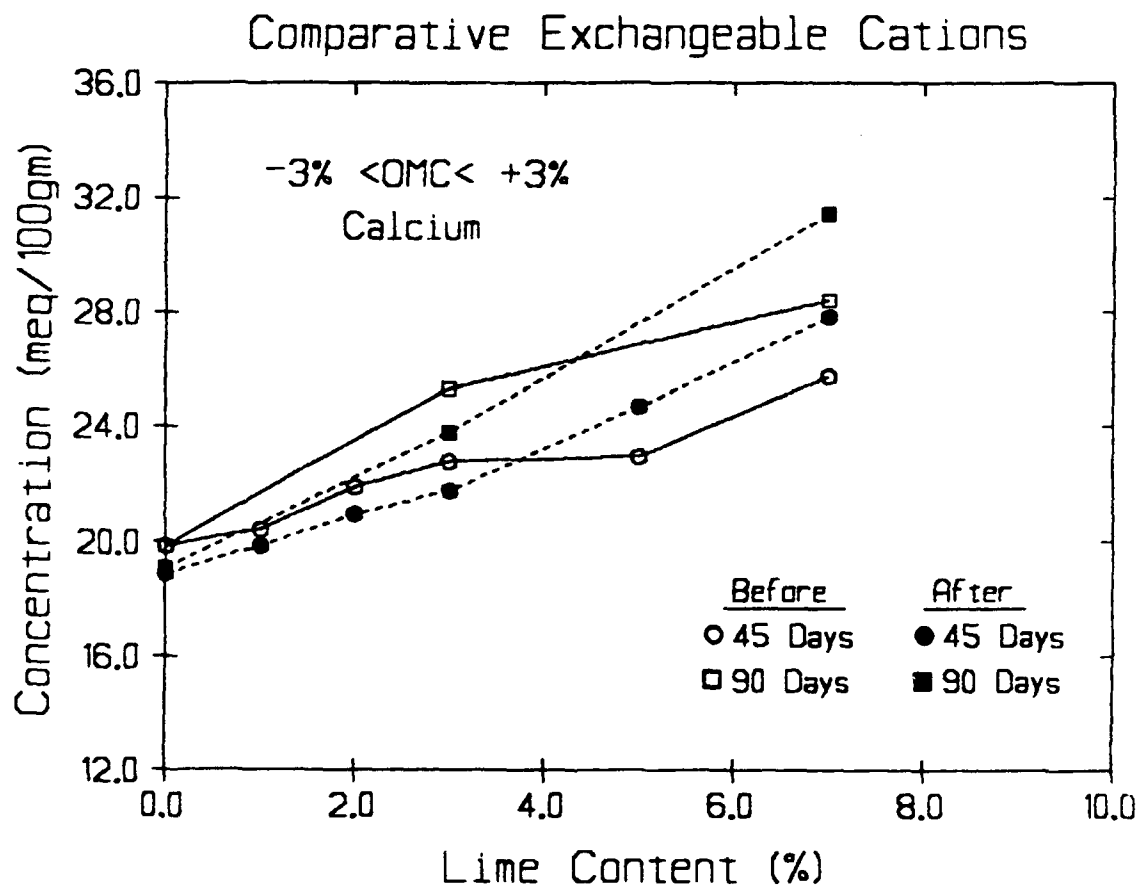
Figure 111. Calcium concentrations in the exchange complex of Site No. 2 samples after leaching.

When lime was added to the samples which were then leached, there was an increase in calcium concentration with increasing lime contents. At the lower lime contents, the calcium concentrations after leaching were lower than those measured before leaching. However, as the amount of lime added reached four percent, the after leach concentrations were larger than the before leach contents for both 45 and 90 day leach tests.

268. Site No. 2 samples compacted dry of optimum moisture displayed larger decreases in the exchange complex calcium concentrations after leaching than those compacted wet or at optimum moisture (Figure E31 in Appendix E). The least amount of calcium removal appears to have occurred in samples compacted wet or at optimum moisture.

269. Natural Site No. 3 material contained approximately the same amount of calcium in its exchange complex as Site No. 2 material and slightly less than Site No. 1 material. As with both previous sites, the addition of lime increased the calcium in the exchange sites (Figure 112). Leach samples also displayed an increase in calcium concentrations with an increase in lime content, but lower concentrations than those before leaching. Samples leached 90 days showed smaller drops in after leach concentrations than those leached 45 days.

270. All three sites displayed similar reactions when lime was added. Calcium was not readily removed from the exchange complex for natural soils simply by leaching. For samples not leached, the increase in lime was proportional to the increase in exchange complex calcium concentration. For samples leached, there was also an increase in exchange complex calcium concentrations with increasing lime contents, but the concentrations were lower (generally) than those present before the samples were leached. This would seem to indicate that leaching does have some negative impact on the amount of calcium in the soil-lime mixture,
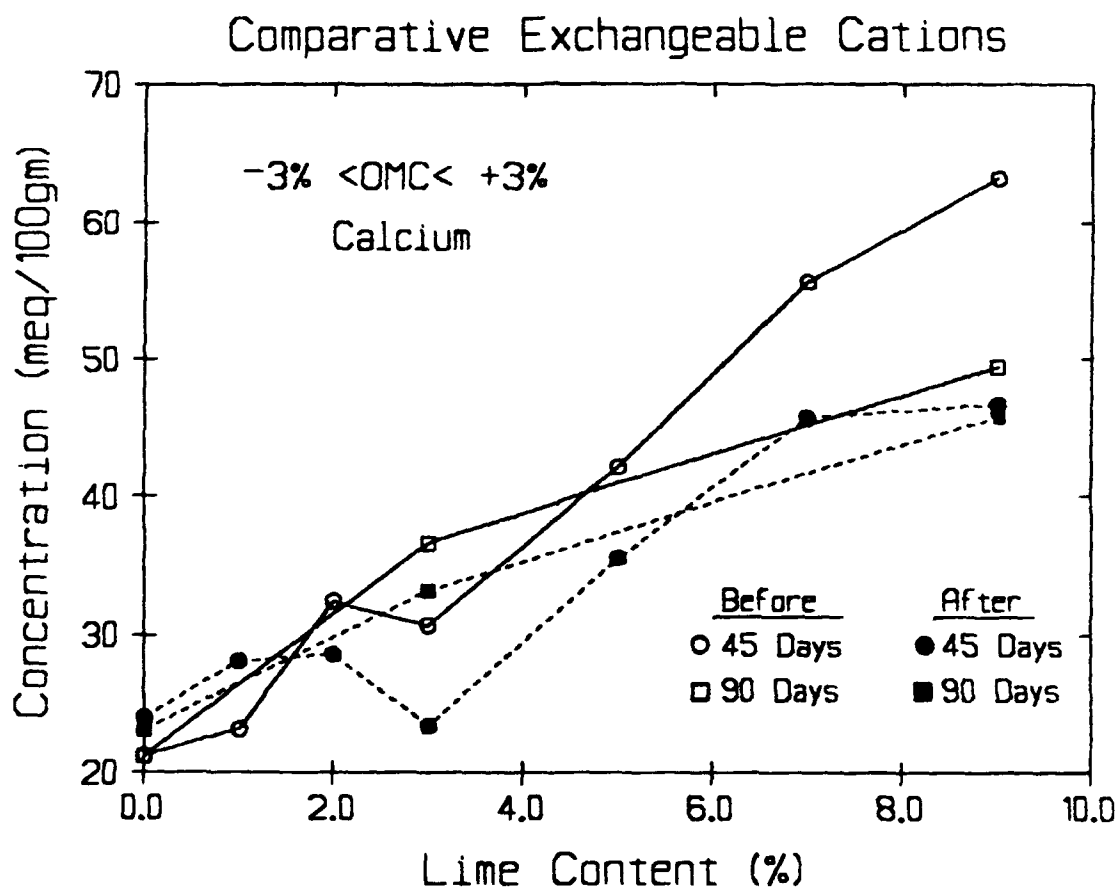
Figure 112. Calcium concentrations in the exchange
complex of Site No. 3 samples after leaching.

although it may simply be that the calcium removed by leaching was excess calcium due to lime addition, and was not being used in the soil modification process.

271. Samples compacted dry for Sites No. 1 and 2 soil showed the largest amount for calcium removal from the exchange sites. Samples compacted wet or at optimum moisture displayed the least amount of calcium removed by leaching.

272. Exchange Complex Sodium. Sodium in the exchange complex of Site No. 1 soil was readily removed by leaching in its natural state (Figure 113). Samples leached 90 days lost more sodium than samples leached 45 days. For samples before leaching, there was a slight increase in sodium in the exchange complex with the addition of lime. When lime treated samples were leached, they showed a general decrease in sodium concentration with increasing lime contents. Exchange complex sodium was only present in limited quantities for all samples with or without lime (1.08 meq/100 g or 10 ppm at zero percent lime).

273. Site No. 1 samples compacted wet, dry or at optimum moisture displayed considerable decrease in sodium concentration after leaching (Figure E32 in Appendix E). Samples compacted wet tended to have the lowest loss rates while samples compacted dry had the highest percentage of sodium removal.

274. Figure 114 shows the effects of leaching on sodium in Site No. 2 samples. Sodium was present in the natural soil in a very small quantity (0.08 meq/100 g or 0.7 ppm), and only slightly increased with the addition of lime. After leaching, sodium in the exchange complex was readily removed whether lime was present or not until only trace (less than 0.01 ppm) amounts of sodium remained in the exchange complex.

275. Site No. 2 samples compacted dry displayed the highest removal rate during leaching. Samples compacted wet showed the lowest sodium removal percentages (Figure E33 in Appendix E).
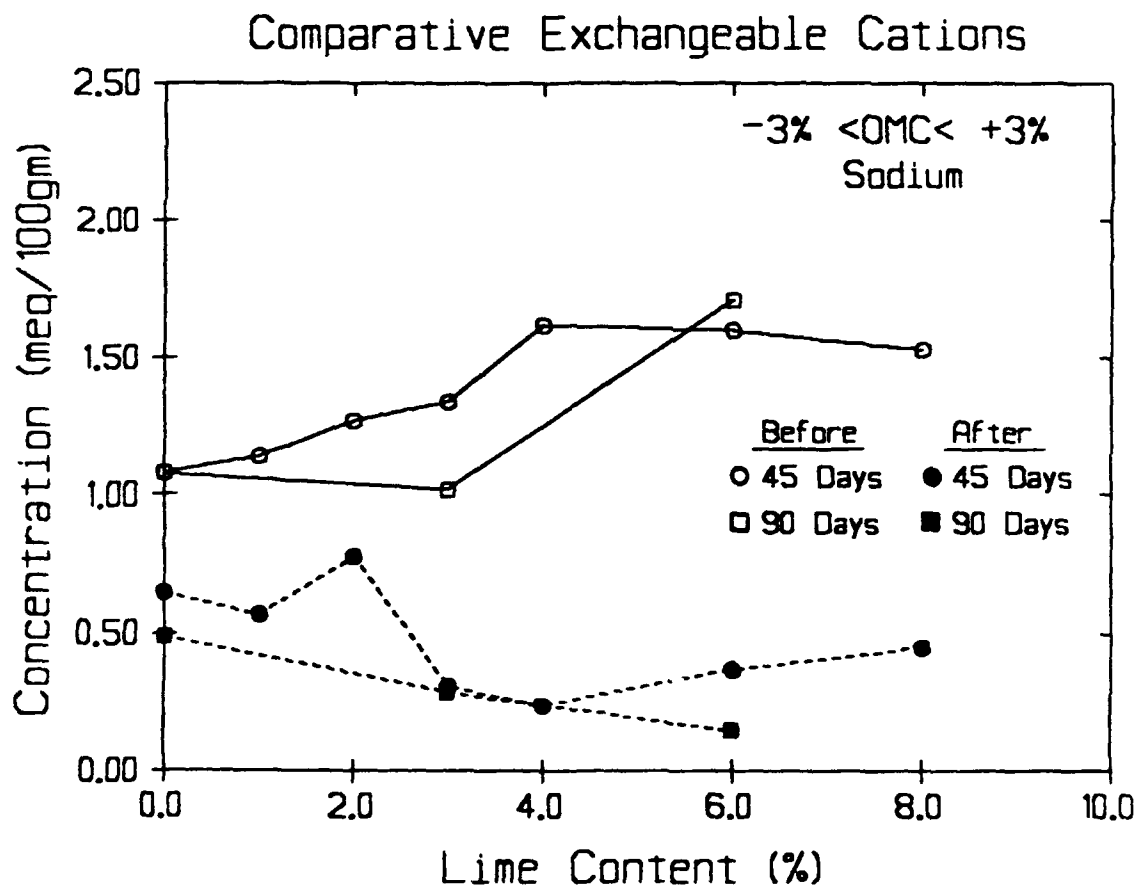
Figure 113. Sodium concentrations in the exchange complex of Site No. 1 samples after leaching.
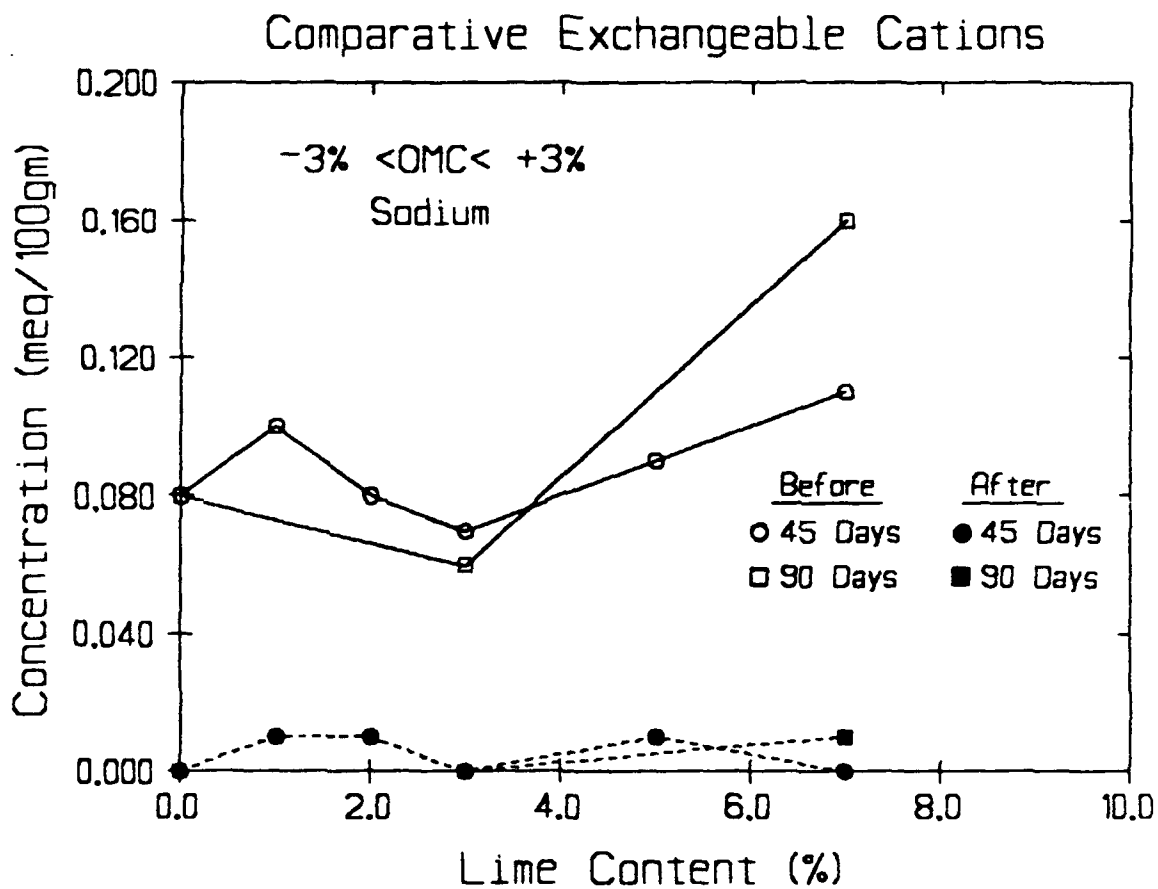
Figure 114. Sodium concentrations in the exchange complex of Site No. 2 samples after leaching.

276. Site No. 3 samples had considerably higher concentrations of sodium in their natural state than those from the other two sites (3.68 meq/100 g or 34 ppm). With the addition of lime, samples before leaching showed a slight decline in sodium concentration. All sodium, regardless of lime content was easily removed by leaching. Ninety day leach tests removed more sodium than 45 day tests. Leached samples showed a sharp decline in their sodium concentrations as the amount of lime increased (Figure 115).

277. All three sites demonstrated that sodium was readily removed by leaching regardless of the lime content. Samples leached 90 days resulted in lower sodium contents in their exchange complex than those leached 45 days. All sites showed declines in their exchange site sodium content after leaching with increasing line contents.

278. Samples compacted dry displayed the highest sodium washout for soils from Sites No. 1 and 2. Samples compacted wet of optimum showed the lowest sodium removal after leaching.

279. Exchange Complex Magnesium. Magnesium in the exchange complex of natural clay was removed by leaching from all three soil sites (Figures 116 through 118). By adding lime, the magnesium content in Sites No. 1 and 2 samples increased as the amount of lime increased. Site No. 3 samples before leaching showed a general decrease in magnesium concentration as the amount of lime increased. Leaching generally removed some of the magnesium in the lime treated soils although the loss was seldom greater than 40 percent. Leached samples followed the same trends as before leached samples, e.g., leach samples concentrations increased with increasing lime contents, or as in Site No. 3 samples, decreased with increasing lime contents. Samples leached 90 days generally showed higher percentage losses than samples leached 45 days.
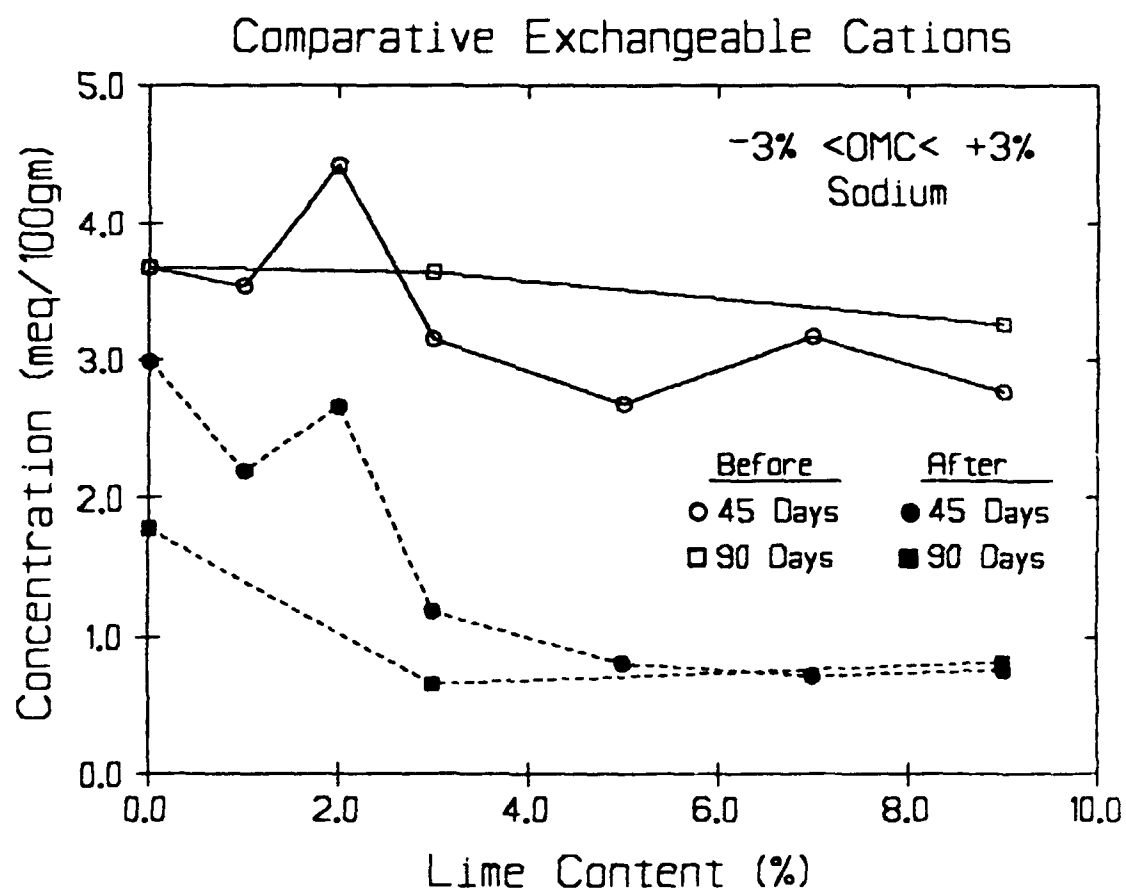
Figure 115. Sodium concentrations in the exchange complex of Site No. 3 samples after leaching.
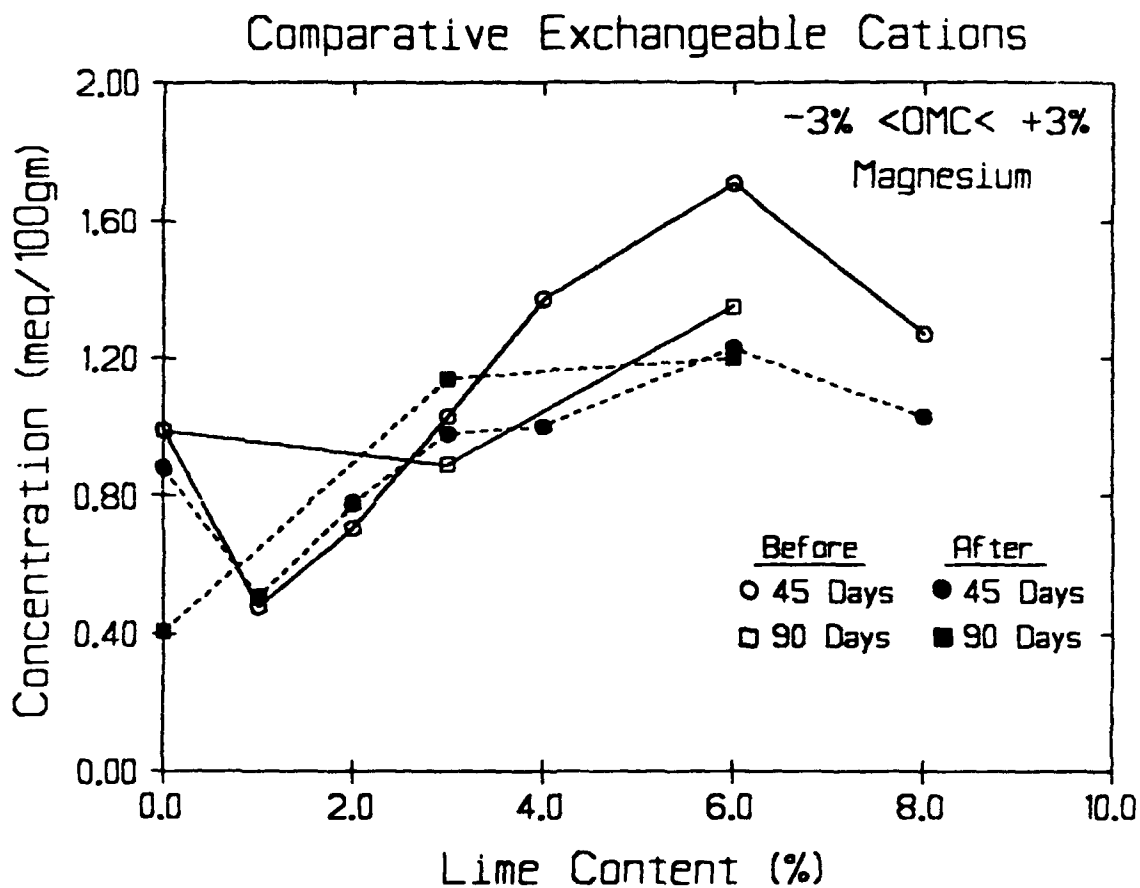
Figure 116. Magnesium concentrations in the exchange complex of Site No. 1 samples after leaching.
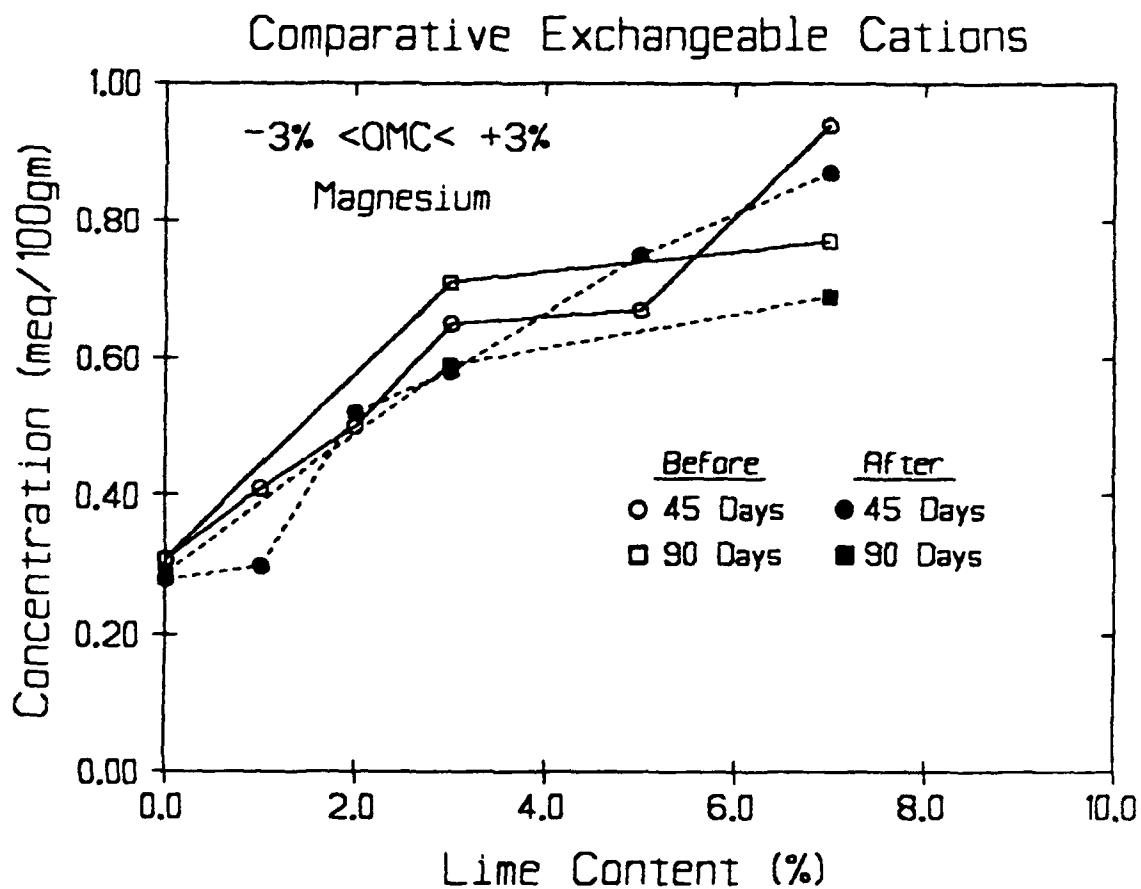
Figure 117. Magnesium concentrations in the exchange complex of Site No. 2 samples after leaching.
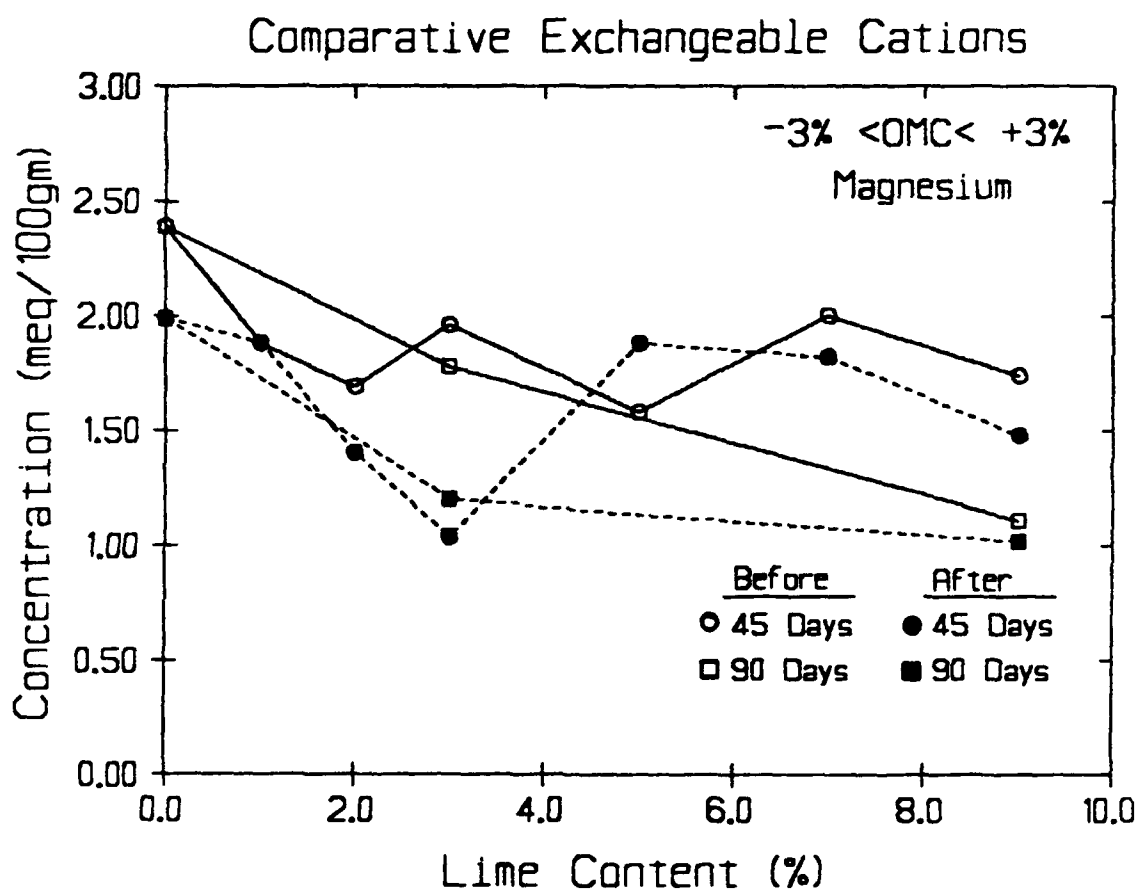
Figure 118. Magnesium concentrations in the ex-
change complex of Site No. 3 samples after leaching.

280. Figures E34 and E35 in Appendix E compare the leaching effects of samples compacted at various moisture contents. Samples compacted wet showed the lowest loss rate while samples compacted dry showed the lowest overall concentrations after leaching. Magnesium concentrations in all samples were very low (magnesium averaged only 1.4 meq/100 g or 13 ppm for all three soils in their natural states).

281. Exchange Complex Potassium. Potassium concentrations were also found to be very small in the natural clay's exchange complex (average of 0.54 meq/100 g or 8 ppm). All soil sites showed a slight increase in potassium in the exchange sites for those samples not leached but allowed to cure 45 or 90 days (Figure 119 through 121). Samples leached in their natural state showed an increase in potassium contents (except for 90 days leaching for Site No. 2 samples). As lime contents were increased, leached samples generally lost only a small percentage of their before leached potassium, seldom losing more than 20 percent of their original concentrations. Tests on Site No. 3 samples showed a slight (9.2 percent) increase in potassium content after leaching samples that had been mixed with seven and nine percent lime. Samples ached 90 days showed larger percentage drops in potassium concentration than samples leached 45 days, except for Site No. 3 tests where there were minimal differences.

282. Figures E36 and E37 in Appendix E compare samples compacted wet, dry and at optimum moisture. Samples compacted wet displayed the smallest decrease in potassium concentration during leaching. Samples compacted dry showed considerable decreases in potassium levels during leaching for all lime contents.
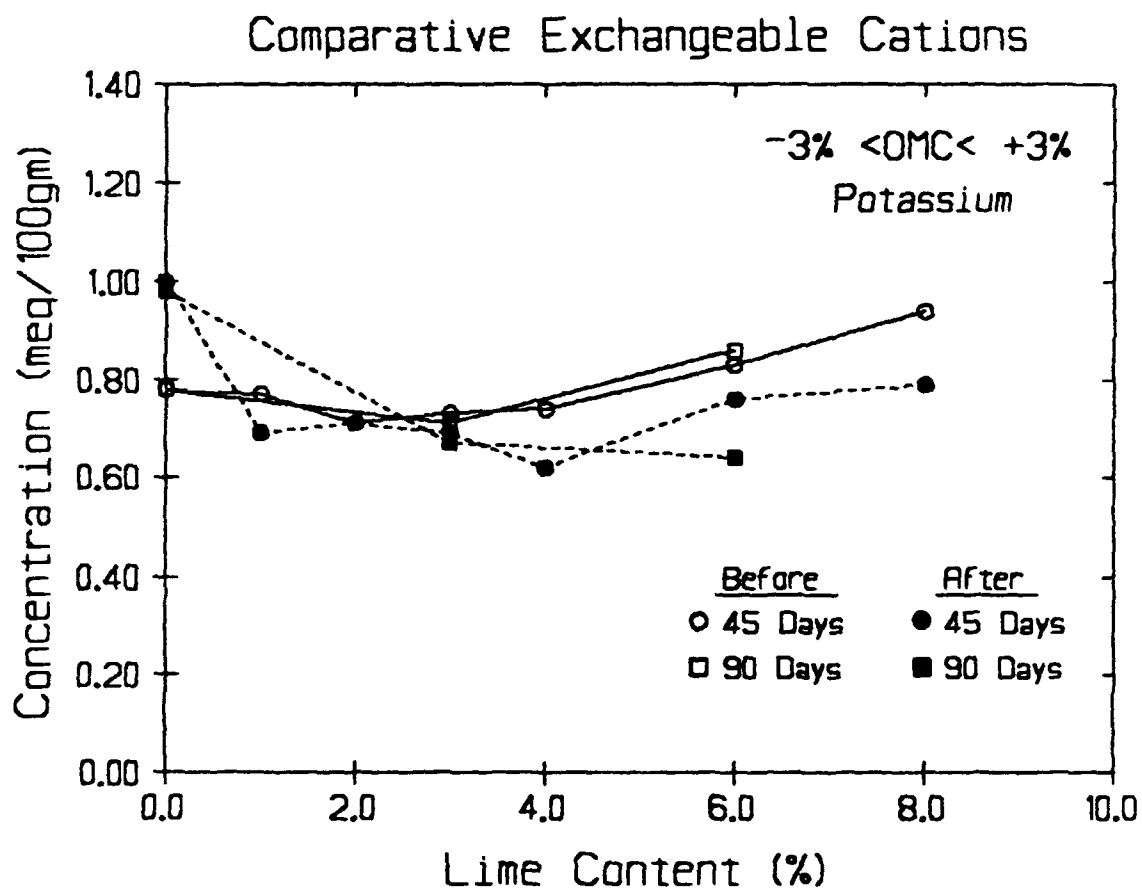
Figure 119. Potassium concentrations in the exchange complex of Site No. 1 samples after leaching.

Comparative Exchangeable Cations

$^{-}3\%$ $<$OMC$<$ $^{+}3\%$

Potassium

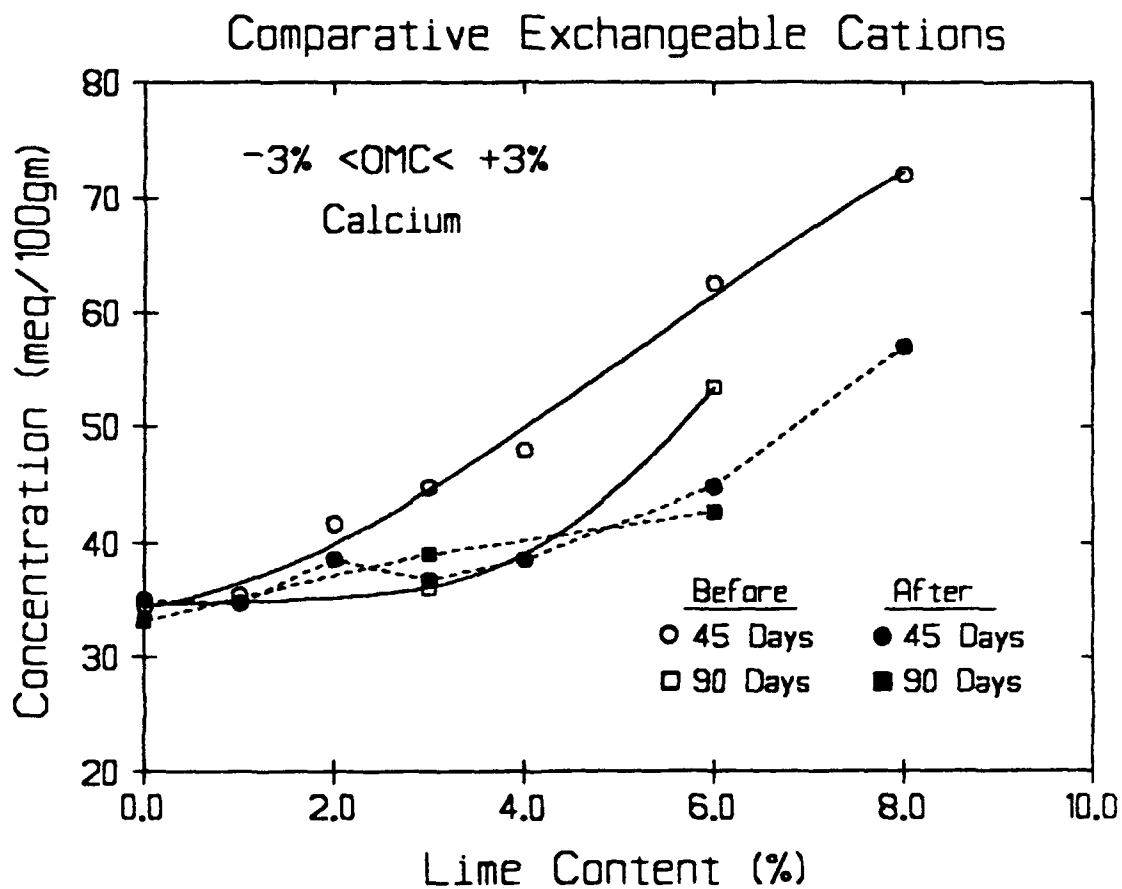|	Before	After
o	45 Days	● 45 Days
□	90 Days	■ 90 Days
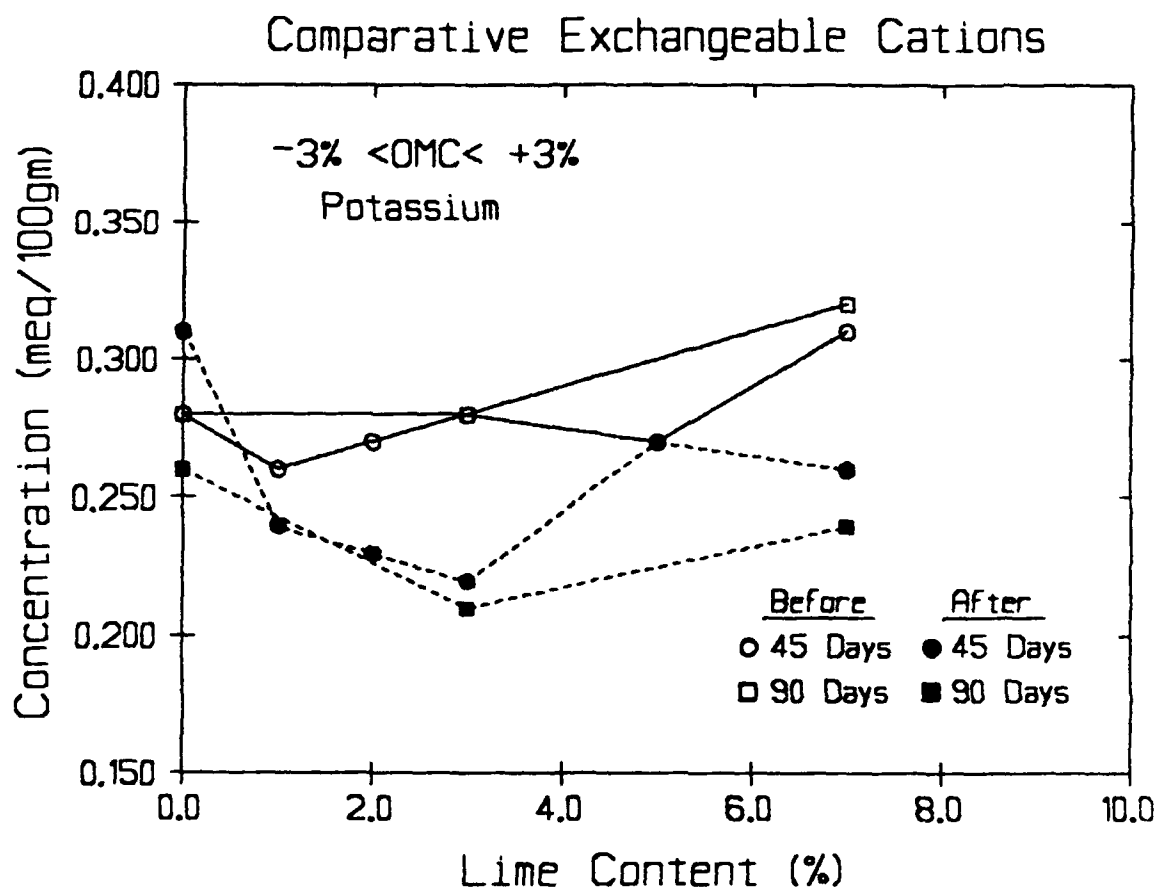
Figure 120. Potassium concentrations in the exchange complex of Site No. 2 samples after leaching.
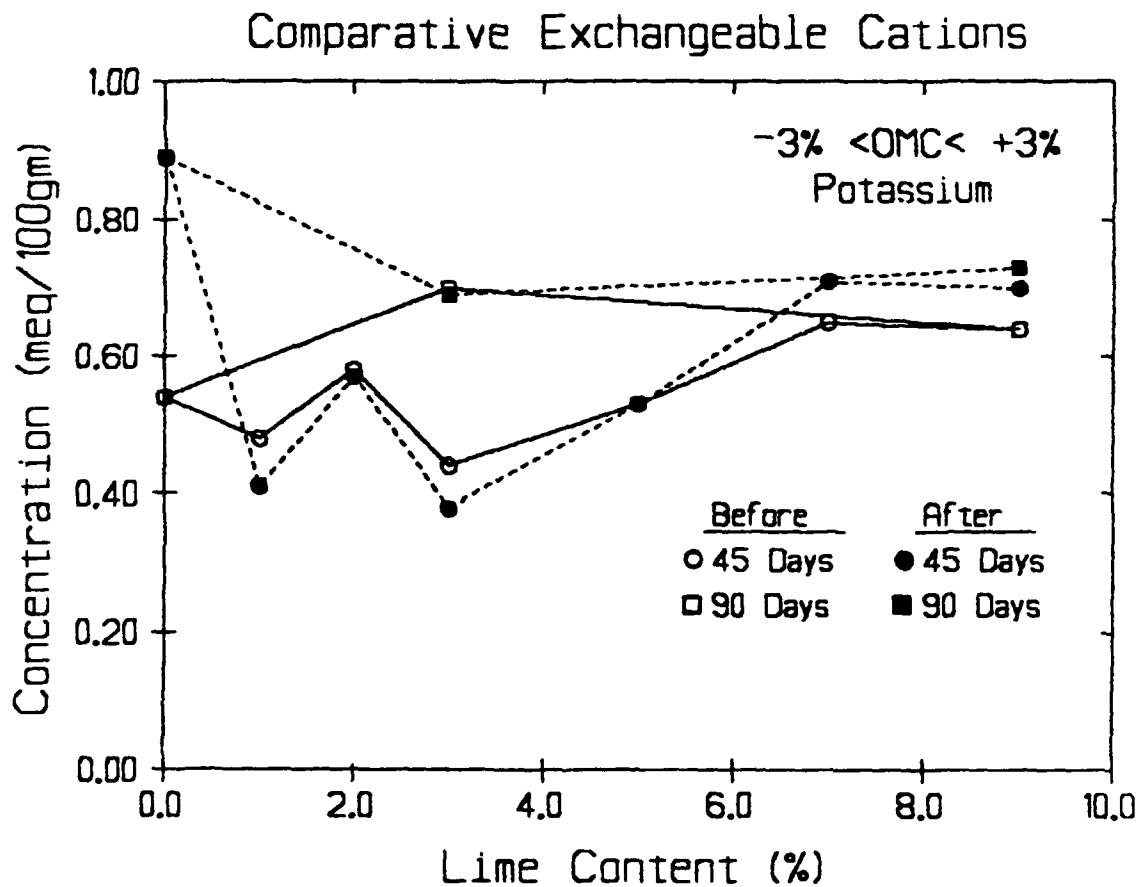
Figure 121. Potassium concentrations in the exchange complex of Site No. 3 samples after leaching.

Analysis of Chemical Property Changes

283. Tables 20, 21 and 22 present summaries of the comparisons of the chemical property changes before and after leaching in terms of percent changes for Sites No. 1, 2 and 3, respectively. As noted in the analysis section of the physical property tests, these percentage changes must be viewed in conjunction with their original values in order to determine physical or practical significance.

284. It has been shown that over time, the pH of lime treated soil will decrease (McElroy 1982). This research verified that after leaching, soil pH declined regardless of lime content. The longer the leach period, the lower the pH in the soil. This is possibly attributed to several factors including leaching of the excess calcium and pozzolanic reaction products utilizing more calcium with increases in time. Before leaching, all lime treated samples reached a maximum pH value at a particular lime content where additional increases in lime contents did not increase the soil pH. This is similar to the results gained in an Eades and Grim LMO test. After samples were leached, the samples still approached a maximum pH though at lower levels than before leaching. The lime content required to reach this maximum level had increased to a range of five to seven percent lime, an increase of approximately two percent lime above that needed to obtain the maximum pHs found before leaching.

285. This follows well from the results from the physical testing which showed that minimum physical property changes occurred at lime contents near or slightly above the site's LSO, approximately six to seven percent. It is theorized that leaching increases the water molecule concentration which will diffuse some of the cations and hydrogen complexes, thereby lowering the pH. As the amount of lime is increased in the soil-water-lime system, the amount of pozzolanic reaction productions are increased along with an increase in pH until a maximum pH is

TABLE 20

SITE NO. 1, PERCENT CHANGES IN CHEMICAL PROPERTIES AFTER LEACHING

Percent Change (%)

Chemical Property	0% Lime		1% Lime			2% Lime	3% Lime				4% Lime			6% Lime				8% Lime
	045*	090	-OMC	045	+OMC	045	-OMC	045	090	+OMC	-OMC	045	+OMC	-OMC	045	090	+OMC	045
Soil pH	-2.4	-3.7	-9.6	-6.1	+1.3	-10.1	-10.7	-9.7	-18.0	-7.5	-8.7	-7.9	-6.3	-4.2	-4.5	-13.3	-3.7	-4.8
Porewater Cations (meq/l)																		
Calcium	-59.0	-68.7	-83.1	-22.5	+8.9	+1.2	-39.0	-16.2	-42.5	-17.5	+6.1	+13.3	-14.5	+77.9	+27.9	+9.0	-15.4	-9.6
Sodium	-62.7	-81.5	-95.6	-36.5	-2.6	-41.9	-94.7	-72.9	-83.8	-85.0	-94.7	-85.2	-86.7	-91.1	-79.6	-92.6	-39.4	-83.4
Magnesium	-33.3	-43.3	+50.0	+88.9	+29.4	+36.4	0.0	+41.7	+84.6	0.0	+46.2	+125.3	-11.8	+366.7	+83.3	+53.8	+7.1	0.0
Potassium	-15.6	-88.2	+8.7	+28.6	+29.2	+17.4	-24.0	+20.8	+37.0	-23.5	-24.11	-7.7	-28.6	+21.7	+3.3	-48.6	-4.0	-8.3
Exchange Complex Cations (meq/100 g)																		
Calcium	+1.6	-3.8	-3.0	-4.7	+0.3	-3.4	-11.4	-17.3	+8.2	-9.8	-7.1	-22.6	-7.3	-11.5	-27.2	-20.1	-3.5	-21.1
Sodium	-39.8	-54.6	-87.9	-50.4	-10.4	-38.6	-90.9	-77.9	-71.6	-83.9	-90.4	-84.2	-85.2	-86.6	-77.6	-91.2	-34.3	-70.4
Magnesium	-11.	-58.6	-5.5	+6.3	-2.2	+9.9	-16.5	-4.9	+28.1	-6.3	-13.7	-27.0	-6.5	-13.7	-28.1	-11.1	-5.9	-18.8
Potassium	+28.2	+25.6	+8.6	-10.4	+1.4	0.0	-3.3	-5.5	-5.6	-8.6	-14.1	-16.2	-7.2	-13.4	-8.4	-25.6	+3.7	-16.0

* 045 = Optimum moisture, 45 day leaching; 090 = Optimum moisture, 90 day leaching; -OMC = Below optimum moisture, 45 day leaching; +OMC = Above optimum moisture, 45 day leaching

* 045 = Optimum moisture, 45 day leaching

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TABLE 21

SITE NO. 2, PERCENT CHANGES IN CHEMICAL PROPERTIES AFTER LEACHING

Chemical Property	Percent Change (%)																
	0% Lime		1% Lime			2% Lime	3% Lime				5% Lime			7% Lime			
	045*	090	-OMC	045	+OMC	045	-OMC	045	090	+OMC	-OMC	045	+OMC	-OMC	045	090	+OMC
Soil pH	-1.0	-2.1	-24.5	-6.4	-4.7	-6.8	-24.6	-5.2	-11.2	-5.9	-9.9	-2.9	-2.7	-8.9	-3.6	-5.7	-1.0
Porewater Cations (meq/l)																	
Calcium	-36.4	-41.7	+1.6	-4.4	-4.5	-7.2	-38.2	-4.8	+17.6	-5.0	-14.6	-5.7	+37.8	-54.9	+28.9	+87.6	+19.8
Sodium	-59.6	-100.0	-84.6	-85.9	-21.9	-72.9	-86.7	-78.9	-77.8	-11.6	-88.6	-71.8	-27.3	-80.4	-76.9	-39.2	-25.0
Magnesium	-18.5	-25.0	-7.1	-29.4	+8.3	0.0	-7.1	-11.8	+15.4	+6.7	+85.7	0.0	0.0	+88.9	+71.4	+500.0	+40.0
Potassium	+40.0	+10.0	-45.5	-46.2	0.0	-18.2	-50.0	-30.0	-22.2	0.0	-70.6	-30.0	-8.3	-66.7	-42.9	-41.2	+7.7
Exchange Complex Cations (meq/100 g)																	
Calcium	-4.8	-3.8	-3.9	-2.8	-1.4	-4.1	-12.1	-4.5	-6.1	-1.9	-3.8	+7.6	+1.3	-19.5	+8.1	+10.6	+1.9
Sodium	-100.0	-100.0	-100.0	-90.0	-33.3	-87.5	-100.0	-100.0	-100.0	-20.0	-100.0	-88.8	-50.0	-87.5	-100.0	-93.8	-28.6
Magnesium	-9.7	-6.5	-18.2	-26.8	-12.9	-4.0	-39.5	-10.7	-16.9	-3.0	-6.1	+11.9	-6.5	-4.4	-7.4	-10.4	-7.6
Potassium	+10.7	-7.1	-28.6	-7.7	+12.0	-14.8	-36.7	-21.4	-25.0	+3.2	-48.4	0.0	0.0	-48.1	-16.2	-25.0	-9.1

* 045 Optimum moisture, 45 day leaching; 090 = Optimum moisture, 90 day leaching; -OMC = Below optimum moisture, 45 day leaching; +OMC = Above optimum moisture, 45 day leaching

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TABLE 22

SITE NO. 3, PERCENT CHANGES IN CHEMICAL PROPERTIES AFTER LEACHING

Chemical Property	0% Lime		1% Lime	2% Lime	3% Lime		5% Lime	7% Lime	9% Lime	
	045*	090	045	045	045	090	045	045	045	090
Soil pH	-1.6	+3.1	-8.8	-4.1	-6.1	-8.8	-5.3	-4.0	-4.1	-5.8
Porewater Cations (meq/l)										
Calcium	-25.4	-83.3	-43.8	-11.1	-39.0	-6.9	+33.4	+3.4	+12.3	+59.9
Sodium	-37.9	-77.2	-36.5	-30.5	-63.0	-81.4	-71.6	-79.4	-78.8	-77.0
Magnesium	-54.8	-88.9	-51.9	+47.4	+28.6	+23.1	+18.2	+400.0	+900.0	+57.1
Potassium	+21.7	-26.1	-50.0	0.0	-18.8	-24.0	+5.0	+10.0	-16.0	-9.1
Exchange Complex Cations (meq/100 g)										
Calcium	+13.2	+9.1	+15.3	-11.9	-23.8	-9.5	-15.5	-17.8	-26.1	-7.2
Sodium	-18.7	-51.3	-38.1	-39.8	-62.2	-81.8	-69.8	-77.3	-72.6	-74.8
Magnesium	-16.7	-16.7	+37.2	-17.2	-46.9	-32.6	+18.9	-9.0	-14.9	-8.1
Potassium	+64.8	+64.8	-14.6	-1.7	-13.6	-1.4	0.0	+9.2	+14.1	+14.1

Percent Change (%)

* 045 = Optimum moisture, 45 days leaching; 090 = Optimum moisture, 90 days leaching

reached at or slightly above the LSO. Enough calcium must be present to offset the excess water molecules present during leaching.

286. Thompson (1966) stated that in poorly-drained soils, the removal of constituents beneficial to reactivity (silicon/alumina sources) are retarded and calcium/magnesium reactions are maintained. Poorly drained soils would, therefore, maintain higher pH levels when lime is added. This is verified in this research as it can be seen that longer leach periods significantly decreased the soil's pH.

287. The initial moisture content of the samples also influences the soil pH. Samples compacted wet showed the least change in pH after leaching, but the lowest initial pH. Samples compacted dry showed the lowest pH after leaching. This is possibly related to the permeabilities of the soils; wet soils produce the lowest permeabilities, therefore, the lowest cation and hydrogen complex washout which would result in smaller declines in the soil's pH.

288. Site No. 1 soil was tested for lime contents after leaching by using ASTM Standard Test D3155-84 which utilized a single wash with ammonium chloride. The wash material is then tested for calcium using an EDTA titration method. This test, though specified in ASTM to be for samples tested within eight hours after mixing with lime, did allow provisions to be used on longer mellow periods as long as the standards curve samples were mellowed or cured under identical conditions. The results of leached samples showed practically no lime remaining in the soil when physical tests indicated otherwise.

289. After leach samples were also tested using three washings of 1 N ammonium acetate, this produced better estimations of the remaining lime in Site No. 1 soil after leaching but still unrealistically low. It is speculated that total calcium dissociation is not complete (as seen in the cation exchange complex

testing), therefore giving lower lime content estimations. For this reason, Sites No. 2 and 3 material were not tested for after leach lime content estimation using either of these two test techniques.

290. All cations measured tended to be easily removed from the porewater by leaching when no lime was present. Generally, the longer the leaching, the more cations washed out of the soils in their natural state. When lime was initially added to the soils, calcium, sodium, magnesium and potassium cations in the porewater initially decreased in all sites before leaching. Calcium and magnesium contents of before leach samples decreased continually as lime contents were increased; sodium decreased initially then increased when approximately five percent lime had been added; and potassium contents decreased only with one percent lime (three percent lime for Site No. 3) then increased slightly with increases in lime content.

291. Porewater cations varied in their reaction to leaching. After leaching, calcium, sodium and magnesium contents in the porewater decreased with increasing lime content while potassium increased. Calcium porewater concentrations were lower after leaching until approximately five percent lime had been added to the samples from all three sites, at which point the porewater calcium increased above the pre-leach level. This suggests that at lower lime contents, calcium is easily eroded due to weak bonding or lack of pozzolanic reaction products, as previously discussed. When enough lime has been added to satisfy the cation exchange requirements and offset the large concentration of water molecules, excess calcium now exists in the porewater which can be partially removed by leaching. This offset point appears to be approximately two percentage points above the LMO, or approximately five percent lime. Note that this is two to three percent below the soil's LSO and two to three percent below the lime content found to minimize leaching effects on physical property changes. Therefore, it

appears that the lime content required to minimize porewater calcium washout is lower than that required to minimize physical property changes due to leaching.

292. Sodium concentrations were much smaller after leaching. This is most likely due to the monovalent sodium's relative ease of being replaced with divalent calcium, and to its low position on the Lyotropic series of cation replacement, i.e., sodium is the simplest of the four cations measured to replace with calcium (Grim 1968).

293. Porewater magnesium concentrations after leaching were slightly higher than those before leaching for all sites for lime contents above two percent. As previously noted, only trace amounts of magnesium were measured in the leachate for all lime treated samples. This may indicate that the divalent magnesium cations are being used to some extent in the inner clay particle modification reactions, although not significantly due to their extremely small concentrations relative to the calcium content. The lime used in this research possibly contains some magnesium which may account for the slight increase in the porewater concentrations as more lime was added.

294. Theoretically, potassium is readily replaced in the presence of lime, but potassium was not present in any great abundance in the porewater after leaching for all three soils. Samples tested before and after leaching showed very little difference in porewater potassium concentrations.

295. Cations in the exchange complex includes those found in the porewater, the diffused water layer (sometimes referred to as the highly viscous water layer), the absorbed water layer and inside the clay particles. All sites showed similar reactions in their exchange complex concentrations before and afater leaching. Calcium, sodium, magnesium (except Site No. 3 samples), and potassium concentrations in all three soils increased with increased lime content for samples

before leaching. This is in agreement with research by Ho and Handy (1963). After leaching, exchange complex concentrations of calcium and magnesium increased with increases in lime content while sodium and potassium decreased. Potassium concentrations for all natural soils increased after leaching but decreased upon the addition of lime. This probably indicates that the leaching water had more potassium in it than the soils did, until it was displaced by the calcium in the lime.

