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PHOSPHOGYPSUM STACK CLOSURE: EVALUATION OF PHOSPHOGYPSUM AS AN ALTERNATE FINAL COVER

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PHOSPHOGYPSUM STACK CLOSURE: EVALUATION OF PHOSPHOGYPSUM AS AN ALTERNATE FINAL COVER

FINAL REPORT

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PERSPECTIVE

Phosphogypsum stack reclamation or closure is regulated under provisions of the Florida Administrative Code chapter 62-673, "Phosphogypsum Management," which became effective in March 1993, and is administered by the Florida Department of Environmental Protection. These rules emphasize control of the potential environmental impacts of leachate from the stack and pond water systems. New stacks are required to have liners beneath them, while both old and new stacks, when closed, must have a barrier layer on top to prevent or greatly reduce infiltration of rain water, and thereby decrease the flow of leachate. Soil and vegetation cover is also addressed by the rules. The barrier layer (e.g. plastic, or compacted clay or soil) on top of the stack must be covered by soil or amended phosphogypsum (PG) able to support a vegetation cover that will control erosion but whose roots will not penetrate the low permeability barrier layer.

The first PG stack closed in accordance with the Florida regulations was the Cargill (formerly Gardinier) stack adjacent to Tampa Bay. A high-density polyethylene (HDPE) geomembrane was applied to the nearly flat top of the stack, while the side slopes remained unlined. The entire surface of the gypsum stack was covered with mineral soil prior to planting vegetation.

Closure of a PG stack with a plastic liner and soil cover on top is very expensive. FIPR Research has shown that vegetation cover and runoff water quality were comparable with either amended PG or overburden soil as the surface cover on the side slope of a gypsum stack. Thus costs could be reduced by using amended PG instead of soil as the growth medium for vegetation. This project examined the potential of using compacted PG, or mixtures of PG and bentonite, phosphatic clay or other amendments, as alternatives to the expensive plastic top liner for reducing infiltration into a PG stack at closure. The project evaluated the permeability of hydrologic barriers comprised of mixtures of PG and various amendments and the possibility of desiccation or tension cracking. The project also studied various factors affecting evapotranspiration with the aim of possibly reducing infiltration by increasing evapotranspiration.

Other research related to phosphogypsum stack closure includes:

- Establishing Vegetation Cover on Phosphogypsum in Florida. FIPR Publication No. 01-086-116.

- Hydrologic Evaluation of Final Cover System Alternatives for Closure of Phosphogypsum Stacks. FIPR Project No. 97-03-126.

- Evaluation of Lime Treatment Sludge Alternate Disposal Methodologies, Including Utilization in Closure of Phosphogypsum Stacks. FIPR Project No. 00-03-143.

Steven G. Richardson
FIPR Reclamation Research Director

ABSTRACT

Phosphogypsum (PG) stack closure rules require a cap to preclude rainwater percolation and groundwater impacts. Industry practice is to use polyethylene liner of permeability 10^{-7} cm/sec or less, overlain with overburden. Alternate approaches using compacted PG, alone or with additives, have not been investigated. Evapotranspiration (ET) from a vegetated stack also needs consideration. Therefore, laboratory work on the effects of PG compaction with additives such as bentonite, phosphatic clay, cement, and lime sludges on the permeability, cost consideration, desiccation, and tension cracking were evaluated on PG stacks. The field component consisted of ET measurements using a chamber method on existing vegetated plots. Phosphogypsum mixed and compacted with 15% phosphatic clay or 10% bentonite appears effective in achieving the 10^{-7} cm/sec permeability desired. The laboratory tests demonstrated low potential for cracking of PG from desiccation. Tension cracks occurred at 3% volumetric shrinkage for compacted PG, which correlated with other research. Cracks likely occur near the transition from side slopes to top of stack, where change in slope is greatest. These areas do not provide significant infiltration and are typically not covered when using liners. Approximately $25,000 per acre savings is possible using compacted clay-PG mixtures with vegetation. Vegetated stacks contribute to additional water loss but may be impacted by mowing, fertilization, and double cropping with grass. Results from this research warrant further field study.

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EXECUTIVE SUMMARY

INTRODUCTION

The current practice for retiring phosphogypsum stacks in Florida involves placing a high-density polyethylene liner as a cap. The liner is then covered with soil and stabilized with a grass cover. The liner is used essentially to eliminate the infiltration of rainwater, and thus reduce the percolation of contaminated water out of the bottom of the stack.

In 1997, BCI proposed alternative methods for retiring phosphogypsum stacks that also minimize the percolation of surface water. One such method is the compaction of a sub-layer of phosphogypsum (PG) alone or with additives to reduce the layer's vertical hydraulic conductivity and subsequent deep percolation from the root zone. Although use of additives can reduce the vertical conductivity to about 10^{-6} cm/sec or less, it cannot eliminate the downward movement of water. Another effective method of reducing deep percolation of water is to maximize the water loss via evapotranspiration (ET) to the atmosphere.

This report presents work completed for the four work elements in Phase I of the study titled *Phosphogypsum Stack Closure: Evaluation of Phosphogypsum (PG) as an Alternative Final Cover*. The four major work elements were:

- Laboratory evaluation of amendments on permeability of PG and a brief cost analysis
- Laboratory evaluation of amendments and moisture changes on desiccation cracking
- Laboratory evaluation of tension cracking
- Field evaluation of Evapotranspiration (ET) from vegetated PG stacks

The conclusions from each work element are summarized and our recommendations for Phase II follow.

PERMEABILITY STUDY

Several conclusions can be drawn from the laboratory evaluation of amendments and compaction on the permeability of PG:

- The permeability of compacted PG without additives is not less than 1×10^{-5} cm/sec.
- The permeability of PG can be decreased through the addition of clay materials and increases in compaction energy. With the addition of 10% bentonite clay or 15% phosphatic clay and the input of modified Proctor compaction energy, the permeability of PG can be reduced to less than 1×10^{-7} cm/sec.

- The addition of lime sludge or cement to compacted PG was not practical for reducing the permeability in a cost-effective manner.
- The input of compaction energy in excess of modified Proctor does not produce a significant decrease in permeability.
- The increase in clay additive for bentonite or phosphatic clay above 15% has a minimal effect on further reductions in the permeability of compacted PG.
- Preliminary cost analysis suggest possible savings of $15,000.00 to $25,000.00 per acre, depending on the use of amendments for the barrier layer.

DESICCATION STUDY

Several conclusions are drawn from the desiccation study test results. The conclusions are based upon three major factors: (1) calculated test results, (2) visual inspection, and (3) previous research and predictions. The conclusions are as follows:

- The amended PG samples showed no desiccation cracking with volumetric strains as large as 12%.
- The amended PG samples typically reached their maximum strain within 5 to 7 days of air-drying, regardless of additive or compaction energy, without cracking.
- Volumetric strains increased as the molding moisture content was increased above the optimum moisture content.
- The amended PG samples showed a strain of about 5% when the moisture content decreased from the molding moisture content, typically 15%, to the expected field moisture content averaging 12%.
- The amended PG does not exhibit the high strain and cracking characteristics of compacted clay liners, which typically show minor cracking at 5% strain and severe cracking at 10%, resulting in significant increases in bulk permeability.
- These laboratory test results demonstrate the low potential for cracking of amended PG due to desiccation. The measured strains are significantly lower than reported values for compacted clay liners, and visual inspection of the amended PG samples found no formation of cracks after the maximum strains had been reached.

TENSION STUDY

The tension crack study produced results that correlate well with previous tension studies, which leads to the following conclusions:

- The laboratory determined failure tensile strain (visible cracking) is approximately 3% for compacted PG.

- The failure strain of 3% correlates well with similar research, which determined the failure strains of compacted clays, silts and embankment materials to range from 0.1 to 4.4%.
- Differential settlements distributed over long horizontal distances will not develop large enough tensile strains to produce tensile cracks.
- If tensile cracks occur, they are most likely to be located near the side slope to top transition where the change in surface slope is the greatest and there is an increase in vertical stresses. These areas do not provide significant infiltration into the stack and are typically not covered even when using a synthetic liner system.

EVAPOTRANSPIRATION STUDY

The conclusion from the field ET study can be summarized as follows:

- The bare plots had significantly lower evapotranspiration rates (60-70%) than the vegetated ones. Vegetating the PG stack will definitely remove more water from the PG-soil matrix.
- Alamo switchgrass had slightly higher evapotranspiration and photosynthesis than the bermudagrass and these values responded more to Nitrogen (N) fertilization.
- Evapotranspiration rate is increased by increased N fertilization for both grasses but the effect was greater for alamo switchgrass than bermudagrass.
- Evapotranspiration rate was decreased at low soil moisture content although this effect is muted if transpiration is limited.
- Evapotranspiration rates were slightly lower for steeper soil slopes. Although evapotranspiration could be lower at higher slope angles, infiltration is also likely to be lower, so that there will be less infiltrated water to export via ET. The net effect of slope angle on deep percolation of water is unclear.
- Evapotranspiration rate was increased with sandy overburden soil on side slope plots but decreased on top plots. The most likely explanation is that the soil has higher infiltration rates but lower available moisture capacity, thus limiting ET on the top sites where infiltration rate is less critical and enhancing infiltration and ET on the side slope plots.
- Photosynthesis values are very low during the summer even under adequate water and nitrogen, which suggests that heat stress is important in the middle of the summer.
- Summer mowing had ambiguous effects on ET because of the complicating effects of moisture and heat stress. Winter mowing seems to be a suitable alternative.

CONCLUSION

This Phase I study demonstrates that compacted and amended PG can significantly reduce the permeability of a barrier layer, and thus reduce infiltration of rainwater into PG stacks. Further, the results of the laboratory study indicate that a compacted PG barrier layer will likely not crack due to desiccation or tensile stresses caused by fluctuations in moisture content or by differential settlement, thus maintaining its integrity.

RECOMMENDATIONS

Before application of findings from this research, a large scale field study should be conducted in order to monitor the effects of factors such as actual field mixing and compaction techniques, moisture content variations, climate changes, vegetation growth and stack settlement on the integrity and permeability of an amended PG liner. Existing stacks should be inspected to evaluate the effects of differential settlement in the field.

In addition, the ET study suggests a number of recommendations for maximizing ET losses from PG stacks:

- Plant a hardy, long-season, cover crop such as bermudagrass over the entire stack.
- Combine bermudagrass and alamo switchgrass to maximize both hot and cool season ET.
- Cap with overburden soil containing significant organic nitrogen or slow-release N (isobutylidene diurea, methylene urea, etc.) for grass crop establishment.
- Use soils with high water-holding capacity on the stack top, and high infiltration rate soils on the side slopes.
- Annually apply slow-release nitrogen fertilizer in the spring using the lowest recommended fertilization rate. This low rate should be sufficient for grass maintenance, while minimizing cost and environmental impact.
- Annually mow grass during the winter when heat and moisture stress are limited.

Therefore, we recommend that an additional study be developed that will better address the management issues, such as mowing frequency, double cropping pest management, and soil amendments, that affect ET rates.

INTRODUCTION

This report presents work completed by BCI to evaluate the benefits and costs associated with the potential use of Phosphogypsum (PG) as a "final top cover" for stack closure. This research work investigated the potential use of PG as a "barrier layer" material to minimize, or preclude, rainwater infiltration and evaluation of evapotranspiration (ET) as a means of additional water loss from surface of a PG stack.

The intent of the Florida Administrative Code (FAC) Chapter 62-673 (1993) is to preclude infiltration of storm water into PG stacks upon closure. Although the design standards do not require exclusive use of High Density Polyethylene (HDPE) liner, they have been the preferred industry method due to lack of data that show alternate, cost-effective methods. There has been no previous work to show that compaction of PG alone or with additives such as clay materials can be a cost-effective method to attain the desired permeabilities. Furthermore, preliminary work has shown that additional loss of water can occur from the surface of PG through evapotranspiration (ET) from vegetated stacks, but additional measurements are required to substantiate this initial finding.

STATEMENT OF PROBLEM

FAC Chapter 62-673 states that "closure plans for phosphogypsum stacks shall include a final cover system designed to: (1) Promote drainage off the stack; (2) Minimize ponding; (3) Minimize erosion; (4) Minimize infiltration into the phosphogypsum stack; and (5) Function with little or no maintenance."

To accomplish the above requirements, it will be necessary to regrade the stack material and emplace a low permeability barrier layer that is further capped by material capable of sustaining vegetation. Previous studies of PG stacks suggest that a vegetative cover significantly improves surface runoff quality (Richardson and others 1995; BCI 1995).

Existing natural vegetation on PG surfaces, though sparse, indicates that establishment of vegetative cover is possible. Residual acidity, nutrient deficiencies or imbalances, along with low nutrient-holding capacity, and surface hardness or "caking" are cited as likely reasons from sparse vegetation. Work by Patel and others (1994) and Richardson and others (1995) has shown the vegetation cover on PG can be significantly improved upon amelioration of the chemical and physical properties using various amendments and tillage operations and the use of suitable plant species.

Currently, Chapter 62-673 requires a geomembrane or low permeability barrier soil layer covered with a layer of soil or amended PG that can sustain a vegetative cover on the flatter top gradient of the stack to preclude rainfall infiltration into the stack.

According to Chapter 62-673, a "final cover may consist of synthetic membranes, soils, or chemically or physically amended soils or phosphogypsum. Final cover shall be placed over the entire surface of the phosphogypsum stack." The use of synthetic covers is not without concerns such as cost and erosion or movement of the soil cover/synthetic cover interface.

Previous studies suggest the use of PG not only as a successful alternate barrier-layer material (Patel and others 1996) but also as the primary media for vegetation establishment (Richardson and others 1995), thus significantly reducing stack closure costs. Should this technology prove successful, it could result in substantial savings for the processing companies while fully maintaining the "intent of the rule" to minimize infiltration into the stack and preclude drainage and improve runoff water quality, thus protecting human health and the environment, the primary goal of Chapter 62-673.

CURRENT REGULATIONS AND INDUSTRY PRACTICES

Chapter 62-673 requires that "the final cover on the top gradient shall consist of a barrier soil layer at least 18 inches thick, emplaced into 6-inch thick lifts. A final 18 inch thick layer of soil or amended phosphogypsum that will sustain vegetation to control erosion shall be placed on top of the barrier layer." Furthermore, if the stack base is "unlined," as is the case with most PG stacks in Florida, then the barrier layer must have a minimum permeability of 1×10^{-7} cm/sec or lower. However, if the stack is "lined," then a permeability of 1×10^{-5} cm/sec or lower is acceptable. It is assumed from this that a permeability of 1×10^{-5} cm/sec will effectively reduce or preclude infiltration so as to minimize the water mound in a stack over time. If such were not the case, then for a lined stack, there would be both infiltration and percolation, and therefore, a need to establish an indefinite water treatment and monitoring program.

Previous Research on Permeability

The engineering properties of PG have been studied in recent years in hopes of finding an economic use for PG. Ho and Zimpfer (1985) performed a comprehensive laboratory study to determine the engineering properties of PG for several stacks in Florida. Their testing program included specific gravity, grain size analysis, limerock bearing ratio (LBR), permeability, triaxial compression, gypsum content and pH. The average test results from their study are summarized below in Tables 1, 2, and 3.

Table 1. Engineering Properties of PG: Specific Gravity, Grain Size Distribution, pH and % Gypsum (Ho and Zimpfer 1985).

Source	Specific Gravity	Sieve Size (% Passing) 40	60	200	pH	% Gypsum
W.R. Grace	2.39	100	99	55	3.5	92.5
AMAX	2.33	100	99	72	4.5	89.0
Occidental 1	2.35	100	98	79	2.5	96.7
Gardinier	2.40	93	88	51	4.3	81.3
Occidental 2	2.34	100	98	80	4.9	98.7
Conserv	2.44	100	96	31	6.0	99.3
IMC	2.34	100	98	69	5.2	95.0

Table 2. Engineering Properties of PG: Moisture-Density, LBR and Shear Strength (Ho and Zimpfer 1985).

Source	Max. Dry Density and Opt. Moist. Content		LBR	Triaxial Shear Strength	
	Modified	Standard		Φ	c
W.R. Grace	97.1 pcf @ 15.0	91.7 pcf @ 12.8	40.2	50.0°	0
AMAX	90.3 pcf @ 18.4	83.0 pcf @ 19.2	5.0	47.5	0
Occidental 1	92.2 pcf @ 17.3	91.7 pcf @ 18.9	13.5	45.0	0
Gardinier	101.0 pcf @ 14.1	95.0 pcf @ 16.8	26.0	49.0	0
Occidental 2	91.6 pcf @ 17.7	84.6 pcf @ 21.6	7.5	43.5	0
Conserv	94.9 pcf @ 15.0	90.4 pcf @ 19.1	21.7	47.5	0
IMC	96.9 pcf @ 16.4	91.9 pcf @ 18.4	17.2	46.5	0

The Ho and Zimpfer (1985) study also included permeability results from falling head tests on compacted PG samples. They found the permeability of unpurified PG was in the range of 3.8×10^{-4} to 1.3×10^{-5} cm/sec. The average test results are summarized in Table 3. The test results generally show a decrease in permeability, on the order of 0.5, when increasing the compaction energy from standard (ASTM D698) to modified Proctor (ASTM D1557).

Table 3. Permeability of PG at Modified and Standard Proctor Density (Ho and Zimpfer 1985).

Source	Permeability (cm/sec)	
	Modified	Standard
W.R. Grace	3.2×10^{-5}	3.5×10^{-4}
AMAX	6.3×10^{-5}	1.7×10^{-4}
Occidental 1	1.5×10^{-5}	3.5×10^{-5}
Gardinier	4.5×10^{-5}	5.9×10^{-5}
Occidental 2	4.1×10^{-5}	7.5×10^{-5}
Conserv	9.7×10^{-5}	4.6×10^{-5}
IMC	5.0×10^{-5}	6.8×10^{-5}

Kenney and others (1992) performed studies on compacted sand and bentonite mixtures showing that as little as 4% bentonite is required to reduce permeability below 1×10^{-7} cm/sec. At 8% bentonite, the permeability of the compacted sample was reduced to 1×10^{-8} cm/sec. The compacted sand and bentonite samples reached a minimum permeability of approximately 1×10^{-10} cm/sec at 22% bentonite. Test results on pure bentonite show the permeability to be in the 1×10^{-9} to 1×10^{-10} cm/sec range.

Haug and Wong (1991) studied the effect of molding moisture content versus the permeability of compacted sand and bentonite mixes. Test samples consisting of Ottawa sand and 8% bentonite were compacted at different moisture contents. The permeability decreased from 6.5×10^{-9} cm/sec for a molding moisture content of 5.8% to 1.1×10^{-9} cm/sec for a molding moisture content of 14.7%. The maximum dry density of the mix was approximately 113.0 pounds per cubic foot (pcf) at an optimum moisture content of 14.5%. The minimum permeability occurred just past the peak of the moisture-density curve on the wet side of the optimum moisture content. As the molding moisture content increased, the permeability increased to 1.45×10^{-9} cm/sec at 16.2% and 1.8×10^{-9} cm/sec at 18.9%. Haug and Wong (1991) showed that for a sand-clay mix the molding moisture content has an effect on the permeability, but the effect is relatively small, causing a variation in permeability of less than one order of magnitude.

Preliminary laboratory work by BCI (1995) using PG has shown that permeability can be reduced to about 10^{-6} cm/sec with additional energy input. Permeability was also found to decrease with additional of smaller amounts (3-5% by dry weight) of materials such as phosphatic clay, pond water neutralization sludge, or bentonite (a material that is commonly used in slurry walls construction to contain or eliminate seepage problems).

Previous Research on Desiccation Cracking

Desiccation cracking of soil barrier layers has been a problem in the landfill industry for years. Cracking of clay layers occurs due to fluctuations in moisture content causing swelling and shrinkage, which in turn leads to cracking. The cracking leads to a significant increase in the overall permeability of the liner. Extensive research has been conducted on this phenomenon in recent years.

Kleppe and Olson (1985) measured the effects of molding moisture content, sand content and volumetric strain due to desiccation on the permeability of compacted clay samples. Volumetric shrinkage strains of less than 5% showed relatively minor cracking having little or no effect on the permeability, while 10% strain led to severe cracking which greatly increased the samples' permeability. Clay samples compacted at high moisture contents, 15 to 20%, showed shrinkage strains in the range of 6 to 10%. Clay samples compacted at moisture contents less than 15% showed strains less than 5%. The addition of 50% sand to compacted clay samples showed a significant decrease in volumetric strains, but the higher percentage also increased the permeability by one to two orders of magnitude.

Drumm, Boles and Wilson (1997) studied the effects of desiccation cracks on the permeability of a compacted clay using a laboratory scale sectored lysimeter. The permeability of the clay was initially tested and was determined to be approximately 1.3 x 10^{-6} cm/sec. The clay was subjected to wetting and drying cycles in different sectors of the lysimeter to produce desiccation cracks. The sample was tested for permeability after each cycle. In the sectors with visible desiccation cracks, the permeability of the clay increased to above 1 x 10^{-4} cm/sec, while the sectors with no cracks showed a smaller increase in permeability to 7 x 10^{-6} cm/sec.

Previous Research on Differential Settlement on Cracking

Differential settlements over short linear distance can cause severe damage to hydraulic barrier performance. Vertical subsidence creates horizontal tensile strains within the soil, which can cause cracking. The cracking can lead to localized zones of high permeability within a liner system.

Lee and Shen (1969) developed a test theory and model to predict horizontal soil movements and tensile strains based upon vertical subsidence. A plot of vertical subsidence versus horizontal distance could be used to determine horizontal strains within a soil profile by calculating the slope of the soil surface at any point. The beam analogy for horizontal movements is shown in Figure 1.

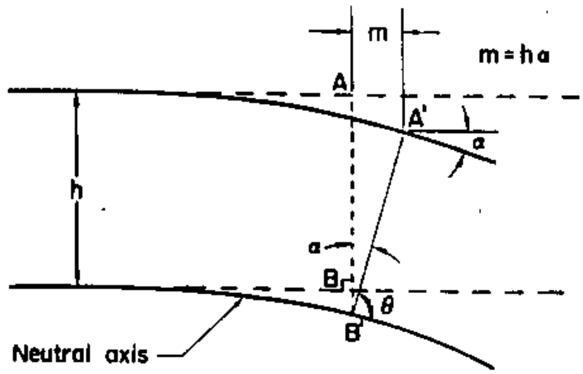

Figure 1. Beam Analogy of Horizontal Movements (from Lee and Shen 1969).

The theory was then compared to a laboratory scale study. A drawing of the test apparatus is shown in Figure 2. A beam of soil was deflected at one end, creating an average slope of 1% across the beam. The soil surface profile was surveyed and graphed, the slope of the soil surface was determined, and plots of horizontal movement and horizontal strain were developed.

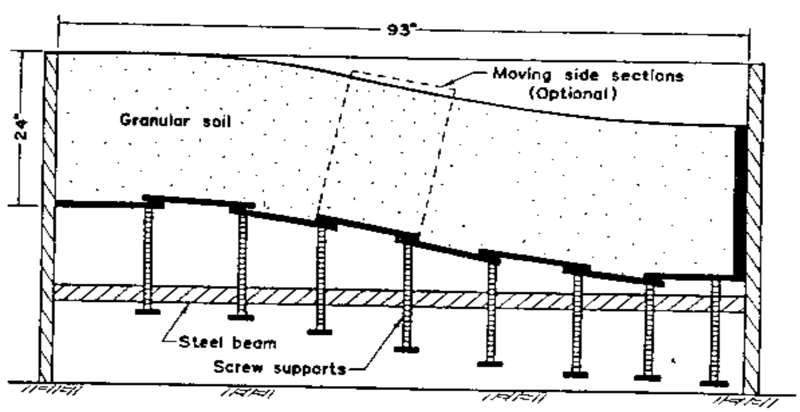

Figure 2. Schematic Drawing of Model Test Apparatus (from Lee and Shen 1969).

Lee and Shen performed several tests on sand and Styrofoam spheres and determined that the actual horizontal movements were approximately two-thirds of the predicted horizontal movements for granular soil, leading to the following equation:

$$m = 2/3H\alpha$$

where m is the horizontal movement, H is the thickness of the soil layer and α is the slope of the soil profile. BCI developed a similar testing apparatus devised for this research to determine the effects of tensile strains on phosphogypsum.

Leonards and Narain (1963) evaluated several embankment soils for tensile strength. Their test procedure included compacting a beam with dimension of 22 1/8 inches long by 3¾ inches deep by 3 inches wide, coating the beam in wax and then inserting pins into the beam of soil. Dead weights were then hung from the pins to cause the beam to bend and fail in tension. Leonards and Narain found the failure tensile strengths of compacted clays and silts to range from approximately 0.1 to 0.3%.

LaGatta, Boardman, Cooley and Daniel (1997) used a steel tank with a deflatable bladder to simulate differential settlement and measure the permeability of different liner systems. A liner system was constructed in the tank on top of a water-filled bladder. A diagram of the apparatus is shown below in Figure 3. The bladder was deflated, causing a settlement. A head of water was placed on the liner system in the tank and permeability measurements were taken as the settlements were increased until failure, the point at which the permeability increased significantly above 1 x 10^{-7} cm/sec. They correlated the permeability results to an angular distortion and average tensile strain based upon vertical subsidence across the entire length of the liner. Their results showed that compacted clay liners could withstand up to approximately 4% tensile strain before failure. Lagatta and others reported previous research showing tensile strains at failure for compacted clays ranged from about 0.1 to 4.4%.

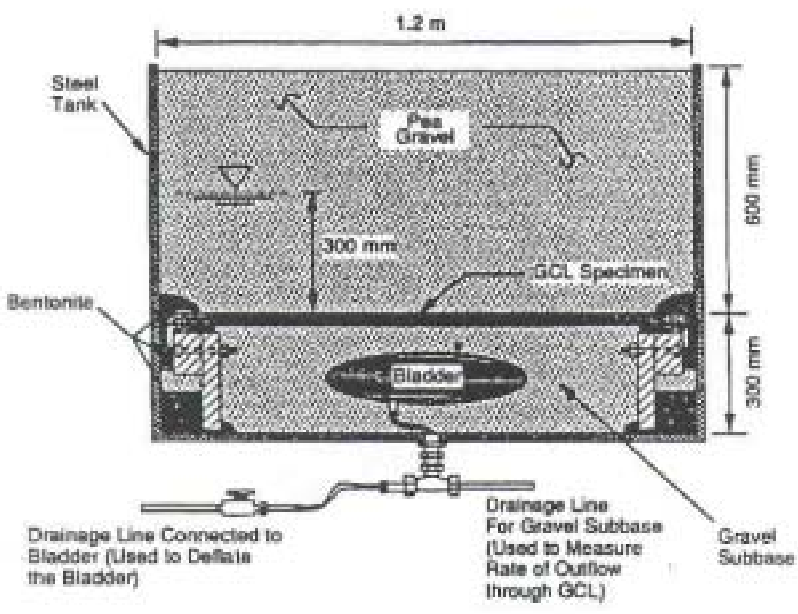

Figure 3. Cross Section of Tank (from LaGatta and others 1997).

RESEARCH PROJECT OBJECTIVES

To address the previously identified stack closure issues, the following objectives were outlined:

- Determine the effects of varying quantities of moisture and additives; phosphatic clay and bentonite, with varying degrees of compaction on the permeability of PG. The aim of this study will be to reduce the permeability of PG (with or without additives) to 1 x 10^{-5} to 1 x 10^{-7} (or lower) cm/sec or the achievable permeability.
- Determine the susceptibility of compacted and/or amended PG to desiccation cracking.
- Estimate costs of constructing a compacted or amended PG barrier layer as compared to a synthetic barrier layer system.
- Determine differences in the ET (water loss) due to different grass species previously established on PG stacks.

METHODOLOGY

EVALUATION OF ADDITIVES AND COMPACTION ON PERMEABILITY OF PHOSPHOGYPSUM

Site Selection

During the initial phase of this research in August 1997, it was BCI's intent to use PG from one of four stacks for the Phase I laboratory work. The stacks in consideration were IMC-Agrico, South Pierce; Cargill Fertilizer, Inc., Bartow Stack; C.F. Industries, Bartow; and Cytec Brewster. However, due to delays and restrictions as discussed below, PG from Farmland Hydro in Bartow was used for all the laboratory work presented in this report. The ET work was conducted at two new sites and utilized work from a previous study. All sites are described in the ET section.

Site Selection for Laboratory Evaluation of PG Permeability

BCI received approval and variance in monitoring from the Environmental Protection Agency on November 20, 1998, to remove up to 700 pounds (lbs) of PG each from the IMC-Agrico New Wales Stack and Farmland Hydro Stack. Due to the delays encountered in obtaining PG from IMC, BCI, following consultation with Dr. Steve Richardson of FIPR, decided to complete all laboratory testing on PG from the Farmland Hydro stack. Samples were collected from the top slopes as well as the side slopes, which was older PG. However, testing was limited to using the newly deposited PG from the top of the stack.

Research Testing Plan

The laboratory experiments of this research include determination of the moisture-density relationship (compaction) and measurement of the hydraulic conductivity or permeability of the PG with and without additives. Laboratory procedures were performed in accordance with ASTM standards (ASTM 1994). The research plan included measuring the effects of three levels of compaction energy and various additives on the permeability of PG. When a design mix showed favorable results (low permeability), the mix was then altered by either increasing the compaction or increasing the additive percentage. This procedure was continued until the test results showed no improvements (i.e., no decrease in permeability). Table 4 lists the matrix of test conditions including variations in compaction effort and additive percentage.

Table 4. Matrix of Test Conditions for Permeability of PG with Variations in Compaction Energy and Percentage of Additives.

Compaction Energy	Additive & Percentage
Standard	0%
Modified	0%
Extra-Mod.	0%
Standard	5% Bentonite
Modified	5% Bentonite
Extra-Mod.	5% Bentonite
Standard	10% Bentonite
Modified	10% Bentonite
Extra-Mod.	10% Bentonite
Modified	12.5% Bentonite
Modified	15% Bentonite
Standard	10% Phos. Clay
Modified	10% Phos. Clay
Standard	15% Phos. Clay
Modified	15% Phos. Clay
Modified	17.5% Phos. Clay
Modified	20% Phos. Clay
Modified	20% Lime Sludge
Modified	20% Cement

Sample Collection and Properties of PG and Additives

Phosphogypsum. Bulk samples of PG were obtained from the top of the Farmland Hydro stack in Bartow, Florida. Samples were collected in five-gallon buckets and transported to the soil mechanics laboratory at Florida Institute of Technology (FIT) in Melbourne, Florida. The PG was removed from the buckets and allowed to air dry. The PG was turned and mixed to ensure thorough drying and prevent buildup of large clods during the drying process. All PG samples were returned to the stack for disposal after completion of testing.

Prior to testing, the index properties of the PG were determined. The grain size distribution of the PG was determined using method ASTM D3282 (ASTM, 1994). From the grain size analysis, 100% of the PG passed the No. 40 (0.425 mm) sieve and approximately 80% of the PG passed the No. 200 (0.075 mm) sieve. The Atterberg limits were conducted in accordance with ASTM D4318 on material passing the No. 40 sieve

(ASTM 1994). The Atterberg limits test showed the PG to be non-plastic. The PG is classified as ML (inorganic silt) in the Unified Soil Classification System (USCS) (Holtz and Kovacs 1981). The specific gravity (G_s) of the PG ranged from 2.33 to 2.55, with an average value of 2.42. A specific gravity of 2.4 was used for all calculations for PG alone; however, it was modified to consider the effects of the additives.

Bentonite. The bentonite clay was donated by WYO-BEN, Inc., of Billings, Montana and was delivered to FIT in a five-gallon bucket. This clay is a commercial grade product called Envirogel 200 Plus and is a high swelling sodium bentonite processed specifically for soil/bentonite membranes. Envirogel 200 Plus is a finely ground bentonite powder capable of filling small void spaces inherent in fine-grained soils. No special preparation of the bentonite was required. The bentonite has a minimum of 80% material by dry weight passing the No. 200 sieve. The Atterberg limits tests yielded a liquid limit of approximately 475% with a plasticity index of 375%. The bentonite is classified as a CH (high plasticity clay) in the USCS (Holtz and Kovacs 1981).

Phosphatic Clay. The phosphatic clay was made available by Mobil from its Ft. Meade, Florida mining facility and was delivered to FIT in five-gallon buckets. Initially the clay was extremely wet, having moisture contents ranging from 500 to 700% and could not be used as an additive in this form. The clay was dried to a moisture content of approximately 50 to 75% before mixing.

The moist phosphatic clay did not mix well with the PG. Small clods formed during mixing providing an uneven mix. Even after phosphatic clay was dried completely and crushed into quarter inch sized particles, the clay clods still formed during mixing. To provide a consistent, homogeneous mix, the phosphatic clay must be dried and then ground into a powdered form similar to the bentonite, which is probably not practical for a field application.

A wet sieve analysis on the phosphatic clay showed 98% of the material passing the No. 200 sieve. The Atterberg limits test yielded an average liquid limit of 180% and a plasticity index of 100%. The phosphatic clay is classified as a CH or high plasticity clay in the USCS (Holtz and Kovacs 1981).

Lime Sludge. The lime sludge was made available by Cytec Industries from its Brewster stack in Bradley Junction, Florida, and was delivered to FIT in five-gallon buckets. Similar to the phosphatic clay, the lime sludge was too wet to mix with the PG initially. The lime sludge was oven-dried at 40ºC and ground easily to yield a fine powder, which provided better mixing characteristics. The chemical composition of the lime sludge was not determined. A wet sieve analysis on the lime sludge showed 55% of the material passed the No. 200 sieve. The Atterberg limits test yielded a liquid limit of 260% and a plasticity index of 100%. The lime sludge is classified as MH (inorganic elastic silt) in the USCS (Holtz and Kovacs 1981).

Cement. The cement used was a Type I Portland cement purchased from a local building supply store. The cement was a fine dry powder and provided good mixing qualities. After mixing and hydration, the PG and cement mix formed brittle clods. The clods were broken down during compaction, but a pozzolanic reaction between the PG and cement was observed.

Sample Preparation

The PG was prepared for permeability testing at three levels of compaction energy (standard, modified and extra-modified) with varying amounts of additives. For each compaction test, five PG samples were prepared with or without additives at varying moisture contents. Two thousand grams of dry PG were weighed for each sample. Each sample was mechanically mixed with varying amounts of water and additives. Each sample was sealed in a plastic container and allowed to hydrate for a minimum of 24 hours prior to compaction.

The compaction tests were performed using the ASTM D698 (standard Proctor) and ASTM D1557 (modified Proctor) methods and a method designated as extra-modified (ASTM, 1994). Each method specifies a designated amount of energy be applied through the drop of a hammer to a certain number of layers of test material. The mold volume, weight of hammer, number of test material layers, number of blows per layer and compaction energy are summarized in Table 5. The extra-modified Proctor method used is not designated by ASTM. This method is the same as the modified Proctor method, however, the number of blows per layer is increased to 50, yielding an equivalent compaction energy of 112,500 foot-pounds per cubic foot (ft-lb/ft^3) as compared to the 56,250 ft-lbs/ft^3 of the modified Proctor method.

Table 5. Proctor Compaction Test Parameters.

Parameter	Standard	Modified	Extra-Modified
Mold Volume (ft^3)	1/30	1/30	1/30
Weight of Hammer (lbs.)	5.5	10	10
Height of Drop (ft.)	1.0	1.5	1.5
Number of Test Material Layers	3	5	5
Number of Blows per Layer	25	25	50
Compaction Energy (ft-lb/ft^3)	12,375	56,250	112,500
ASTM Designation	D 698	D 1557	N/A

After compaction, each sample was weighed to determine the wet density. The moisture content of each compacted sample was determined from the trimmings. The dry density was calculated and the moisture-density curve was plotted. The samples were then extracted from the mold using a hydraulic press. Extraction did not present any difficulties due to the apparent cohesion of the PG.

The temperature at which the non-structural or free water is removed from PG is critical and should not exceed 104^{o}F (40^{o}C) when determining the moisture content. Temperatures above 104^{o}F may cause crystalline water molecules within the dihydrate PG structure to evaporate, thus giving the appearance of a higher moisture content, and altering the chemical structure of the PG to hemihydrate or anhydrite (Saylak and others 1988). Three of the five compacted samples were chosen for permeability testing. The three samples were chosen as either the closest to the optimum moisture content or highest dry density.

Permeability Test Methods and Procedures

The ASTM D5084 Method C (increasing tailwater level) for the measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter was used in this research project (ASTM 1994). This test method is typically utilized with undisturbed or compacted specimens that have a hydraulic conductivity less than or equal to 1 x 10^{-3} cm/sec. The test specimen is encased in a thin rubber latex membrane and sealed inside a permeameter chamber filled with water, as shown in Figure 4. A small confining pressure is applied to the outside of the sample. A backpressure, less than the confining pressure, is applied to the specimen to induce saturation by forcing the air voids to dissolve into the porewater. The saturation percentage is determined using the Skempton’s B value (Holtz and Kovacs 1981), which is the ratio of change in confining pressure to change in porewater pressure as measured by electronic pressure transducers

Once a saturation ratio of greater than 95% is obtained, a hydraulic gradient is applied across the test specimen. For materials with a permeability in the range of 1 x 10^{-6} to 1 x 10^{-7} cm/sec, ASTM recommends a maximum hydraulic gradient (change in total head/length of flow path) of 20 to 30, which approximately equates to three to five pounds per square inch (psi) pressure difference for a 4.5-inch sample length. Inflow and outflow values are recorded periodically until a constant value of hydraulic conductivity is achieved (Daniel 1994).

The compacted samples were extracted from the Proctor mold, encased in a latex membrane, and sealed in the flexible wall permeability chamber. An initial confining pressure of 10 psi and a backpressure of five psi were applied to the sample. The confining pressure and backpressure were then simultaneously increased, maintaining the five psi difference to induce saturation of the sample. Typically, a saturation percentage greater than 90% was obtained after the confining pressure was increased to 70 psi. The confining pressure was then increased to 80 psi. A five psi pressure difference was applied across the sample as the top and bottom stones were subjected to a pressure of 70 and 75 psi respectively. The pressure difference of five psi equates to a hydraulic gradient of approximately 30 for a 4.5-inch sample length. The inflow and outflow volumes of permeated water were measured periodically. Once a consistent permeability value was obtained, the test was stopped. The sample was removed from the flexible wall permeameter, and the moisture content of the sample was measured at the ends and the center of the sample to check the final saturation percentage. Durham-Geo Enterprises, Inc., of Stone Mountain, Georgia, supplied the permeameter cells and pressure panel.

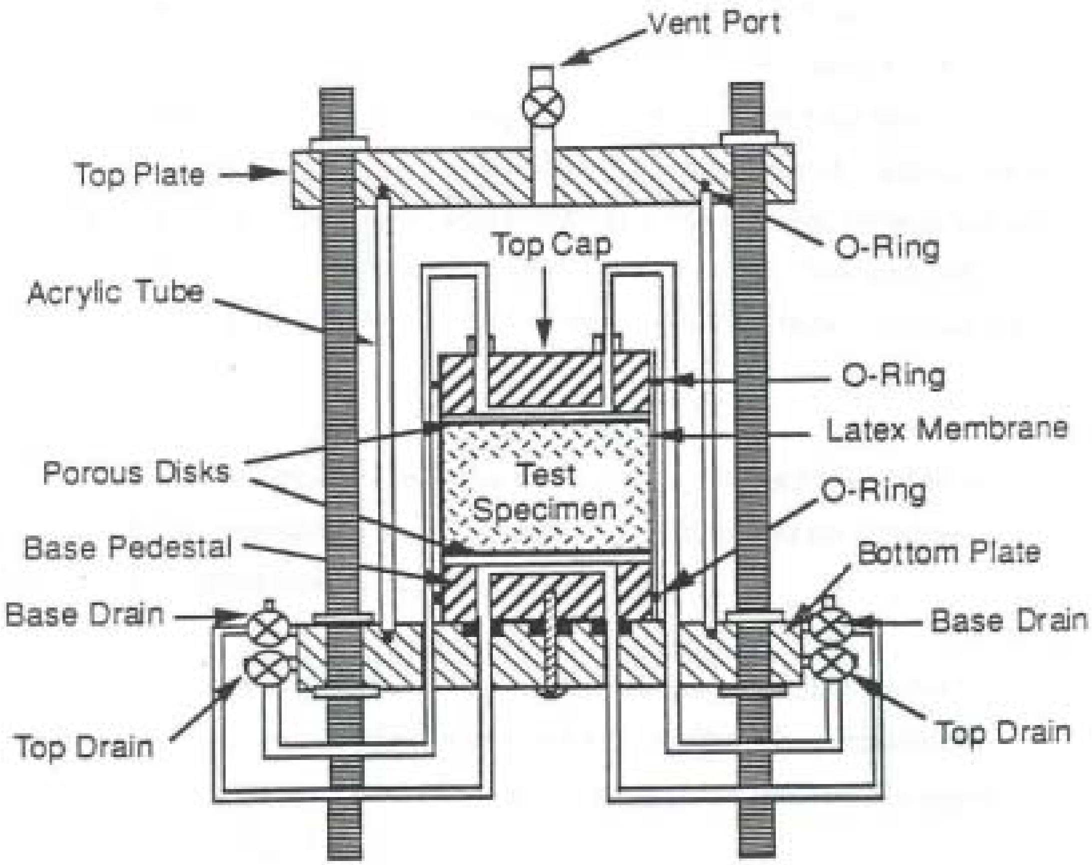

Figure 4. Flexible Wall Permeameter.

Results

Effects of Compaction Energy on Phosphogypsum

Initially, the PG was compacted using the standard, modified and extra-modified Proctor methods without amendments. Table 6 summarizes the maximum dry density, ($\rho_{d\ max}$), optimum moisture content (OMC) and permeability of the PG for the various compaction energy levels. Figure 5 shows the moisture-density curves for each sample, and Figure 6 shows the permeability values vs. molding moisture content. The 100% saturation (zero air voids) line for PG without additive is shown for a specific gravity (G_s) of 2.40.

The standard Proctor method yielded a $\rho_{d\ max}$ of 91.0 lb/ft^3 at an OMC of 14.5%. The permeability of the three samples near the peak of the moisture-density curve ranged from 8.5 x 10^{-5} to 7.1 x 10^{-5} cm/sec.

With modified Proctor compaction, the $\rho_{d\ max}$ was 100.0 pcf with an OMC of 12.0%. The permeability ranged from 3.8 x 10^{-5} to 3.0 x 10^{-5} cm/sec. The $\rho_{d\ max}$ was considerably higher than the standard Proctor $\rho_{d\ max}$. Using extra-modified Proctor compaction, the $\rho_{d\ max}$ was 102.0 lb/ft^3 at an OMC of 11.0%. The permeability ranged from 1.7 to 1.1 x 10^{-5} cm/sec. The maximum dry density, optimum moisture content and respective permeability values compared well with values reported by Ho and Zimpfer (1985).

Table 6. Maximum Dry Density, Optimum Moisture Content and Permeability for PG without Additive.

Compaction Energy	Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Standard	0%	91.0	14.5	7.1E-05
Modified	0%	100.0	12.0	3.0E-05
Extra-Mod.	0%	102.0	11.0	1.1E-05

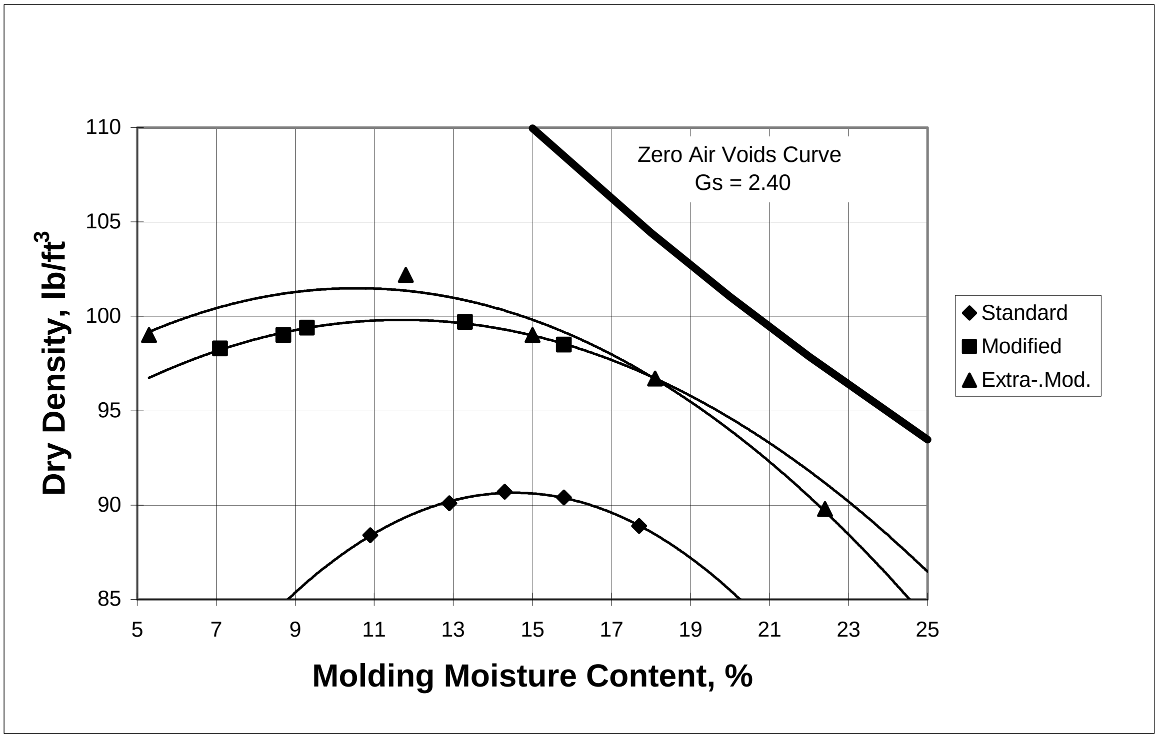

Figure 5. Dry Density Versus Molding Moisture Content for PG without Additive.