296. As a general rule, the longer the leach duration, the lower the cation concentrations remaining in the exchange complex. Samples leached 90 days showed higher calcium contents than samples leached 45 days. However, when compared to samples cured, but not leached, for those same durations, the percentage decrease in 90 day leach tests were greater than those for 45 day leach test.

297. All three soils showed that their exchange complex cation concentrations were less after leaching than before, for all lime contents (except potassium at zero percent lime as previously discussed). Calcium cations constituted the overwhelming majority in the exchange complex in all three soils, even before lime was added. Because of its strong bonding characteristics and divalent state, calcium in the exchange complex was not easily removed except through the porewater. With the addition of lime, some calcium was removed from the exchange sites by leaching, but this could be attributed to excess calcium in the porewater not yet being utilized for pozzolan formation. There did not appear to be a lime content at which calcium removal was minimized, except in soil from Site No. 2 once at least four percent lime had been added.

298. Sodium concentrations in the exchange complex were readily removed by leaching. The longer the leach duration, the more sodium removed. This is similar to the results measured during porewater extractions. Again this is most

likely due to sodium's relative ease at being replaced (Lyotropic series) by other cations.

299. Magnesium concentrations in the exchange complex were less after leaching than before, but still continued to increase with increases in lime content. It is possible that the magnesium measured was that found only in the porewater.

300. Potassium concentrations in the exchange complex were lower after leaching than those measured before leaching, except in samples with no lime present. After leaching, all three sites showed lower potassium remaining in their exchange sites than before leaching. These results are similar to those seen in testing porewater extractions for potassium, with the overall concentration after leaching not significantly reduced.

301. For all three soils, there did not appear to be a lime content that minimized the loss of cations from the exchange complex after leaching, as there was in studying porewater extractions. This, compounded with the fact that all soil sites displayed after leach exchange complex cation concentrations lower than those before leaching, would seem to indicate that leaching does have some detrimental effect on all soils tested regardless of the amount of lime present. However, at some point the detrimental effects of leaching are outweighed by the amount of pozzolanic reactions taking place within the soil-lime-water system once sufficient lime is available to offset the excess amount of water present during saturation.

302. The amount of water used to compact the samples has an important effect on the leaching of cations. Sites No. 1 and 2 samples compacted wet of optimum moisture displayed the lowest change during leaching of cation concentrations, both for porewater and exchangeable complex extractions. Samples compacted dry showed the highest washout of all cations for both sites except for magnesium in the porewater for Sites No. 1 and 2 which showed the

highest after leach concentrations for samples compacted dry. Overall, porewater concentrations were more significantly influenced by compaction moisture content than exchange complex cations. This is to be expected since the clay particle's absorbed water layer, because of its very nature, is not readily influenced by compaction moisture.

303. Permeability also played an important role in determining cation washout, as permeability was directly affected by compaction moisture content. Drier soils mean higher permeabilities which translates into higher cation removal. Wet soils tended to have the opposite effects.

304. Thompson (1966) suggests that magnesium remains in the soil in nature while calcium will be leached due to drainage and, therefore, the calcium/ magnesium ratio (Ca/Mg) in the exchange complex is indicative of the degree of weathering (or leaching). Thompson found that the Ca/Mg ratio decreased with increased weathering for Illinois soils. From this research, the Ca/Mg ratios for Sites No. 1, 2 and 3 soils were 34.9, 64.0 and 26.6, respectively, prior to adding lime or leaching. After leaching non-lime treated samples for 45 days, the Ca/Mg ratios were 39.0, 67.4 and 12.1 for Sites No. 1, 2 and 3 soils, respectively. Only Site No. 3 soil, which had the largest initial magnesium concentration, had a decrease of the Ca/Mg ratio with continuous leaching. However, since magnesium was present in such small quantities, the measuring of these reactions may be in error.

305. For samples with three percent lime, Ca/Mg ratios were 43.2, 33.8 and 22.5 before leaching and 37.5, 37.5 and 15.7 after 45 days of leaching for material from Sites No. 1, 2 and 3, respectively. For samples with six percent lime (Site No. 1) and seven percent lime (Sites No. 2 and 3), the Ca/Mg ratios were 36.4, 27.4 and 27.8 before leaching and 35.9, 31.9 and 25.1 after leaching 45 days for Sites No. 1,

2 and 3 soils, respectively. Therefore, it can be seen that in the material from Sites No. 1 and 3, the Ca/Mg ratio does decrease after leaching for all lime contents, although the overall Ca/Mg ratio increases with increasing lime. However, the high ratios indicate that leaching has only minimal detrimental effect on the exchange complex of the lime treated soils in this research as the amount of calcium in the soils remained high after leaching.

Leach Tests—Differential Thermal Analyses

306. Differential thermal analyses (DTA) were run on selected samples from all three sites. Samples were tested using a Perkin-Elmer 1700 DTA furnace controlled by Model 3600 Data Station. Thirty-four DTAs were run to compare before leach data to after leach data. All tests were for samples originally compacted at optimum moisture. All samples were tested at a heating rate of 40 °C/min up to a maximum temperature of 1100 °C using nitrogen purge gas. Endothermic (minimum) and exothermic (maximum) peaks were recorded and are shown in Table 23 for Sites No. 1, 2 and 3. All initial endotherms are from desorption of the absorbed water in the soil-water system.

Site No. 1 Analysis

307. Figures 122 through 124 show typical DTA curves for Site No. 1 soils before and after leaching. With increasing additions of lime, endotherms at 560 and 870 °C gradually decreased in peak definition. Additionally, the exotherm at 920 °C dramatically decreased in peak height with the addition lime. This is in agreement with DTA tests run by Glenn and Handy (1963) which showed that pure montmorillonite endotherms of 850 °C disappeared completely when lime was added. Since the soil contained large quantities of natural calcium, it was difficult

TABLE 23

DIFFERENTIAL THERMAL ANALYSES

Soil Description	Peak Temperature (°C)							
	MIN*	MAX	MIN	MAX	MIN	MAX	MIN	MAX
Site No. 1								
0% lime, before	165	475	568	646	869	924	--	--
After 45 days	160	455	573	650	870	947	--	--
1% lime, before	159	409	573	636	868	950	--	--
After 45 days	168	435	578	649	888	942	--	--
3% lime, before	165	436	573	637	874	952	--	--
After 45 days	166	443	578	647	879	940	--	--
After 90 days	170	444	578	654	897	954	--	--
6% lime, before	161	426	572	629	873	900	910	967
After 45 days	166	439	575	638	875	950	--	--
After 90 days	165	439	572	634	872	954	--	--
8% lime, before	155	453	575	625	873	895	900	962
After 45 days	167	436	568	630	873	962	--	--
Site No. 2								
0% lime, before	153	486	566	638	901	999	1015	--
After 45 days	145	436	560**	--	909	960	1011	--
1% lime, before	142	436	565**	--	916	959	986	--
After 45 days	140	434	--	--	910	955†	1022	--
3% lime, before	144	433	--	--	915	961	1001	--
After 45 days	147	435	--	--	910	955	1015	--
After 90 days	143	444	--	--	911	953	1013	--
7% lime, before	141	422	--	--	922	960**	970**	1014
After 45 days	137	422	--	--	916	960**	970**	1008
After 90 days	142	436	--	--	919	960**	970**	1016
Site No. 3								
0% lime, before	165	425	579	663	812	841	--	--
After 45 days	162	439	578	664	822	845	--	--
1% lime, before	160	419	577	660	816	847**	--	--
After 45 days	162	430	580	673	824	845**	--	--
3% lime, before	162	433	578	694	810	837**	--	--
After 45 days	163	433	580	667	826	849**	--	--
After 90 days	158	438	577	667	816	841**	--	--
7% lime, before	158	462	583	678	824	897	--	--
After 45 days	158	456	581	675	825	888	--	--
9% lime, before	151	462	583	653	835	896	--	--
After 45 days	157	454	582	657	834	892	--	--
After 90 days	156	455	585	685	834	888	--	--

*   Peak due to desorption of absorbed water.

** Small peak or shoulder

†   Small endothermic peak at 980 °C

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Figure 122.   DTA plots of Site No. 1 samples, 0% lime.

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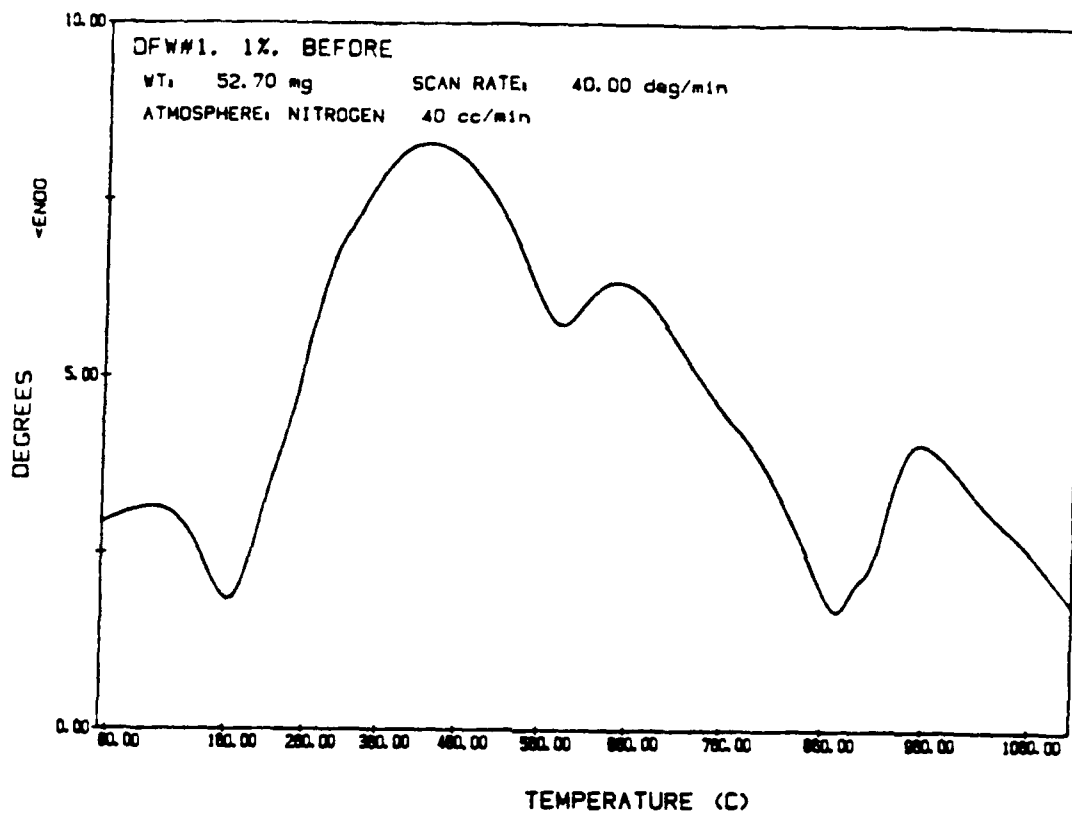
Figure 123.   DTA plots of Site No. 1 samples, 1% lime.

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Figure 124.   DTA plots of Site No. 1 samples, 8% lime.

to distinguish the endothermic reactions indicative of lime (500-570 °C) from the natural soils endothermic peak at 568 °C. It is estimated that the peak at 568 °C is most likely an indication of the presence of illite in the soil rather than a distinctive peak indicating the presence of lime. Additionally, DTA tests by Eades and Grim (1960) showed that cured samples of montmorillonite and kaolinite did not show distinctive endotherms for lime while those not cured did. All samples tested in Site No. 1 were cured at least 48 hours at 120 °F.

308. After six percent lime had been added to the soil, a double exothermic peak develops at about 900 °C and continued to become more distinct as eight percent lime was added. This may have been a development of $CaCO_3$ (at approximately 750 to 850 °C) or possibly an increase of pozzolanic reaction (Ho and Handy 1963; Glenn and Handy 1963). Since this double peak was not present after leaching, it is speculated that the double exotherm was most likely $CaCO_3$ or some other weakly bonded reaction product which could be removed by leaching.

309. After leaching, endothermic peaks at 570 °C remained unchanged while those at 870 °C generally increased slightly (by 2 to 10 °C). Exotherms at 650 and 940 °C also shifted slightly to the right after leaching, i.e., slightly increased in peak temperatures. The longer the leaching duration, the greater the increase in peak temperature. With an increase in lime content, the increases in after leach peak temperatures diminished. For example, at three percent lime, the exotherm at 650 °C increased by 17 °C after 90 days of leaching, but at eight percent lime it had increased only 5 °C after leaching. It is speculated that these small shifts or peaks are not detrimental the soil-lime structure as there is no significant elimination of any peaks nor were there formations of new peaks.

Site No. 2 Analysis

310. Typical DTA plots for Site No. 2 soils are shown in Figures 125 through 127. Perhaps the most noticeable effect is that there was initially an endothermic peak at 560 °C in the natural soil, but with leaching or the addition of lime this peak disappeared. This may have been an indication of the high calcium content in Site No. 2 soil originally, but which can be somewhat eroded. When lime is added, that calcium may be forced to react with the additional lime in forming pozzolanic reactions that do not show up in thermal analysis at small lime contents (Ho and Handy 1963).

311. At lime contents below three percent, there was a significant exothermic peak at approximately 960 °C with an adjoining endotherm at 1010 °C. With seven percent lime, the 960 °C exotherm was barely distinguishable and the adjoining endothermic peak had dropped to 970 °C and was also barely present. It is speculated that these peaks were indications of pozzolanic reactions that, with the addition of more calcium, were being further utilized in the soil-lime structure forming permanent products. Leaching of samples with below seven percent lime showed some change in these peaks while at seven percent lime, no change appeared, further supporting the theory that the reactions were permanent (Ho and Handy 1963).

312. Endotherms at 900 °C increased in temperature with the addition of lime and then decreased slightly (2 to 9 °C) after leaching. Longer leaching produced lower temperatures after leaching. This is opposite of the reactions found in Site No. 1 tests where leaching produced increases in temperature peaks.
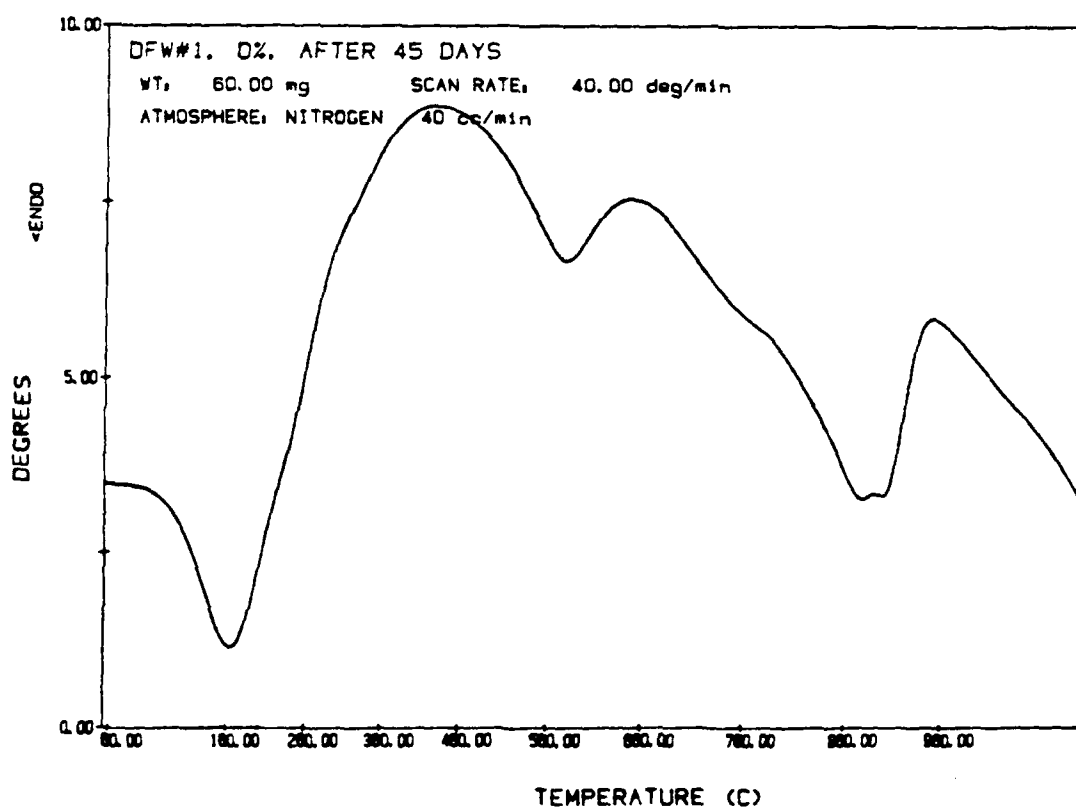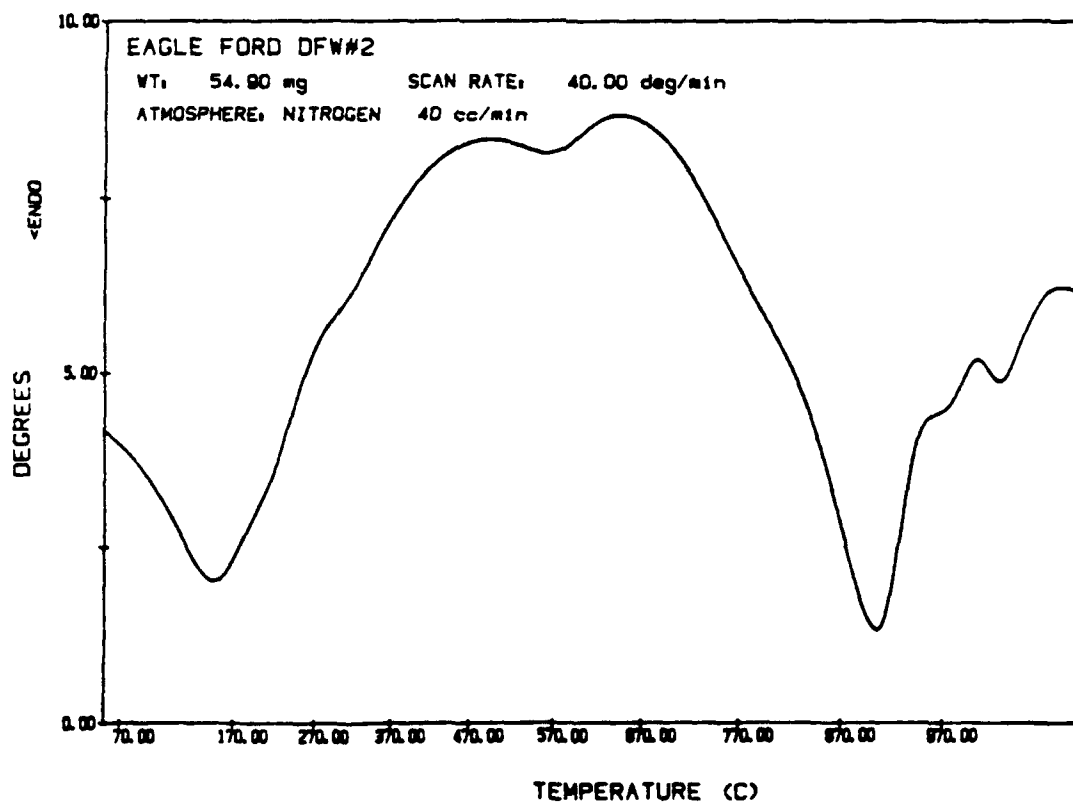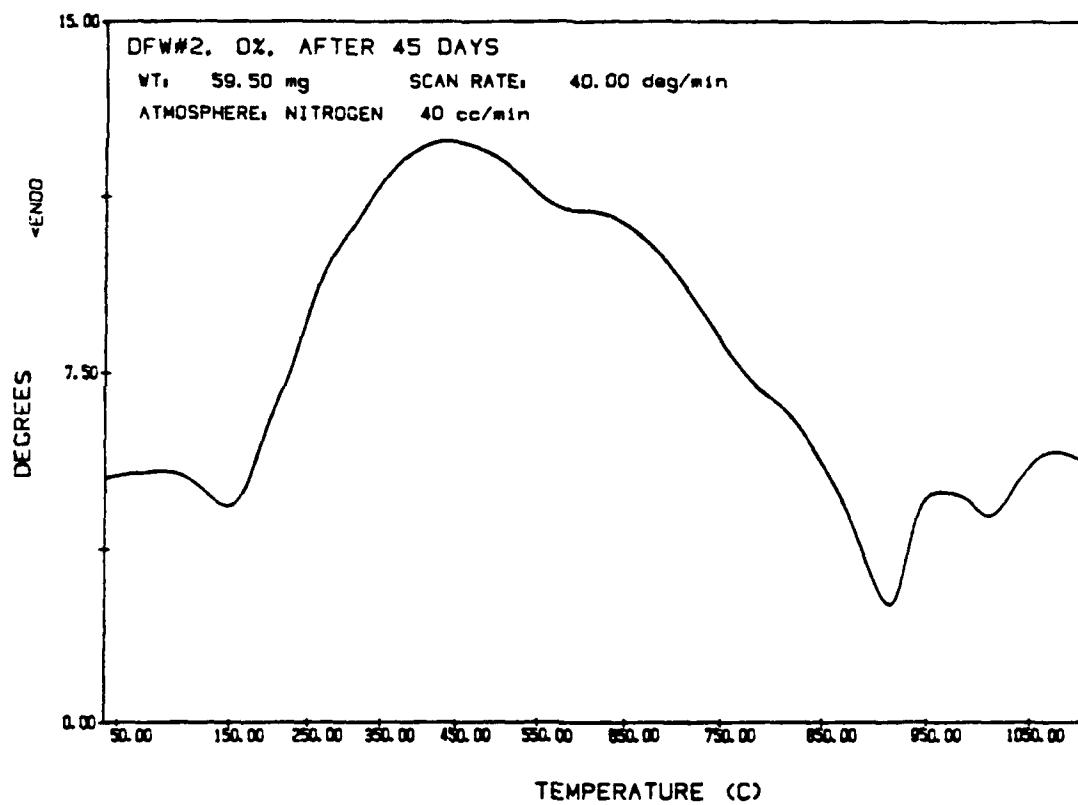
Figure 125.   DTA plots of Site No. 2 samples, 0% lime.
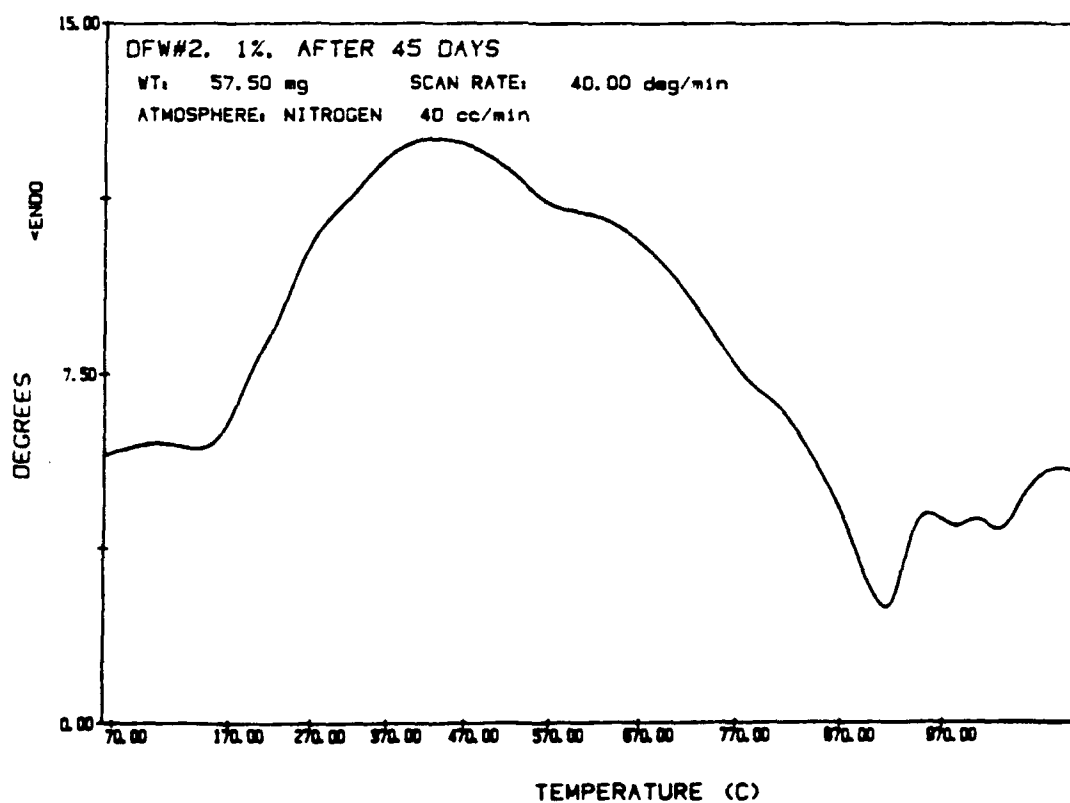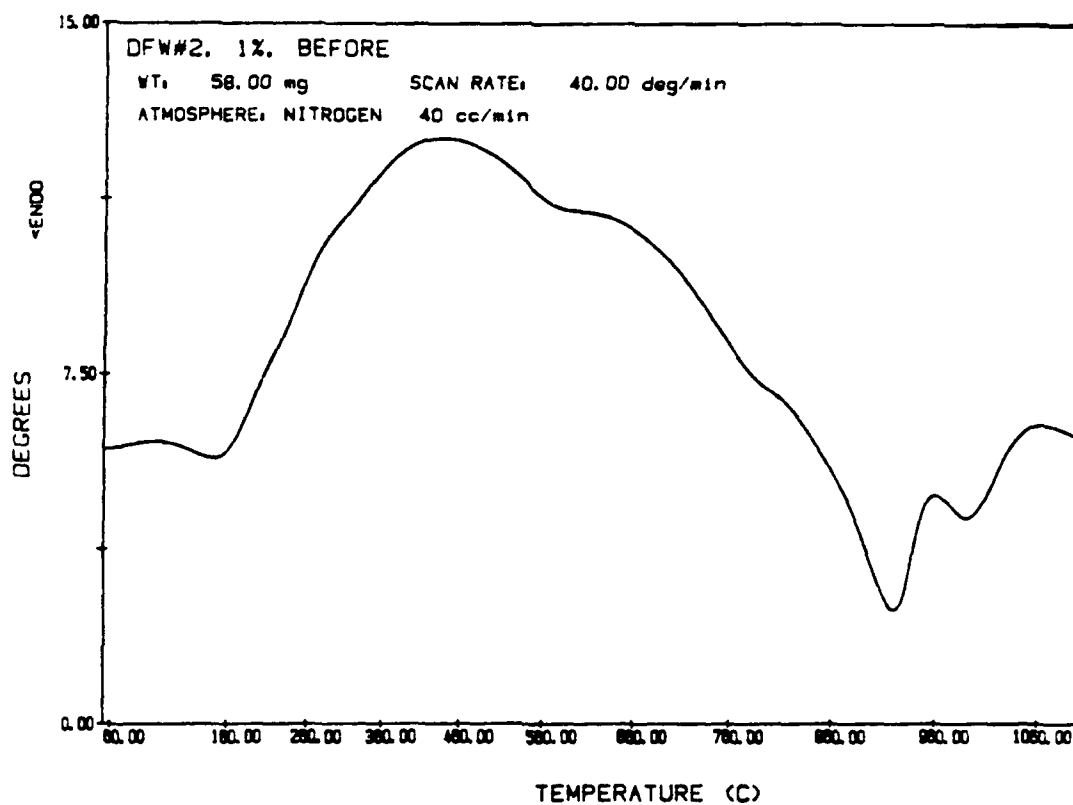
Figure 126.   DTA plots of Site No. 2 samples, 1% lime.
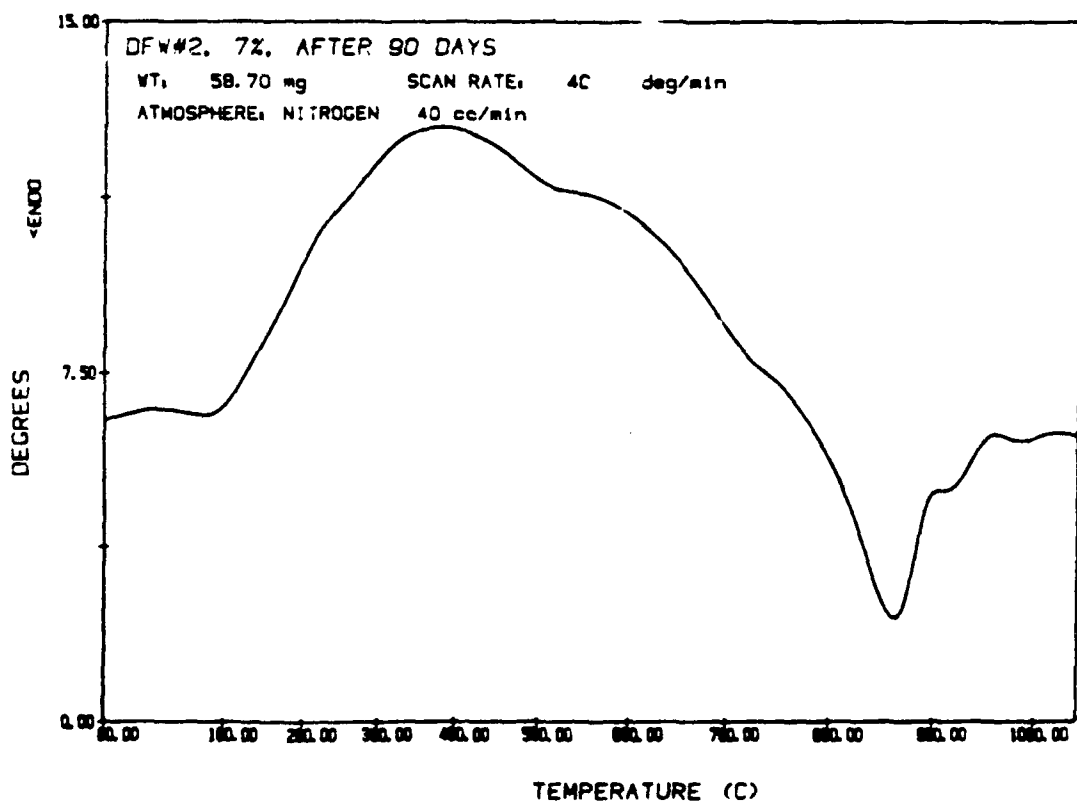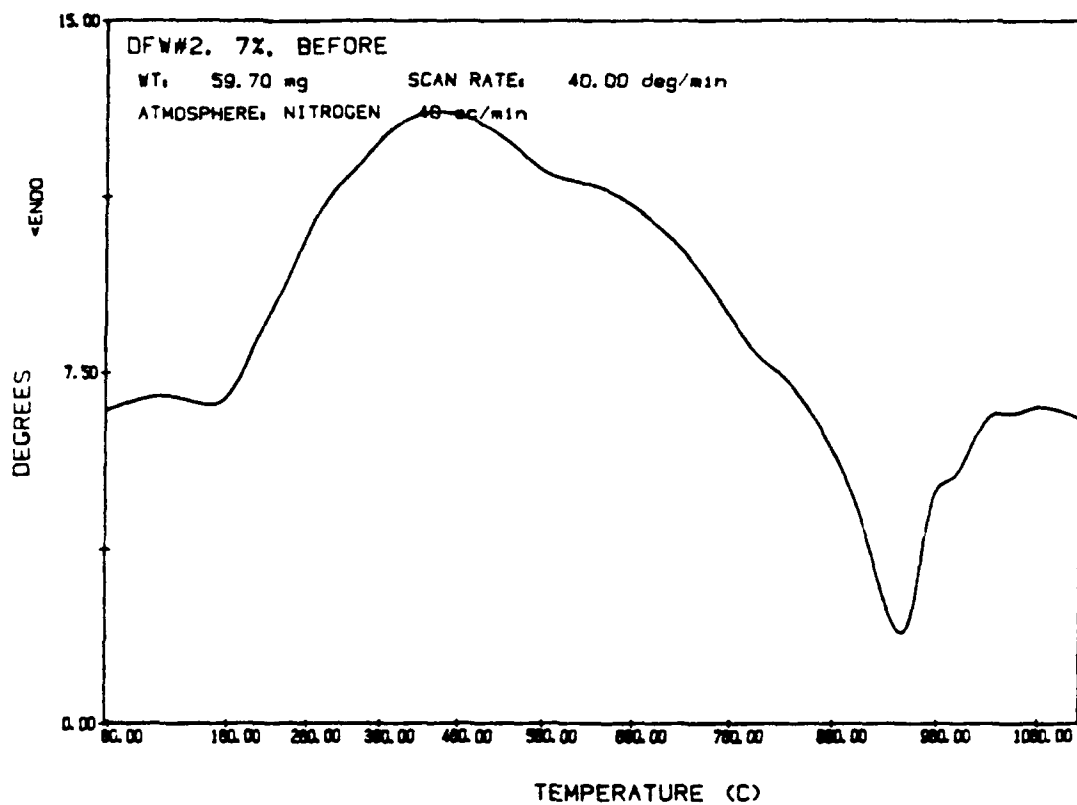
Figure 127.   DTA plots of Site No. 2 samples, 7% lime.

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Site No. 3 Analysis

313. Figures 128 through 130 show DTA plots of Site No. 3 samples before and after leaching. The most significant reaction appears to be the exothermic peak at 840 °C. With the addition of of lime, this peak became much more pronounced and shifted considerably to the right so that at nine percent lime it was at approximately 900 °C. This predominant peak with increasing lime was seen in Site No. 1 tests and in research by others (Glenn and Handy 1963; Ho and Handy 1963). It is speculated to be an indication of permanent to semi-permanent pozzolanic reaction or possibly $CaCO_3$. Since the peak definition was somewhat lessened after leaching, but not removed, it was most likely a weakly bonded $CaCO_3$ or other weakly bonded product.

314. There was no distinct pattern in the changes in the exothermic and endothermic temperatures after leaching, but with the addition of lime, peaks at 670 and 810 °C tended to increase. With increases in lime, the exothermic peak at 670 °C became less pronounced but still distinct. As with Site No. 1 soil, the endotherm at 580 °C is most likely indicative of the high calcium content in the natural soil rather than a distinctive peak indicating lime, as was previously discussed.

Summary of DTA

315. All three sites showed similar reaction products at approximately 900 °C. Exothermic peaks for Sites No. 1 and 3 material became more pronounced with increases in lime while Site No. 2 material displayed a rounding of the smaller endothermic and exothermic peaks to make one large exotherm at 970 °C. It was suggested that these peaks were indications of pozzolanic products or $CaCO_3$ products (or both). From a study of the soil's exchangeable complex cations, it was shown that Sites No. 1 and 3 material contain higher amounts of calcium than Site
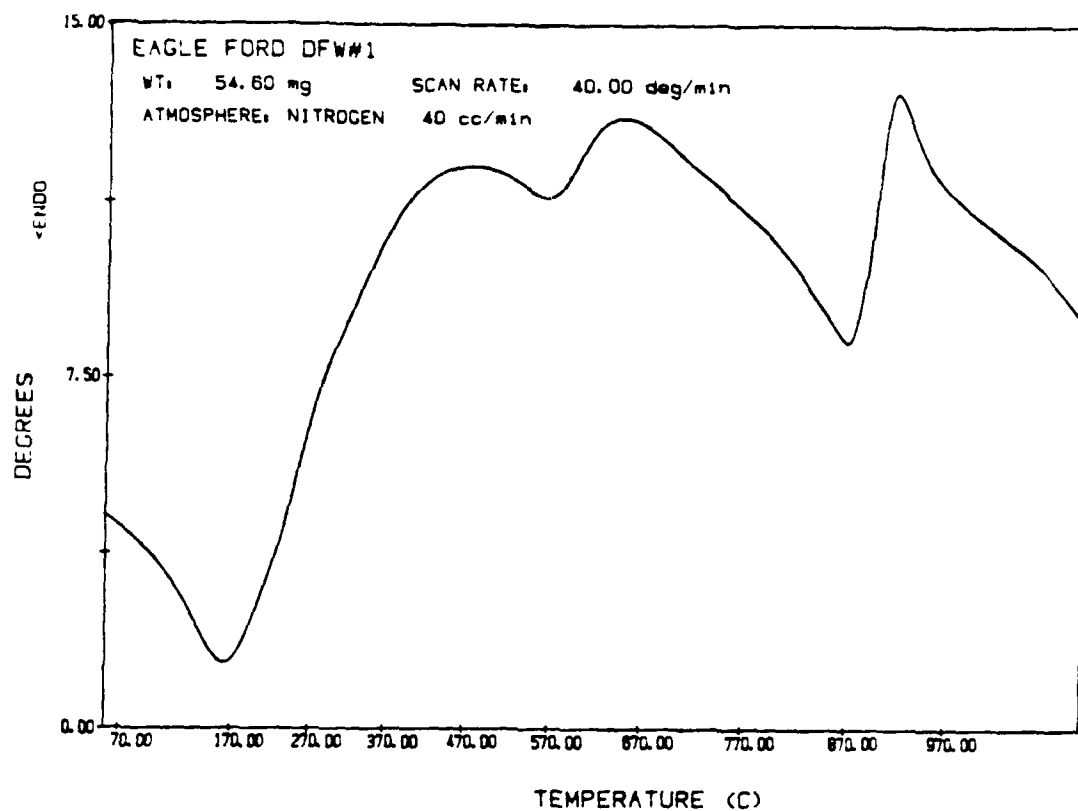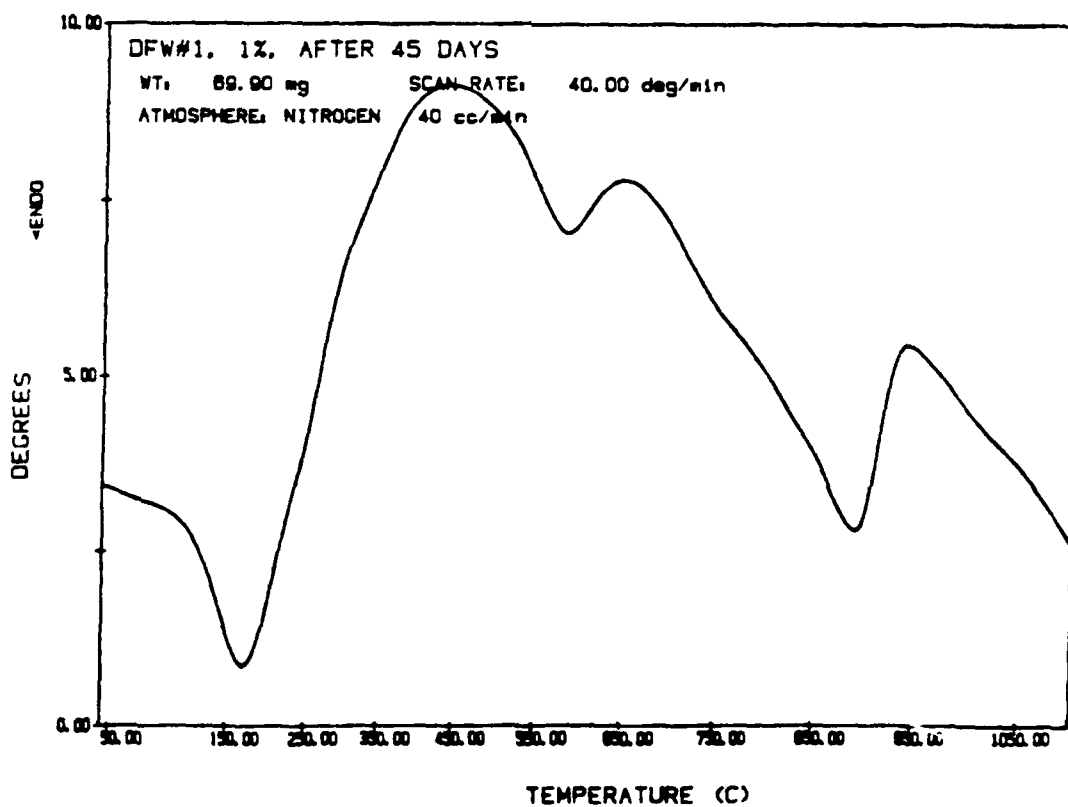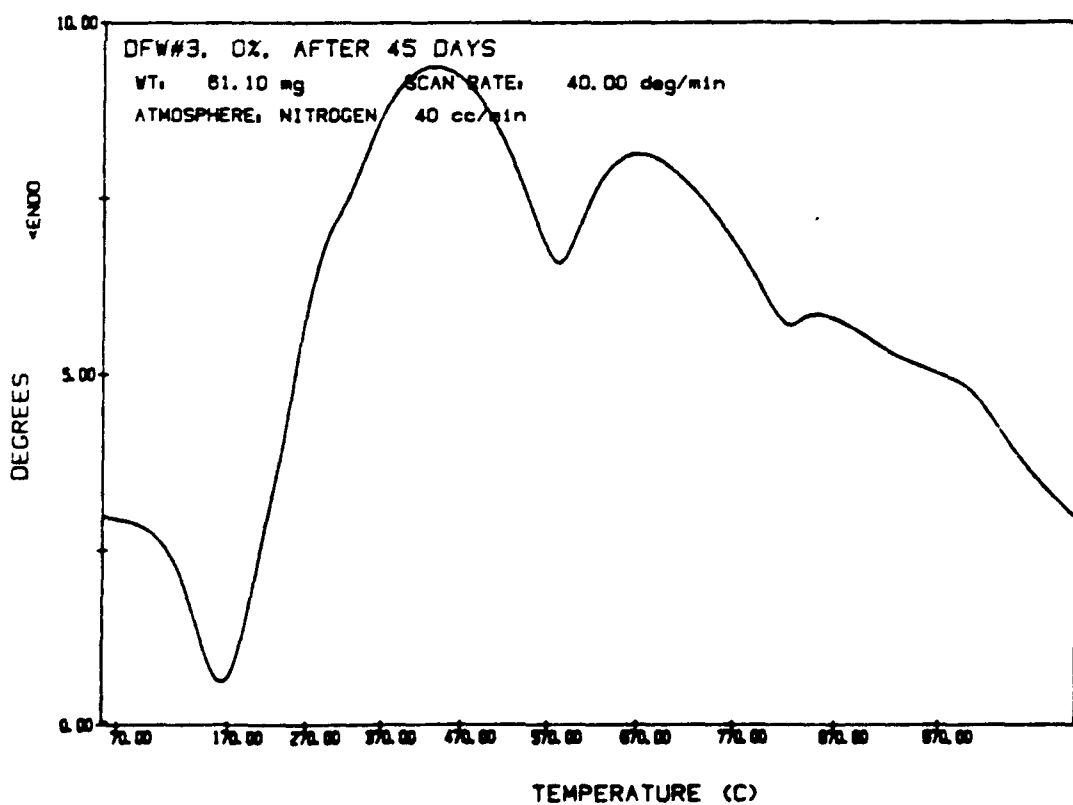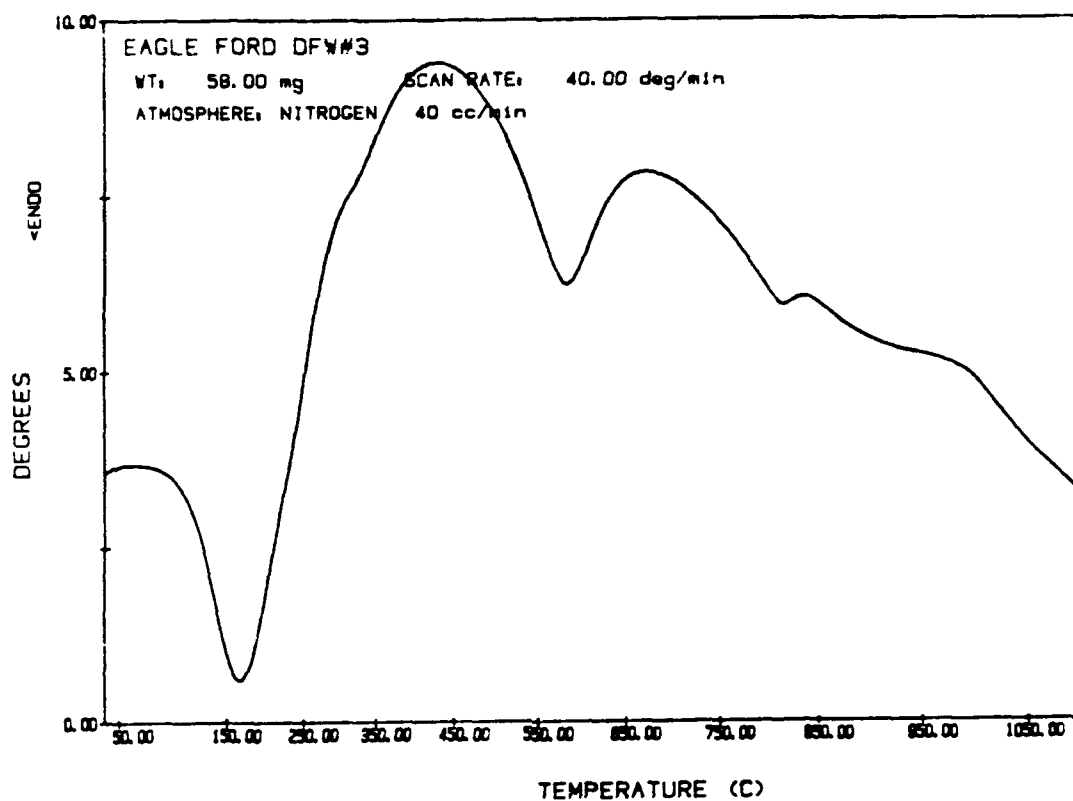
Figure 128.   DTA plots of Site No. 3 samples, 0% lime.

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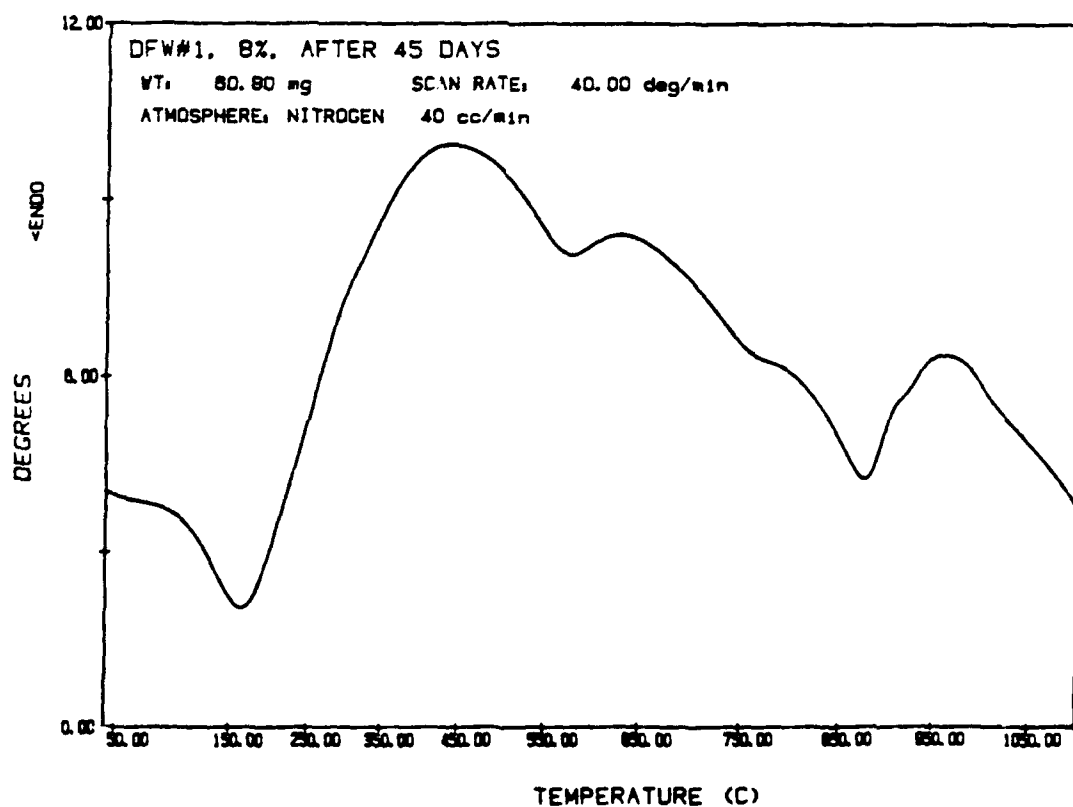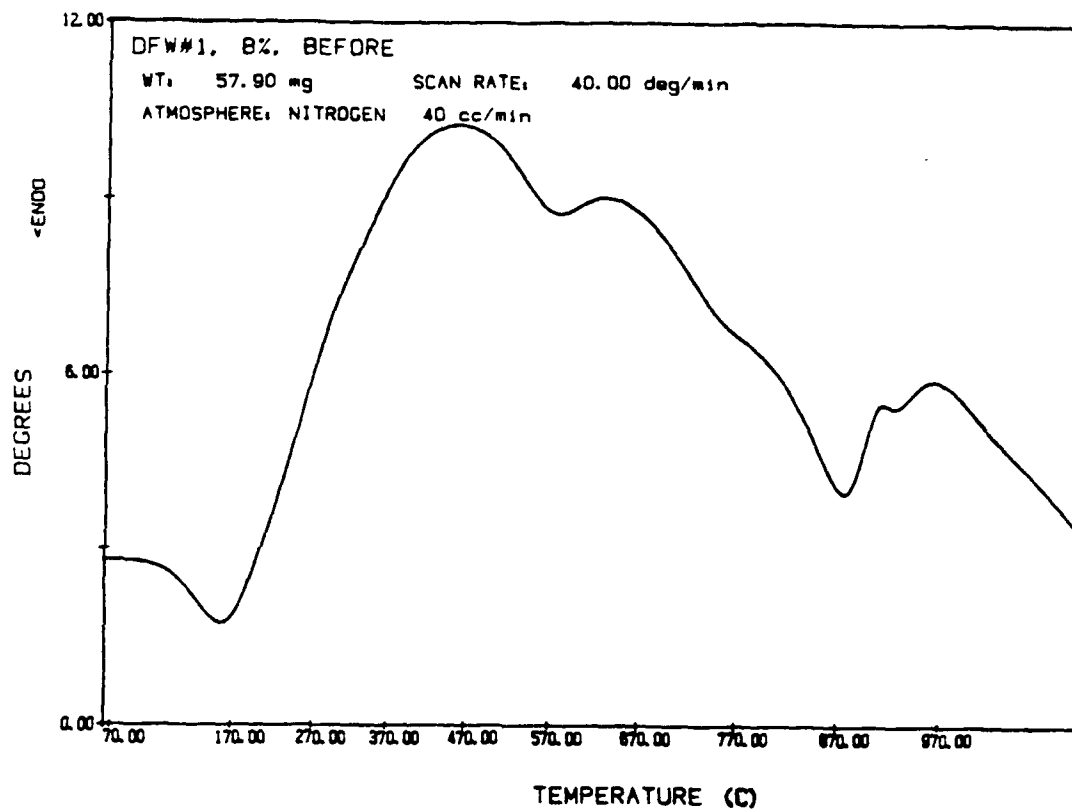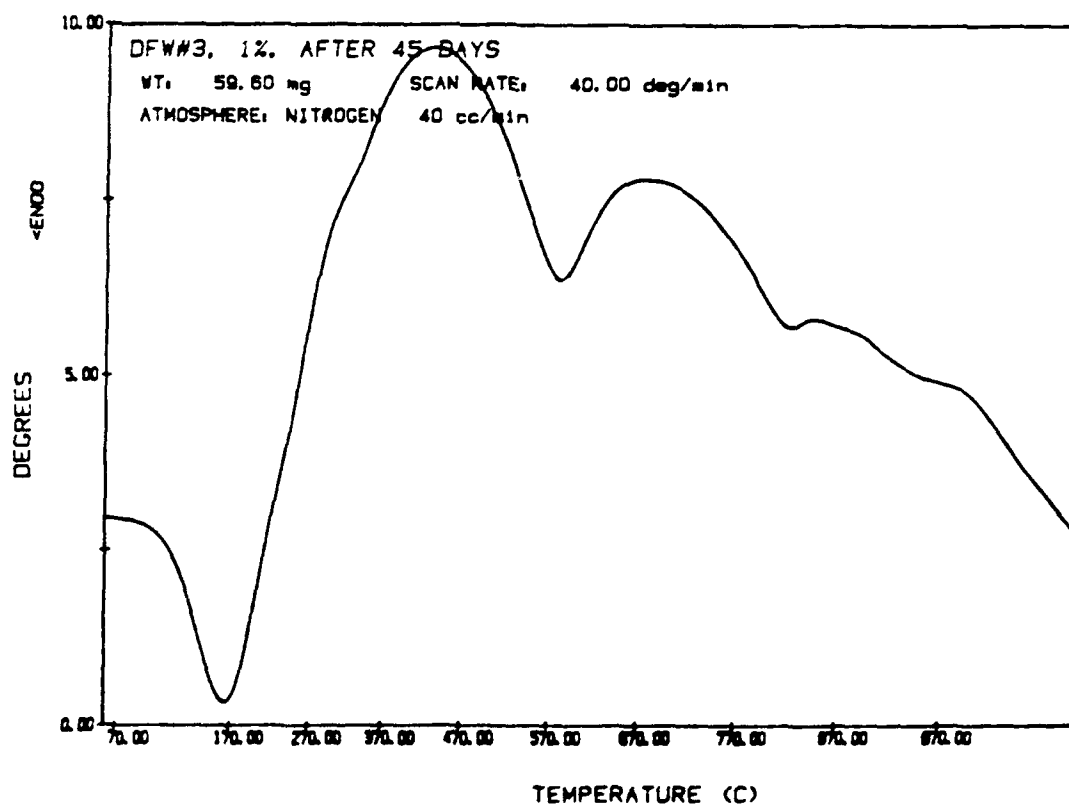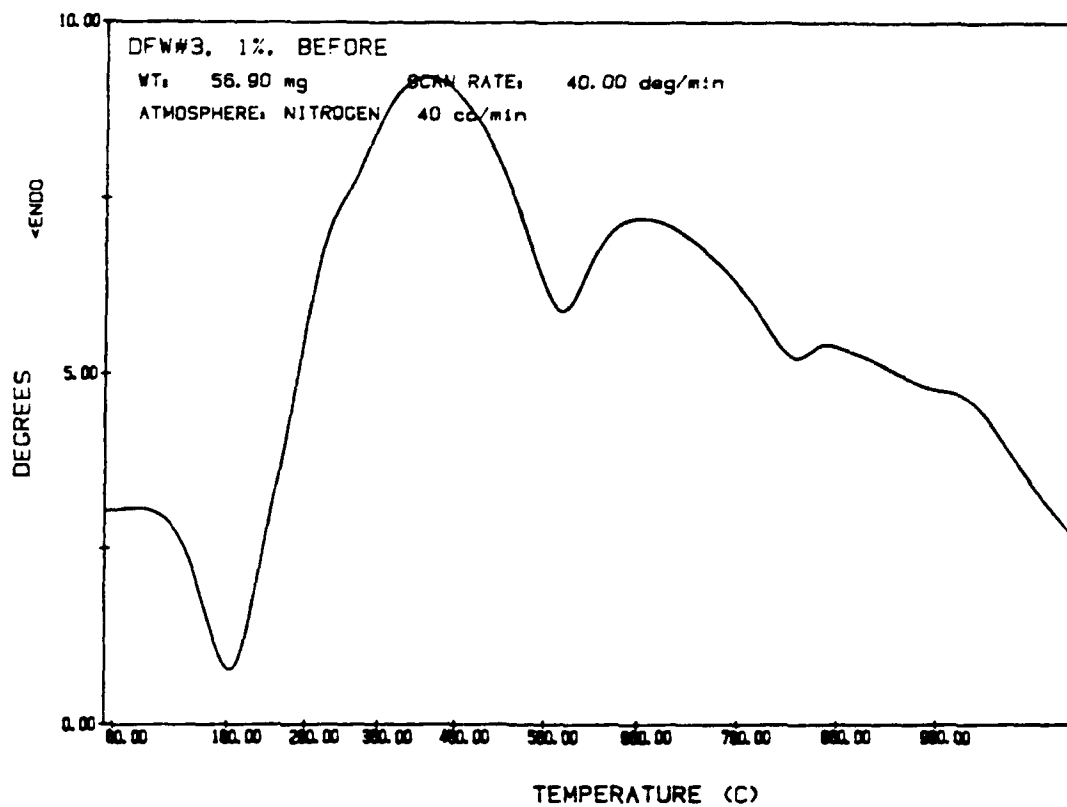Figure 129.   DTA plots of Site No. 3 samples, 1% lime.

273
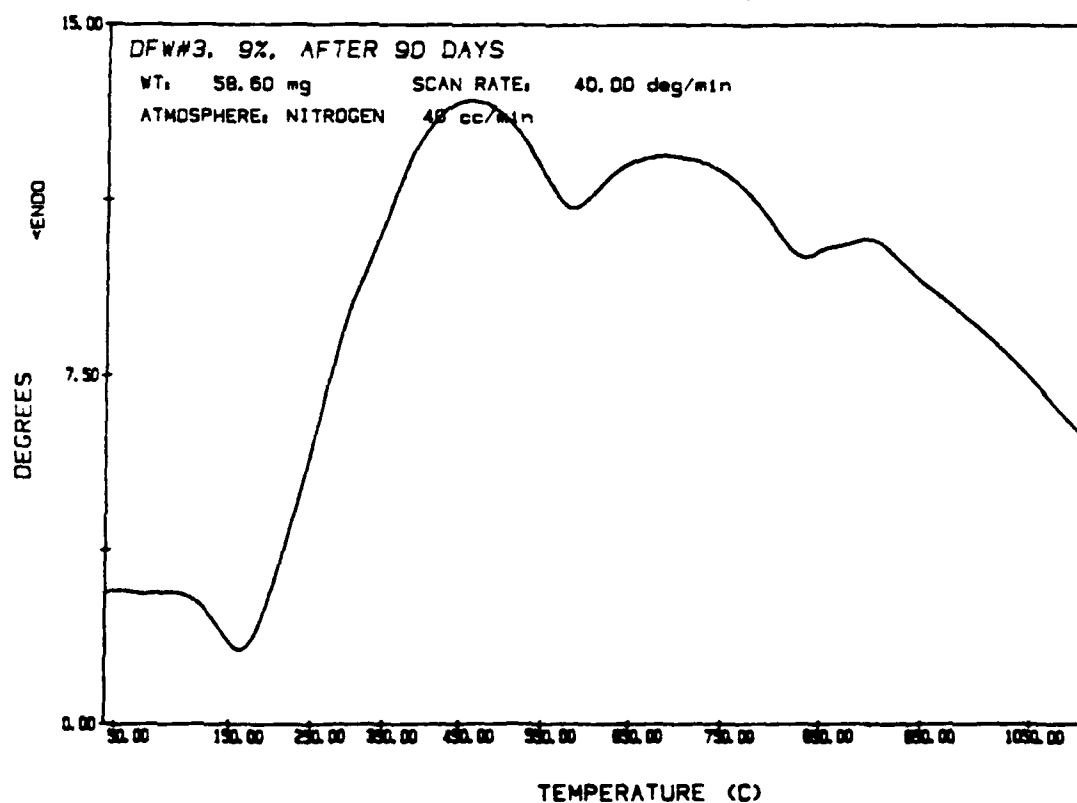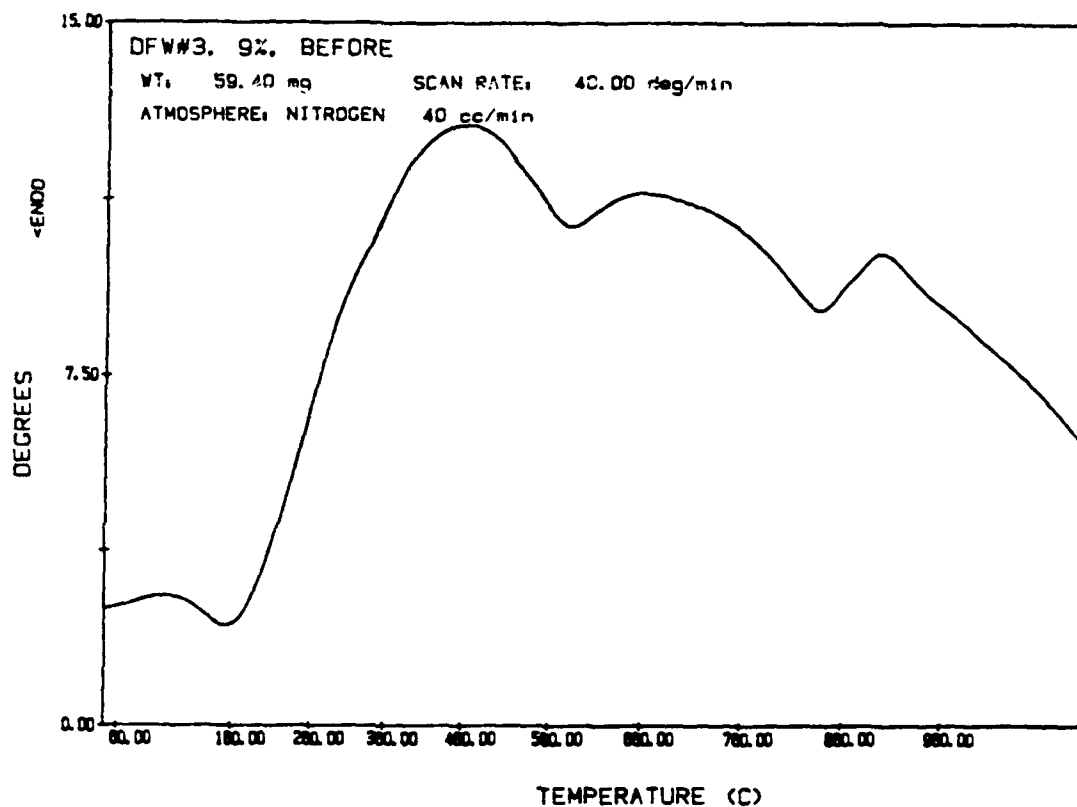
Figure 130. DTA plots of Site No. 3 samples, 9% lime.

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No. 2 soil. This may indicate that since Sites No. 1 and 3 soils contained more initial calcium, large quantities of lime produced permanent pozzolanic reactions and also, some weakly bonded products (possibly $CaCO_3$) with the excess calcium. As Site No. 2 soil had lower initial calcium, it may not have had excess calcium available for producing these additional products.

316. Leaching of material from all three sites produced minimal changes in the exothermic and endothermic peaks except for the prominent exothermic peak discussed above. The intensity of this prominent peak decreased as leaching increased. The higher the lime content, the more noticeable the lessening of the peak, particularly for Sites No. 1 and 3 soils and much less so for Site No. 2 soils. This would tend to support the idea that this peak was a carbonate product that can be removed by leaching.

317. All sites showed some peaks that tended to increase slightly in temperature with increases in lime content after leaching, but a study of all the temperature shifts after leaching was not conclusive. Site No. 1 material showed the most increases in peak temperatures after leaching while Site No. 2 material showed decreases in peak temperatures after leaching. Site No. 3 tests showed no pattern in temperatures shifts caused by leaching.

Statistical Analysis of Leach Data

Hypothesis Established

318. Physical and chemical property analyses were conducted on all test samples prior to leaching and after leaching. Samples tested before leaching were duplicated at least twice and usually three times, with the test results averaged and a sample standard deviation recorded. All leach samples were duplicated during leaching then split in half at the completion of the test. Each half was independently

tested for physical and chemical properties. Therefore, each property change result (based on lime content and/or moisture content variation) tested after leaching was the average of four independent tests.

319. One of the objectives of this research was to detect the difference, if any, between the mean of the tested property (physical and chemical) before leaching and the mean of the property after leaching. The t statistic (often called the Student's t statistic) was used to test the statistical significance of the difference between the means. The null hypothesis was established as being no difference between the tested means before and after leaching.

320. The alternative hypothesis varied depending on expected results after leaching. For example, based on preliminary tests, previous work by others and theorized results of the leaching effects on lime treated clays, it was expected that detrimental effects would be achieved if the after leaching results were greater than the before test results for plasticity index, linear shrinkage, swell pressure and percent free swell. Therefore, the alternative hypothesis established for those four tests was that before leach results were less than after leach results (negative one-tail test). By the same reasoning, detrimental effects would be achieved if before leach results were greater than after leach results for liquid limit, plastic limit, unconfined compression strength, and soil pH. The alternative hypothesis established for these four properties was that before leach results were greater than after leach results (positive one-tail test). All chemical extraction tests, because of the uncertainty of leaching, were tested as two-tail tests with the alternative hypothesis being before leach not equal to the after leach results.

321. In order to use the t statistic, one of the assumptions that must be verified is whether the population variances are equal ($s_1^2 = s_2^2$). Prior to testing for significant difference between the means, equal population variances were

tested using the F distribution at an $\alpha = 0.05$ level of significance. All F distribution tests were conducted as two-tail tests as only significant differences in the before versus after leach variances were required.

322. All F tests showed that there was insufficient evidence to refute the assumption of equal population variances at the $\alpha = 0.05$ level. This was not unexpected as a look at the F distribution table for $F_{\alpha/2}$ shows that very low number of tests will yield extremely high F test rejection regions (McClave and Benson 1982). Furthermore, large sample variances occurred primarily only in swell pressure tests, but the before and after tests produced similar variances which, when divided for the F test statistic, produced small numbers. Therefore, the t statistic was valid for testing the differences between the means for all comparisons.

323. All t statistics were tested at the $\alpha = 0.05$ level of significance (primary) and the $\alpha = 0.10$ level of significance (secondary). Results of samples compacted at optimum moisture are presented in tables 24, 25 and 26 for Sites No. 1, 2 and 3 material, respectively. All results are recorded as either statistically significant (SS) difference in before and after means or insufficient evidence (IE) to refute the null hypothesis at the $\alpha = 0.05$ level. Also noted are comparisons which produced insufficient evidence to refute the null at $\alpha = 0.05$ but were statically significant at the $\alpha = 0.10$ level.

Test Results Versus Statistical Results

324. <u>Physical Property Changes</u>. It can be seen from Tables 24, 25 and 26 and from previous discussions on property changes after leaching, only by testing the statistical significance of the property change can an initial assessment of the leaching effects be made. Final analysis of the effects can only be made after also studying the practical significance of any changes.

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TABLE 24

SITE NO. 1, STATISTICAL RESULTS
(-3% < OMC < +3%)

Property	0% Lime A45*	0% Lime A90	1% Lime A45	2% Lime A45	3% Lime A45	3% Lime A90	4% Lime A45	6% Lime A45	6% Lime A90	8% Lime A45
Physical										
Liquid Limit	--	--	IE**	SS	SS	SS	SS	SS	SS	SS
Plastic Limit	--	--	SS	SS	SS	SS	SS	SS	SS	SS
Plasticity Index	--	--	SS	SS	SS	SS	SS	IE	IE	IE
Linear Shrinkage	--	--	IE	IE	IE	IE	SS	IE	IE	IE
Trimmed Samples										
Swell Pressure	--	--	SS	SS	SS	SS	SS	SS	IE	SS
Free Swell	--	--	IEc	IE	IE†	SS	SS	SS	IE†	IE
Shear Strength	--	--	SS	IE	IE	IE†	SS	SS	SS	IE
Failure Stain	--	--	IE	IE	SS	IE	IE	IE	IE†	SS
Reworked Samples										
Swell Pressure	--	--	SS	SS	SS	SS	SS	SS	SS	SS
Free Swell	--	--	SS	IE	SS	IE†	SS	SS	SS	IE
Shear Strength	--	--	SS	IE	IE	IE	IE	IE	IE	SS
Failure Strain	--	--	IE	IE	IE	IE	SS	SS	SS	IE
Chemical										
Soil pH	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
Porewater Cations (meq/l)										
Calcium	SS	SS	SS	IE	SS	SS	IE†	SS	IE	SS
Sodium	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
Magnesium	SS	SS	SS	IE	SS	SS	SS	SS	SS	IE
Potassium	IE	SS	IE†	IE	IE	SS	IE	IE	SS	IE
Exchange Complex Cations (meq/100 g)										
Calcium	IE	IE	IE	IE	SS	SS	SS	SS	SS	SS
Sodium	SS	SS	SS	IE†	SS	SS	SS	SS	SS	SS
Magnesium	SS	SS	IE	IE	IE	SS	SS	SS	IE	IE
Potassium	IE	IE	IE	IE	IE	IE	IE	IE	IE†	SS

* A45 = After 45 days leaching; A90 = After 90 days leaching

** SS = Statistically significant at the α = 0.05 level of significance; IE = Insufficient evidence to refute the null hypothesis ($\mu_1 = \mu_2$) at the α = 0.05 level

† Statistically significant at the α = 0.10 level of significance

TABLE 25

SITE NO. 2, STATISTICAL RESULTS
(-3% < OMC < +3%)

Property	0% Lime A45[*]	0% Lime A90	1% Lime A45	2% Lime A45	3% Lime A45	3% Lime A90	5% Lime A45	7% Lime A45	7% Lime A90
Physical									
Liquid Limit	--	--	SS[**]	IE	IE	IE	IE[†]	SS	IE
Plastic Limit	--	--	SS	SS	IE	IE	SS	IE[†]	IE
Plasticity Index	--	--	SS	SS	IE[†]	IE[†]	IE	IE	IE
Linear Shrinkage	--	--	SS	SS	SS	SS	IE	IE	IE
Trimmed Samples									
Swell Pressure	--	--	IE	IE[†]	IE	IE	IE	IE	IE
Free Swell	--	--	IE	IE	IE	IE	IE	SS	SS
Shear Strength	--	--	SS	IE[†]	IE	IE	IE	IE	IE
Failure Stain	--	--	IE	SS	IE[†]	SS	SS	IE	SS
Reworked Samples									
Swell Pressure	--	--	IE	SS	IE	SS	SS	IE	IE
Free Swell	--	--	IE	SS	IE[†]	SS	SS	IE[†]	IE
Shear Strength	--	--	IE	SS	IE[†]	SS	SS	SS	SS
Failure Strain	--	--	SS	IE	IE	IE	SS	IE	IE
Chemical									
Soil pH	IE	IE	SS	SS	SS	SS	SS	IE[†]	SS
Porewater									
Cations (meq/l)									
Calcium	SS	SS	IE	IE[†]	IE[†]	IE	IE	SS	SS
Sodium	SS	IE	SS	SS	SS	SS	SS	SS	SS
Magnesium	IE[†]	IE	SS	IE	IE[†]	IE	IE	SS	SS
Potassium	IE[†]	IE	SS	IE[†]	SS	SS	SS	SS	SS
Exchange Complex									
Cations (meq/100 g)									
Calcium	IE	IE	IE	IE	IE[†]	IE	IE[†]	SS	IE[†]
Sodium	SS	SS	SS	IE[†]	SS	SS	SS	SS	SS
Magnesium	IE	IE	SS	IE	SS	IE[†]	IE[†]	SS	IE
Potassium	IE	IE	IE	SS	SS	SS	IE	IE	SS

[*]   A45 = After 45 days leaching; A90 = After 90 days leaching

[**]   SS = Statistically significant at the $\alpha = 0.05$ level of significance; IE = Insufficient evidence to refute the null hypothesis ($\mu_1 = \mu_2$) at the $\alpha = 0.05$ level.

[†]   Statistically significant at the $\alpha = 0.10$ level of significance

TABLE 26

SITE NO. 3, STATISTICAL RESULTS
(-3% < OMC < +3%)

Property	0% Lime A45*	0% Lime A90	1% Lime A45	2% Lime A45	3% Lime A45	3% Lime A90	5% Lime A45	7% Lime A45	9% Lime A45	9% Lime A90
Physical										
Liquid Limit	--	--	SS**	IE	IE	IE	IE†	IE†	IE†	IE
Plastic Limit	--	--	SS	SS	SS	SS	SS	IE	IE	IE
Plasticity Index	--	--	IE	SS	SS	IE†	IE†	IE	IE	IE
Linear Shrinkage	--	--	SS	SS	SS	SS	SS	IE	IE	SS
Trimmed Samples										
Swell Pressure	--	--	IE	SS	SS	SS	SS	SS	SS	IE
Free Swell	--	--	SS	SS	SS	SS	IE†	SS	IE	IE
Shear Strength	--	--	IE	SS	SS	SS	SS	IE†	IE	IE
Failure Stain	--	--	IE	SS	IE	IE	IE	IE	IE†	SS
Reworked Samples										
Swell Pressure	--	--	SS	SS	SS	SS	SS	SS	SS	IE
Free Swell	--	--	SS	SS	SS	SS	SS	SS	SS	IE†
Shear Strength	--	--	IE	IE	IE	IE	IE	IE	IE	IE
Failure Strain	--	--	IE	IE	IE	SS	SS	SS	IE	IE†
Chemical										
Soil pH	IE	IE	SS	SS	SS	SS	SS	SS	SS	SS
Porewater Cations (meq/l)										
Calcium	SS	SS	IE†	IE	SS	IE	IE†	IE	IE	IE†
Sodium	SS	SS	SS	IE†	SS	SS	SS	SS	SS	SS
Magnesium	SS	SS	SS	IE†	IE†	IE†	IE†	SS	SS	IE†
Potassium	IE†	SS	SS	IE	IE	SS	IE	IE	SS	IE
Exchange Complex Cations (meq/100 g)										
Calcium	IE	IE	IE†	SS	SS	IE	IE†	SS	SS	IE
Sodium	IE	IE†	SS	IE	SS	SS	SS	SS	SS	IE†
Magnesium	IE	IE†	SS	IE	SS	SS	IE	SS	SS	IE
Potassium	SS	SS	IE	IE	IE	IE	IE	IE†	IE	IE

* A45 = After 45 days leaching; A90 = After 90 days leaching

** SS = Statistically significant at the α = 0.05 level of significance; IE = Insufficient evidence to refute the null hypothesis ($\mu_1 = \mu_2$) at the α = 0.05 level

† Statistically significant at the α = 0.10 level of significance

325. Linear shrinkage of the material from the three sites generally increased after leaching when up to approximately five to six percent lime had been added. Table 24 shows that only the three and four percent lime tests were significantly changed for Site No. 1 tests. However, Sites No. 2 and 3 tests showed that the increase in shrinkage were significant until five and seven percent lime, respectively, had been added to the soils. This is in general agreement with the physical data.

326. Atterberg limits testing showed that leaching generally decreased the soil's liquid and plastic limits and increased its plasticity index. For all three soil sites, the plasticity index increased after leaching until approximately five or six percent lime had been added. Statistical analysis revealed that the PI was significantly increased after leaching up to when lime contents of six, five and seven percent had been added to Sites No. 1, 2 and 3 material, respectively. At lime contents between three to five percent, the significance for Sites No. 2 and 3 tests dropped from $\alpha = 0.05$ to the $\alpha = 0.10$ level. Liquid and plastic limits for Site No. 1 tests were significantly lower for all lime contents while for Sites No. 2 and 3 tests, only the plastic limits showed uniformly significant decreases after leaching (up until seven percent lime had been added). Only at one percent lime were liquid limit changes in Sites No. 2 and 3 tests significant at $\alpha = 0.05$.

327. This suggests that only the plasticity index and the plastic limit were significantly affected by leaching. Plasticity index was the most significantly changed, up until approximately six to seven percent lime had been added to all three soils. This is in general agreement with the physical data presented earlier.

328. Physical testing of swelling pressures and percent free swell showed that there was a general increase in both properties after leaching for all lime contents tested for Sites No. 1 and 3. Samples with greater than six to seven percent

lime showed much lower after leach swelling potential. Site No. 2 samples displayed decreases or only slight increases in swelling after leaching for all lime contents.

329. Statistical analysis showed that for trimmed samples, the swell pressures were statistically significantly higher for all lime contents tested on Sites No. 1 and 3 samples leached 45 days. At the highest lime contents, however, there was insufficient evidence to show significant increases after 90 days of leaching. Free swell statistical results were much less well defined for trimmed samples, but they did show that statistically significant increases in percent free swell took place during leaching at most lime contents below eight to nine percent (Sites No. 1 and 3 only). However, from a practical standpoint, when at least six to seven percent lime had been added to the soils, the increases in swell potential were quite small.

330. Swelling potential tests run on reworked samples revealed considerable swell pressure and free swell for all sites at all lime contents. Statistical tests run on Sites No. 1 and 3 test results showed that changes in the after leach reworked swell pressure were significant for all lime contents, but that free swell changes were statistically significant only up to the addition of approximately eight percent lime. Site No. 2 samples had significant increases in reworked swell potential for lime contents below seven percent.

331. Strength tests on samples trimmed from leached soils showed decreases in strength until lime contents of eight, three and nine percent had been added to Sites No. 1, 2 and 3 samples, respectively. Statistical analyses showed that the decreases in strength were significant until eight, two, and eight percent lime were used in Sites No. 1, 2 and 3 samples, respectively. Reworked strength tests for Sites No. 1 and 3 material showed insufficient evidence to support a decrease in after leach results, while Site No. 2 test results showed statistically significant reductions

in strength for all leach tests. Strain at failure showed considerable variation after leaching on trimmed samples, but most tests revealed insufficient evidence to refute the null hypothesis at the $\alpha = 0.05$ level, i.e., there was no different in the failure strain means after leaching.

332. Statistical analyses on the physical properties tested for samples compacted at optimum moisture reveals some interesting data. Generally, the statistical data substantiated the detrimental results of leaching on the three soils tested. A statistical review of the data does suggest that some detrimental effects were not significant at the same lime contents as depicted by graphical analysis. For example, liquid limit changes were generally not significantly changed for Sites No. 2 and 3 samples at most lime contents at the $\alpha = 0.05$ level, although graphically they appeared lower after leaching at nearly all lime contents.

333. Additionally, statistical analysis showed more accurately where the detrimental effects can be offset by the addition of more lime. Statistical analyses on strength and linear shrinkage data showed that non-detrimental effects can be achieved at lime contents approximately one-half to one percent below those revealed by the physical comparisons made earlier.

334. <u>Chemical Property Changes</u>. Soil pH was significantly reduced for all lime contents on all soil sites, but not significantly reduced when leached in its natural state (for Sites No. 2 and 3 soil). This is in good agreement with the graphical comparison.

335. Statistical analysis of porewater extractions showed that calcium and sodium concentrations were significantly changed for all three sites at essentially all lime contents at the $\alpha = 0.10$ level of significance. However, for calcium concentrations in Sites No. 2 and 3 material, there was insufficient evidence to state there was a significant difference in their means after leaching at the $\alpha = 0.05$ level,

except for samples leached with no lime. This is partially attributed to larger variances when conducting chemical tests (wide ranges in ppm) than in conducting physical property tests. Additionally, calcium was most prevalent in Site No. 1 soil, by two to five times as great as Sites No. 3 and 2 soils, respectively. The greater concentration of natural calcium cations would likely be in excess when lime was added, at those levels below the LSO, and could probably be more readily removed by leaching.

336. Porewater magnesium was altered significantly (statistically) after leaching for Sites No. 1 and 3 soils, and less so for Site No. 2 soil at the $\alpha = 0.10$ level. All sites had magnesium concentrations of less than 9 ppm when as little as one percent lime was added to the soils, but the concentrations increased slightly after leaching, for all lime contents. From a physical perspective, the change in magnesium after leaching was relatively minor in aiding lime modification.

337. Potassium changes in the porewater were altered significantly only after leaching 90 days for Sites No. 1 and 3 soils, but for all tests in Site No. 2 material. The concentrations of potassium ions were extremely small (less than 11 ppm) and statistical analysis verifies that leaching removed what little potassium was available to help satisfy the negative nature of the clay structure.

338. Statistical analysis of the exchange complex shows that the higher the lime content, the more likely that there was a significant change in calcium concentrations during leaching. Sites No. 1 and 3 soils had the highest calcium concentrations on their exchange sites and showed the most statistically significant changes after leaching. As lime content increased, the calcium not being used for cation exchange or pozzolanic reactions was more susceptible to leaching, which was verified statistically.

339. Sodium in the exchange complex was readily removed by leaching. All three soil sites showed the reductions to be statistically significant at all lime contents. This is consistent with porewater extraction data.

340. Magnesium and potassium concentrations in the exchange complex varied considerably after leaching, and statistically significant differences in means varied considerably as well. Although magnesium concentrations tended to be lower after leaching, no pattern could be statistically verified that showed which lime contents were the most helpful in preventing excessive magnesium washout after leaching. All three soil sites showed that there was insufficient evidence to suggest that leaching was detrimental to the potassium cations in the exchange complex in the soil at all lime contents (except two and three percent lime for Site No. 2 soil). This indicates that the majority of the leaching of potassium and magnesium cations takes place in the porewater and not so much in the remainder of the exchange sites.

341. Wet and Dry Samples. Tables D9 and D10 in Appendix D show the statistical analyses of Sites No. 1 and 2 test results, respectively, for samples compacted wet and dry of optimum. Physical property tests showed that samples compacted wet of optimum had the highest plasticity indexes, free swelling and swell pressures, and lower linear shrinkages after leaching than tests at other moisture contents. Samples compacted dry displayed the highest linear shrinkage, the lowest strength, and lowest swell properties after leaching.

342. Statistical analysis revealed that plasticity index increases after leaching were statistically significant for wet and dry samples of Site No. 1 material, but mostly for those compacted wet for Site No. 2 material (below five percent lime). Linear shrinkage increases were significant for all dry Site No. 2 tests, but only significant for wet samples which had below five percent lime. There was

insufficient evidence to determine a difference in Site No. 1 shrinkage tests, compacted either wet or dry.

343. Site No. 1 tests verified that samples compacted wet have statistically significant increases in swell properties (pressure and free swell) after leaching. Site No. 2 tests showed that only samples compacted wet were most likely to show significant increases in free swell. There was insufficient evidence to refute the null hypothesis for Site No. 2 swell pressures, and for all swell properties when samples were compacted dry.

344. Sites No. 1 and 2 tests both revealed significant reductions in strength after leaching for samples compacted dry. Samples compacted wet were only significantly lowered in strength at lime contents of less than five percent. Soil pH test conducted at all moisture contents produced statistically significant decreases in soil pH after leaching.

345. Samples compacted dry displayed the highest washout of porewater and exchange site cations while those compacted wet generally displayed the lowest cation washout rate. Statistical analyses showed that calcium was significantly reduced after leaching for dry samples but not for wet samples. Sodium was significantly reduced in Site No. 1 soil for all moisture contents but only for dry samples in Site No. 2 soil. Magnesium was most significantly affected by dry samples in Site No. 1 but was affected by samples compacted wet in Site No. 2 soil (in the exchange complex only). Potassium was also significantly changed in dry samples but was largely unaffected (statistically) in wet samples for Sites No. 1 and 2 material.

Correlations between Laboratory and Field Data

346. The original intent of the field sampling was to accurately test what physical and chemical property changes had occurred in the lime treated soils in a field environment over a known period of time. It soon became apparent that this would not be completely possible. First, there were considerable problems obtaining adequate samples. Only seven, nine and five useable field samples were obtained from curb sides at Sites No. 1, 2 and 3, respectively. Second, of these samples, only a small percentage (approximately 26 percent) showed any indication of retaining some of their original soil-lime characteristics.

347. The lack of soil-lime characteristics in the curb side samples may be a result of one or more of three reasons. The first is possibly poor sampling technique by perhaps, not sampling to the proper depth or not staying within the lime treated area behind the curb. Second, poor construction of soil-lime treatment in the sampled area may have occurred whereas the soil-lime was not adequately mixed and placed or, possibly, the soil-lime layer did not extend the proper distance beyond the curb. A third possibiliy is that the lime has leached out of the soil at a sufficient rate that the soil-lime mixture no longer retains any of its original characteristics.

348. It is highly unlikely that all soil-lime reaction products would have been leached from the soil since at these three sites, three to nine percent lime was mixed in with the soil, which is more than enough to provide retention of at least some soil-lime pozzolanic products. Additionally, the soil-lime layer at all sites were covered by at least 14 in. of plastic topsoil that helped to diffuse the percolating effects of rainfall. It is also unlikely that sampling did not occur at the proper depth or distance beyond the curbs. All sampling was done by hand auger after removing

the topsoil to a depth of 14 inches. The sampling was done as close to the back of the curb as possible, generally within six inches of the curb. All depths were closely monitored with a tape measure and recorded. Samples were obtained from each site throughout a 50 to 75 yd. distance along the roadways.

349. Construction placement seems the most likely problem as uniform mixing and placement of a soil-lime mixture cannot be guaranteed along the entire road way at the specified distance beyond the expected curb position. Final grading and placement of the concrete pavement and curb may have altered the depth of the soil-lime mixture. Additionally, disturbance of the soil-lime layer may have been further aggravated when the topsoil cover was spread, graded and compacted.

350. The soil-lime layer at Site No. 3 was most likely constructed with the greatest control as this was to be a test section for various lime, lime-fly ash and cement treatments (Hansen and Abrams 1988). However, the lime treated section was removed after it had been in place for 27 days in order to lower the subgrade, then replaced and recompacted. This undoubtedly affected the original soil-lime characteristics. This research has already demonstrated the detrimental effects that reworking a cured soil-lime mixture has on swelling properties and strength.

351. Since all samples were obtained by hand auger, they were considered disturbed samples. Samples were initially tested in the field for reaction to phenolphthalein (an alkaline indicator). Samples were divided as reactive and nonreactive for testing. In the laboratory, the samples were tested for moisture content then slaked to remove organics, air dried, lightly crushed then passed through a No. 40 sieve. All testing was conducted on remolded samples.

352. Table 27 shows the results of the laboratory tests on the curbside samples for all three sites. Only two of seven, one of nine and two of five samples showed any indication of retaining their original lime characteristics for material

TABLE 27

PROPERTIES OF FIELD SAMPLES

Property	Site No. 1			Site No. 2			Site No. 3		
	B3*	NR	PR	B7	NR	PR	B9	NR	PR
Field Moisture (%)	--	33.2	34.0	--	26.9	25.0	--	32.1	33.4
Liquid Limit (%)	60	64	37	47	60	55	55	69	62
Plastic Limit (%)	47	32	26	34	27	31	43	35	41
Plasticity Index (%)	13	32	11	13	33	24	12	34	21
LinearShrinkage (%)	9.1	18.2	9.4	5.5	18.3	14.6	2.4	22.1	13.8
Swell Pressure (psf)	197.6	970.8	249.6	232.4	1138.3	814.6	301.9	1335.9	1162.2
Free Swell (%)	0.34	2.50	0.19	0.11	3.35	2.71	0.19	6.39	2.04
Reworked Strength (ksf)	9.71	10.26	12.20	15.20	6.68	9.96	5.93	7.11	9.27
Failure Strain (%)	1.57	5.75	1.62	1.51	5.01	1.97	1.16	3.58	1.79
Soil pH	12.40	7.91	9.36	12.63	8.33	8.39	12.63	8.26	10.34
Porewater Cations (meq/l)									
Calcium	8.29	2.98	3.9**	1.80	1.08	1.56	5.60	5.74	8.52
Sodium	3.54	0.15	0.6	0.52	0.59	0.75	12.67	12.44	10.89
Magnesium	0.12	0.13	0.3	0.07	0.16	0.18	0.01	0.75	0.29
Potassium	0.24	0.94	--	0.14	0.11	0.06	0.25	0.21	0.19
Exchange Complex Cations (meq/100 g)									
Calcium	44.46	26.90	40.2**	25.73	21.20	21.52	63.26	25.54	36.53
Sodium	1.40	0.31	0.3	0.11	0.17	0.28	2.77	3.94	1.66
Magnesium	1.03	0.99	2.5	0.94	0.46	0.63	1.74	1.43	1.56
Potassium	0.73	0.59	0.5	0.31	0.35	0.24	0.64	0.68	0.44

* B3 = Before leaching, 3% lime; B7 = Before leaching, 7% lime; B9 = Before leaching, 9% lime; NR = Non-reactive to phenolphthalein; PR = Reactive to phenolphthalein.

** As determined by the Soil Conservation Service, South National Technical Center, Fort Worth, Texas.

from Sites No. 1, 2 and 3, respectively. Results are those averaged for reactive (PR) and non-phenolphthalein reactive (NR) tests.

353. Due to the inconsistency of results from the field samples and the small percentage of samples that appear to have retained any soil-lime characteristics, accurate correlations between field and laboratory data are not possible at this time. Extensive field sampling, both of undisturbed and disturbed samples, would be required at various points along the roads at each site in order to develop statistically averaged data. Some general observations can be made from Table 27, however, based on the limited field data and knowledge of the leaching characteristics of lime treated soils as determined in this report.

Estimation of Field pH and Calcium Washout

354. It was suggested during the discussion of permeability that permeability changes could be used to estimate cation leach rates through lime treated soils. Haji-Djafari and Wright (1983) developed a series of equations to predict cation leaching through clay liners based on laboratory accelerated leach tests. Time scale factors were developed to correlate field leach effects to the accelerated leach effects produced in a laboratory. The time factor is a function of hydraulic gradient (or permeability) and the thickness of the soil specimen or strata. Appendix F shows the development of the three sites' time scale factors, t_s, as well as the assumptions and limitations associated with using these factors.

355. The time factors developed were 66.0, 13.0 and 20.4 for Sites No. 1, 2 and 3, respectively. These factors are limited in use for rough estimates of only those properties directly influenced by permeability changes such as soil cation washout or, indirectly, soil pH changes. They may or may not be appropriate for

estimations of engineering property changes as these properties are more readily influenced by lime content and compaction moisture.

356. Soil calcium washout and pH decreases will be the two properties investigated with comparisons made between laboratory and field data. The linear relationships developed earlier in this chapter for leachate pH and calcium concentration will be used in the correlations. These correlations are based on the premise that the laboratory leachate calcium concentration and pH are direct indicators of the remaining effectiveness of the lime in the field, and that the leachate pH will approximate the pH of the field soil. When the leachate pH has reduced to its natural soil pH, it is speculated that no further reduction of lime induced characteristics will occur. Furthermore, when the leachate calcium concentration has reached zero ppm it is speculated that no further decline in calcium within the soil is likely. Of course, zero ppm calcium concentration in the leachate is unlikely as some small amount of calcium will most likely always be removed from the soil, even with no lime present.

357. The following is a summary of the information used in the analysis for each soil site.

Site No. 1:

$$\text{Leachate pH} = 11.62 - (2.74 \times 10^{-4}) \text{ (hrs)} \tag{2}$$

$$\text{Leachate Ca (ppm)} = 111.9 - (2.54 \times 10^{-2}) \text{ (hrs)} \tag{3}$$

Time factors, $t_s = 66.0$

Field age = 16 years

Lime content = 3%

Site No. 2:

$$\text{Leachate pH} = 12.59 - (9.75 \times 10^{-5}) \text{ (hrs)} \tag{4}$$

$$\text{Leachate Ca (ppm)} = 651.2 - 0.13 \text{ (hrs)} \tag{5}$$

Time factor, t_s = 13.0

Field age = 8 years

Lime content = 7%

Site No. 3:

$$\text{Leachate pH} = 12.52 - (5.10 \times 10^{-4}) \text{ (hrs)} \tag{6}$$

$$\text{Leachate Ca (ppm)} = 425.1 - 0.20 \text{ (hrs)} \tag{7}$$

Time factor, t_s = 20.4

Field age = 3 yrs

Lime content = 9%

358. Based on the above equations, the laboratory leach times required to achieve a calcium washout concentration of zero ppm (i.e., no further loss of calcium from the soil-lime system) and a return to the natural soil pH (8.40) are 184 and 490 days, 271 and 1791 days, and 89 and 337 days for Sites No. 1, 2 and 3, respectively. Using the time scale factors, the corresponding estimated equivalent field times are 33.2 and 88.4 years, 7.4 and 63.8 years, and 4.9 and 18.8 years for Sites No. 1, 2 and 3, respectively. These values suggest that, in general, the time required to achieve neutral effects of leaching increases as the lime content decreases and permeability increases. By comparison, McElroy (1982) presented equation 2.1 that shows that on selected field locations, 11.8 years (plus or minus three years) are required to reduce the soil's pH down to natural soil (estimated at 7.00). McElroy also states that topsoil will decrease the rate of pH reduction by 50 percent. Since most projects are covered by topsoil, this would increase the time of

McElroy's calculation to 23.6 years (plus or minus three years). This is approximately the same time required as shown in the Site No. 3 pH estima-tion, though considerably under Sites No. 1 and 2 projections.

359. The time scale factors can also be used to convert field time (age) to laboratory leaching time. This would convert the age of the sites from 16 years to 2124 hours, 8 years to 5391 hours, and 3 years to 1288 hours for Sites No. 1, 2 and 3, respectively. Notice that the back calculated laboratory equivalent time for Site No. 2 exceeds the range of actual laboratory leach periods (2160 hours) and, therefore, cannot be correlated using equations 4 and 5. Field data for calcium washout and pH for Sites No. 1 and 3, however, can be checked against laboratory data by using equations 2, 3, 6 and 7.

360. The calculated pH of the soils, using the equivalent laboratory time of their field age, and equations 2 and 6, shows that Site No. 1 pH would be 11.04 and Site No. 3 pH would be 11.86. Table 27 shows that the phenolphthalein-reactive soil displayed actual field pH values of 9.36 and 10.34 for Sites No. 1 and 3, respectively. Actual field pH values are lower than estimated values by 15 and 12 percent for Sites No. 1 and 3, respectively.

361. Total calcium content of a soil is the combined concentrations of the calcium remaining in the soil's exchange complex and the calcium present in the leachate. Normalized calcium concentrations, with respect to the total calcium originally present (to include the calcium projection at zero hours using equations 2, 5 and 7) are shown in Table 28 and plotted in Figure 131 for Sites No. 1, 2 and 3. Linear regression analysis shows high correlation coefficients for all three sites (Table 28).

362. For Site No. 1, the estimated leachate calcium content, after the laboratory equivalent of 16 years (laboratory time = 2124 hours), would be
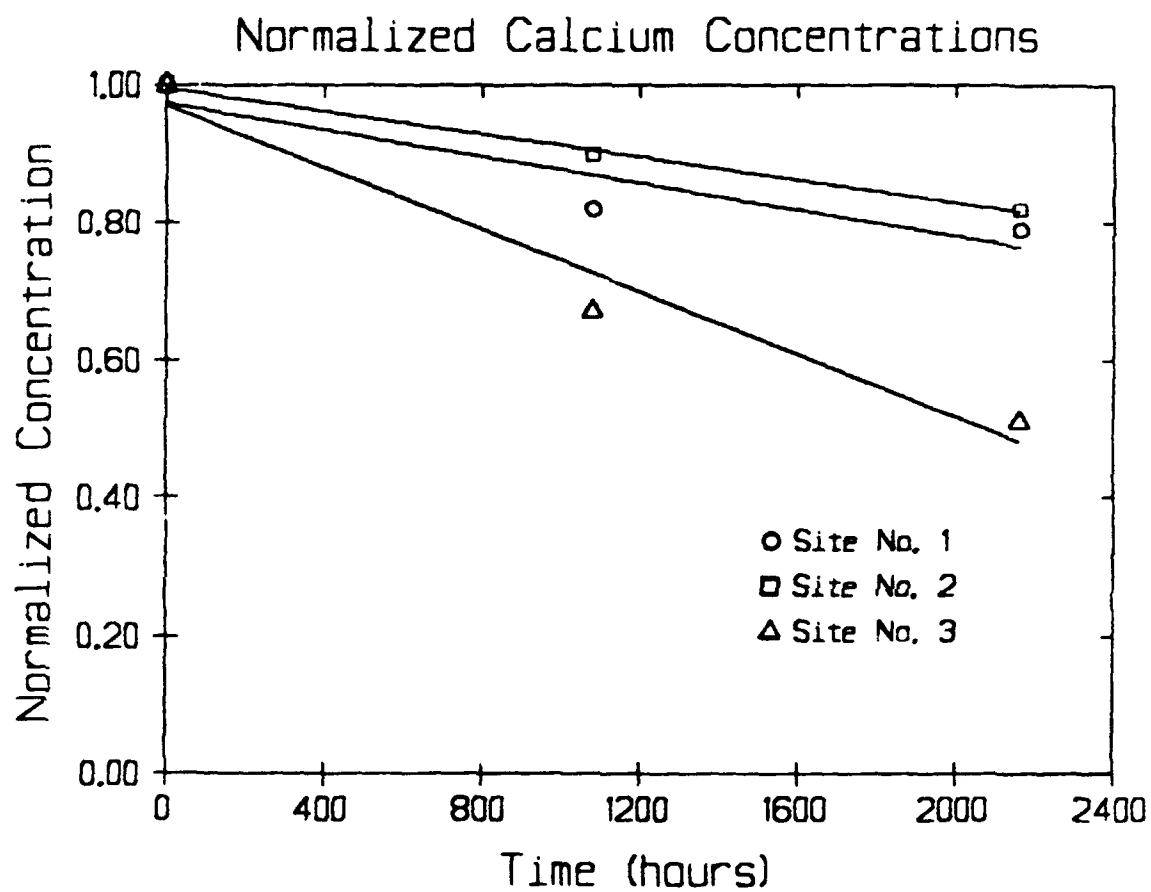
Figure 131. Normalized concentrations of total calcium cations.

Leachate, Ca (ppm) = 111.9 - (2.54 x 10^{-2}) (2124) = 58 ppm. $\qquad$ (8)

From Figure 131, after 2124 hrs of leaching, only 77 percent (0.77) of the total calcium content is left in the soil. Therefore, that portion of the total concentration found in the field exchange complex (EC) would be estimated as

EC + Leachate = % of total concentration $\qquad$ (9)

EC = (0.77) (832) - 58

= 583 ppm = 36.0 meq/100 g

TABLE 28

NORMALIZED CALCIUM CONCENTRATIONS

Site No.	Leach Time (hrs)	Leachate Cations (ppm)	Exchange Complex Cations (ppm)	Total (ppm)	Normalization
1*	0	112	720	832	1.0
	1080	84	595	679	0.82
	2160	57	602	659	0.79
2**	0	651	417	1068	1.0
	1080	511	450	961	0.90
	2160	370	509	879	0.82
3†	0	425	1024	1449	1.0
	1080	209	757	966	0.67
	2160	0	742	742	0.51

* Regression equation, Norm = 0.98 - 9.72 x 10^{-5} x (hrs); r = -0.92
** Regression equation, Norm = 1.00 - 8.33 x 10^{-5} x (hrs); r = -0.99
† Regression equation, Norm = 0.97 - 2.26 x 10^{-4} x (hrs); r = -0.98

From Table 27, the Site No. 1 reactive column gives the field exchange complex concentration of calcium to be 40.2 meq/100 g (12 percent higher than estimated).

363. Similar calculations for Site No. 3 based on 3 years field time (laboratory time = 1288 hrs) show that only 65 percent of the total calcium is estimated to remain in the soil. This corresponded to a calcium concentration in the exchange complex of 47.8 meq/100 g. Table 27 gives the calcium concentration in the reactive soil for Site No. 3 field samples as 36.53 meq/100 g (23 percent lower than estimated).

364. The estimated calcium concentrations for Sites No. 1 and 3 are both within approximately plus or minus 20 percent of field data. The estimated pH values are within 15 percent of field values. However, the above correlations should be viewed as only rough approximations. The field values are the result of limited test data, and the estimation processes is based on several assumptions. Furthermore, the normalization curves developed for calcium have only three points to establish linearity. Though the correlation coefficients were high for all curves, additional testing at other leach periods would generate more data points and greater reliability in the normalization curves.

365. Finally, as discussed previously, the use of time scale factor should be limited to those functions directly affected by permeability, in this case pH and calcium washout.

General Observations on Field Data

366. Site No. 1 Field Data. Site No. 1 phenolphthalein-reactive (PR) field data showed that the field soil-lime layer had maintained its low plasticity index and linear shrinkage, and had lowered its liquid and plastic limits. Swell pressure had increased (139 percent), but free swell percentage had dropped and reworked

strength had increased. Some of the calcium in the soil had been removed over the years, but the exchange complex concentration remains higher than natural soil. Overall, it would appear that the soil has retained much of its original properties after 16 years of leaching. However, the soil layer under investigation was located 25 in. below the ground surface and beneath a lime treated and a cement treated layer. These layers could greatly help protect the lower lime treated soil.

367. <u>Site No. 2 Field Data</u>. Site No. 2 PR field data indicates that considerable change may have taken place in the field since original construction. The plasticity index of the soil has doubled, linear shrinkage tripled, swell pressure has increased by a factor of 3.5, and free swell percentage has increased over 24 times its original seven percent lime value, as determined in the laboratory. Reworked strength had decreased by 34 percent over 8 years. The calcium content in the soil was lower in the PR material than it was in seven percent soil before leaching. Additionally, the sodium content has increased in the PR material.

368. These data indicate that Site No. 2 soil has not withstood the effects of leaching as well as Site No. 1. The soil's plasticity index, swell properties and linear shrinkage have all reverted back to essentially natural soil. The exchange complex calcium concentration remains sightly higher than natural soil, equivalent to that in soil with two percent lime, before leaching. However, the PR field data is only the result of one test sample (repeated for an average), and should not be weighed heavily until more data is available.

369. <u>Site No. 3 Field Data</u>. Site No. 3 PR field data also showed an indication of change since its original construction. Its plasticity index approximately doubled, linear shrinkage increased approximately six fold, swelling pressure increased by a factor of four, and free swelling percentage increased 10 times over those values measure for a nine percent lime treated soil before leaching. Strength

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increased by 56 percent over its original reworked value. Calcium concentrations in the exchange complex have diminished by about one-half its pre-leach value, as determined in the laboratory.

370. Based on this limited field data, it would appear that detrimental effects due to leaching have occurred in the field at Site No. 3. However, the physical properties have not reverted to their natural soil conditions. Most PR properties tested showed results equivalent to those in Site No. 3 soils with between one and three percent lime (before leaching), with the amount of calcium in the exchange complex approximately that of a sample with five percent lime. However, as with Sites No. 1 and 2 analyses, these observations are based on limited field data, in this case only two samples (duplicated then averaged).

PART V: SUMMARY AND CONCLUSIONS

371. The intent of this research was to test the effects of long-term leaching on lime treated expansive clays found in the Dallas/Fort Worth (D/FW) Metroplex. Laboratory prepared lime-treated specimens were subjected to accelerated water leaching with variables tested to include soil material (three separate clay soil locations), lime content (ranging from zero to nine percent lime, by dry weight of soil), moisture content at time of compaction (five percent dry of optimum moisture, at optimum moisture, and five percent wet of optimum moisture), and duration of leaching (45 and 90 days continuous leaching). Constants used through the testing included accelerated curing conditions for compacted lime treated samples (48 hours at 120 °F), constant leaching pressure (generally 10 psi) and compacting all samples using Standard Proctor density (with a goal of achieving 95 percent of maximum density).

372. At the onset of the research it was hoped to compare the field lime treated soil that had been subjected to natural leaching to laboratory prepared and leached samples. Therefore, three field sites of known lime treatment specifications (lime content, moisture content, compaction control and time of construction completion) were chosen from the D/FW International Airport area, and samples were prepared in the laboratory to duplicate the field conditions for each site.

373. Seventy accelerated leach tests were conducted in the laboratory using various soil-lime mixture and moisture contents for the three sites. All three sites were from the same weathered geologic formation, Eagle Ford Shale, and were classified as highly expansive clays (CH). Their expansive potential varied from site to site with plasticity indexes ranging from 30 to 45. Lime contents tested for each site were chosen based on preliminary lime reaction data and to simulate field

lime percentages. Lime contents of one, two, three, four, six and eight percent were used to test Site No. 1 material; one, two three, five and seven percent to test Site No. 2 material; and one, two, three, five, seven and nine percent to test Site No. 3 material.

374. Samples made with all the above lime contents were compacted at optimum moisture then leached 45 days. Ninety day leach tests were conducted on Site No. 1 samples with three and six percent lime, on Site No. 2 samples with three and seven percent lime, and on Site No. 3 samples with three and nine percent lime. Additionally, material from Sites No. 1 and 2 were compacted at below and above optimum (dry and wet) moisture conditions for selected lime contents then leached 45 days. Duplicate specimens of all leach samples were simultaneously tested.

375. The leach samples were tested before leaching and after leaching to identify changes. Physical testing of the soil included Atterberg limits, linear shrinkage, swelling pressure, percent free swell, unconfined compression strength, and permeability. The reworked samples (remolding of remolded soils) of cured lime treated soils were tested before and after leaching to monitor changes in physical properties such as strength and swelling potential. Over 1700 physical property tests were conducted on pre- and post-leach samples. Chemical tests included soil pH, lime content titration (for Site No. 1 only) and measurement of porewater cations and exchange complex cations (calcium, sodium, magnesium and potassium). The leachate passing through the samples was collected and monitored for cation concentration and pH changes with leach time. Differential thermal analyses were conducted on selected samples to monitor the effects of leaching on the clay-lime structure. Over 1600 chemical analyses were conducted on pre- and post-leach samples

376. Graphical analysis of changes affected by leaching were presented and discussed in this report, in order to judge the physical significance of leaching on lime treated clays. Additionally, statistical analyses were conducted on the results of the physical and chemical testing before and after leaching. This analysis determined the statistical significance of the changes (if any) in the physical and chemical properties after leaching.

377. Field samples of lime treated clays from the three soil sites were tested in the laboratory for the same physical and chemical properties as used to test laboratory prepared soil-lime mixtures. Very general use time scale factors were developed for the three sites that were used to estimate property changes in the field based on laboratory leach testing. Based on these time scale factors, estimates were made of the field site's calcium washout rate and soil pH declination. These estimates were compared to preliminary field sample test results to correlate the prediction method.

378. The research showed that there was a change in the lime treated soil after continuous leaching. In general, the longer the leach period, the greater was the change. The amount of change varied considerably depending on which soil property was investigated. Additionally, the magnitude of change was very highly dependent on the lime content of the soil. Soils with lime contents above the lime stabilization optimum, LSO, (six to seven percent) exhibited the least change while those soils with lime contents below the lime modification optimum, LSO, (three to four percent) tended to display the greatest change after leaching. The moisture content at the time of compaction was also important in controlling leaching effects. Samples compacted wet of optimum showed the greatest increase in plasticity and swell potential after leaching, but the lowest cation washout rates. Specific conclusions are presented below.

Leachate Analysis

379.   From chemical analyses of the leachate for pH and cation concentrations (calcium, sodium, potassium and magnesium), the following conclusions are made:

a.   The pH of the leachates increased as the lime content of the soil increased, regardless of compaction moisture content. Samples compacted wet of optimum moisture displayed the lowest leachate pH's.

b.   The leachate pH decreased linearly with leach time. In general, the higher the lime content, the slower was the rate of decline. At lime contents above the soil's LMO, the decline in pH was very uniform and consistent. Linear regression analyses of the rates of declines showed correlation coefficients that were above -0.90 for all three soils when tested at lime contents above their LMO.

c.   Minimum calcium concentrations in the leachate occurred in samples with only two or three percent lime. At lime contents above the LMO, the calcium concentrations in the leachate increased significantly with increased lime contents.

d.   Sodium and potassium concentrations were minimum in the leachate for all three sites in samples with three percent lime. Maximum sodium concentration occurred in samples with very low (one percent) or very high lime contents. Maximum potassium concentrations were found in samples with the highest lime contents. Magnesium was only detected in trace amounts in all leach tests.

e.   All leachate cation concentrations decreased during leaching. The majority of the leachate curves displayed good linearity, particularly calcium cations. The maximum rate of declination occurred in samples mixed with the highest lime contents or when only mixed with one percent lime.

f.   Samples compacted wet of optimum had the highest sodium and the lowest calcium concentrations in their leachate.

Physical Property Changes

380. From an analysis of the physical property changes in the samples tested before and after leaching, the following conclusions are drawn:

a. The permeabilities of all lime treated soils were substantially higher (7 to 340 times higher) than the permeability of the natural clays. Maximum permeabilities occurred in sample with three percent lime for all three sites, i.e., approximately the LMO for the sites. This indicates a direct relationship between LMO and permeability. The lowest permeabilities in lime treated samples occurred in the samples with very low (one percent) or very high (seven to nine percent) lime contents. Samples compacted wet had the lowest permeabilities while those compacted dry had the highest.

b. All permeabilities decreased with time, but approached a steady flow condition after approximately 300 hours (12.5 days) of continuous leaching, signifying saturated flow.

c. Continuous leaching resulted in detrimental effects in all physical and engineering properties of the lime treated clays in this study. For example, linear shrinkage, plasticity index, and swelling properties tended to increase after leaching while strength, liquid and plastic limits decreased. In general, maximum detrimental effects occurred in samples compacted with lime contents at or below the soil's LMO. Longer leach periods produced higher free swell and swell pressures at the lower lime contents.

d. There appeared to be a specific lime content for each physical property tested that, when added to the soil, minimized or eliminated the detrimental effects of leaching. This "optimal" lime content varied for each property, e.g., it was established as five to six percent lime for plasticity index and shrinkage tests, and seven to eight percent lime for swelling properties and strength tests.

e. It is speculated that the detrimental effects are directly related to the ion exchange, ion crowding, flocculation and pozzolanic reactions within the soil-lime mixture. At lime contents below the established LSO, the pozzolanic reactions are secondary to flocculation and ion exchange, increasing the soil's permeability. The infusion of water in the system produces diffusion of some calcium away from the clay particles which

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are then leached out of the soil, increasing the soil's affinity for water. If the LSO is reached, pozzolanic reactions are predominant, minimizing the detrimental effects of leaching.

f. Reworked samples displayed much larger increases in swell properties after leaching than specimens trimmed from the leach samples. It is speculated that reworking cured lime treated samples breaks the pozzolanic cementation, even at low lime contents. Therefore, limited additional lime is available for autogenous healing. Strength tests on reworked (and recurred) lime treated samples were only approximately equal to the natural soil's strength, but two to four times below original remolded strength at all lime contents.

g. Samples compacted wet of optimum moisture had the highest detrimental changes after leaching for all physical properties tested except for linear shrinkage and strength tests. Maximum strength and minimum shrinkage after leaching occurred in samples compacted wet or at optimum moisture.

h. Statistical analysis of the physical property changes affected by leaching confirmed the statistical significance of the detrimental effects found by graphical comparisons. However, statistical analysis did reveal that there was insufficient evidence to suggest significant decreases in the soil's liquid limit after leaching (for lime contents greater than one percent). Additionally, statistical analyses of shrinkage and strength results showed that one-half to one percent less lime could be used to minimized detrimental effects than was revealed by graphical analysis.

i. From a practical significance, swelling properties and plasticity did not increase enough after leaching to be of a major concern if at least five percent lime was added to the soils. Of course, this would depend on the design specifications and construction limitations.

Chemical Property Changes

381. The following conclusions are made from the graphical and statistical analyses for changes in soil pH, porewater cations, and exchange complex cations after leaching:

a. There was a significant decrease in the soil's pH after leaching. The pH continued to decline with longer leach durations. After the addition of four to five percent lime, the pH of the samples tested before leaching maintained a maximum pH of approximately 12.5. Leached samples also approached and maintained a maximum pH, though lower than before leaching, at lime contents of five to seven percent. It is speculated that the pH is directly related to the diffusion of lime caused by the leaching fluid (thereby indirectly diluting the complex hydrogen compounds). Therefore, enough lime has to be added to offset the water diffusion. The amount of lime necessary to offset the diffusion appeared to be approximately the LSO of the soils.

b. Maximum decrease in the pH of the soils after leaching occurred in samples compacted dry. The minimum decrease in soil pH was for soils compacted wet or at optimum moisture.

c. Lime content estimation in cured soil-lime mixtures cannot be accurately measured by either EDTA titration or calcium extraction methods as both tests grossly underestimates the amount of lime remaining in the soil. This is most likely because the curing process produces substantial pozzolanic products that cannot be broken down during the limited mixing times in the tests in order to extract an accurate estimate of the calcium concentration.

d. Porewater calcium, sodium, magnesium and potassium were easily removed from the natural clays by leaching. Generally, the longer the leach period, the more cations removed (termed "washout"). The clays had naturally high concentrations of calcium and two soil sites had high concentrations of sodium. Potassium and magnesium were present in the natural clay's porewater but only in very small concentrations.

e. When lime was added to the soils, the pre-leached porewater concentrations of all four cations initially decreased with increasing lime contents. Porewater sodium and potassium concentrations increased slightly after approximately three to five percent lime had been added.

f. After leaching, porewater calcium concentrations were lower than before leaching, but steadily increased with increases in lime contents. At lime contents greater than four to five percent, the difference between before and after leaching concentrations were negligible. The lime content required to minimize porewater calcium washout appeared to be two to

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three percent lower than the lime content that was required to minimize physical property changes.

g. Porewater sodium concentrations after leaching remained much below levels measured before leaching with the concentration differences increasing with increasing lime contents. This is most likely because sodium is the easiest cation, of the four measured, in the porewater to be be replaced with calcium.

h. Samples compacted dry displayed the largest washout concentrations in the porewater after leaching for all cations except magnesium. Samples compacted wet showed the lowest washout concentrations in the porewater after leaching for all cations.

i. Calcium, sodium, magnesium and potassium concentrations in the exchange complex increased with increases in lime content prior to leaching. Calcium increased nearly linearly. After leaching, all cations displayed lower concentrations than before leaching. Calcium and magnesium concentrations in the exchange complex after leaching increased with increasing lime contents, calcium much more so than magnesium, but remained at levels below original pre-leached values. Sodium was readily removed from the exchange sites by leaching resulting in much lower post-leach values.

j. Generally, longer leach durations produced greater cation washout from the exchange complex for all cations measured.

k. Samples compacted dry of optimum displayed the largest cation washout in the exchange complex after leaching, while those compacted wet showed the lowest concentration removal rate. This is probably a function of permeability as it relates to moisture content.

l. There did not appear to be a lime content range that minimized the loss of cations (particularly calcium) from the exchange complex due to leaching.

m. The Ca/Mg ratios of lime treated clays decreased after leaching supporting the theory that poorly drained soils are most affected by weathering (leaching). However, the Ca/Mg ratios determined in this research still remained high after leaching.

n. Statistical analysis of the chemical data verified that the soil's pH was significantly reduced after leaching for all lime contents except for soil leached in its natural state.

o. Statistical analysis of the porewater extractions verified that the calcium and sodium concentrations were significantly reduced after leaching for all three soil sites, at the $\alpha = 0.10$ level of significance. Only Site No. 1 tests showed significant changes in its calcium concentrations at the $\alpha = 0.05$ level of significance. Site No. 1 material contained two to five times as much calcium as the other two sites.

p. Based on statistical analyses of the changes in the exchange complex cations after leaching, calcium was significantly reduced after leaching as lime contents were increased above the soil's LMO. Sodium was significantly reduced for all lime contents, and potassium and magnesium were most likely significantly changed in the porewater but not in the exchange sites.

Differential Thermal Analysis

382. A study of the results of differential thermal analyses (DTA) conducted on the soil-lime mixtures before and after leaching produces the following conclusions:

a. All samples tested before leaching tended to show a reaction produced at approximately 900 °C, forming a more pronounced exothermic peak with increases in lime. These reactions have been suggested to be either pozzolanic products, or $CaCO_3$ products, or both. Leaching reduces this exothermic peak, particularly at the higher lime content, suggesting that the product was most likely a carbonate product that can be readily leached.

b. Leaching produced minimal changes on the other exothermic and endothermic results of lime treated clays. All soil sites had some peaks that tended to slightly increase in temperature after leaching, but a study of the shifts was not conclusive.

c. A distinct peak to signify lime on the DTA plots could not be differentiated from the endotherms of the soil-lime mixture, regardless of the lime content tested. However, this is probably because all lime treated samples were cured prior to testing which tends to suppress the endothermic peak (Eades and Grim 1960).