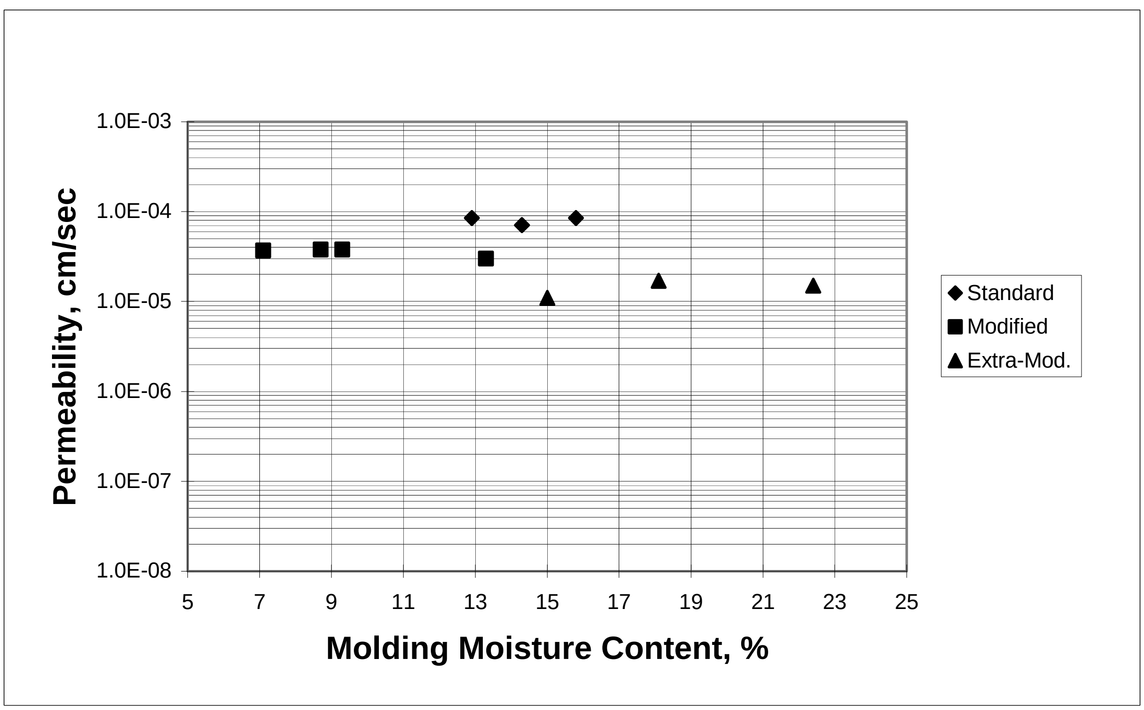

Figure 6. Permeability Versus Molding Moisture Content for PG without Additive.

PG with 5% Bentonite. The PG was mixed with 5% (by dry weight) bentonite clay and compacted using the three different Proctor methods. Table 7 summarizes the maximum dry density, ($\rho_{d\ max}$), OMC, additive percentage and permeability of the PG for all compaction energy levels. Figures 7 and 8 show the moisture-density curves and permeability, respectively, for each sample versus molding moisture content. The 100% saturation (zero air voids) curves for PG with 5% bentonite are shown for a G_s of 2.42.

The standard Proctor $\rho_{d\ max}$ was 93.0 lb/ft^3 at an OMC of 15.0%. The permeability near the peak of the moisture-density curve ranged from 2.5 to 1.3 x 10^{-5} cm/sec. The modified Proctor $\rho_{d\ max}$ was 101.5 lb/ft^3 at an OMC of 12.0%. The permeability near the peak of the moisture-density curve ranged from 6.0 to 3.4 x 10^{-7} cm/sec. The extra-modified Proctor $\rho_{d\ max}$ was 106.5 lb/ft^3 at an OMC of 11.0%. The permeability near the peak of the moisture-density curve was 1.2 x 10^{-7} to 8.9 x 10^{-8} cm/sec.

Table 7. Maximum Dry Density, Optimum Moisture Content and Permeability for PG with 5% Bentonite.

Compaction	Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Standard	5% Bentonite	93.0	15.0	1.3E-05
Modified	5% Bentonite	101.5	12.0	3.4E-07
Extra-Mod.	5% Bentonite	106.5	11.0	8.9E-08

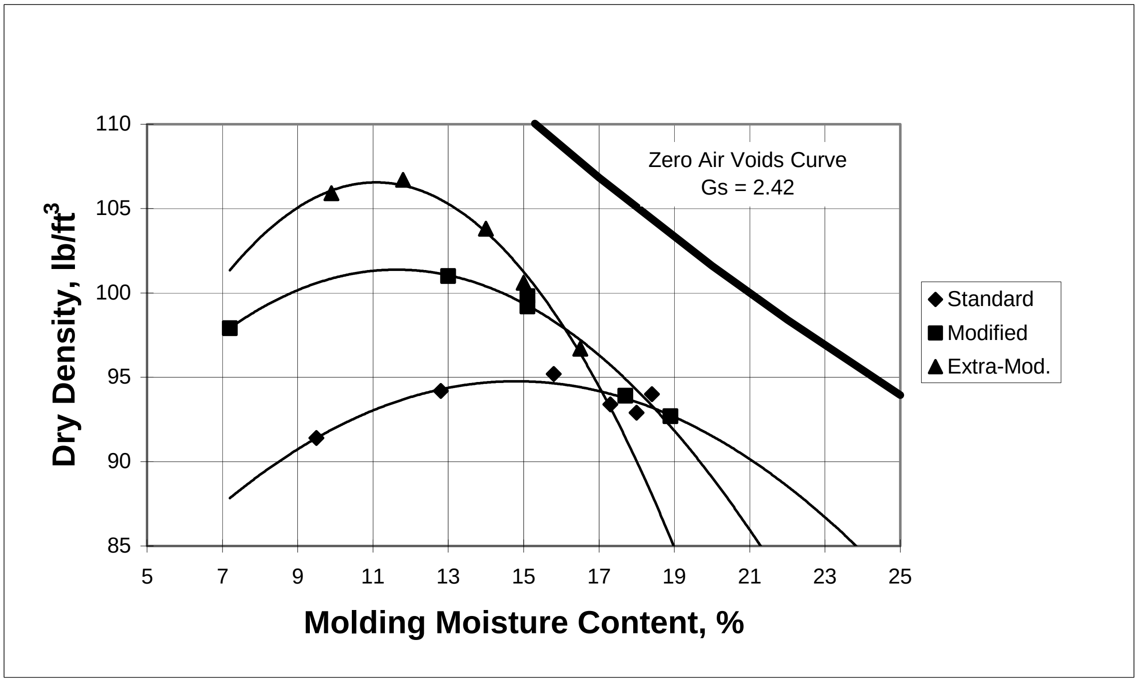

Figure 7. Dry Density Versus Molding Moisture Content for PG with 5% Bentonite.

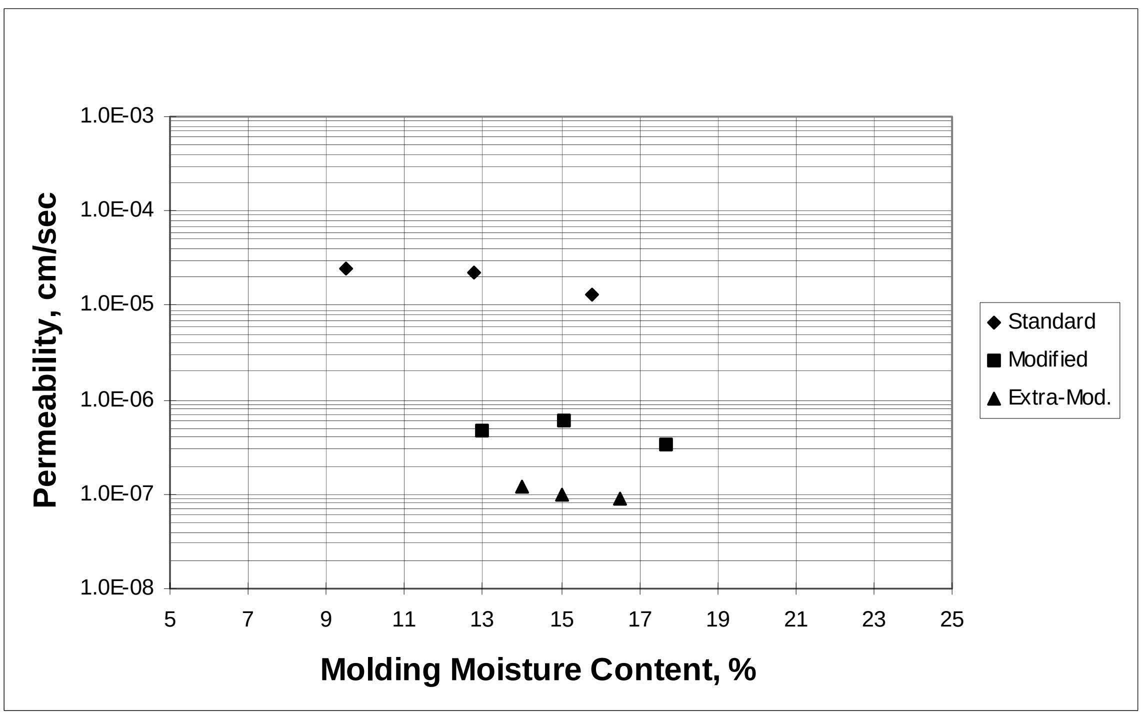

Figure 8. Permeability Versus Molding Moisture Content for PG with 5% Bentonite.

PG with 10% Bentonite. The PG was mixed with 10% (by dry weight) bentonite and compacted using the three Proctor methods. Table 8 summarizes the maximum dry density, $\rho_{d\ max}$, OMC, additive percentage and permeability of the PG for all compaction energy levels. Figures 9 and 10 show the moisture-density curves and permeability, respectively, for each sample versus molding moisture content for PG with 10% bentonite. The 100% saturation (zero air voids) curves for PG with 10% bentonite are shown for a G_s of 2.44.

The standard Proctor $\rho_{d\ max}$ was 96.0 lb/ft^3 at an OMC of 17.0%. The permeability ranged from 1.7 x 10^{-6} to 2.5 x 10^{-7} cm/sec. The modified Proctor $\rho_{d\ max}$ was 104.5 lb/ft^3 at an OMC of 13.0%. The permeability near the peak of the moisture-density curve ranged from 3.7 x 10^{-7} to 2.5 x 10^{-8} cm/sec. The extra-modified Proctor $\rho_{d\ max}$ was 106.5 lb/ft^3 at an OMC of 10.5%, while the permeability near the peak ranged from 2.3 x 10^{-7} to 2.1 x 10^{-8} cm/sec.

The effects of the extra-modified compaction energy on the permeability values of PG with 10% bentonite were almost insignificant. Therefore, a decision was made to not continue the permeability tests on PG with additives greater than 10% at this energy level.

Table 8. Maximum Dry Density, Optimum Moisture Content and Permeability for PG with 10% Bentonite.

Compaction Type	Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Standard	10% Bentonite	96.0	17.0	2.5E-07
Modified	10% Bentonite	104.5	13.0	2.5E-08
Extra-Mod.	10% Bentonite	106.5	10.5	2.1E-08

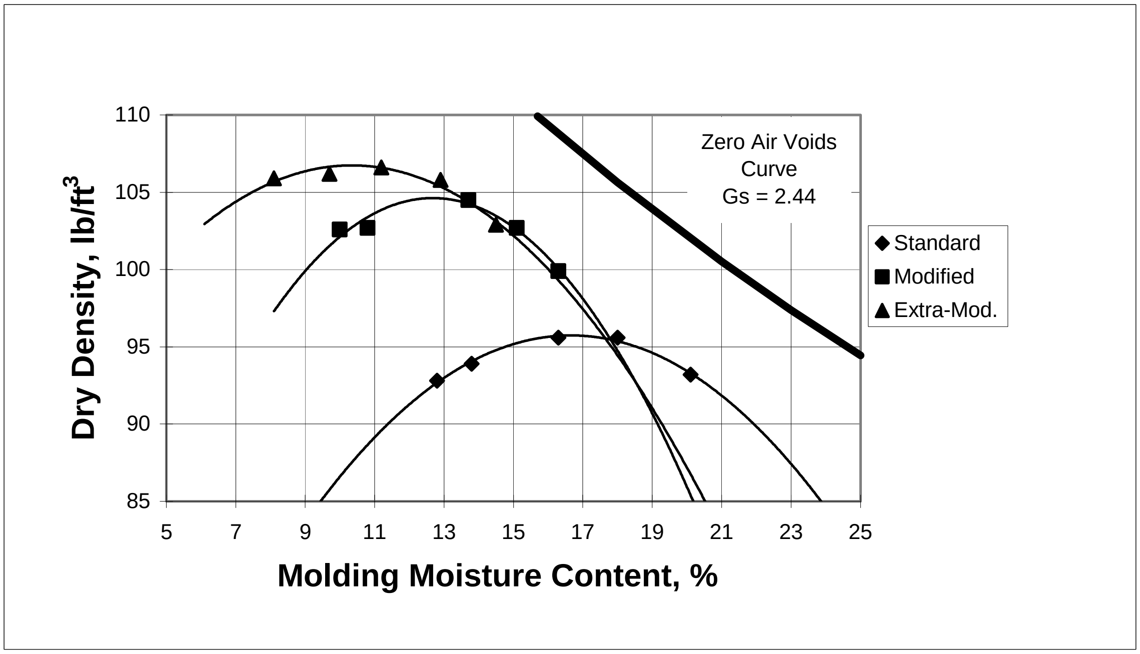

Figure 9. Dry Density Versus Molding Moisture Content for PG with 10% Bentonite.

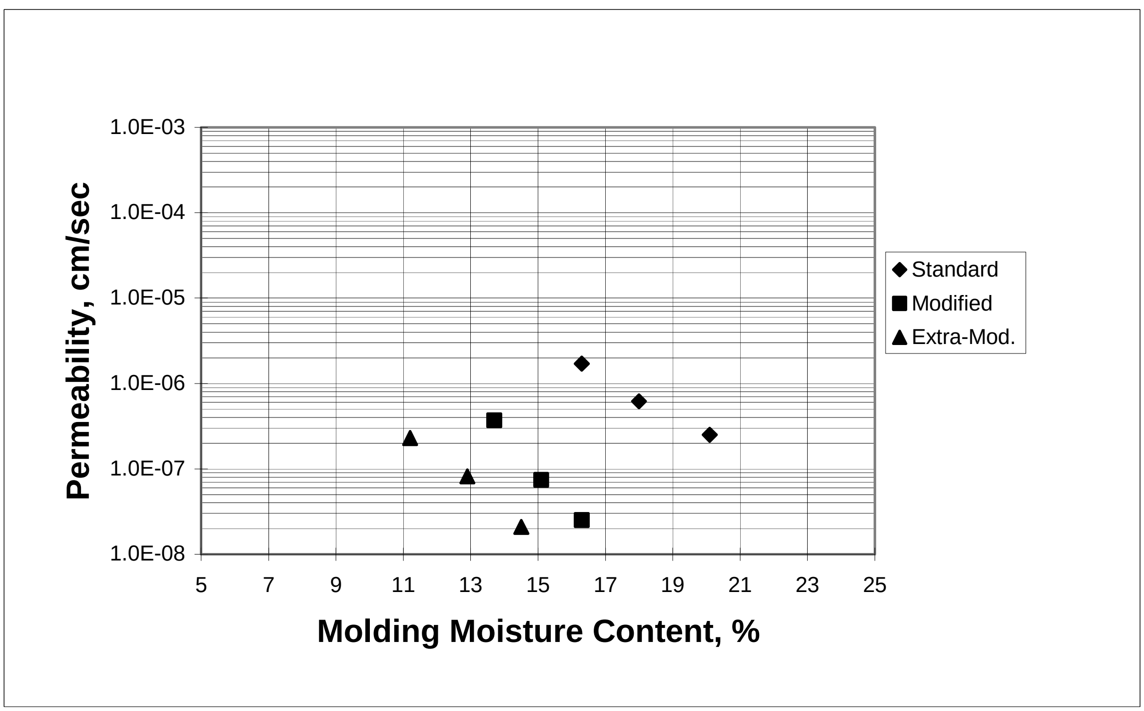

Figure 10. Permeability Versus Molding Moisture Content for PG with 10% Bentonite.

PG with 10% Phosphatic Clay. The PG was mixed with 10% (by dry weight) phosphatic clay and was compacted using the standard and modified Proctor methods. Table 9 summarizes the maximum dry density, ($\rho_{d\ max}$), OMC, additive percentage and permeability of the PG for standard and modified compaction energy levels. Figures 11 and 12 shows the moisture-density curves and permeability, respectively, for each sample versus molding moisture content for PG with 10% phosphatic clay. The 100% saturation (zero air voids) curves for PG with 10% phosphatic clay are shown for a G_s of 2.44.

The standard Proctor $\rho_{d\ max}$ was 95.5 lb/ft^3 at an OMC of 18.0%. The permeability near the peak of the moisture-density curve ranged from 1.1 x 10^{-4} to 4.9 x 10^{-5} cm/sec. The modified Proctor $\rho_{d\ max}$ was 98.0 lb/ft^3 at an OMC of 16.0%. The permeability near the peak ranged from 1.2 x 10^{-5} to 6.0 x 10^{-7} cm/sec. The permeability on the wet side of the OMC ranged from 3.3 x 10^{-6} to 6.0 x 10^{-7} cm/sec.

During mixing and compaction, it was observed that the moist phosphatic clay did not blend evenly with the PG. The phosphatic clay still formed small clods, which could not be blended evenly with extra mixing. The permeability test results would likely be influenced by the degree of clodding of the phosphatic clay within the test samples. Previous tests have shown that clay clodding can increase the permeability of a compacted soil up to six orders of magnitude (Benson and Daniel 1990). The test results indicate that the higher compaction energy of the modified Proctor test broke down the clods and helped to homogenize the sample, leading to a much lower permeability.

Table 9. Maximum Dry Density, Optimum Moisture Content and Permeability for PG with 10% Phosphatic Clay.

Compaction Type	Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Standard	10% Phos. Clay	95.5	18.0	4.9E-05
Modified	10% Phos. Clay	98.0	16.0	6.0E-07

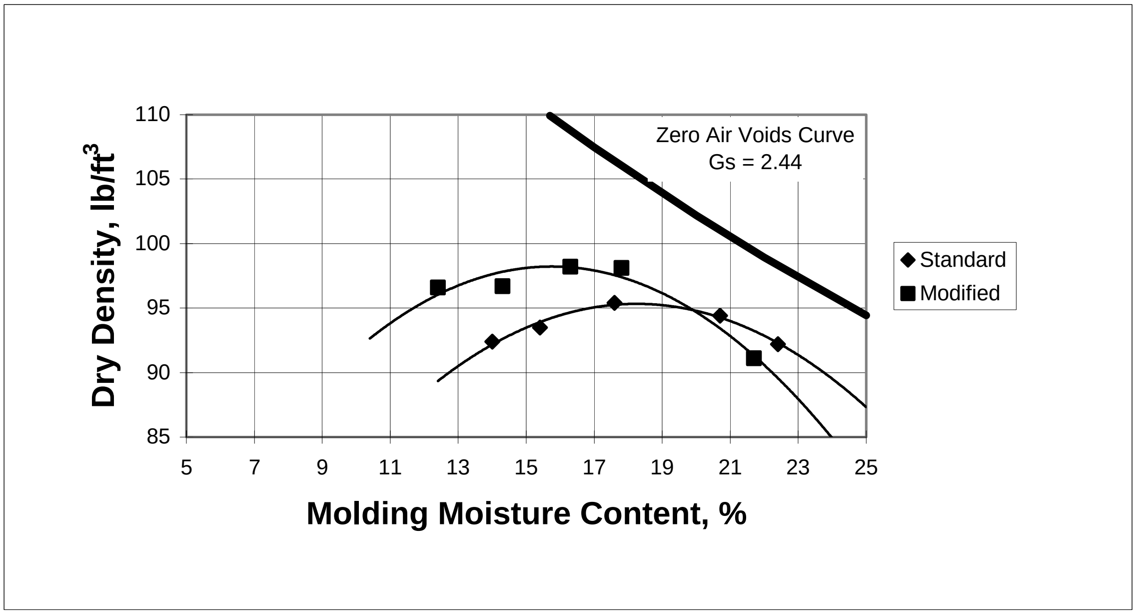

Figure 11. Dry Density Versus Molding Moisture Content for PG with 10% Phosphatic Clay.

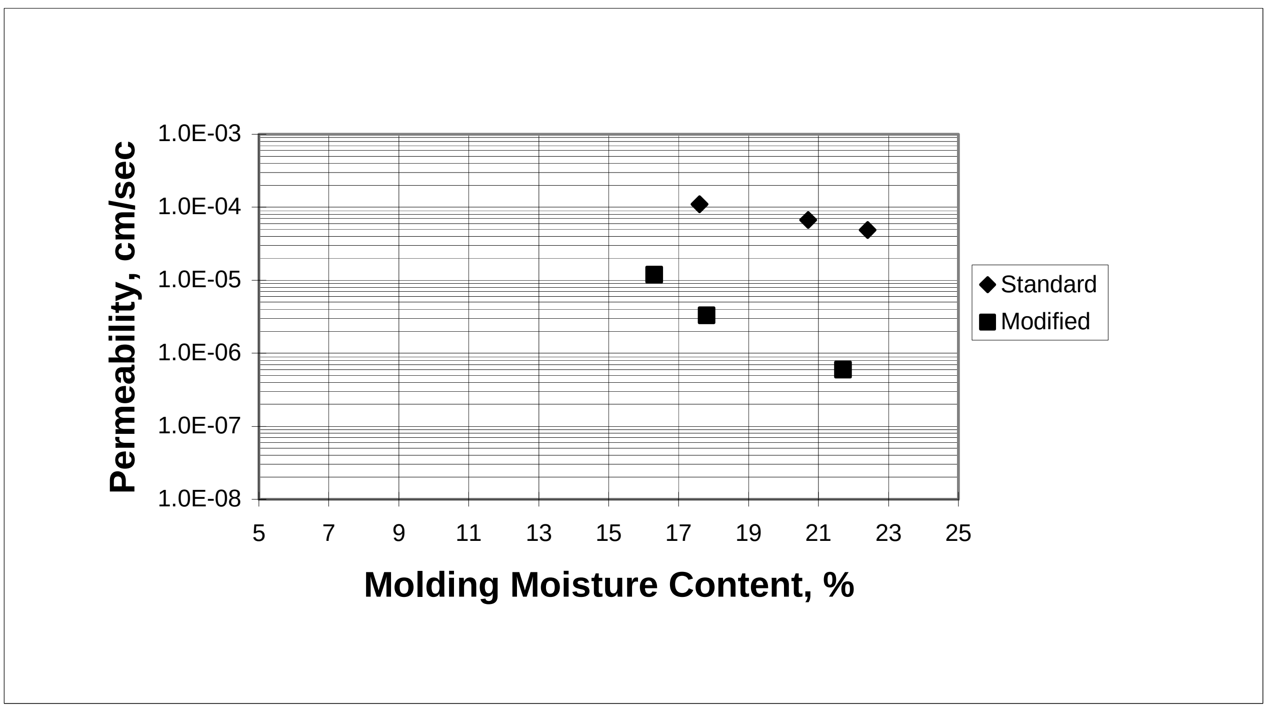

Figure 12. Permeability Versus Molding Moisture Content for PG with 10% Phosphatic Clay.

PG with 15% Phosphatic Clay. The PG was mixed with 15% phosphatic clay and was compacted using the standard and modified Proctor methods. Table 10 summarizes the maximum dry density, ($\rho_{d\ max}$), OMC, additive percentage and permeability of the PG for standard and modified compaction energy levels. Figures 13 and 14 shows the moisture-density curves and permeability, respectively, for each sample versus molding moisture content for PG with 15% phosphatic clay. The 100% saturation (zero air voids) curves for PG with 15% bentonite are shown for a G_s of 2.46.

The standard Proctor $\rho_{d\ max}$ was 87 lb/ft^3 at an OMC of 16.0%. The permeability near the peak of the moisture density curve ranged from 4.0 x 10^{-5} to 2.7 x 10^{-5} cm/sec. The modified Proctor $\rho_{d\ max}$ was 98.0 lb/ft^3 at an OMC of 15.0%. The permeability near the peak ranged from 2.1 x 10^{-7} to 9.8 x 10^{-8} cm/sec, again indicating that the higher compaction energy helped to homogenize the sample and resulted in a much lower permeability.

Table 10. Maximum Dry Density, Optimum Moisture Content and Permeability for PG with 15% Phosphatic Clay.

Compaction Type	Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Standard	15% Phos. Clay	87.0	16.0	2.7E-05
Modified	15% Phos. Clay	98.0	15.0	9.8E-08

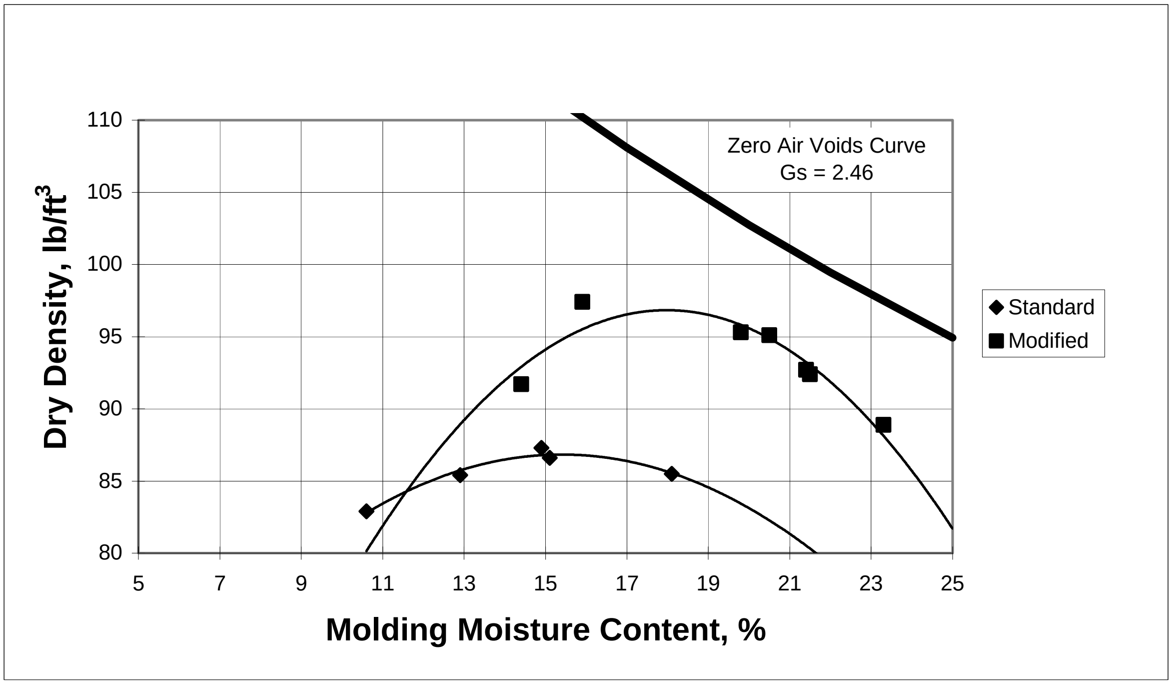

Figure 13. Dry Density Versus Molding Moisture Content for PG with 15% Phosphatic Clay.

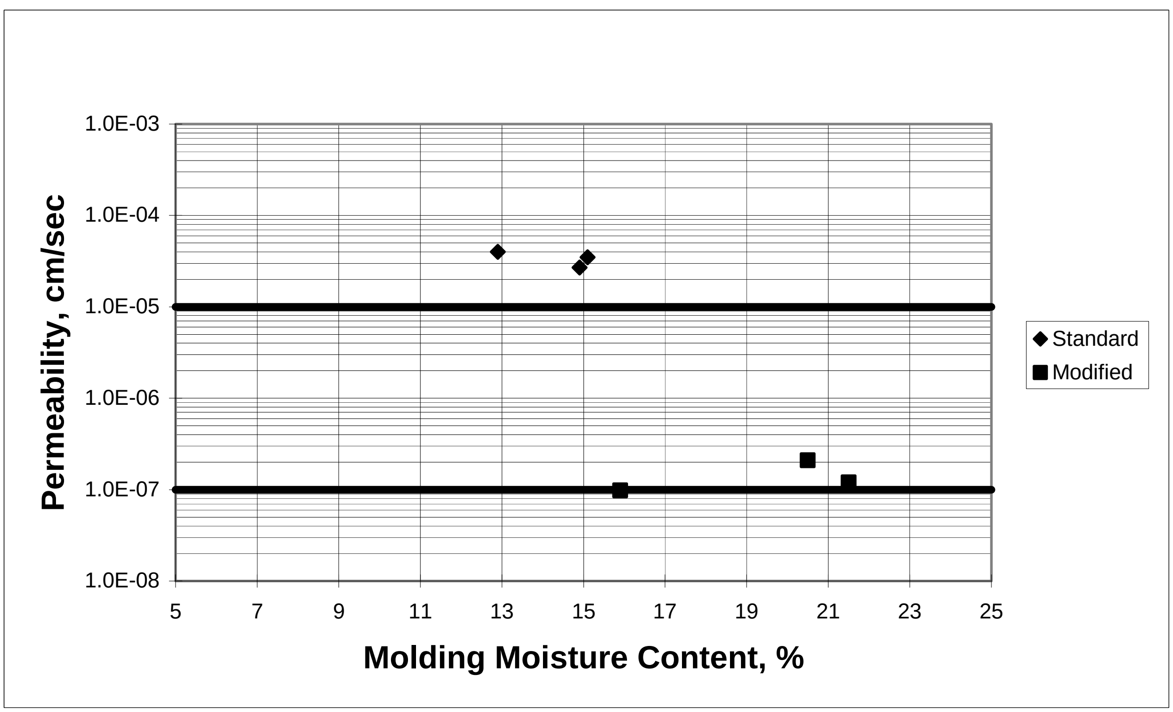

Figure 14. Permeability Versus Molding Moisture Content for PG with 15% Phosphatic Clay.

PG with 20% Lime Sludge. The PG was mixed with 20% (by dry weight) neutralized pond water sludge (lime sludge) and was compacted using the modified Proctor method. Table 11 summarizes the maximum dry density ($\rho_{d\ max}$), OMC, additive percentage and permeability of the PG for the modified energy level. Figures 15 and 16 show the moisture-density curve and permeability, respectively, for each sample versus molding moisture content for PG with 20% lime sludge. The 100% saturation (zero air voids) curves for PG with 20% lime sludge are shown for a G_s of 2.62.

The modified Proctor $\rho_{d\ max}$ was 89.0 lb/ft^3 at an OMC of 23%. The permeability near the peak of the moisture density curve ranged from 3.8 x 10^{-5} to 2.0 x 10^{-5} cm/sec. The addition of lime sludge to PG had little or no effect on the permeability, but the maximum dry density was significantly decreased and the optimum moisture content was significantly increased as compared to the bentonite and phosphatic clay additives. The permeability of PG with no additive at modified compaction was 3.0 x 10^{-5} cm/sec, and therefore no further tests with lime sludge as an additive were conducted.

Table 11. Maximum Dry Density, Optimum Moisture Content and Permeability for PG with 20% Lime Sludge.

Compaction Type	Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Modified	20% Lime Sludge	89.0	23.0	2.0E-05

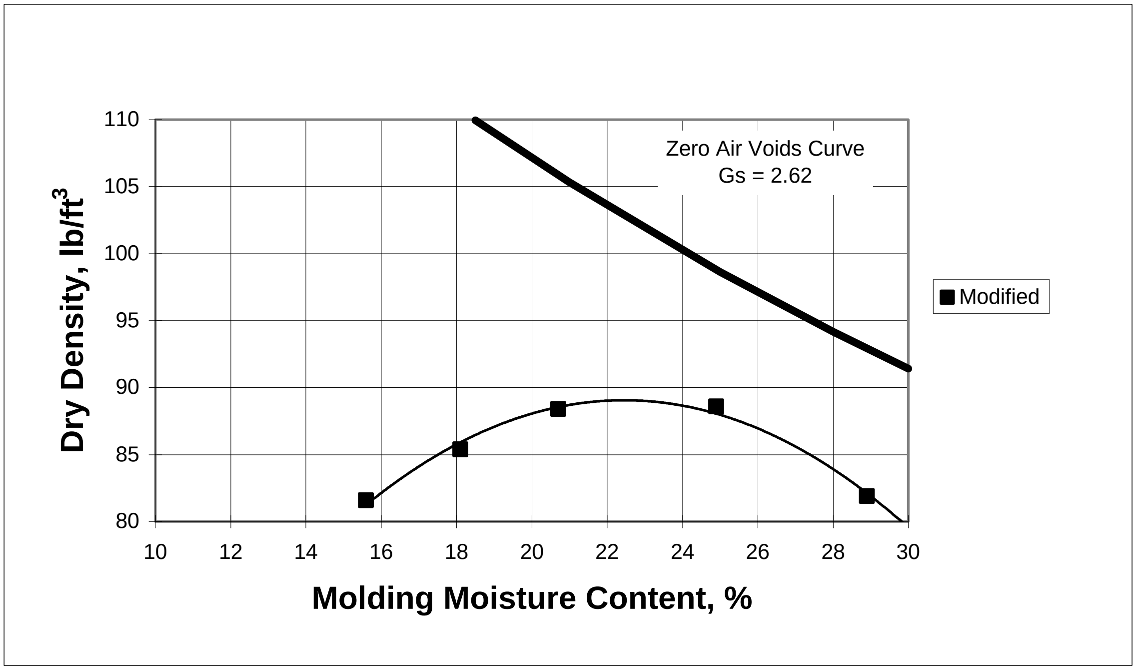

Figure 15. Dry Density Versus Molding Moisture Content for PG with 20% Lime Sludge.

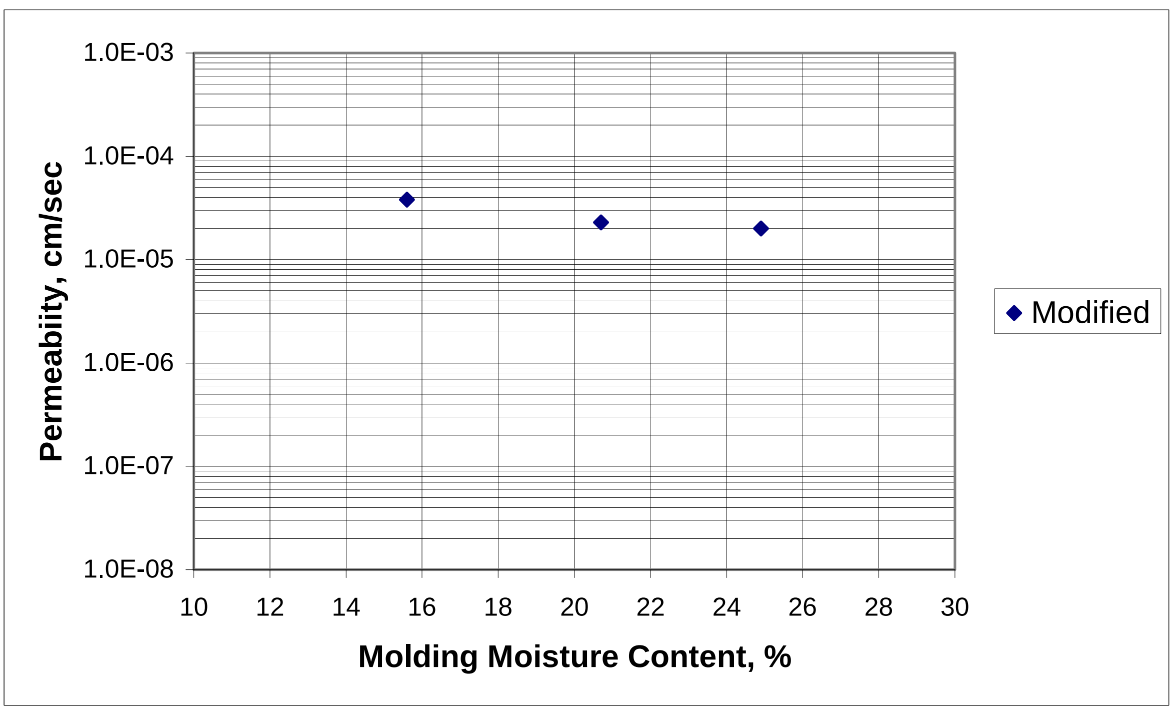

Figure 16. Permeability Versus Molding Moisture Content for PG with 20% Lime Sludge.

PG with 20% Portland Cement. The PG was mixed with 20% cement and was compacted using the modified Proctor method. Table 12 summarizes the maximum dry density, ($\rho_{d\ max}$) OMC, additive percentage and permeability of the PG for the modified energy level. Figures 17 and 18 show the moisture-density curve and permeability versus molding moisture content for PG with 20% cement. The 100% saturation (zero air voids) curves for PG with 20% cement are shown for a G_s of 2.55.

The modified Proctor $\rho_{d\ max}$ was 97.0 lb/ft^3 at an OMC of 16%. The permeability ranged from 5.8 x 10^{-6} to 2.4 x 10^{-6} cm/sec. Although the addition of cement to PG did decrease the permeability by about a factor of 10, the high percentage of cement required to lower the permeability indicated that this is not a cost effective additives. Therefore, no further tests were conducted using cement as an additive.

Table 12. Maximum Dry Density, Optimum Moisture Content and Permeability for PG with 20% Cement.

Compaction Type	Additive & Percentage	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
Modified	20% Cement	97.0	16.0	2.4E-06

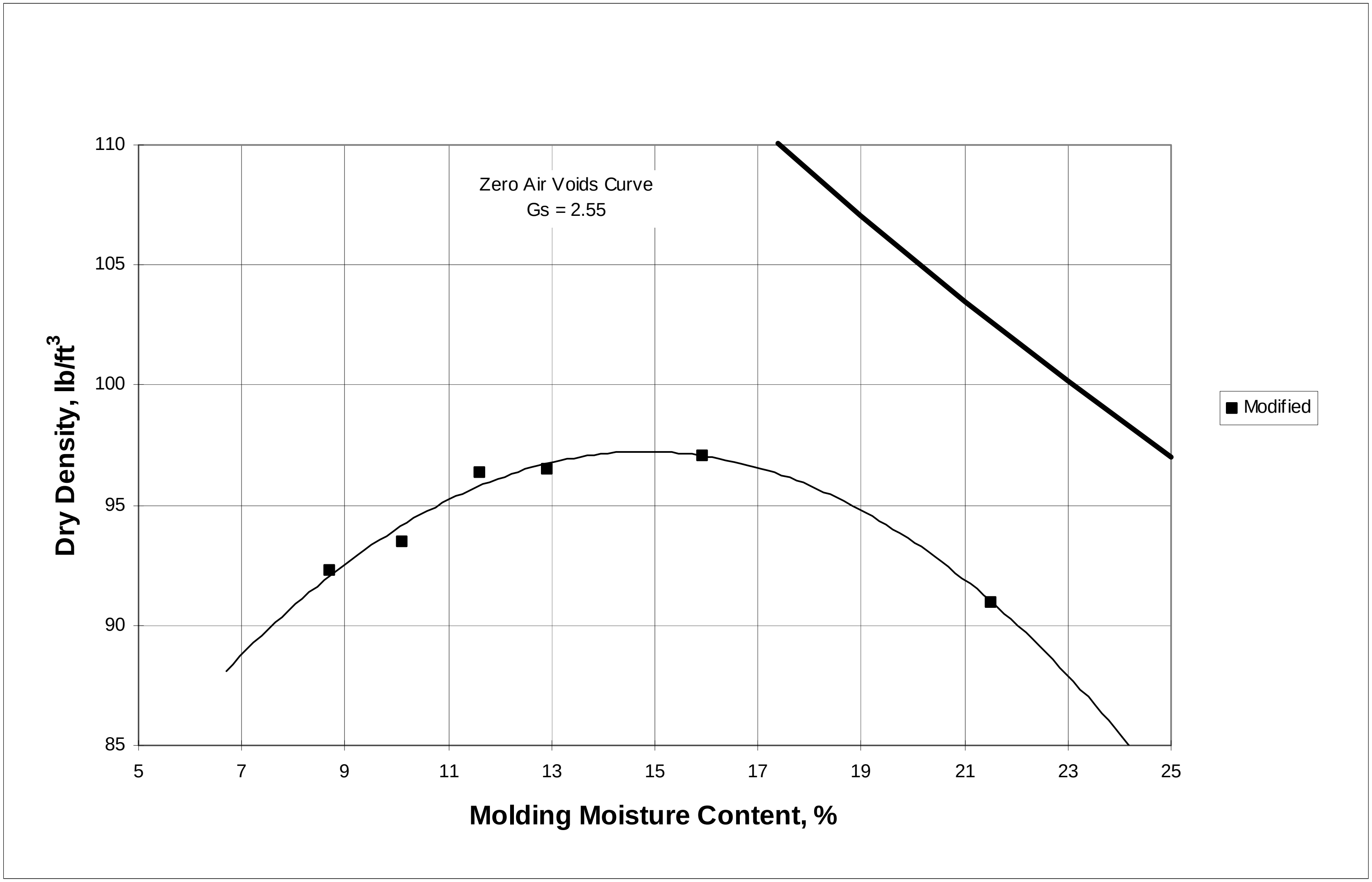

Figure 17. Dry Density Versus Molding Moisture Content for PG with 20% Cement.

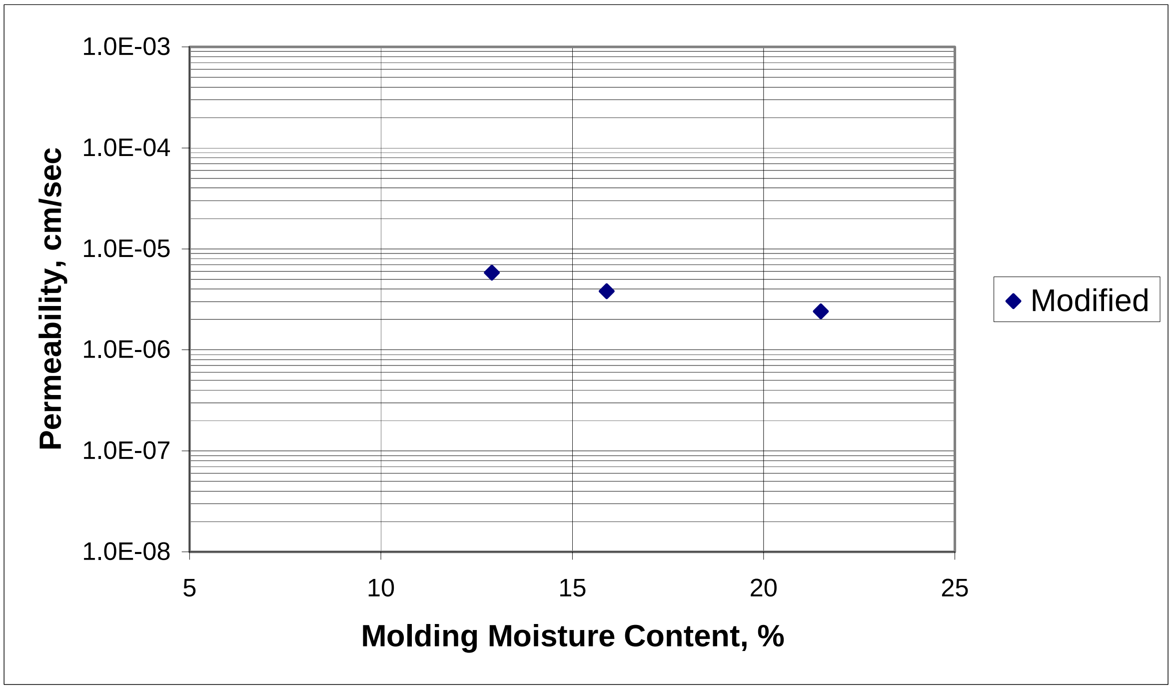

Figure 18. Permeability Versus Molding Moisture Content for PG with 20% Cement.

Summary and Comparison of Test Results

Density and Permeability as a Function of Compaction Energy

Figure 19 shows the relationship between maximum dry density and compaction energy for PG with and without additives. The maximum dry densities showed a significant increase when increasing the compaction energy from standard (12,275 ft-lb/ft^3) to modified (56,250 ft-lb/ft^3). The maximum dry density of PG without additive increased from 91.0 lb/ft^3 to 100.0 lb/ft^3, the PG with 5% bentonite increased from 93.0 to 101.5 lb/ft^3 and PG with 10% bentonite increased from 96.0 to 104.5 (lb/ft^3). PG with 10% phosphatic clay increased from 95.5 to 98.0 lb/ft^3 and PG with 15% phosphatic clay increased from 87.0 to 98.0 lb/ft^3. The extra-modified compaction (112,500 ft-lb/ft^3) provided slightly higher densities as compared to the modified Proctor densities. The density of PG with no additive increased from 100.0 to 102.0 lb/ft^3. The PG with 5% bentonite increased from 101.5 to 106.5 lb/ft^3 and that of PG with 10% bentonite increased from 104.5 to 106.5 (lb/ft^3).

The PG without additives and with either bentonite or phosphatic clay yielded an 8.5 to 10% increase in maximum dry density with an approximate fourfold increase in compaction energy from standard to modified. When the compaction energy was doubled from modified to extra-modified, the maximum dry density increased only 2 to 5%.

Figure 20 shows the relationship between permeability and compaction energy for PG with no additives, bentonite and phosphatic clay. The permeability of PG with bentonite and phosphatic clay showed a significant decrease when increasing the compaction effort from standard to modified. The permeability was decreased by approximately two orders of magnitude. The permeabilities for each mix decreased minimally with the increase in compaction energy from modified to extra-modified. The permeabilities for the extra-modified energy decreased less than one order of magnitude versus the modified energy. The permeability of PG with no additives decreased from 3.0×10^{-5} cm/sec at modified compaction to 1.1×10^{-5} cm/sec at extra-modified compaction. Similarly, PG with 5% bentonite decreased from 3.4×10^{-7} to 8.9 x 10-8 cm/sec and PG with 10% bentonite decreased from 2.5×10^{-8} to 2.1×10^{-8} cm/sec. The increase in compaction energy from modified to extra-modified does not appear to justify the extra energy effort that would be required in the field. The permeabilities for the modified and extra-modified tests are essentially the same and to achieve the extra-modified densities in the field the time and equipment costs would probably double. The extra-modified energy does not provide a significant benefit for reducing permeability or reducing installation costs.

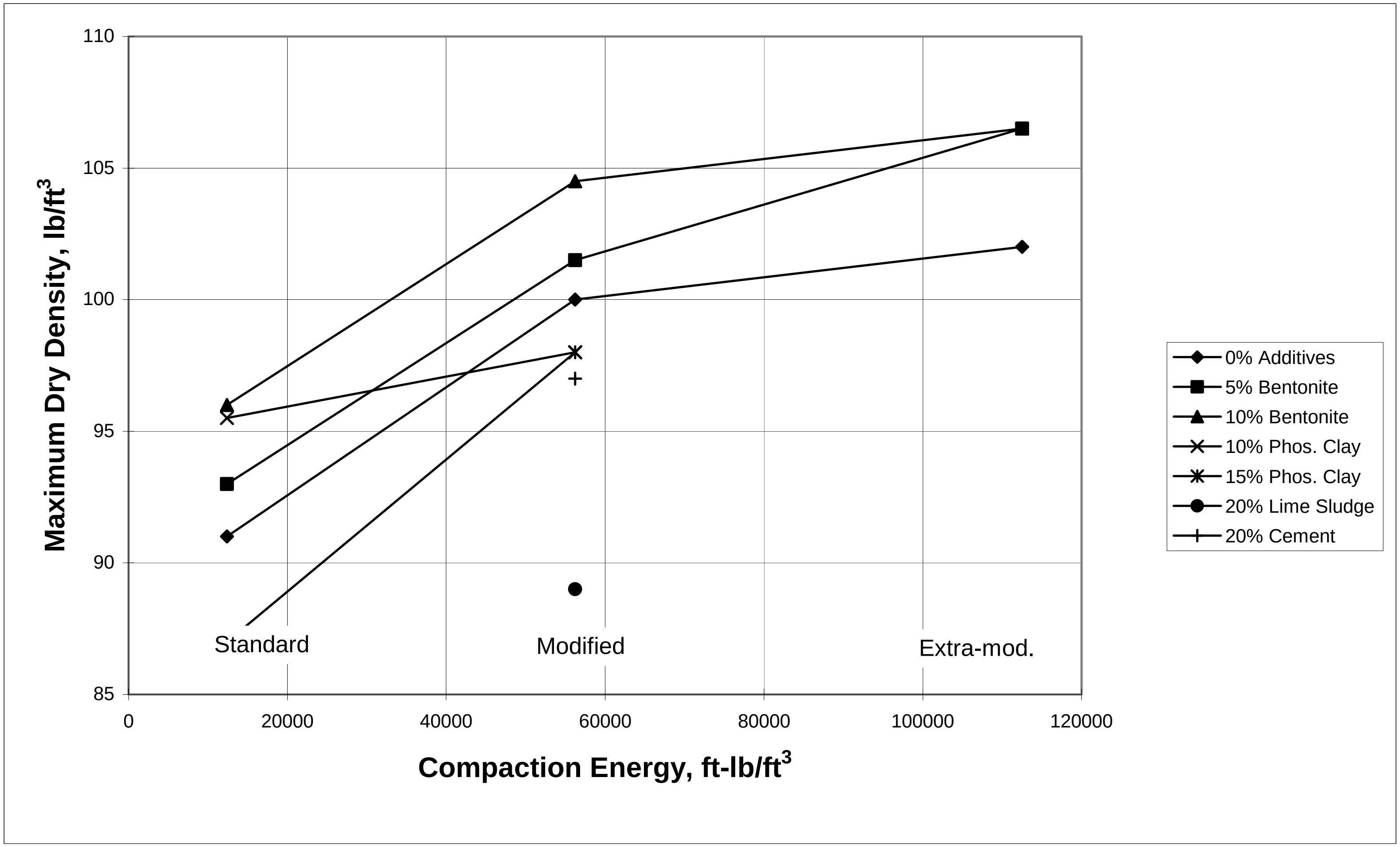

Figure 19. Maximum Dry Density Versus Compaction Energy for All Additives.

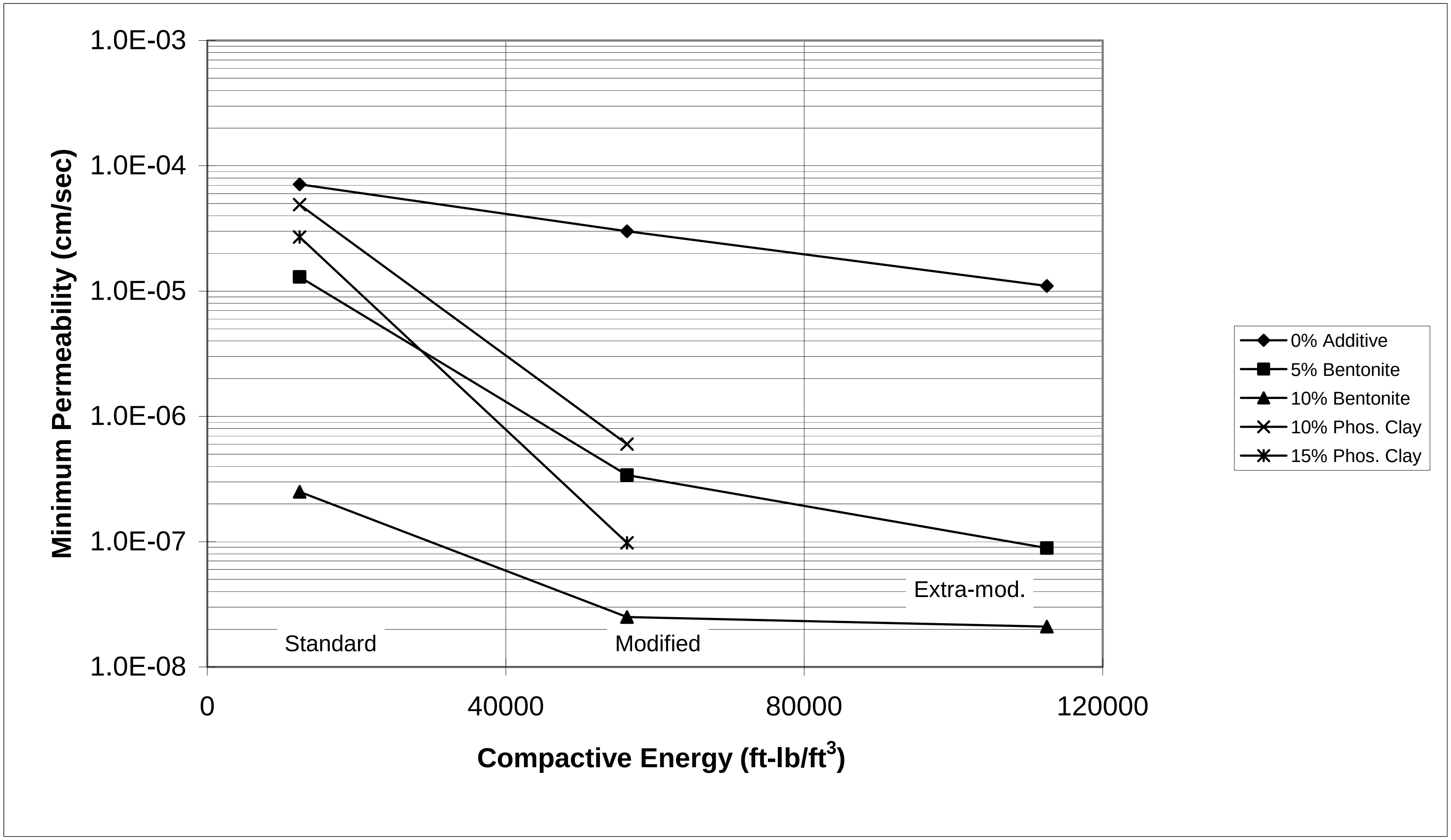

Figure 20. Permeability Versus Compaction Energy.

Comparison of Permeability Results

Upon review of the permeability data and soil liner criteria, only the bentonite and phosphatic clay appear to be viable options as soil amendments to achieve a permeability of less than 10^{-5} cm/sec. As reported by others and confirmed during this study, unamended PG will not likely perform satisfactorily as an impermeable layer because the in-situ surface PG permeability is generally greater than 10^{-3} cm/sec and compacted PG without soil additives is generally greater than 10^{-5} cm/sec. The lime sludge was also ineffective and the cement required a percentage too high to be cost effective as compared to bentonite. Table 13 summarizes the compaction effort, percentage of additive and permeability comparison to requirements for "lined (< 1×10^{-5}cm/sec) versus unlined (< 1×10^{-7}cm/sec) stacks.

Table 13. Compaction Effort, Percentage of Additive, and Permeability.

Compaction Effort	Percentage of Additive	Permeability (cm/sec) < 1×10^{-5}	Permeability (cm/sec) < 1×10^{-7}
Standard	0%	NO	NO
Modified	0%	NO	NO
Extra-mod.	0%	NO	NO
Standard	5% Bentonite	NO	NO
Modified	5% Bentonite	YES	NO
Extra-mod.	5% Bentonite	YES	YES
Standard	10% Bentonite	YES	NO
Modified	10% Bentonite	YES	YES
Extra-mod.	10% Bentonite	YES	YES
Standard	10% Phos. Clay	NO	NO
Modified	10% Phos. Clay	YES	NO
Standard	15% Phos. Clay	NO	NO
Modified	15% Phos. Clay	YES	YES
Modified	20% Lime Sludge	NO	NO
Modified	20% Cement	YES	NO

Figure 21 shows the relationship of the permeabilities, compaction levels and additive amounts for all samples. In Figure 21, the data defined several important trends and boundaries. PG with 5% bentonite using standard Proctor compaction showed a permeability slightly greater than 1 x 10^{-5} cm/sec, however when the bentonite was increased to 10%, the permeability decreased to 2.5 x 10^{-7} cm/sec. Using modified compaction the permeability of PG with 5% bentonite was 3.4 x 10^{-7} cm/sec and was decreased to 2.5 x 10^{-8} cm/sec with 10% bentonite. When the bentonite was increased to 12.5% and 15% under modified compaction the permeability reached a minimum constant value of approximately 1.3 x 10^{-8} cm/sec. PG with 5 and 10% bentonite using extra-modified compaction consistently showed permeability values less than 1 x 10^{-7} cm/sec. When the phosphatic clay content was increased to 15%, 17.5%, and 20% using modified compaction, the permeability decreased to a constant value of approximately 1 x 10^{-7} cm/sec.

FDEP rule 62-673 requires an in-situ permeability of 1 x 10^{-7} cm/sec or less for closure of an unlined PG stack. The test data indicate that such minimum permeabilities can be achieved by using high compaction effort (modified Proctor) and either 10% bentonite additive or 15% phosphatic clay. It should be noted that phosphatic clays from different mines have been shown to exhibit varying plastic values and permeabilities. Therefore, use of a phosphatic clay having Atterberg Limits of lower than those used in these tests would require additional testing to confirm satisfactory results (i.e., permeability values less than 1 x 10^{-7} cm/sec).

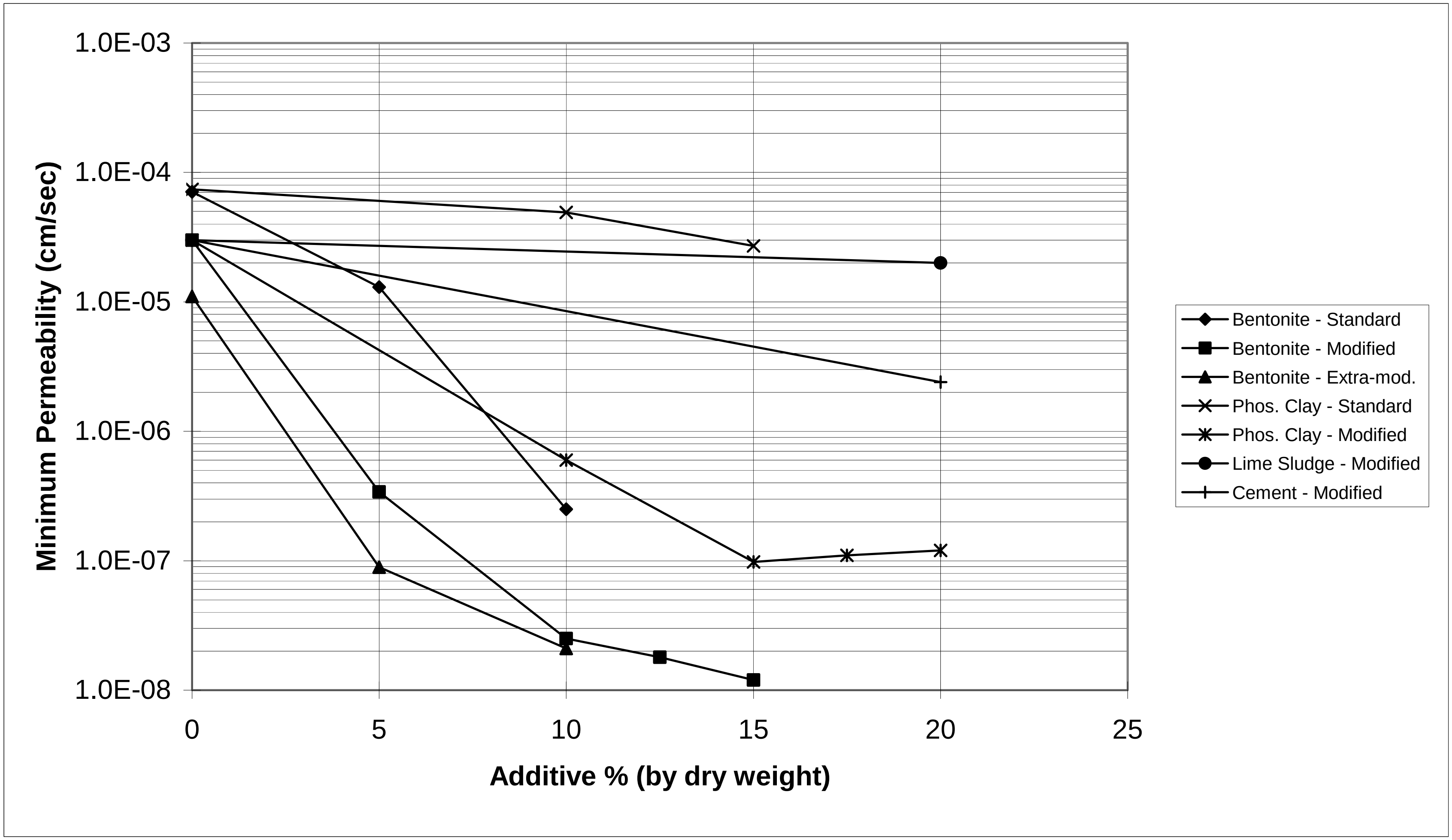

Figure 21. Permeability Versus Additive Percentage for All Samples.

Additional Permeability Testing

Upon review of the permeability test results the FIPR TAC committee recommended additional permeability testing to provide more data. The additional testing included further evaluation of varying percentages of bentonite and phosphatic clay additives at the modified Proctor compaction energy. PG samples were again obtained from the Farmland Hydro stack and the same additives from the initial testing phase were also utilized.

The additional testing was initiated in January 2000 at the FIT Geomaterials Laboratory. The testing was performed using the same procedures as previously described for the initial permeability testing. The testing program is outlined in Table 14.

Table 14. Matrix of Additional Test Conditions for Permeability of PG with Bentonite and Phosphatic Clay Additives.

Percentage of Additive	Compaction Type
1% Bentonite	Modified
3% Bentonite	Modified
5% Bentonite (2)	Modified
7.5% Bentonite	Modified
10% Bentonite (2)	Modified
3% Phosphatic Clay	Modified
5% Phosphatic Clay	Modified
10% Phosphatic Clay (2)	Modified
12.5% Phosphatic Clay	Modified
15% Phosphatic Clay (2)	Modified
20% Bentonite	Modified
20% Phosphatic Clay	Modified
5% Cement/Bentonite	Modified
10% Cement/Bentonite	Modified
10% Cement/Phosphatic Clay	Modified
15% Cement/Phosphatic Clay	Modified

Note: (2) denotes duplicate test from initial testing

Additional Testing of PG with Bentonite Clay

The PG was mixed with varying amounts of bentonite clay as outlined in Table 14. The results including the maximum dry density, optimum moisture content and permeability are summarized in Table 15. The moisture-density curves and permeability versus molding moisture content are shown in Figures 22 to 31. In general, the maximum dry density ranged from 101 to 104 lb/ft^3 with an optimum moisture content near 12%. The permeability decreased from 1.5 x 10^{-4} cm/sec to 8.2 x 10^{-9} cm/sec with increasing percentage of bentonite.

Table 15. Additional Permeability Test Results for PG with Bentonite.

Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
1% Bentonite	102.5	11.0	1.5E-04
3% Bentonite	103.0	12.0	1.5E-06
5% Bentonite	101.0	13.0	3.9E-07
7.5% Bentonite	102.5	13.0	2.0E-07
10% Bentonite	104.0	13.0	1.0E-07
20% Bentonite*	104.0	12.0	8.2 E-09

*Indicates only one sample tested, sample within 95% of estimated maximum dry density

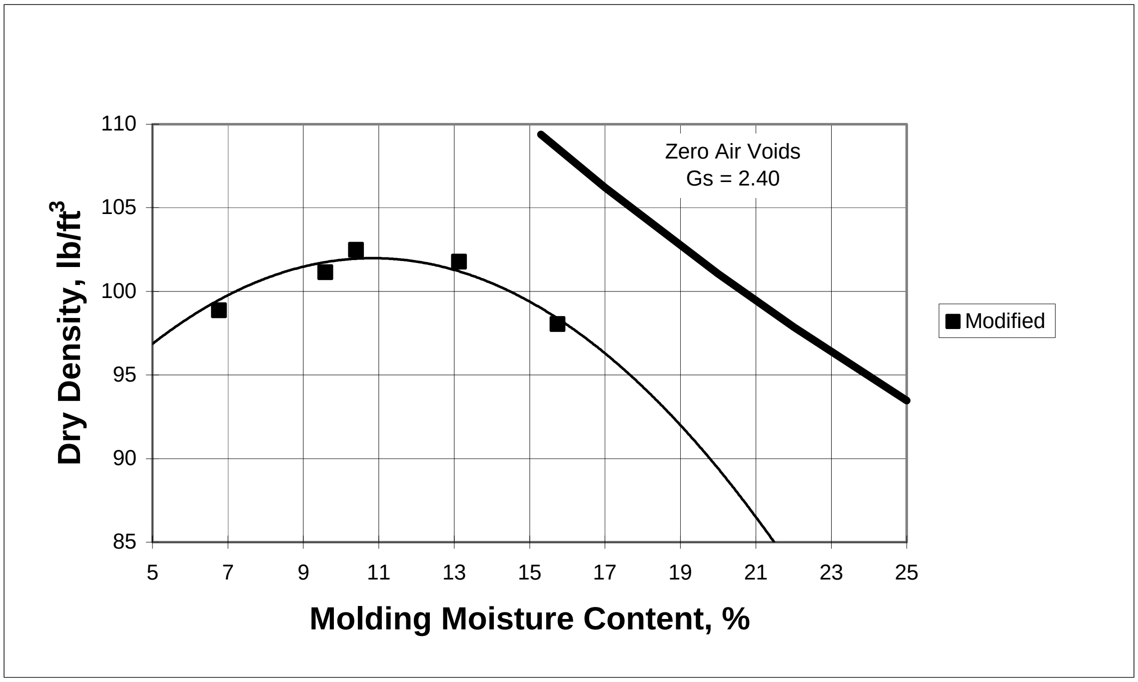

Figure 22. Dry Density Versus Molding Moisture Content for PG with 1% Bentonite.

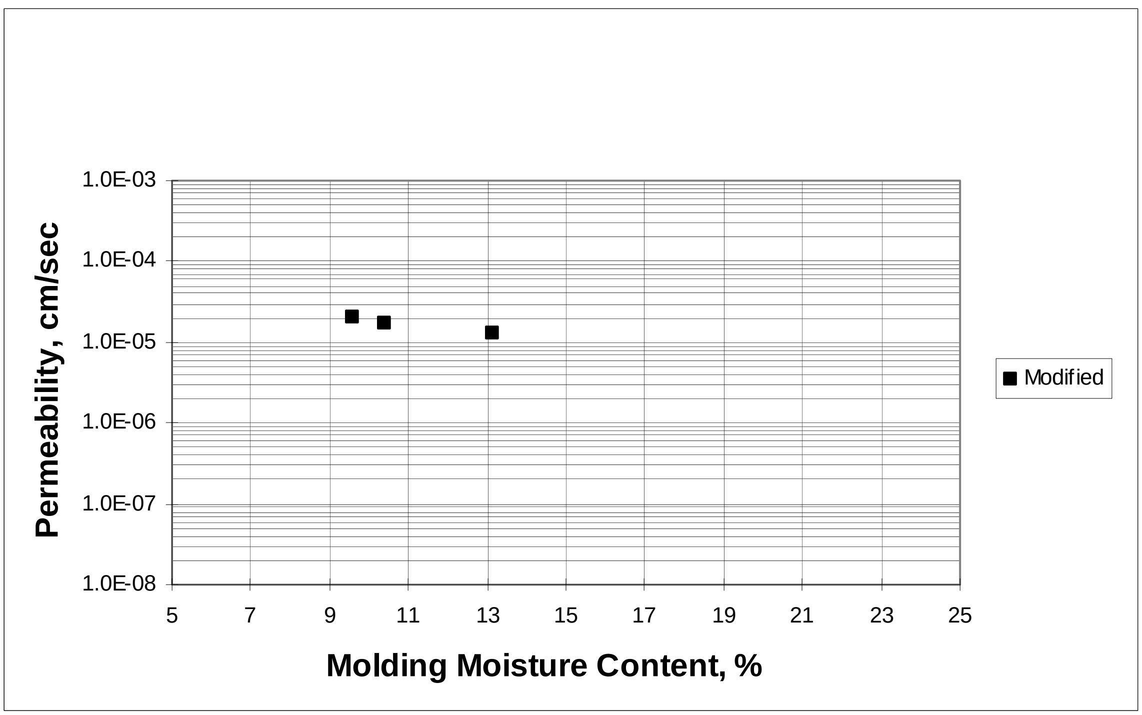

Figure 23. Permeability Versus Molding Moisture Content for PG with 1% Bentonite.

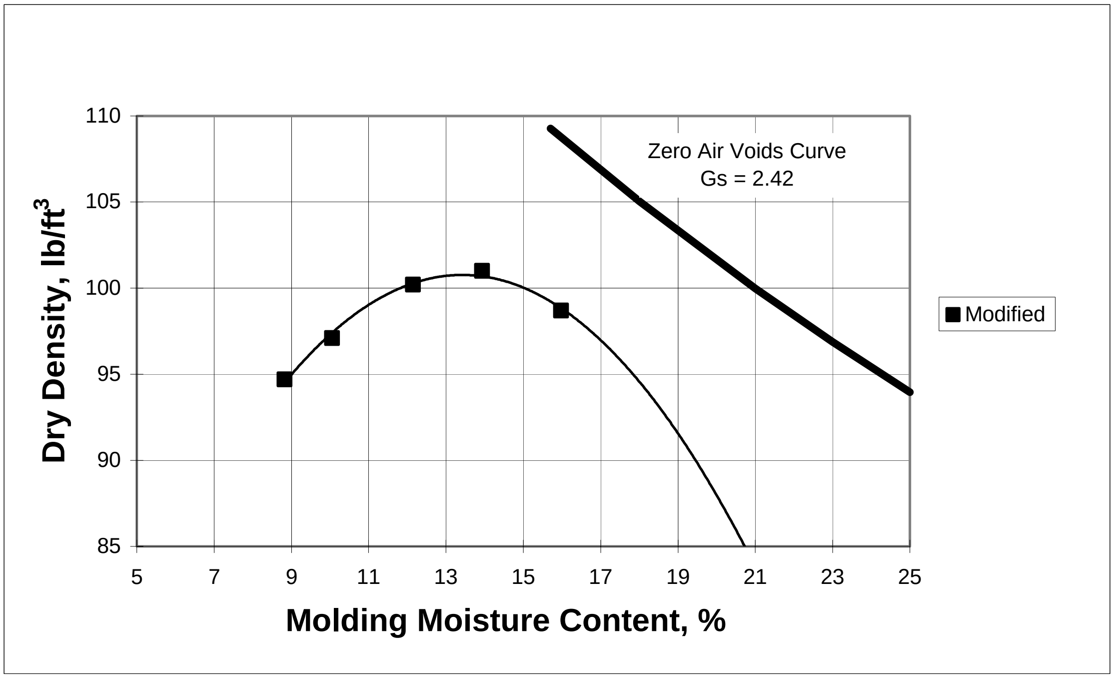

Figure 24. Dry Density Versus Molding Moisture Content for PG with 3% Bentonite.

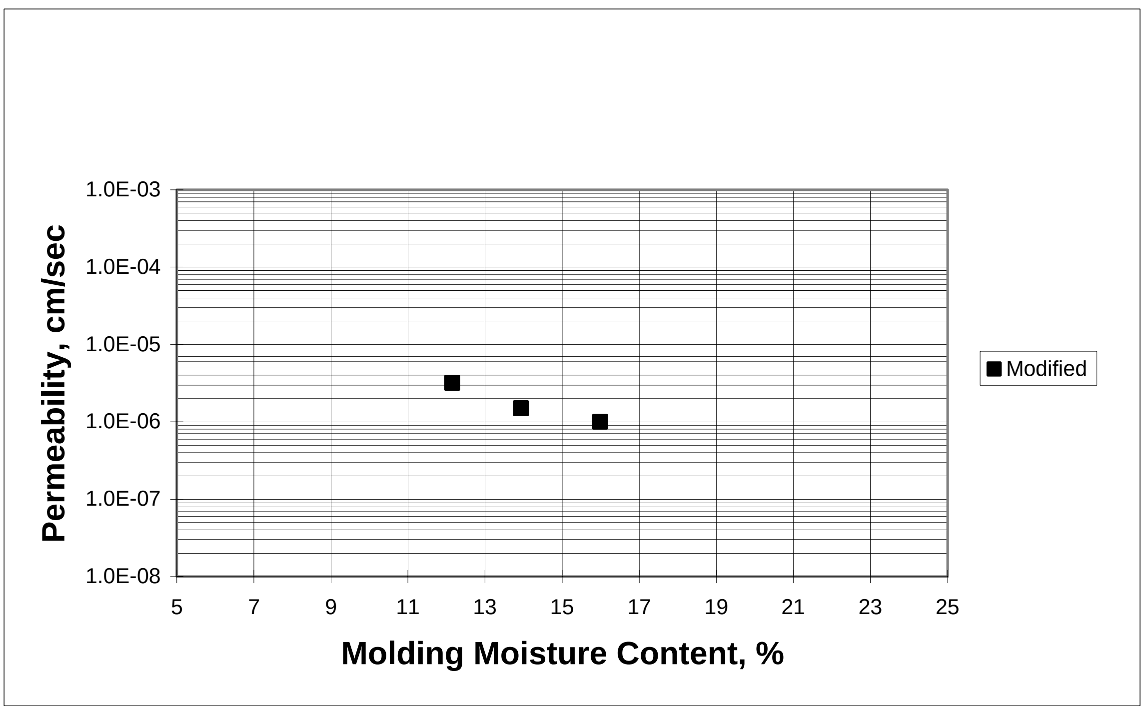

Figure 25. Permeability Versus Molding Moisture Content for PG with 3% Bentonite.

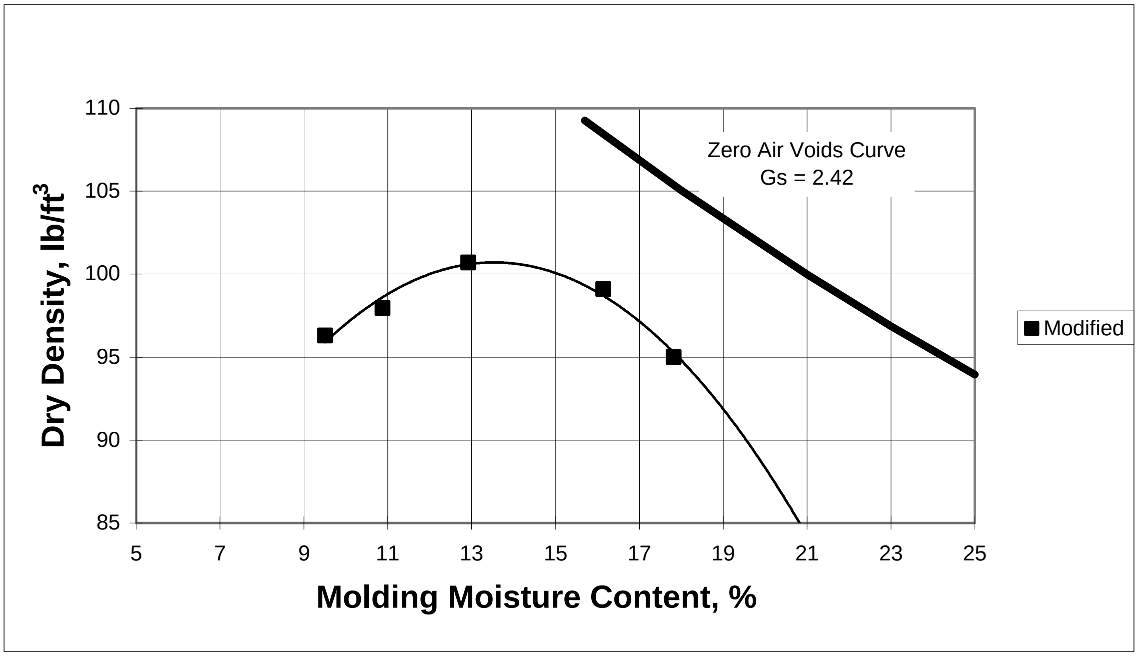

Figure 26. Dry Density Versus Molding Moisture Content for PG with 5% Bentonite.

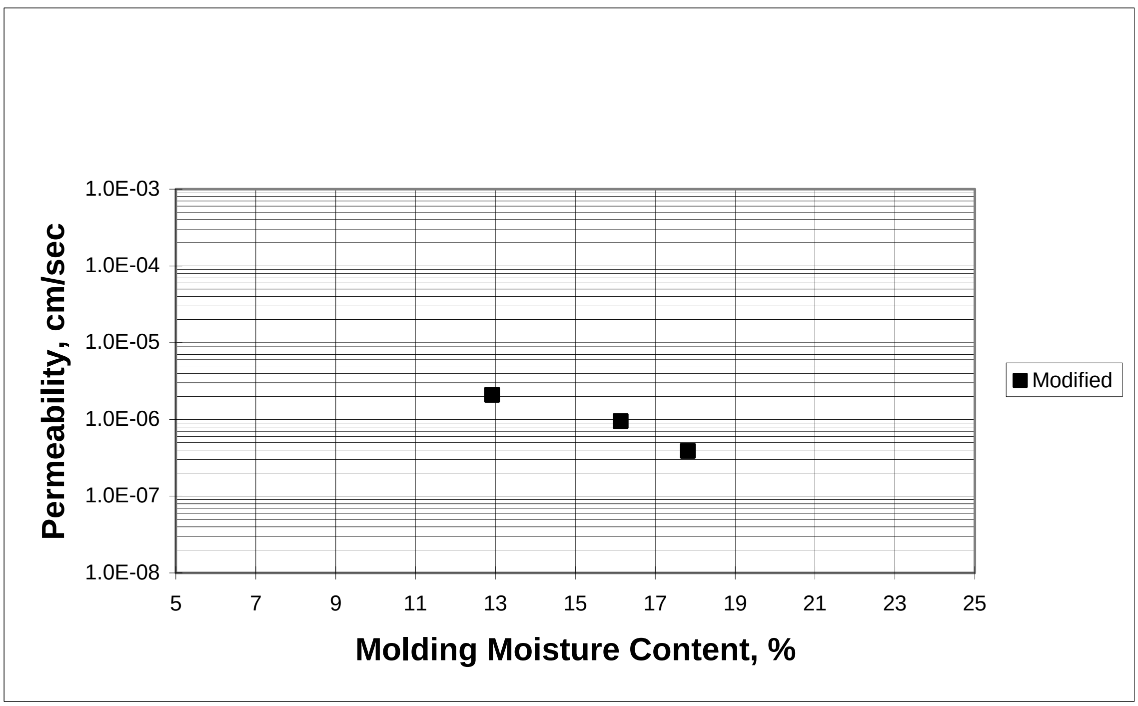

Figure 27. Permeability Versus Molding Moisture Content for PG with 5% Bentonite.

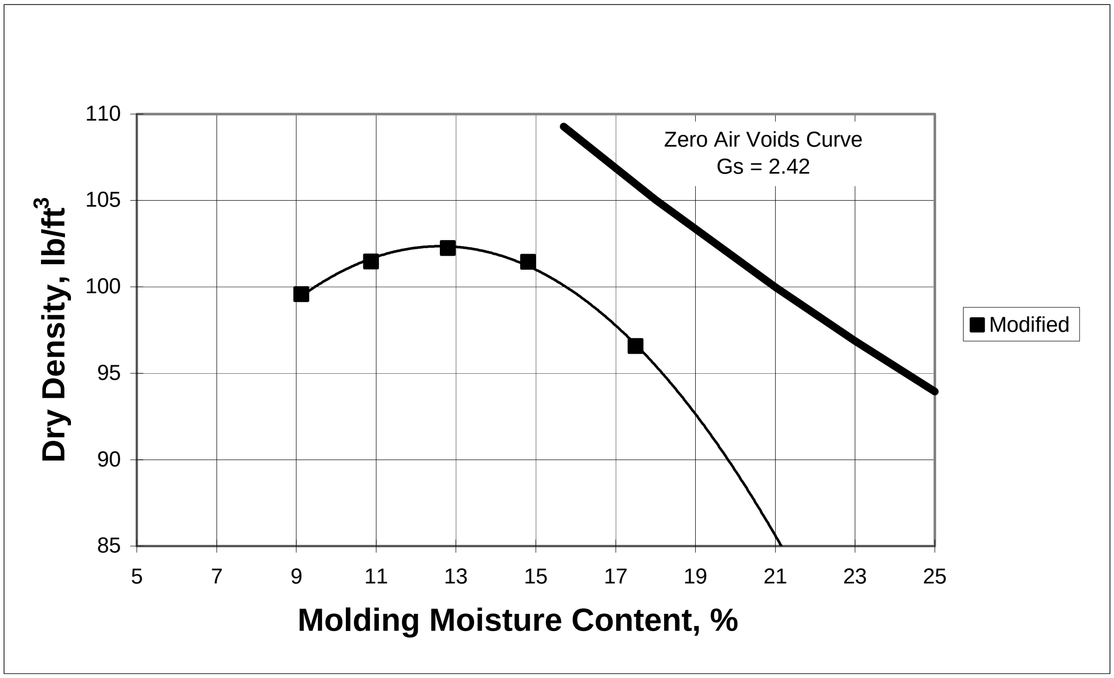

Figure 28. Dry Density Versus Molding Moisture Content for PG with 7.5% Bentonite.

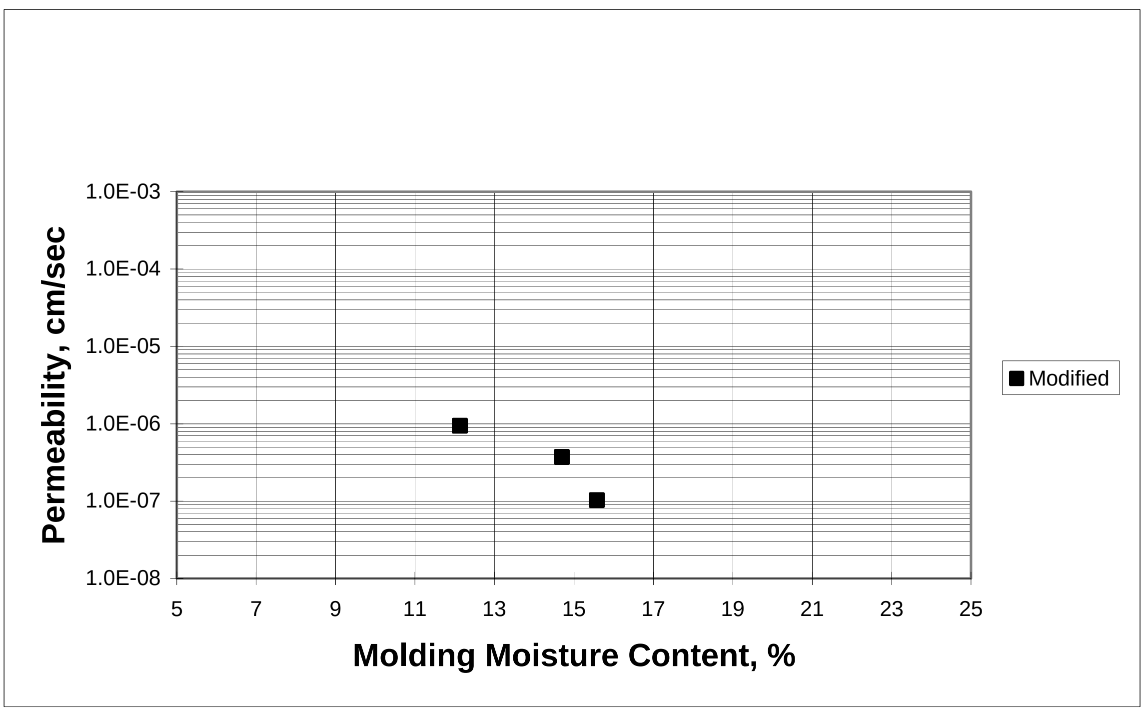

Figure 29. Permeability Versus Molding Moisture Content for PG with 7.5% Bentonite.

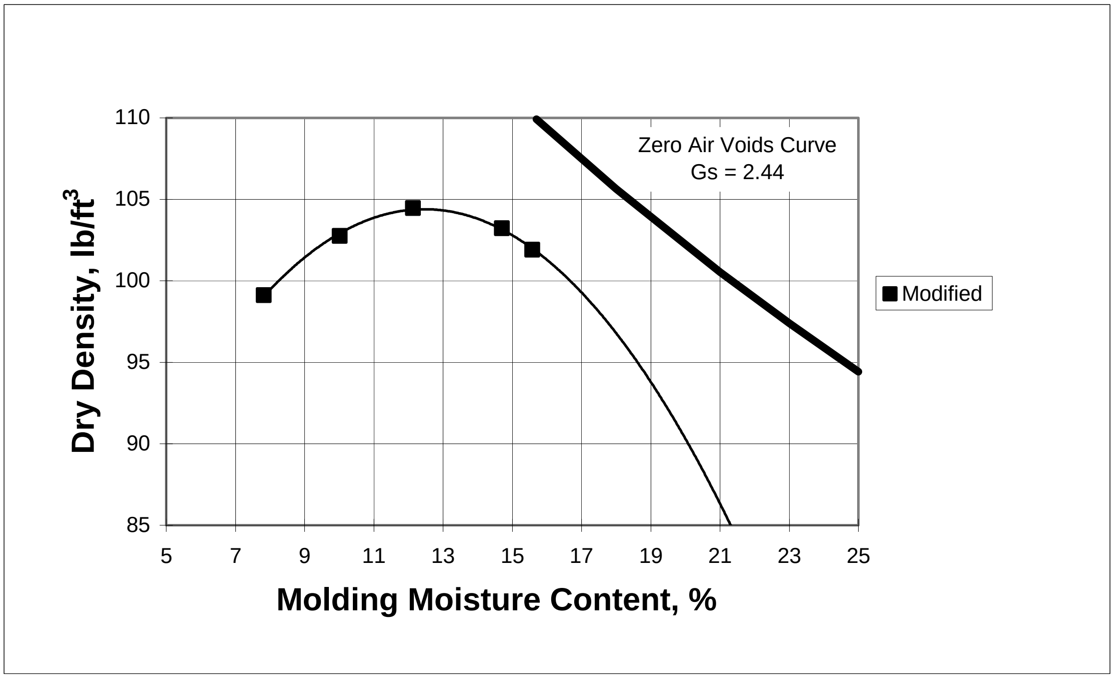

Figure 30. Dry Density Versus Molding Moisture Content for PG with 10% Bentonite.

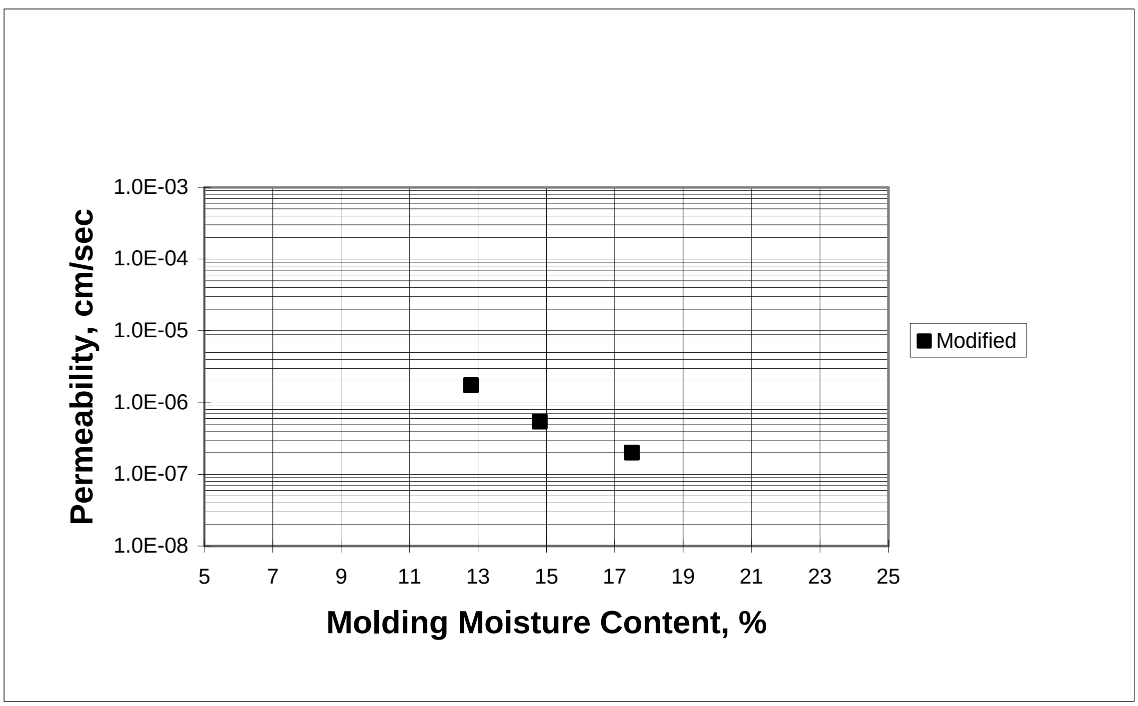

Figure 31. Permeability Versus Molding Moisture Content for PG with 10% Bentonite.

Additional Testing of PG with Phosphatic Clay

The PG was mixed with various amounts of phosphatic clay as outlined in Table 14. The results, including the maximum dry density, optimum moisture content and permeability, are summarized in Table 16. The moisture-density curves and permeability versus molding moisture content are shown in Figures 32 to 41. In general, the maximum dry density ranged from 99 to 102 lb/ft^3 with an optimum moisture content near 14%. The permeability decreased from 7.4 x 10^{-6} cm/sec to 2.7 x 10^{-7} cm/sec with an increase in the percentage of phosphatic clay from 3% to 20%. Permeability values less than 1 x 10^{-7} cm/sec were not obtained using phosphatic clay in these tests. This result is attributed to inadequate breaking down of the clay clods during these tests.

Table 16. Additional Permeability Test Results for PG with Phosphatic Clay.

Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
3% Phosphatic Clay	101.5	13.0	7.4E-06
5% Phosphatic Clay	102.0	13.0	1.2E-06
10% Phosphatic Clay	101.0	14.0	1.0E-06
12.5% Phosphatic Clay	100.0	15.0	4.3E-07
15% Phosphatic Clay	99.0	16.0	3.0E-07
20% Phosphatic Clay*	101.0	14.0	2.7E-07

*Indicates only one sample tested, sample within 95% of estimated maximum dry density

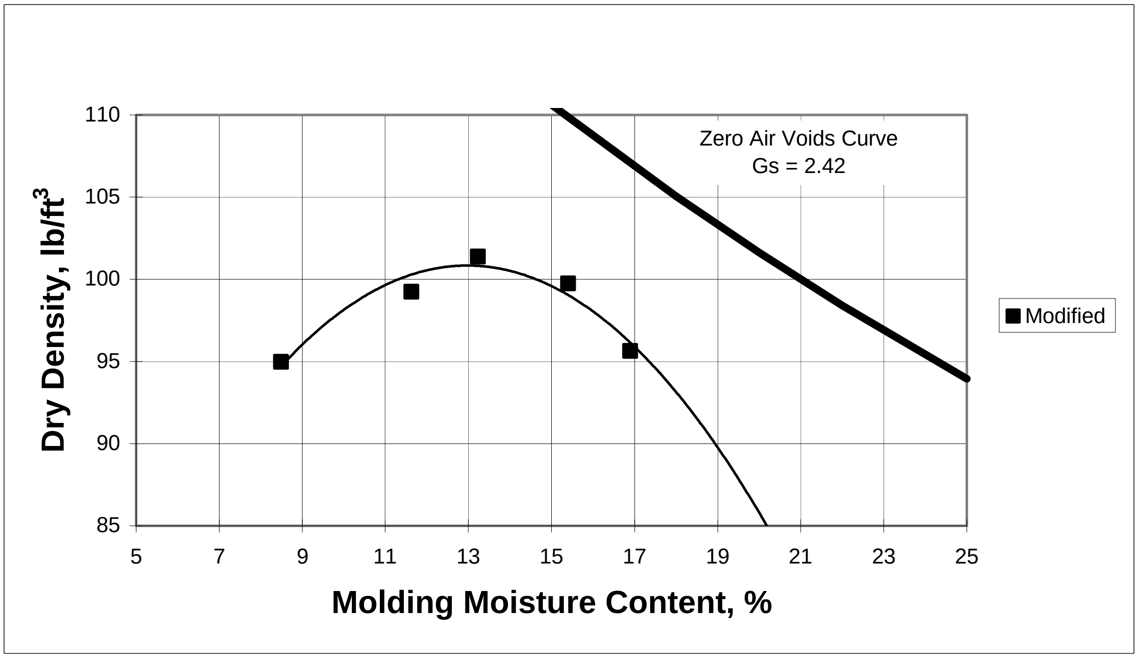

Figure 32. Dry Density Versus Molding Moisture Content for PG with 3% Phosphatic Clay.