Field Correlations and Estimations

383. Correlations between laboratory and field data were made for selected properties. An estimation or prediction technique was presented to relate actual laboratory time to projected field time with the following conclusions:

a. Only 26 percent of the field samples obtained showed significant evidence of retaining any lime in the soil layers after prolonged weathering. This is most likely attributed to the non-uniformity of constructing the field soil-lime layers and to the limited number of samples that could be obtained and tested. Therefore, only very limited correlations were possible between laboratory and field data.

b. Time scale factors were developed to relate accelerated leach time in the laboratory to actual field leaching time based on the hydraulic gradients and thicknesses of the lime treated soils. Only those properties directly affected by permeability, e.g., cation removal and pH, should be predicted using the time scale factors.

c. The time scale factors, along with regression analysis for selected leachate functions, were used to predict the times to zero calcium washout and to achieve a soil pH of 8.40 in the field. These two properties are excellent indicators of the detrimental effects leaching has in lime treated soils.

d. The estimated times to achieve a field soil pH of 8.40 ranged from 18.8 to 88.4 years and for zero calcium washout from 4.9 to 33.2 years. The predicted times increased as the field lime content decreased.

e. Field weathering data of known age were converted to equivalent laboratory leach times using the time scale factors. When the actual soil pH and calcium washout of the field samples were compared to the estimated laboratory properties at their equivalent laboratory times, the actual field pH values were approximately 15 percent lower than the

estimated values, while the calcium concentrations were within plus or minus 20 percent of actual field data.

f.   From an analyses of the limited field data, it would appear that some detrimental effects have occurred in the field due to leaching. Materials at Sites No. 2 and 3 showed the largest detrimental changes, with some properties (swelling properties and plasticity index) reverting back to, or almost to, natural soil conditions.

g.   Site No. 1 field samples showed the least detrimental changes after the longest time period, 16 years. However, the soil layer tested was 25 in. below the ground and located beneath two stabilized soil layers which most likely aided in protecting the tested layer from leaching effects.

PART VI: RECOMMENDATIONS

384. The following recommendations are presented for utilizing the results of this research, and for future research in this important field of monitoring and predicting the behavioral changes associated with the leaching of lime treated expansive clays:

a. This research suggests that minimum or negligible detrimental effects due to leaching of lime treated Eagle Ford expansive clays can be achieved if the lime content is at least at the lime stabilization optimum of the clay. For maintaining maximum strength gain, one percent above the LSO appears appropriate. For expansive clays other than those tested, leach tests would be required to estimate the most beneficial lime contents to use in order to minimize the detrimental effects of leaching.

b. Lime treated soils should be compacted at or slightly above (one or two percent) their optimum moisture content in order to minimize the detrimental effects due to leaching. Lime treated soils should not be compacted dry of optimum as this greatly increases the detrimental effects of leaching.

c. Once lime treated soil has been compacted and cured, it should not be removed and recompacted. Its strength will be severely reduced and its swelling potential generally increased.

d. Lime should not be added to Eagle Ford clays for the sole purpose of reducing their permeabilities. Lime in all quantities greatly increased the clay's permeability in this research. This does not preclude the addition of lime to Eagle Ford clays that have shown extreme increases in their permeabilities as a result of large shrinkage cracks. Lime will reduce the effects of shrinkage, but care must be exercised to insure the increase in permeability due to lime does not exceed specification limits. Since the permeabilities decreased with time, extremely long-term leach testing (180 to 270 days) should be conducted on this clay to determine when the permeability reduces to or close to its natural state. Further, various curing times should be investigated prior to leaching to test the correlation between curing and permeability.

e. The EDTA titration test and calcium extraction methods considerably underestimated the lime contents of the post-leach soils and should not be used on soil-lime mixtures cured for 45 or more days. Testing should be conducted with the EDTA titration test to determine what the time limits of curing are that will yield accurate estimates of lime content.

f. The time scale factors developed for these three sites were based on very conservative estimates of the amount of rainfall that would infiltrate through the soil-lime strata in the fields. More accurate estimates of the infiltration should be based on evapotranspiration, run off, rainfall intensity, and duration of precipitation converted to monthly or yearly infiltration rates. Corely (1979) developed a weather simulation program that could possibly be modified to more accurately predict moisture movement through the soil-lime layers in the Dallas/Fort Worth area.

g. Because of their conservatism, the time factors must be used with caution, and then only for those properties directly affected by permeability changes, i.e., cation washout and pH.

h. Validation of the field estimates of calcium washout and soil pH were not totally reliable because of the limited number of field samples obtained that displayed lime treated characteristics. It is recommended that an extensive field sampling program be initiated to obtain numerous samples, disturbed and undisturbed, in the lime treated zones along the roadways of the three sites. The results of these samples should be used to validate the estimation procedures.

i. A leach test of Site No. 2 soils with seven percent lime should be conducted for at least 8 months (240 days) in order to correlate the field data to the laboratory data for Site No. 2.

j. Additional leach testing should be conducted on other types of expansive clays in order to test the validity of this research and to develop a comprehensive analysis of the leaching effects of various types of expansive clays. Items such as mineral composition and percent initial calcium concentrations may play an important role in determining the long-term effects of leaching.

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APPENDIX A

TEST PROCEDURES

TEST PROCEDURES

Swell Pressure Test

1. The swell pressure test monitors the amount of overburden necessary to keep a completely submerged clay sample from swelling. Only total swell resistant pressure was required for this research. The following test procedure was used throughout this research:

a. Samples were either trimmed to fit consolidation rings or were remolded samples. Remolded samples were prepared from clay or clay/lime samples slaked in distilled water, air dried, lightly crushed and passed through a U. S. Standard No. 40 sieve.

b. Determine the water content of the air dried material. Weigh out 110 g of the soil and add moisture (minus present moisture content) to bring to optimum moisture level. Cover and allow to sit overnight.

c. Compact moist sample into consolidation ring using three layers, compacting each layer with 40 blows using a Harvard miniature hammer. Final sample dimensions are 4.9 cm in diameter by 3.2 cm high with the use of a 0.635 cm spacer.

d. Place a pre-saturated porous stone in the bottom of the consolidation water reservoir and place the sample mold, with sample, on the stone. Fasten the sample mold to the consolidation reservoir securely. Place another saturated porous stone on top of the sample.

e. Place the reservoir in the consolidation load frame and place a loading cap and ball (of known weight) on the upper stone. Fasten a dial indicator to measure vertical deflections of the sample. A small seating load of 100 g is usually added to the loading frame. This load could also be increased to the estimated overburden pressure if that was to be the basis of zero swell pressure.

f. Fill the reservoir with distilled water, ensuring that the sample is completely submerged. Maintain the water level throughout the test.

g. The dial gauge is monitored closely and increased loads are added to the loading frame until there is no change in dial readings in 12 hours. The dial reading should not be allowed to move more than 0.1 percent of the sample's total height during the swell pressure test. The total duration of the swell pressure test should not be less than 24 hours.

h. The total load applied at the end of the test, at which no further dial readings are noted, is the swell load. Convert the load to pressure and express in pounds per square foot (psf). The load should include the weight of the seating load, ball and loading cap.

Free Swell Test

2. The free swell test measures the vertical rise in a submerged, laterally confined clay sample. The test utilizes the same consolidation ring and loading frame as described for swell pressure tests. For purposes of this research, only the total vertical rise was required. The following is a brief description of the test:

a. The sample is prepared, compacted and placed consolidation rings as described above. A small seating load may be added to minimize loading frame bounce.

b. Fill the reservoir with distilled water until the sample is completely submerged. Maintain the water level throughout the test.

c. Periodically monitor the dial gauge reading. The sample should be allowed to swell unrestrained until no change is noted after 12 hours. Minimum duration of the test is 48 hours.

d. The free swell is a measure of the amount of vertical rise expressed as a percent of the initial height, recorded as a noted overburden pressure (e.g., the weight of the seating load, ball, and loading cap).

Linear Shrinkage Test

3. This test is modelled after the Texas Bar Method, Texas Highway Department, Test Method Tex-107-E. It measures the horizontal shrinkage of a bar of soil paste. A brief description is as follows:

    a.   Prepare air dried soil as discussed under swell pressure testing. Mix approximately 50 g of the dry soil in an evaporating dish with distilled water. Add enough water until the soil is a smooth paste. Test the wet paste for consistency by shaping the sample into a smooth layer about one-half inch thick on the bottom of the dish. Make a groove in the sample using a liquid limit grooving tool. If the sample just flows to close the groove on its own, the right amount of moisture is present. Make sure the sample is not too wet or too dry.

    b.   Lightly grease the inside of the bar linear shrinkage mold (128 mm long) and place the wet paste uniformly in the mold. Tap the mold to get rid of trapped air bubbles and strike off the top of the sample level with the mold.

    c.   Let the sample set in the open for 12 hours (overnight) then place in an oven at 110 °C for 24 hours. Remove the specimen and measure the length.

    d.   The linear shrinkage is the measured loss in the soil bar's original length expressed as a percent of the initial length.

Soil pH Test

4. The soil pH is measured on all leach samples before and after leaching. The pH test is conducted as follows:

    a.   For soil-lime mixtures to be compacted for leach testing, a 30.0 g to 100.0 g sample of the mixture is placed in a evaporating dish with an equal weight of distilled water. The soil sample is obtained from the soil-lime mixture after water has been added and the mixture has set 24 hours.

<u>b</u>. For pH measurements of soil-lime samples after leaching is complete, trim 30.0 g to 100.0 g of soil from the top and bottom halves of the leached sample for separate analysis.. Add an equal amount of distilled water.

<u>c</u>. Let the pH sample set for 24 hours.

<u>d</u>. Thoroughly mix the pH sample until a fairly smooth paste is obtained. Measure the pH while continuously stirring the sample.

<u>Porewater Cation Extractions</u>

5. Calcium, sodium, magnesium, and potassium cation concentrations in the porewater were extracted and computed as follows:

<u>a</u>. Prepare soil samples as described for remolded swell pressure samples. Place 100.0 g of the air dried soil in a clean 200 ml plastic centrifuge bottle.

<u>b</u>. Add 100 ml of distilled-demineralized water to the bottle. Shake the bottle until dry soil can no longer be seen in the bottom of the bottle.

<u>c</u>. Place the bottle on a high speed shaker for 15 minutes.

<u>d</u>. Centrifuge the mixture for 2500 revolutions per minute (rpm) for 15 minutes.

<u>e</u>. Remove the supernatant from the sample with a pipette, being careful not to mix any soil paste with the supernatant. Place the supernatant in a clean 60 ml polypropylene bottle and add approximately one-half percent (by volume of sample) concentrated nitric acid, to lower the pH to less than 2.0.

<u>f</u>. Measure the concentration of the cations in the supernatant using spectrophotometry methods (Atomic Absorption, AAS, or Inductively Coupled Plasma, ICP). Record the results in parts per million (ppm) or mg/l. If sample dilution is required, the dilution factor must be recorded as well.

<u>g</u>. Convert ppm to milliequivalent per liter (meq/l) of solution by:

$$meq/l = ppm/\text{Atomic Weight of Cation} \qquad (A1)$$

Exchange Complex Cation Extraction

6. Calcium, sodium, magnesium, and potassium cation concentrations in the exchange complex were extracted and computed as follows:

a. Prepare a 1 Normal solution of ammonium acetate by placing 77.1 g of crystal ammonium acetate in a container and bringing the volume up to one liter with distilled-demineralized water.

b. Prepare soil samples as described for remolded samples for swell pressure tests. Weigh out 4.0 g of the air dried soil and place in a 50 ml polypropylene centrifuge tube with sealing cap.

c. Add 33 ml of the ammonium acetate solution and shake until no dry soil is visible at the bottom of the tube.

d. Place the tube on a high speed shaker for 15 minutes.

e. Centrifuge at 2500 rpm for 15 minutes.

f. Remove the supernatant with a pipette, being careful not to mix any soil paste with the supernatant.

g. Repeat steps 2 through 6 two more times on the same soil sample. Place all collected supernatant in a clean polypropylene bottle and add one-half percent (by volume of solution) concentrated nitric acid, lowering the pH to below 2.0.

h. Measure the cation concentrations by spectrophotometry methods (AAS or ICP) and record the results in ppm or mg/l. Record the dilution factor if required.

i. Convert ppm to milliequivalent per 100 g (meq/100 g) of soil as follows:

$$meq/100 \text{ g} = ppm \times 2.475/\text{Atomic Weight of Cation} \qquad (A2)$$

where 2.475 is a constant used to account for the amount of soil and ammonium acetate used, and to convert mg/l (ppm) to meq/100 g.

APPENDIX B

GRAPHICAL PRESENTATION OF
LIME REACTIVITY
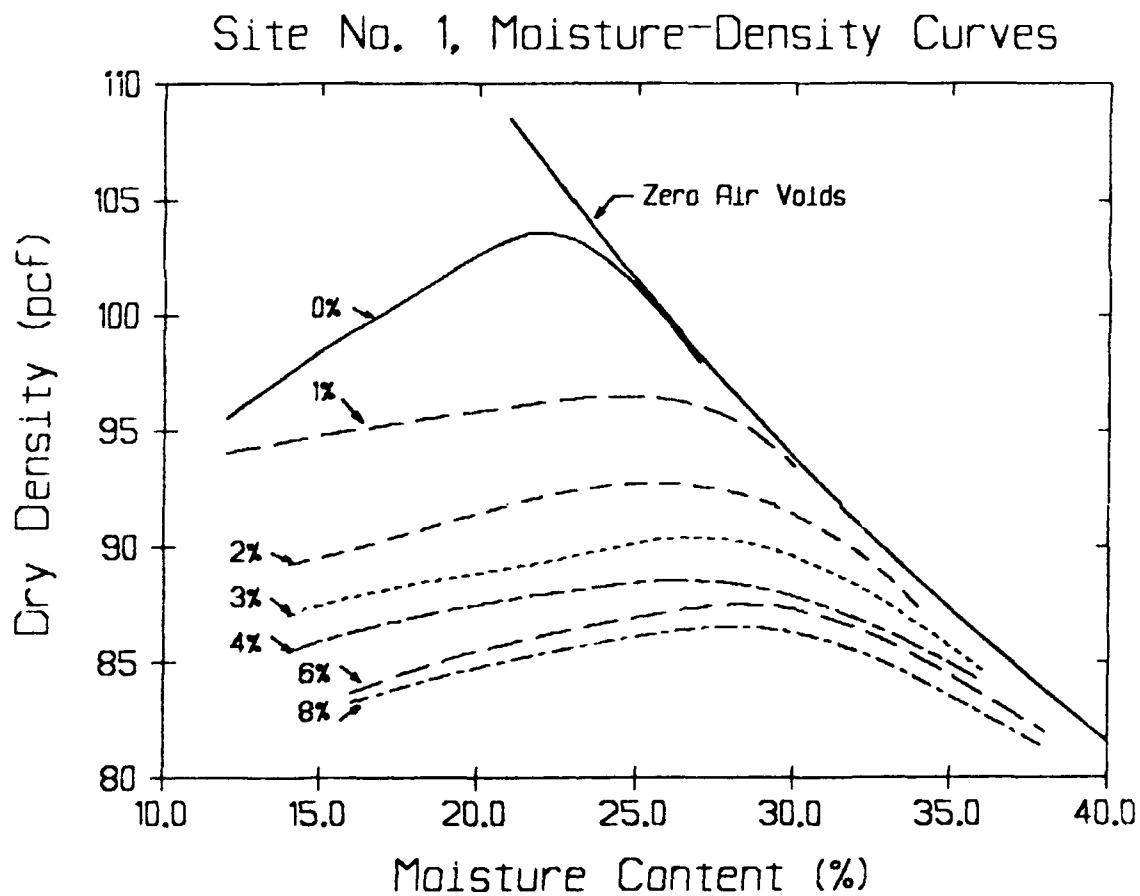
Figure B1. Moisture-density relationships for
Site No. 1 at various lime contents.
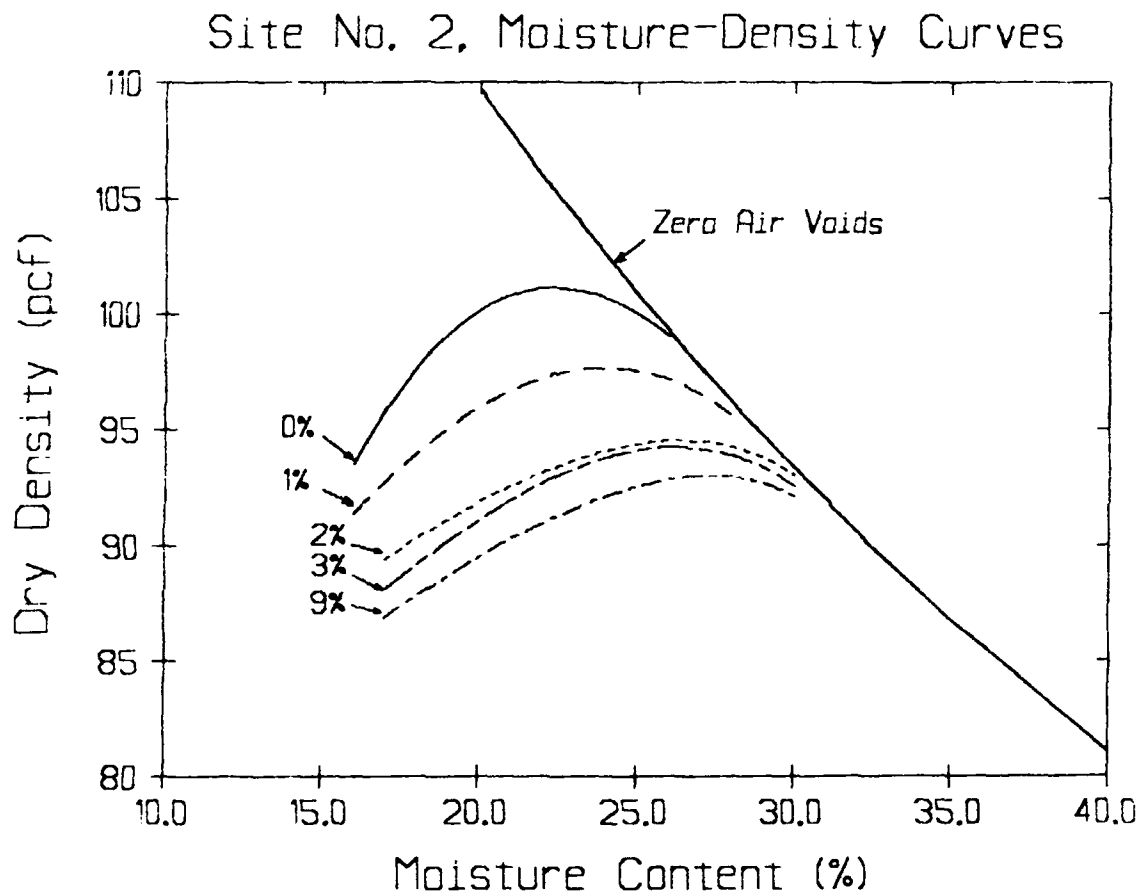
Figure B2. Moisture-density relationships for Site No. 2 at various lime contents.
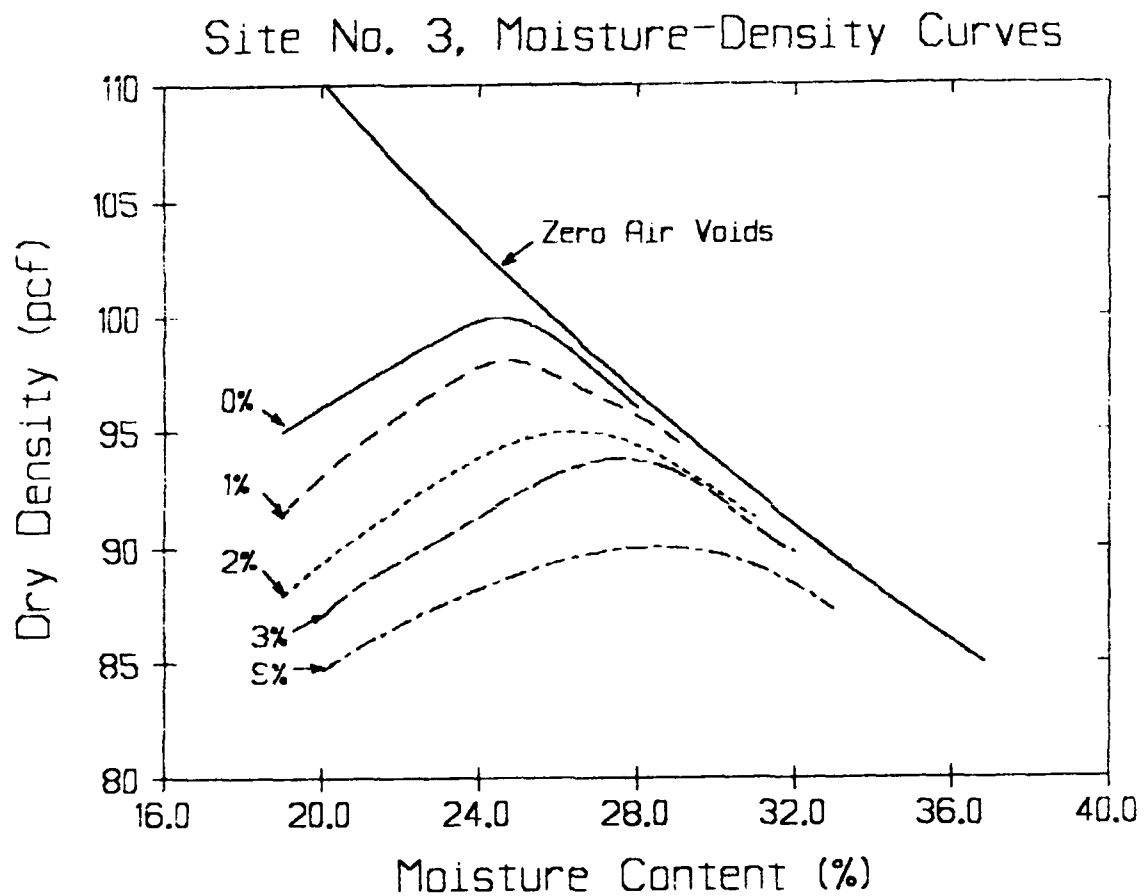
Figure B3. Moisture-density relationships for
Site No. 3 at various lime contents.

B4
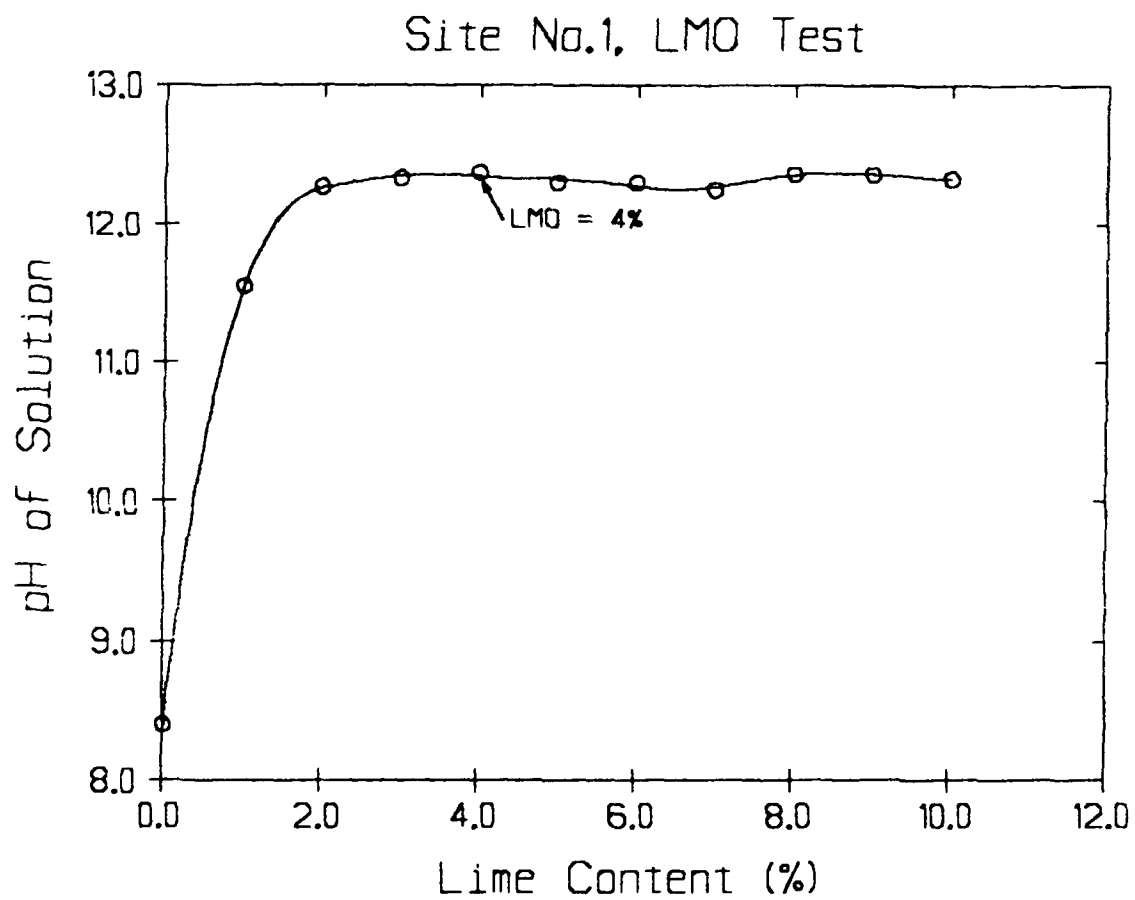
Figure B4. Lime modification optimum test, Site No. 1.
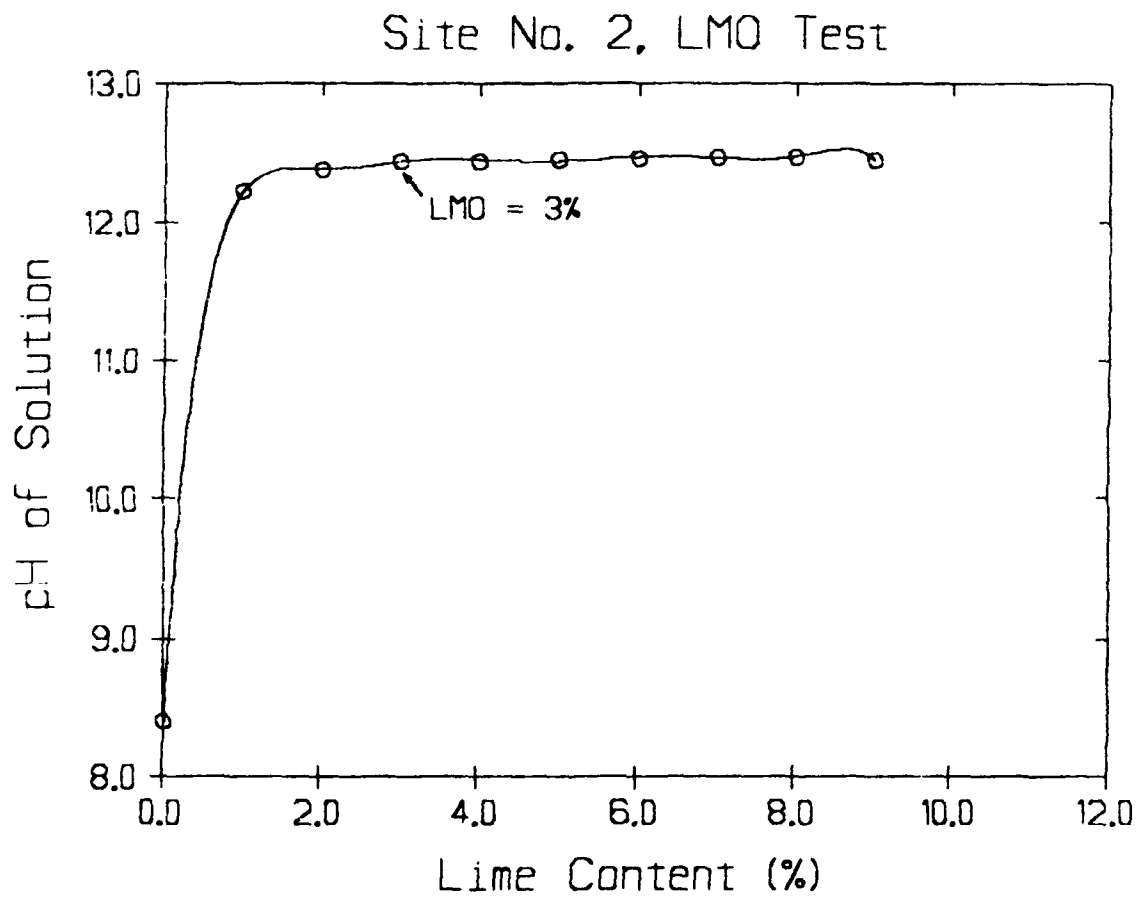
Figure B5.   Lime modification optimum test,
Site No. 2.

Site No. 3, LMO Test

LMO = 3%

pH of Solution

Lime Content (%)
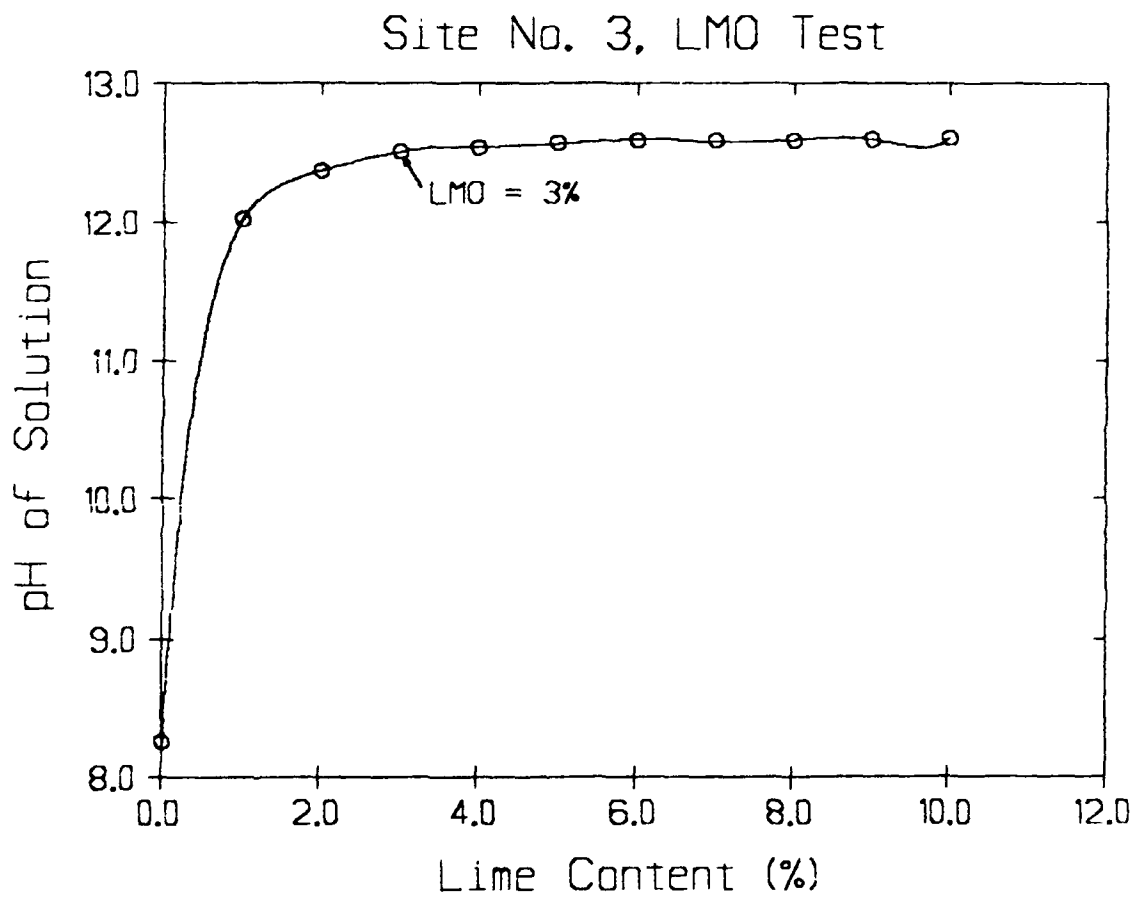
Figure B6. Lime modification optimum test, Site No. 3.
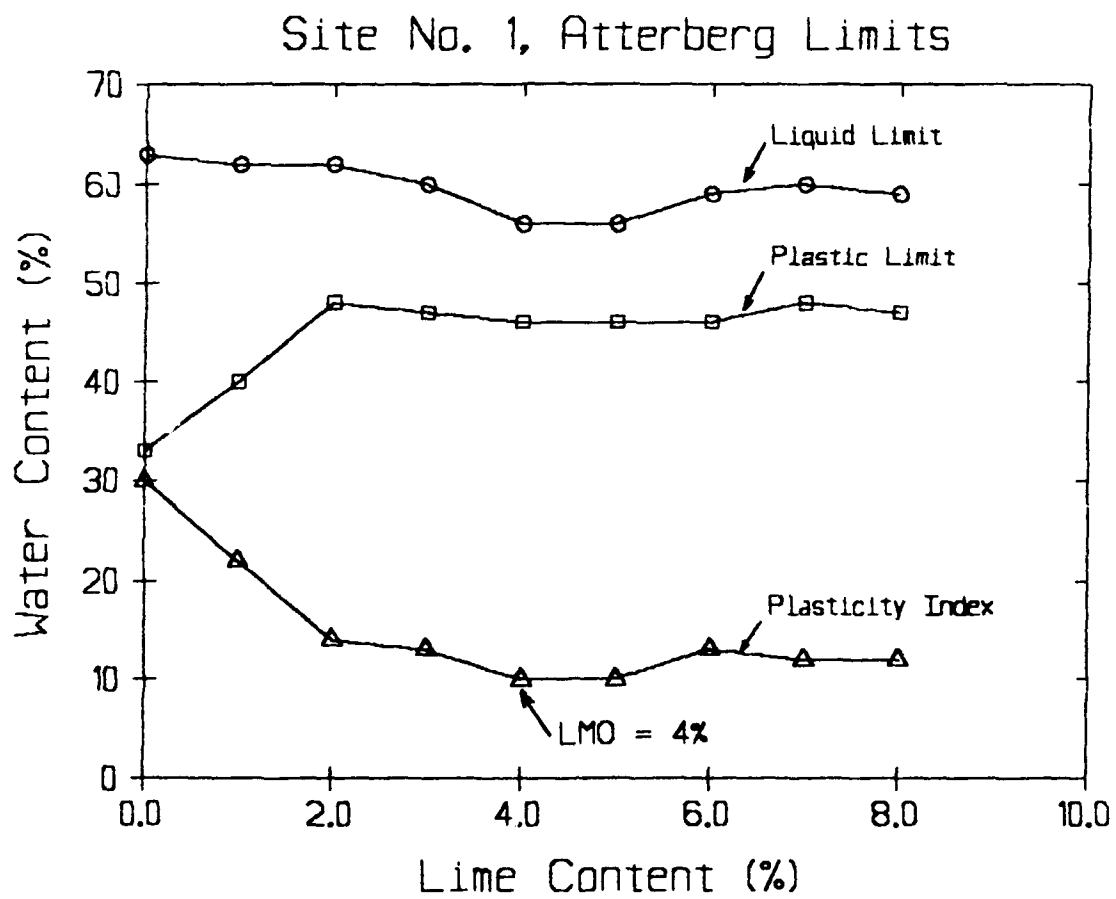
Figure B7. Atterberg limits for Site No. 1 material before leaching.
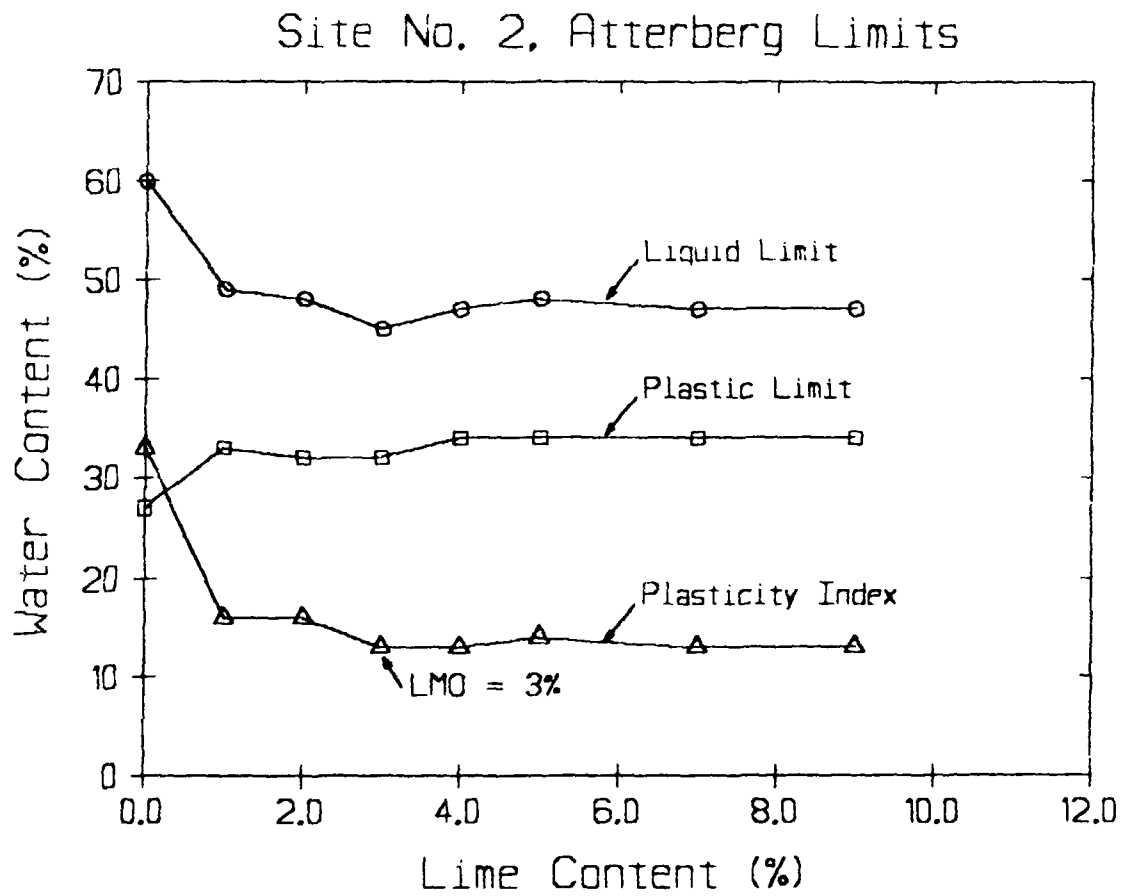
Figure B8.   Atterberg limits for Site No. 2
material before leaching.
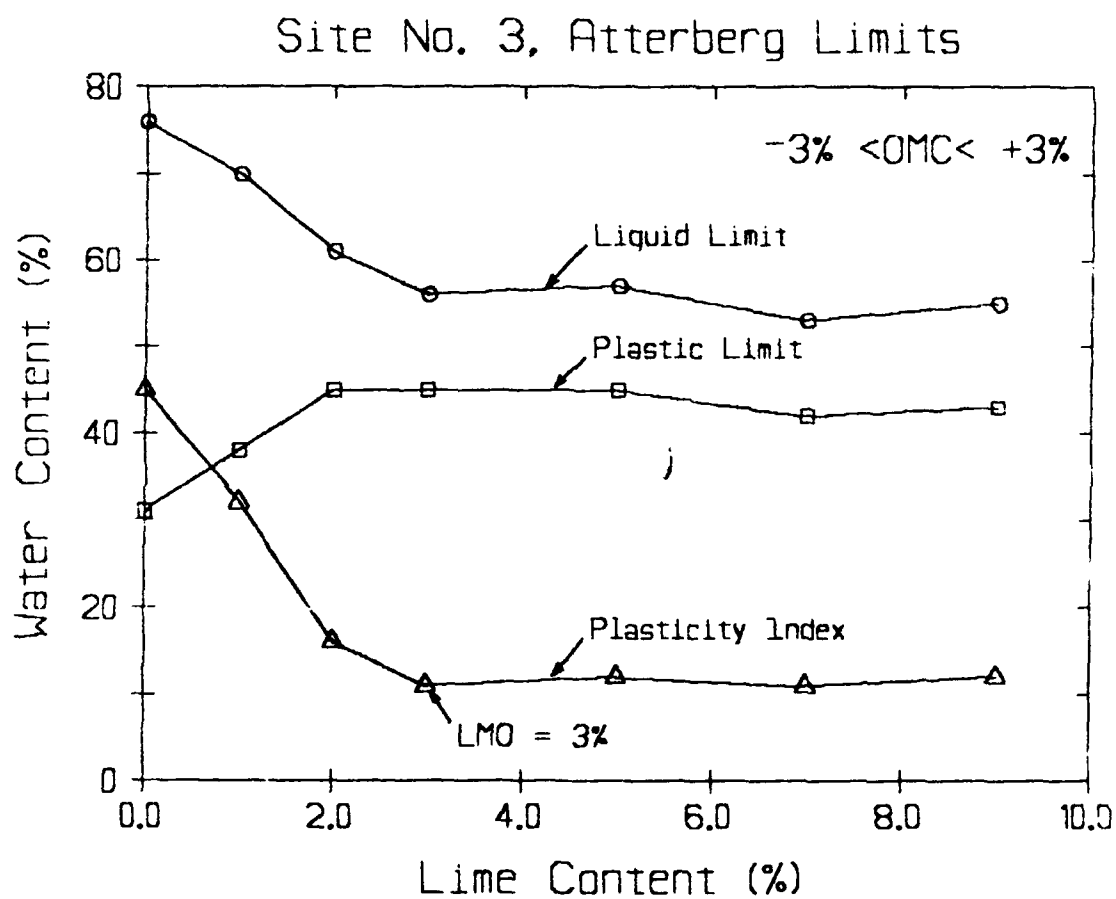
Figure B9. Atterberg limits for Site No. 3
material before leaching.
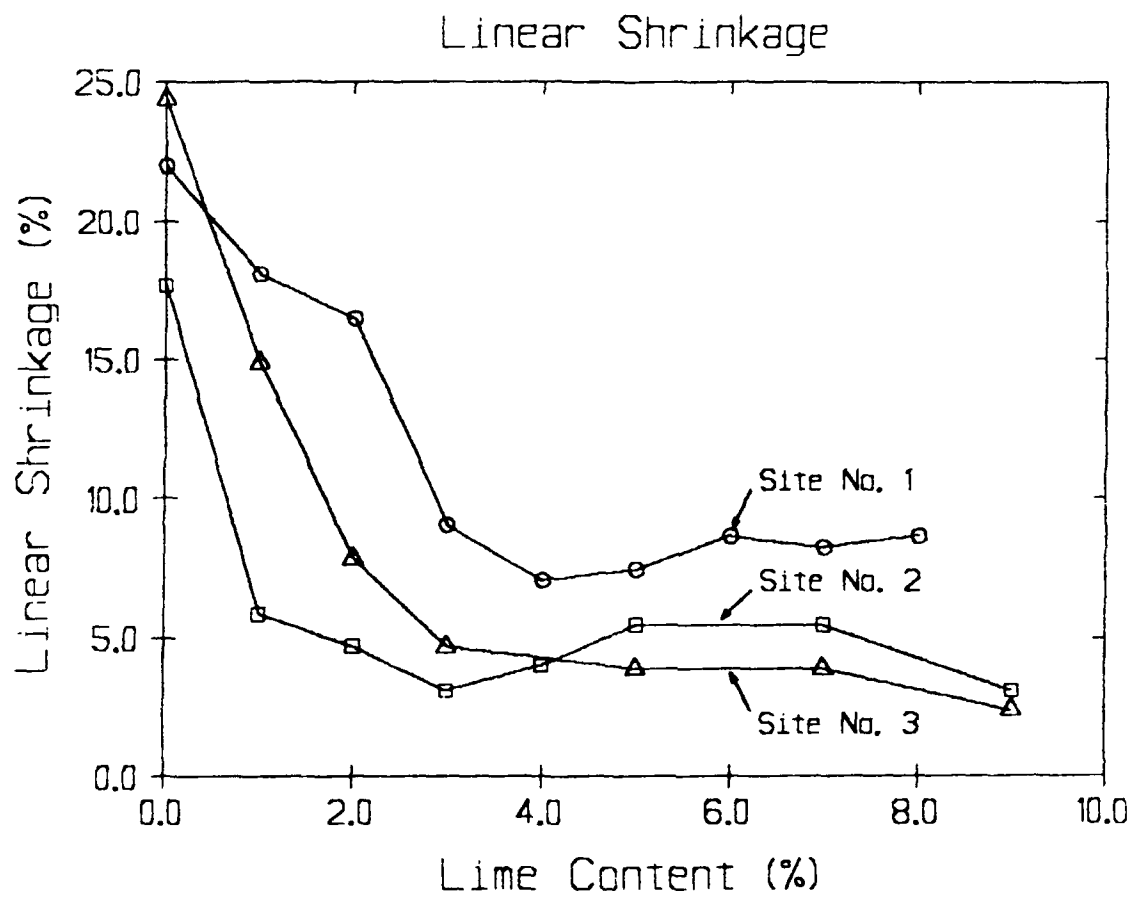
Figure B10. Linear shrinkage tests for all sites before leaching.
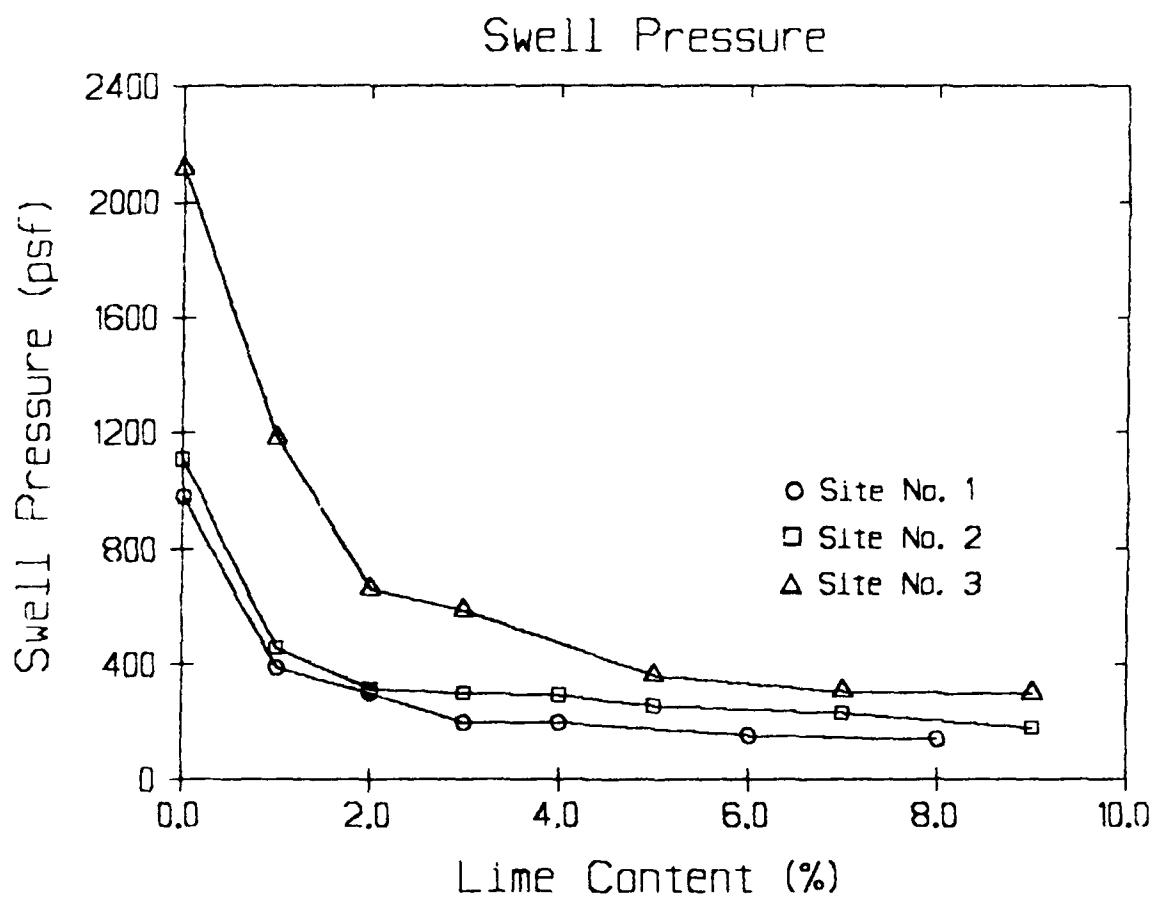
Figure B11. Swell pressure tests for all sites
before leaching.
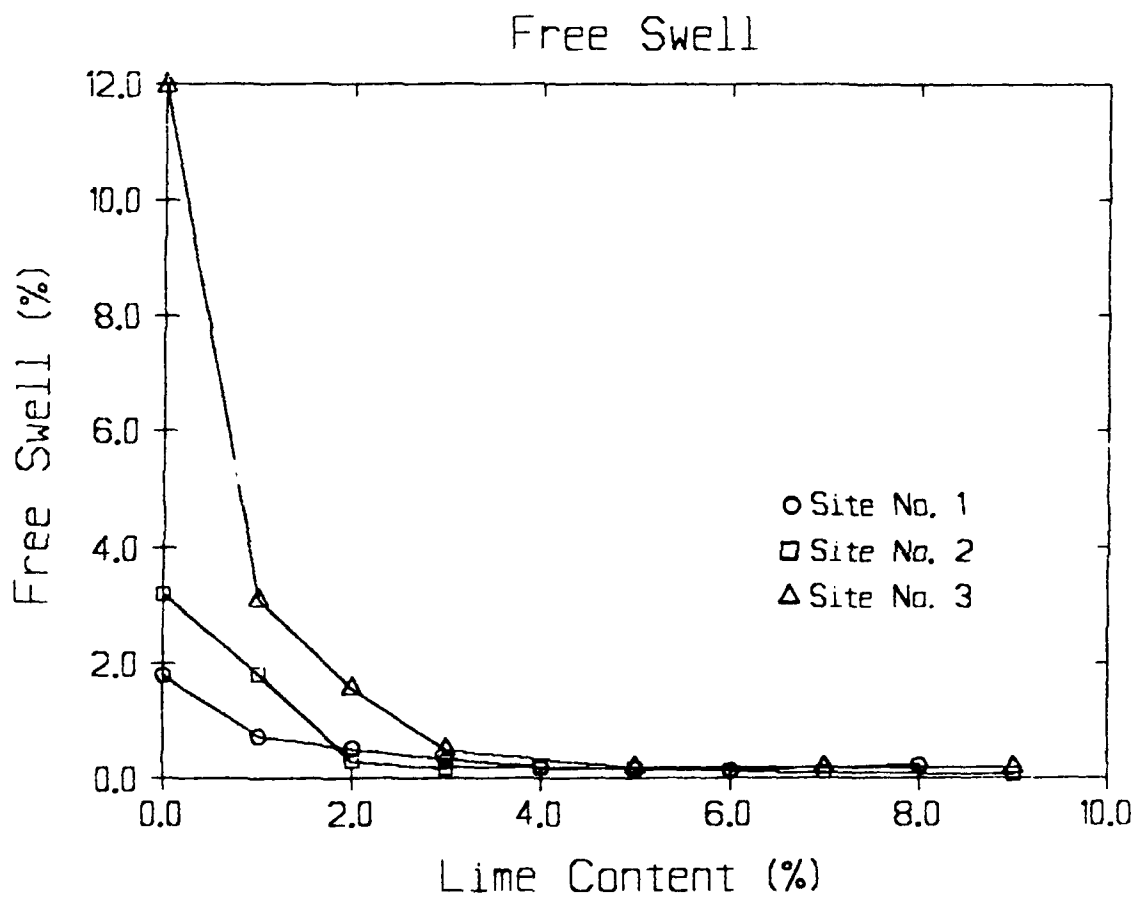
Figure B12.   Free swell tests for all sites before leaching.