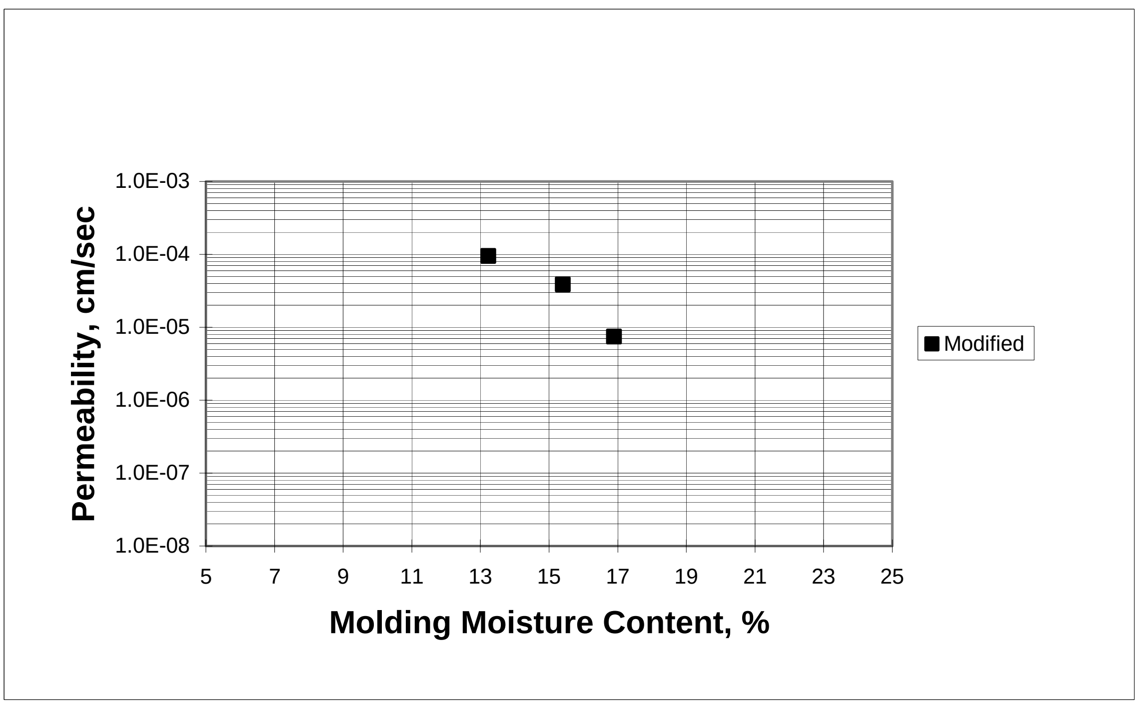

Figure 33. Permeability Versus Molding Moisture Content for PG with 3% Phosphatic Clay.

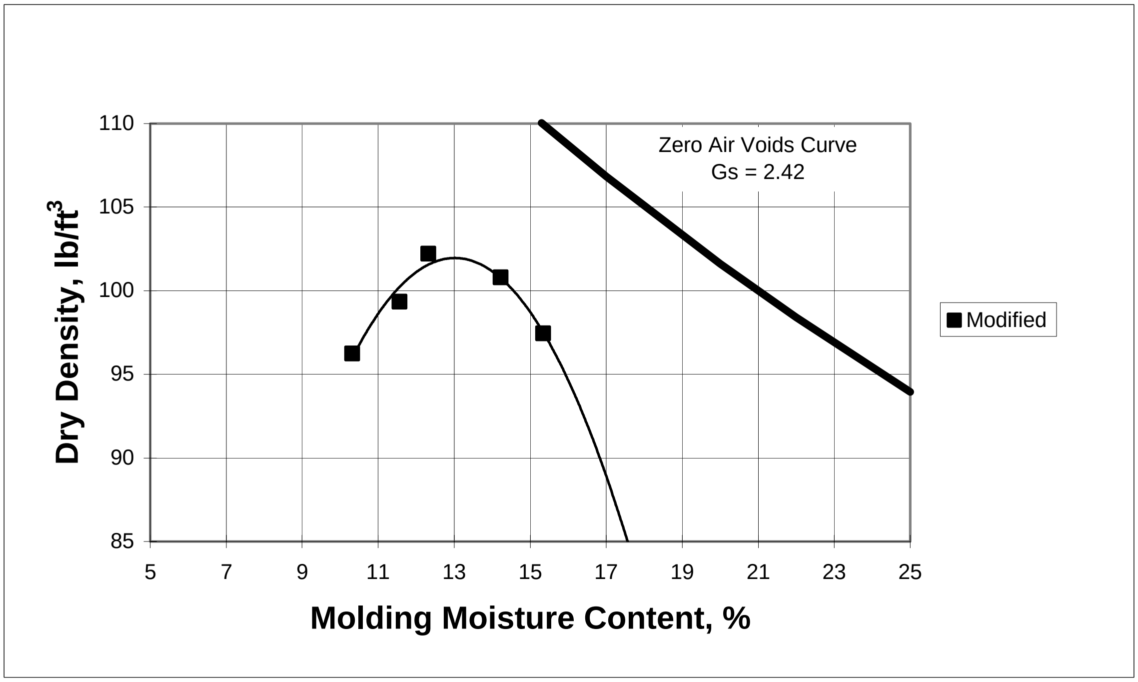

Figure 34. Dry Density Versus Molding Moisture Content for PG with 5% Phosphatic Clay.

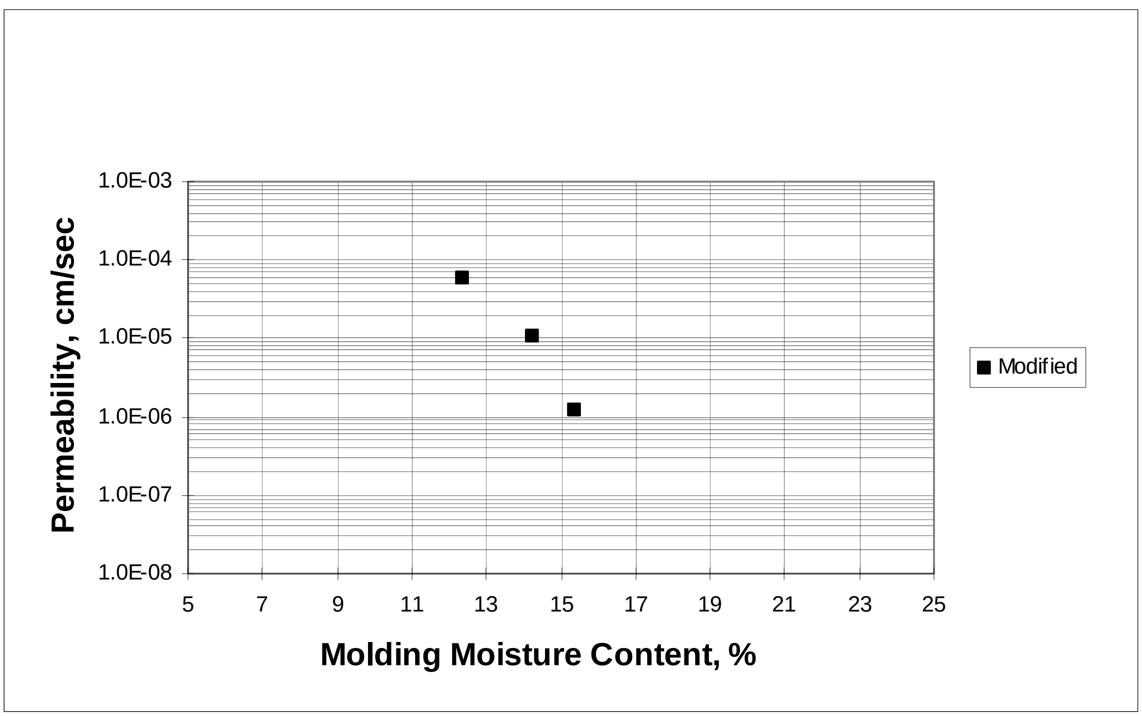

Figure 35. Permeability Versus Molding Moisture Content for PG with 5% Phosphatic Clay.

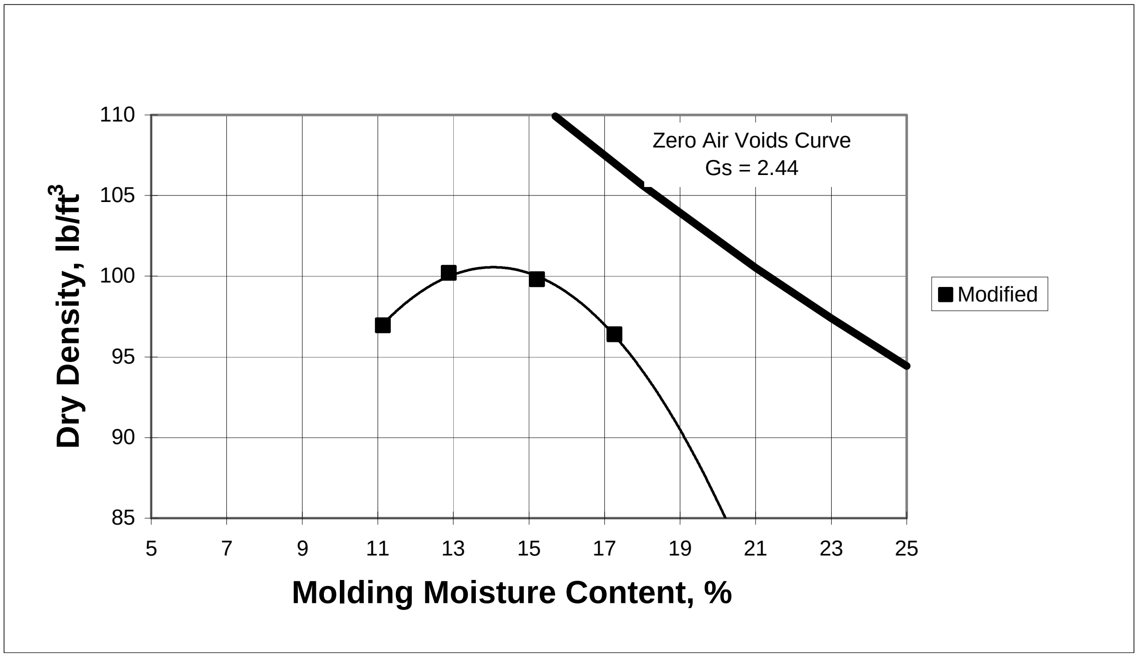

Figure 36. Dry Density Versus Molding Moisture Content for PG with 10% Phosphatic Clay.

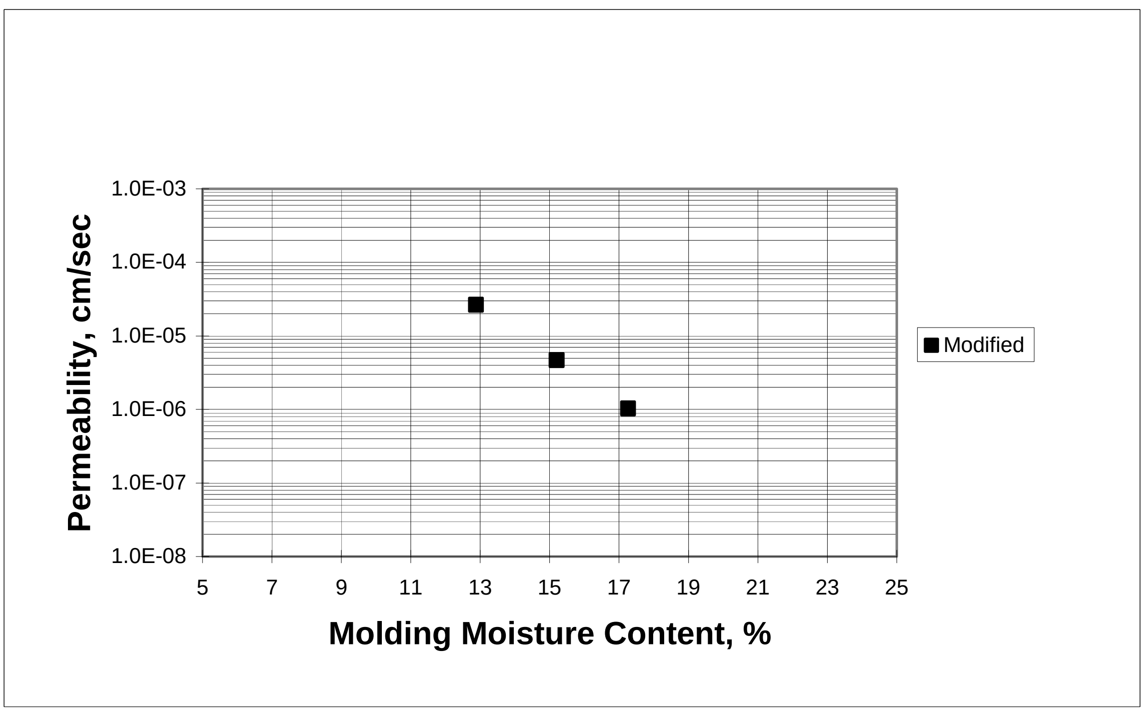

Figure 37. Permeability Versus Molding Moisture Content for PG with 10% Phosphatic Clay.

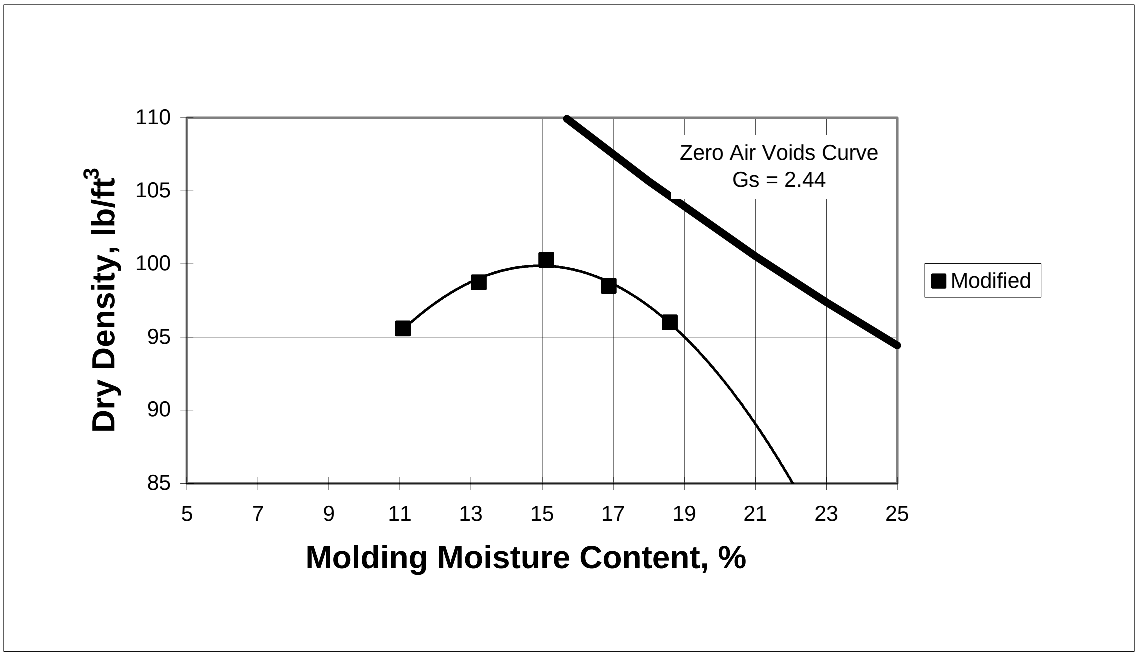

Figure 38. Dry Density Versus Molding Moisture Content for PG with 12.5% Phosphatic Clay.

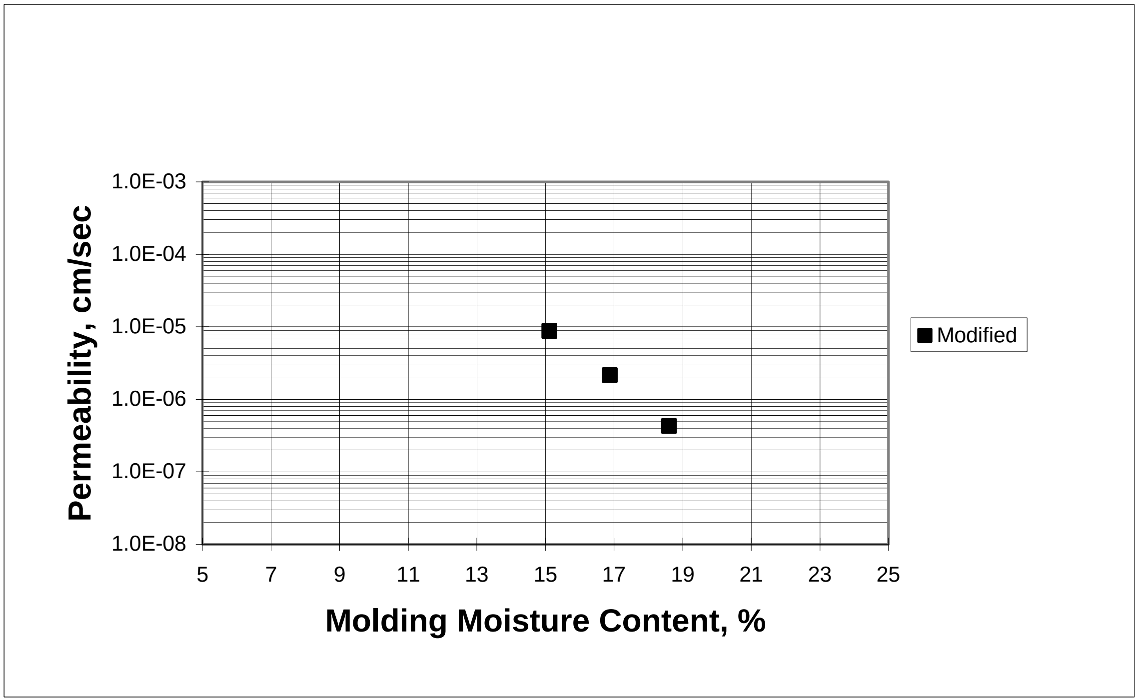

Figure 39. Permeability Versus Molding Moisture Content for PG with 12.5% Phosphatic Clay.

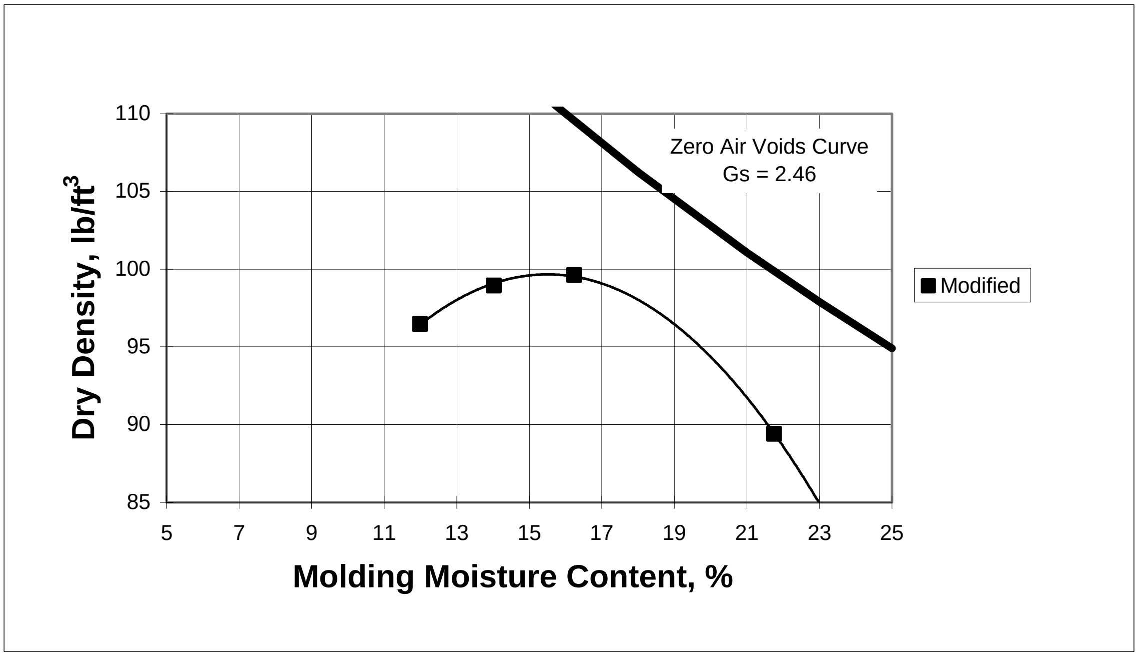

Figure 40. Dry Density Versus Molding Moisture Content for PG with 15% Phosphatic Clay.

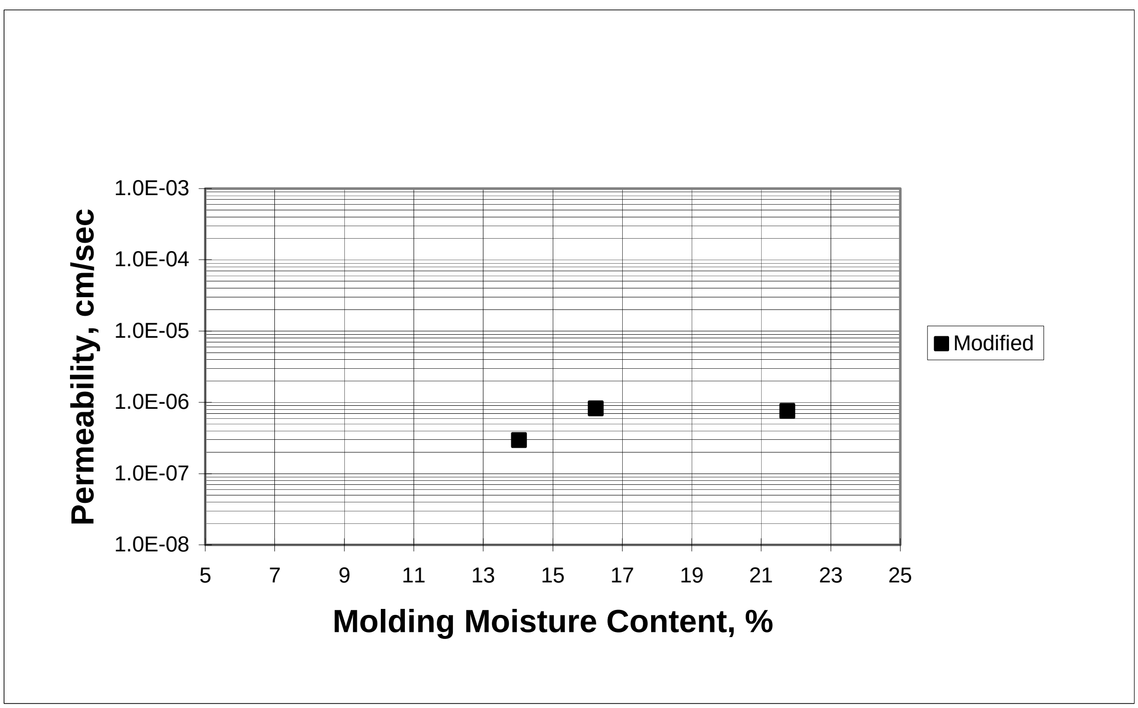

Figure 41. Permeability Versus Molding Moisture Content for PG with 15% Phosphatic Clay.

Additional Testing of Cement, Bentonite and Phosphatic Clay Mixes

The PG was mixed with a combination of Portland cement and bentonite or phosphatic clay as outlined in Table 14. These tests were only conducted on a single sample. The sample was mixed and compacted near the estimated optimum moisture content to determine the permeability. The results including the dry density, molding moisture content and permeability are summarized in Table 17.

Table 17. Additional Testing for Cement, and Bentonite or Phosphatic Clay Mixes.

Percentage of Additive	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)	Permeability (cm/sec)
2.5% Cement & 2.5% Bentonite	102.0	11.0	2.3E-06
5% Cement & 5% Bentonite	103.0	12.0	7.3E-07
5% Cement & 5% Phosphatic Clay	102.0	15.0	1.0E-05
7.5% Cement & 7.5% Phosphatic Clay	104.0	15.0	4.6E-06

The addition of Portland cement to PG with bentonite or phosphatic clay does not decrease the permeability of a compacted sample over the use of clay additive alone. In fact, the cement actually increases the permeability when compared with similar samples without the cement. The compacted PG sample with 5% bentonite had a permeability of 3.9×10^{-7} cm/sec and when 5% cement was added to the mix, the permeability increased to 7.3×10^{-7} cm/sec. Similarly, the addition of cement to a 5% phosphatic clay mix increases the permeability from 1.2×10^{-6} cm/sec to 1.0×10^{-5} cm/sec.

Summary of Additional Testing

The additional test results were analyzed along with the initial test results for the bentonite and phosphatic clay additives using modified Proctor compaction energy. Figures 42 and 43 show the relationships between additive percentage and permeability. Both the bentonite and phosphatic clay additives gave a significant decrease, three to four orders of magnitude, in permeability as the additive percentage was increased to 15%. Addition of bentonite or phosphatic clay at greater than 15% percent did not produce a significant decrease in permeability, as shown in the figures.

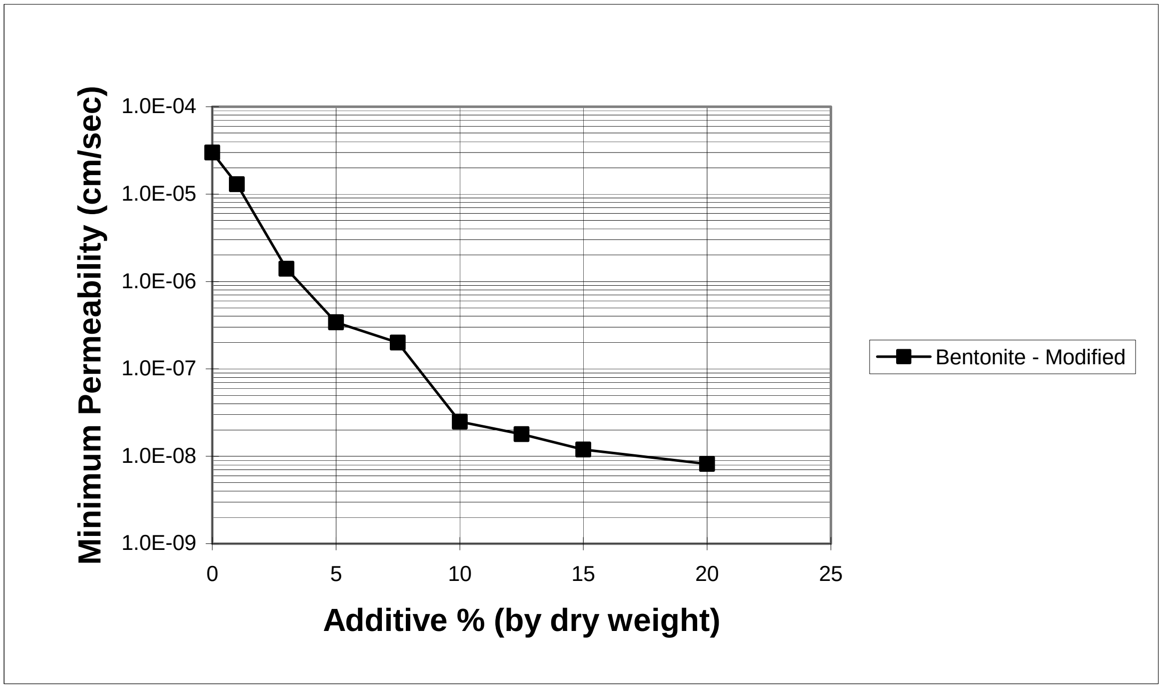

Figure 42. Permeability Versus Bentonite Additive Percentages.

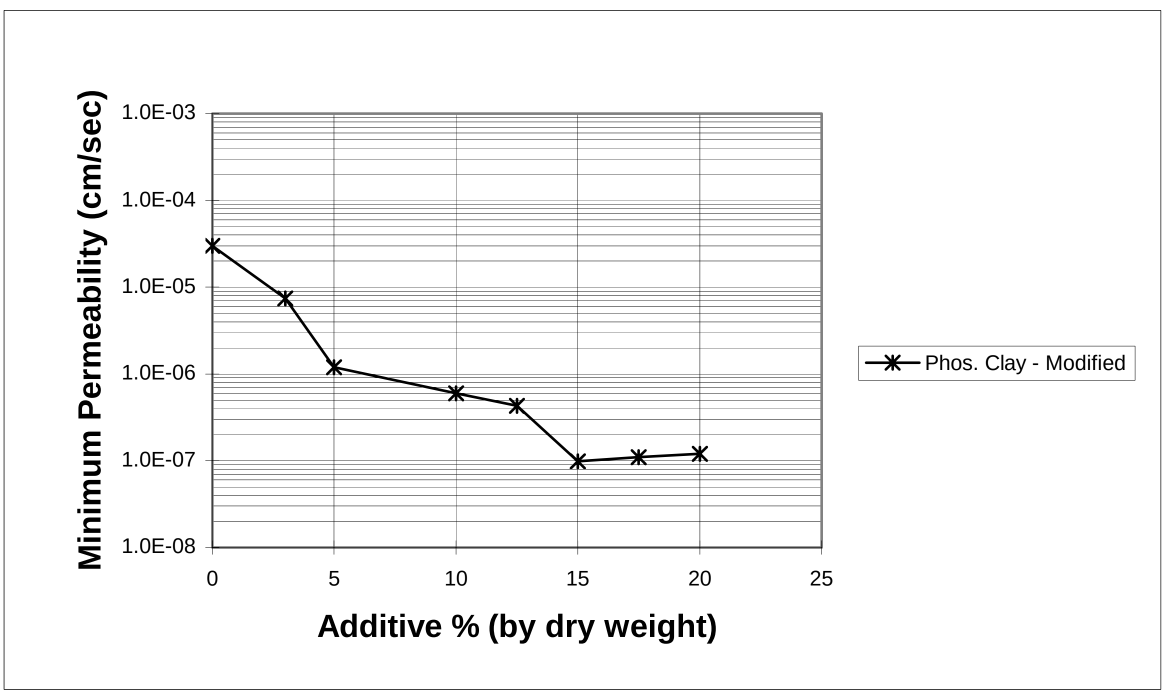

Figure 43. Permeability Versus Phosphatic Clay Additive Percentages.

Conclusions

Several conclusions are drawn from data presented in this report based upon the requirements for closure of a phosphogypsum stack. The conclusions are as follows:

- The permeability of compacted PG without additives is not less than 1 x 10^{-5} cm/sec.
- The permeability of PG can be decreased through the addition of clay materials and increases in compaction energy. With the addition of 10% bentonite clay or 15% phosphatic clay and the input of modified Proctor compaction energy, the permeability of PG can be reduced to 1 x 10^{-7} cm/sec or less.
- The addition of lime sludge or cement to compacted PG was not practical for reducing the permeability in a cost-effective manner.
- The input of compaction energy in excess of modified Proctor does not provide a significant decrease in permeability.
- The increase in additive percentage for bentonite and phosphatic clay above 15% has a minimal effect on the permeability of compacted PG.

This laboratory study has shown that compacted and amended PG can significantly reduce the permeability of a barrier layer, which may prevent or greatly reduce infiltration of rainwater into PG stacks. Before application of this research, however, a large scale field study should be conducted in order to monitor the effects of factors such as field mixing and compaction techniques, moisture content variations, climate changes, vegetation growth (ET) and stack settlement upon the permeability of the amended PG barrier layer.

Cost Analysis

One of the objectives of this research was to determine if an amended PG cover is a cost effective alternative for stack closure. The quantity of additive required to produce a suitable liner system will have to be evaluated in the field to determine the effects of mixing and compaction on the permeability of a barrier layer. Laboratory observations indicate that the ability to mix PG with moist phosphatic clay to create a homogenous layer may be a challenge but perhaps attainable and would require field verifications. Once the minimum percent of additive to meet the FAC requirements is determined in the field, a total cost for stack closure can be estimated.

The use of synthetic covers is not without concerns such as cost (estimates of $50,000 per acre or higher), resistance to settlement, erosion or movement of the soil cover/synthetic cover interface and the finite life (typically 30 years as per manufacturer's specifications). Therefore, further investigation of alternate, cost-effective final covers that satisfy the "intent of the rule," which is to minimize infiltration into the stack with little or no maintenance, is needed.

The cost of dry, powdered bentonite clay is approximately $140 to $160 per dry ton. For a 5% bentonite mix in an 18-inch thick PG layer, the material cost is approximately $20,000 to $25,000 per acre, and a 10% bentonite mix increases the material cost to approximately $50,000 per acre.

The use of phosphatic clay as an amendment for the barrier layer should be further evaluated, as it may prove to be the most cost effective alternative due to its availability. However, the cost of excavating, drying, pulverizing and transporting phosphatic clay will have to be further evaluated in the field to determine if this is a feasible alternative.

EVALUATION OF MOISTURE CONTENT VARIATIONS ON CRACKING OF PHOSPHOGYPSUM

Research Testing Plan

The major laboratory element of this research element was measurement of the volumetric strain of compacted and amended PG samples. The PG compacted at various energy levels and molding moisture contents with varying percentages of clay additive. Based on the permeability study, bentonite and phosphatic clay additives were the only viable options as amendments. Therefore, this research element concentrated on only those additives. Table 18 lists the matrix of test conditions including variations in compaction effort, molding moisture content and additive percentage.

Table 18. Matrix of Test Conditions for Volumetric Strain of PG with Variations in Compaction Energy, Molding Moisture Content and Additives and Percentages.

Compaction Energy	Additive & Percentage	Molding Moisture Content
Modified	5% Bentonite	13.0%
Modified	5% Bentonite	15.0%
Extra-Mod.	5% Bentonite	14.5%
Standard	10% Bentonite	16.5%
Standard	10% Bentonite	21.0%
Modified	10% Bentonite	14.0%
Modified	10% Bentonite	16.0%
Extra-Mod.	10% Bentonite	11.5%
Extra-Mod.	10% Bentonite	13.5%
Modified	10% Phos. Clay	17.0%
Modified	15% Phos. Clay	17.0%
Modified	15% Phos. Clay	19.0%

Sample Preparation

For each test set five-2000 gram samples were mechanically mixed with the same amount of water and additive. Each sample was sealed in a plastic bag and allowed to hydrate for a minimum of 24 hours. Figure 44 shows the samples after mixing. After hydration, the samples were compacted in a Proctor mold at the desired energy level and the molding moisture content was determined from the trimmings. Each sample was then extracted from the Proctor mold using a hydraulic press and placed on a Plexiglas pedestal to air dry in the laboratory as shown in Figure 45.

Test Procedures

When all five samples of the set were extracted, the initial volume of each was determined. The volume was measured using a caliper capable of measuring to 0.001 inch. Three height measurements and four diameter measurements were taken on each sample. The average value of the height and diameter were used to calculate the initial cylindrical volume. Volume measurements and moisture content by weight samples were taken over 14 day and 28 day periods.

For the first three sets of samples, volume measurements were taken every day for the first week of drying and then twice a week for the remaining three weeks of the test. After each week of drying, one sample was used to determine the moisture content. After reviewing the data from the first samples, the procedure was altered to provide more relevant data. Essentially the samples would reach their minimum moisture content after a 14 day period; therefore the testing interval was concentrated into a two week period. For the remaining sample sets, volume measurements were taken on a daily basis for a week and then every other day for the next week. Moisture content samples were taken after 1, 2, 4, 7 and 14 days.

Figure 44. Desiccation Test Samples before Compaction.

Figure 45. Desiccation Samples after Compaction and Extraction.

Five Percent Bentonite

Three sets of PG samples were compacted with 5% bentonite using the modified and extra-modified compaction energies. For the modified energy, the molding moisture contents were 13.0 and 15.0%. The optimum moisture content (OMC) was determined to be 12.0%. The extra-modified samples were compacted at a molding moisture content of 14.5% and the OMC was 11.0%

Table 19 summarizes the average volumetric ($\Delta v/Vo$) strain and moisture content values for compacted PG samples with 5% bentonite. Figures 46 through 51 show the volumetric strain and moisture content versus drying time for compacted PG samples with 5% bentonite. The modified sample at 13% demonstrated a volumetric strain of 1% per day for the first week as the moisture content decreased to approximately 2%. After one week the strain remained constant between 3 and 6% as the moisture content decreased to less than 1%. The modified samples at 15% displayed similar results as the strain increased to between 4 and 6% after one week while the moisture content decreased to approximately 3%. The strain remained constant between 5 and 7% for the next three weeks as the moisture content decreased to less than 1%. The extra-modified samples showed a strain of 7 to 8% after one week and remained constant between 8 and 9% strain for the remaining three weeks of the test period.

Table 19. Average Volumetric Strain (ε_v%) and Moisture Content (w%) During Drying for PG with 5% Bentonite.

Sample Identification	Optimum Moisture (%)	Initial Moisture (%)	7 Days		14 Days		21 Days		28 Days	
			ε_v%	w%	ε_v%	w%	ε_v%	w%	ε_v%	w%
MD-#-5B	12.0	13.0	5	2	5	1	5	0.5	6	0
MD-#-5B	12.0	15.0	7	3	7	1	7	0.5	7	0
EM-#-5B	11.0	14.5	8	3	8.5	0.5	8.5	0.5	8.5	0

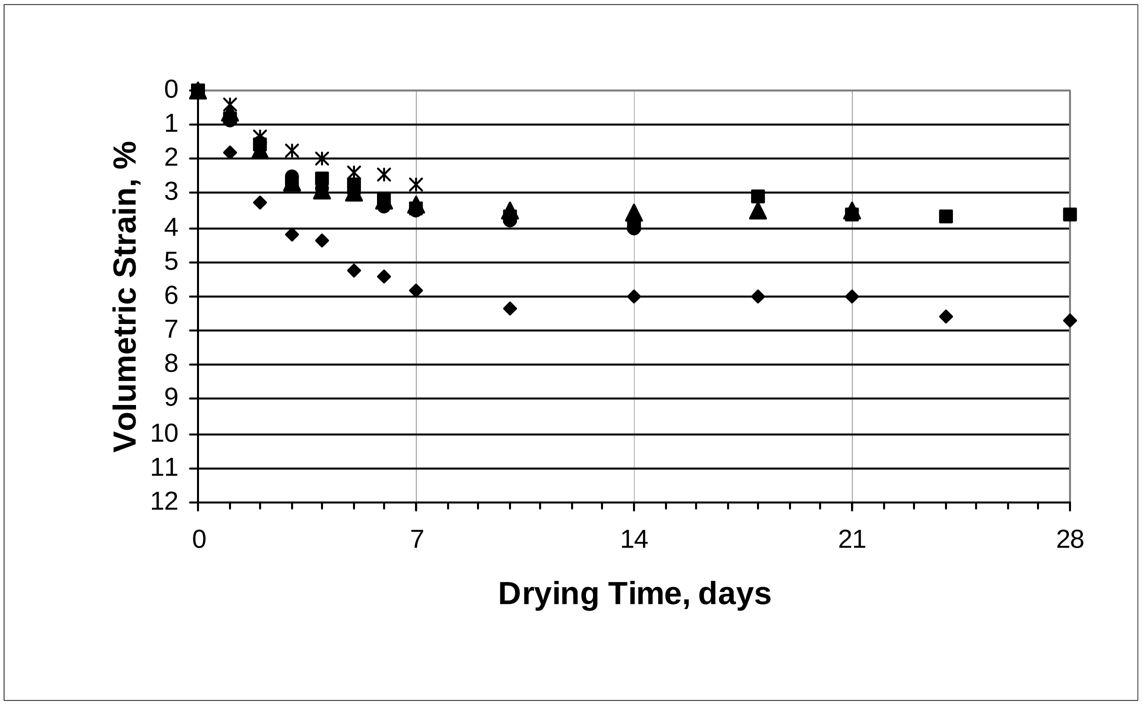

Figure 46. Volumetric Strain Versus Drying Time for PG with 5% Bentonite under Modified Compaction at a Molding Moisture Content of 13% (MD-#-5B-13%).

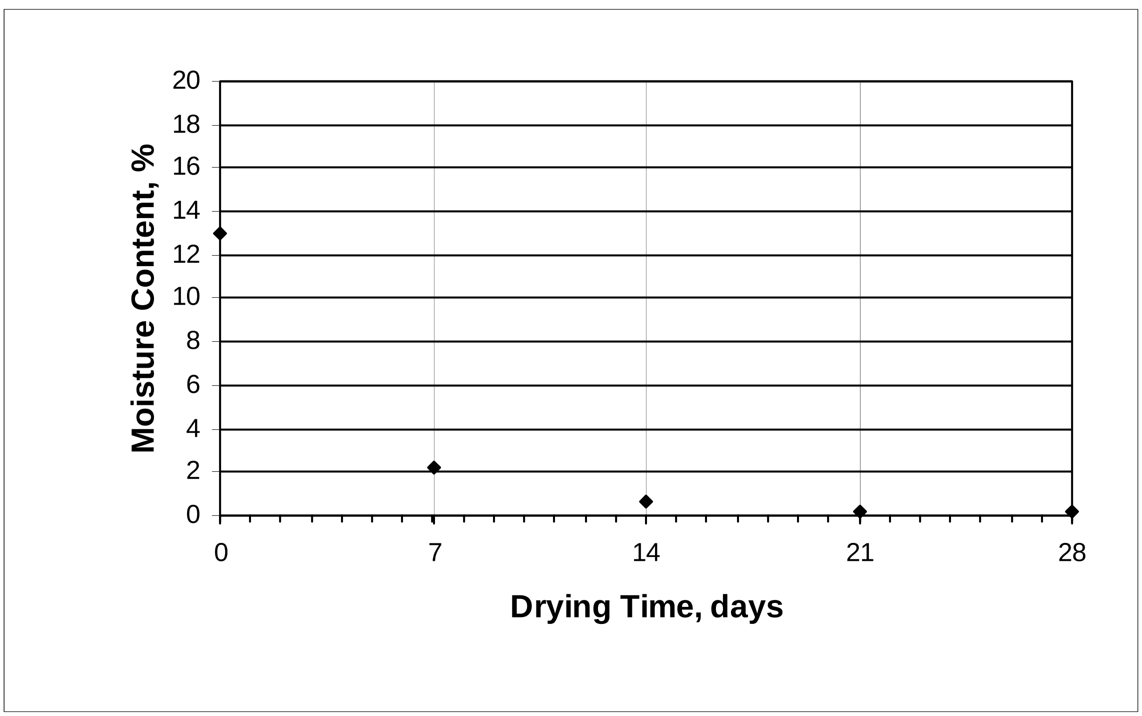

Figure 47. Moisture Content Versus Drying Time for MD-#-5B-13%.

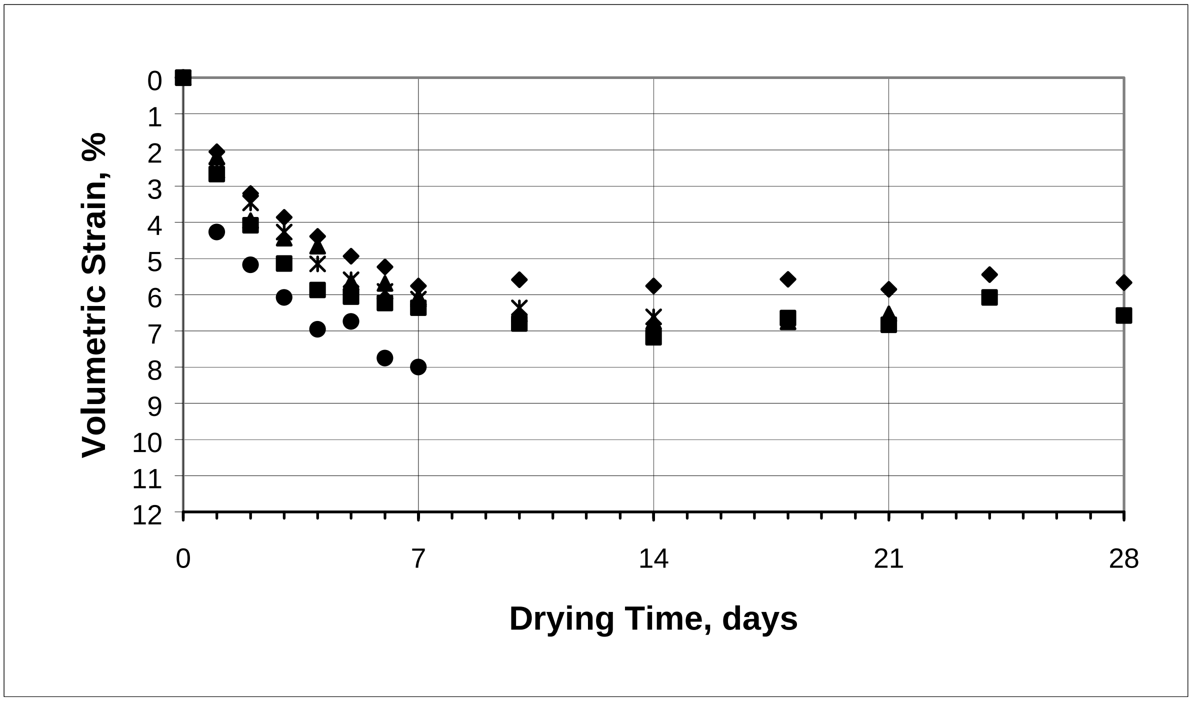

Figure 48. Volumetric Strain Versus Drying Time for PG with 5% Bentonite under Modified Compaction at a Molding Moisture Content of 15% (MD-#-5B-15%).