APPENDIX C

LEACHATE GRAPHS FOR WET
AND DRY SAMPLES
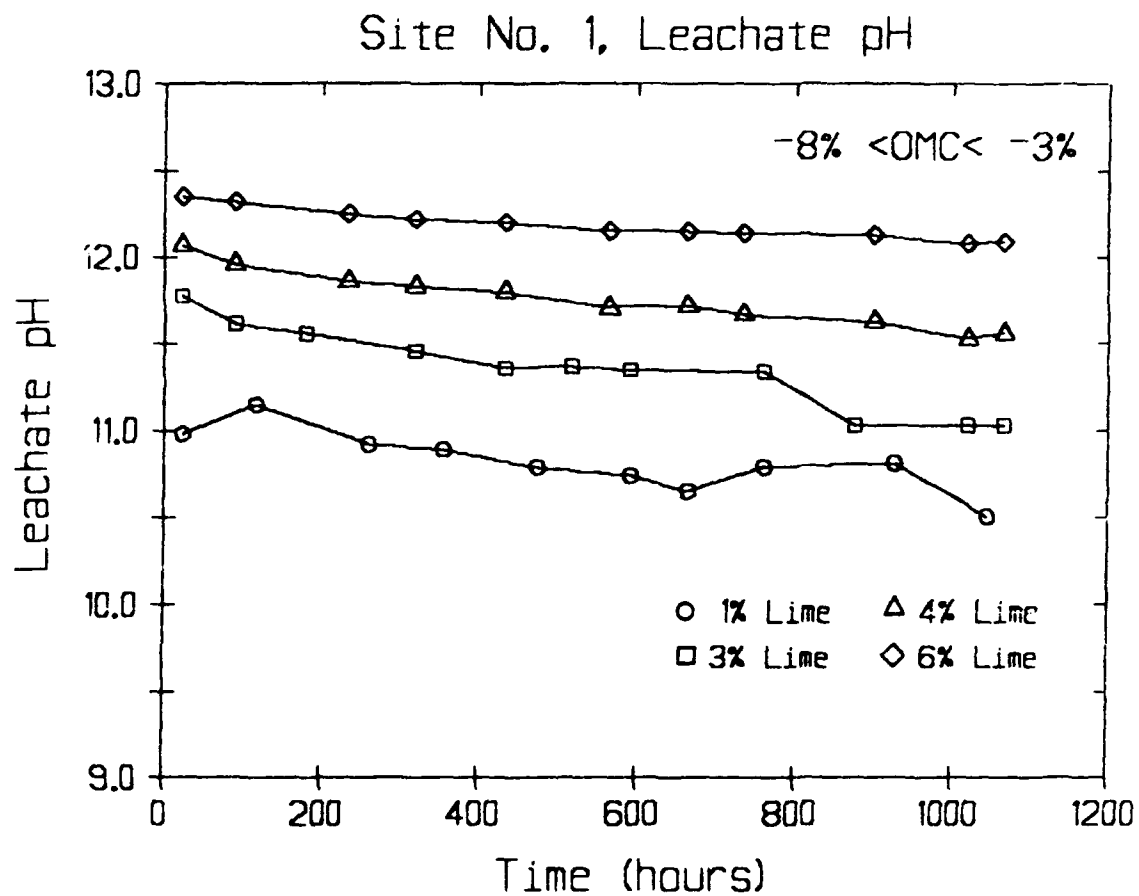
Figure C1. Leachate pH for Site No. 1 samples compacted dry.
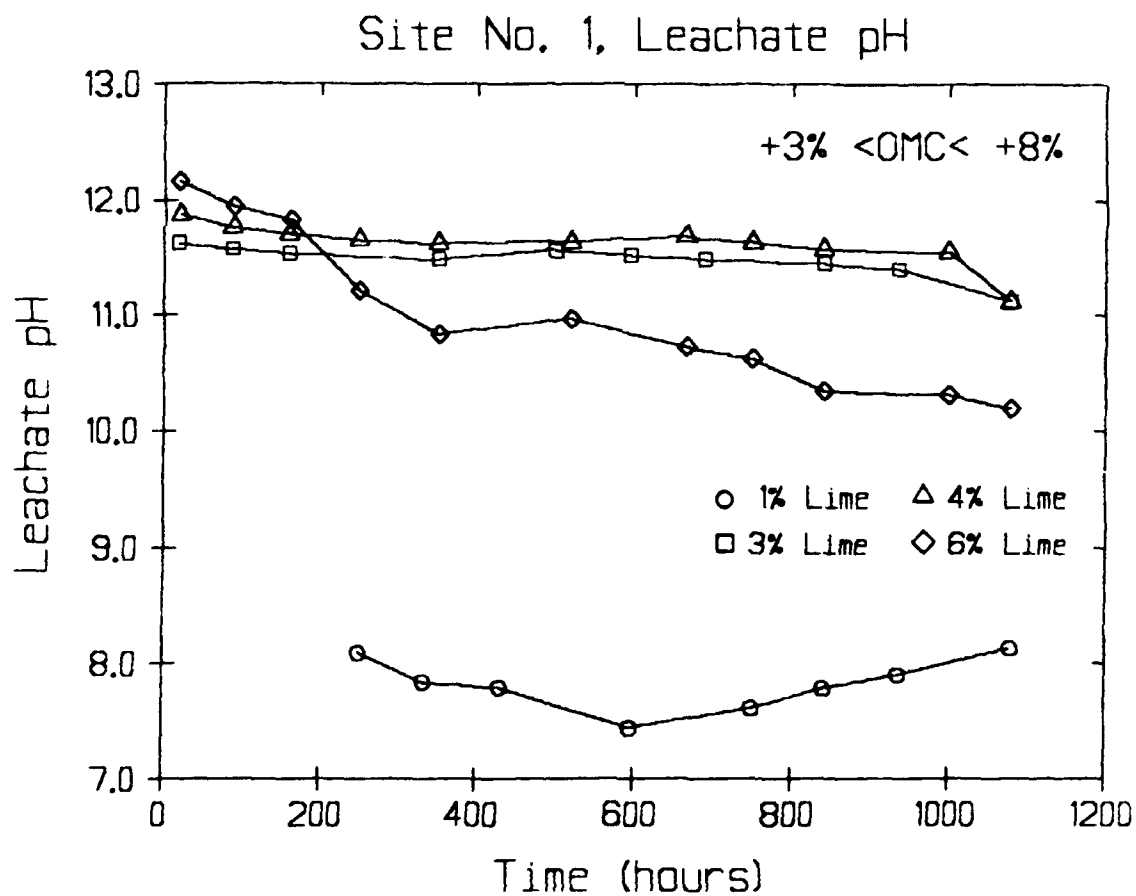
Figure C2. Leachate pH for Site No. 1 samples compacted wet.
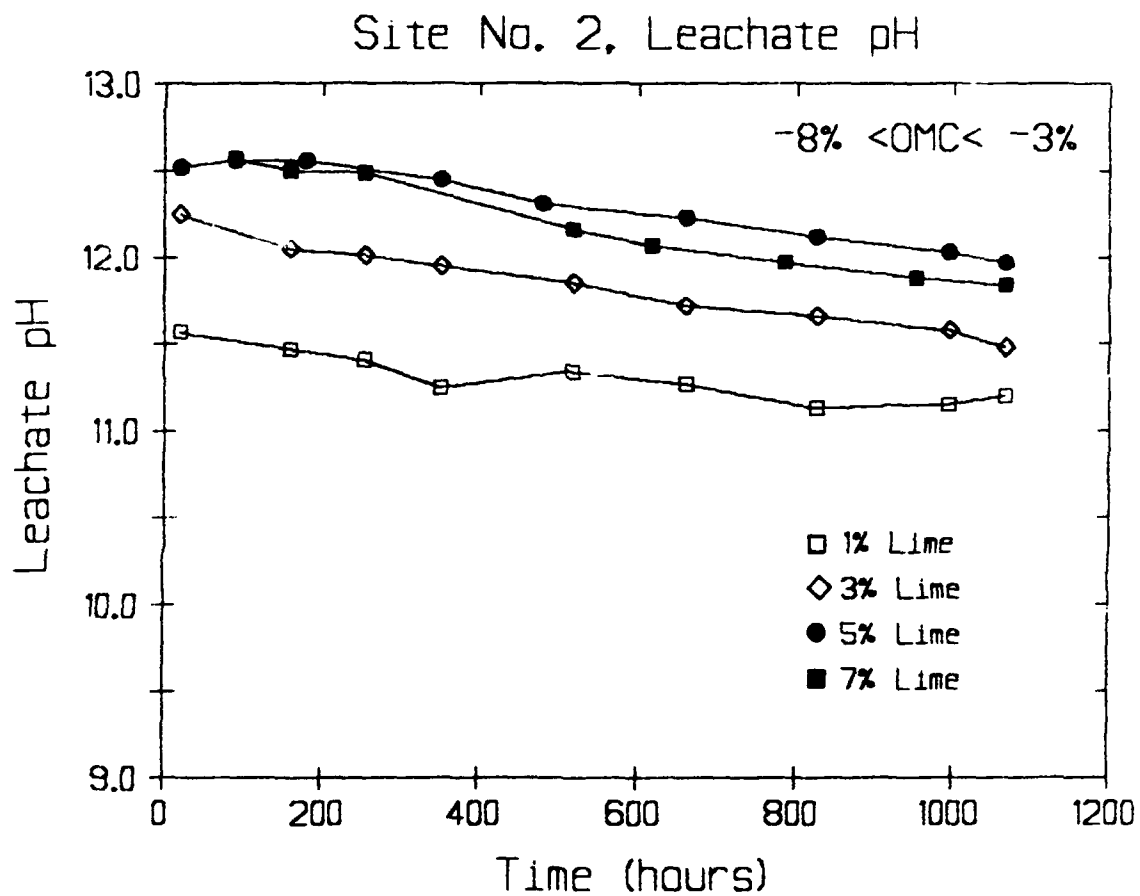
Figure C3. Leachate pH for Site No. 2 samples
compacted dry.
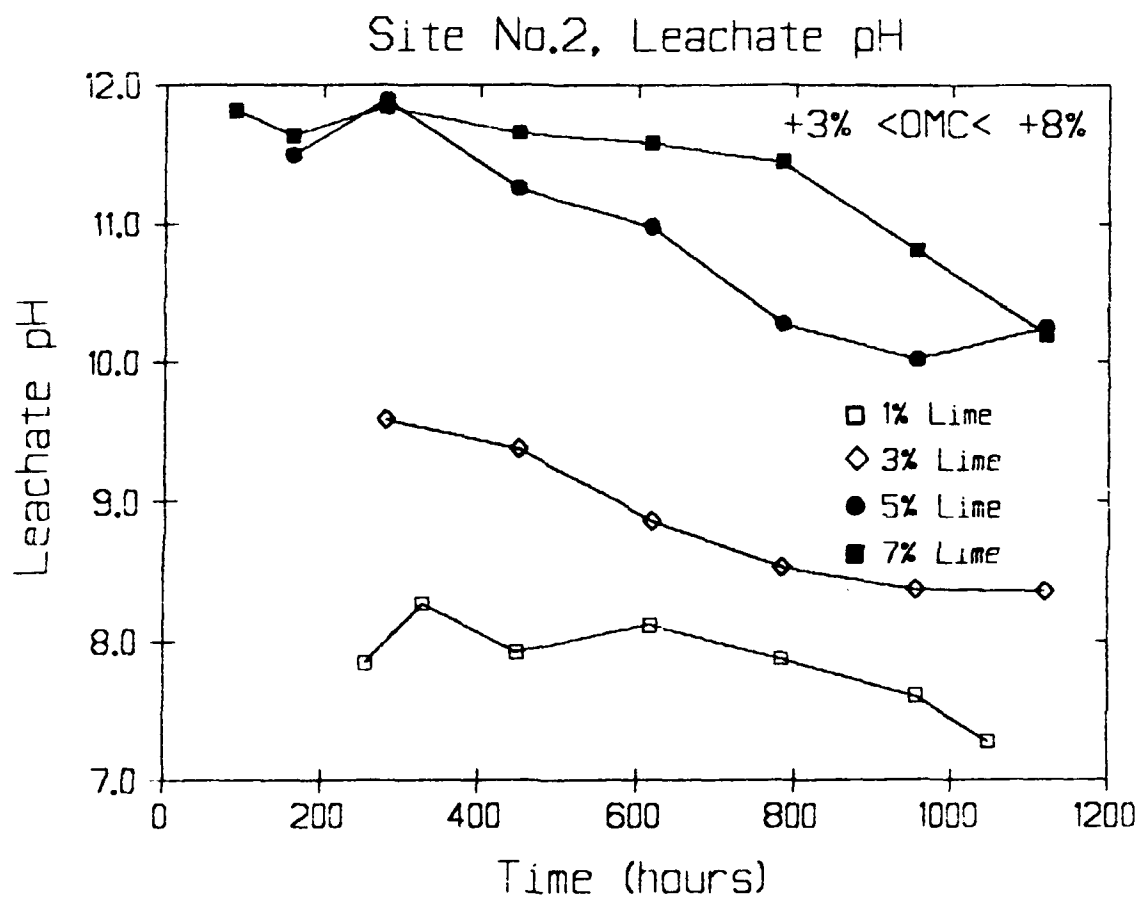
Figure C4. Leachate pH for Site No. 2 samples compacted wet.
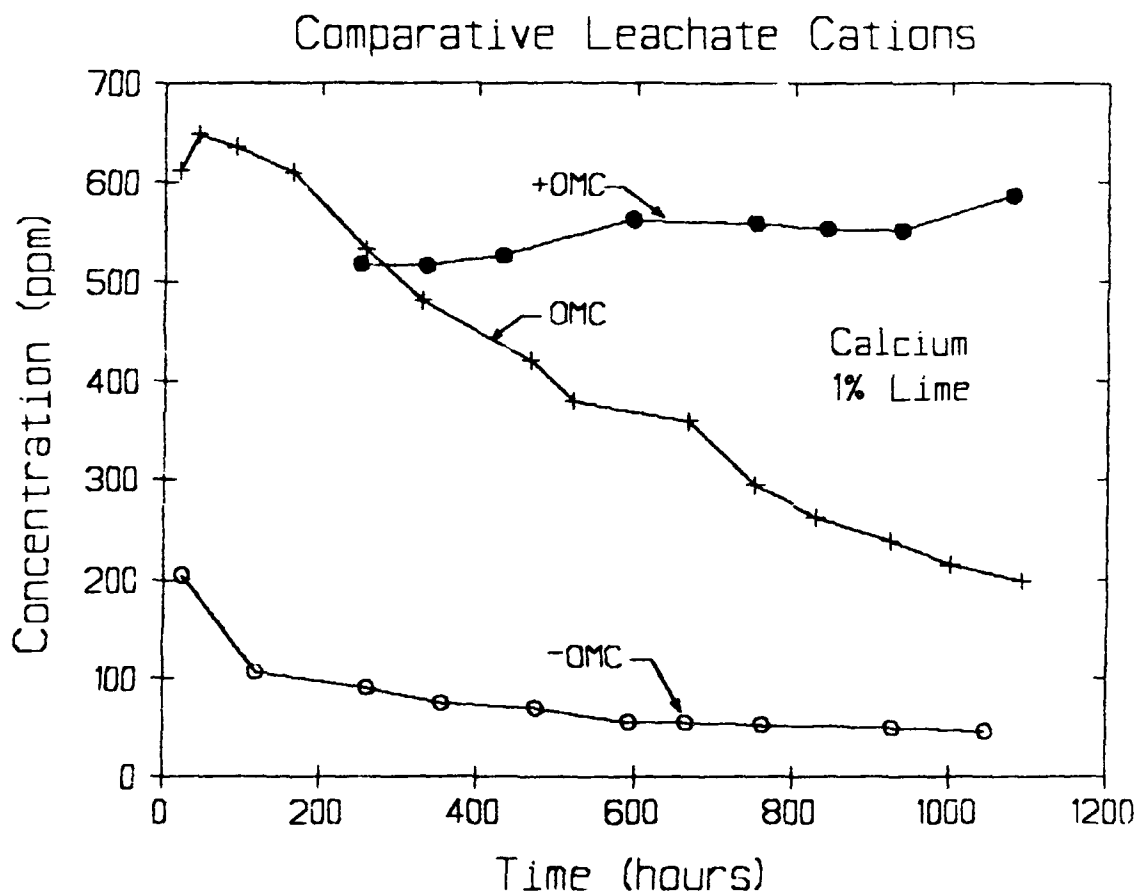
Figure C5. Moisture content effects on calcium
in Site No. 1 leachates at 1% lime.
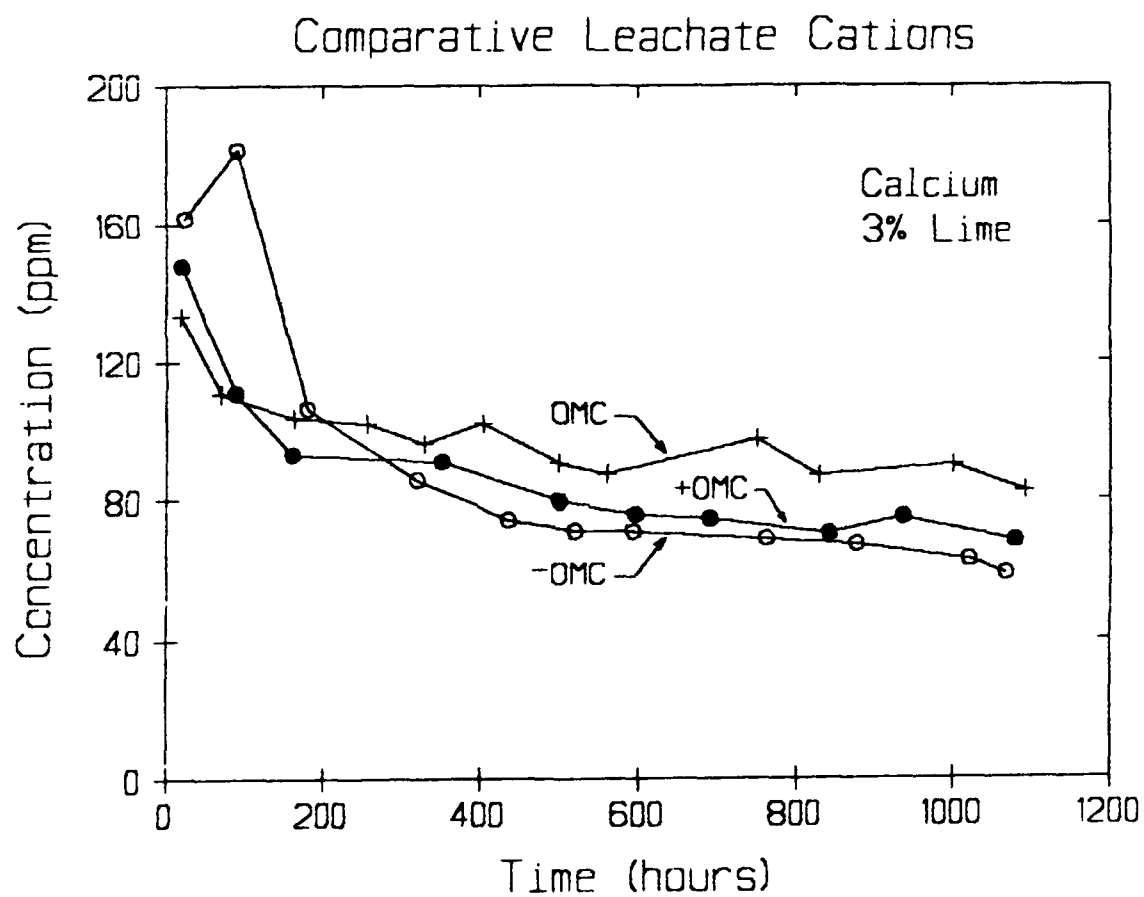
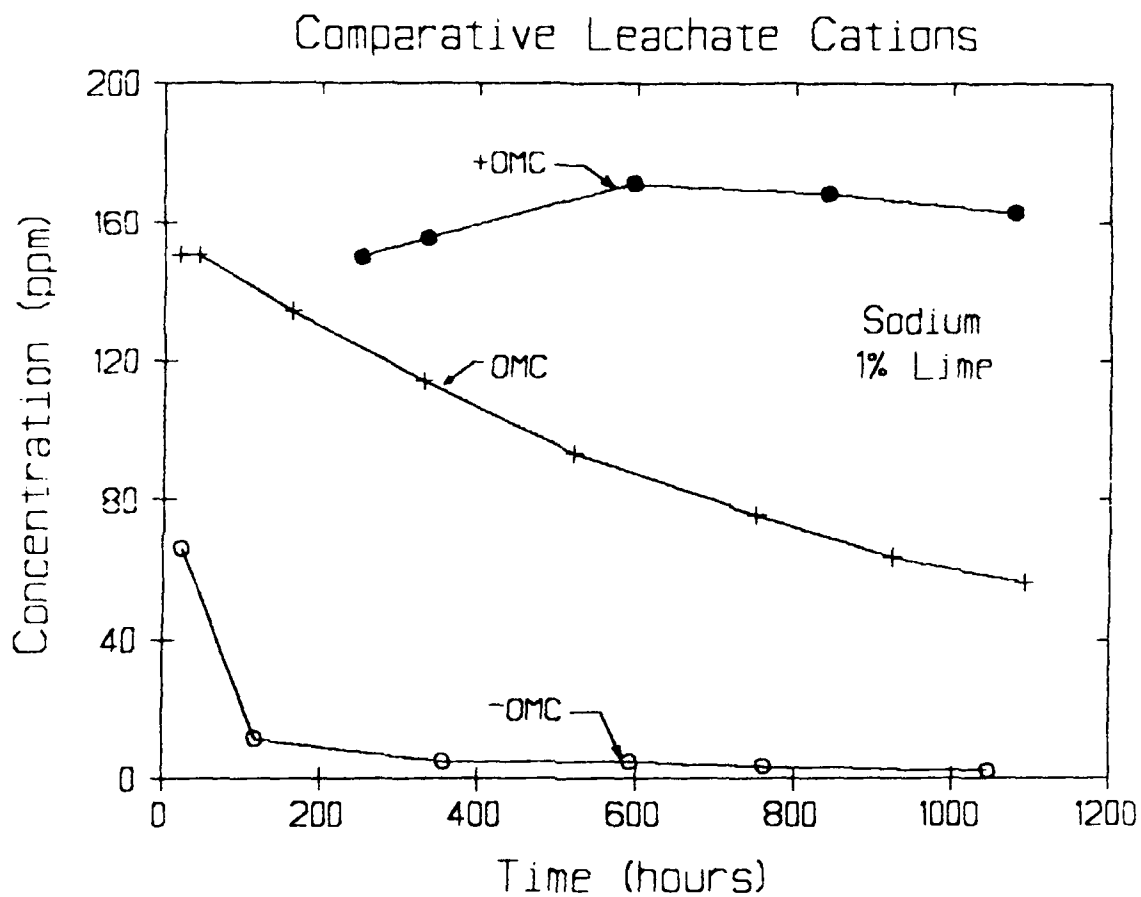Figure C6. Moisture content effects on calcium
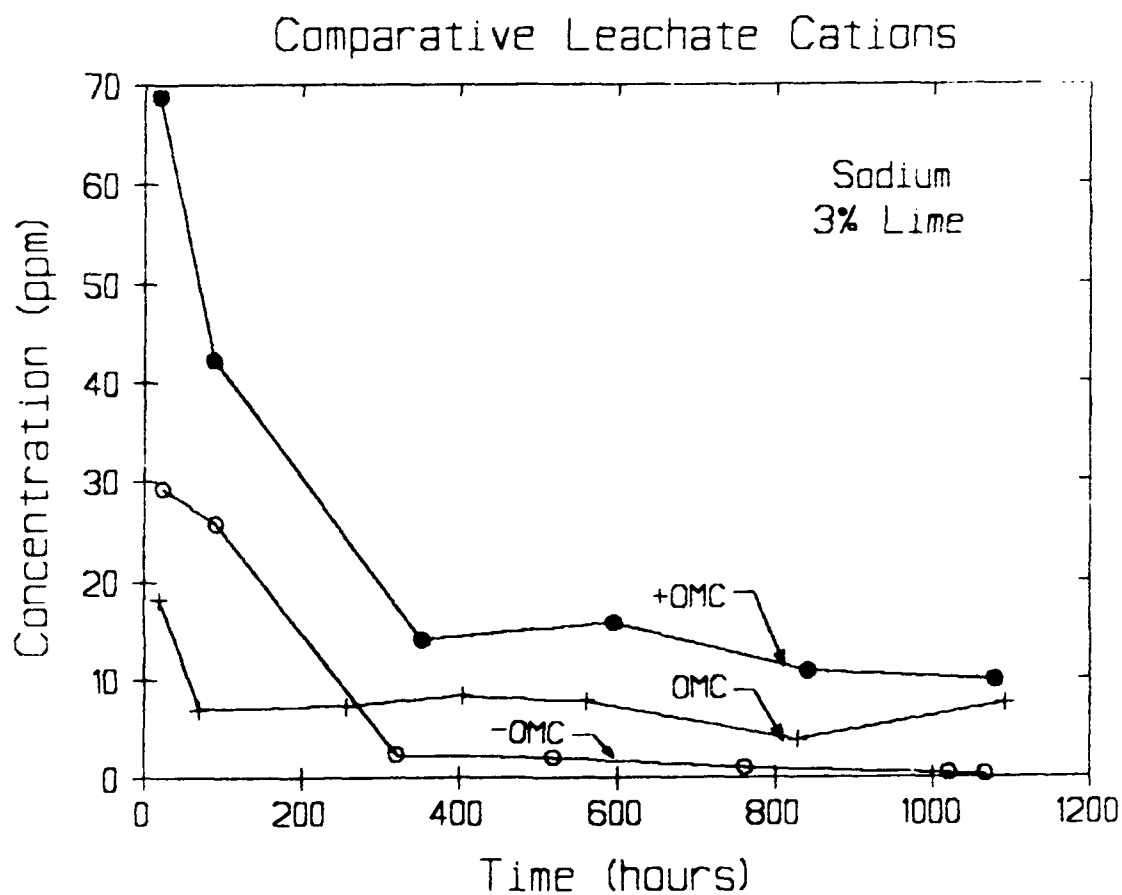in Site No. 1 leachates at 3% lime.
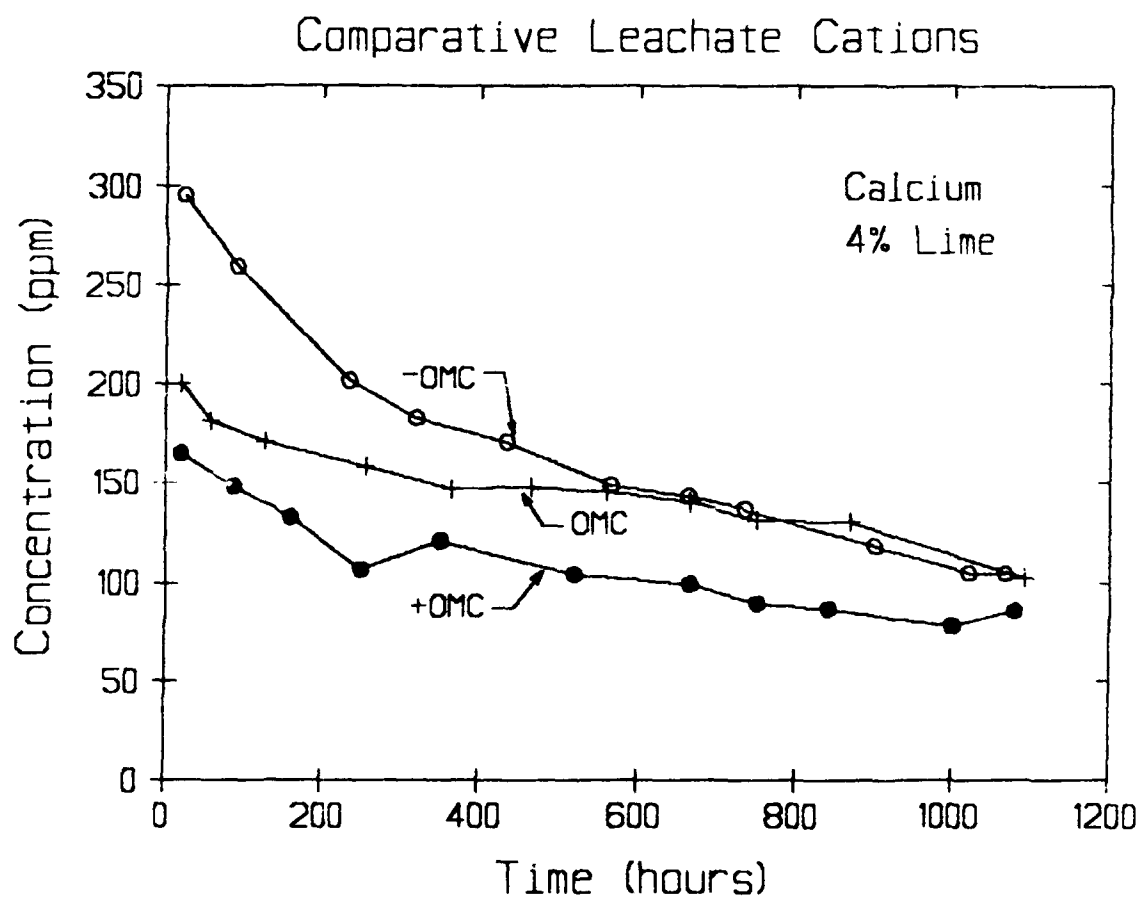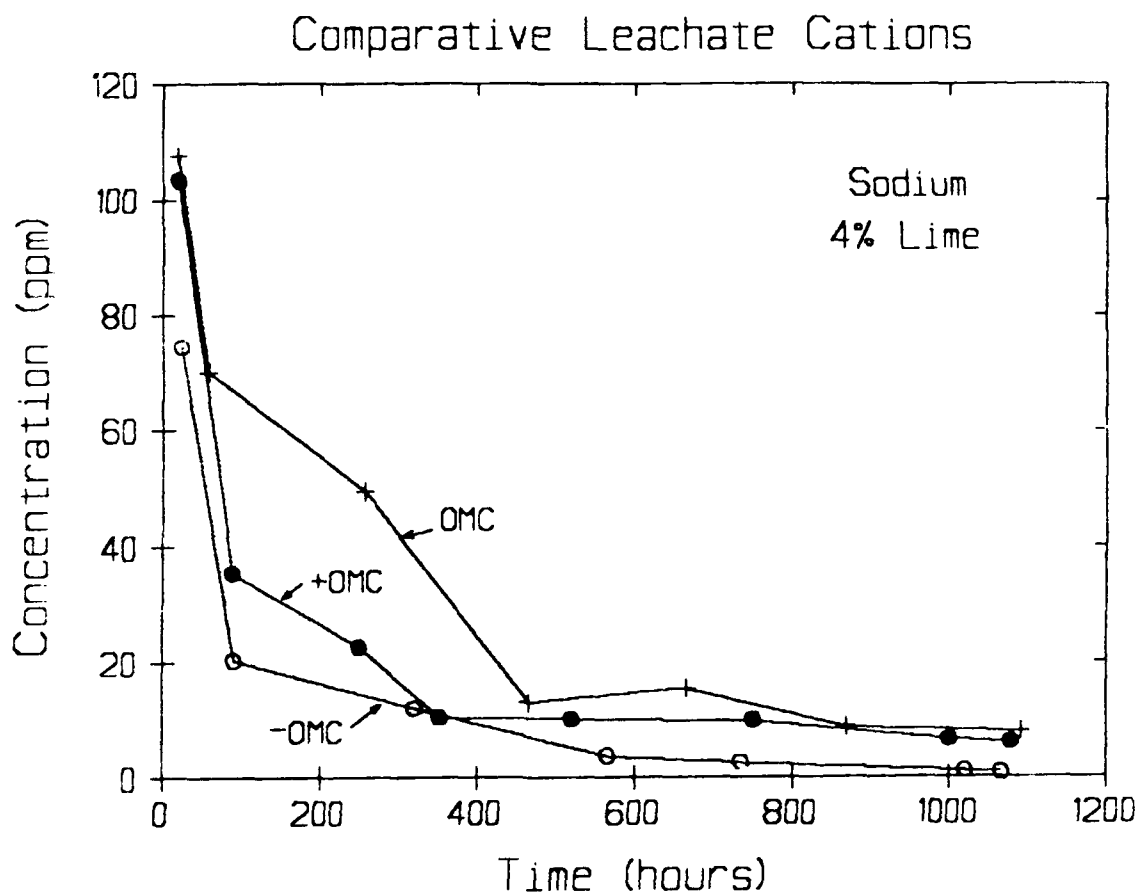
Figure C7. Moisture content effects on calcium in Site No. 1 leachates at 4% lime.
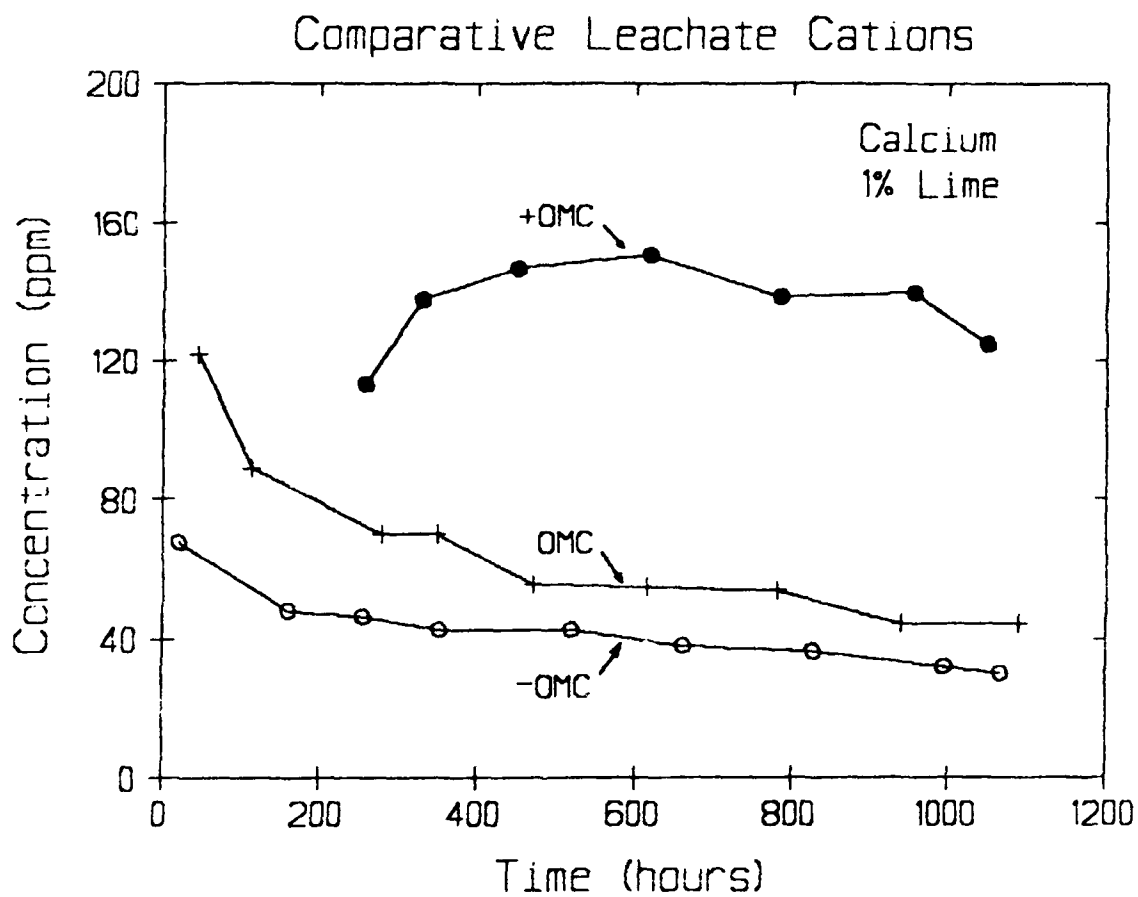
Figure C8. Moisture content effects on calcium in Site No. 2 leachates at 1% lime.
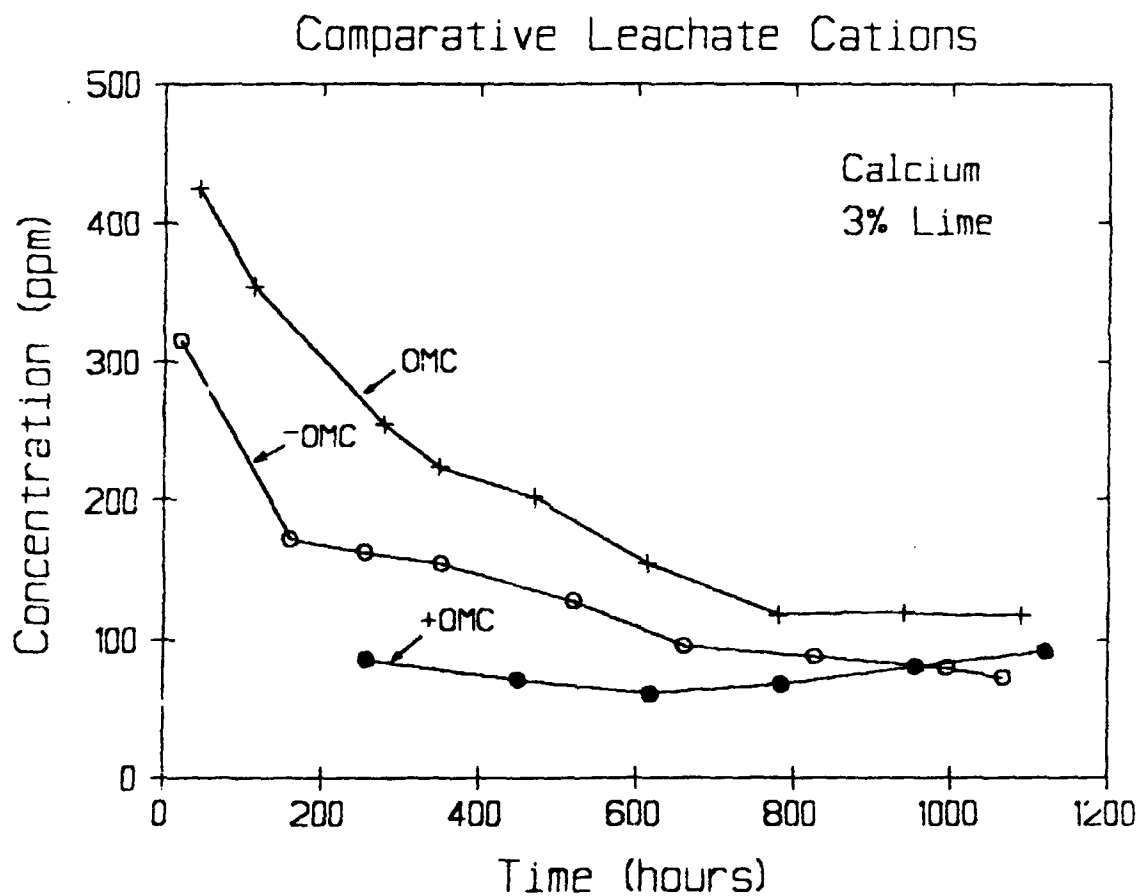
Figure C9. Moisture content effects on calcium in Site No. 2 leachates at 3% lime.
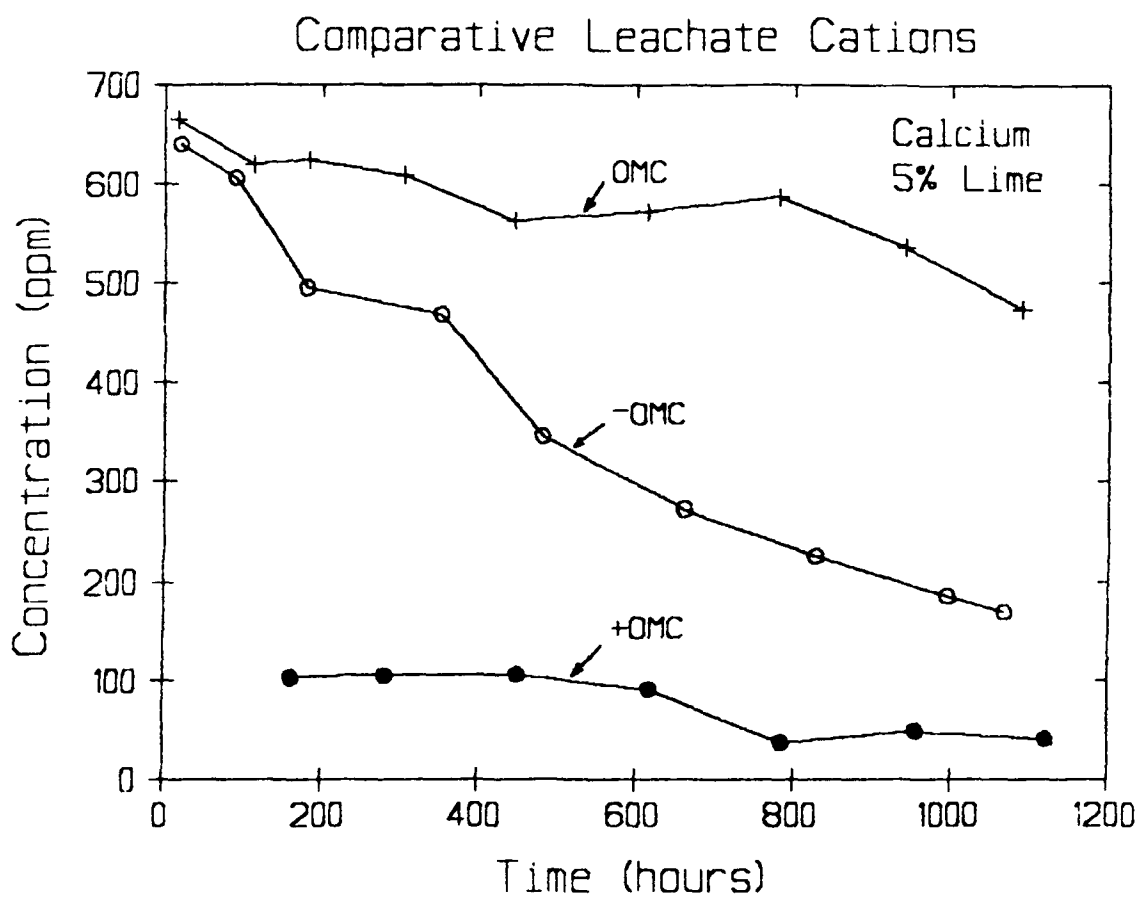
Figure C10. Moisture content effects on calcium
in Site No. 2 leachates at 5% lime.
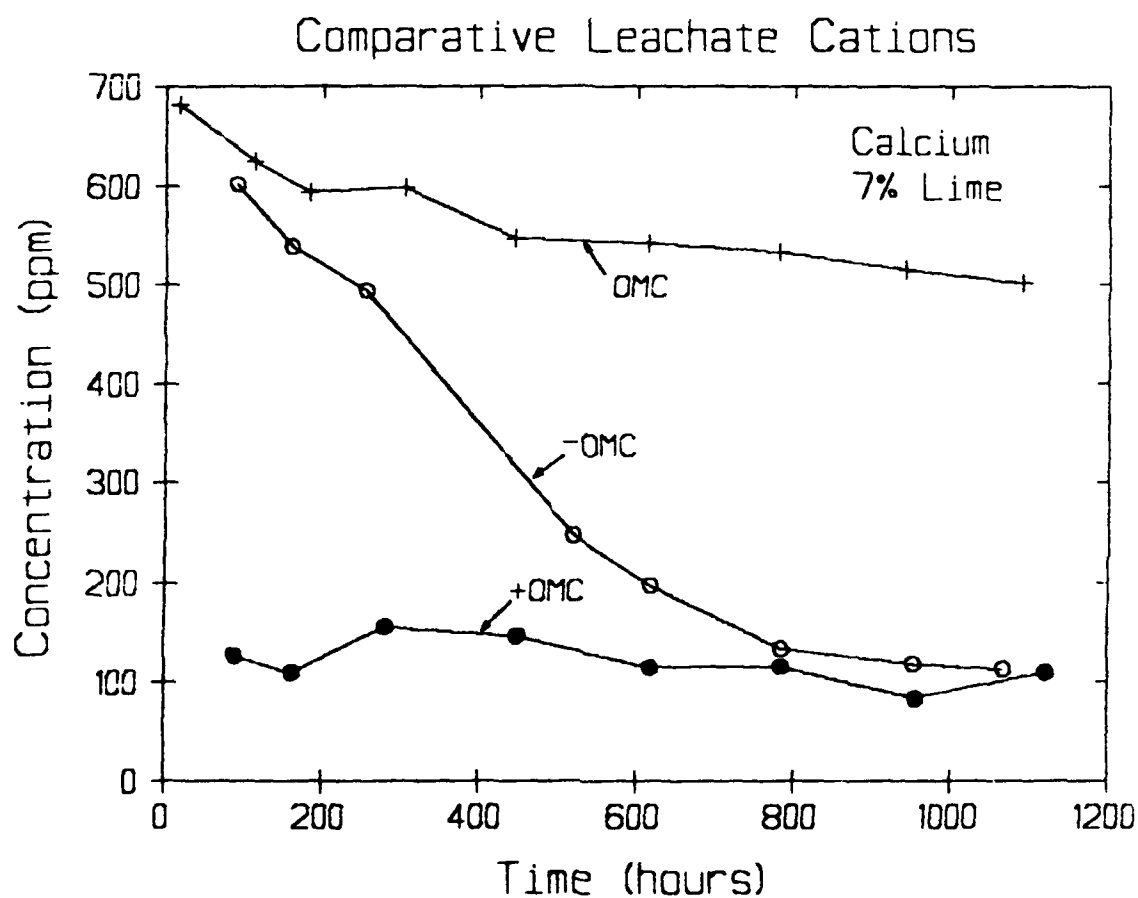
Figure C11.   Moisture content effects on calcium
in Site No. 2 leachates at 7% lime.

Figure C12. Moisture content effects on sodium
in Site No. 1 leachates at 1% lime.

Figure C13. Moisture content effects on sodium in Site No. 1 leachates at 3% lime.
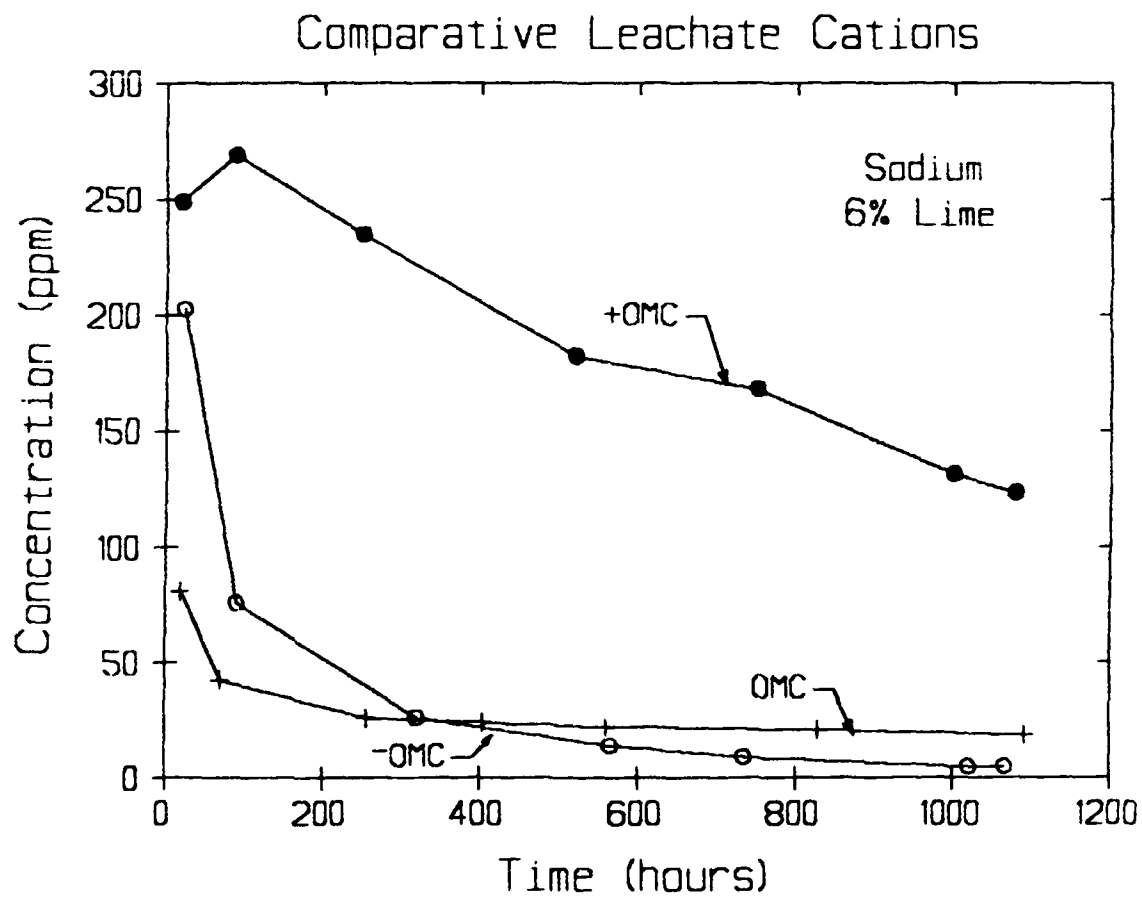
Figure C14. Moisture content effects on sodium
in Site No. 1 leachates at 4% lime.

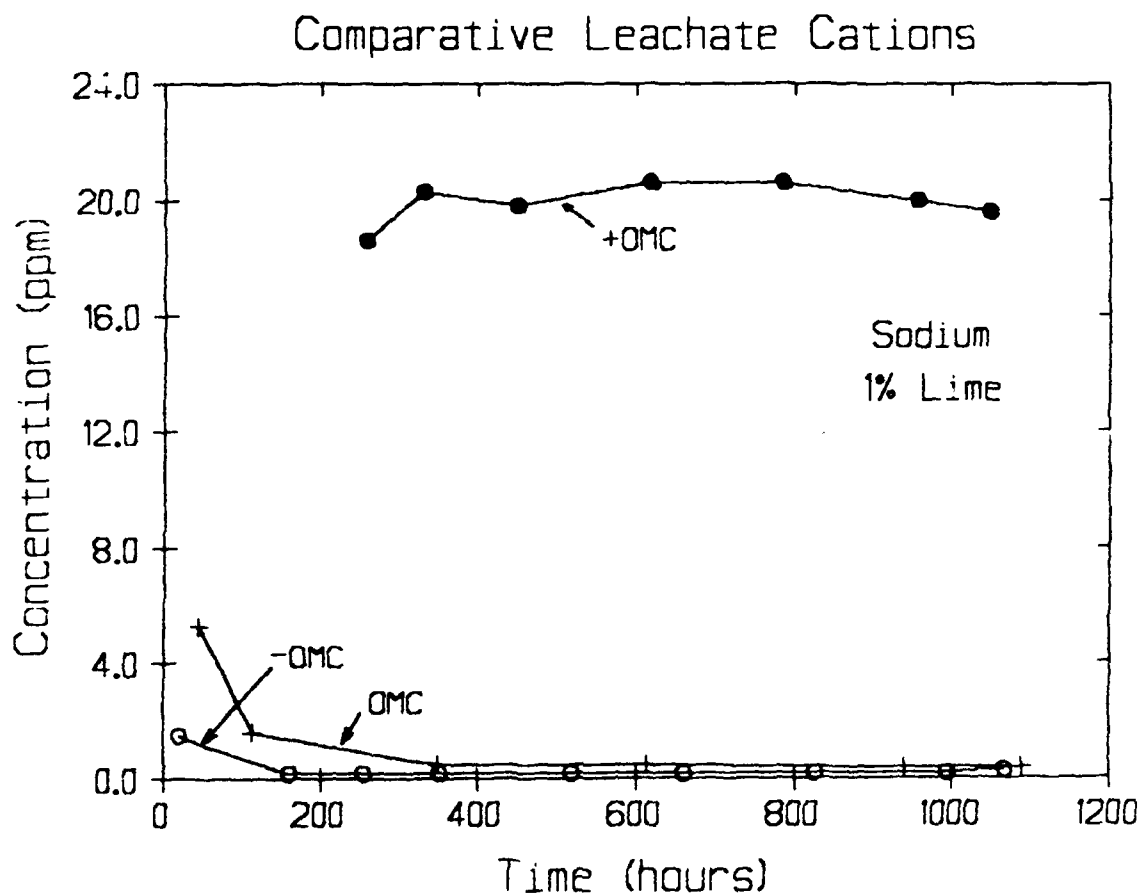Figure C15. Moisture content effects on sodium in Site No. 1 leachates at 6% lime.

Figure C16. Moisture content effects on sodium
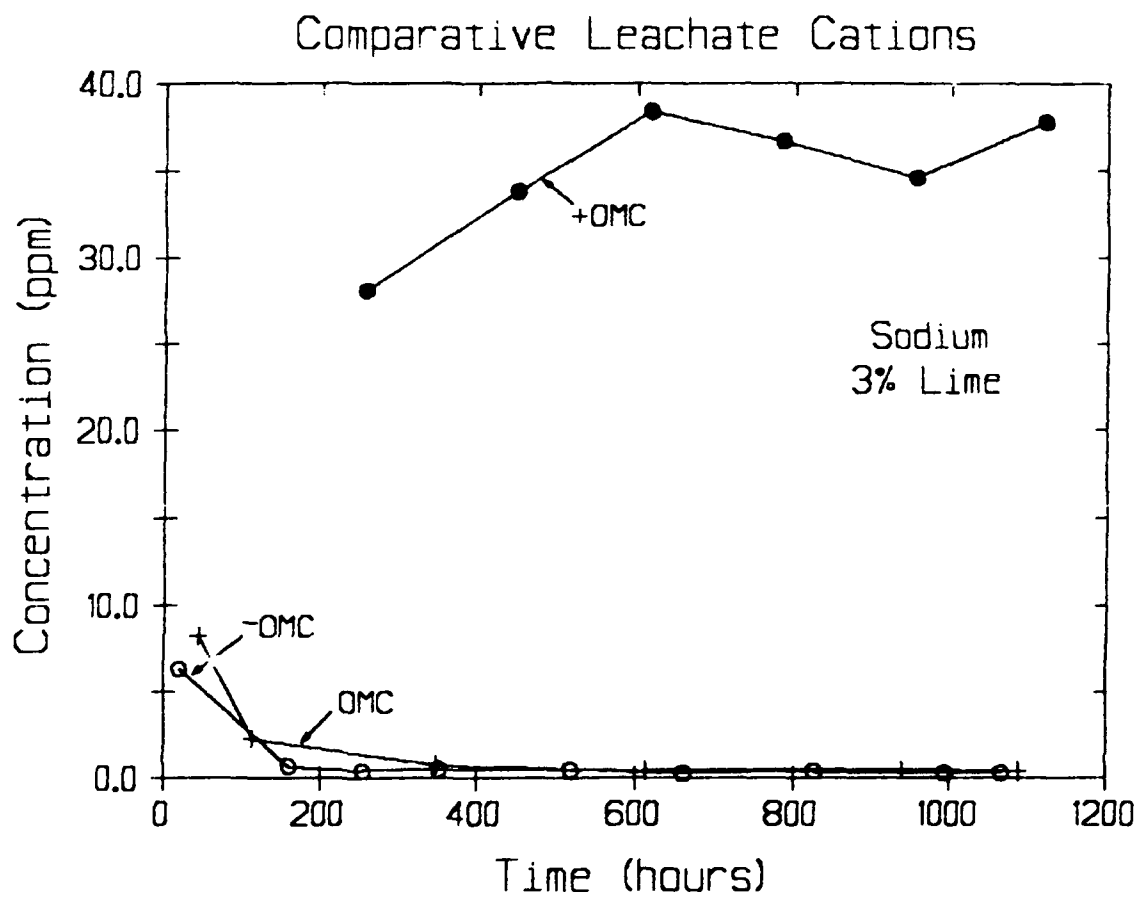in Site No. 2 leachates at 1% lime.

Figure C17. Moisture content effects on sodium
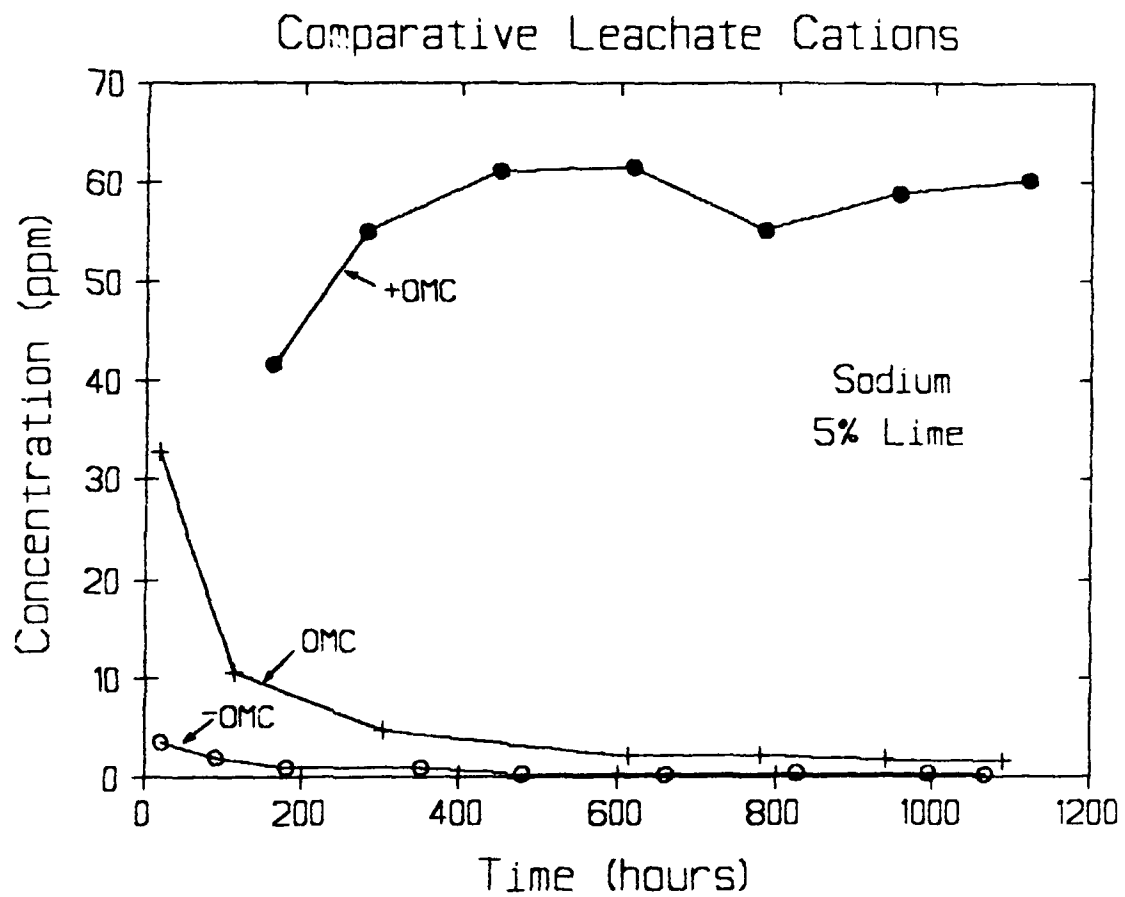in Site No. 2 leachates at 3% lime.

Figure C18. Moisture content effects on sodium in Site No. 2 leachates at 5% lime.
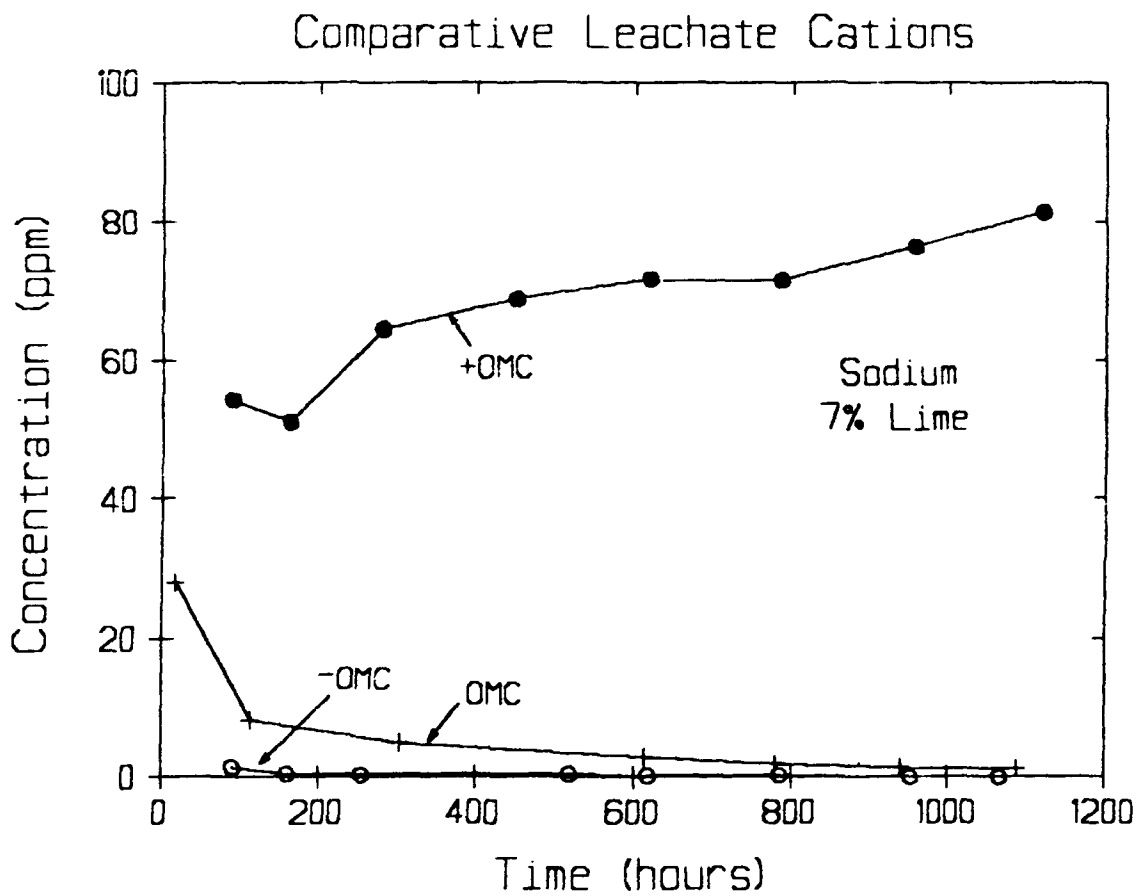
Figure C19. Moisture content effects on sodium
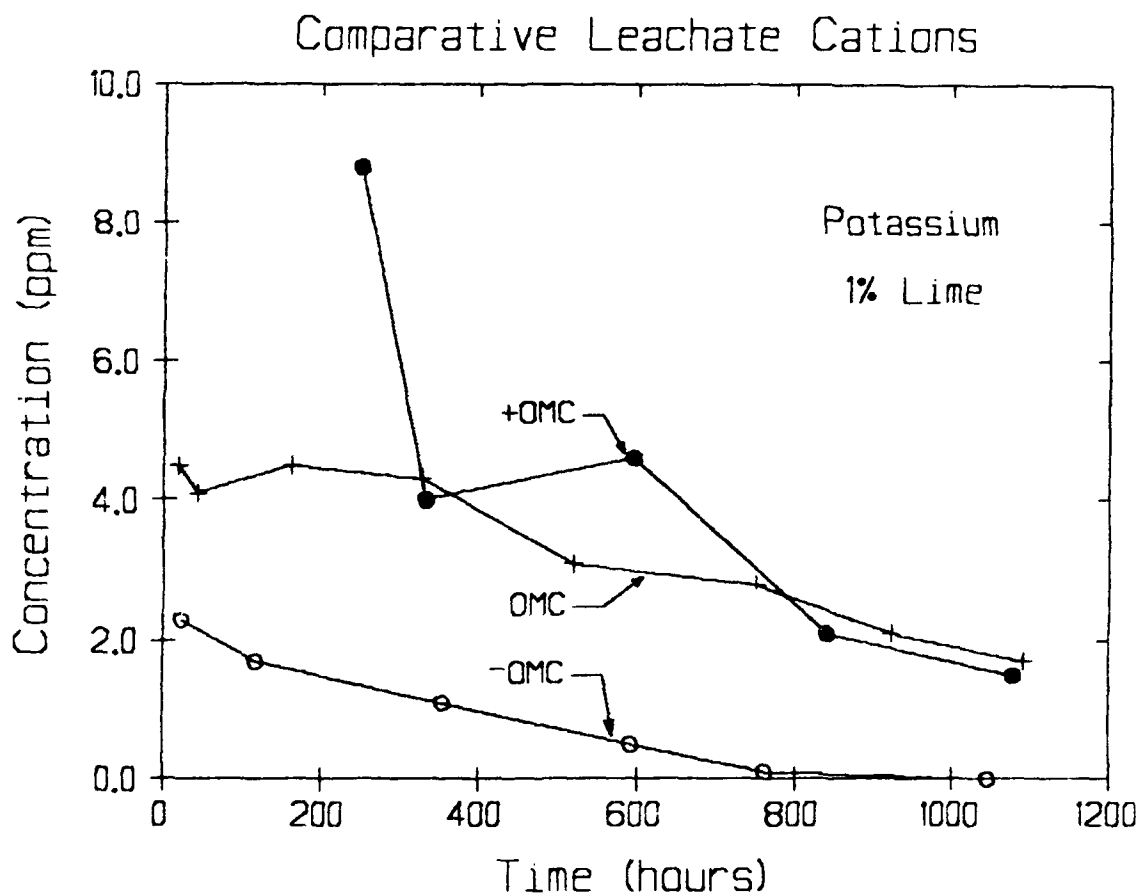in Site No. 2 leachates at 7% lime.