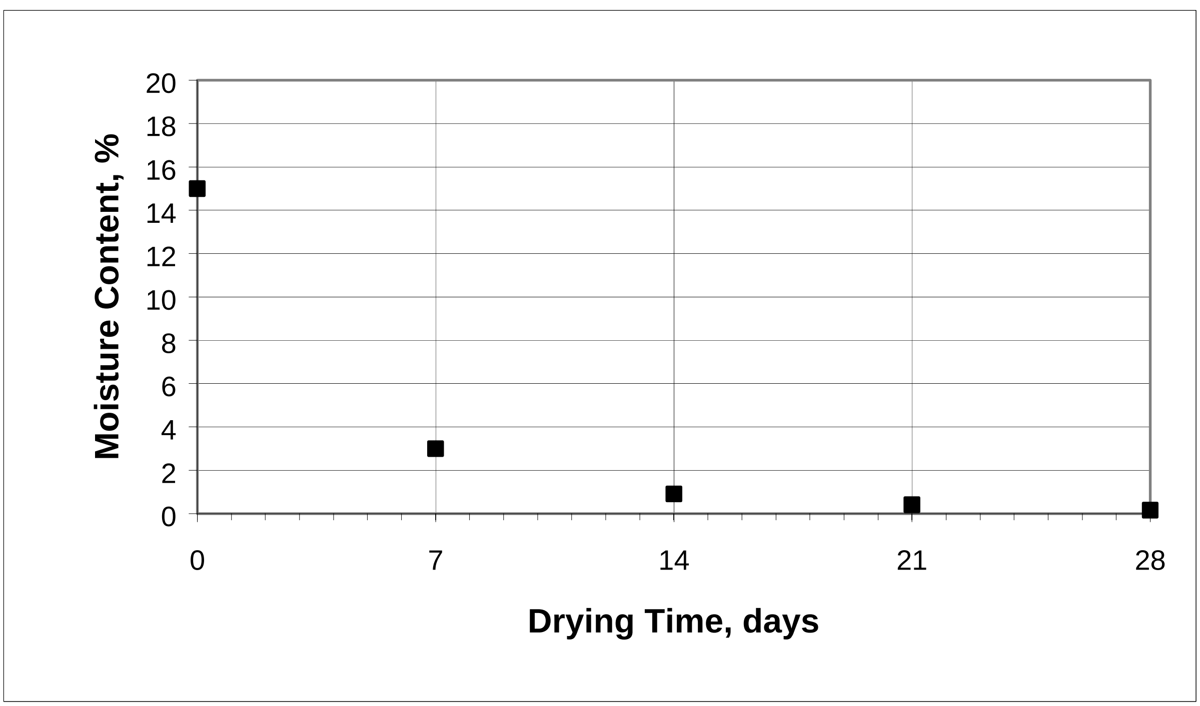

Figure 49. Moisture Content Versus Drying Time for MD-#-5B-15%.

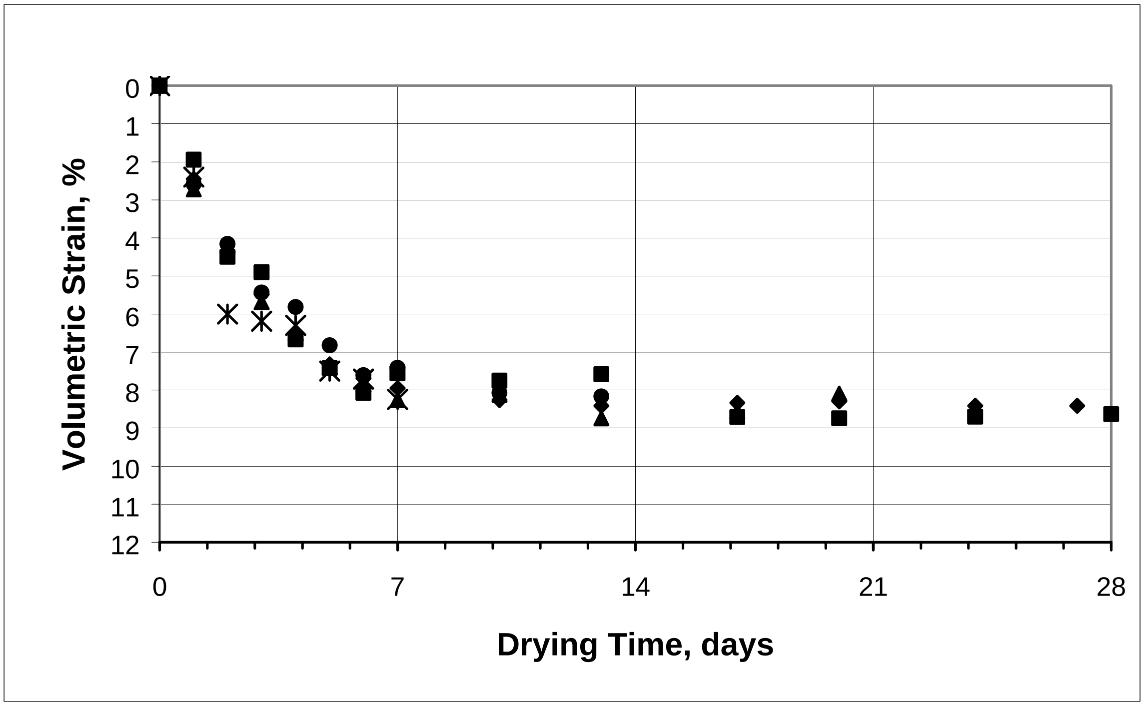

Figure 50. Volumetric Strain Versus Drying Time for PG with 5% Bentonite under Extra-Modified Compaction at a Molding Moisture Content of 14.5% (EM-#-5B-14.5%).

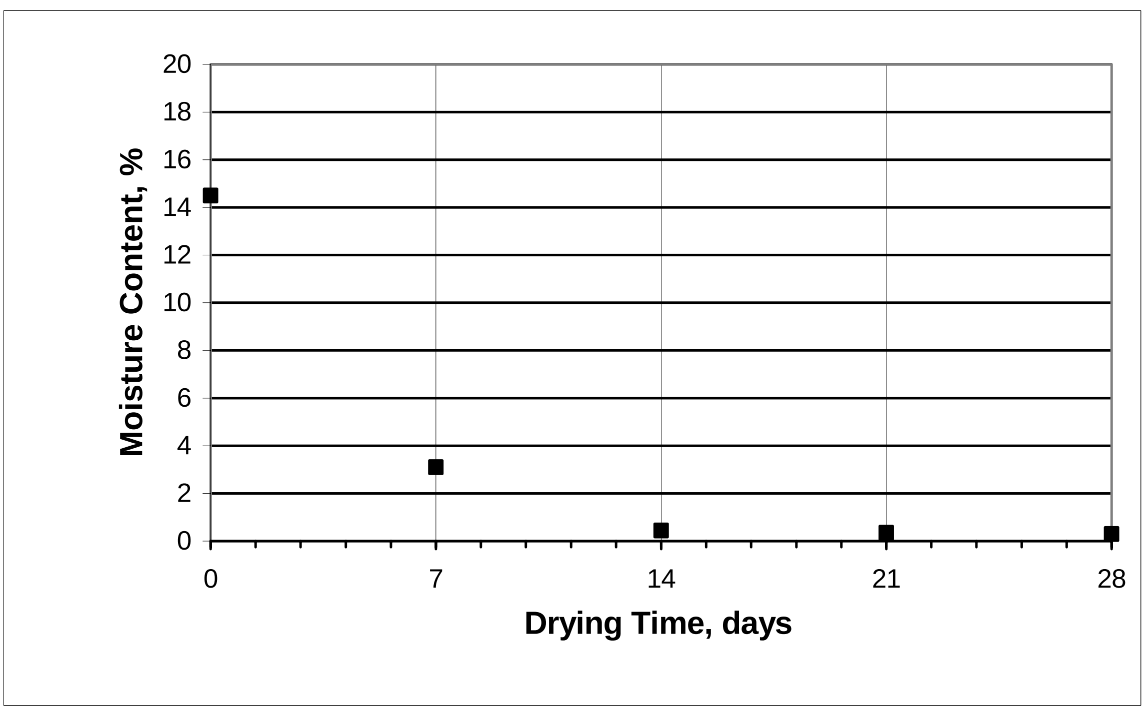

Figure 51. Moisture Content Versus Drying Time for EM-#-5B-14.5%.

Ten Percent Bentonite

Six sets of PG samples were compacted with 10% bentonite using the modified, standard and extra-modified compaction energies. For the standard energy the molding moisture contents were 16.5 and 21.0%. The optimum moisture content (OMC) was determined to be 17.0%. For the modified energy, the molding moisture contents were 14.0 and 16.0% while the OMC was 13%. The extra-modified samples were compacted at a molding moisture content of 11.5 and 13.5% while the OMC was 10.5%.

Table 20 summarizes the average volumetric strain and moisture content values for compacted PG samples with 10% bentonite. Figures 52 through 63 show the volumetric strain and moisture content versus drying time relationships for compacted PG samples with 10% bentonite. The standard sample at 16.5% showed a 5% volumetric strain after 7 days as the moisture content decreased to 5%. The strain remained constant at 5% as the samples dried to 2% after 14 days. The standard sample at 21.0% showed a 9% strain after 7 days as the moisture content decreased to 6%. After 14 days, the strain was constant at 10% while the moisture content decreased to 2%. The modified sample at 14% showed strains between 6 and 8% as the moisture content decreased to 2% after 7 days. The strains remained constant at an average of 8% as the moisture content decreased to less than 1% after two weeks. The modified sample at 16% showed a 9% strain after one week as the moisture decreased to 5%. The strains decreased to 11 to 12% after 14 days. The extra-modified sample at 11.5% shows a strain of 4% at a moisture content of 2% after one week. The strain remained constant at 4% as the moisture content decreased to 1% after 14 days. The extra-modified sample at 13.5% showed strains of 9% at a moisture content of 4% after a week. The strain increased to 11% as the moisture content decreased to 1% after 14 days.

Table 20. Average Volumetric Strain (ε_v%) and Moisture Content (w%) During Drying for PG with 10% Bentonite.

Sample Identification	Optimum Moisture (%)	Initial Moisture (%)	1 Day		2 Days		4 Days		7 Days		14 Days	
			ε_v%	w%	ε%	w%	ε_v%	w%	ε_v%	w%	ε_v%	w%
ST-#-10B	17.0	16.5	1	14	2	13	4.5	7	4.5	5	4.5	2
ST-#-10B	17.0	21.0	2	16	4	16	7	10	8	6	10	2
MD-#-10B	13.0	14.0	4	12	7	10	8	5.5	8	2	8	2
MD-#-10B	13.0	16.0	2	13.5	4	13	8	7	10	5	12	2
EM-#-10B	10.5	11.5	1.5	8	2.5	ND	4	2	4.5	2	4.5	2
EM-#-10B	10.5	13.5	3	ND	4	6	7	5	3	ND	10.5	1

ND – no data

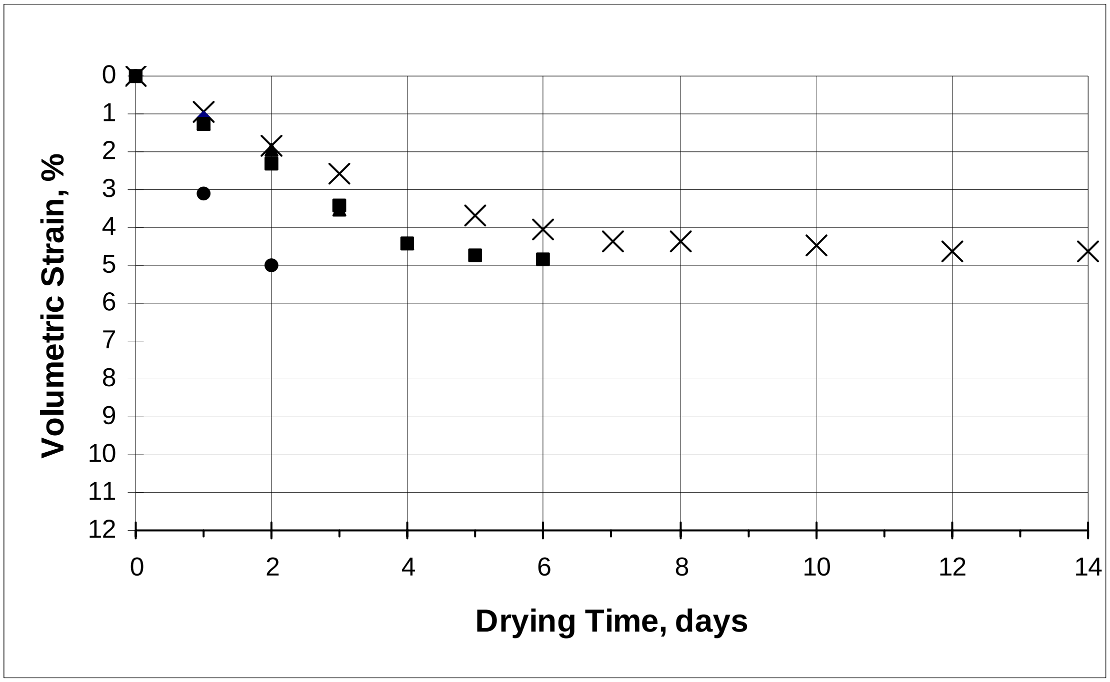

Figure 52. Volumetric Strain Versus Drying Time for PG with 10% Bentonite under Standard Compaction at a Molding Moisture Content of 16.5% (ST-#-10B-16.5%).

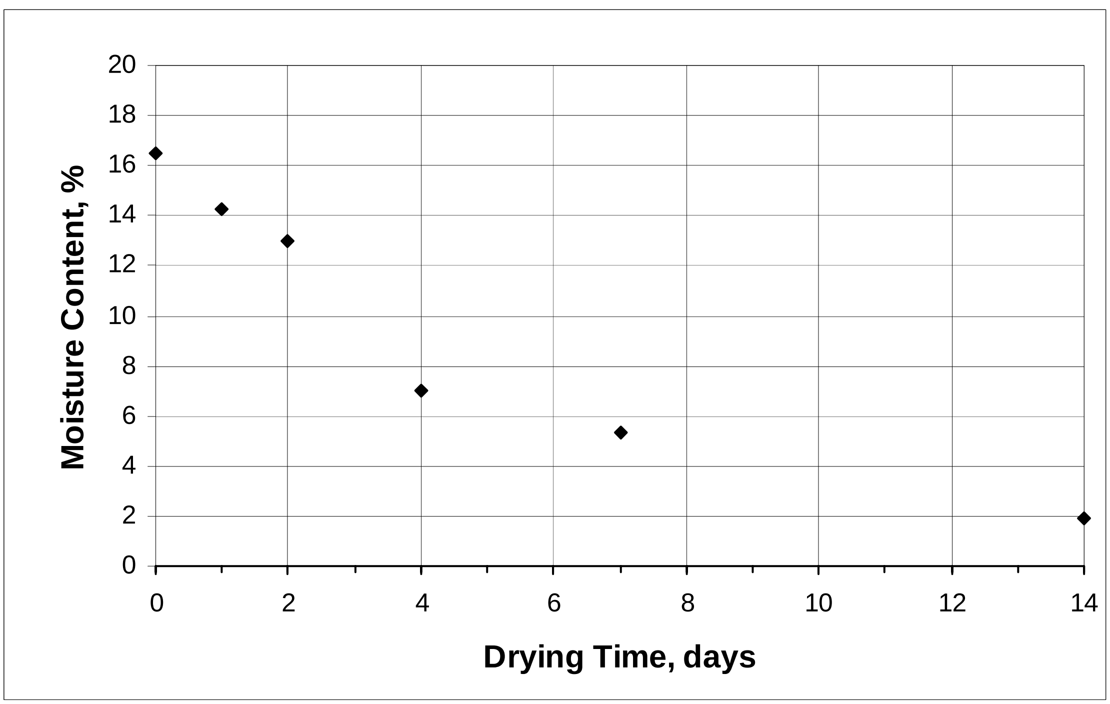

Figure 53. Moisture Content Versus Drying Time for ST-#-10B-16.5%.

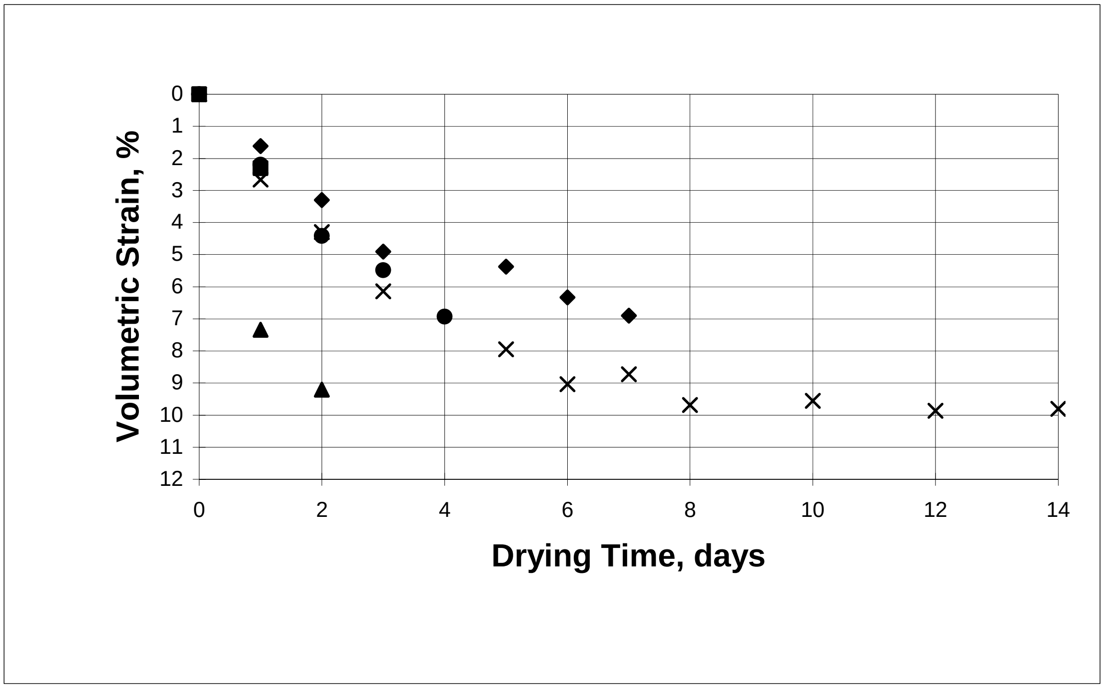

Figure 54. Volumetric Strain Versus Drying Time for PG with 10% Bentonite under Standard Compaction at a Molding Moisture Content of 21% (ST-#-10B-21%).

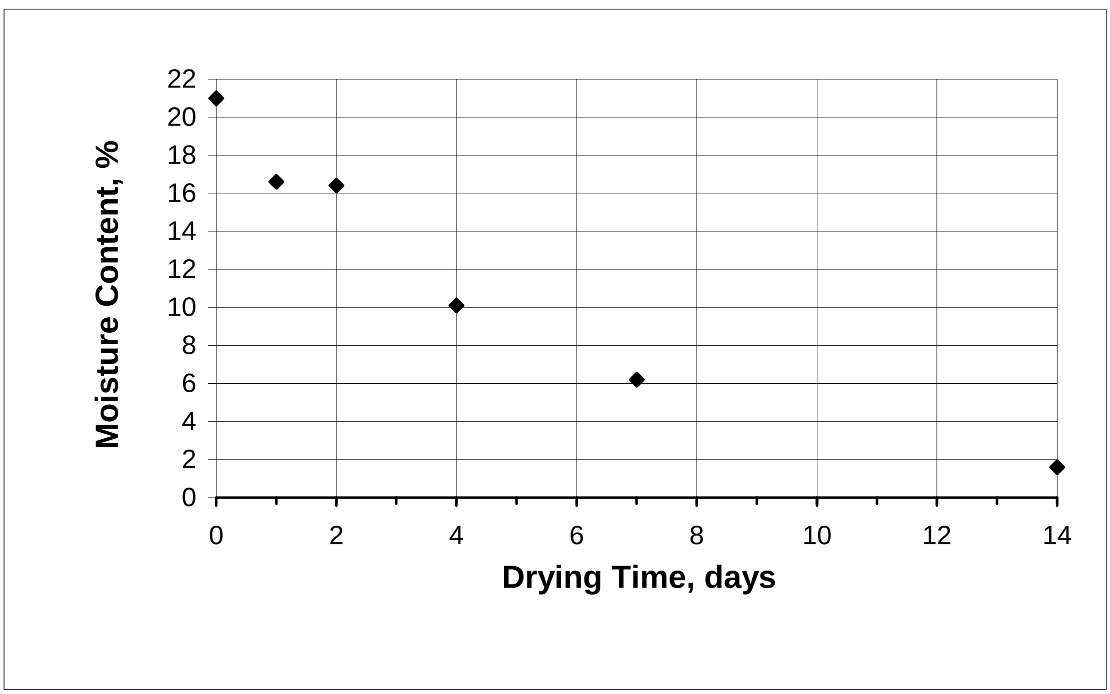

Figure 55. Moisture Content Versus Drying Time for ST-#-10B-21%.

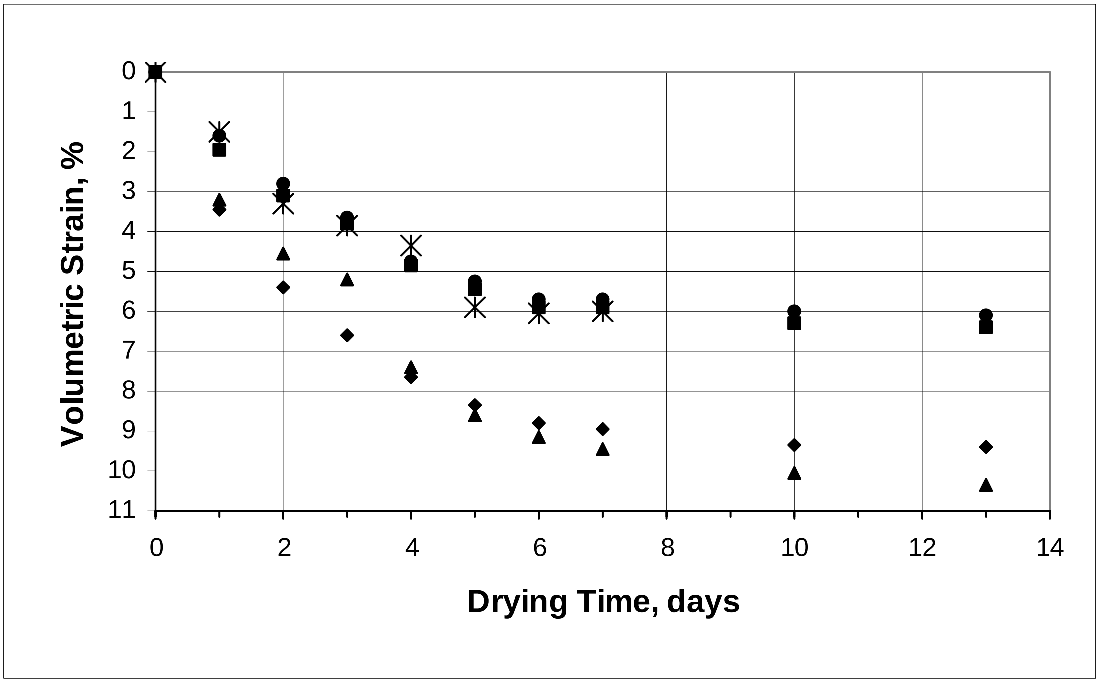

Figure 56. Volumetric Strain Versus Drying Time for PG with 10% Bentonite under Modified Compaction at a Molding Moisture Content of 14% MD-#-10B-14%).

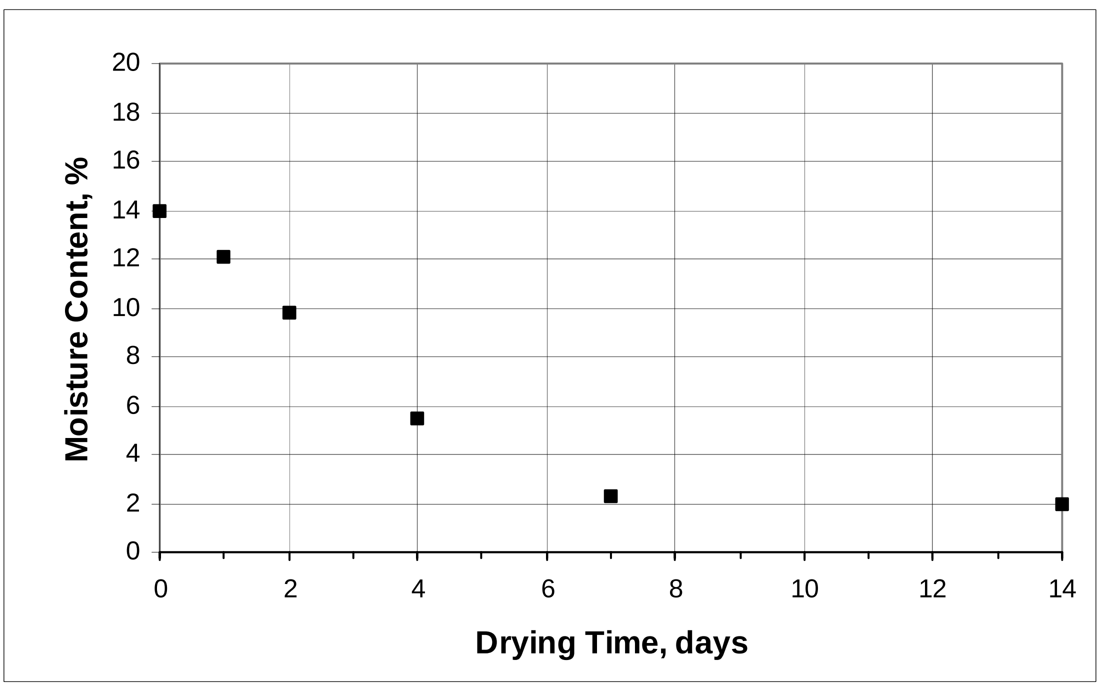

Figure 57. Moisture Content Versus Drying Time for MD-#-10B-14%.

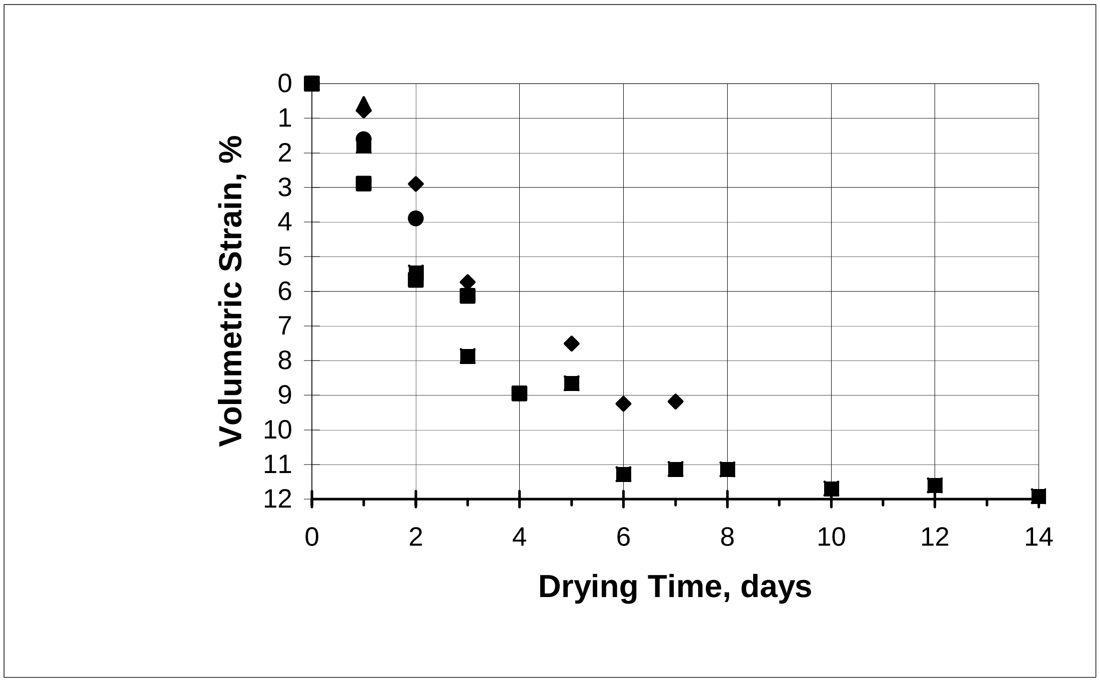

Figure 58. Volumetric Strain Versus Drying Time for PG with 10% Bentonite under Modified Compaction at a Molding Moisture Content of 16% (MD-#-10B-16).

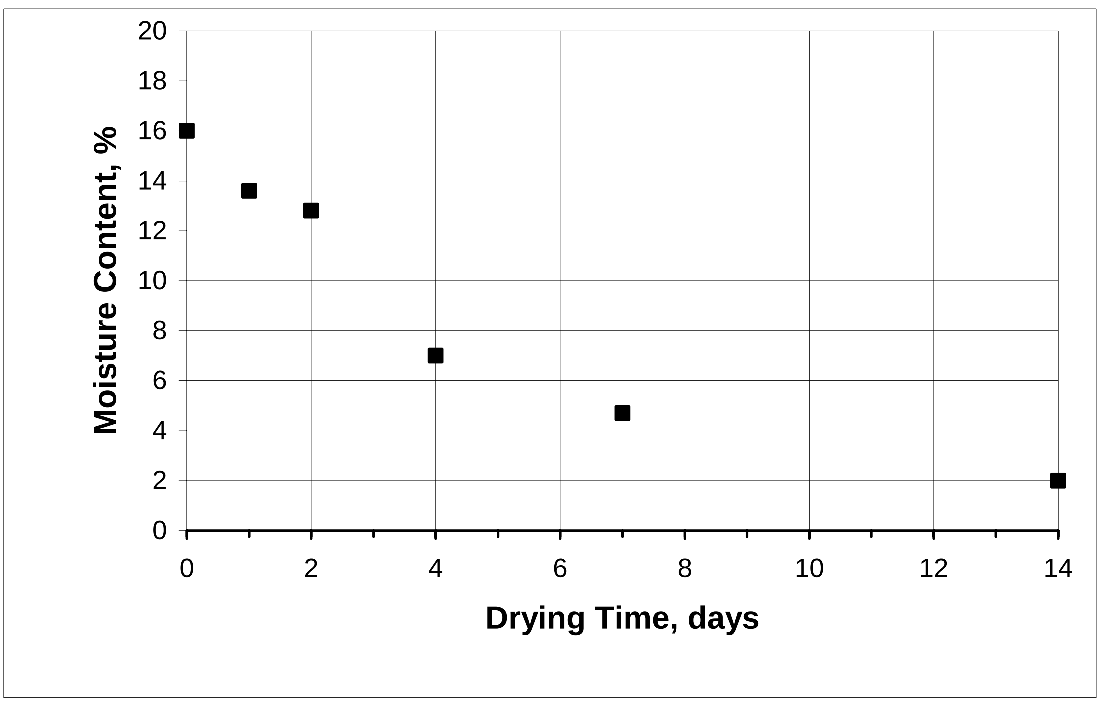

Figure 59. Moisture Content Versus Drying Time for MD-#-10B-16%.

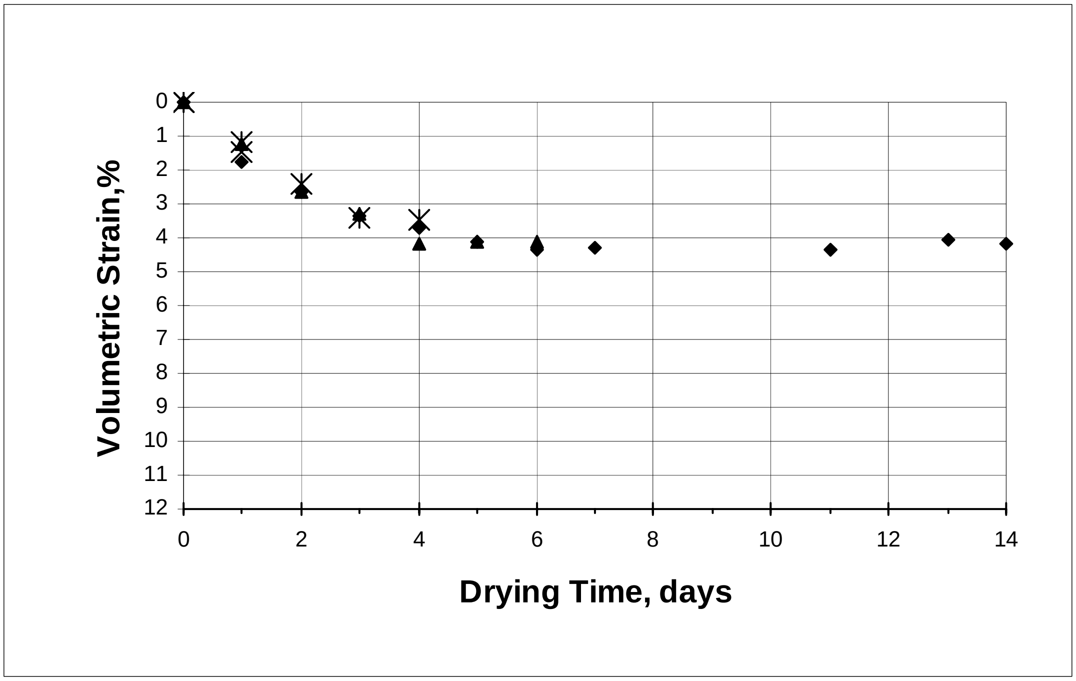

Figure 60. Volumetric Strain Versus Drying Time for PG with 10% Bentonite under Extra-Modified Compaction at a Molding Moisture Content of 11.5% (EM-#-10B-11.5%).

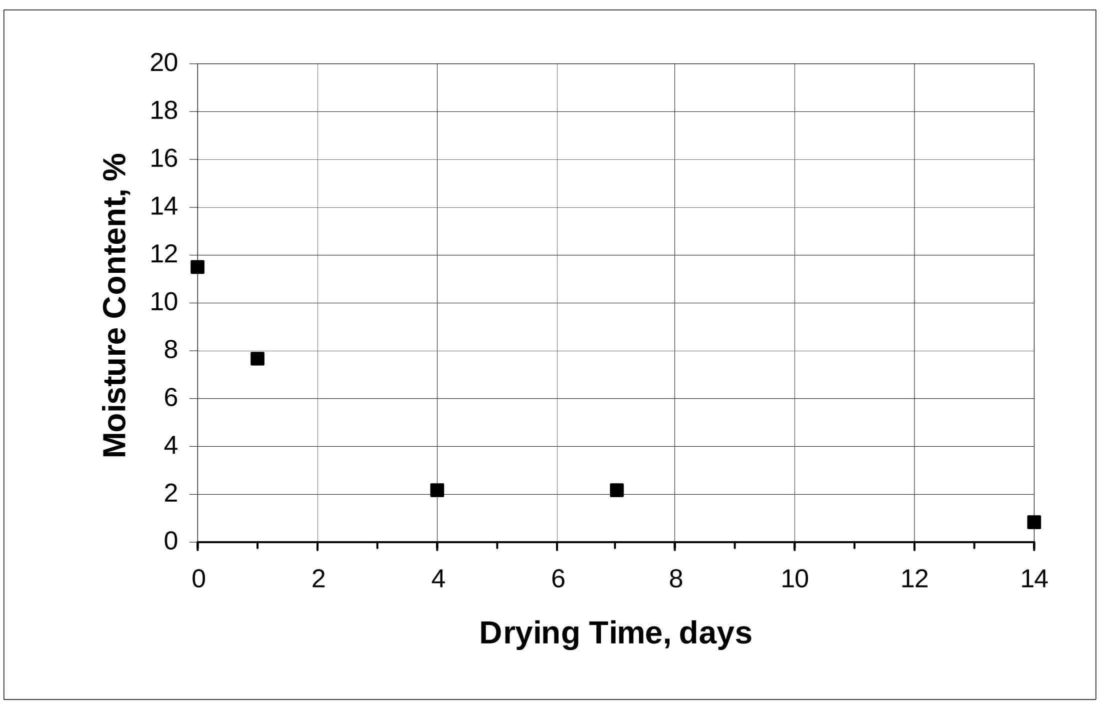

Figure 61. Moisture Content Versus Drying Time for EM-#-10B-11.5%.

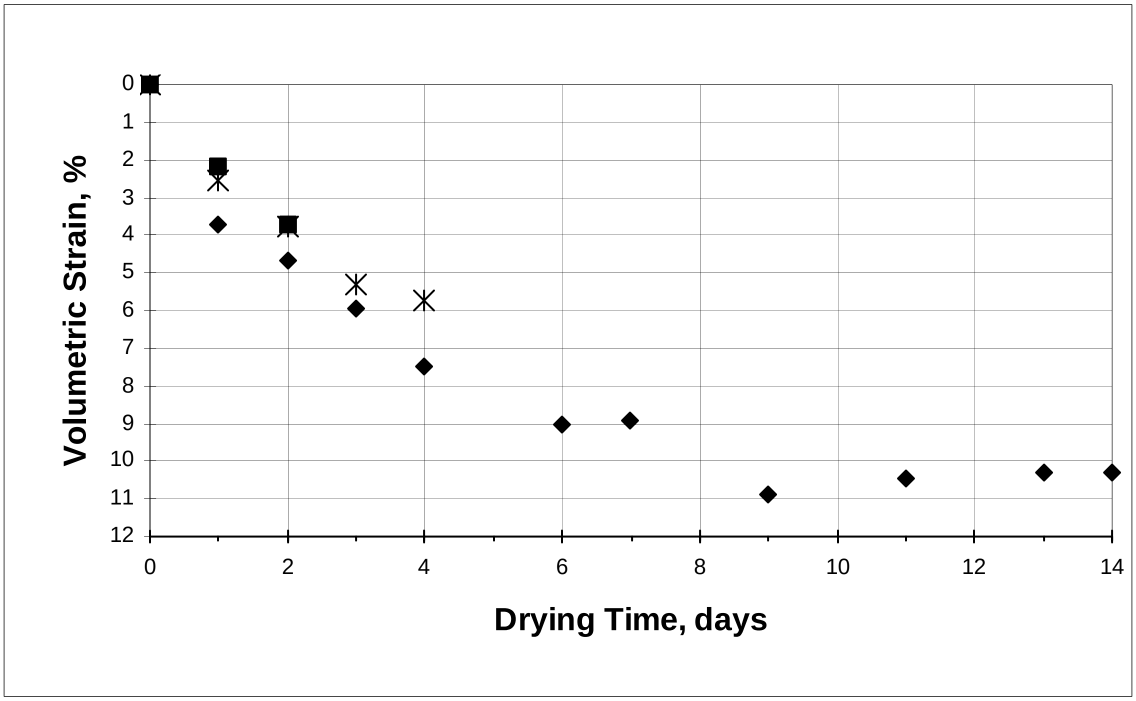

Figure 62. Volumetric Strain Versus Drying Time for PG with 10% Bentonite under Extra-Modified Compaction at a Molding Moisture Content of 13.5% (EM-#-10B-13.5%).

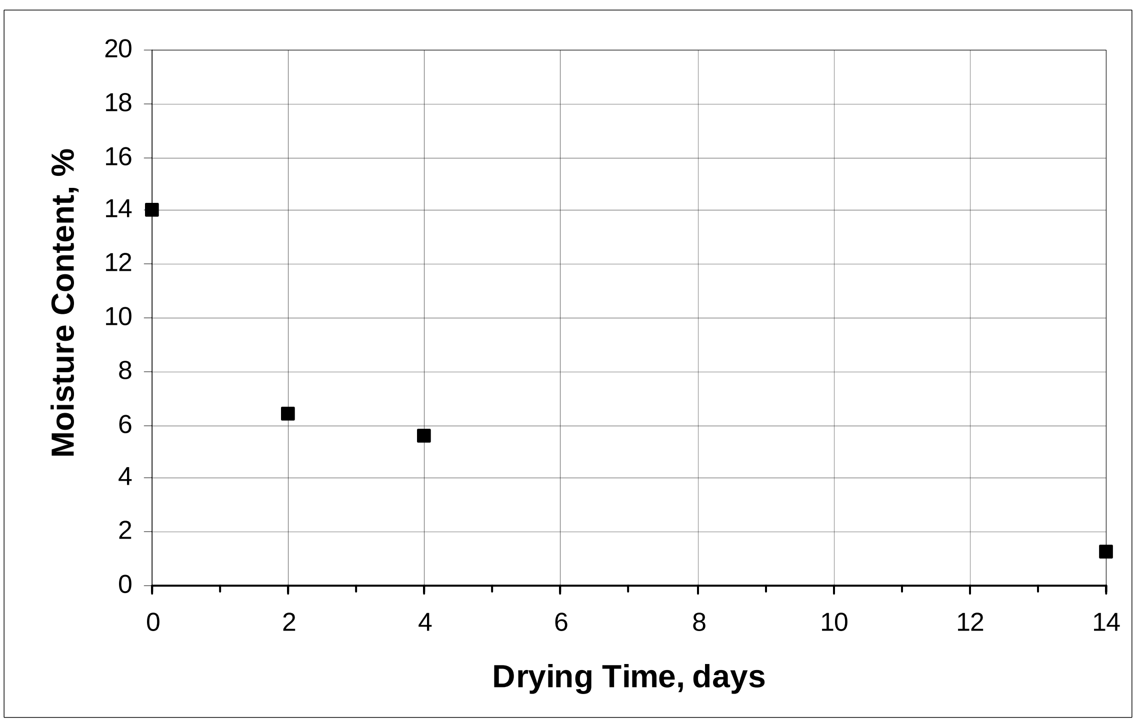

Figure 63. Moisture Content Versus Drying Time for EM-#-10B-13.5%.

Phosphatic Clay

Three sets of PG samples were compacted at modified energy with 10% and 15% phosphatic clay. For the PG sample with 10% phosphatic clay, the molding moisture content was 17%, while the OMC was 16.0%. For the PG samples with 15% phosphatic clay, the molding moisture contents were 17.0 and 19.0%, while the OMC was 15.0%.

Table 21 summarizes the average volumetric strain and moisture content values for the compacted PG samples with 10% and 15% phosphatic clay. Figures 64 through 69 show the volumetric strain and moisture content versus drying time relationships for the compacted PG samples with 10% and 15% phosphatic clay. The modified sample with 10% phosphatic clay showed a volumetric strain of 4 to 6% in one week as the moisture content decreased to 2%. The strain remained at approximately 5% as the moisture content decreased to less than 1% after 14 days. The modified PG with 15% phosphatic clay at an initial moisture content of 17% showed a 6% strain after 7 days as the moisture content decreased to 4%. The strain remained at 6 to 7% as the moisture content decreased to 2% after 14 days. The modified PG with 15% phosphatic clay at an initial moisture content of 19% showed a 6% strain as the moisture content decreased to 6% after 7 days. The strain remained constant at 6% as the moisture content decreased to 1% after 14 days.

Table 21. Average Volumetric Strain (ε_v%) and Moisture Content (w%) During Drying for PG with Phosphatic Clay.

Sample Identification	Optimum Moisture (%)	Initial Moisture (%)	1 Day		2 Days		4 Days		7 Days		14 Days	
			ε_v%	w%	ε_v%	w%	ε_v%	w%	ε_v%	w%	ε_v%	w%
MD-#-10PC	16.0	17.0	1	15	2	14.5	4	8	5	2	5	1
MD-#-15PC	15.0	17.0	2	16	2.5	13.5	5	9	6	4	6.5	2
MD-#-15PC	15.0	19.0	1	16	2	14	4	9	5.5	6	6	1

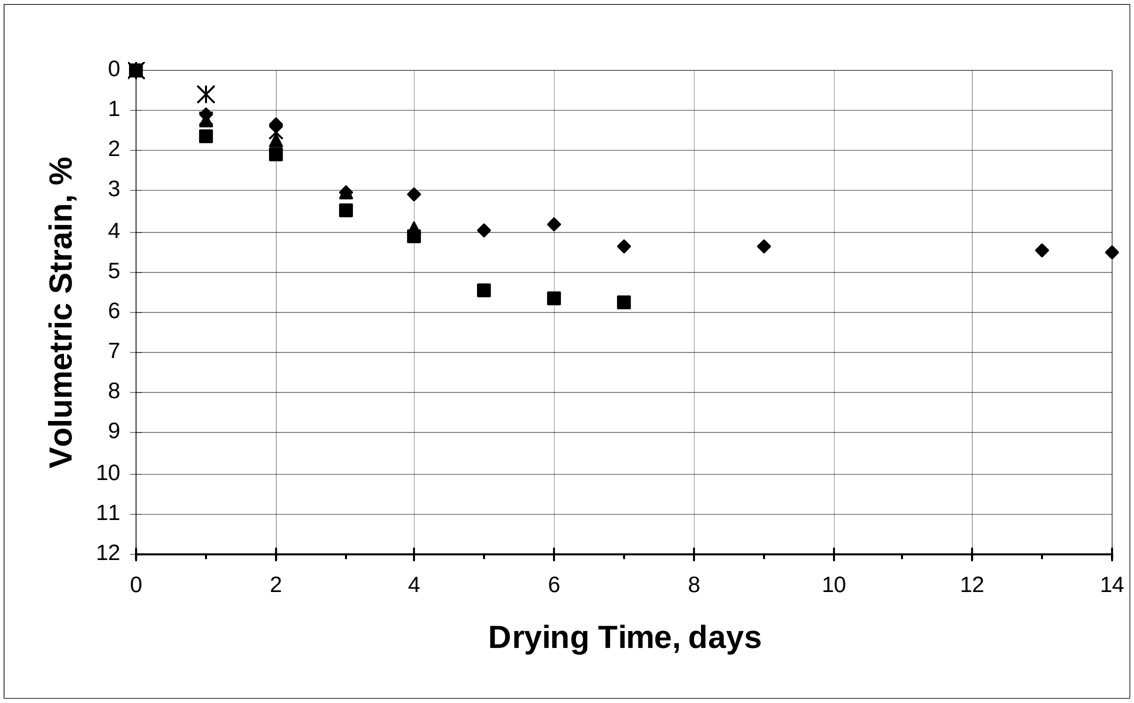

Figure 64. Volumetric Strain Versus Drying Time for PG with 10% Phosphatic Clay under Modified Compaction at a Molding Moisture Content of 17% (MD-#-10PC-17%).

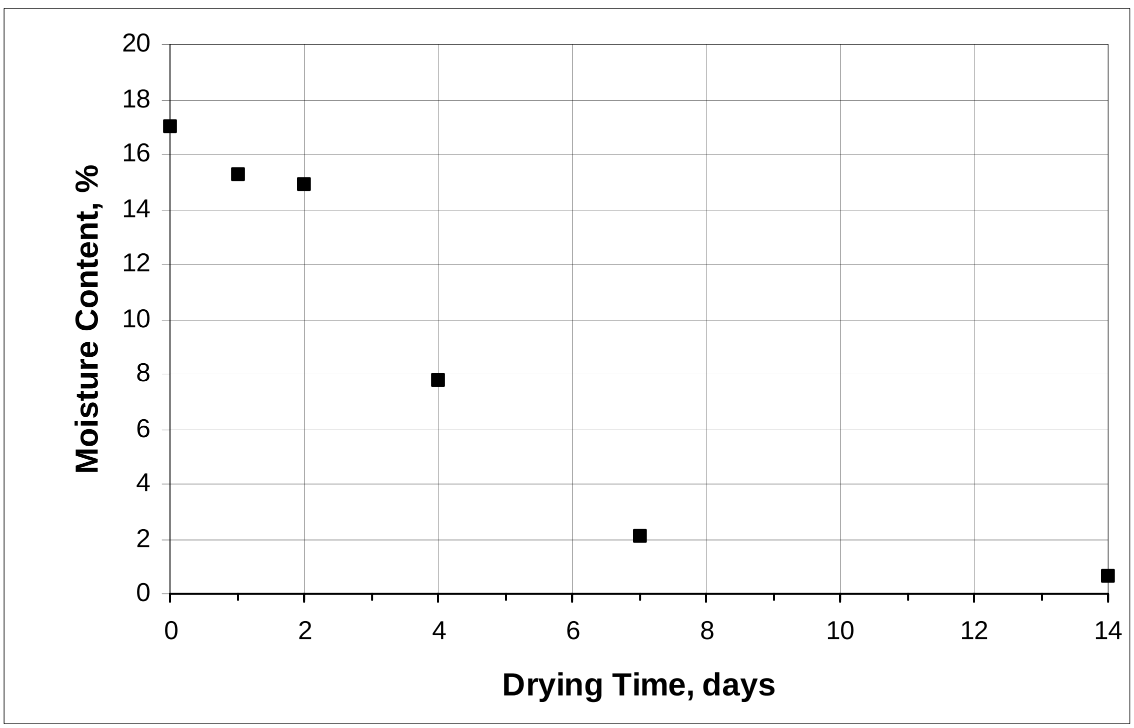

Figure 65. Moisture Content Versus Drying Time for MD-#-10PC-17%.

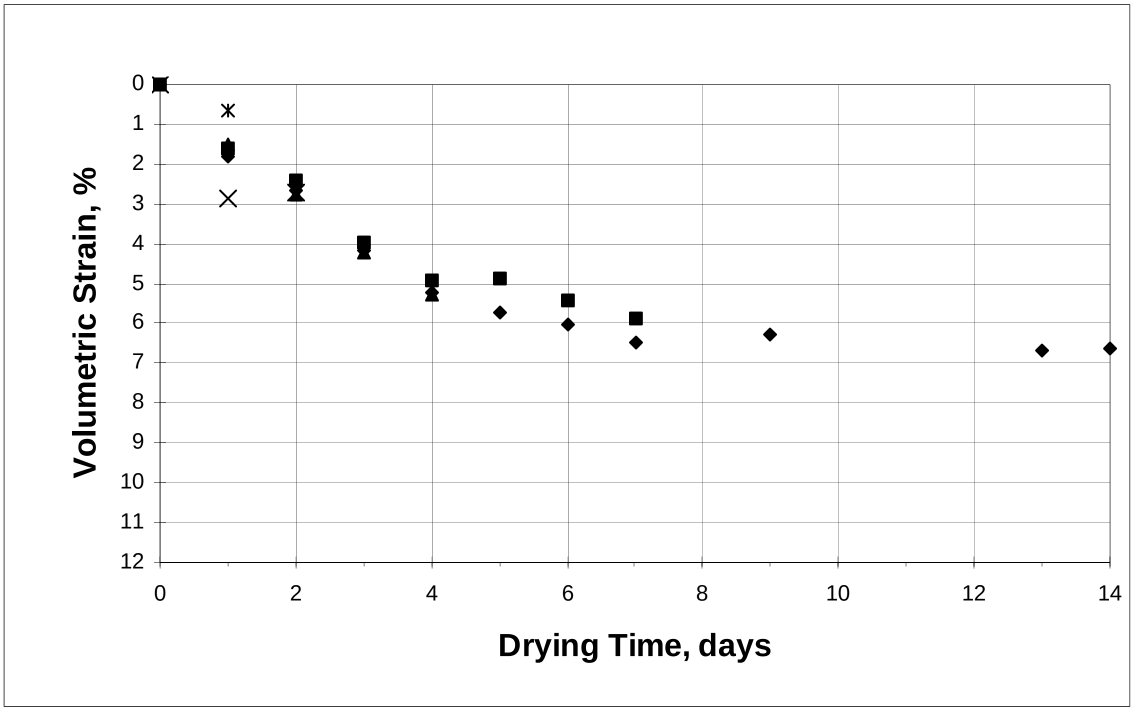

Figure 66. Volumetric Strain Versus Drying Time for PG with 15% Phosphatic Clay under Modified Compaction at a Molding Moisture Content of 17% (MD-#-15PC-17%).

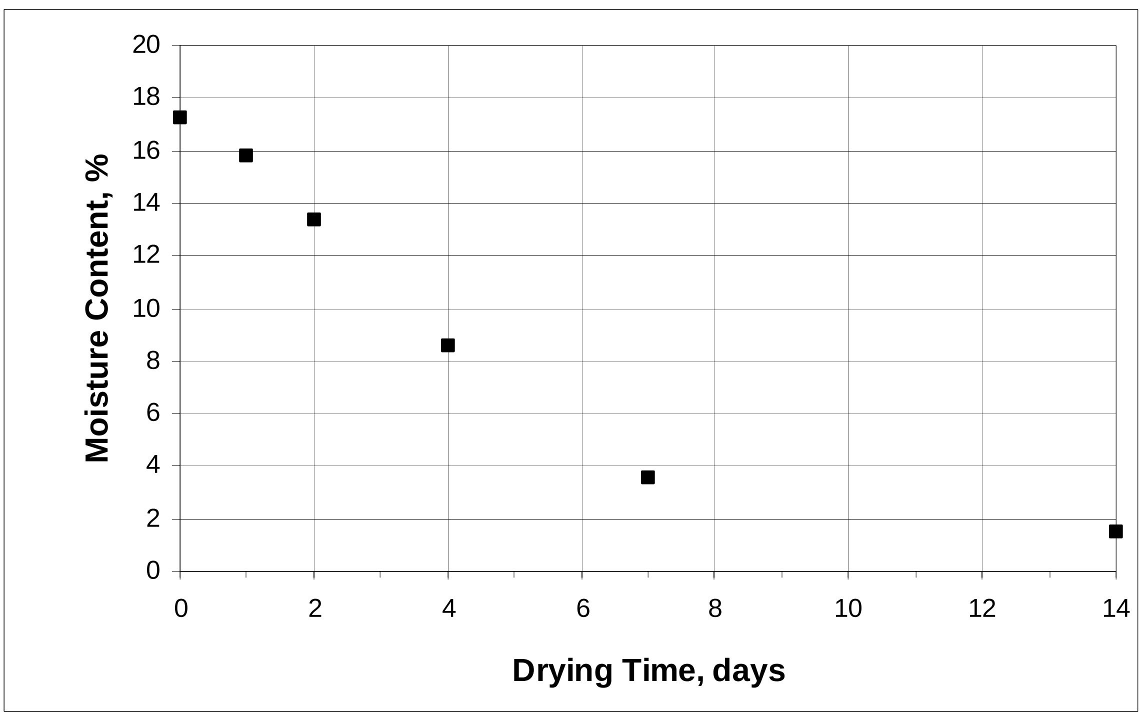

Figure 67. Moisture Content Versus Drying Time for MD-#-15PC-17%.

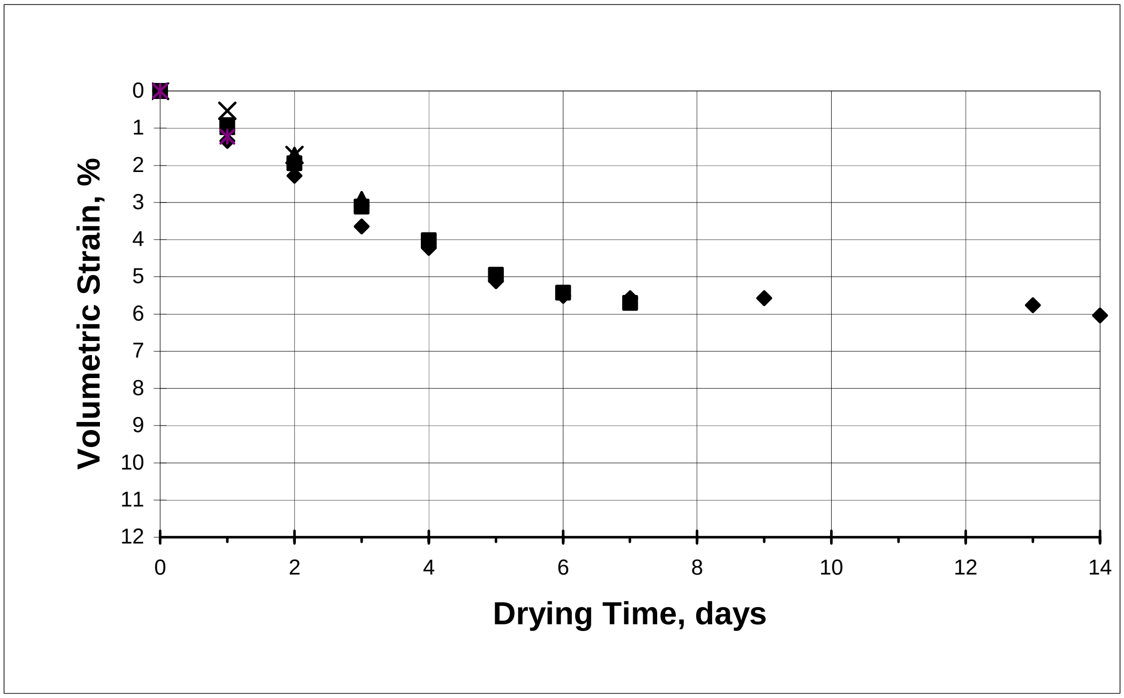

Figure 68. Volumetric Strain Versus Drying Time for PG with 15% Phosphatic Clay under Modified Compaction at a Molding Moisture Content of 19% (MD-#-15PC-19%).

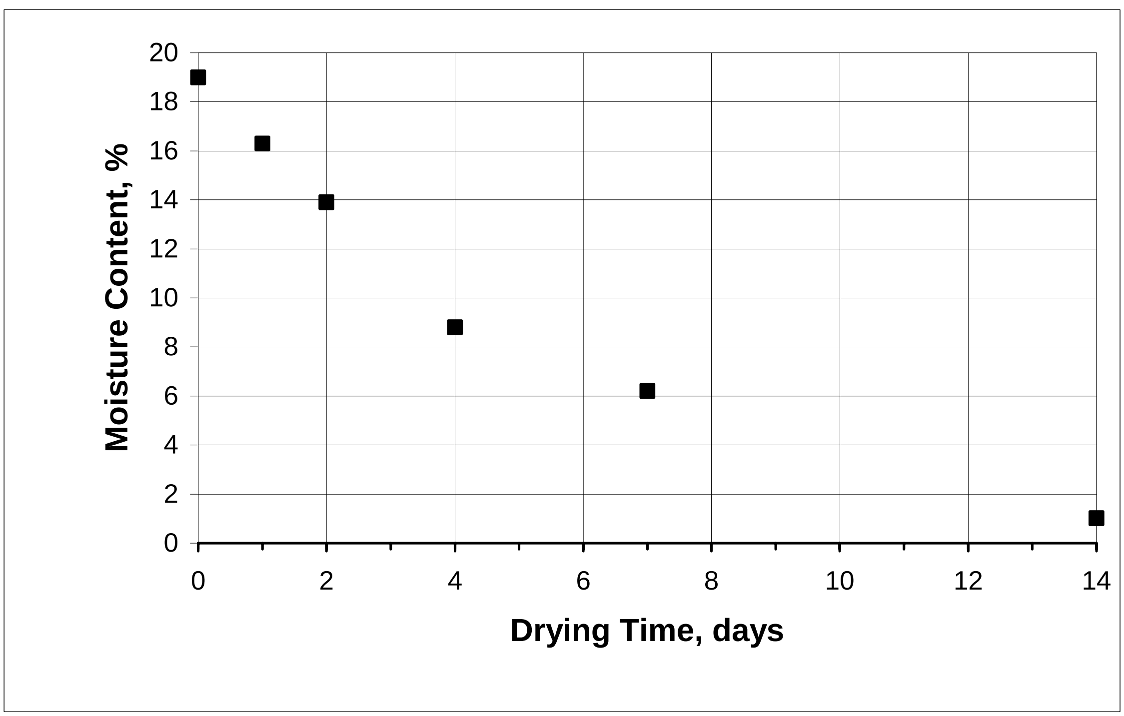

Figure 69. Moisture Content Versus Drying Time for MD-#-15PC-19%.

Summary and Comparison of Test Results

Twelve sets of amended PG samples were measured for volumetric strain as the samples were air-dried under laboratory conditions. The sample amendments and compaction energies were chosen based upon the permeability test data and most probable field applications. The majority of the samples were compacted at a moisture content of 1 to 3% above the optimum moisture to duplicate typical field compaction techniques.

The desiccation test results showed very similar trends for all samples. For the first 5 days of the tests each sample demonstrated a volumetric strain of approximately 1 to 2% per day as the moisture content decreased 1 to 2% per day. After 7 days, the samples reached a constant strain value at a moisture content of 2% or less. None of the samples showed any visible signs of cracking during the test periods. Figures 70 through 73 show a range of sample mixes at various points during drying.

For a liner system consisting of an 18 inch thick layer of amended gypsum compacted above the modified optimum moisture content (15% to 18%), and buried beneath an 18 inch layer of vegetated PG, the expected in-situ moisture content of the compacted layer is in the range of 10% to 15%. Samples taken at depth from lysimeter plots at Cytec Industries Brewster stack in June 1998 had moisture contents ranging from 11% to 16%. These plots had been in place at the Brewster stack for over four years.

Figures 74 and 75 show a comparison of PG with 5% bentonite under modified and extra-modified compaction with different molding moisture contents. The maximum strains ranged from 4% to 8.5%. The strains within the predicted in-situ moisture content range of 11% to 16% varied from 0 to 6%.

Figures 76 and 77 show a comparison of PG with 10% bentonite under standard, modified and extra-modified compaction with different molding moisture contents. The maximum strains ranged from 4% to 12%. The strains within the predicted in-situ moisture varied from 0% to 5%.

Figures 78 and 79 show a comparison of PG under modified compaction with 10% and 15% phosphatic clay with different molding moisture contents. The maximum strains ranged from 5% to 6.5%. The strains within the in-situ moisture content range varied from 0% to 4.5%.

Figure 70. PG with 15% Phosphatic Clay under Modified Compaction After 2 Days Drying – Approximately 2% Volumetric Strain.

Figure 71. PG with 15% Phosphatic Clay under Modified Compaction After 14 Days Drying – Approximately 6% Volumetric Strain.

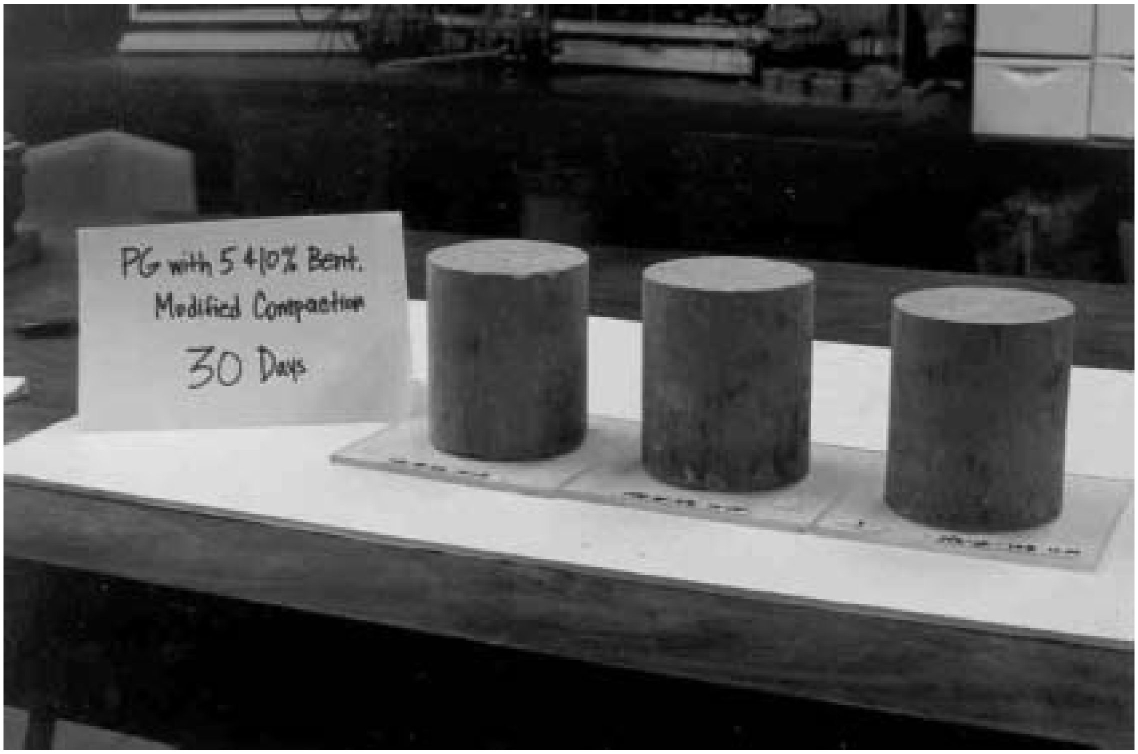

Figure 72. PG with Bentonite under Modified Compaction after 30 Days.

Figure 73. PG with Bentonite under Modified Compaction after 45 Days.

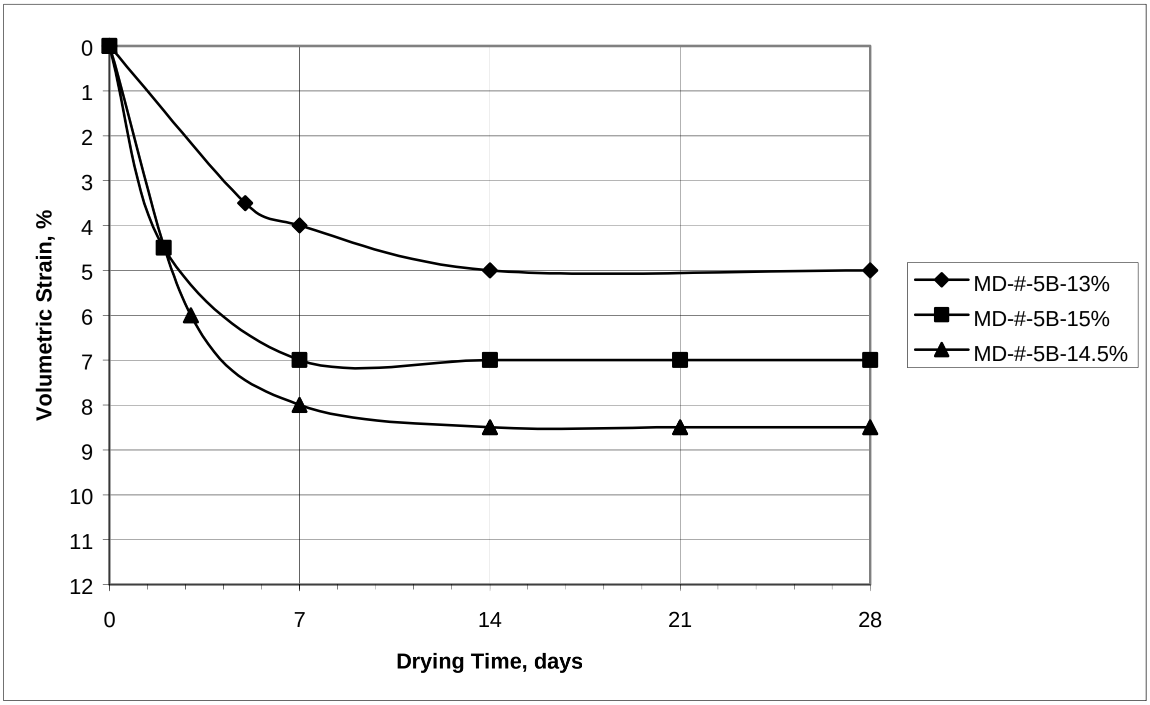

Figure 74. Volumetric Strain Versus Drying Time for PG with 5% Bentonite for All Compaction Energies.

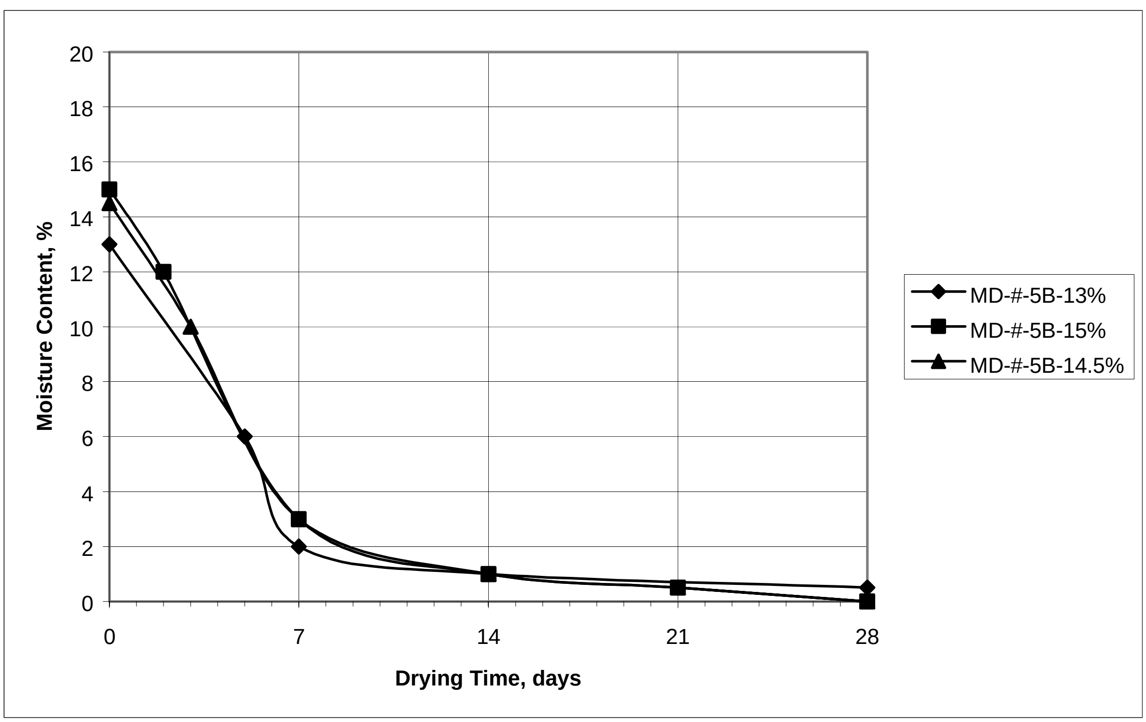

Figure 75. Moisture Content Versus Drying Time for PG with 5% Bentonite.

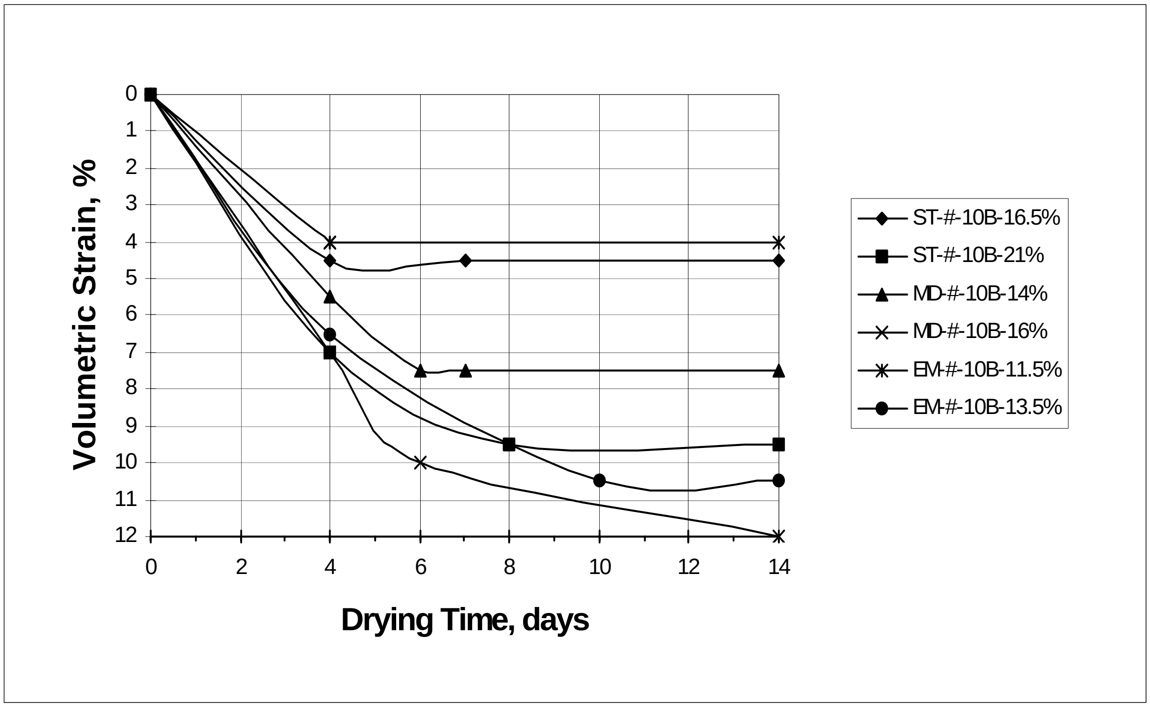

Figure 76. Volumetric Strain Versus Drying Time for PG with 10% Bentonite for All Compaction Energies.

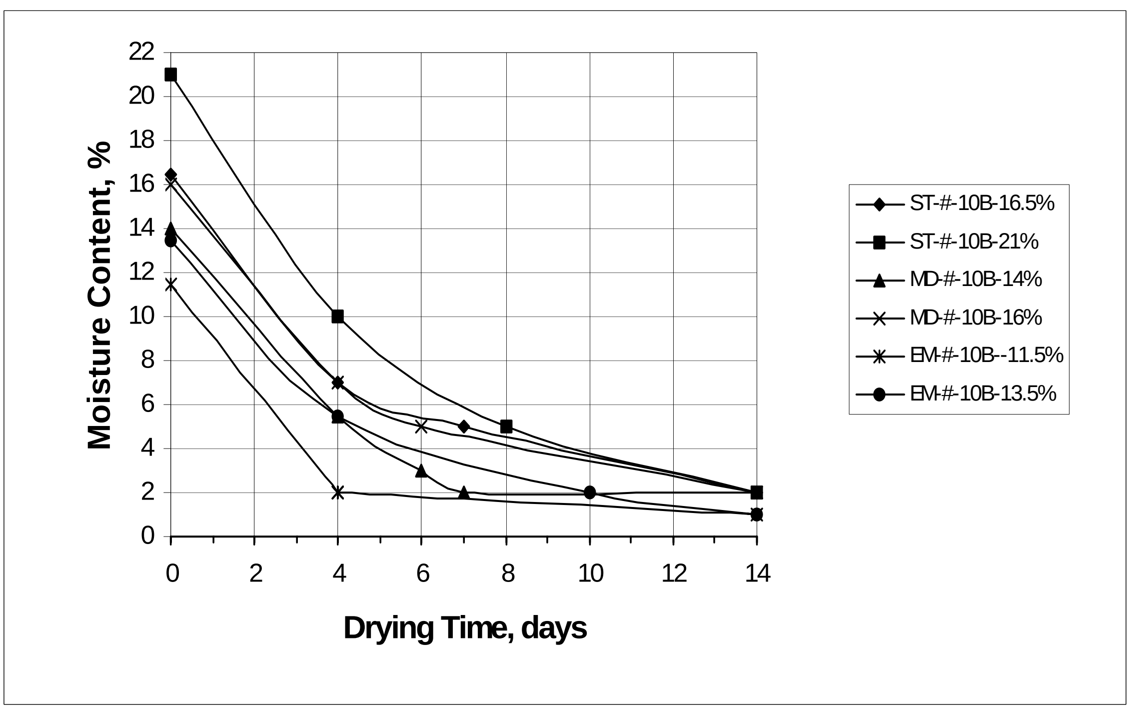

Figure 77. Moisture Content Versus Drying Time for PG with 10% Bentonite.

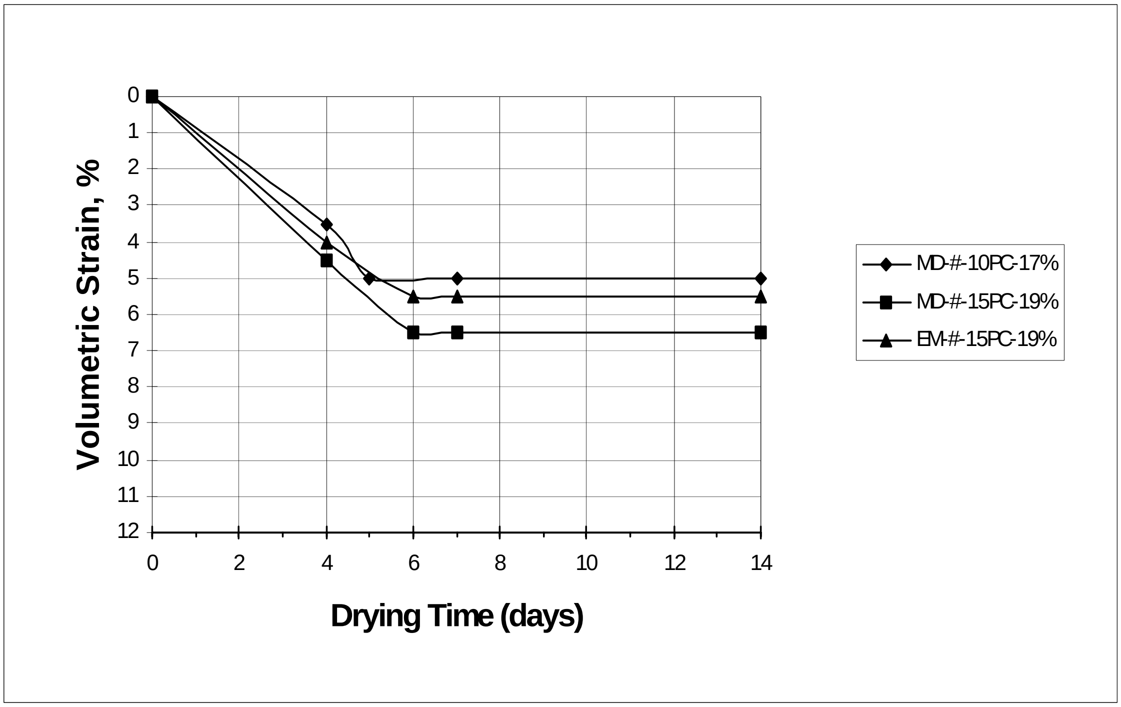

Figure 78. Volumetric Strain Versus Drying Time for PG with Phosphatic Clay for All Compaction Energies.

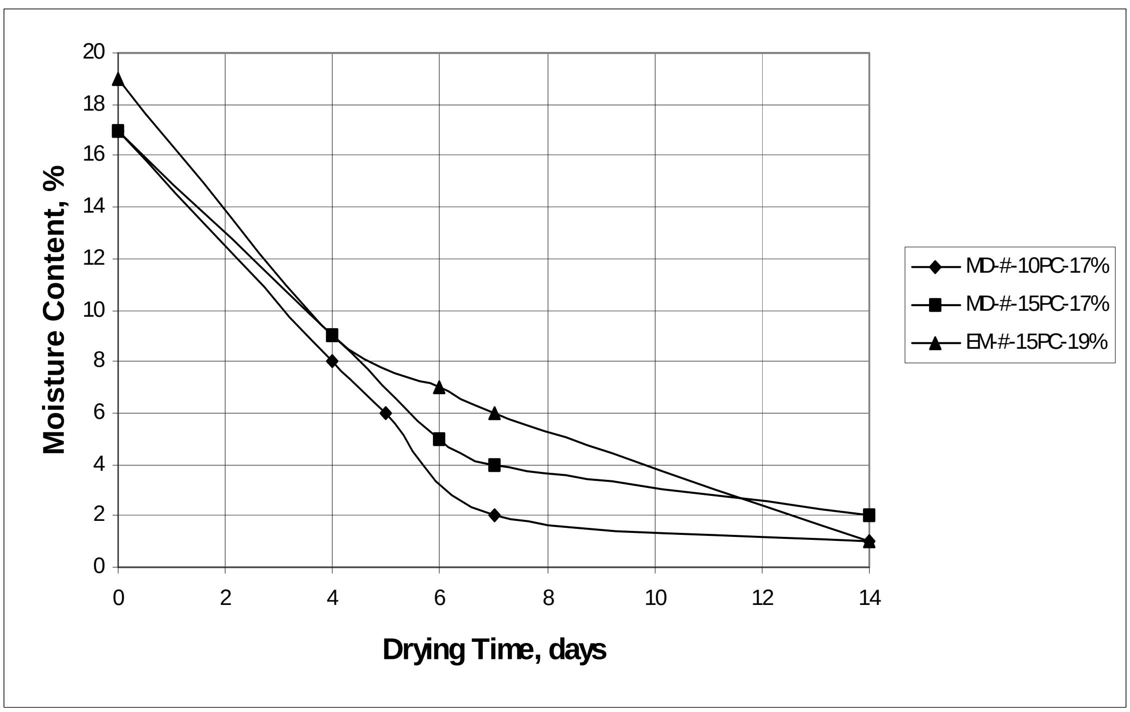

Figure 79. Moisture Content Versus Drying Time for PG with Phosphatic Clay.

Conclusions

Several conclusions result from the desiccation study. The conclusions are based upon three major factors, (1) calculated test results, (2) visual inspection and (3) previous research and predictions. The conclusions are as follows:

- The amended PG samples showed no visible desiccation cracking with volumetric strains as large as 12%.
- The amended PG samples typically reached their maximum strain within five to seven days of air-drying, regardless of additive or compaction energy, and did not exhibit visible cracking.
- Volumetric strains increased as the molding moisture content was increased above the optimum moisture content.
- The amended PG samples showed a maximum strain of about 4% when the moisture content decreased from the laboratory molding moisture content, typically between 12 and 17%, to the expected field moisture content range of 10 to 15%.
- The amended PG does not exhibit the high strain and cracking characteristics of compacted clay liners, which showed minor cracking at 5% strain and severe cracking at 10% strain, resulting in significant increases in bulk permeability.
- These laboratory test results demonstrate the low potential for cracking of amended PG due to desiccation. The measured strains are significantly lower than reported values for compacted clay liners and visual inspection of the amended PG samples found no formation of cracks after the maximum strains had been reached.

This laboratory study demonstrates that compacted and amended PG can significantly reduce the permeability of a barrier layer that will reduce infiltration of rainwater into PG stacks. Further, the results of the laboratory study indicate that a compacted PG barrier layer will likely not crack due to desiccation thus maintaining its integrity.

The effects of desiccation should be monitored in a field application. A field study would provide a different environment than the laboratory study. The amended PG in the field would not be directly exposed to the air as in the laboratory. A vegetative layer would cover the amended PG and thus the moisture contents should remain near the optimum moisture content for the desired compaction level.

Evaluation of Differential Settlement on Cracking of Phosphogypsum

Research Testing Plan

The major laboratory experiment of this research element was the measurement of vertical subsidence and the monitoring of PG's ability to withstand cracking due to tensile strains. The PG was compacted at typical field densities into BCI's test box with a variable-height base, which allowed for the application of multiple settlement scenarios. The settlement scenarios included a simple beam model and a PG stack model.

The BCI test box was modeled after Lee and Shen's test apparatus shown previously in Figure 79. The test box measured 25 inches in length and seven inches in width. The base of the box is comprised of ten 2.5 inch wide slats, which can be individually raised or lowered to provide a maximum vertical deflection of two inches. The box is primarily constructed from hardwood covered with a teflon backing. A layer of spandex fabric is placed between the soil and the teflon to diminish any friction effects. A Plexiglas front panel was installed for visual and photographic observation. The test box is shown in Figures 80 and 81.

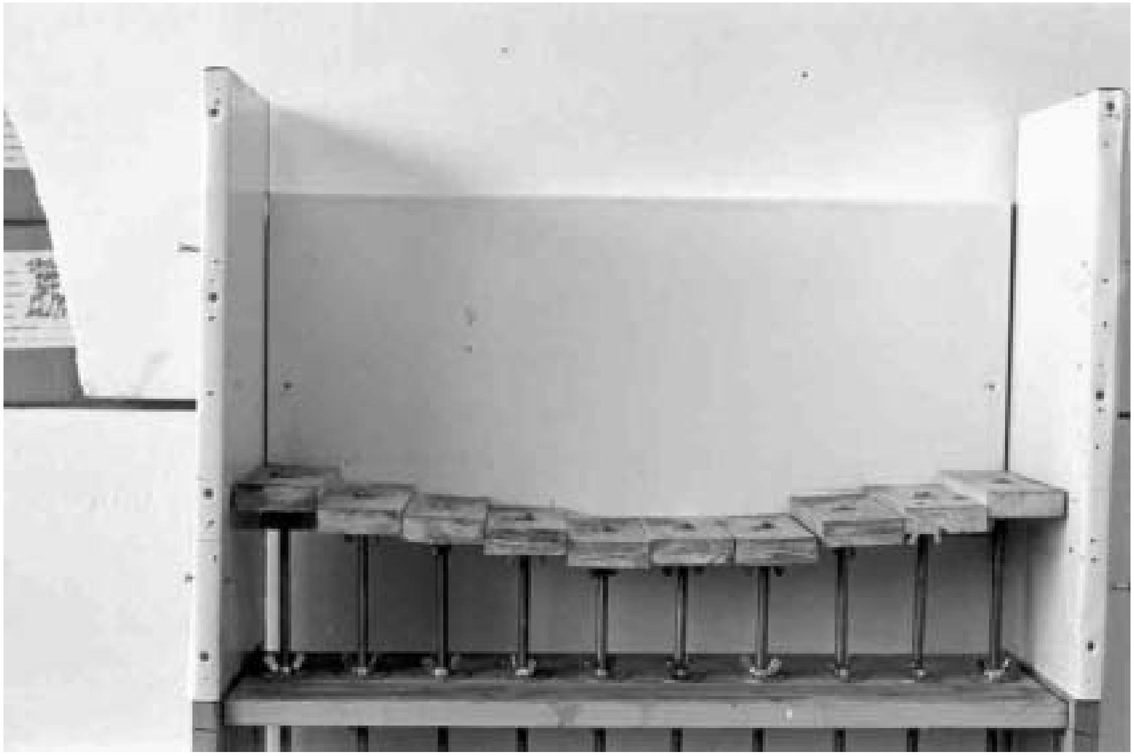

Figure 80. Tension Crack Test Box.

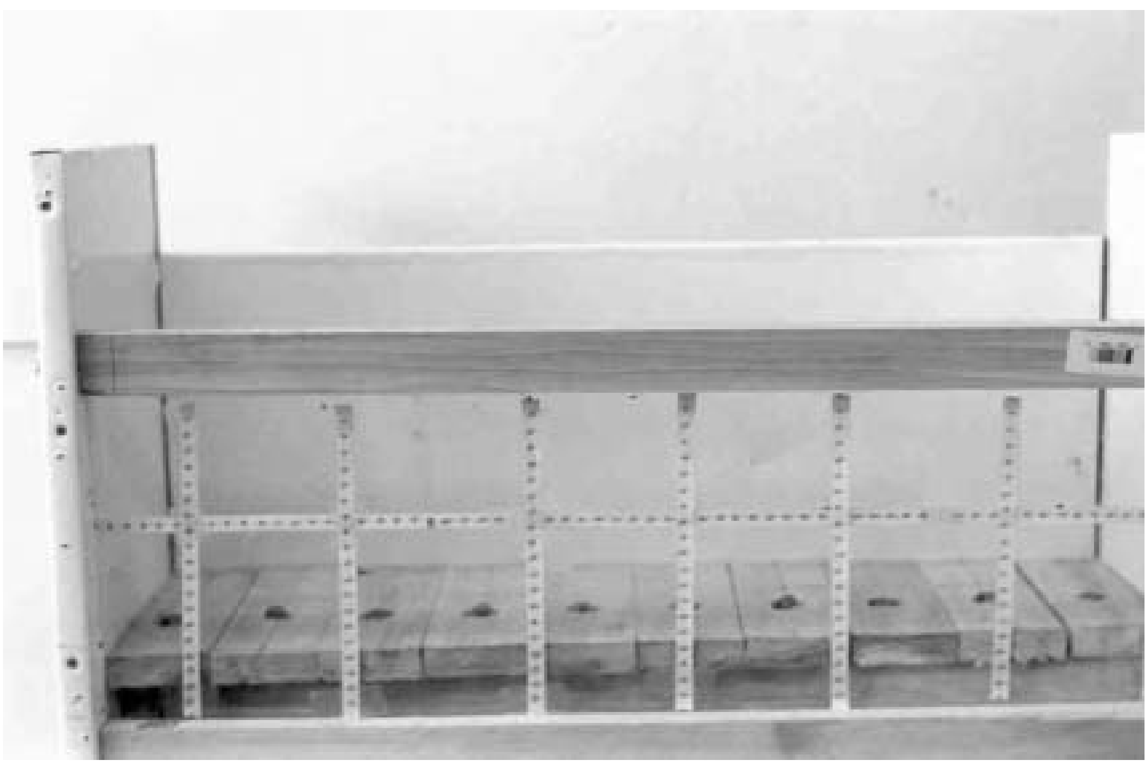

Figure 81. Tension Crack Test Box.

Each test scenario included the measurement of vertical subsidence at four different deflections and the monitoring of the PG cracking. A matrix of test conditions including dimensions, dry density and deflection location and amounts is shown in Table 22.

Table 22. Matrix of Test Conditions for Evaluation of Differential Settlement.

Model Type	Dimensions	Dry Density (pcf)	Deflection Location	Deflection Magnitude
Beam	25” X 7” X 4.7”	87.0	End	0.5,1.0,1.5,2.0”
PG Stack	25” X 7” X 5.1” with 3:1 Side Slopes	80.0	Center	0.5,1.0,1.5,2.0”

Sample Preparation

For each test, approximately 40 pounds of dry gypsum was mechanically mixed with water to a moisture content near 20%. The PG was sealed in plastic containers and allowed to hydrate for a minimum of 24 hours. After hydration, the PG was placed into the test box in layers. Each layer was compacted by hand with a small tamping device and then scarified before the next layer was compacted in the box. The compacted PG was allowed to drain, as shown in Figure 82, before being subjected to vertical deflections.

Figure 82. Drainage of Test Sample.

Test Procedures

After the sample was prepared, a small vertical deflection was applied to the end or the center of the sample depending upon the test scenario. The height changes along the length of the sample were recorded to the nearest millimeter at every 1.6 inch (40 millimeters) interval. The sample was then examined for signs of cracking. The vertical deflection was increased and the same procedures repeated. These procedures were continued until the maximum vertical deflection of 2.0 inches (51 mm) was applied.

Beam Model

PG was compacted into the BCI test box to a thickness of approximately 4.7 inches (120 mm) yielding a dry density of approximately 87.0 pcf (1.4 Mg/m^3). The PG beam was subjected to vertical deflections at an end of 0.5 inches (13 mm), 1.0 inches (25 mm), 1.5 inches (38 mm) and 2.0 inches (51 mm) and the resulting surface profile was graphed. The soil surface profile data was represented using a 3rd order linear curve fit. The equation of the surface profile was then differentiated to determine the slope of the profile at any point along the length of the beam. The Lee and Shen (1969) model was then used to calculate the horizontal movements and ultimately the horizontal tensile strains within the PG beam.

The results of the beam test are shown in Figures 83 to 91. Each set of graphs shows the vertical subsidence profiles with best-fit curve, the horizontal movement profile along the length of the beam, and the horizontal strain profile for each end deflection. The maximum horizontal movements ranged from approximately 0.08 to 0.30 inches (2 to 8 mm) as the end deflection increased. These horizontal movements produced maximum horizontal tensile strains of approximately 1 to 2.5%. The compacted PG showed no signs of cracking over this range of tensile strains.

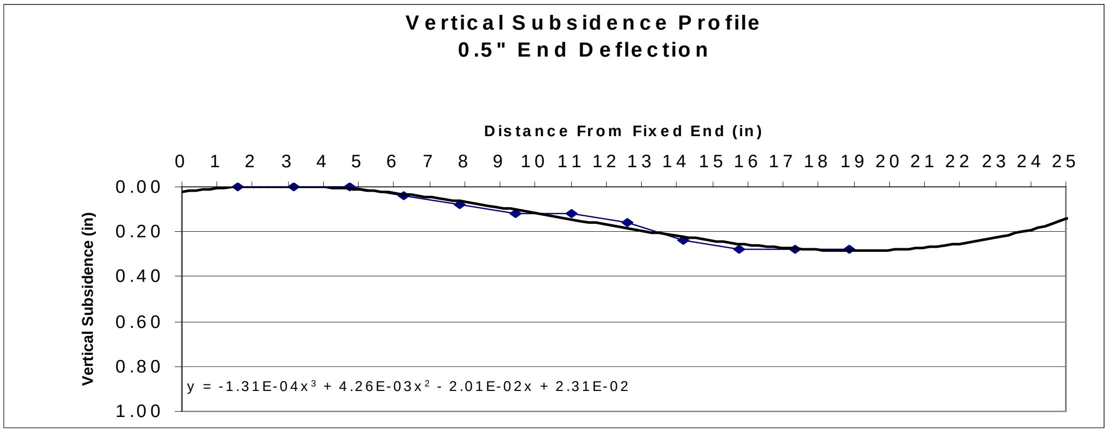

Figure 83. Vertical Subsidence Profile for the Beam Model with a 0.5-Inch End Deflection.