Figure C20. Moisture content effects on potassium in Site No. 1 leachates at 1% lime.

Figure C21. Moisture content effects on potassium in Site No. 1 leachates at 3% lime.

Figure C22.   Moisture content effects on potassium
in Site No. 1 leachates at 4% lime.

Figure C23. Moisture content effects on potassium
in Site No. 1 leachates at 6% lime.

Figure C24. Moisture content effects on potassium
in Site No. 2 leachates at 1% lime.

Figure C25.   Moisture content effects on potassium
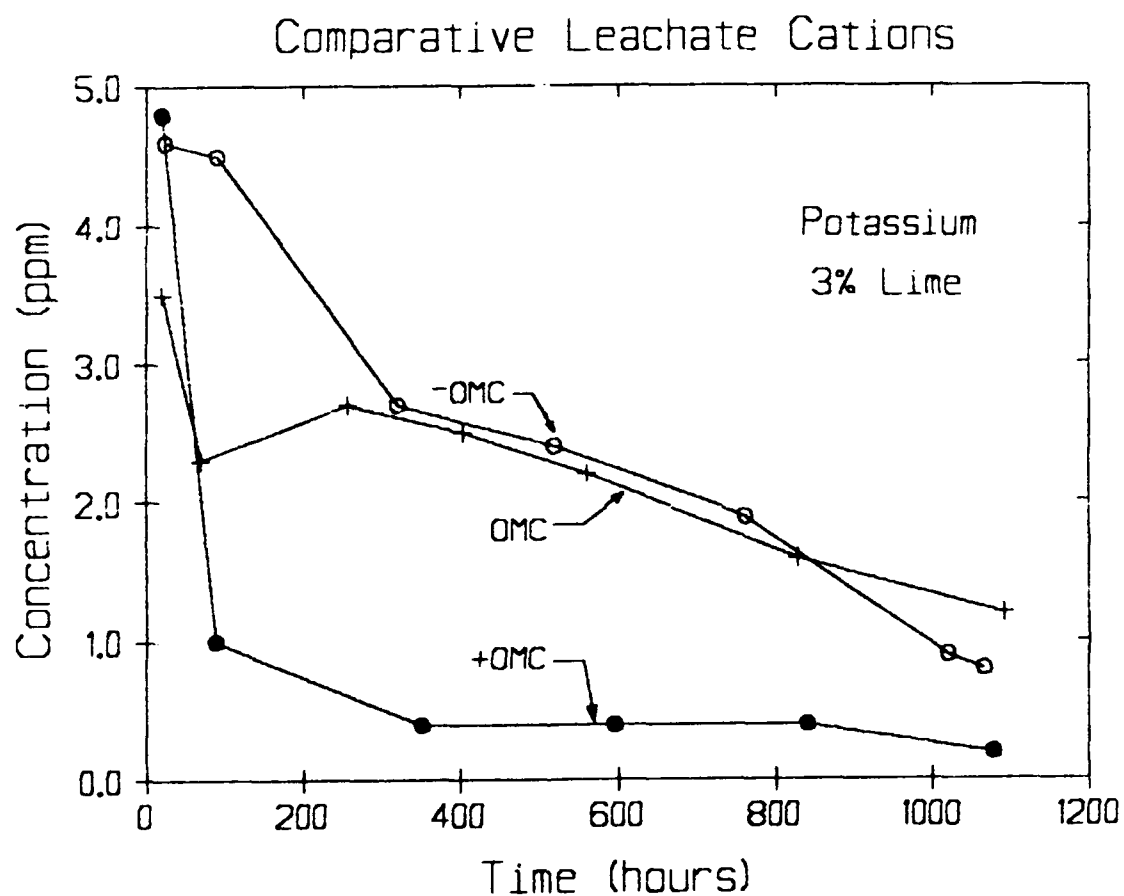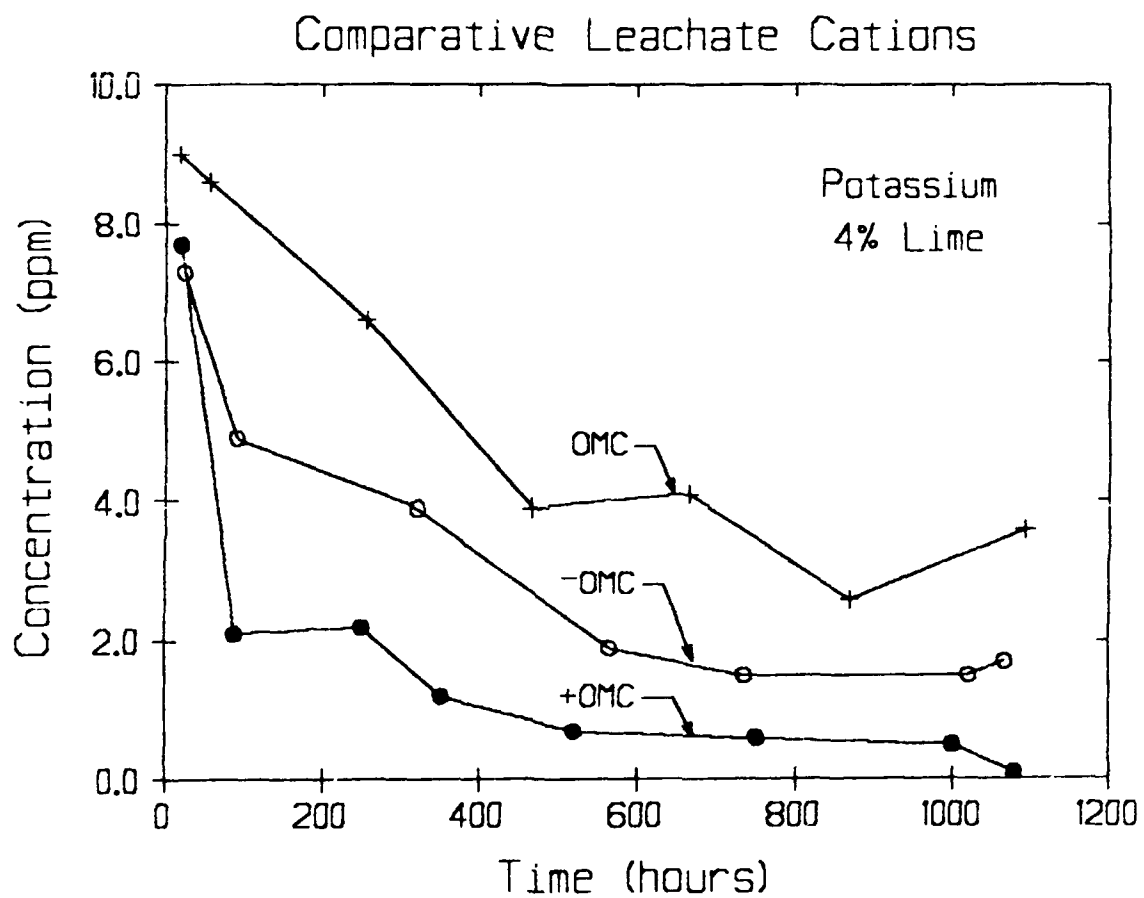in Site No. 2 leachates at 3% lime.

Figure C26. Moisture content effects on potassium
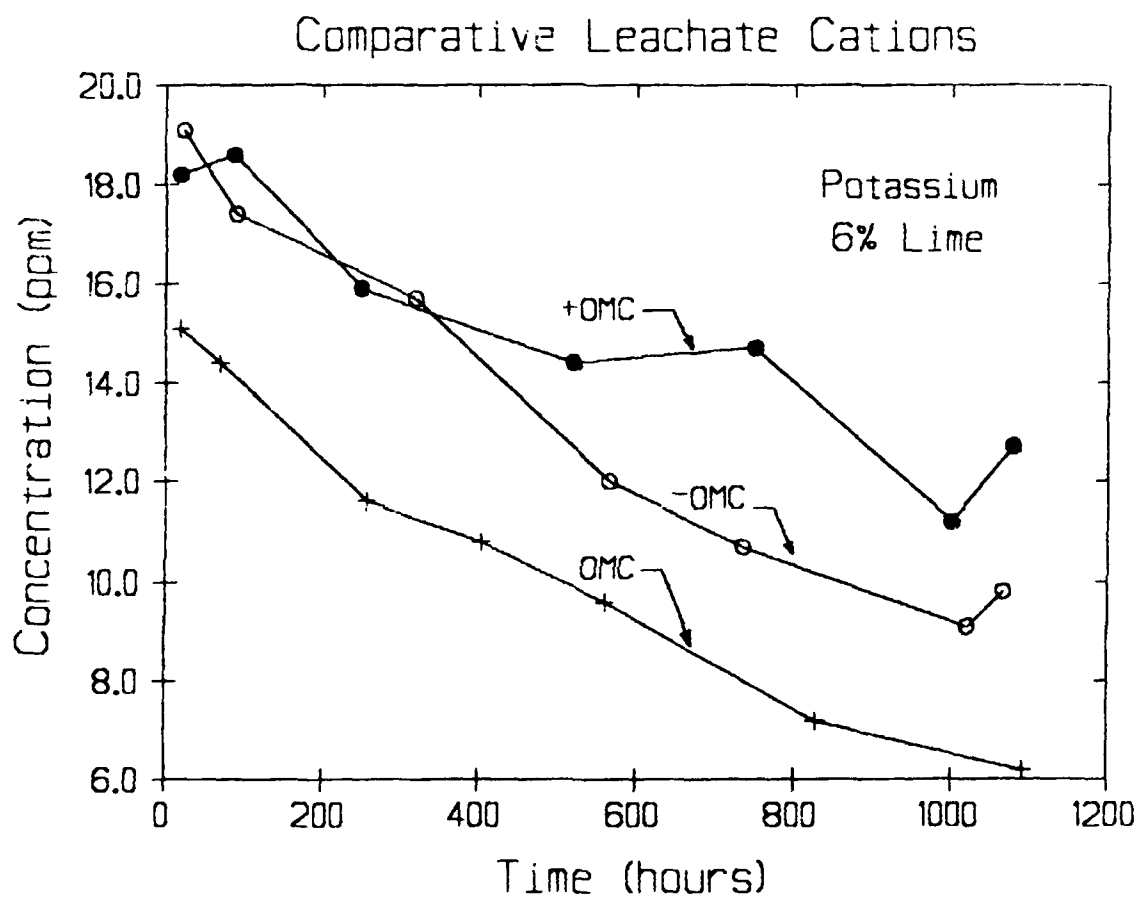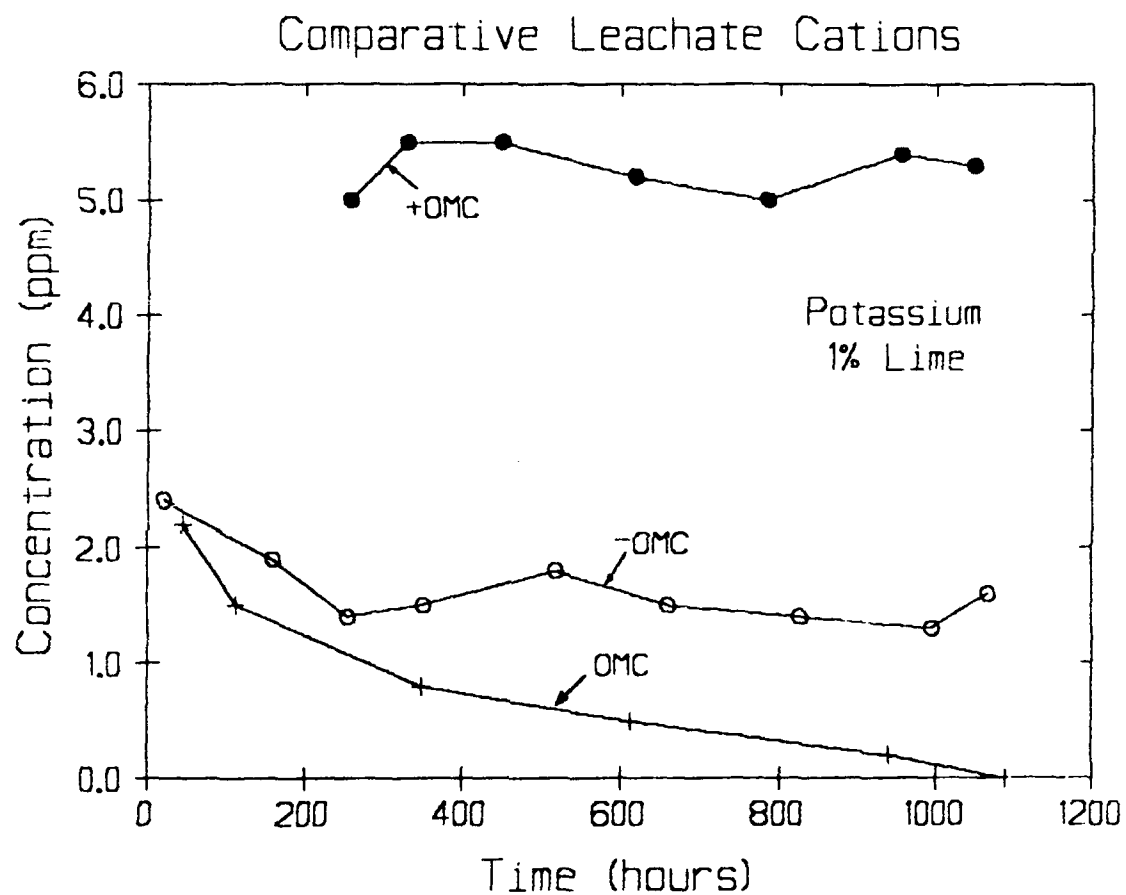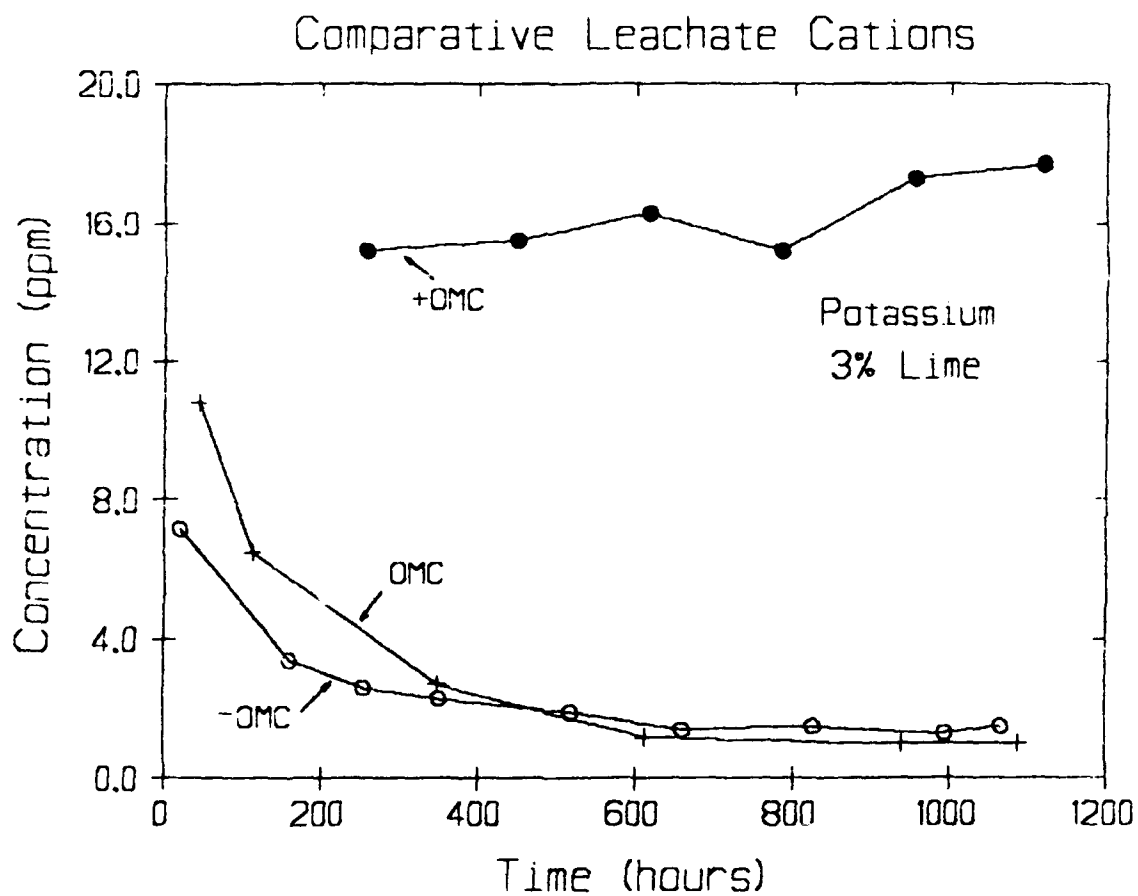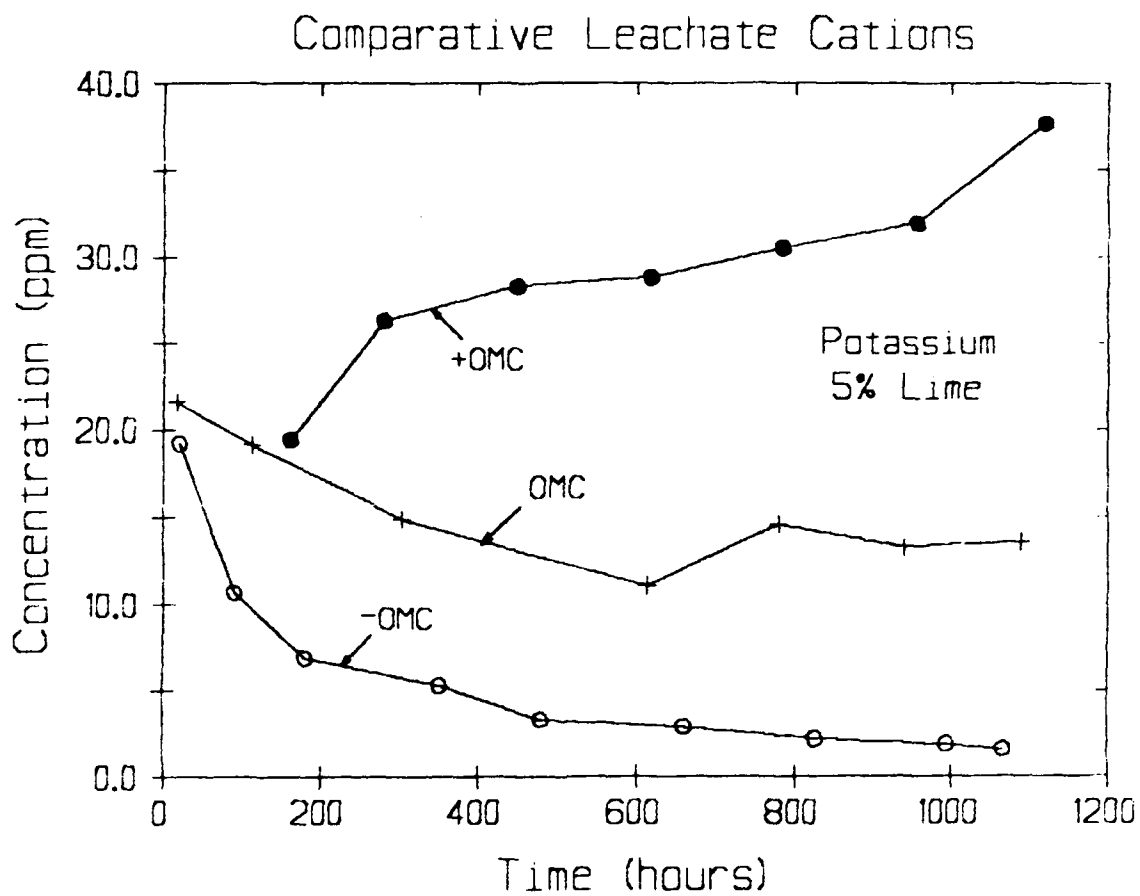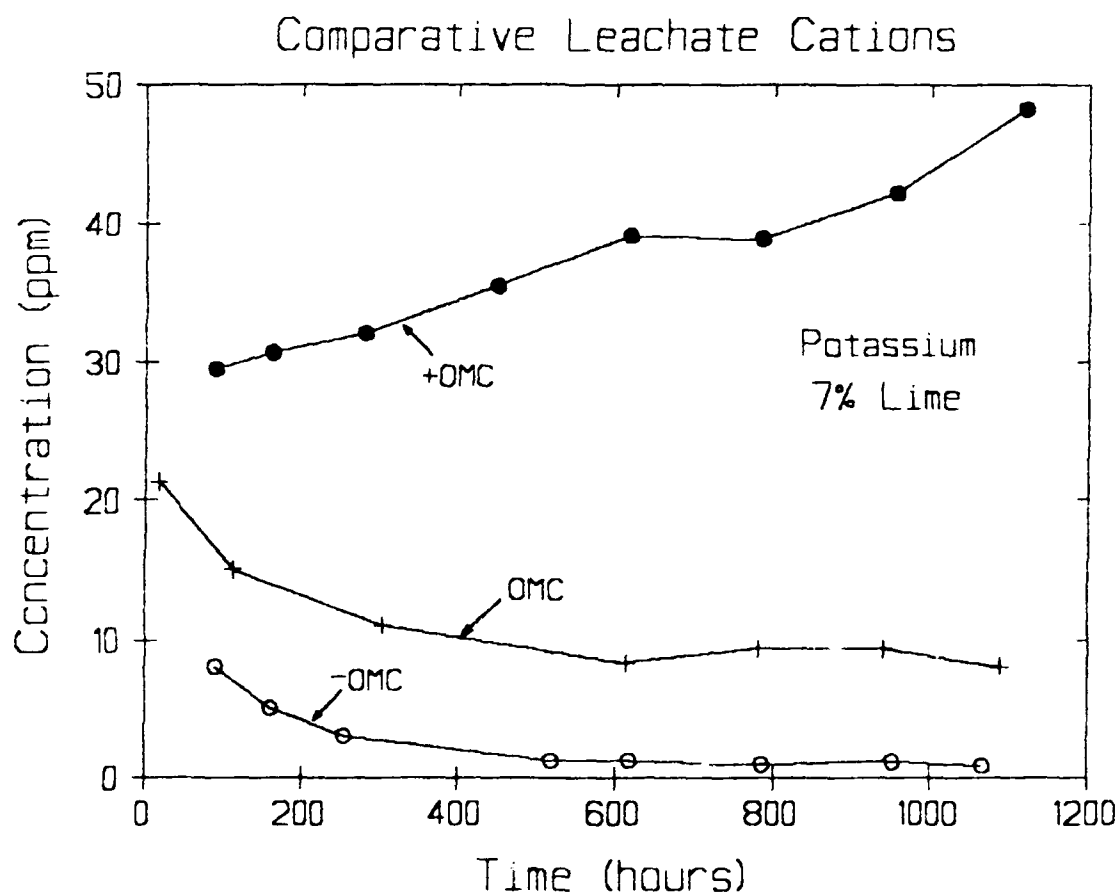in Site No. 2 leachates at 5% lime.

Figure C27. Moisture content effects on potassium
in Site No. 2 leachates at 7% lime.

APPENDIX D

TABLES OF PHYSICAL AND CHEMICAL CHANGES
FOR WET AND DRY SAMPLES

TABLE D1

SITE NO. 1, PHYSICAL PROPERTY CHANGES FOR SAMPLES COMPACTED DRY
(-8% < OMC < -3%)

Physical Property	1% Lime		3% Lime		4% Lime		6% Lime	
	B*	A45	B	A45	B	A45	B	A45
Dry Unit Weight (pcf)	89.8	--	87.4	--	88.6	--	88.1	--
Percent Max. Weight (%)	93.1	--	96.6	--	100.0	--	100.7	--
Moisture Content (%)	20.6	33.0	22.5	35.9	22.6	38.9	23.4	34.5
Percent OMC (%)	-4.9	+7.5	-5.5	+7.9	-5.9	+10.5	-6.1	+.0
Degree of Saturation (%)	62.2	99.8	64.6	+100.0	66.4	+100.0	68.2	+100.0
Liquid Limit (%)	62	63	60	55	56	54	59	54
Plastic Limit (%)	40	33	47	38	46	38	46	40
Plasticity Index (%)	22	30	13	17	10	16	13	14
Linear Shrinkage (%)	18.1	16.6	9.1	9.9	7.1	6.7	8.7	5.5
Trimmed Samples								
Swell Pressure (psf)	389.2	506.1	197.6	197.8	197.0	202.2	154.1	173.8
Free Swell (%)	0.74	1.09	0.34	0.18	0.20	0.17	0.14	0.20
Shear Strength (ksf)	13.47	11.10	29.08	11.55	46.50	28.39	55.26	39.12
Failure Strain (%)	2.07	2.13	1.57	1.09	1.80	1.40	1.96	1.70
Reworked Samples								
Swell Pressure (psf)	--	543.1	--	680.0	--	289.0	--	271.6
Free Swell (%)	--	1.33	--	1.34	--	0.65	--	0.36
Shear Strength (ksf)	12.32	10.31	9.71	10.39	6.01	9.40	5.40	7.30
Failure Strain (%)	2.46	2.97	2.16	3.69	3.60	2.43	1.66	1.26

* B = Before leaching; A45 = After leaching 45 days.

D2

TABLE D2

SITE NO. 1, PHYSICAL PROPERTY CHANGES FOR SAMPLES COMPACTED WET
(+3% < OMC < +8%)

Physical Property	1% Lime		3% Lime		4% Lime		6% Lime	
	B*	A45	B	A45	B	A45	B	A45
Dry Unit Weight (pcf)	89.8	--	81.6	--	81.4	--	81.9	--
Percent Max. Weight (%)	98.3	--	90.3	--	92.0	--	93.6	--
Moisture Content (%)	30.6	33.5	33.9	40.8	33.2	43.2	34.8	41.5
Percent OMC (%)	+5.1	+8.0	+5.9	+12.8	+4.7	+14.7	+5.3	+12.0
Degree of Saturation (%)	91.6	99.8	84.7	+100	82.6	+100	87.4	+100
Liquid Limit (%)	62	63	60	59	56	58	59	56
Plastic Limit (%)	40	33	47	39	46	40	46	41
Plasticity Index (%)	22	30	13	20	10	18	13	15
Linear Shrinkage (%)	18.1	15.2	9.1	10.4	7.1	7.7	8.7	4.5
Trimmed Samples								
Swell Pressure (psf)	389.2	549.6	197.6	262.9	197.0	293.3	154.1	232.5
Free Swell (%)	0.74	0.93	0.34	0.52	0.20	0.49	0.14	0.36
Shear Strength (ksf)	13.47	20.65	29.08	36.51	46.50	44.35	55.26	58.41
Failure Strain (%)	2.07	3.46	1.57	2.33	1.80	2.44	1.96	2.49
Reworked Samples								
Swell Pressure (psf)	--	708.2	--	527.9	--	738.6	--	256.4
Free Swell (%)	--	1.94	--	0.77	--	1.04	--	0.27
Shear Strength (ksf)	12.32	10.44	9.71	10.23	6.01	9.70	5.40	7.64
Failure Strain (%)	2.46	2.25	2.16	1.70	3.60	1.41	1.66	1.25

* B = Before leaching; A45 = After leaching 45 days

D3

TABLE D3

SITE NO. 2, PHYSICAL PROPERTY CHANGES FOR SAMPLES COMPACTED DRY
(-3% < OMC < -8%)

Physical Property	1% Lime		3% Lime		5% Lime		7% Lime	
	B*	A45	B	A45	B	A45	B	A45
Dry Unit Weight (pcf)	89.8	--	89.0	--	89.3	--	87.7	--
Percent Max. Weight (%)	92.1	--	94.2	--	95.0	--	93.7	--
Moisture Content (%)	18.4	33.2	20.8	34.7	22.8	34.6	22.6	36.2
Percent OMC (%)	-5.6	+9.2	-5.7	+8.2	-4.3	+7.6	-4.9	+8.7
Degree of Saturation (%)	56.3	+100.0	62.4	+100.0	68.9	+100.0	65.9	+100.0
Liquid Limit (%)	49	40	45	43	48	48	47	49
Plastic Limit (%)	33	21	32	27	34	34	34	32
Plasticity Index (%)	16	19	13	16	14	14	13	17
Linear Shrinkage (%)	5.9	12.8	3.1	9.1	5.5	7.5	5.5	9.4
Trimmed Samples								
Swell Pressure (psf)	458.4	210.7	301.3	180.3	258.5	206.4	232.4	215.1
Free Swell (%)	1.82	0.26	0.17	0.15	0.17	0.17	0.11	0.25
Shear Strength (ksf)	16.12	4.54	25.47	4.83	26.51	15.89	27.41	6.62
Failure Strain (%)	1.08	2.25	1.17	1.91	1.32	1.35	1.51	1.44
Reworked Samples								
Swell Pressure (psf)	--	393.2	--	289.6	--	282.4	--	271.6
Free Swell (%)	--	1.00	--	1.20	--	0.84	--	0.36
Shear Strength (ksf)	9.21	4.52	8.78	5.95	10.67	6.45	15.20	6.01
Failure Strain (%)	2.16	5.01	2.16	4.21	1.35	5.01	1.40	3.04

* B = Before leaching; A45 = After leaching 45 days

D4

TABLE D4

SITE NO. 2, PHYSICAL PROPERTY CHANGES FOR SAMPLES COMPACTED WET
(+3% < OMC < +8%)

Physical Property	1% Lime		3% Lime		5% Lime		7% Lime	
	B*	A45	B	A45	B	A45	B	A45
Dry Unit Weight (pcf)	90.9	--	86.7	--	87.7	--	86.1	--
Percent Max. Weight (%)	93.2	--	91.6	--	93.5	--	92.0	--
Moisture Content (%)	29.4	32.2	32.7	34.7	30.8	36.7	32.7	37.2
Percent OMC (%)	+5.4	+8.2	+6.2	+8.2	+3.8	+9.7	+5.2	+9.7
Degree of Saturation (%)	92.0	+100.0	92.9	+100.0	90.2	+100.0	91.7	+100.0
Liquid Limit (%)	49	49	45	48	48	48	47	46
Plastic Limit (%)	33	27	32	33	34	35	34	36
Plasticity Index (%)	16	22	13	15	14	13	13	10
Linear Shrinkage (%)	5.9	14.2	3.1	6.5	5.5	5.5	5.5	3.5
Trimmed Samples								
Swell Pressure (psf)	458.4	395.4	301.3	308.6	258.5	206.4	232.4	254.2
Free Swell (%)	1.82	0.52	0.17	0.33	0.17	0.17	0.11	0.26
Shear Strength (ksf)	16.12	10.27	25.47	19.09	26.51	28.77	27.41	25.36
Failure Strain (%)	1.08	2.68	1.17	2.10	1.32	2.29	1.51	2.37
Reworked Samples								
Swell Pressure (psf)	--	401.9	--	375.9	--	245.5	--	223.8
Free Swell (%)	--	1.41	--	0.88	--	0.39	--	0.21
Shear Strength (ksf)	9.21	5.52	8.78	8.66	10.67	7.07	15.20	6.10
Failure Strain (%)	2.16	4.92	2.16	1.52	1.35	1.43	1.40	1.50

* B = Before leaching; A45 = After leaching 45 days

D5

TABLE D5

SITE NO. 1, CHEMICAL PROPERTY CHANGES FOR SAMPLES COMPACTED DRY
(-8% < OMC < -3%)

Chemical Property	1% Lime		3% Lime		4% Lime		6% Lime	
	B*	A45	B	A45	B	A45	B	A45
EDTA Titration (ml)	9.3	6.3	9.7	5.6	11.9	7.1	16.3	9.4
Soil pH	11.18	10.11	12.26	10.95	12.45	11.37	12.49	11.96
Porewater Cations (meq/l)								
Calcium	11.51	1.94	8.99	5.48	11.10	11.78	5.43	9.66
Sodium	5.01	0.22	3.93	0.21	4.56	0.24	4.36	0.39
Magnesium	0.12	0.18	0.13	0.13	0.13	0.19	0.03	0.14
Potassium	0.23	0.21	0.25	0.19	0.29	0.22	0.23	0.28
Exchange Complex Cations (meq/100 g)								
Calcium	35.22	34.15	45.13	40.00	46.02	42.75	54.02	47.80
Sodium	1.16	0.14	1.11	0.10	1.25	0.12	0.12	0.15
Magnesium	0.55	0.52	1.03	0.86	1.17	1.01	1.17	1.01
Potassium	0.58	0.63	0.60	0.58	0.64	0.55	0.67	0.58

* B = Before leaching; A45 = After leaching 45 days

D6

TABLE D6

SITE NO. 1, CHEMICAL PROPERTY CHANGES FOR SAMPLES COMPACTED DRY
(+3% < OMC < +8%)

Chemical Property	1% Lime		3% Lime		4% Lime		6% Lime	
	B*	A45	B	A45	B	A45	B	A45
EDTA Titration (ml)	8.5	6.2	5.9	6.4	6.3	7.4	10.4	10.7
Soil pH	10.54	10.68	11.73	10.85	12.00	11.25	12.42	11.96
Porewater Cations (meq/l)								
Calcium	13.20	14.38	12.07	9.96	12.85	10.99	10.81	9.14
Sodium	4.55	4.43	4.87	0.73	4.83	0.64	6.32	3.83
Magnesium	0.17	0.22	0.17	0.17	0.17	0.15	0.14	0.15
Potassium	0.24	0.31	0.34	0.26	0.42	0.30	0.50	0.52
Exchange Complex Cations (meq/100 g)								
Calcium	32.71	32.82	39.85	35.93	43.62	40.45	48.39	46.71
Sodium	1.06	0.95	1.12	0.18	1.15	0.17	1.34	0.88
Magnesium	0.46	0.45	0.96	0.90	1.07	1.00	1.36	1.28
Potassium	0.72	0.73	0.70	0.64	0.72	0.66	0.82	0.85

* B = Before leaching; A45 = After leaching 45 days

D7

TABLE D7

SITE NO. 2, CHEMICAL PROPERTY CHANGES FOR SAMPLES COMPACTED DRY
(-8% < OMC < -3%)

Chemical Property	1% Lime		3% Lime		5% Lime		7% Lime	
	B*	A45	B	A45	B	A45	B	A45
Soil pH	12.02	9.07	12.28	9.26	12.49	11.25	12.59	11.45
Porewater Cations (meq/l)								
Calcium	1.82	1.85	2.20	1.36	2.80	2.39	3.71	1.67
Sodium	0.39	0.06	0.45	0.06	0.70	0.08	0.46	0.09
Magnesium	0.14	0.13	0.14	0.13	0.07	0.13	0.09	0.17
Potassium	0.11	0.06	0.10	0.05	0.17	0.05	0.12	0.04
Exchange Complex Cations (meq/100 g)								
Calcium	21.69	20.85	23.70	20.83	25.23	24.26	27.49	22.12
Sodium	0.07	0.0	0.08	0.0	0.10	0.0	0.08	0.01
Magnesium	0.44	0.36	0.76	0.46	0.82	0.77	0.68	0.65
Potassium	0.28	0.20	0.30	0.19	0.31	0.16	0.27	0.14

* B = Before leaching; A45 = After leaching 45 days

TABLE D8

SITE NO. 2, CHEMICAL PROPERTY CHANGES FOR SAMPLES COMPACTED WET
(+3% < OMC < +8%)

Chemical Property	1% Lime		3% Lime		5% Lime		7% Lime	
	B*	A45	B	A45	B	A45	B	A45
Soil pH	11.32	10.79	12.57	11.83	12.61	12.27	12.64	12.51
Porewater Cations (meq/l)								
Calcium	2.01	1.92	2.39	2.27	2.17	2.99	3.43	4.11
Sodium	0.41	0.32	0.43	0.38	0.44	0.32	0.44	0.33
Magnesium	0.12	0.13	0.15	0.16	0.11	0.11	0.10	0.14
Potassium	0.10	0.10	0.12	0.12	0.12	0.11	0.13	0.14
Exchange Complex Cations (meq/100 g)								
Calcium	21.35	21.05	24.85	24.37	24.28	24.60	27.42	27.93
Sodium	0.03	0.02	0.05	0.04	0.06	0.03	0.07	0.05
Magnesium	0.31	0.27	0.66	0.64	0.62	0.58	0.66	0.61
Potassium	0.25	0.28	0.31	0.32	0.28	0.28	0.33	0.30

* B = Before leaching; A45 = After leaching 45 days

D9

TABLE D9

SITE NO. 1, STATISTICAL RESULTS FOR SAMPLES COMPACTED WET AND DRY

Property	1% Lime -OMC*	1% Lime +OMC	3% Lime -OMC	3% Lime +OMC	4% Lime -OMC	4% Lime +OMC	6% Lime -OMC	6% Lime +OMC
Physical								
Liquid Limit	IE**	IE	SS	IE	SS	IE	SS	SS
Plastic Limit	SS	SS	SS	SS	SS	SS	SS	SS
Plasticity Index	SS	SS	SS	SS	SS	SS	IE	SS
Linear Shrinkage	IE	IE	IE	IE†	IE	IE	SS	IE
Trimmed Samples								
Swell Pressure	IE†	SS	IE	SS	IE	SS	IE	SS
Free Swell	IE†	IE	IE	IE†	IE	SS	IE	SS
Shear Strength	IE†	IE	SS	IE	SS	IE	SS	IE
Failure Strain	IE	IE	IE†	SS	SS	IE†	IE	IE
Reworked Samples								
Swell Pressure	SS	SS	SS	SS	SS	SS	SS	SS
Free Swell	SS	SS	SS	SS	SS	SS	SS	SS
Shear Strength	IE	SS	IE	IE	IE	IE	IE	IE
Failure Strain	IE	IE	IE	SS	IE	SS	SS	SS
Chemical								
Soil pH	IE†	IE	SS	SS	SS	SS	SS	SS
Porewater Cations (meq/l)								
Calcium	SS	IE	SS	IE†	IE	IE†	SS	IE†
Sodium	SS	IE	SS	SS	SS	SS	SS	SS
Magnesium	IE	IE	IE	IE	IE†	IE†	SS	IE
Potassium	IE	IE†	IE	IE	SS	IE†	IE	IE
Exchange Complex Cations (meq/100 g)								
Calcium	IE	IE	IE†	IE†	SS	IE	SS	IE
Sodium	SS	IE	SS	SS	SS	SS	SS	SS
Magnesium	IE	IE	SS	IE	SS	IE	IE†	IE
Potassium	IE	IE	IE	SS	SS	IE	IE†	IE

* -OMC = Compacted dry of optimum moisture, leached 45 days; +OMC = Compacted wet of optimum, leached 45 days.

** SS = Statistically significant at $\alpha = 0.05$; IE = Insufficient evidence to refute the null hypothesis ($\mu_1 = \mu_2$) at $\alpha = 0.05$.

† Statistically significant at $\alpha = 0.10$.

TABLE D10

SITE NO. 2, STATISTICAL RESULTS FOR SAMPLES COMPACTED WET AND DRY

Property	1% Lime		3% Lime		5% Lime		7% Lime	
	-OMC*	+OMC	-OMC	+OMC	-OMC	+OMC	-OMC	+OMC
Physical								
Liquid Limit	SS**	IE	IE	IE	IE	IE	IE†	IE†
Plastic Limit	SS	SS	IE	IE	IE	IE	SS	IE
Plasticity Index	IE†	SS	IE†	SS	IE	IE	SS	IE
Linear Shrinkage	SS	SS	SS	SS	IE†	IE	SS	IE
Trimmed Samples								
Swell Pressure	IE	IE	IE	IE	IE	IE	IE	IE
Free Swell	IE	IE	IE	SS	IE	IE	SS	SS
Shear Strength	SS	SS	SS	SS	SS	IE	SS	IE
Failure Strain	IE	SS	IE†	IE	IE	SS	IE	SS
Reworked Samples								
Swell Pressure	IE	IE	IE	SS	IE†	IE	IE	IE
Free Swell	IE	IE†	SS	SS	SS	SS	SS	IE†
Shear Strength	SS	SS	SS	IE	SS	SS	SS	SS
Failure Strain	SS	SS	IE	SS	SS	IE	IE	IE
Chemical								
Soil pH	SS	SS	SS	SS	SS	SS	SS	SS
Porewater Cations (meq/l)								
Calcium	IE	IE	SS	IE	SS	SS	SS	IE
Sodium	SS	IE	SS	IE	SS	IE†	SS	SS
Magnesium	IE	IE	IE	IE†	IE	IE	IE†	IE
Potassium	SS	IE	SS	IE	SS	IE	SS	IE
Exchange Complex Cations (meq/100 g)								
Calcium	IE	IE	SS	IE	IE	IE	SS	IE
Sodium	SS	IE	SS	IE	SS	SS	SS	IE†
Magnesium	SS	SS	SS	IE†	IE	SS	IE	IE†
Potassium	SS	IE	SS	IE	SS	IE	SS	IE

* -OMC = Compacted dry of optimum moisture, leached 45 days; +OMC = Compacted wet of optimum, leached 45 days.

** SS = Statistically significant at $\alpha = 0.05$; IE = Insufficient evidence to refute the null hypothesis ($\mu_1 = \mu_2$) at $\alpha = 0.05$.

† Statistically significant at $\alpha = 0.10$.

APPENDIX E

PHYSICAL AND CHEMICAL CHANGE GRAPHS
FOR WET AN DRY SAMPLES

Comparative Permeability
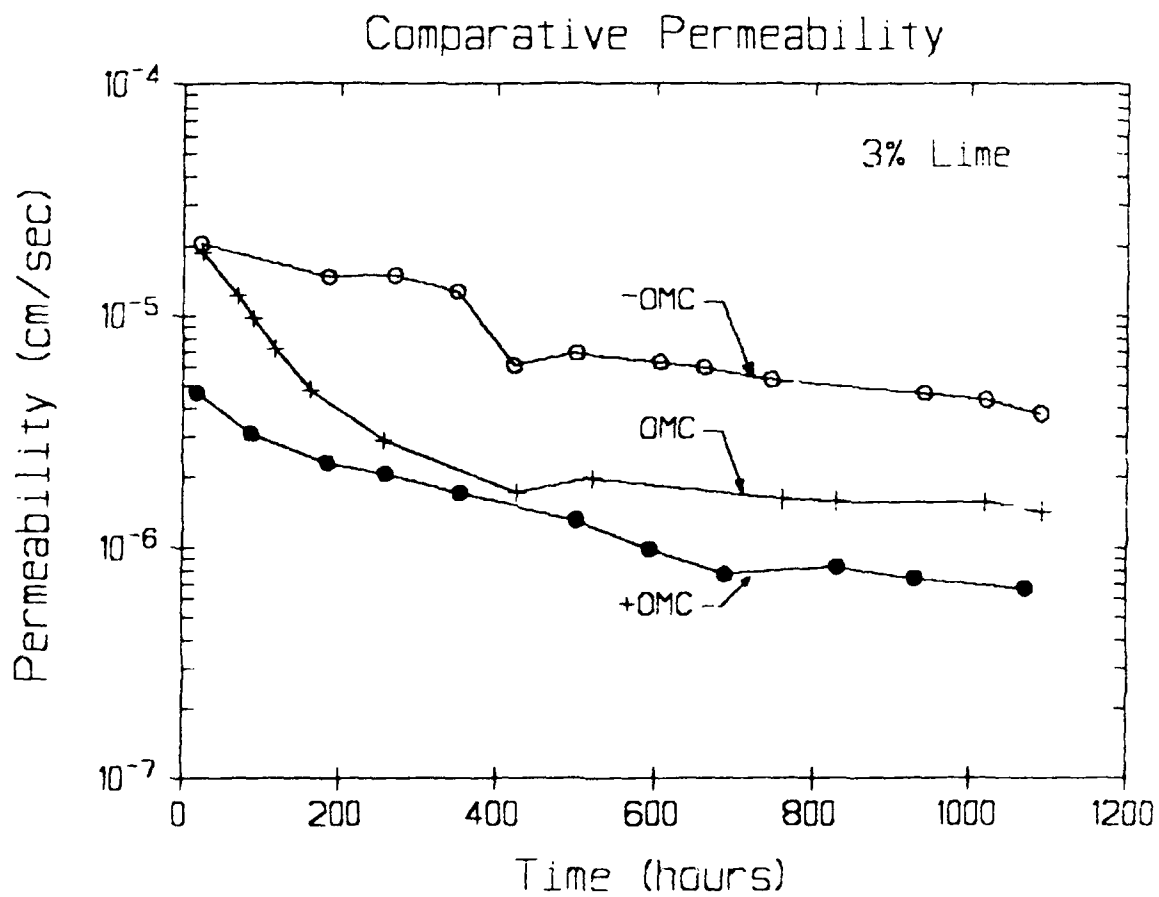
Figure E1. Moisture content effects on Site No. 1 permeability using 3% lime.
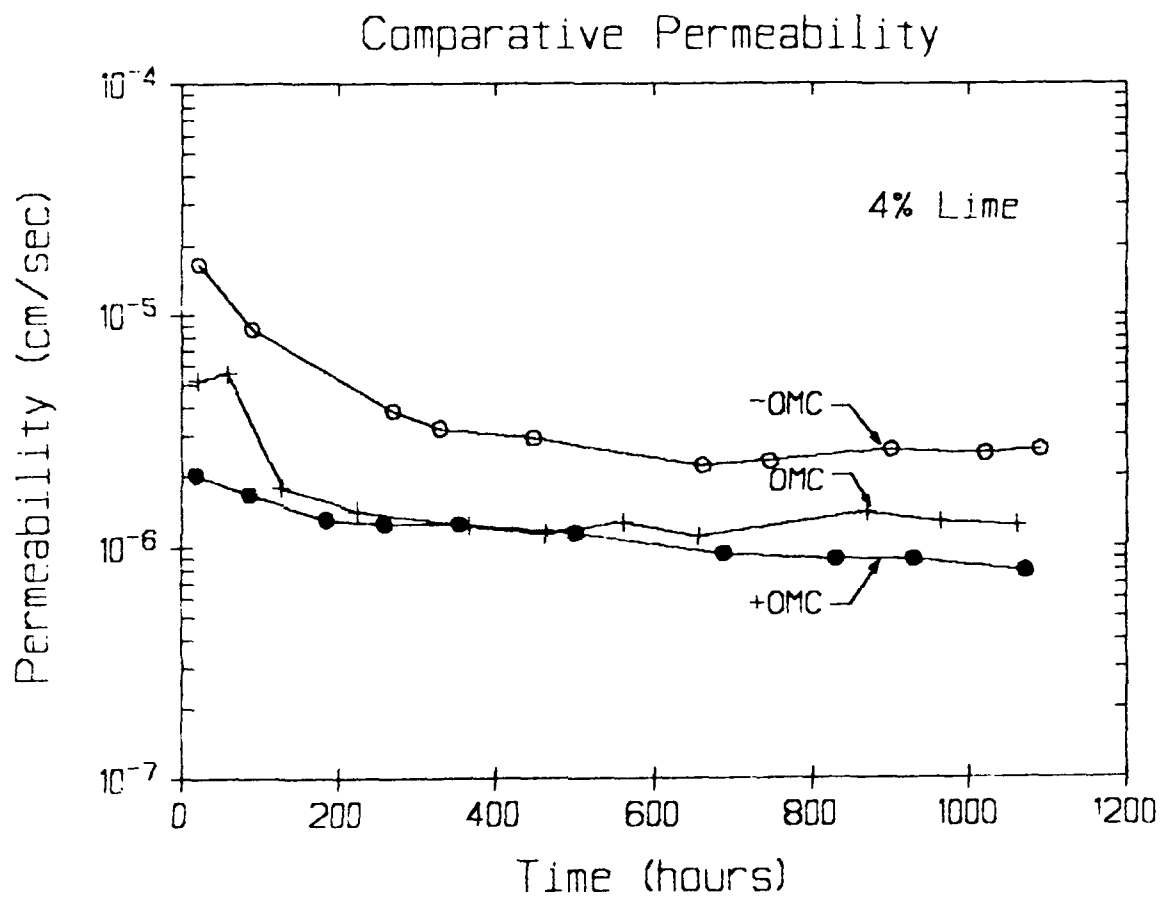
Figure E2. Moisture content effects on Site No. 1 permeability using 4% lime.
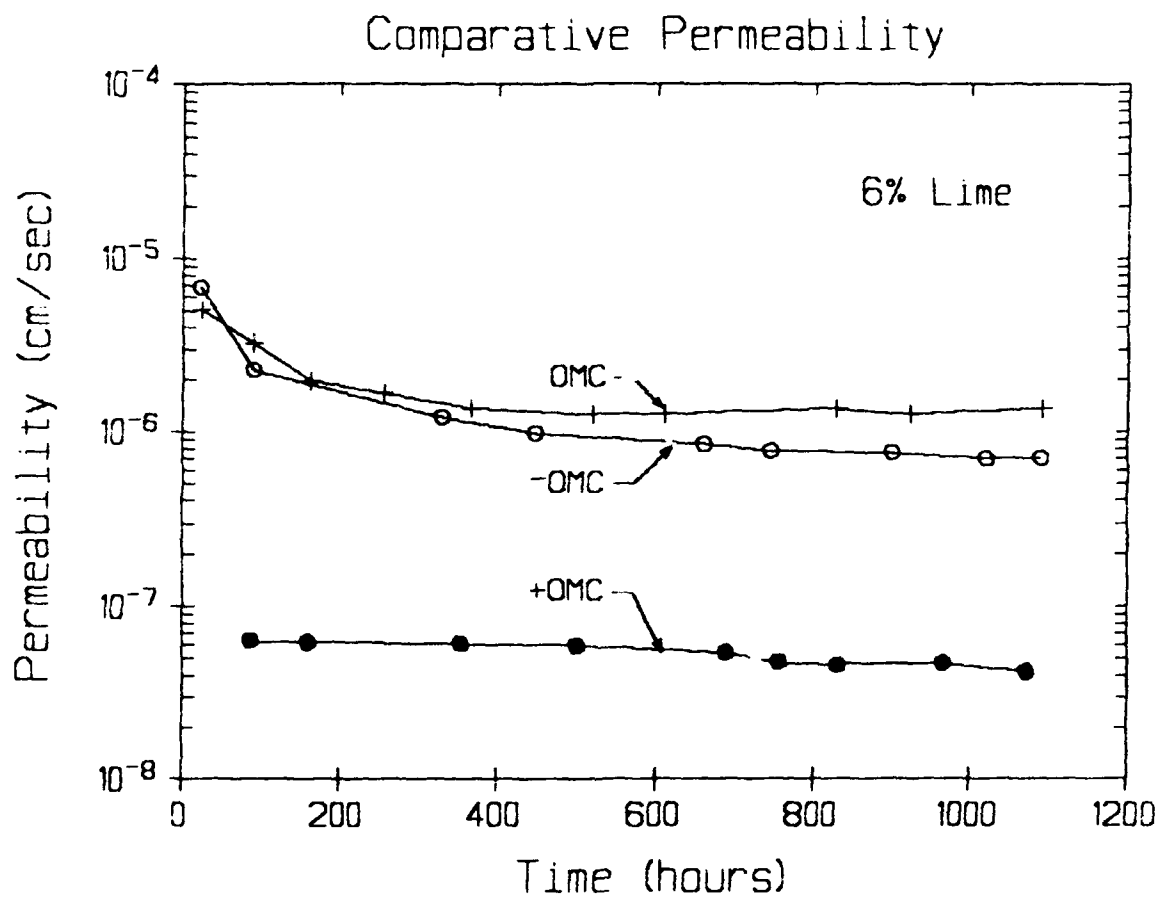
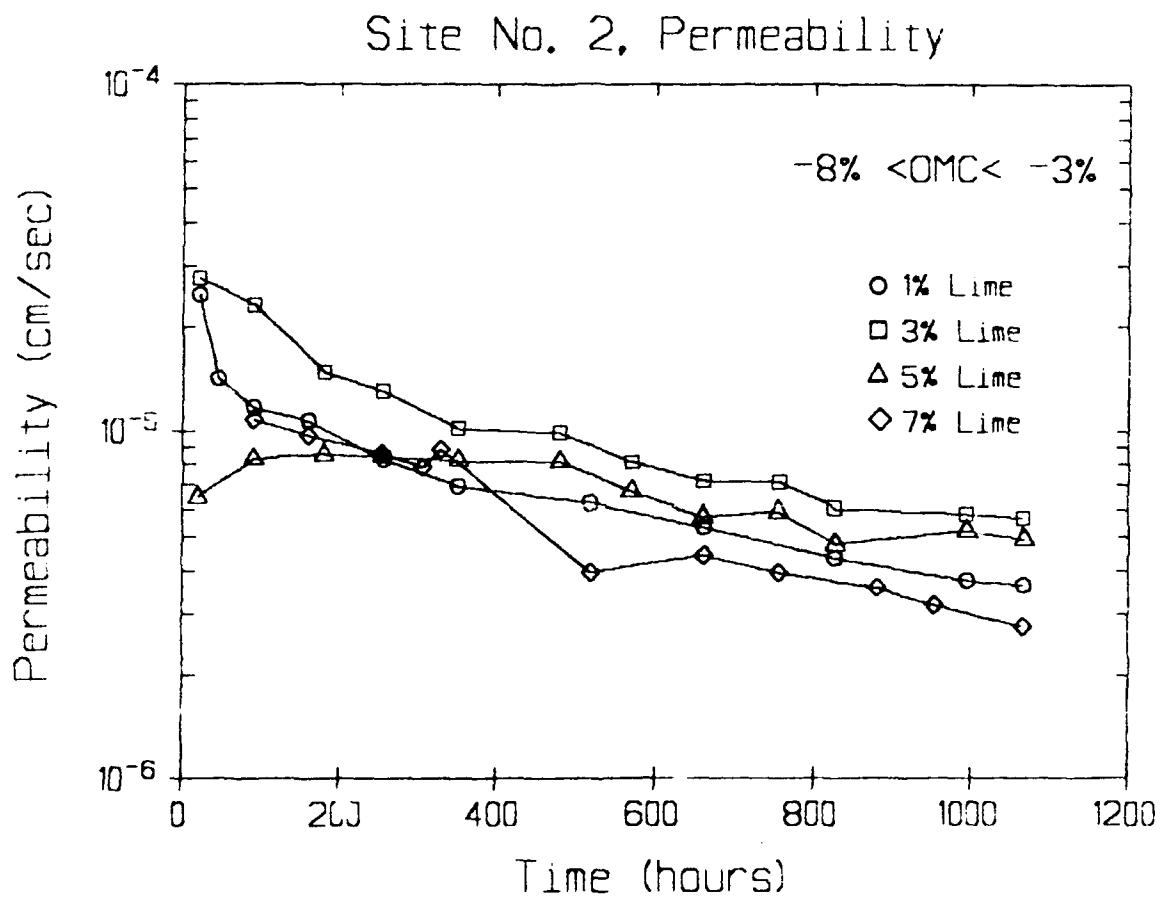Figure E3. Moisture content effects on Site No. 1
permeability using 6% lime.
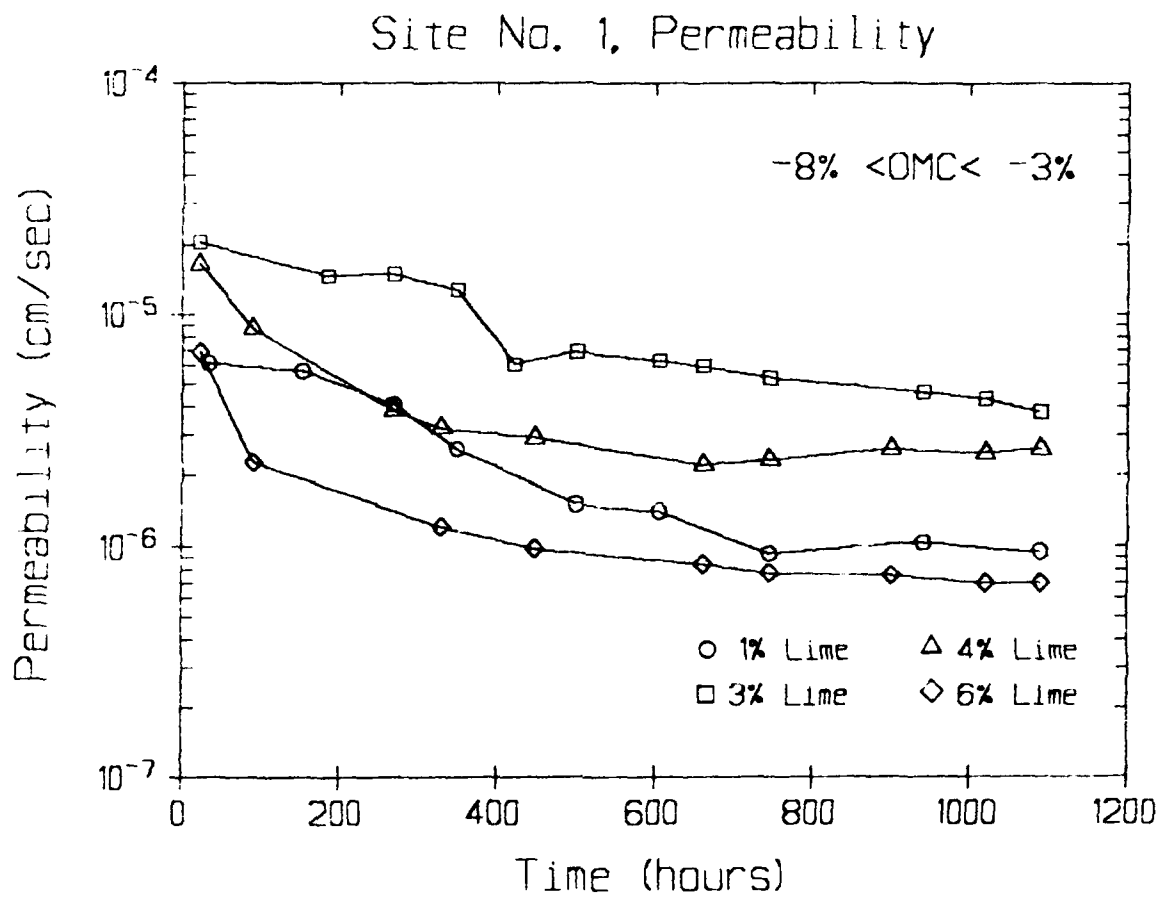
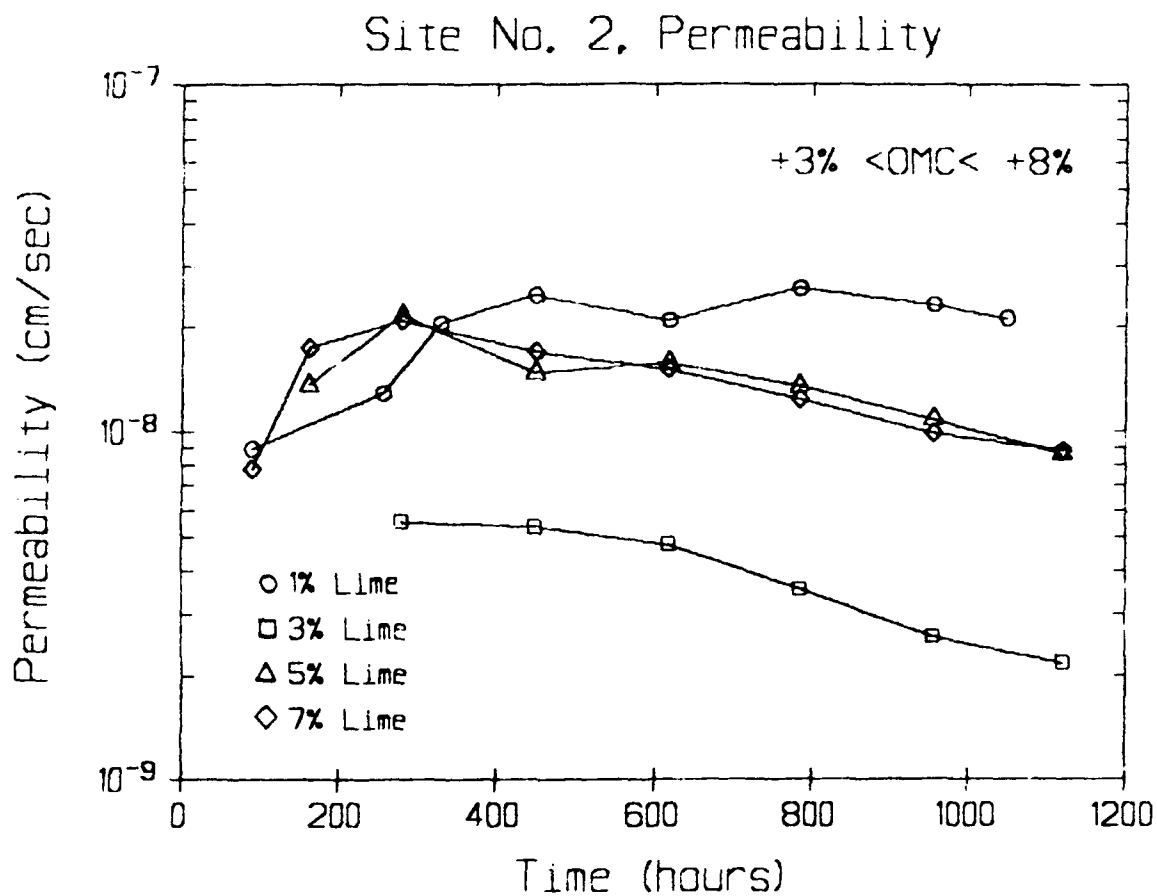Figure E4. Permeabilities of Site No. 1 samples compacted dry during 45 days of leaching.
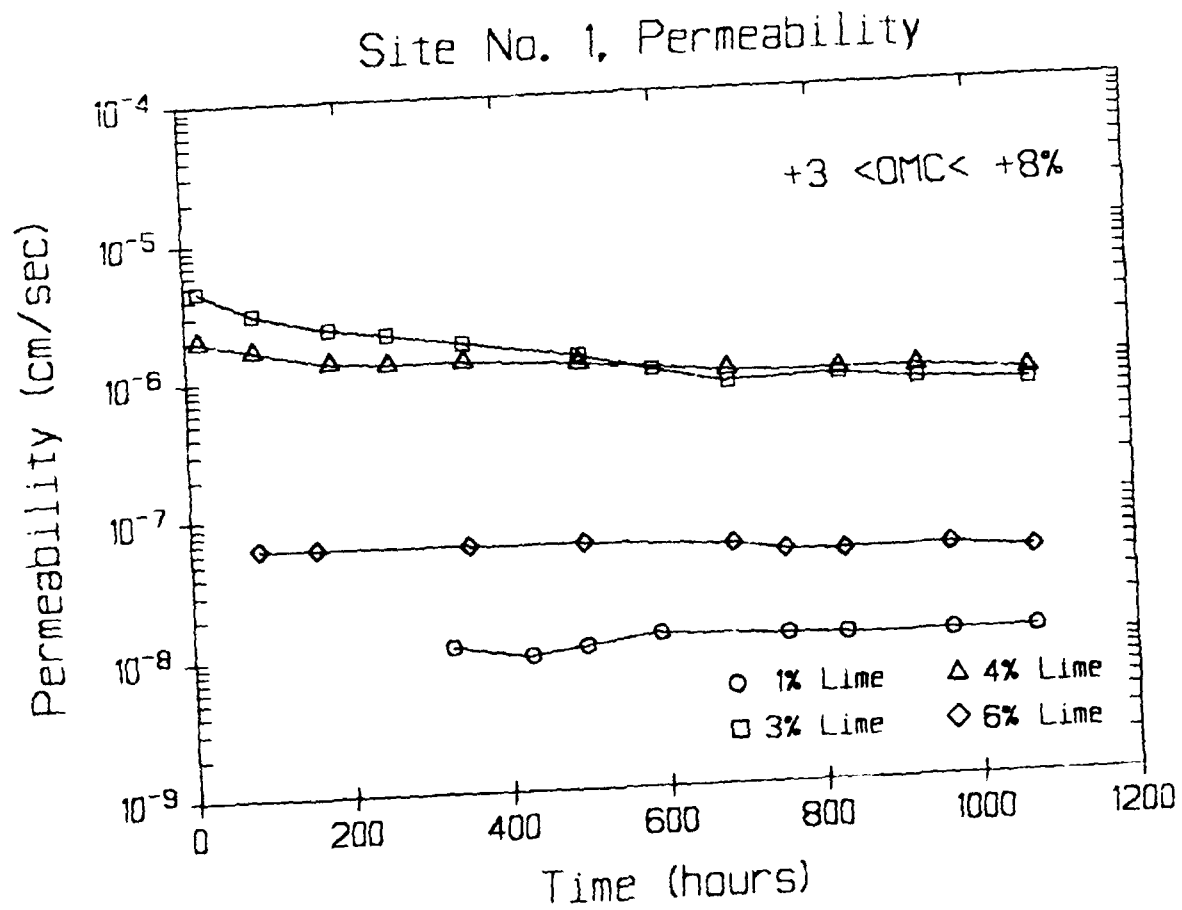
Figure E5. Permeabilities of Site No. 1 samples compacted wet during 45 days of leaching.
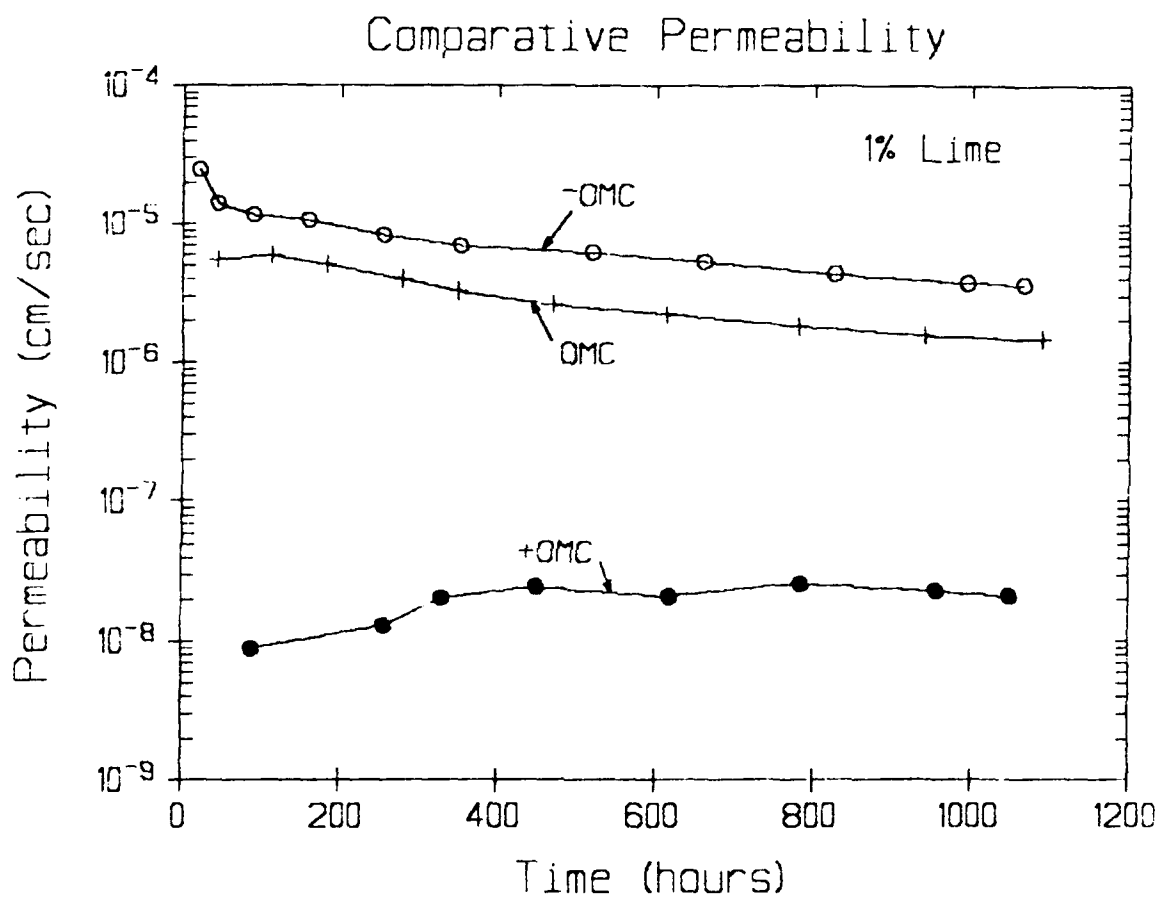
Figure E6. Moisture content effects on Site No. 2 permeability using 1% lime.
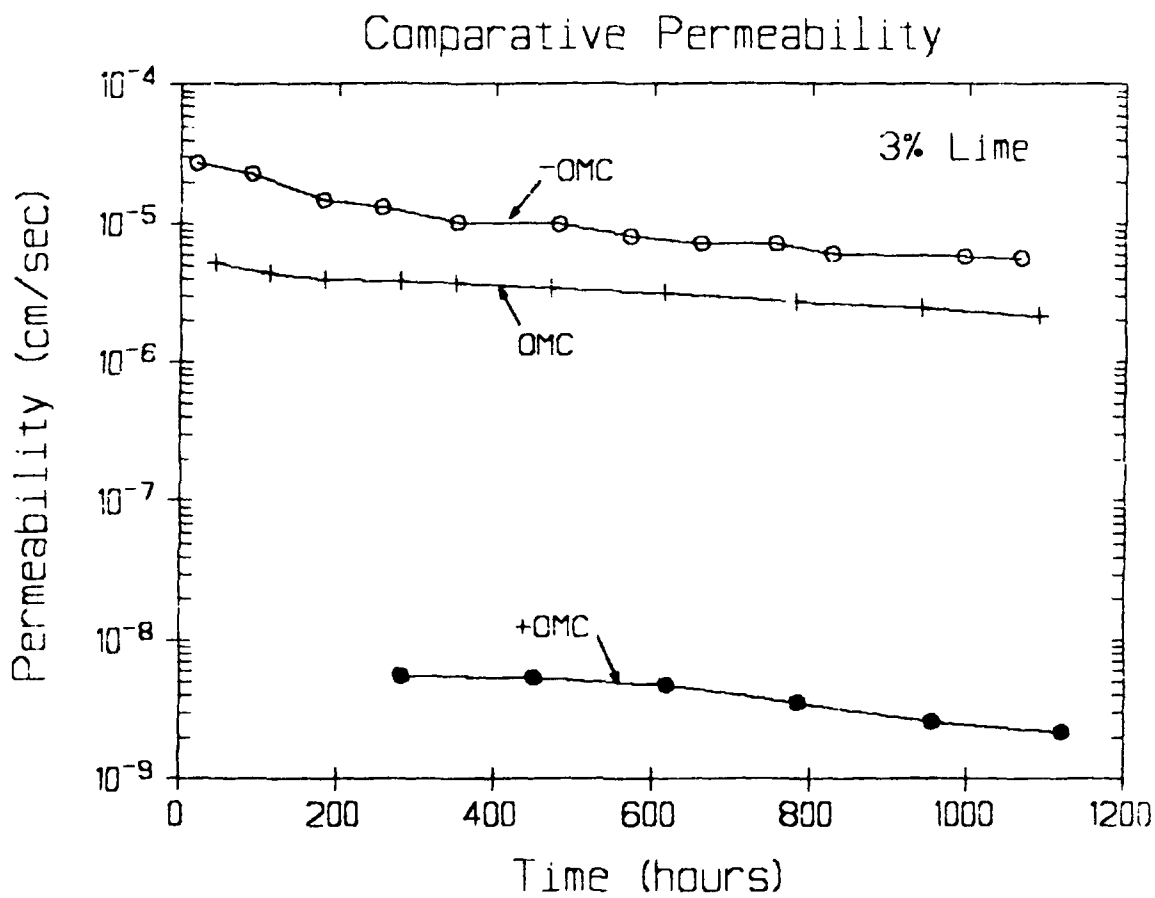
Figure E7. Moisture content effects on Site No. 2 permeability using 3% lime.
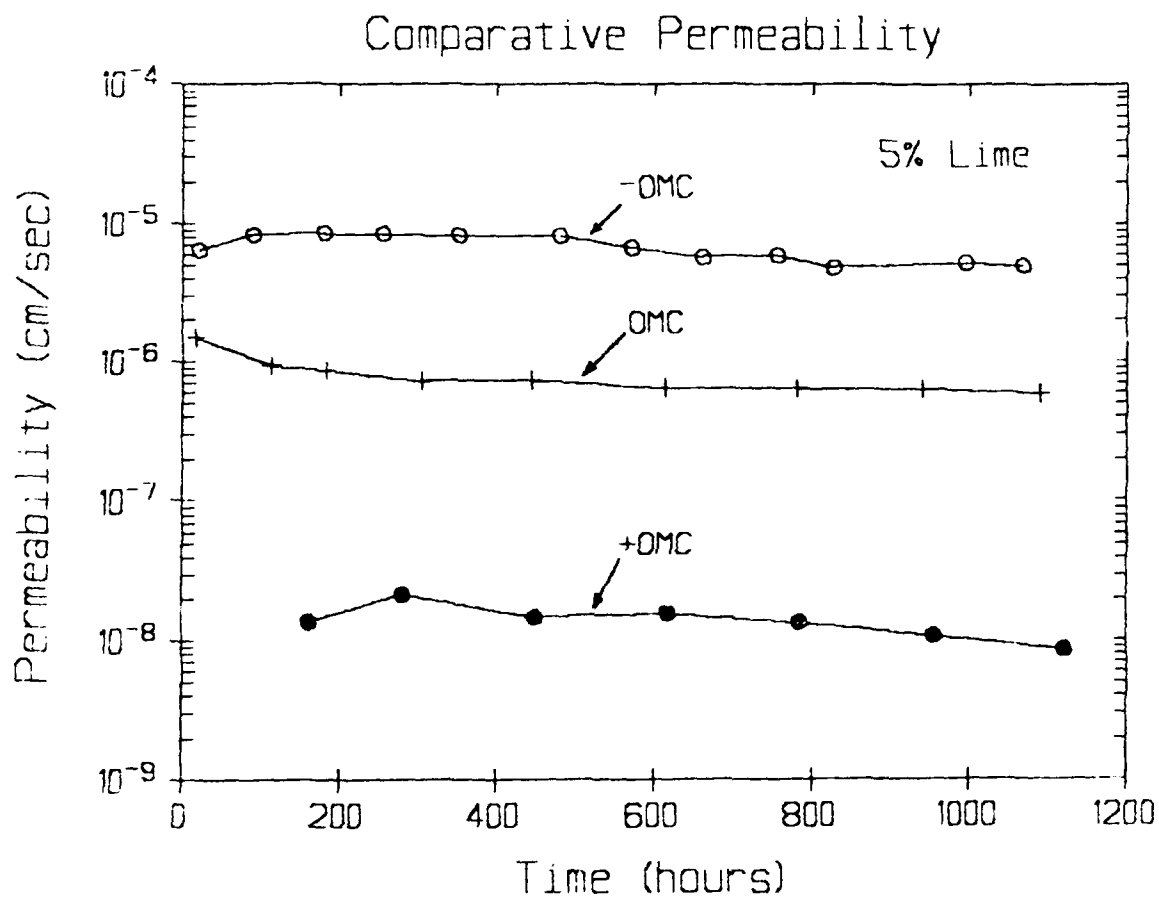
Figure E8. Moisture content effects on Site No. 2
permeability using 5% lime.
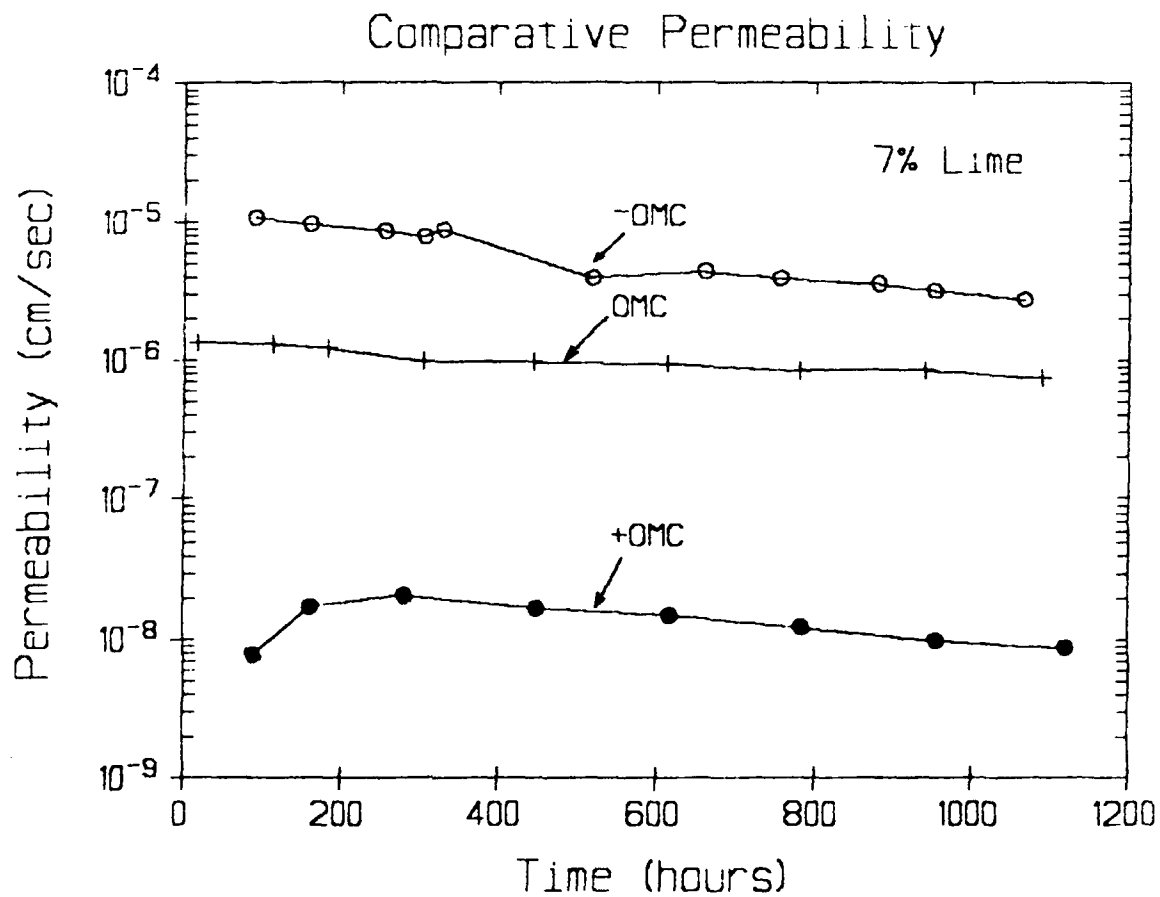
Figure E9. Moisture content effects on Site No. 2
permeability using 7% lime.

Figure E10. Permeabilities of Site No. 2 samples
compacted dry during 45 days of leaching.

Figure E11. Permeabilities of Site No. 2 samples
compacted wet during 45 days of leaching.
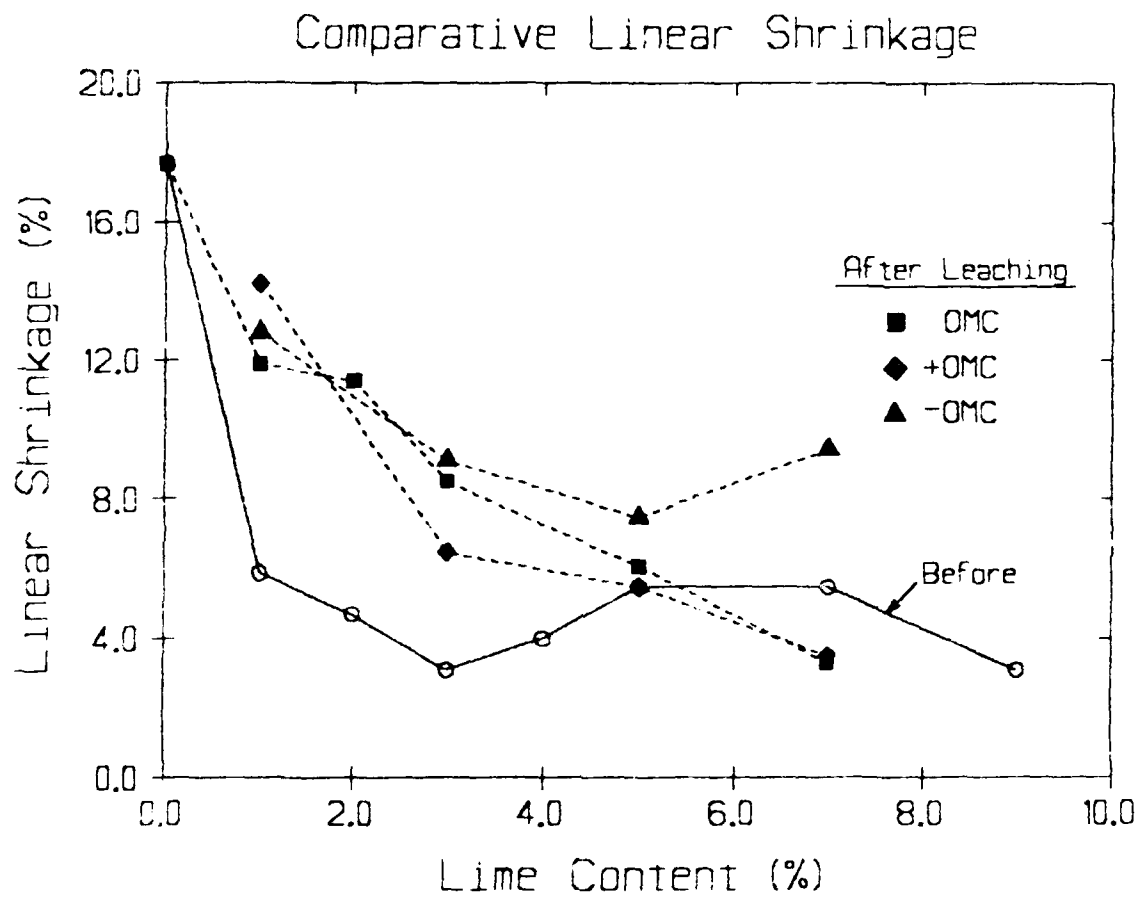
Figure E12. Moisture content effects on linear shrinkage for Site No. 2 samples after 45 days of leaching.
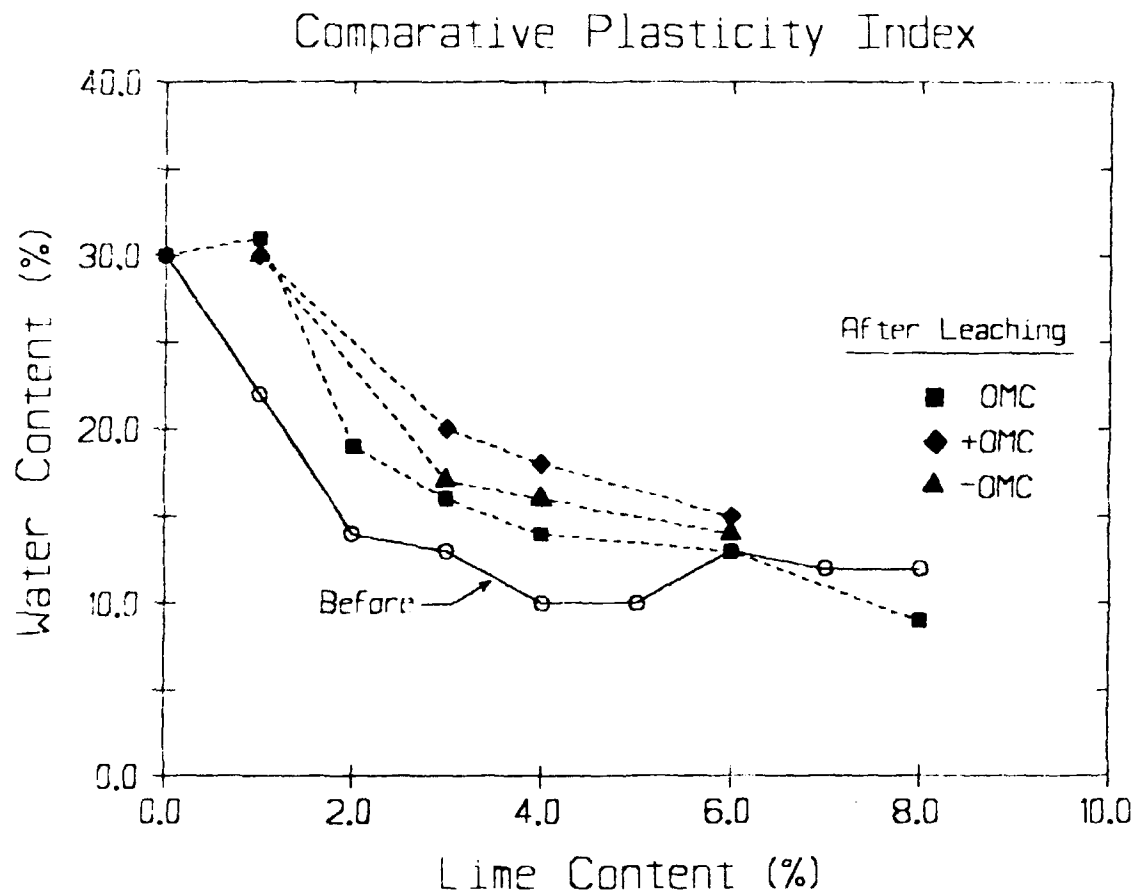
Figure E13. Moisture content effects on plasticity index for Site No. 1 samples after 45 days of leaching.

Comparative Plasticity Index
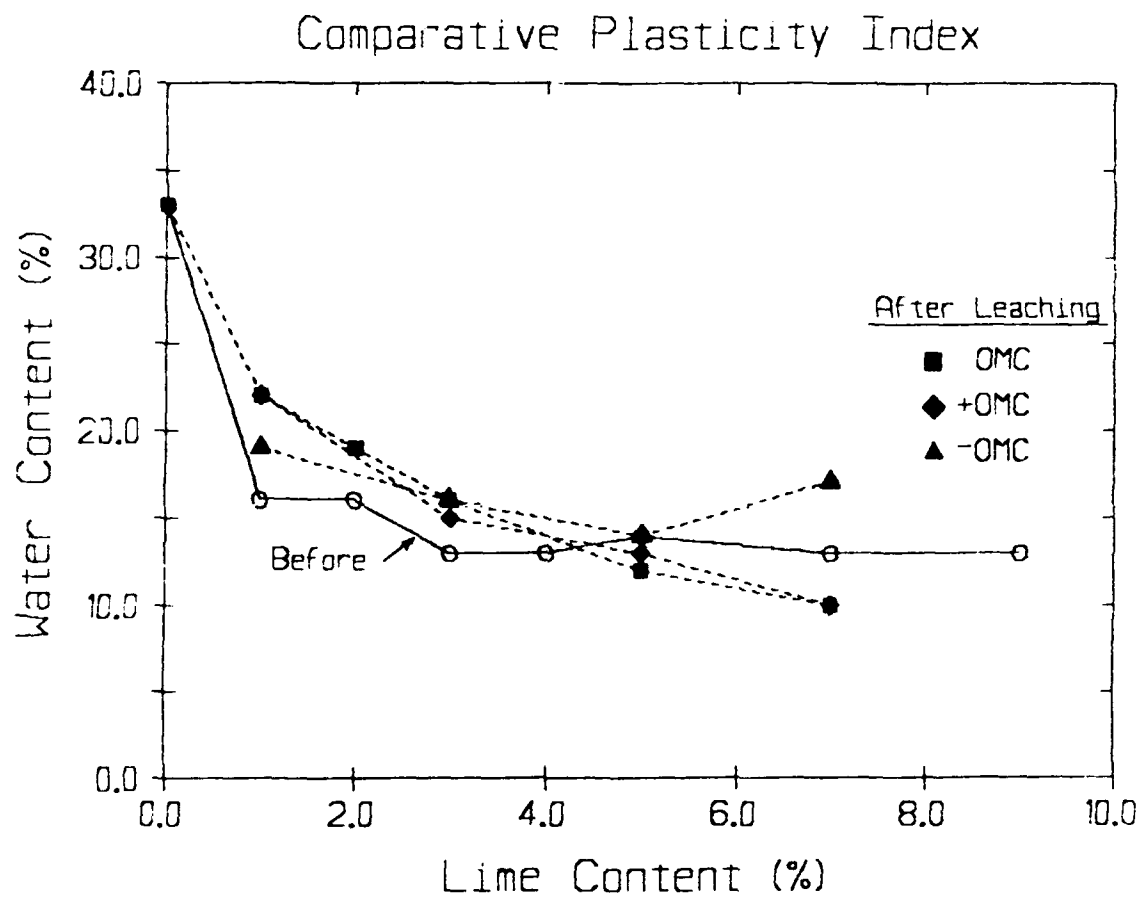
Figure E14. Moisture content effects on plasticity index for Site No. 2 samples after 45 days of leaching.
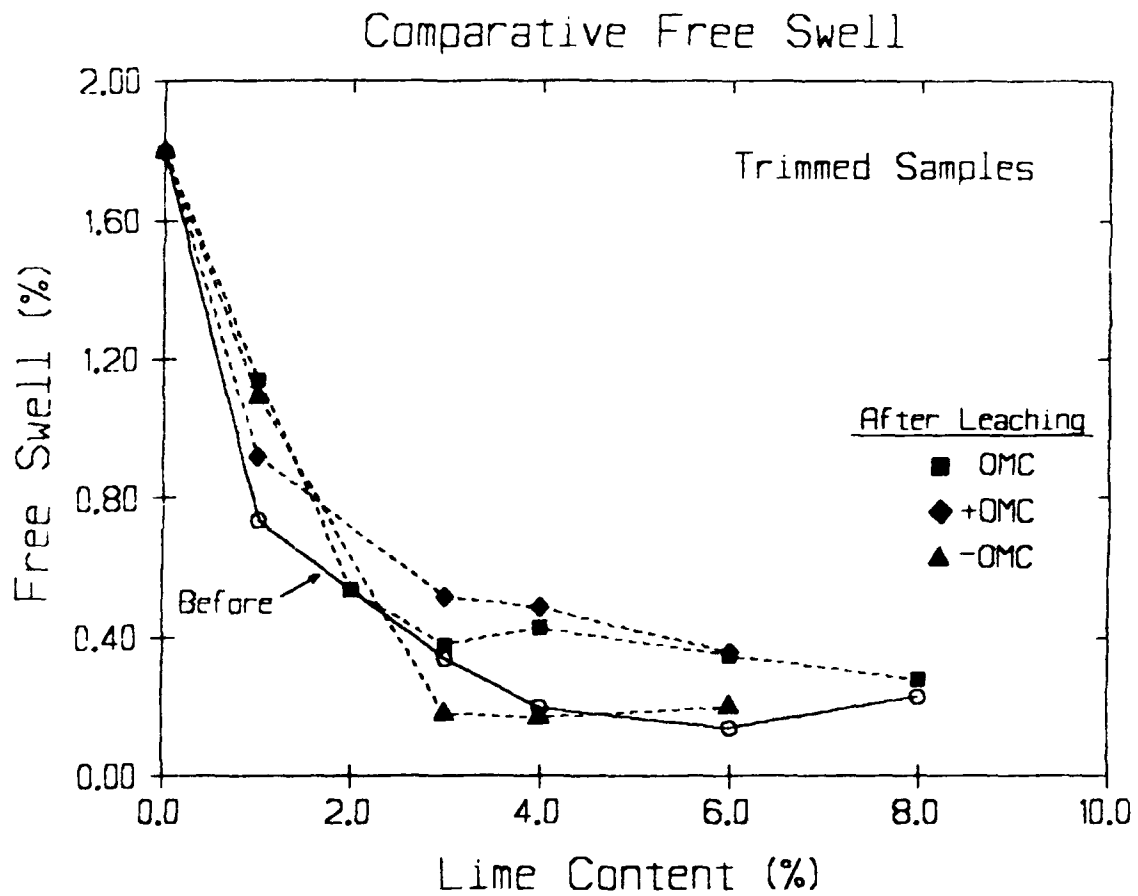
Figure E15. Moisture content effects on free swell
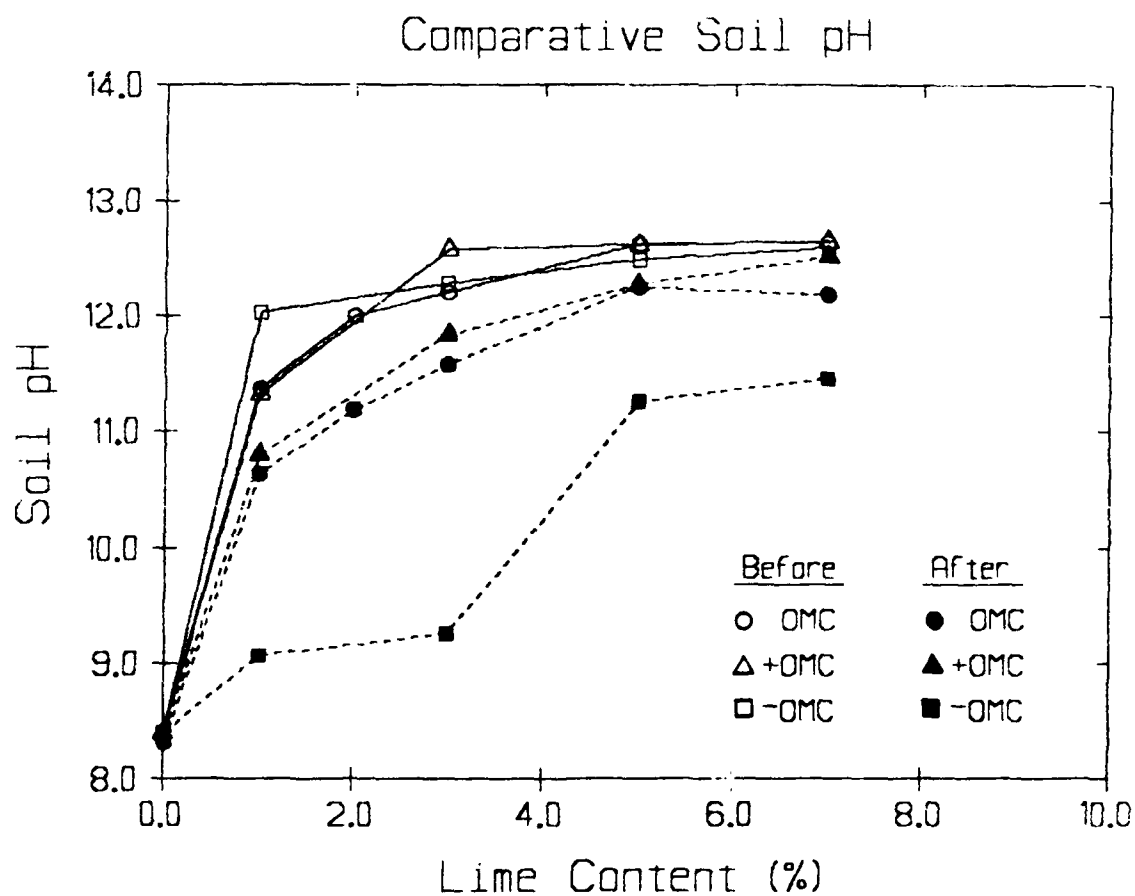for Site No. 1 samples after 45 days of leaching.
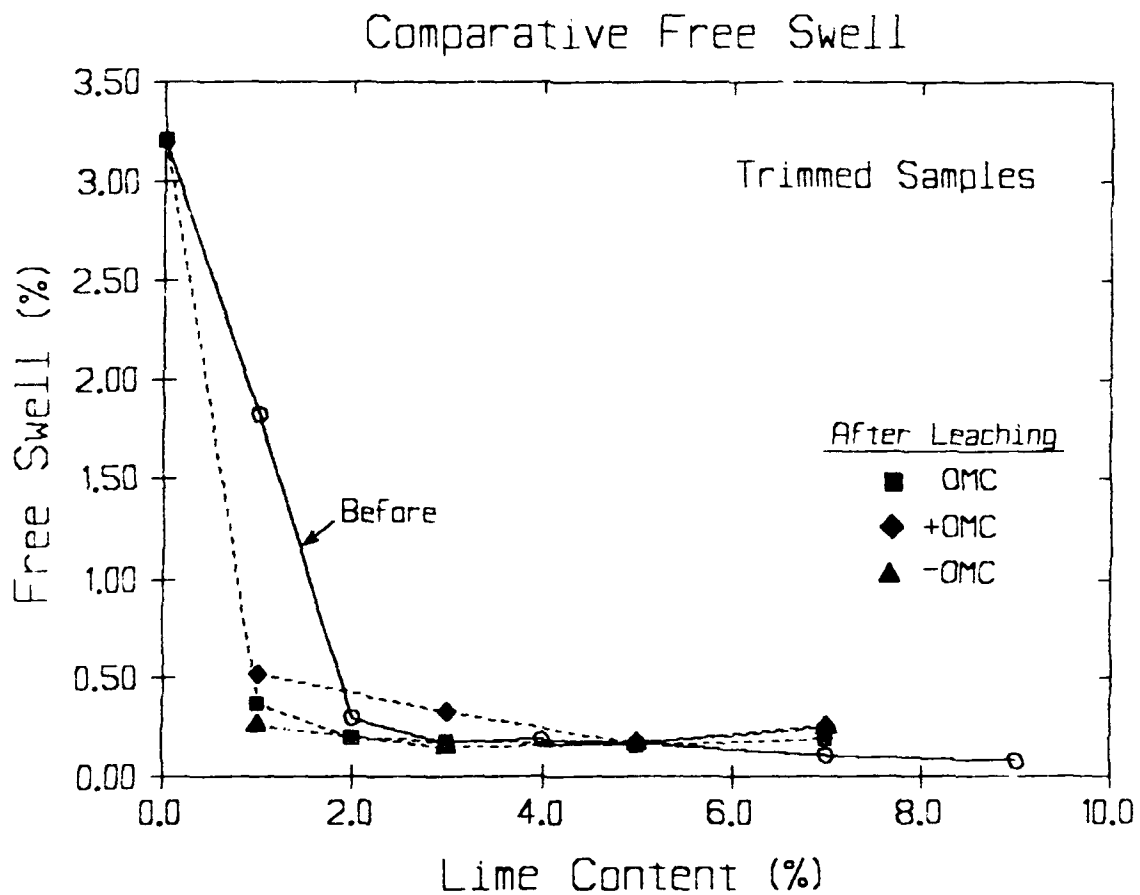
Figure E16. Moisture content effects on free swell
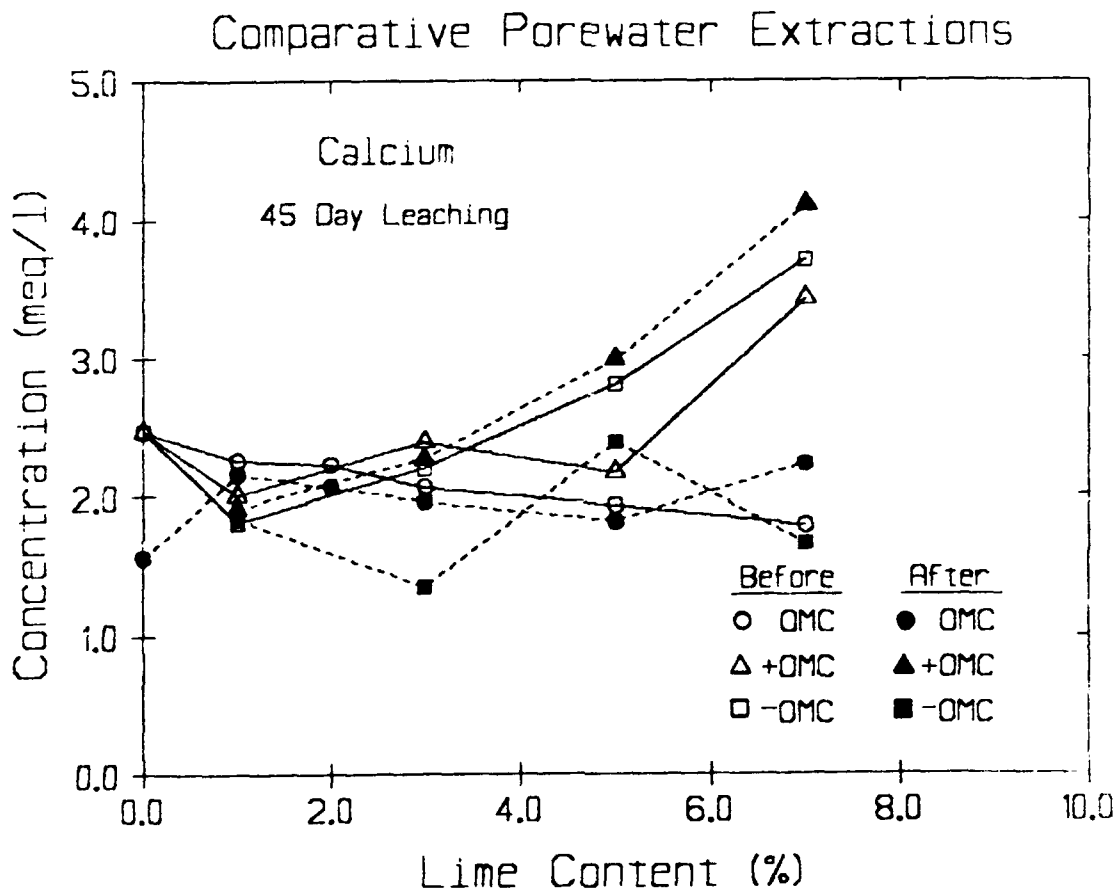for Site No. 2 samples after 45 days of leaching.
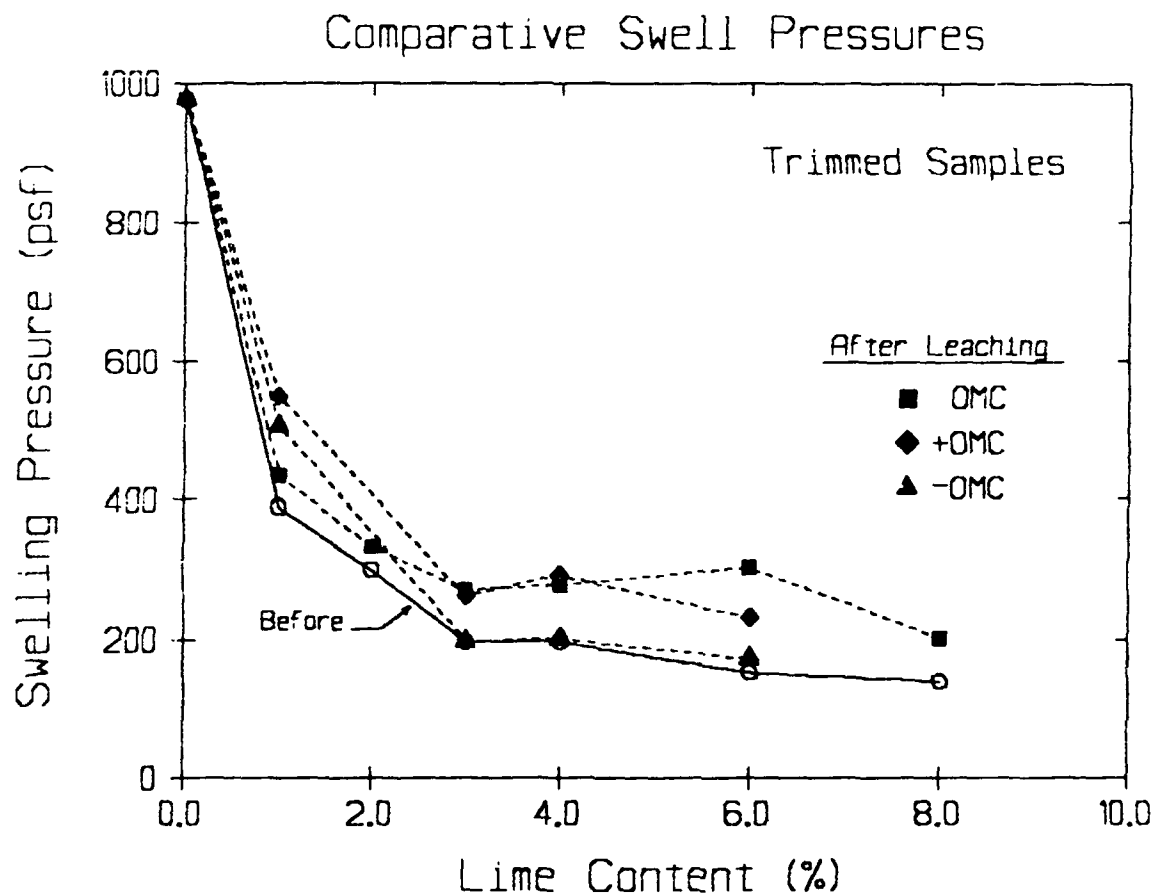
Figure E17. Moisutre content effects on swell
pressure for Site No. 1 samples after 45 days of
leaching.
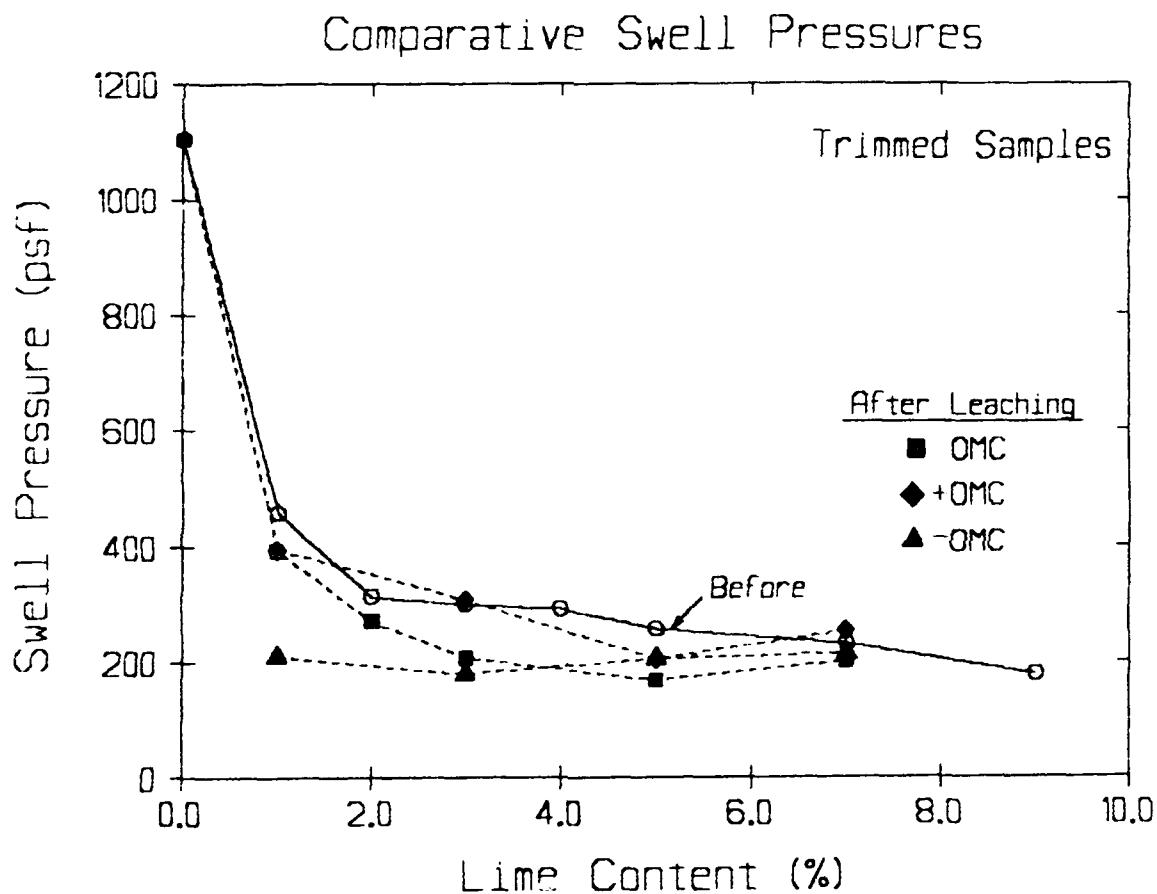
Figure E18. Moisture content effects on swell pressure for Site No. 2 samples after 45 days of leaching.
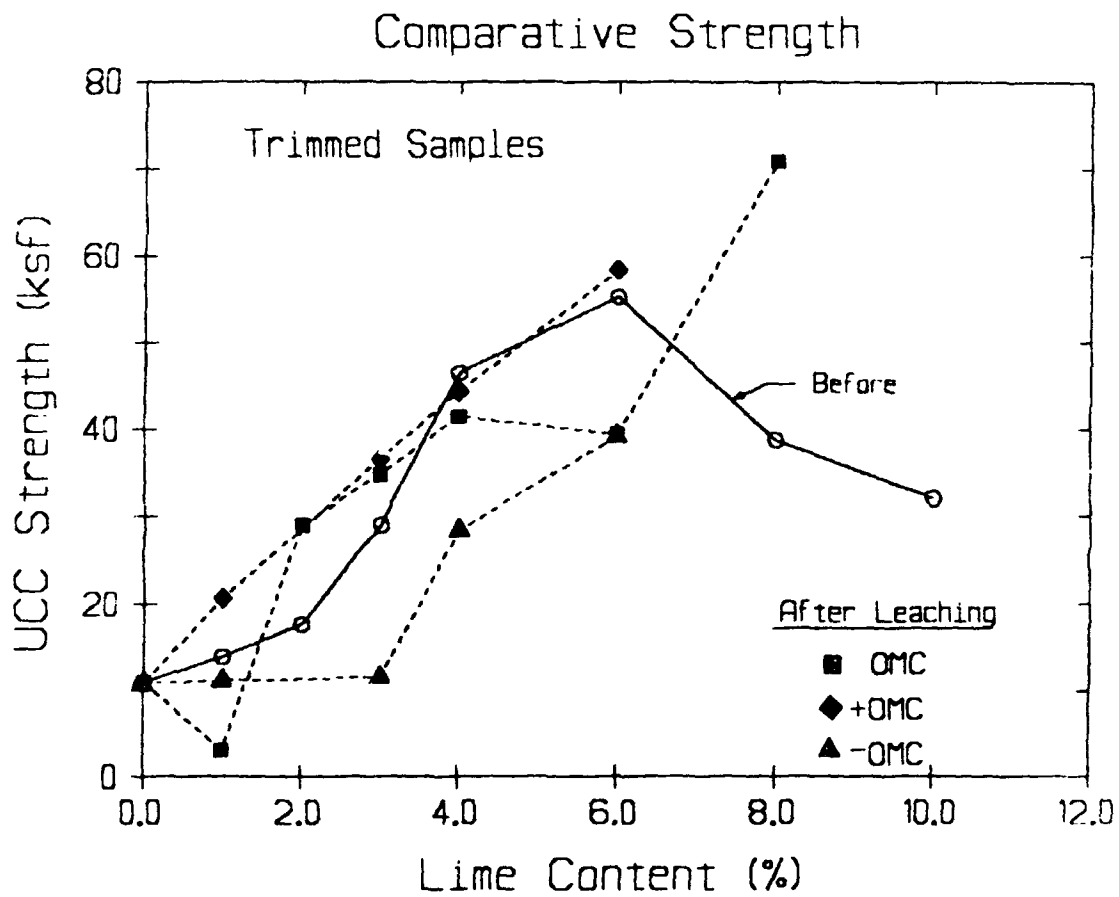
Figure E19. Moisture content effects on the
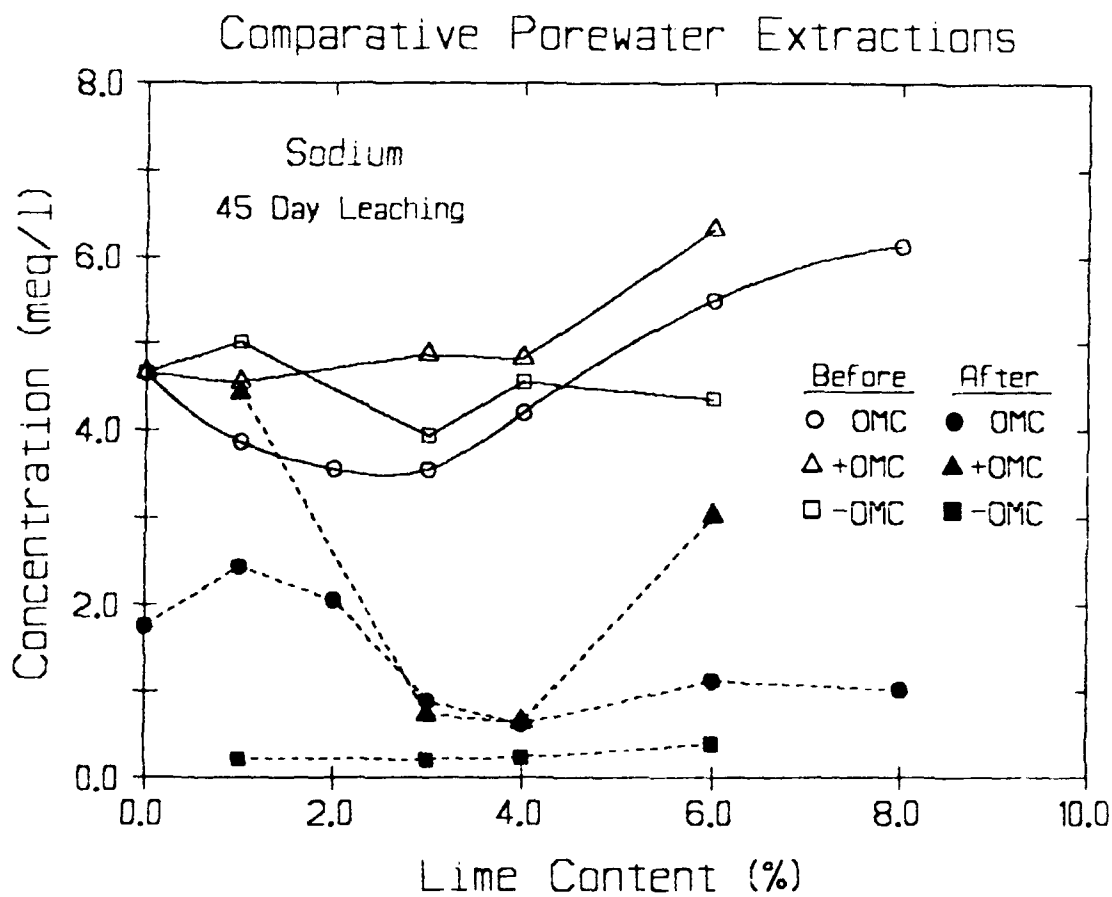strength of Site No. 1 samples after 45 days of
leaching.
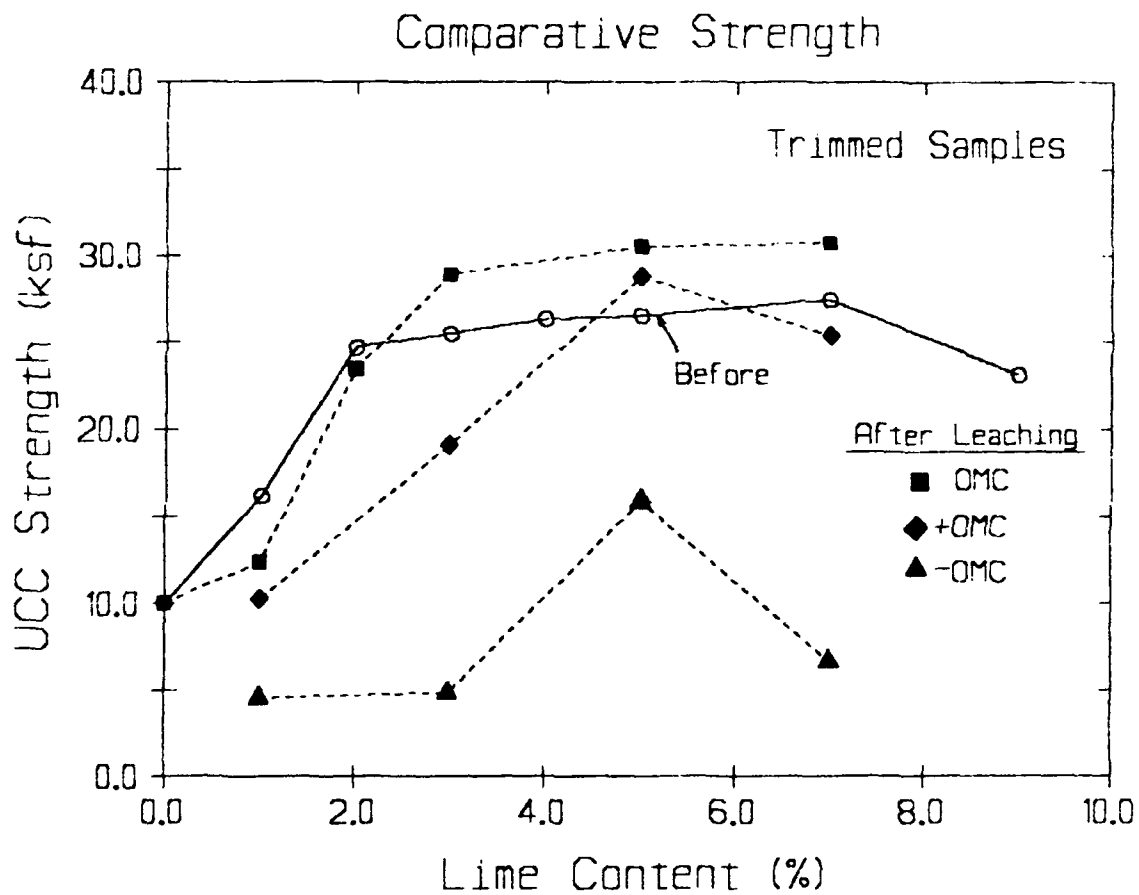
Figure E20. Moisture content effects on the strength of Site No. 2 samples after 45 days of leaching.
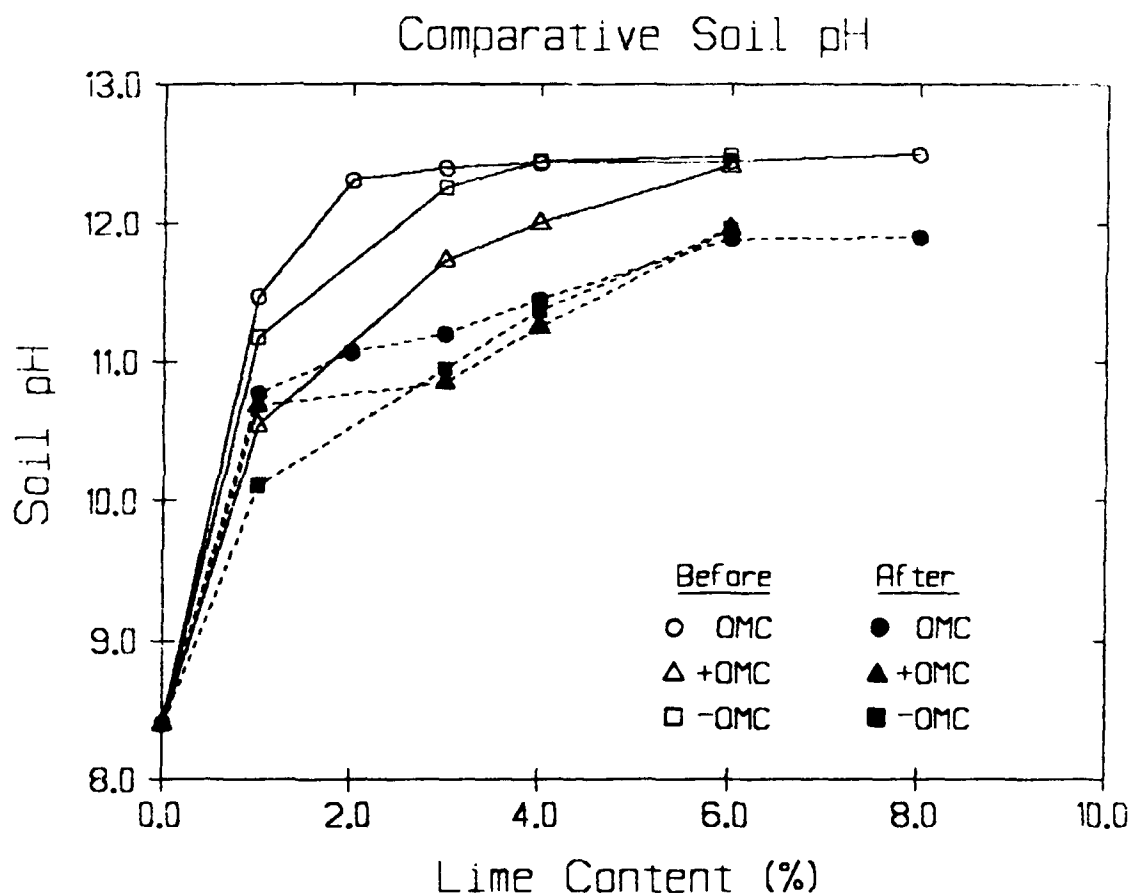
Figure E21. Moisture content effects on the soil pH of Site No. 1 samples after 45 days of leaching.