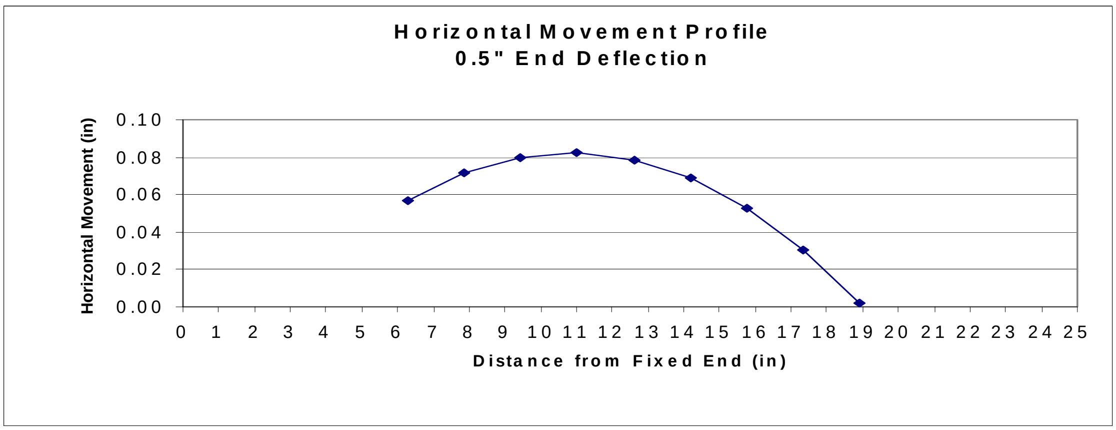

Figure 84. Horizontal Movement Profile for the Beam Model with a 0.5-Inch End Deflection.

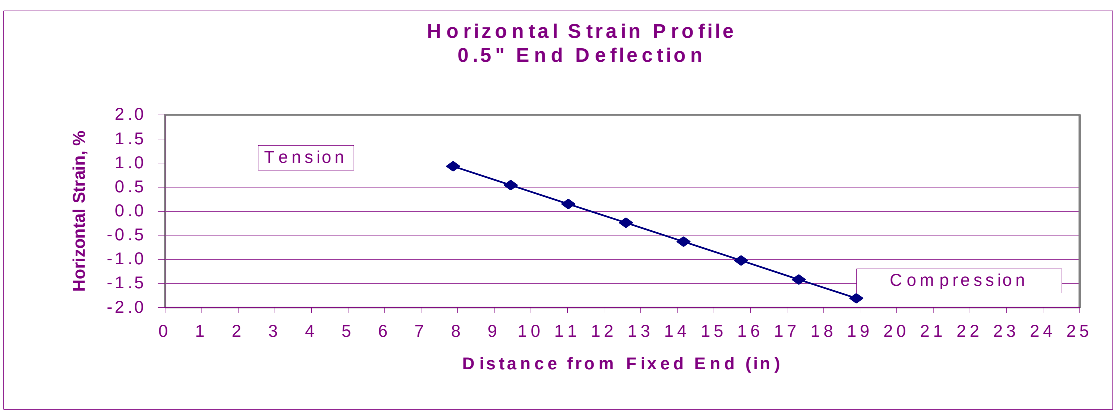

Figure 85. Horizontal Strain Profile for the Beam Model with a 0.5-Inch End Deflection.

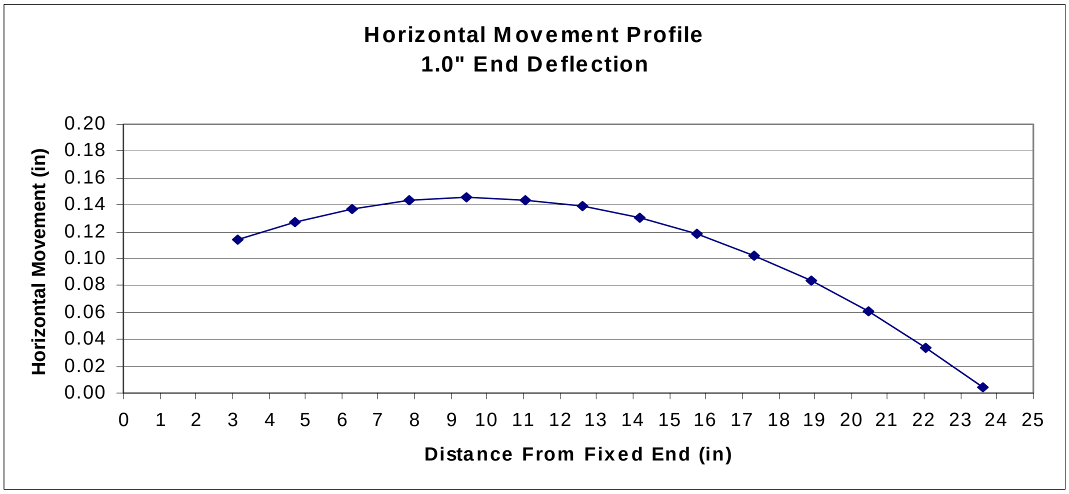

Figure 86. Vertical Subsidence Profile for the Beam Model with a 1.0-Inch End Deflection.

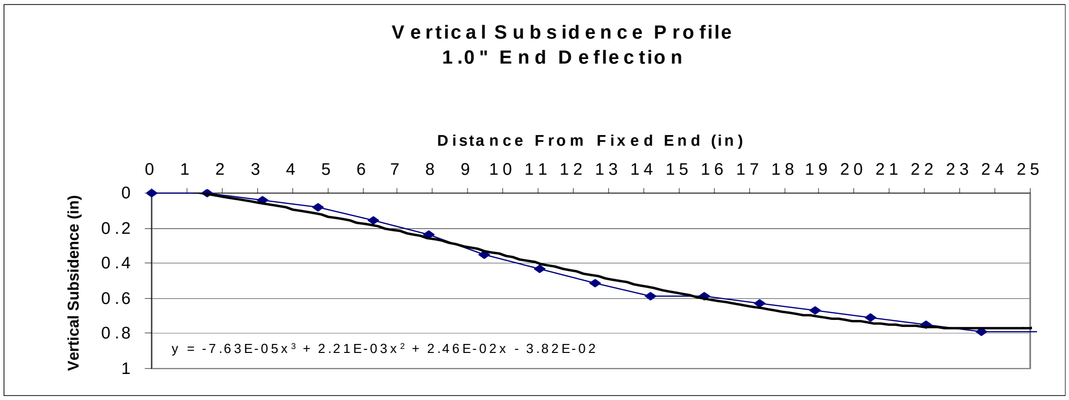

Figure 87. Horizontal Movement Profile for the Beam Model with a 1.0-Inch End Deflection.

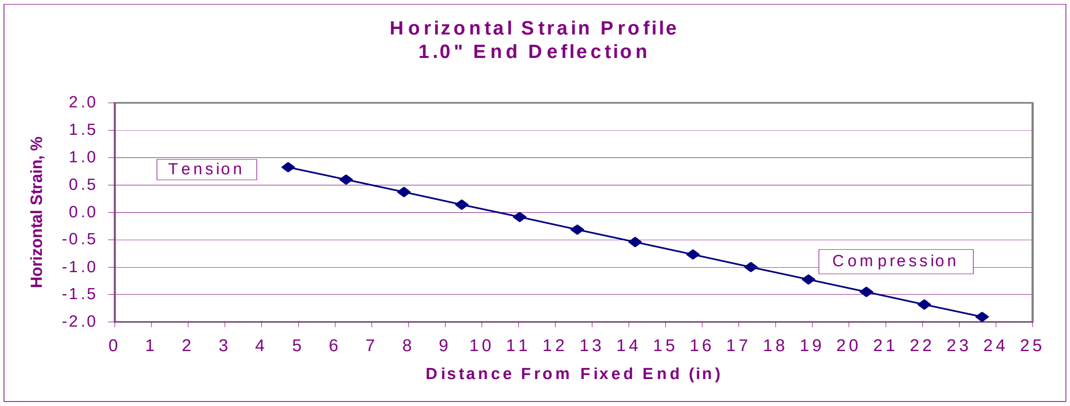

Figure 88. Horizontal Strain Profile for the Beam Model with a 1.0-Inch End Deflection.

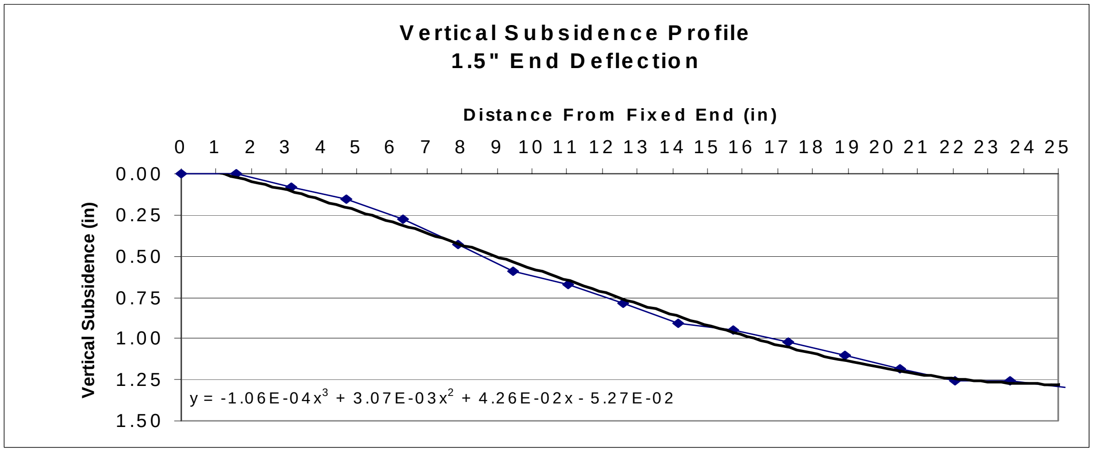

Figure 89. Vertical Subsidence Profile for the Beam Model with a 1.5-Inch End Deflection.

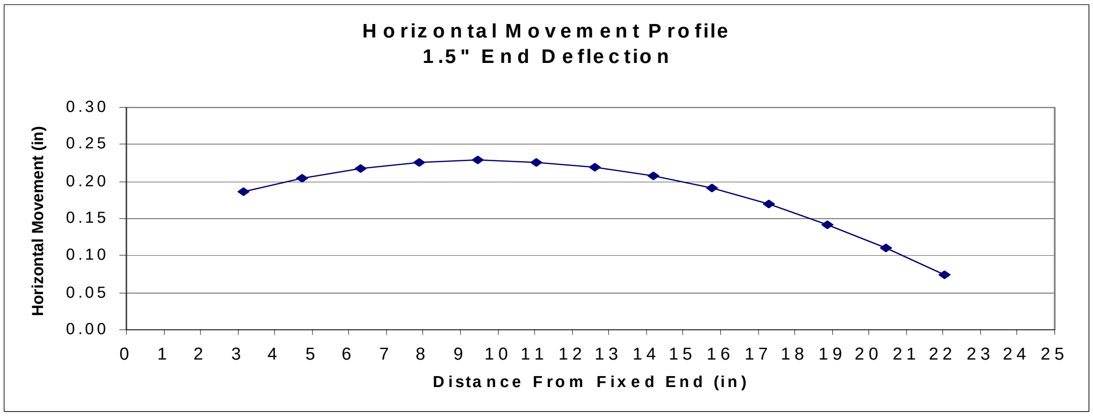

Figure 90. Horizontal Movement Profile for the Beam Model with a 1.5-Inch End Deflection.

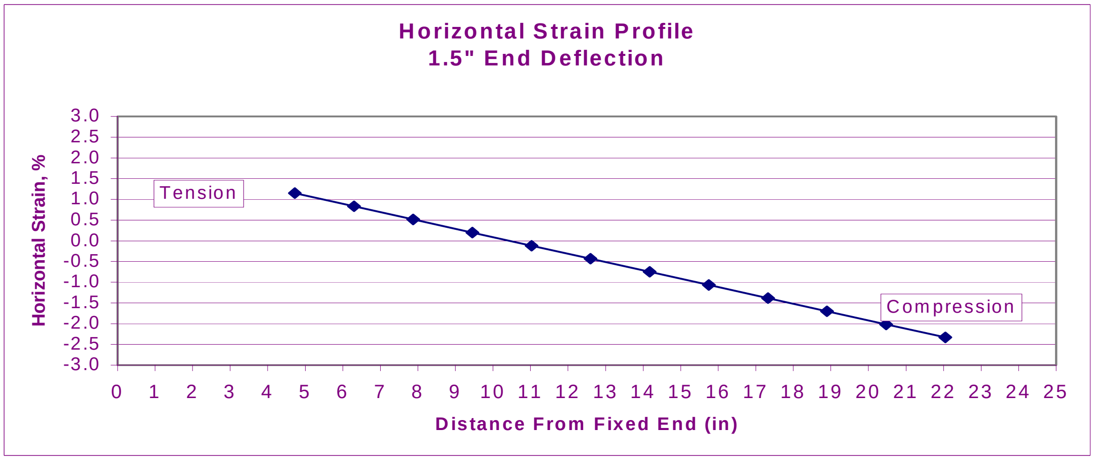

Figure 91. Horizontal Strain Profile for the Beam Model with a 1.5-Inch End Deflection.

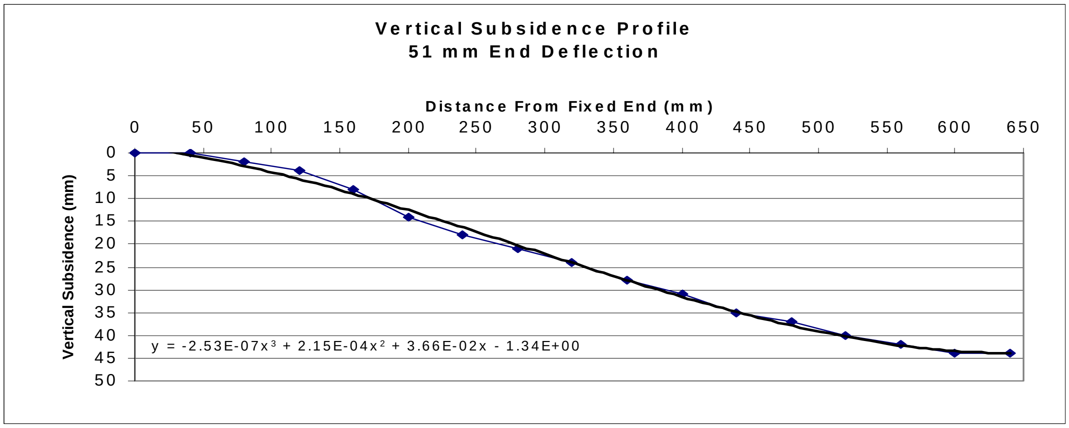

Figure 92. Vertical Subsidence Profile for the Beam Model with a 2.0-Inch End Deflection.

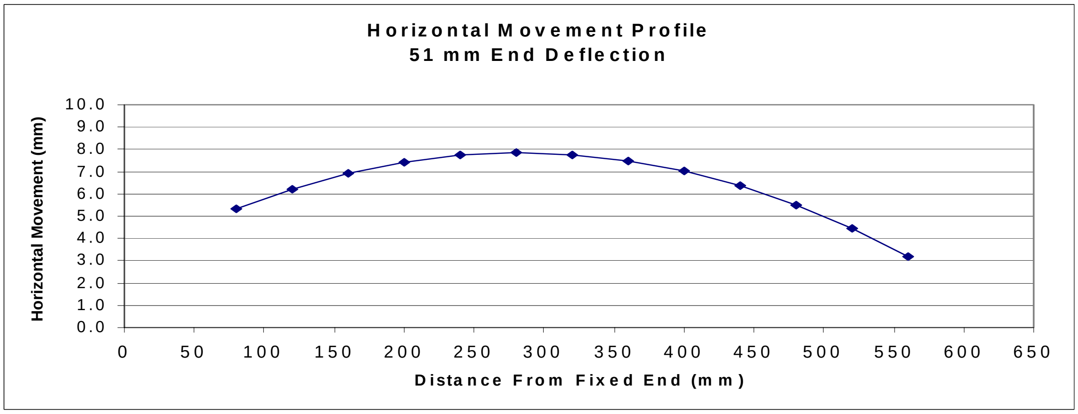

Figure 93. Horizontal Movement Profile for the Beam Model with a 2.0-Inch End Deflection.

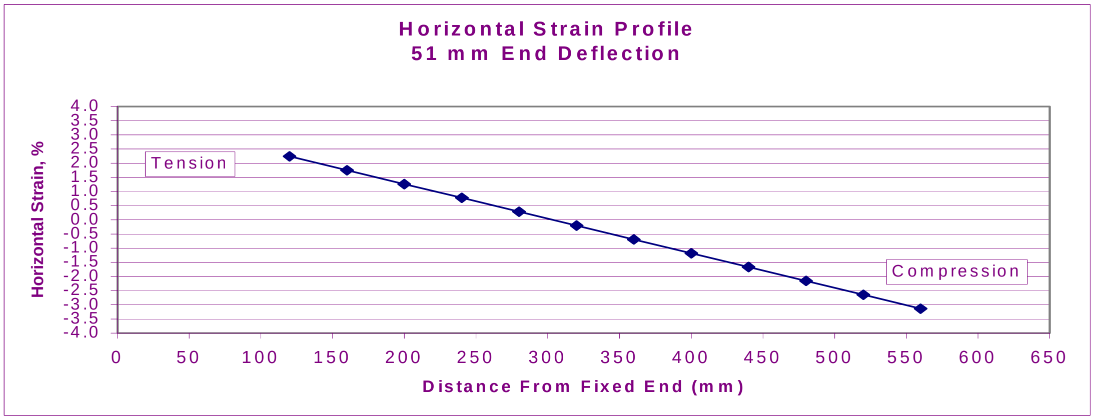

Figure 94. Horizontal Strain Profile for the Beam Model with a 2.0-Inch End Deflection.

Stack Model

A compacted PG beam was created in the test box with a typical gypsum stack configuration, having 3:1 side slopes at the ends of the beam. The ultimate height of the beam in the center was 5.1 inches (130 mm) and the dry density was 80.0 pcf (1.3 Mg/m^3). The stack was subjected to vertical displacements in the center of the beam to simulate subsidence related to consolidation within the middle or underneath a gyp stack.

The displacements applied to the stack model were the same as the beam model except they were applied over half the distance. Due to the symmetry of the model, only half of the stack was analyzed for horizontal movements and strains.

Figures 95 to 103 show the results of the stack model deflections. The stack was deflected 0.5 inches (13 mm) in the center resulting in a maximum horizontal movement of approximately 0.15 inches (4 mm) which corresponded to a maximum horizontal tension strain of 2.5% The stack model showed no signs of cracking along the top surface or face, as shown in Figure 104. When the stack was deflected 1.0 inch (25 mm), the maximum horizontal movement increased to 0.30 inches (7.5 mm) and the maximum horizontal tensile strain increased to 3.6%. At this deflection, a large crack developed at the bottom of the front face as shown in Figure 105. The crack extended half way up the face of the stack and through the entire width. The deflection was increased to 1.5 inches (38 mm), which resulted in a maximum horizontal movement of approximately 0.55 inches (14 mm), which would equate to a maximum horizontal tensile strain of 9%. With the development of a crack, the actual horizontal movement is the widening of the crack and not an extension of the soil and thus the strain equations are no longer valid. With the additional deflection, the crack began to propagate in a circular direction, as shown in Figure 106. The vertical displacement was increased to monitor the propagation of the crack. At a 2.0 inch (51 mm) deflection, the crack propagated into a full circular failure through the entire width of the stack as shown in Figures 104 and 105.

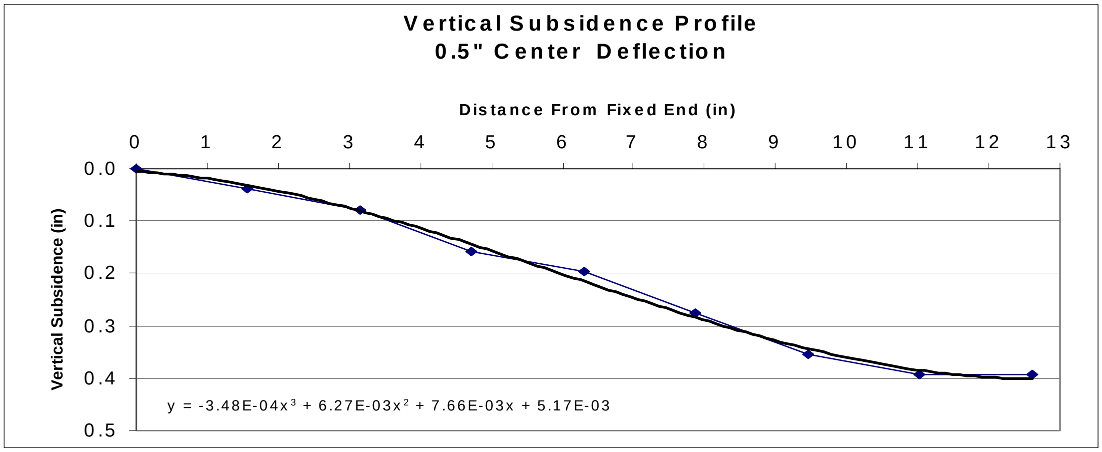

Figure 95. Vertical Subsidence Profile for the Stack Model with a 0.5-Inch Center Deflection.

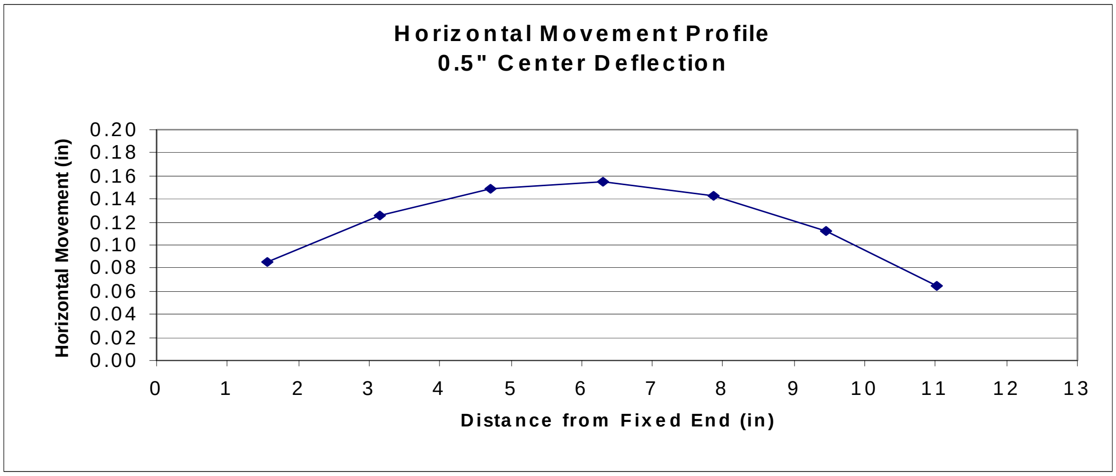

Figure 96. Horizontal Movement Profile for the Stack Model with a 0.5-Inch Center Deflection.

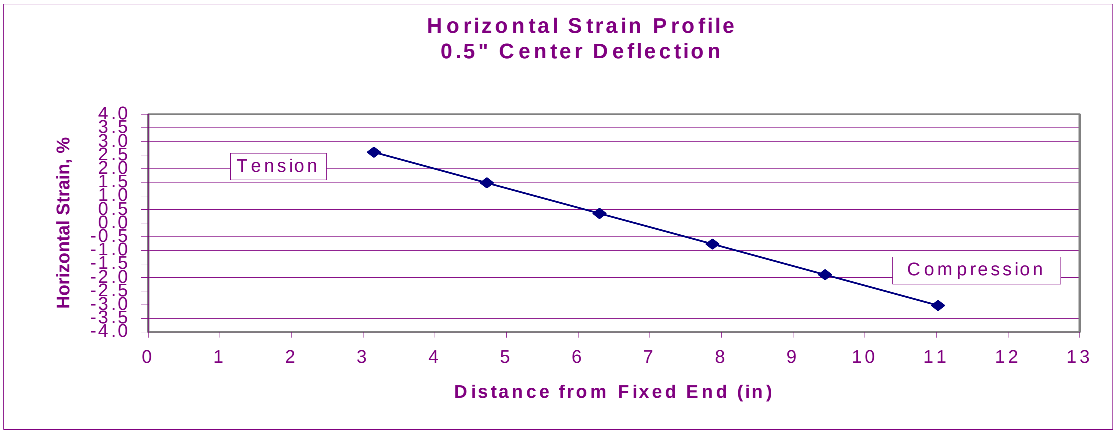

Figure 97. Horizontal Strain Profile for the Stack Model with a 0.5-Inch Center Deflection.

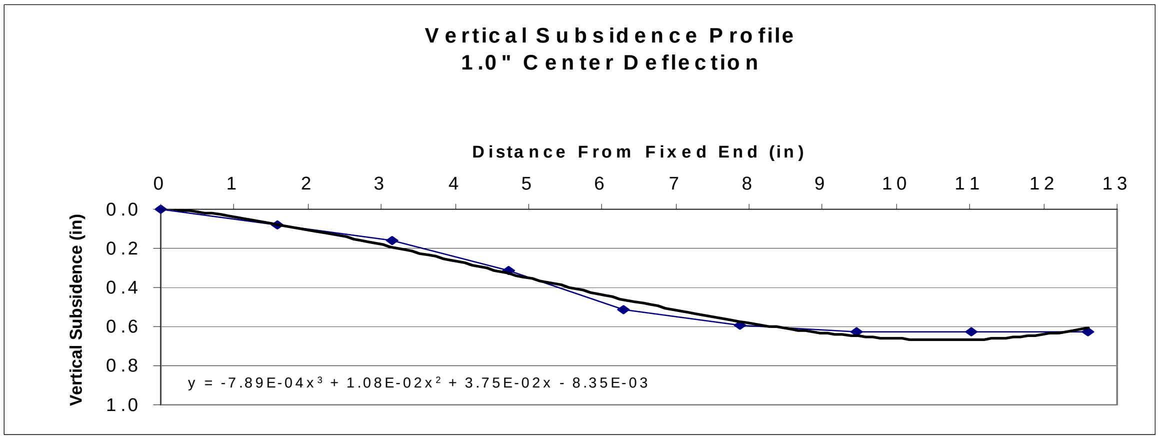

Figure 98. Vertical Subsidence Profile for the Stack Model with a 1.0-Inch Center Deflection.

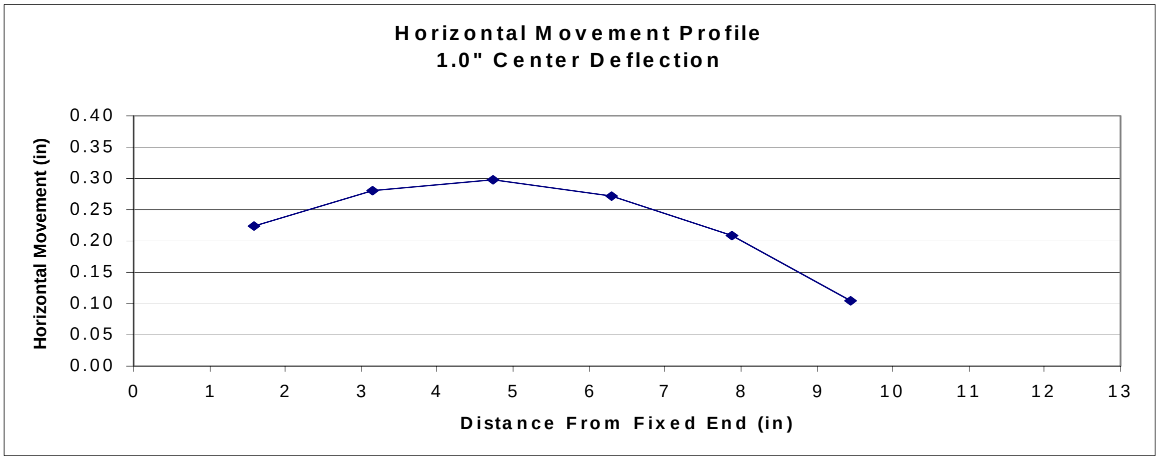

Figure 99. Horizontal Movement Profile for the Stack Model with a 1.0-Inch Center Deflection.

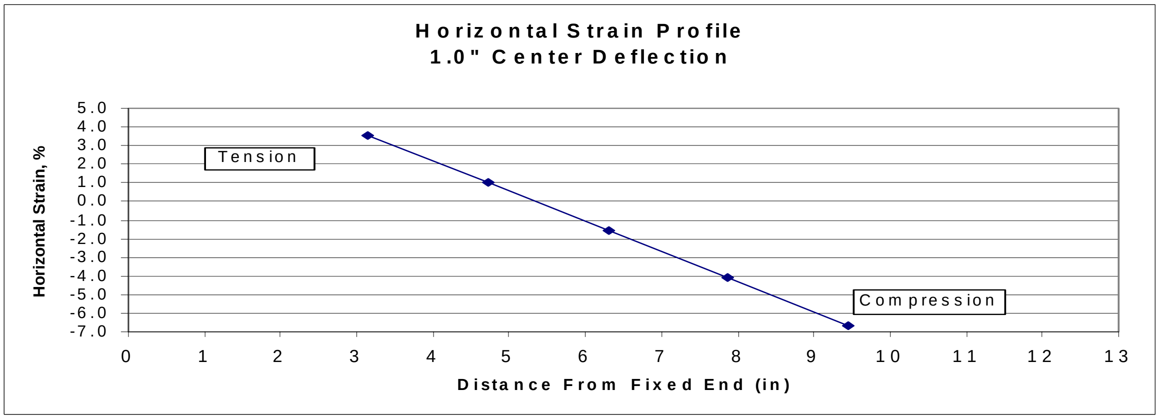

Figure 100. Horizontal Strain Profile for the Stack Model with a 1.0-Inch Center Deflection.

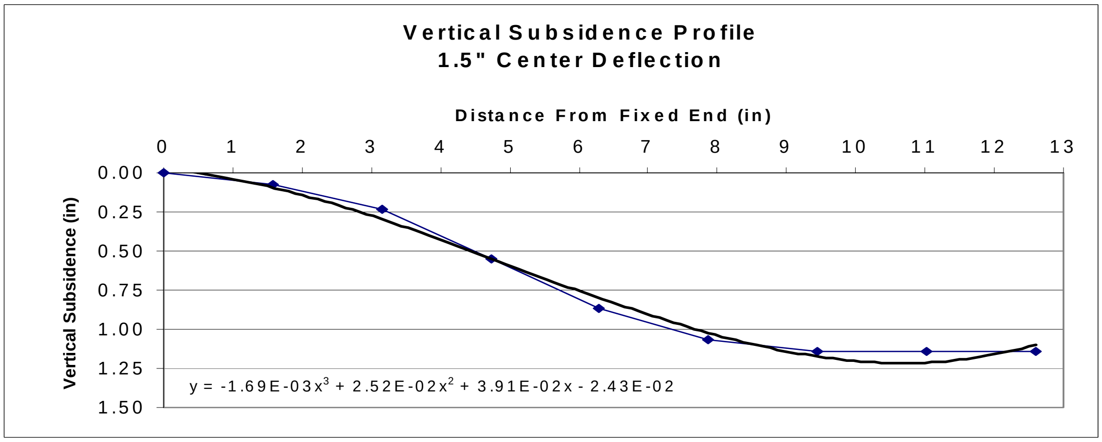

Figure 101. Vertical Subsidence Profile for the Stack Model with a 1.5-Inch Center Deflection.

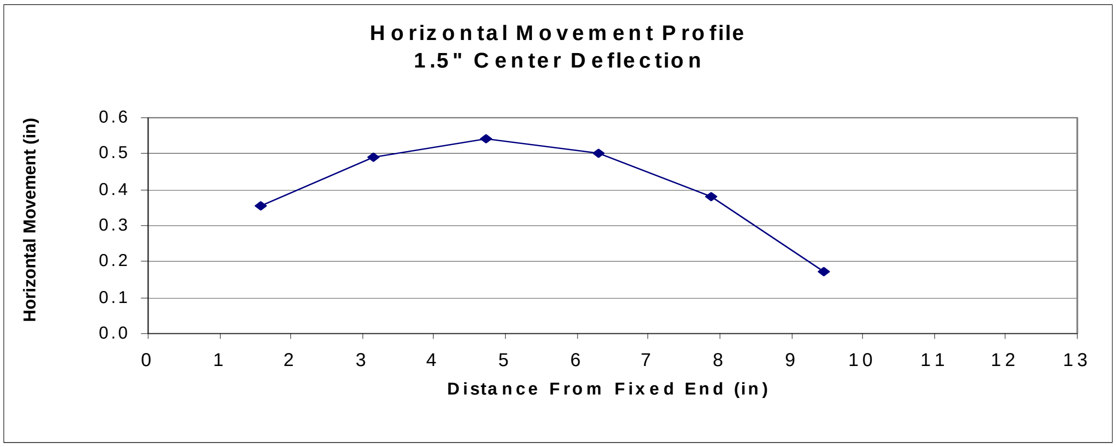

Figure 102. Horizontal Movement Profile for the Stack Model with a 1.5-Inch Center Deflection.

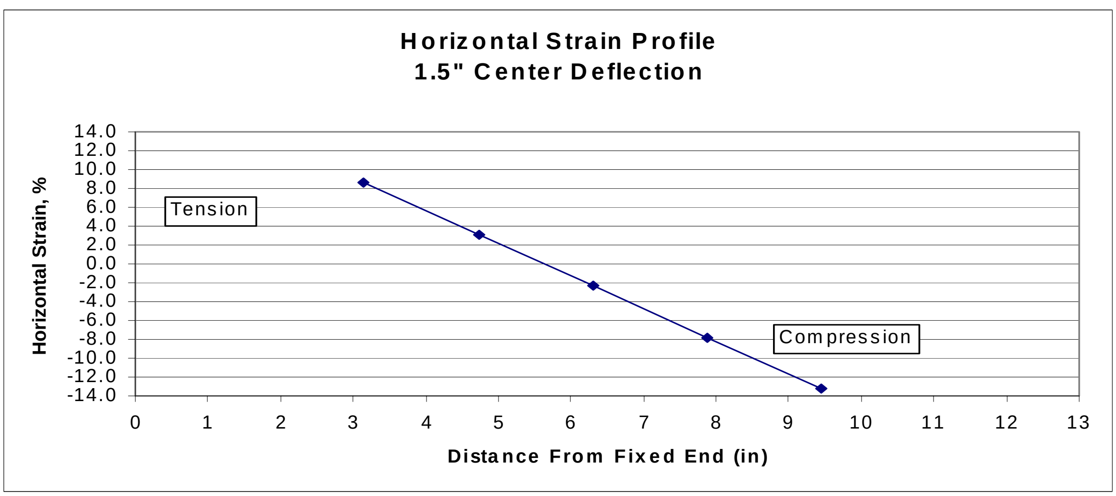

Figure 103. Horizontal Strain Profile for the Stack Model with a 1.5-Inch Center Deflection.

Figure 104. PG Stack Model with 0.5-Inch Center Deflection.

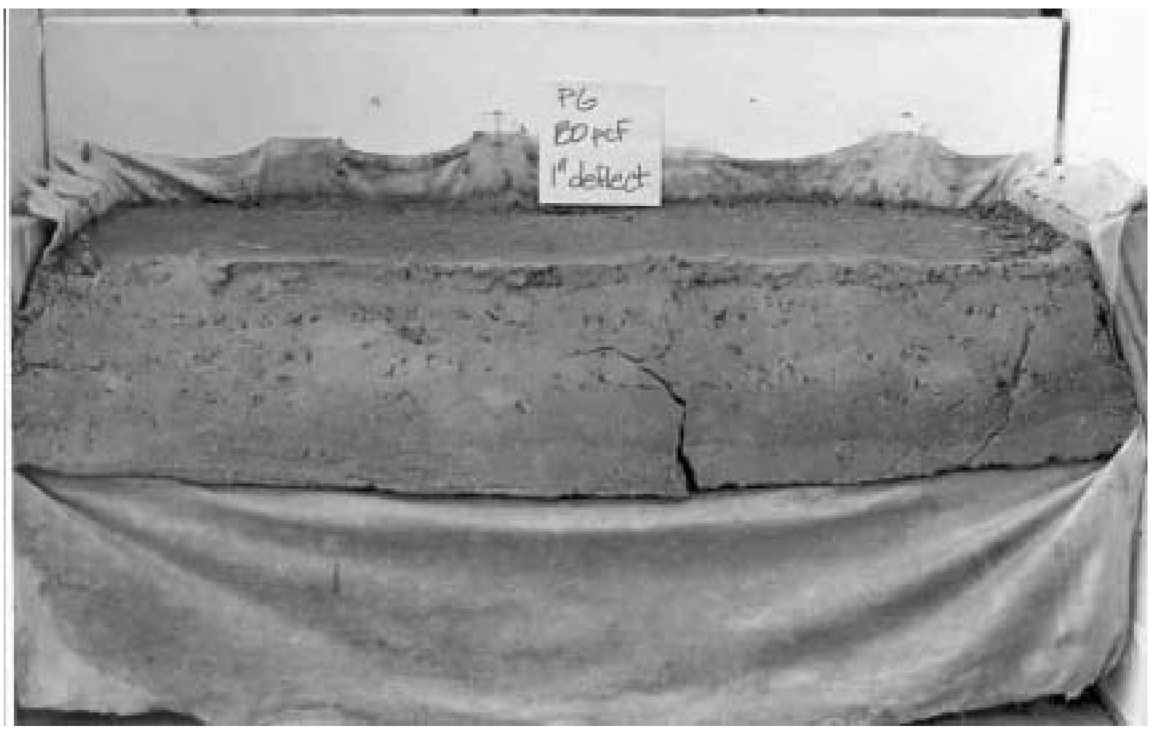

Figure 105. PG Stack Model with 1.0-Inch Center Deflection.

Figure 106. PG Stack Model with 1.5-Inch Center Deflection.

Figure 107. PG Stack Model with 2.0-Inch Center Deflection.

Figure 108. PG Stack Model with 2.0-Inch Center Deflection.

Summary and Comparison of Results

Table 23 summarizes the results of the tension cracking analysis including deflections, maximum horizontal strains and crack development. In the laboratory, the failure tensile strain for compacted PG was determined to be approximately 3%. Cracking did not occur at strains less than 3%, but did occur as the strain was increased above 3.5%.

Table 23. Summary of Model Type, Deflection and Maximum Tensile Strain for All Tensile Tests.

Model Type	Deflection Magnitude (inches)	Max Tensile Strain (%)	Cracking
Beam	0.5	0.9	No
Beam	1.0	0.9	No
Beam	1.5	1.2	No
Beam	2.0	2.2	No
PG Stack	0.5	2.6	No
PG Stack	1.0	3.6	Yes
PG Stack	1.5	9.1 *	Yes

* Calculated but not valid

Based on these laboratory values, full-scale PG stack settlement scenarios were developed to predict tension cracking in the field. A PG stack with a height of 200 feet with 3:1 side slopes was used as a representative model. The stack surface was deflected and tension strains were calculated for a soil layer thickness of 10 feet to simulate a compacted PG cover system. Table 24 summarizes the full-scale stack model parameters including the layer thickness, deflection, maximum tensile strains and predicted cracking. Figures 109 to 117 show the full-scale PG stack profile and settlements, horizontal movement and strain profiles.

Table 24. Summary of Full-Scale Stack Model Deflections and Predicted Maximum Tensile Strains.

Model Type	Layer Thickness (ft)	Deflection (ft)	Predicted Max. Tensile Strain (%)	Predicted Cracking
Full PG Stack	10	10	0.2	No
Full PG Stack	10	25	0.5	No
Full PG Stack	10	50	0.8	No

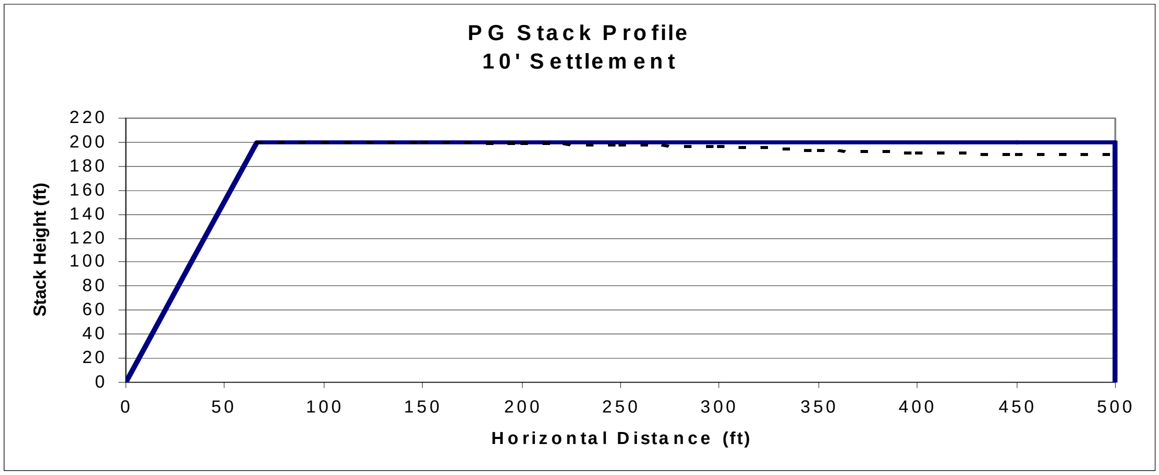

Figure 109. Vertical Subsidence Profile for the Full Stack Model with a 10-Foot Settlement.

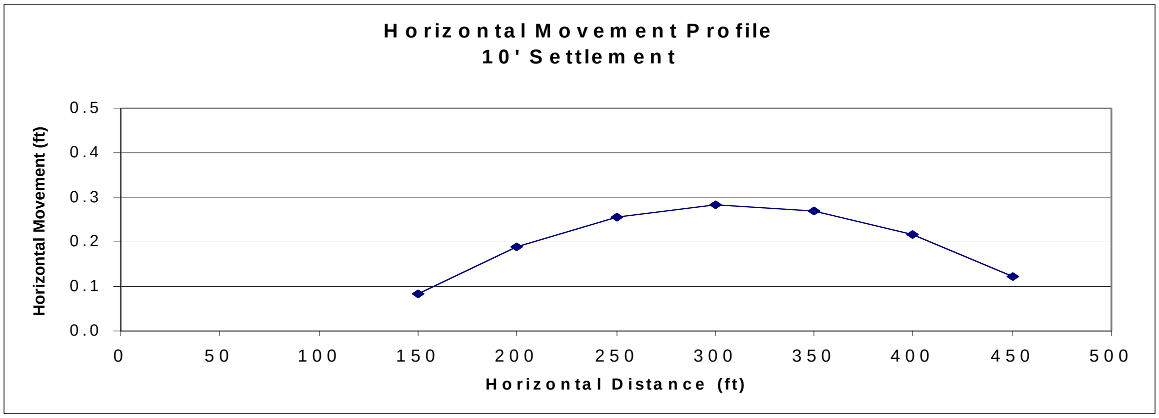

Figure 110. Horizontal Movement Profile for the Full Stack Model with a 10-Foot Settlement.

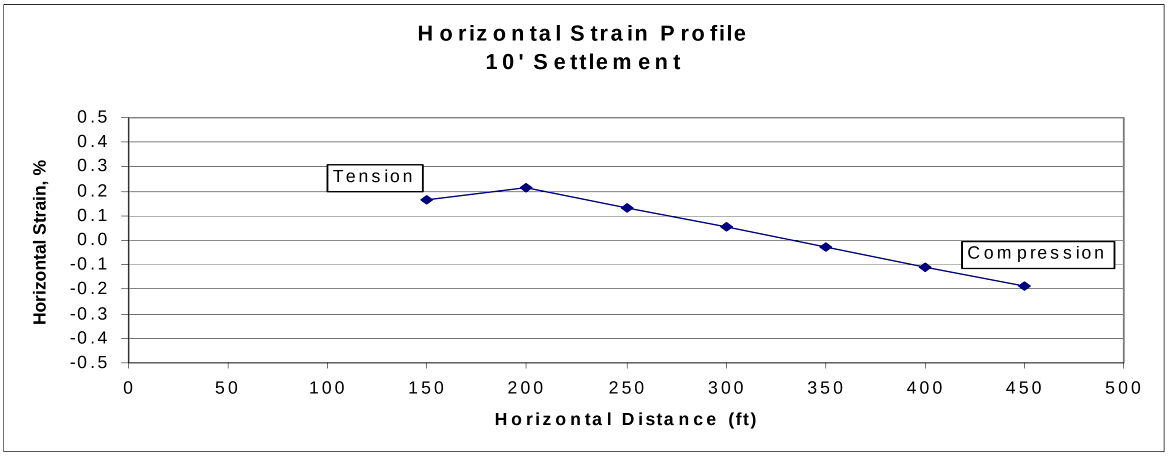

Figure 111. Horizontal Strain Profile for the Full Model with a 10-Foot Settlement.

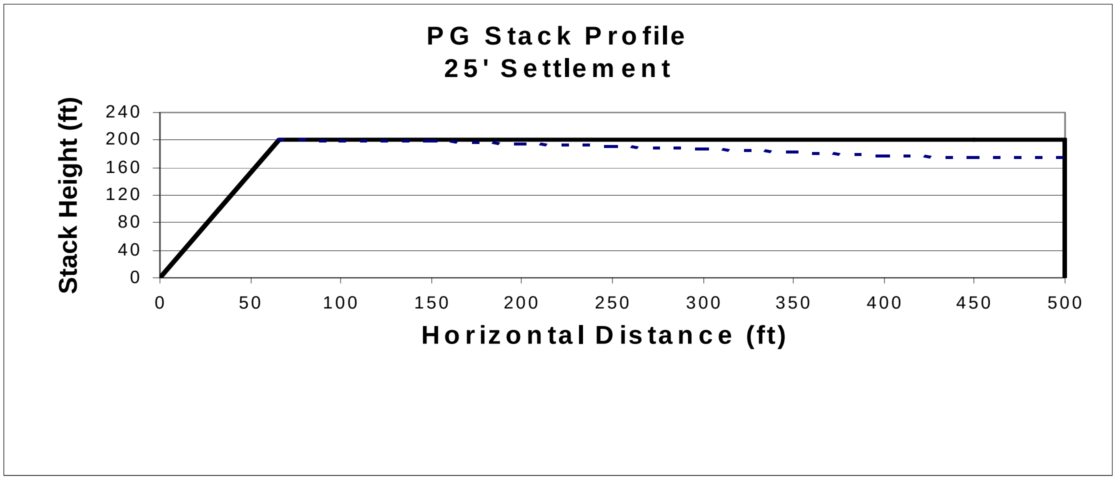

Figure 112. Vertical Subsidence Profile for the Full Stack Model with a 25-Foot Settlement.