Figure E22. Moisture content effects on the soil
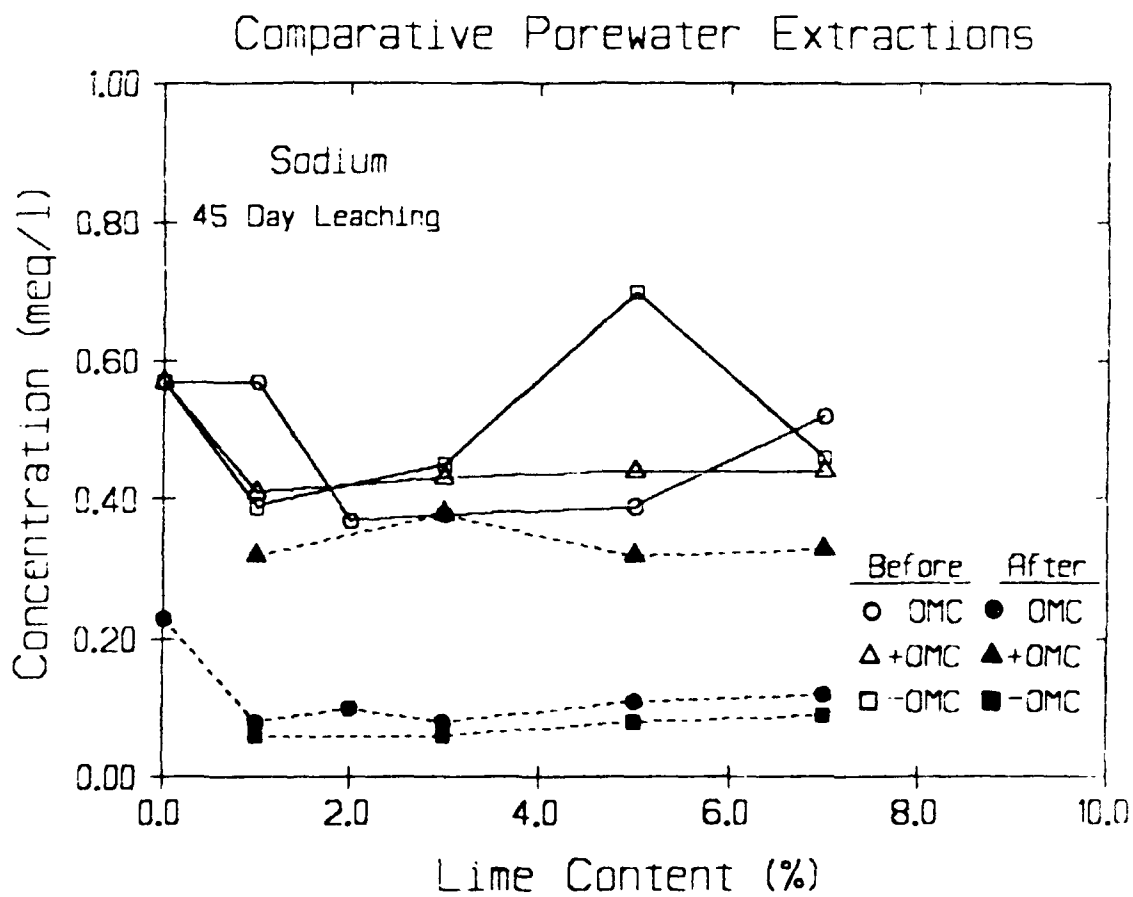pH of Site No. 2 samples after 45 days of leaching.

Figure E23. Moisture content effects on calcium
in the porewater of Site No. 2 samples after
45 days of leaching.

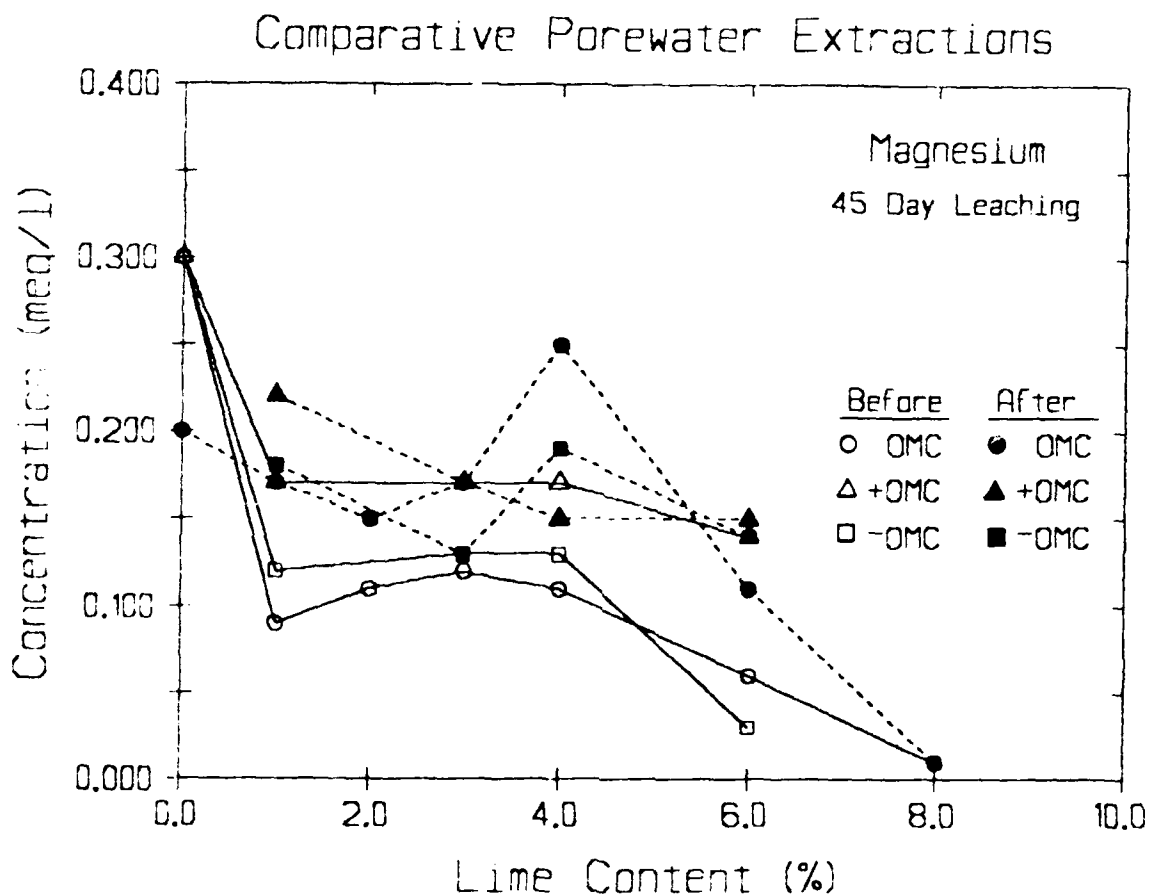Figure E24. Moisture content effects on sodium in the porewater of Site No. 1 samples after 45 days of leaching.

Comparative Porewater Extractions

Figure E25. Moisture content effects on sodium in the porewater of Site No. 2 samples after 45 days of leaching.
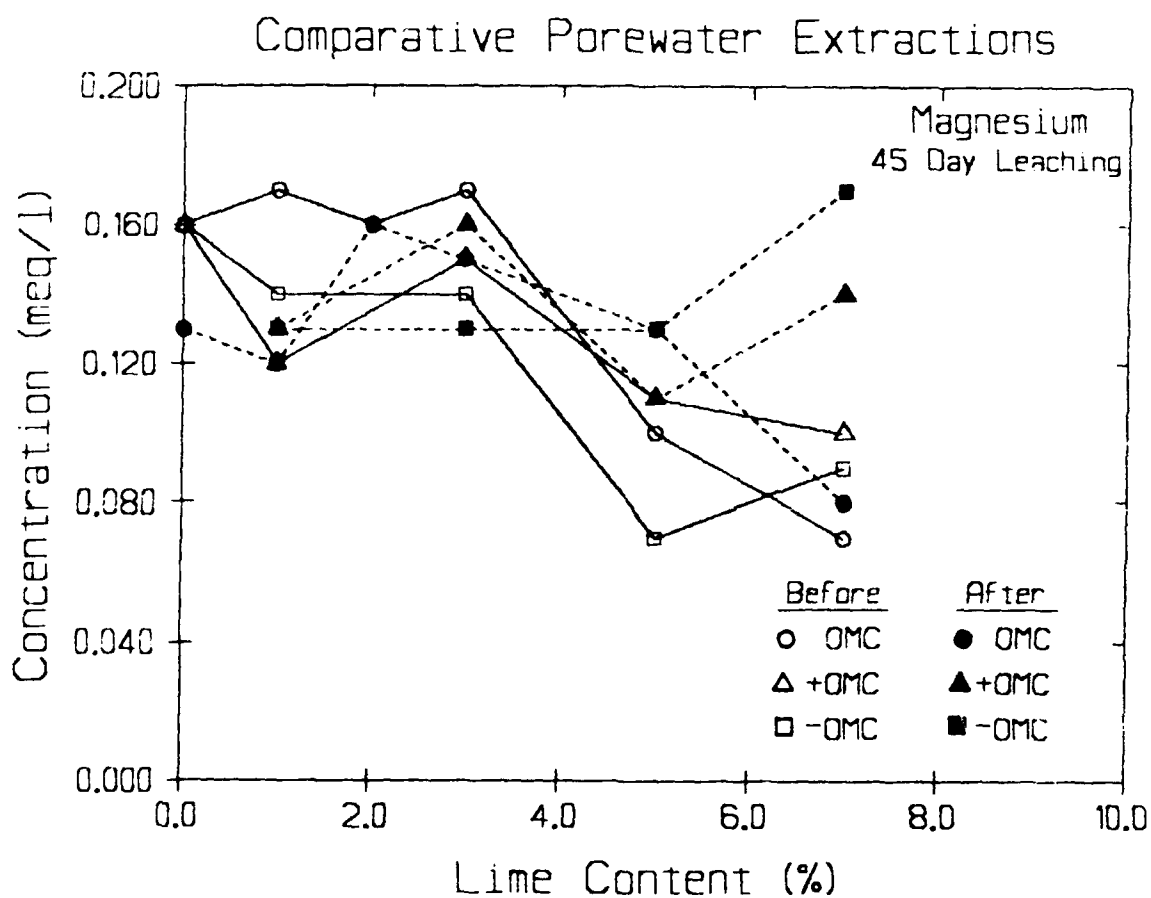
Figure E26. Moisture content effects on magnesium
in the porewater of Site No. 1 samples after
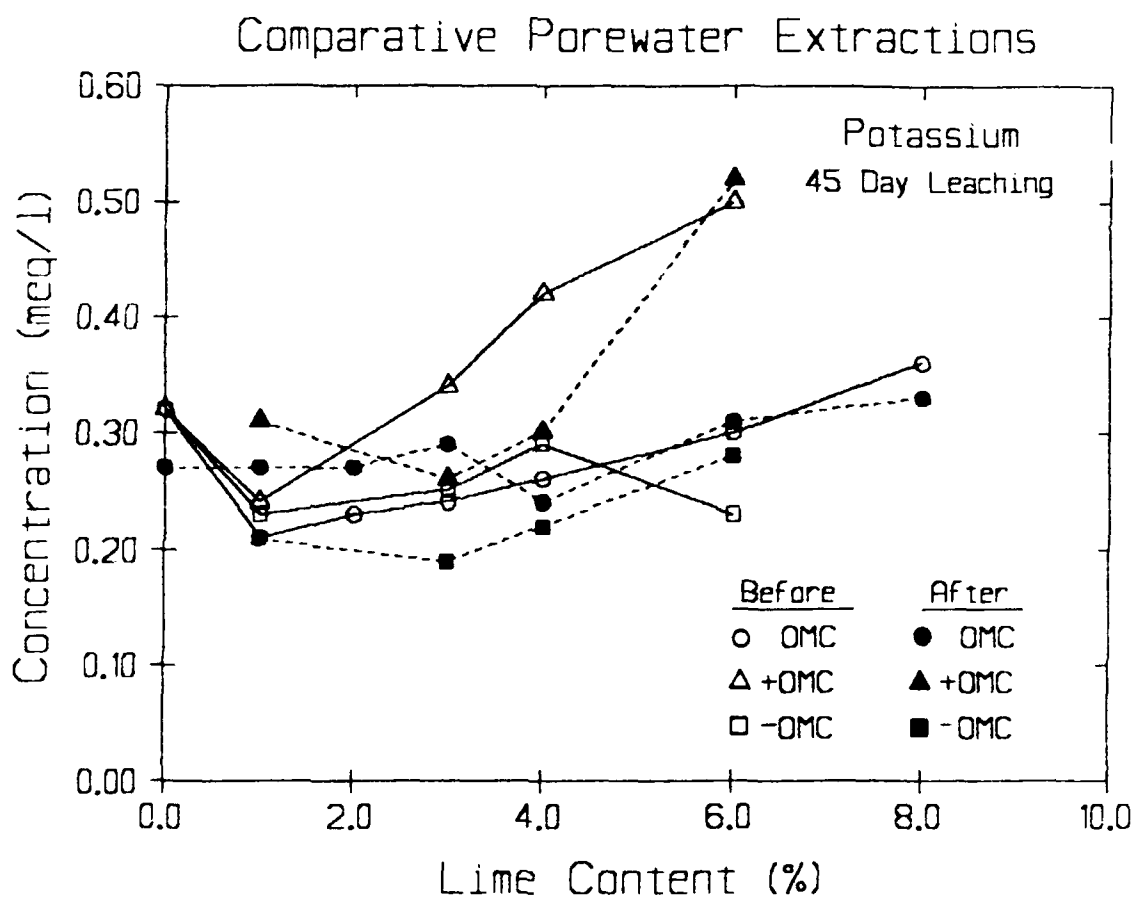45 days of leaching.

Figure E27. Moisture content effects o.1 magnesium
in the porewater of Site No. 2 samples after
45 days of leaching.

Comparative Porewater Extractions

Figure E28. Moisture content effects on potassium in the porewater of Site No. 1 samples after 45 days of leaching.
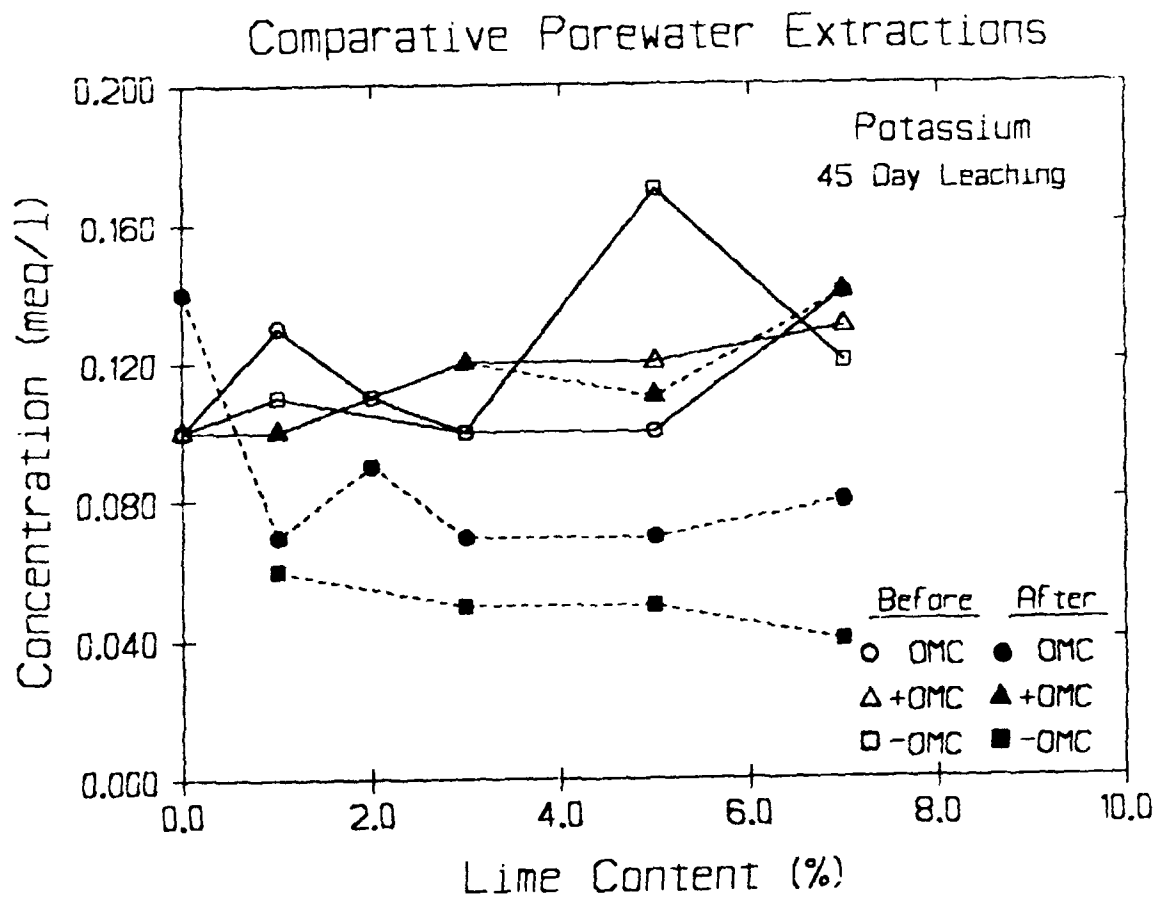
Figure E29. Moisture content effects on potassium
in the porewater of Site No. 2 samples after
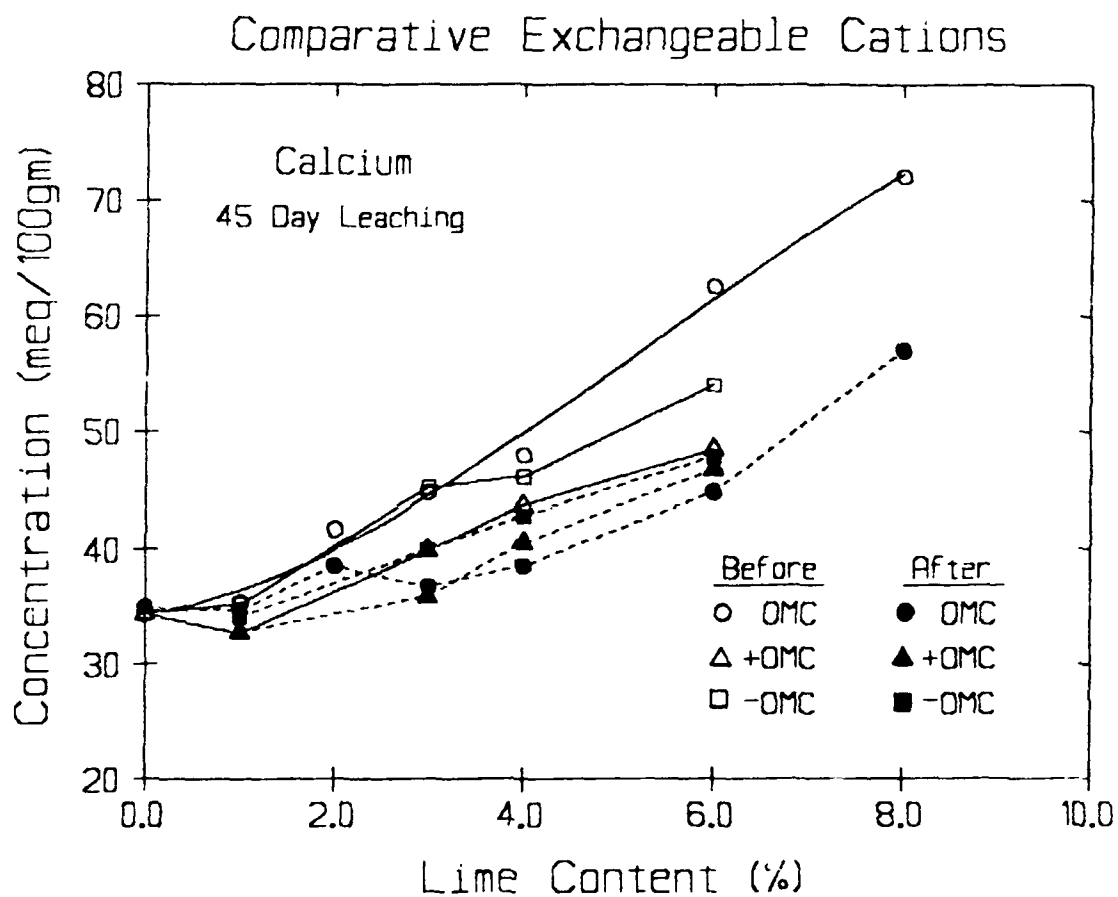45 days of leaching.

Figure E30. Moisture content effects on calcium in
the exchange complex of Site No. 1 samples after
45 days of leaching.

Figure E31. Moisture content effects on calcium in
the exchange complex of Site No. 2 samples after
45 days of leaching.

Figure E32. Moisture content effects on sodium in
the exchange complex of Site No. 1 samples after
45 days of leaching.
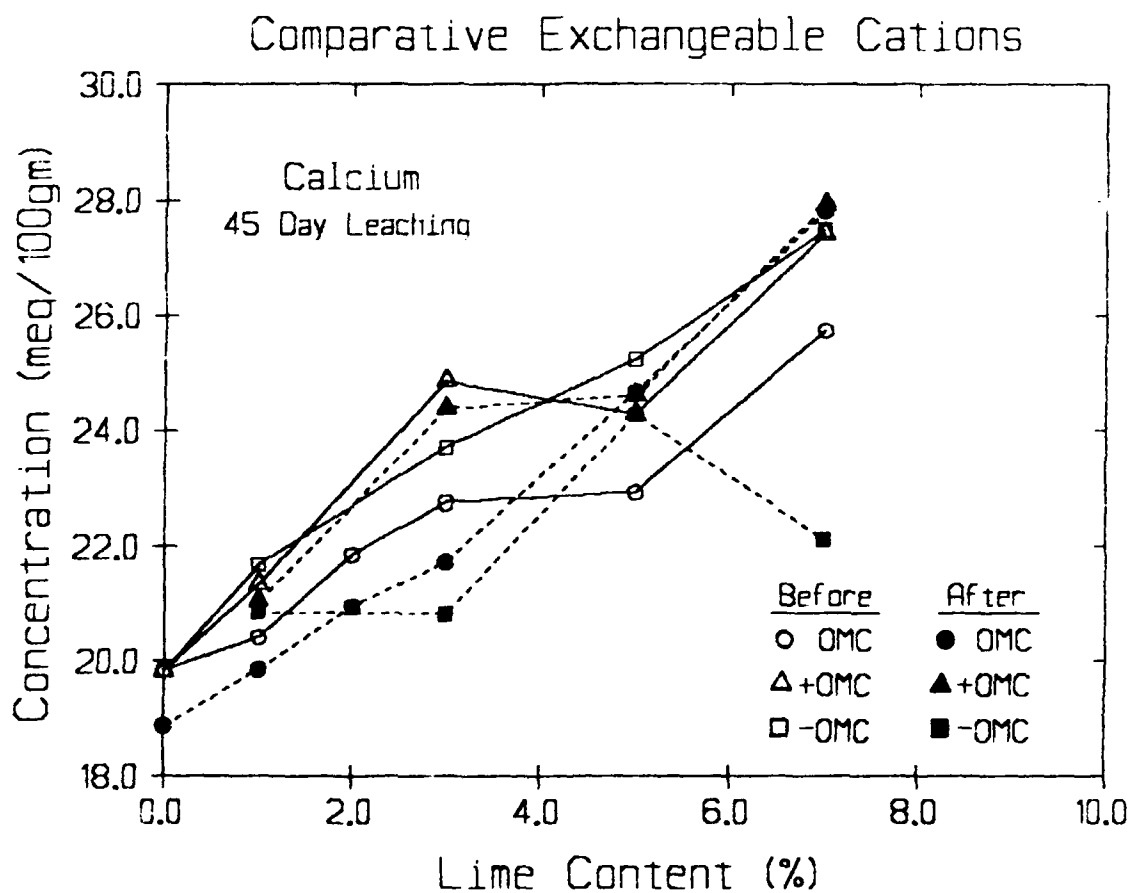
Comparative Exchangeable Cations

Figure E33. Moisture content effects on calcium in
the exchange complex of Site No. 2 samples after
45 days of leaching.

Figure E34. Moisture content effects on magnesium
in the exchange complex of Site No. 1 samples after
45 days of leaching.

Figure E35. Moisture content effects on magnesium in the exchange complex of Site No. 2 samples after 45 days of leaching.
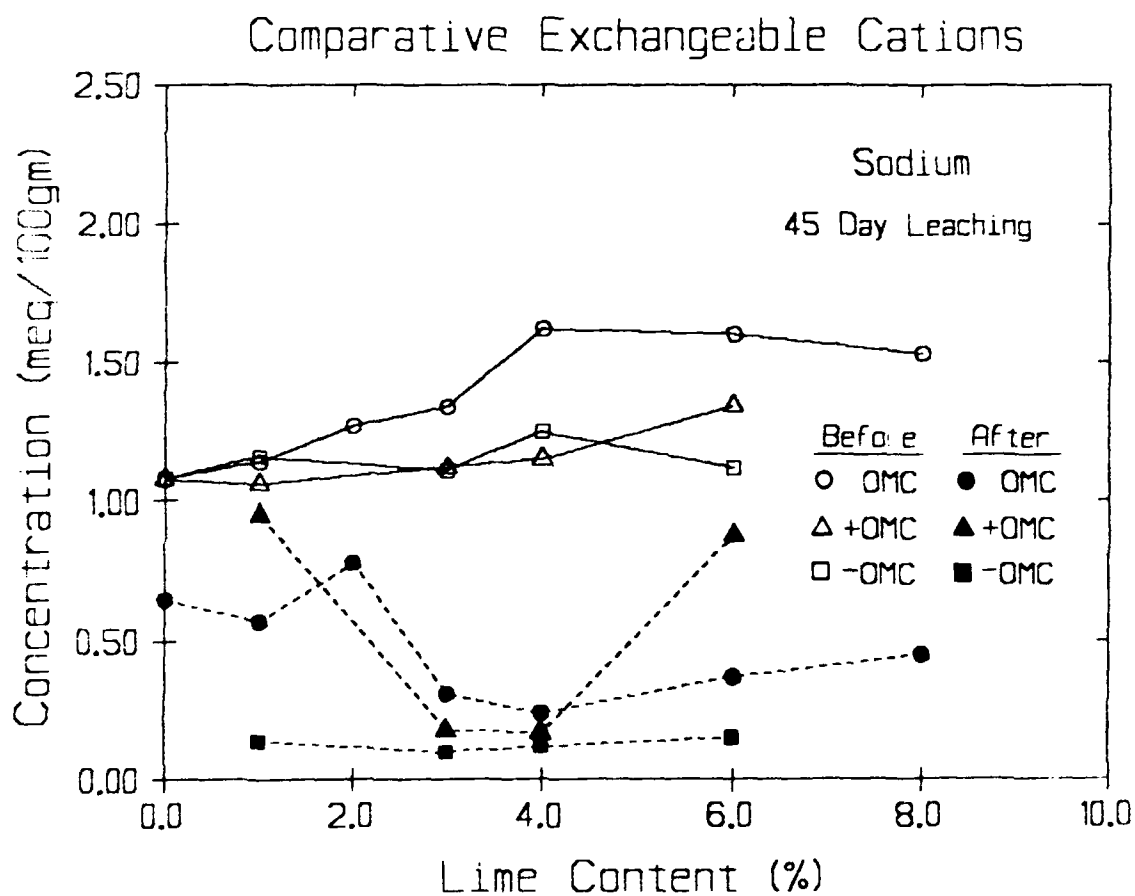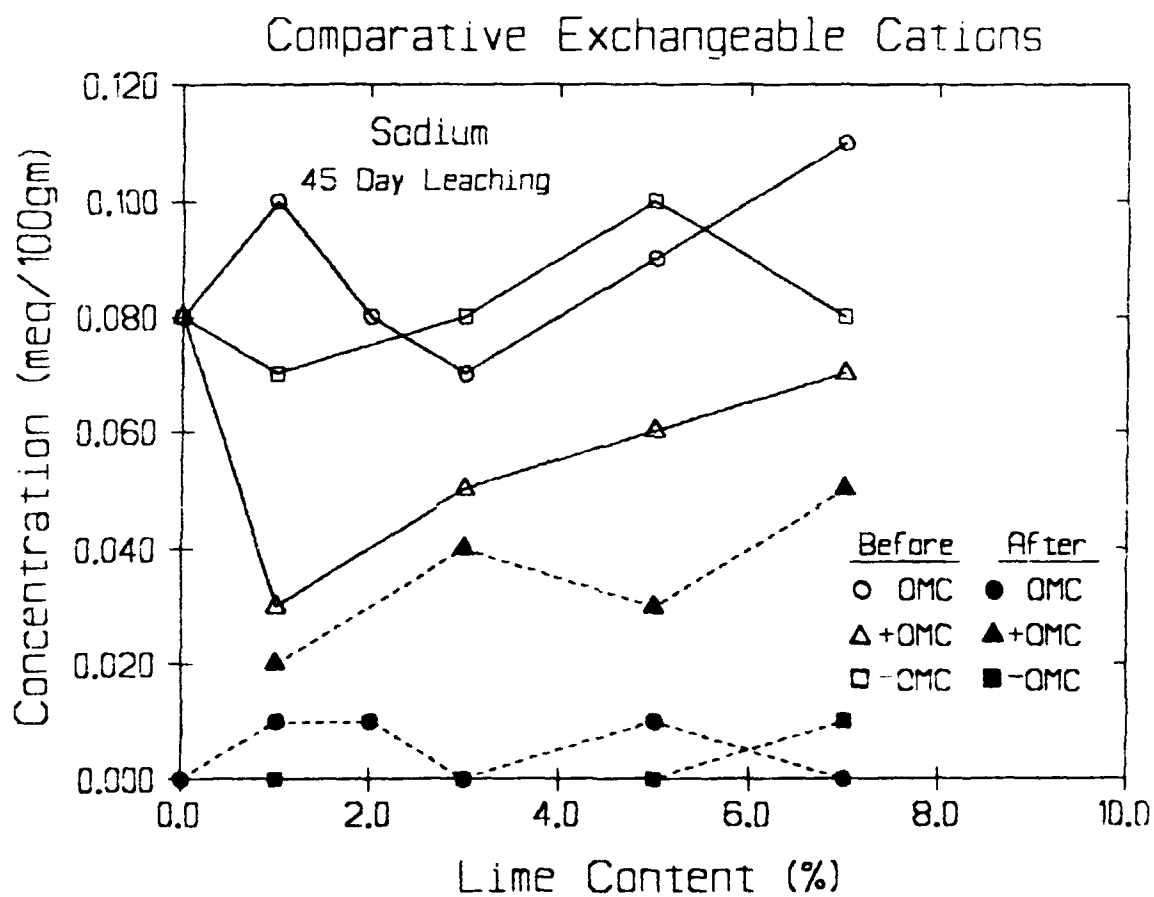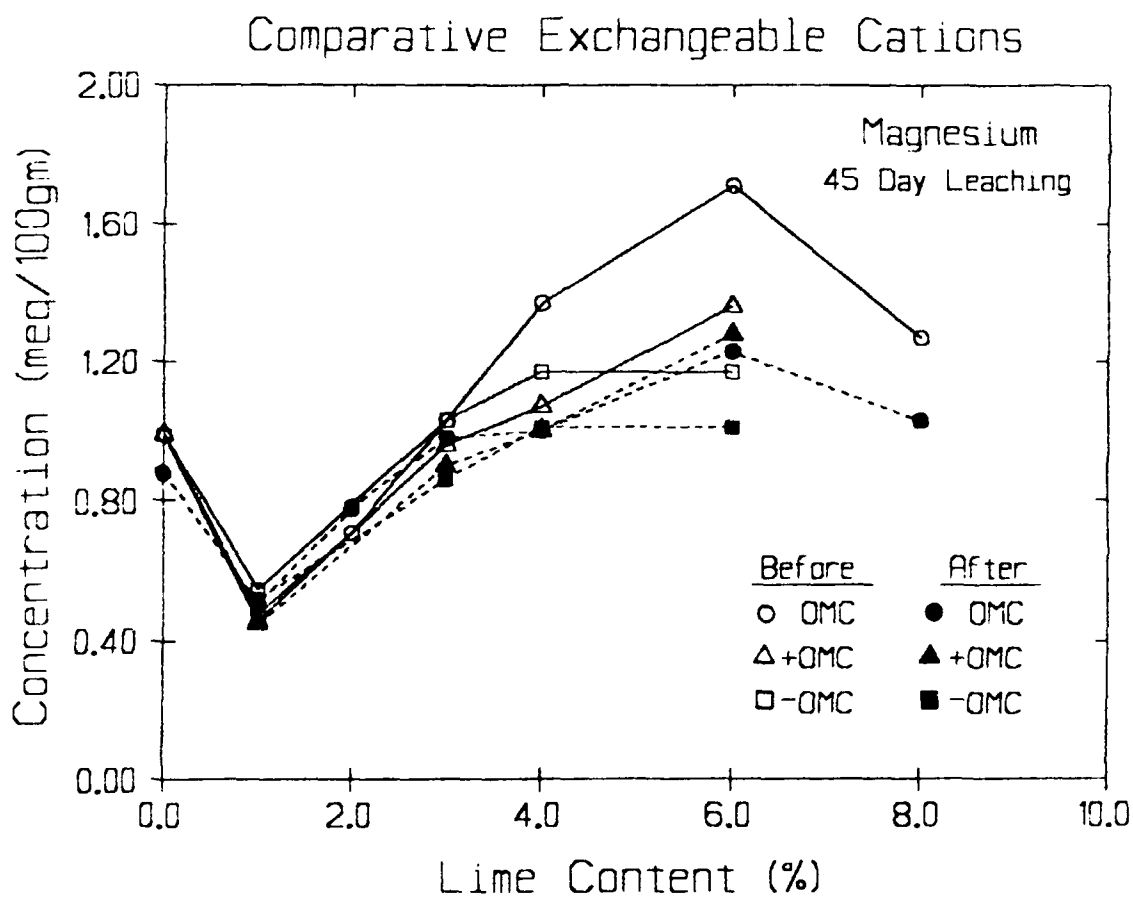
Figure E36. Moisture content effects on potassium
in the exchange complex for Site No. 1 samples
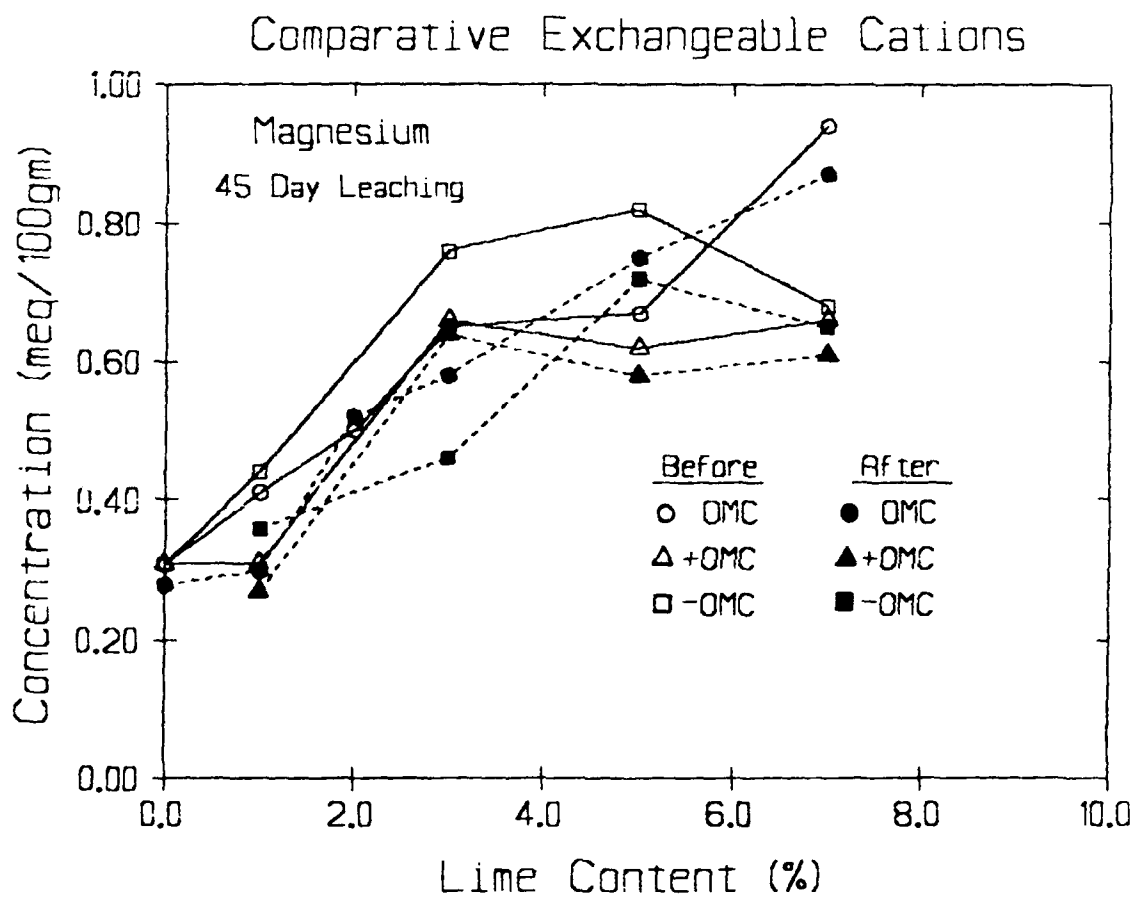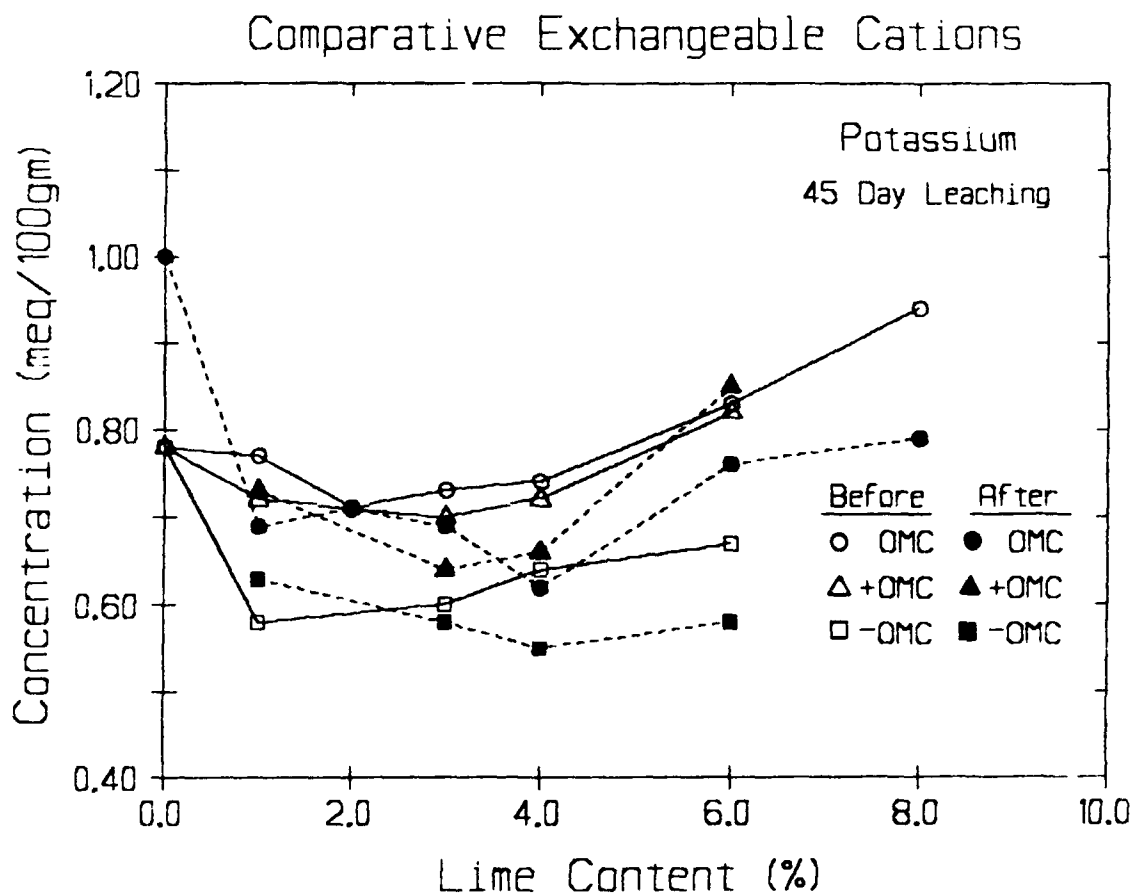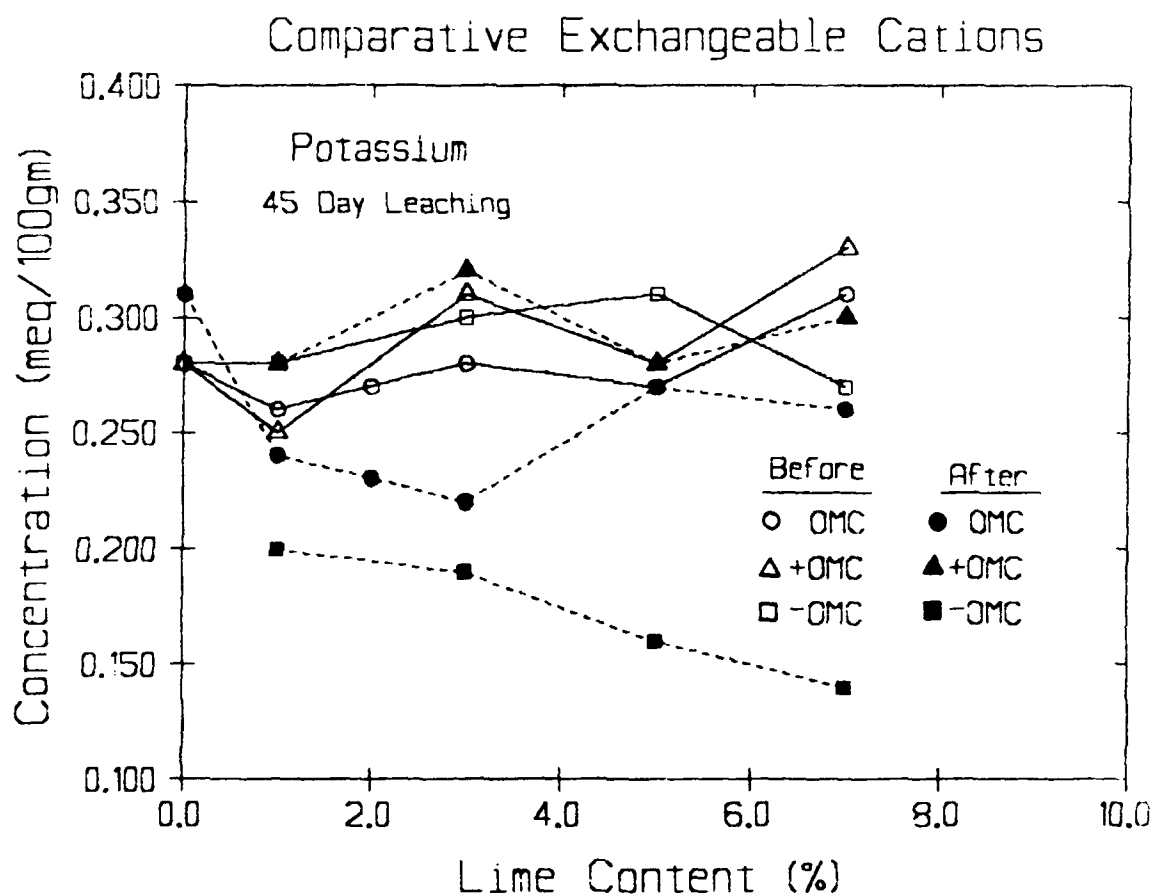after 45 days of leaching.

Figure E37. Moisture content effects on potassium
in the exchange complex for Site No. 2 samples
after 45 days of leaching.

APPENDIX F

TIME FACTOR DETERMINATION

TIME FACTOR DETERMINATION

1. In order to use accelerated leach test data to estimate field behavior of soil-lime mixtures, it is first necessary to determine a time factor correlation between the time of accelerated laboratory leaching and field precipitation information. While it is beyond the scope and intent of this research to make accurate estimations of infiltration, runoff and evapotranspiration, general rainfall information can be used to calculate a time factor, t_F, to relate accelerated leaching to actual field data.

2. Time factors developed for Sites No. 1, 2, and 3 are based on equations presented by Haji-Djafari and Wright (1983). Several assumptions were required:

   a. Mean annual rainfall for the D/FW area is 34 inches (Ralson 1965). In order to simplify correlations and eliminate rainfall infiltration, runoff and evapotranspiration calculations, annual rainfall was looked at as a standing head of water above the soil-lime layer. Since this will greatly overestimate the amount of rainfall that will percolate through the soil-lime layer, only approximately one-third (or 10 inches) of standing water was used to establish the time factor. This will still overestimate the rainfall infiltration but estimation results will be conservative. This method of approach effectively means both laboratory and field data will be under constant heads.

   b. Laboratory leach tests eventually became saturated during testing, therefore the field soil-lime layer is also assumed saturated to facilitate uniform flow.

   c. The topsoil layer covering the soil-lime layer is not included in the calculations. This will also produce a conservative estimate of the amount of rainfall infiltration through the soil-lime layer as some of the water will dissipate before reacting the soil-lime layer.

3. Based on saturated flow and information about the laboratory conductivity of soil-lime mixtures, the following equations can be derived:

$$i_F = (H + b)/b \tag{F1}$$

$$i_L = \Delta h/L \tag{F2}$$

$$Q_F = Q_L \times (i_F / i_L) \tag{F3}$$

$$t_F = t_L \times t_S \tag{F3}$$

$$t_F = t_L \times (b/L) \times (i_L/i_F) \tag{F5}$$

where

i_F = field hydraulic gradient,

i_L = laboratory hydraulic gradient,

H = water level above field soil-lime layer = 25.4 cm,

b = thickness of field soil-lime layer, cm,

Δh = laboratory leach pressure converted to cm of water,

L = length of laboratory leach samples = 17.46 cm,

Q_F = field seepage rate per unit area, liter/yr $\cdot$ m^2,

Q_L = Laboratory flowrate per unit area, liter/hr $\cdot$ cm^2,

t_F = field time, hr,

t_L = laboratory time, hr, and

t_S = time scale factor.

For Site No. 1, the following data were available

Field: Lime content = 3%

              Age = 16 yrs

              b = 18 in. = 45.72 cm

              H = 10 in. = 25.4 cm

Laboratory: Lime content = 3%

Δh = 10 psi = 704.51 cm of water

L = 6.875 in. = 17.46 cm

K_L = 1.5 x 10^{-6} cm/sec

A_L = 28.27 in. = 182.41 cm^2

Field and laboratory hydraulic gradients are calculated as follows:

$$i_F = (H + b)/b = (25.4 + 45.72)/45.72 = 1.6 \qquad (F6)$$

$$i_L = \Delta h/L = 704.51/17.46 = 40.3 \qquad (F7)$$

The laboratory flowrate per area is

$$Q_L = k_L i_L = (1.5 \times 10^{-6} \text{ cm/sec})(40.3)\times(\text{liter}/10^3 \text{ cm}^3)\times(3600 \text{ sec/hr}) \qquad (F8)$$

$$= 2.18 \times 10^{-4} \text{ liter/hr} \cdot \text{cm}^2$$

The field seepage rate per area is estimated as

$$Q_F = Q_L \times (i_F/i_L) = (2.18 \times 10^{-4}) (1.6/40.3) \times (8760 \text{ hr/yr}) \times 10^4 \text{ cm}^3/\text{m}^2 \qquad (F9)$$

$$= 758 \text{ liter/yr} \cdot \text{m}^2$$

The time scale factor to relate laboratory time to field time is calculated as

$$t_F = t_L \times (b/L) \times (i_L/i_F) = t_L \times (45.72/17.46) \times (40.3/1.6) \qquad (F10)$$

$$= t_L \times 66.0$$

Site No. 1: Time Scale factor, $t_{s1} = t_F/t_L = 66.0$ \qquad (F11)

4. By similar calculations, Sites No. 2 and 3 time scale factors and field seepage estimations are

Site No. 2: Time Scale, t_{s2} = 13.0; Q_{F2} = 7.7 L/yr $\cdot$ m^2 (F12)

Site No. 3: Time Scale, t_{s3} = 20.4; Q_{F3} = 247 L/yr $\cdot$ m^2 (F13)

Site No. 2 time scale, t_{s2}, is based on a field layer of 7% lime, 6 in. thick, 8 yrs old, and a laboratory permeability of 9.0 x 10^{-7} cm/sec. Site No. 3 time scale, t_{s3}, is based on a field layer of 9% lime, 8 in. thick, 3 yrs old, and a laboratory permeability of 3.4 x 10^{-7} cm/sec.

5. These time scales can be used to represent the equivalent field data based on laboratory tests for various accelerated leach times. For example, Site No. 1 exchange complex tests revealed that at the end of 90 days (2160 hrs) of continuous leaching, the calcium concentration was only 80% of its original (before leaching) rate. This same percentage loss of calcium in the field would be estimated to occur at 2160 hr x 66.0 = 142,560 hr (16.3 yrs).

6. This method of estimation is severely limited in that it assumes identical leaching effects on both laboratory and field soil-lime mixtures. Additionally, it is only applicable to cation washout or soil pH as it is a measure of the loss of chemical properties through permeability changes between the field and laboratory samples. Physical property or engineering property changes may or may not be directly influenced by permeability alone. Finally, the time factors developed are for the three soils tested in this research only and are not applicable to other expansive clays.

APPENDIX G

NOTATIONS

NOTATIONS

The following symbols and abbreviations are used in this report:

AAS .... Atomic Absorption Spectrophotometry

ASTM .... American Society for Testing and Materials

A45 .... After 45 days of leaching

A90 .... After 90 days of leaching

α (alpha) .... Probability of rejecting the null hypothesis if, in fact, the null is true (Type I error).

B .... Before leaching

Ca .... Periodic table symbol for calcium

CBR .... California Bearing Ratio

CH .... Highly plastic clay (unified soil classification system)

CSH .... Calcium Silicate Hydrates

D/FW .... Dallas/Fort Worth

DTA .... Differential Thermal Analysis

EC .... Exchange Complex

ICP .... Inductively Coupled Plasma

IE .... Insufficient Evidence to refute the null hypothesis

K .... Periodic table symbol for potassium

ksf .... Kips (1000 pounds) per square foot

LCFAA .... Lime-Cement-Fly Ash Aggregate

LL .... Liquid Limits from Atterberg limits test

LMO .... Lime Modification Optimum

LSO .... Lime Stabilization Optimum

meq .... Milliequivalents

Mg .... Periodic table symbol for magnesium

N .... Chemical abbreviation of normality

Na .... Periodic table symbol for sodium

NEB .... New Engineering Building

NR .... Non-phenolphthalein Reactive

OMC .... Optimum Moisture Content

pcf .... Pounds per cubic foot

PI ....Plasticity Index from Atterberg limits tests
PL ....Plastic Limit from Atterberg limits tests
ppm ....Parts per million
PR ....Phenolphthalein Reactive
psf ....Pounds per square foot
psi................Pounds per square inch
r ....Correlation coefficient
SCS..............Soil Conservation Service
SS ....Statistically significant
t_s ....Time scale factor
UTA ....The University of Texas at Arlington
WES ....Waterways Experiment Station