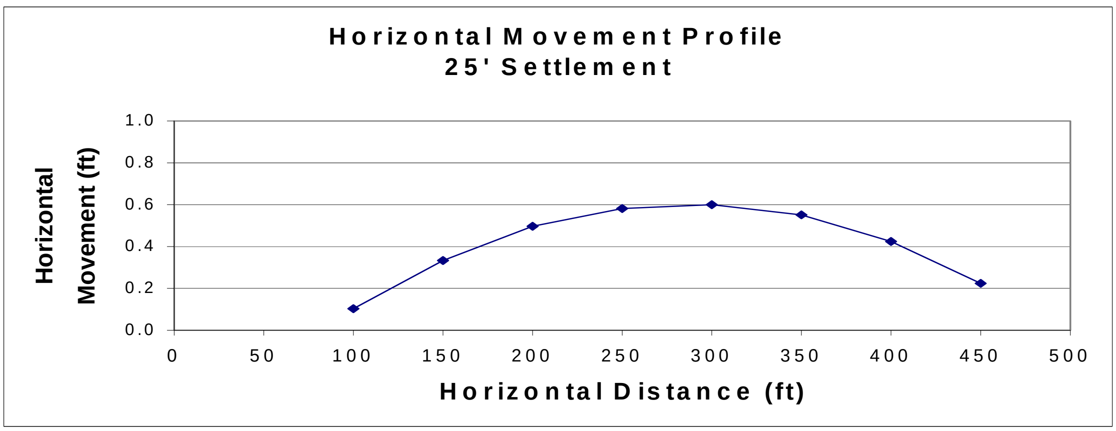

Figure 113. Horizontal Movement Profile for the Full Stack Model with a 25-Foot Settlement.

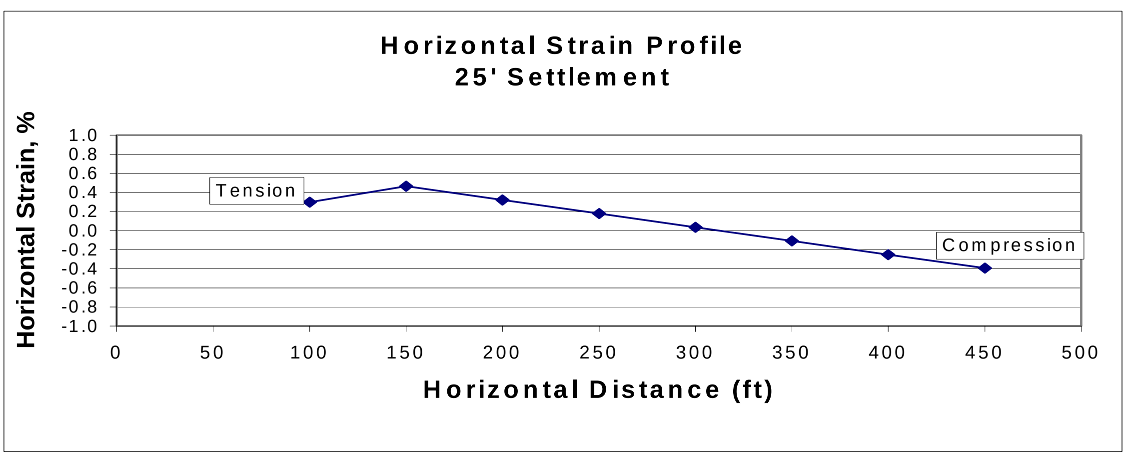

Figure 114. Horizontal Strain Profile for the Full Stack Model with a 25-Foot Settlement.

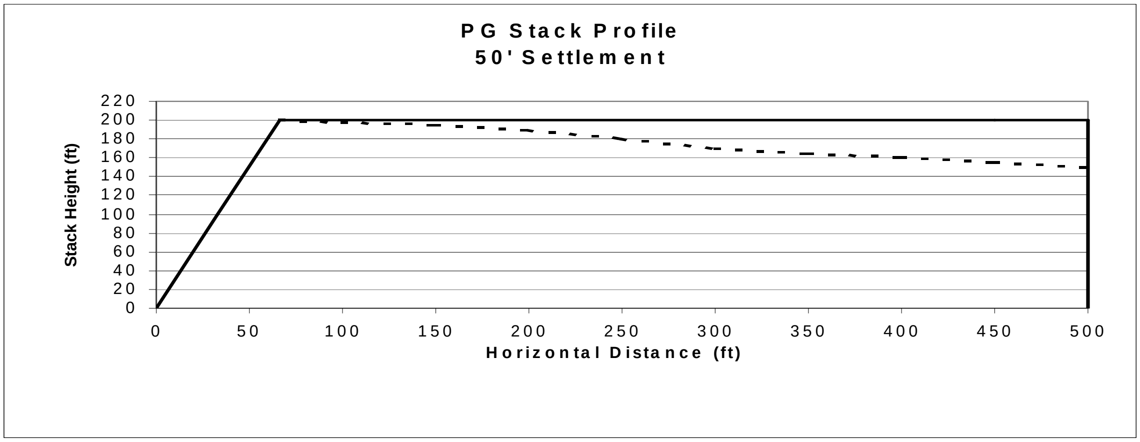

Figure 115. Vertical Subsidence Profile for Full Stack Model with a 50-Foot Settlement.

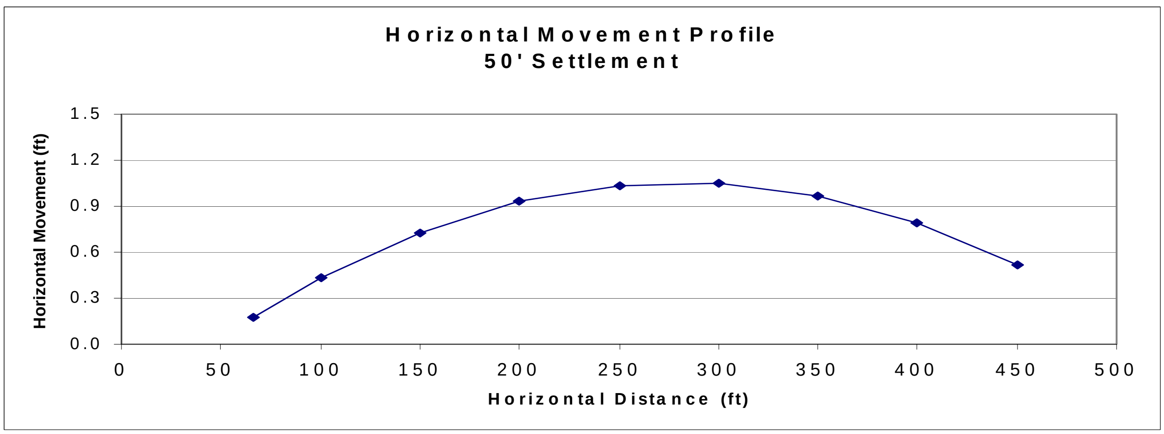

Figure 116. Horizontal Movement Profile for Full Stack Model with a 50-Foot Settlement.

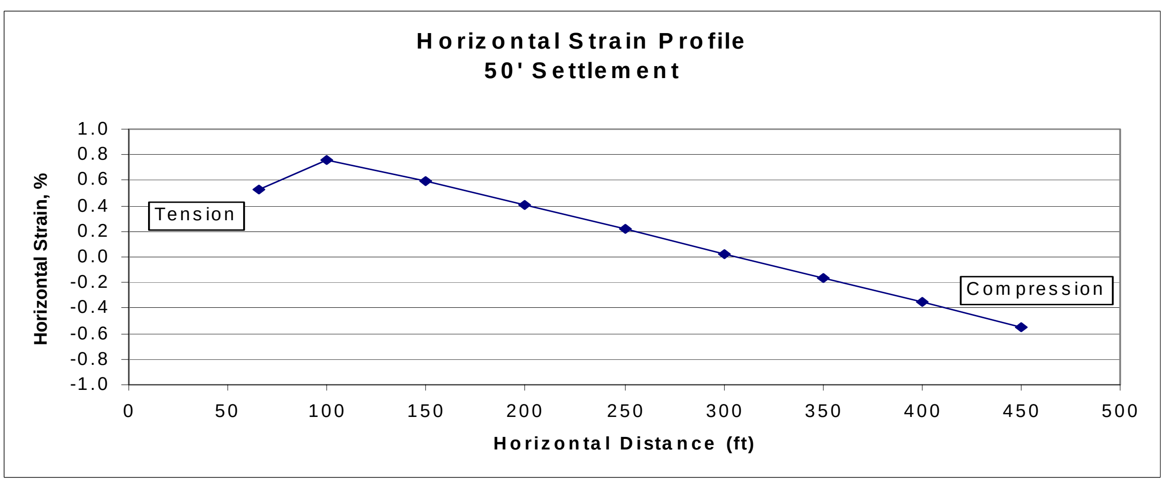

Figure 117. Horizontal Strain Profile for Full Stack Model with a 50-Foot Settlement.

The full-scale PG stack models show that the tensile stresses for typical settlements within a soil layer are well below the predicted failure tensile strain of 3%. Settlements up to 50 feet develop tensile strains less than 1%. The strains are low due to the large distances over which the settlement is spread, producing a shallow surface slope, much shallower than the laboratory study.

The predicted maximum tensile strain will occur at the point along the soil profile with the largest slope. The points of maximum slope occur near the edges of the soil profile. For a full stack model, these edges correspond to the transition area between the top of the sideslopes and the crest of the outer dikes. These areas have the highest potential for cracking, yet a low potential for infiltration due to high runoff characteristics provided by the slopes, and would likely be outside the area typically covered by a final synthetic cover material.

Conclusions

Conclusions from these laboratory results are based upon theories and models originally developed in the 1960's. The results correlate well with recent test results and predictions. The conclusions are as follows:

- The laboratory determined failure tensile strain, the strain at which visible cracking occurs, is approximately 3% for compacted phosphogypsum. At tensile strains less than 3%, no visible cracking was observed on the face or along the upper surface of the test specimens. At strains above 3.5%, cracking was observed along the face, but not along the upper surface.
- The failure strain of 3% correlates well with similar research studies, which determined failure strains of 0.1 to 4.4% for compacted clays, silts and embankments materials. The previous studies used similar methods to determine the effects of differential settlement and tension cracks on the permeability of soil cover systems.
- The differential settlements in a gypsum stack, typically caused by consolidation within the center of the stack, are generally distributed over the entire horizontal length. The magnitudes of vertical deflections distributed over the entire length of a stack will probably not develop tensile strains large enough to cause tensile cracks.
- If cracking occurs, it will most likely be near the sideslope to top transition where the change in surface slope is the greatest and there is an increase in vertical stresses, yet this area has a low potential for infiltration due to high runoff characteristics and would probably be located outside the area of a stack that would have a synthetic cover.

To further evaluate the potential for tension cracking due to differential settlement, we recommend a program of field inspections of existing stacks during the second phase of this project.

EVAPOTRANSPIRATION MEASUREMENT

INTRODUCTION

In the study being reported here, we used a portable chamber method of measuring evapotranspiration (ET) from previously established (vegetated) field plots at three PG stacks in central Florida to quantify the effects of various management strategies on ET. With appropriate management strategies, water loss via ET can be maximized and the percolation through the compacted soil sub-layer minimized. This study investigates management alternatives to maximize ET loss and recommends further management options to consider.

This report presents a comprehensive evaluation of the measurements, results, and findings from past ET work on PG stacks as well as work completed under this study.

FACTORS THAT AFFECT EVAPOTRANSPIRATION

Evapotranspiration (ET) from a vegetative surface is the sum of soil evaporation (E) and plant transpiration (T). The actual ET is the combined effect of the potential evapotranspiration (PET) and processes that limit PET (see Table 25 for a list of abbreviations).

Table 25. Summary of Abbreviations.

Abbreviation	Definition
CSI	Campbell Scientific Inc
E	Evaporation
T	Transpiration
ET	Evapotranspiration
ET2000	Estimated ET at PAR=2000 mmol/m^2/s or solar radiation=1000 W/m^2
ET Ratio	Ratio of actual to potential ET expressed as a percentage (ET/PET)
PAR	Photosynthetically active radiation
PET	Potential evapotranspiration
PGROSS	Gross photosynthesis = PNET – RESP (RESP < 0)
PGROSS 2000	Estimated gross photosynthesis at PAR=2000 μmol/m^2/s or solar radiation=1000 W/m^2
PNET	Net photosynthesis or carbon exchange
RESP	Combined plant and soil respiration

Potential Evapotranspiration

Potential evapotranspiration (PET) is the atmospheric demand on a standardized surface, which is typically a full-cover, well-watered, frequently mowed grass, and is affected by solar radiation, temperature, dew point, and wind speed. In humid environments, where the advective effect of dry air is limited, PET is predominantly driven by solar radiation.

This statement is corroborated by the fact that the Priestly-Taylor equation for PET uses only solar radiation as input yet it performs remarkably well when compared to more sophisticated methods like the Penman or Penman-Monteith equations which use all the abovementioned weather variables as input. Solar energy is important because it provides the latent energy required to convert liquid water to vapor that is then lost to the atmosphere.

Type of Vegetative Cover

Most equations used to predict PET use a reference plant, like full-cover, well-watered, frequently mowed grass. Actual PET for a specific plant might be slightly higher or lower depending on the plant height and stomatal conductance. The ratio of the actual PET for a plant to the PET of the reference plant is called the crop coefficient. Taller plants will have slightly lower aerodynamic resistance to water vapor loss and thus will have slightly higher PET. Plants with higher leaf conductance to water vapor loss will also have slightly higher PET. Plant-specific effects on PET are small in magnitude.

Previous work by FIPR (1995) established that bermudagrass and Alamo switchgrass are suitable grass covers for the PG stacks in Florida. Bermudagrass is a low (1-ft) runner-type while Alamo switchgrass is a tall (4-ft) bunch-type. Because the Alamo switchgrass is much taller than bermudagrass, it is expected to have slightly higher PET and ET rates if the grasses have comparable leaf conductance.

Extent of Vegetative Cover

The extent of vegetative cover, or leaf area index (ratio of leaf area to ground area), affects the amount of solar radiation absorbed by the surface. Although some dark, wet soils can absorb more energy than vegetated surfaces, on average, a vegetated surface will absorb more energy than a bare one. Vegetative cover will therefore play an important role in the amount of radiation absorbed by the surface.

Under fully vegetated situations, the leaves will absorb most of the solar energy and T will dominate E. With sparse vegetation cover, the relative role of E and T depends on the soil moisture content. Under wet conditions, E will dominate T, but the reverse is true under dry conditions, since the top layer of exposed soil quickly dries out and limits E.

Soil Moisture Content

Water loss can only occur freely when there is an adequate supply of water in the soil. Soil moisture content is therefore a crucial factor that can limit the actual ET to below PET. When water is not freely available for latent heat loss (evaporative cooling), the surface loses heat via radiative, conductive and convective (wind) cooling, i.e. the surface heats up and heat is lost because of the temperature difference between the surface and the overlying atmosphere.

The reduction of ET under low soil moisture content is the result of two effects. Firstly, there is the effect on T via increased resistance to water transport from soil to the roots, roots to the leaves, and leaves to the atmosphere. Increased leaf resistance to water is the result of leaf stomatal closure in response to water deficit in the soil. Secondly, soil water content also has an effect on E via the vapor pressure of the surface soil layer. Decreased soil moisture reduces the soil vapor pressure, lowers the vapor pressure gradient from soil to atmosphere, and therefore reduces E.

The relative effect of soil water content on E and T is a complicated interaction of the energy available and water available to each process. Short crops have more energy reaching the soil surface, and therefore more energy is available for E than with tall crops. Deep-rooted crops have more soil water available for extraction and are less susceptible to reduced T from water stress than shallow-rooted crops.

Soil Nitrogen Content

Soil nitrogen content (N) has an indirect effect on ET. Nitrogen fertilization of soils increases the soil and leaf N content. Leaf N content is directly related to leaf photosynthesis and leaf conductance, and leaf conductance affects T. High soil N can therefore result in increased ET. Higher soil N also results in greater seasonal leaf area growth. For fully-vegetated canopies, the leaves will absorb most of the solar energy and T will dominate E.

Soil Type and Slope

The slope and type of soil has an indirect effect on ET via the soil moisture content. Soils with high slope and low infiltration rates will result in greater runoff, thereby reducing the amount of rainfall infiltrating and being stored by the soil. Additionally, soils with higher available moisture capacity can potentially hold more water. More stored soil water means that ET will remain higher for longer periods during a dry period.

METHODOLOGY

Portable Chamber Instrument

Measurements for this study were made using the portable chamber technique. The technique has been validated on a number of crop species for a wide range of moisture and leaf area index (LAI) conditions (Pickering and others 1993; Reicosky and others 1983).

The portable chamber technique involves placing a sealed, clear plastic chamber on the plot and measuring the rate of increase of water vapor inside the chamber. The chambers are comprised of a base and a top; the base remained implanted in the soil while the top was used on a number of bases. The two parts were clamped together at the time of the measurement so that the closed-cell foam used in the joint formed an airtight seal.

The LI-COR 6200 is a portable instrument that calculates the ET and net photosynthesis (PNET) rates by measuring the rate of increase in the water vapor pressure and the rate of decrease in the carbon dioxide (CO_2) concentration. The instrument has fast-response (approximately 1-s response time) ceramic humidity and precision thermistor sensors to measure relative humidity and air temperature. The vapor pressure is calculated from relative humidity and air temperature. The air in the chamber is pumped to an infra-red gas analyzer to measure the CO_2 concentration. Data are recorded by the LI-COR data logger every 2-3 seconds. Details of the portable chamber measurement technique are given in Pickering and others (1993).

Measurements were made with two sizes of chamber. The measurements on low grass used the normal sized chamber (chamber volume = 485.8 L) while the measurements on tall grass used a special extender chamber to accommodate the extra height (chamber volume = 1,004.0 L). The computations for ET used the appropriate chamber volume for the corresponding measurement.

Evapotranspiration measurements are highly dependent on the instantaneous level of solar radiation during the measurement. To minimize the effect of radiation on the comparisons, normally the ET measurements were made in conjunction with potential evaporation (PET) measurements from a weather station and expressed as an ET ratio (ET/PET).

A Campbell Scientific Inc. (CSI) automated weather station managed by BCI near the Cytec site was used to obtain the estimates of PET. The CSI station uses the Penman-Monteith equation to determine the PET for grass (reference evapotranspiration) as suggested by the Food and Agriculture Organization of the United Nations. The station makes 10-s calculations of PET and averages them to output an hourly value, however, the instantaneous radiation at the site changes rapidly with moving cloud cover, so a different approach that used local conditions had to be developed.

An existing Penman-Monteith computer algorithm was adapted to estimate PET on a shorter time interval. The input data for the algorithm were solar radiation, air temperature, vapor pressure, and wind speed. The algorithm was checked using the input weather data from the CSI station and comparing the computed values of PET from the CSI station versus the output from the computer algorithm (see Figure 118). When predicting PET for the time of measurement, solar radiation was estimated from the photosynthetically active radiation (PAR) that is measured by the LI-COR 2000 at the time of the ET measurement. Other input data were interpolated from the hourly CSI weather station measurement using the time of the ET measurement. This is a reasonable approach for these data since they change slowly through the day.

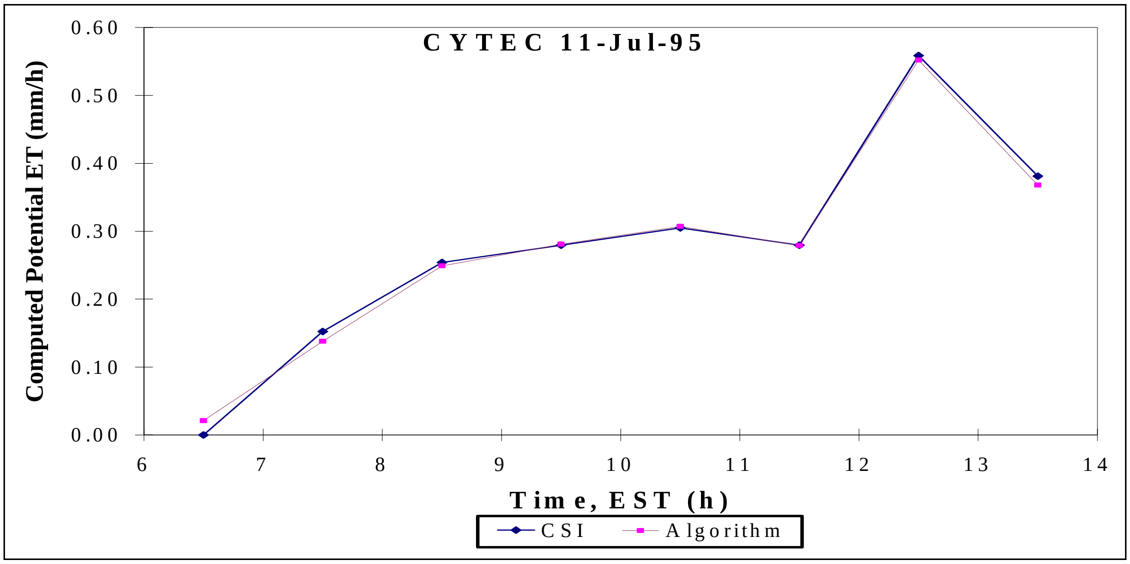

Figure 118. Computed PET from the CSI Datalogger and Penman-Monteith Algorithm.

Calculation of PET was only possible at the Cytec site since the other sites were too far from the weather station. For the other sites, care was taken to try to make all measurements across treatments at the same radiation level. Evapotranspiration measurements were also standardized to the expected noon radiation value (PAR ≅ 2000 $\mu mol/m^2/s$ or solar radiation ≅ 1000 W/m^2) using the measured values of PAR from the LI-COR 6200. This standardization procedure helps to eliminate some of the measurement differences caused by differences in solar radiation.

SUMMARY OF MEASUREMENTS

Field-Plot Descriptions

For an overall evaluation of the effects of water loss via ET, previous results from work completed by BCI (1997) at the Cytec PG stack was evaluated. The Cytec plots were constructed to measure percolation, and specific plot descriptions are presented in Table 26 and the BCI (1997) report. All plots were vegetated with bermudagrass (*Cynodon dactylon*) grown directly on PG. Five sets of measurements were made over the duration of the project (Table 26). The Cytec measurements looked at different degrees of soil compaction and the effect of slope on soil moisture and ET.

This study included additional ET measurements from previously established and vegetated plots (FIPR 1995) at the Estech, Silver city stack as well as the IMC Agrico, New Wales stack (FIPR 1995; Ardaman & Associates, Inc. 1997).

The Estech measurements focused on distinguishing differences between grass species (bermudagrass and Alamo switchgrass [*Panicum virgatum*]) and the response to nitrogen fertilizer, while the work at IMC-1 looked at different soil surface amendments. The IMC 2 and IMC 3 data used the plots set up by Ardaman and Associates, Inc. (Ardaman 1997). All plots at the IMC-Agrico stack were previously vegetated with bermudagrass. These plots were set up to study the hydrology of a retired PG stack with different soil amendments on the side slopes and over an impervious liner on the top of a stack. The first set of measurements addressed the question of early senescence of the bermudagrass by making a series of light and dark photosynthesis measurements. Both sets of data on these plots also looked at the effect of mowing to stimulate growth and ET.

The first measurements at Cytec included measurements during the morning and at noon under both sunny and cloudy conditions. Experience at Cytec showed that the best ET comparisons could be made under full radiation conditions at midday so the subsequent measurements at the Estech and IMC sites were only made at noon under sunny conditions.

A summary of results is given in Table 26 along with the date of the measurement, number of observations, characteristics of the site, and verbal description. The Appendix contains all additional data collected and generated during the field ET measurements.

Cytec

Evapotranspiration measurements were made on the Cytec PG stack on July 11, 1995. A description of the plots is given in Table 26. The objective of this set of measurements was to investigate the ET differences across a range of soil compactions and side slopes. Surface soil moisture content (top 12”) was measured gravimetrically at the end of the day after the ET measurements were made. Plots L1A-L4B were monitored from 7:52 am to 2:06 pm EST while the last four plots (L6-BC) were monitored only around solar noon (1:30 pm EST).

Table 26. Description and Results of the Measured Plots at All Sites.

Date	Site	ID	Num	Slope (%)	Moisture (% mass)	Grass	Nitrogen (lb/ac)	Mowed	Plot Description	PAR (µmol/m2/s)	ET (mm/h)	ET2000 (mm/h)
11-Jul-95	Cytec	L-1A	10	0	Dry (9.1)	None	0	No	Uncompacted PG	1705.7	0.26	0.30
11-Jul-95	Cytec	L-2A	10	0	Dry (10.2)	Bermuda	0	No	Uncompacted PG	1825.2	0.46	0.51
11-Jul-95	Cytec	L-3A	10	0	Dry (10.6)	Bermuda	0	No	24" compacted PG, surface scarified	1864.0	0.47	0.50
11-Jul-95	Cytec	L-4B	10	0	Dry (10.2)	Bermuda	0	No	6" uncompacted PG cover over 24" compacted	1925.9	0.48	0.50
11-Jul-95	Cytec	L-6	3	3	Dry (10.3)	Bermuda	0	No	6" uncompacted PG cover over 24" compacted	2052.0	0.56	0.54
11-Jul-95	Cytec	L-7	4	25	Dry (5.3)	Bermuda	0	No	Uncompacted PG	1939.3	0.51	0.52
11-Jul-95	Cytec	L-8	3	50	Dry (1.9)	Bermuda	0	No	Uncompacted PG	1888.2	0.49	0.51
11-Jul-95	Cytec	BC	3	0	Dry	None	0	No	Bare, unaltered PG surface	1703.0	0.43	0.50
25-Aug-98	Estech	A0	5	0	Moist	Alamo	0	No	0 lb/ac N applied, PG surface	1785	0.56	0.62
25-Aug-98	Estech	A150	5	0	Moist	Alamo	150	No	150 lb/ac N applied, PG surface	1868	0.78	0.84
25-Aug-98	Estech	B0	5	0	Moist	Bermuda	0	No	0 lb/ac N applied, PG surface	1728	0.53	0.61
25-Aug-98	Estech	B150	5	0	Moist	Bermuda	150	No	150 lb/ac N, PG surface	1787	0.61	0.68
26-Aug-98	IMC1	S3	6	30	Moist	Bermuda	150	No	3" overburden soil	1494	0.61	0.82
26-Aug-98	IMC1	SDOL	6	30	Moist	Bermuda	150	No	PG surface	1494	0.61	0.82
26-Aug-98	IMC1	S6	6	30	Moist	Bermuda	150	No	6" soil overburden	1560	0.67	0.86

Table 26 (Cont.). Description and Results of the Measured Plots at All Sites.

Date	Site	ID	Num	Slope (%)	Moisture (% mass)	Grass	Nitrogen (lb/ac)	Mowed	Plot Description	PAR (μmol/m2/s)	ET (mm/h)	ET2000 (mm/h)
26-Aug-98	IMC1	BI	2	30	Moist	None	0	No	Bare gypsum stack	1701	0.45	0.53
30-Nov-99	IMC2	T1	6	30	Dry	Bermuda	100	No	24" compacted soil	1217.6	0.19	0.31
30-Nov-99	IMC2	T2	6	0	Dry	Bermuda	100	No	6" amended PG over 18" compacted PG	1190.5	0.23	0.38
30-Nov-99	IMC2	T3	6	0	Dry	Bermuda	100	No	6" soil over 18" compacted PG	1260.3	0.20	0.32
30-Nov-99	IMC2	S2B	5	30	Dry	Bermuda	100	No	6" amended PG over 18" compacted PG	999.1	0.18	0.35
30-Nov-99	IMC2	S2G	5	30	Dry	Bermuda	100	No	6" soil over in-situ leached PG	1013.3	0.24	0.47
30-Nov-99	IMC2	S2B-CUT	5	30	Dry	Bermuda	100	Yes	6" amended PG over 18" compacted PG	1038.5	0.17	0.34
14-Sep-00	IMC3	T1-M	4	0	Dry	Bermuda	100	Yes	24" compacted soil	1450.0	0.37	0.51
14-Sep-00	IMC3	T1-U	2	0	Dry	Bermuda	100	No	24" compacted soil	1559.2	0.48	0.61
14-Sep-00	IMC3	T2-U-T	2	0	Dry	Bermuda	100	No	6" amended PG over 18" compacted PG, grass poor condition	1345.9	0.30	0.45
14-Sep-00	IMC3	T2-U-G	2	0	Dry	Bermuda	100	No	6" amended PG over 18" compacted PG, grass good condition	1584.3	0.54	0.68
14-Sep-00	IMC3	T3-M	2	0	Dry	Bermuda	100	Yes	6" soil over 18" compacted PG	1385.2	0.31	0.44
14-Sep-00	IMC3	T3-U	2	0	Dry	Bermuda	100	No	6" soil over 18" compacted PG	1565.5	0.34	0.43
14-Sep-00	IMC3	S2B-U	4	30	Dry	Bermuda	100	No	6" amended PG over 18" compacted PG	1803.7	0.43	0.48
14-Sep-00	IMC3	S2G-M	2	30	Dry	Bermuda	100	Yes	6" soil over in-situ leached PG	1792.8	0.44	0.49
14-Sep-00	IMC3	S2G-U	2	30	Dry	Bermuda	100	No	6" soil over in-situ leached PG	1778.9	0.38	0.43

The first four plots were monitored during the morning whenever radiation was constant enough to allow a comparison of ET rates among the treatments. Some of the measurements were made under sunny conditions while others were made under cloudy conditions. Seven measurements were made on each of these plots. In addition, all eight plots were measured at solar noon when the conditions were sunny. At least three noon measurements were made on the plots and the bare stack.

This set of preliminary measurements was unreplicated i.e. only one base was used on a single plot to make repeated measurements. Graphical results for this day therefore do not show standard error bars. All subsequent measurement days had two replicates and the graphs show the standard error bars.

Estech

Evapotranspiration measurements were made on the Estech stack on August 25, 1998. A description of the plots at each site is given in Table 26. The objective of this set of measurements was to investigate the ET between two grass species (bermudagrass vs. Alamo switchgrass) and two nitrogen fertilizer application rates.

The measurement day had high radiation levels with relatively low humidity. Soil moisture content was not measured but the soil was moist. The four Estech plots were measured from 1:40 p.m. to 3:47 p.m. when the conditions were sunny. Five measurements per treatment were made (two replications, one with three and the other with two repetitions).

IMC 1

Evapotranspiration measurements were made on the IMC phosphogypsum stack on August 26, 1998. A description of the plots is given in Table 26. The objective of this set of measurements was to investigate the ET across a range of soil surface amendments.

The measurement day had high radiation levels with relatively low humidity. Soil moisture content was not measured but the soil was moist. The four IMC plots were monitored from 10:50 a.m. to 12:20 p.m. when the conditions were sunny. Six measurements per treatment were made on three plots (two replications, each with three repetitions) and two were performed on the bare stack.

IMC 2

Evapotranspiration measurements were made on the IMC phosphogypsum stack on November 30, 1999. A description of the plots at both locations is given in Table 26. The objective of this set of measurements was to investigate the variation of ET on the Ardaman (1997) plots, which were set up to monitor the hydrology of a range of stack retirement treatments both on the top (T plots) and the side (S plots) of the stack. This site was also used to investigate the high plant respiration manifested by bermudagrass in previous measurements by using a series of light and dark photosynthesis measurements. A limited comparison of mowed and unmowed plots was also made.

The day was clear but had low radiation levels because of the time of year. It was windy (~15 mph) and had relatively low humidity. Soil moisture content was not measured but the soil moisture was moderate at both sites. The plots on top of the stack (T1-T3) were monitored from 10:59 a.m. to 12:01 p.m. while the side slope plots (S2B, S2G, S2B-CUT) were monitored from 1:06 p.m. to 1:51 p.m. Both sets of measurements were made when the conditions were sunny.

Because the top and side slope sites are not adjacent, the top set of measurements were made before noon, then the setup was moved, and the side slope measurements were made after noon. Six measurements per treatment were made at the top site (two replications both with three repetitions) while five measurements were made on the side slope site (two replications, one with two repetitions, one with three repetitions).

IMC 3

Evapotranspiration measurements were made on the IMC phosphogypsum stack on September 14, 2000. A description of the plots is given in Table 26. The objective of this set of measurements was to investigate the variation of ET on the Ardaman (1997) plots which were set up to monitor the hydrology of a range of stack closure treatments both on the top (T plots) and the side (S plots) of the stack. This set of measurements was also used to compare ET differences between mowed and unmowed plots and segments of a plot with visibly poor versus good grass coverage.

The eight plots were measured close to solar noon when the conditions were sunny. An additional measurement was made on a good condition segment of plot T2 to compare it to the typical poor condition of the plot. For this set of measurements, two measurements per treatment were made at both sites (two replications with one repetition) except for plots T1-M and S2G-U, which had four measurements per treatment (two replications with two repetitions).

RESULTS

Cytec

The first set of results show the time course of measurements that were made on plots L-1A to L-4B. Figure 119 shows a comparison of ET rates measured on plots L-1A to L-4B (see Table 26 for descriptions). The non-vegetated plot (L-1A) had significantly lower ET than the other plots except at 9:45 a.m. when the measurements were all made under cloudy conditions. In the early morning, it had an ET rate of about 0.15 mm/h and it increased to a value of 0.3 mm/h at solar noon. The other vegetated plots had an ET rate of about 0.25 mm/h in the morning and increased to about 0.5 mm/h at solar noon. The low value at about 9:45 am is a measurement made under cloudy conditions. There were no consistent differences among the three vegetated plots.

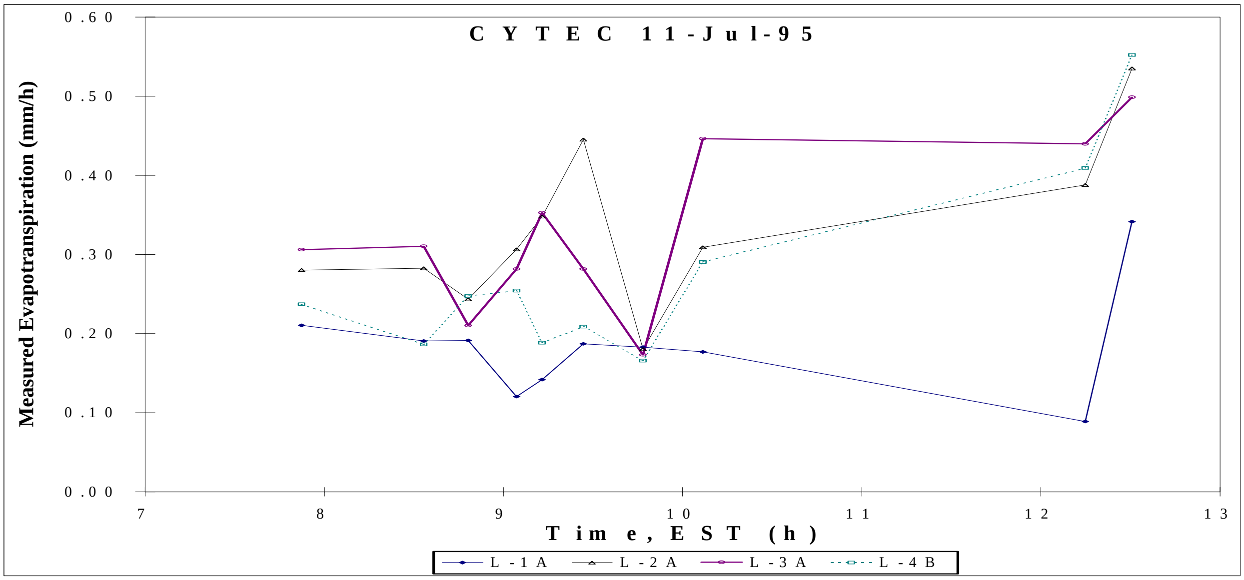

Figure 119. Timecourse of Evapotranspiration Ratio on Four Plots of Varying Soil Compaction.

The average ET values are also given in Figure 120. The non-vegetated (L-1A) and the bare stack (BC) plots had the lowest ET values (0.26 and 0.43 mm/h) while the vegetated plots had ET rates around 0.5 mm/h. The bare stack ET might have been higher than the non-vegetated plot (L-1A) because of the soil conditions. The bare stack measurement was made below the ridge where all the other plots were located and could have been slightly wetter. There was a tendency of ET to decrease with increasing slope probably because the steeper slope plots have less infiltration of water and less soil moisture. This explanation is validated by the measured soil moisture values of 10.3, 5.3, and 1.9 % (mass) for the 3%, 30%, and 50% slopes, respectively.

Estech

Figure 121 shows the ET results for the noon measurements. Experience at the Cytec site showed the need for replication, but measurement time and the number of bases were limited so measurements were only made on two replicates. In most cases, the differences in ET between treatments were not large enough to be statistically significant at a high level but there was enough consistent information to investigate the trends in the differences.

There was no difference between ET measured on the Alamo switchgrass and bermudagrass at the zero fertilization level (0.56 vs. 0.53 mm/h) but Alamo switchgrass

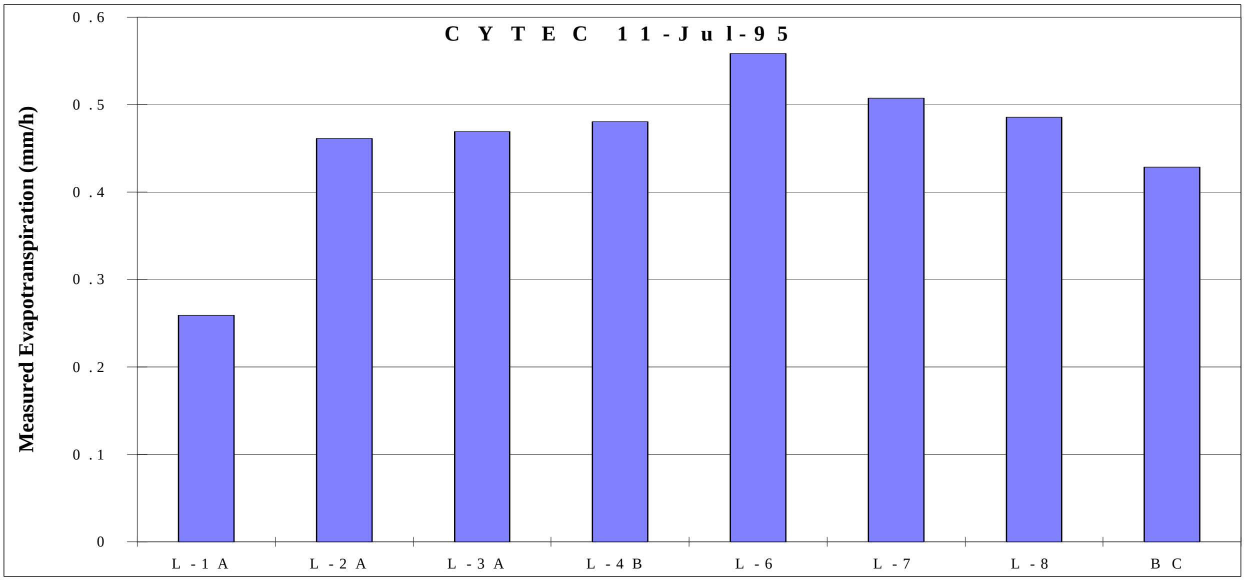

Figure 120. Measured Noontime Evapotranspiration on Eight Plots at Cytec.

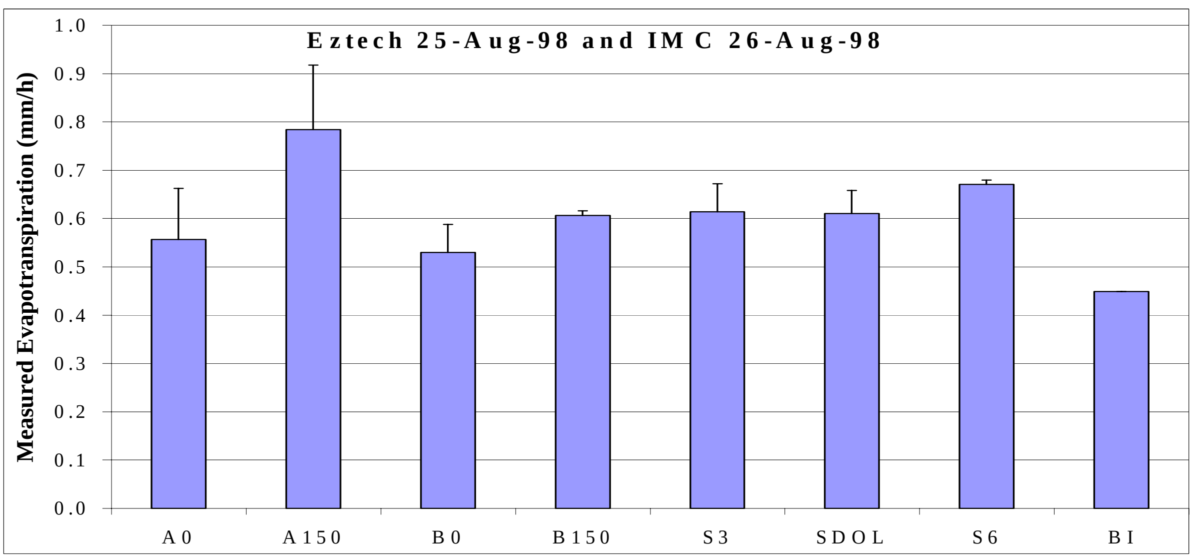

Figure 121. Measured Noontime Evapotranspiration on Eight Plots at Estech and IMC 1.

had higher ET than bermudagrass at the 150 lb/ac N fertilization level (0.78 vs. 0.61 mm/h). Both grasses exhibited slightly higher ET at the high versus low fertilization level.

IMC 1

As with the Estech site (Figure 121), IMC1 site measurements were made on two replicates. Statistical differences in ET among treatments might not be highly significant but there is enough consistent information to investigate the trends in the differences.

The measured ET at noon was highest for the S6 plot and the other two plots were about the same (0.67 vs. 0.61 mm/h). In contrast, the bare stack ET was about 70% of the average grass ET rate (0.45 mm/h). The six-inch surface soil amendment appears to moderately increase measured ET rates.

IMC 2

IMC2 site results are shown in Figure 122. As with the Estech site, measurements were made on two replicates. Statistical differences in ET among treatments might not be highly significant but there is enough consistent information to investigate the trends in the differences.

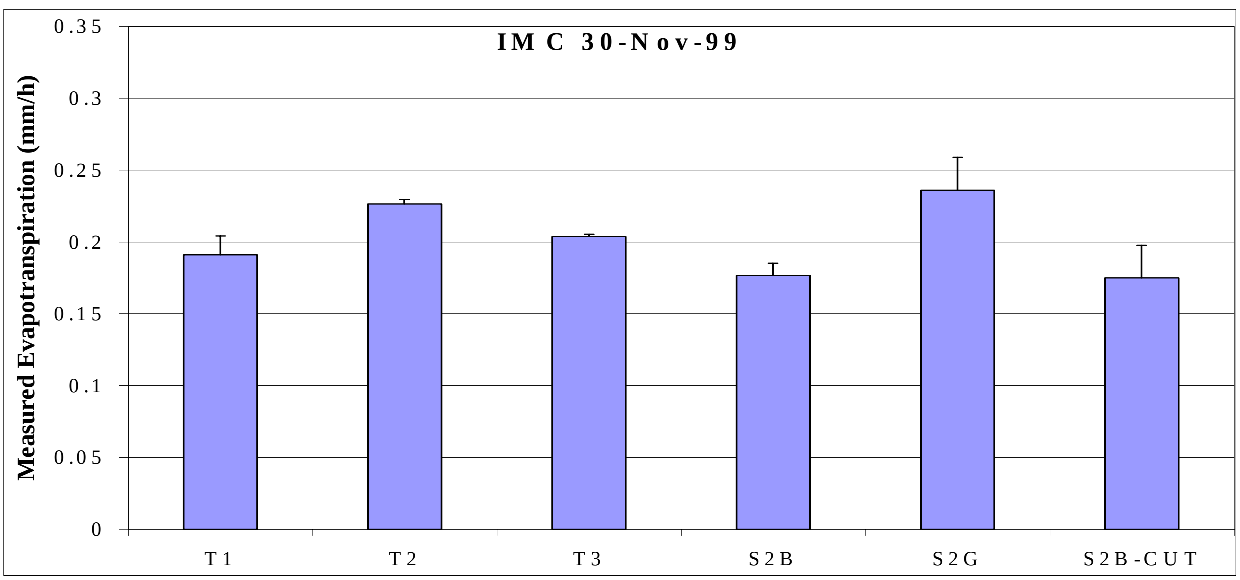

Figure 122. Measured Noontime Evapotranspiration on Six Plots at IMC 2.

Measured ET at noon for this set of measurements was significantly lower than previous measurement days. The values are probably low because of low radiation levels for this time of year (Nov. 30). At the top site, the measured ET at noon was highest for plot T2 compared to the other plots (0.23 vs. 0.2 mm/h) while for the side slope site, the measured ET at noon was highest for plot S2G relative to the rest of the plots (0.24 vs. 0.18 mm/h). The mowed S2G plot had lower measured ET than the unmowed plot probably because there is less radiation captured by the lower leaf area on the mowed plot. The difference could also be due to the poorer condition of the newly mowed plot.

IMC 3

Figure 123 shows the ET results for the IMC3 site. As with the Estech site, measurements were made on two replicates. Statistical differences in ET among treatments might not be highly significant but there is enough consistent information to investigate the trends in the differences.

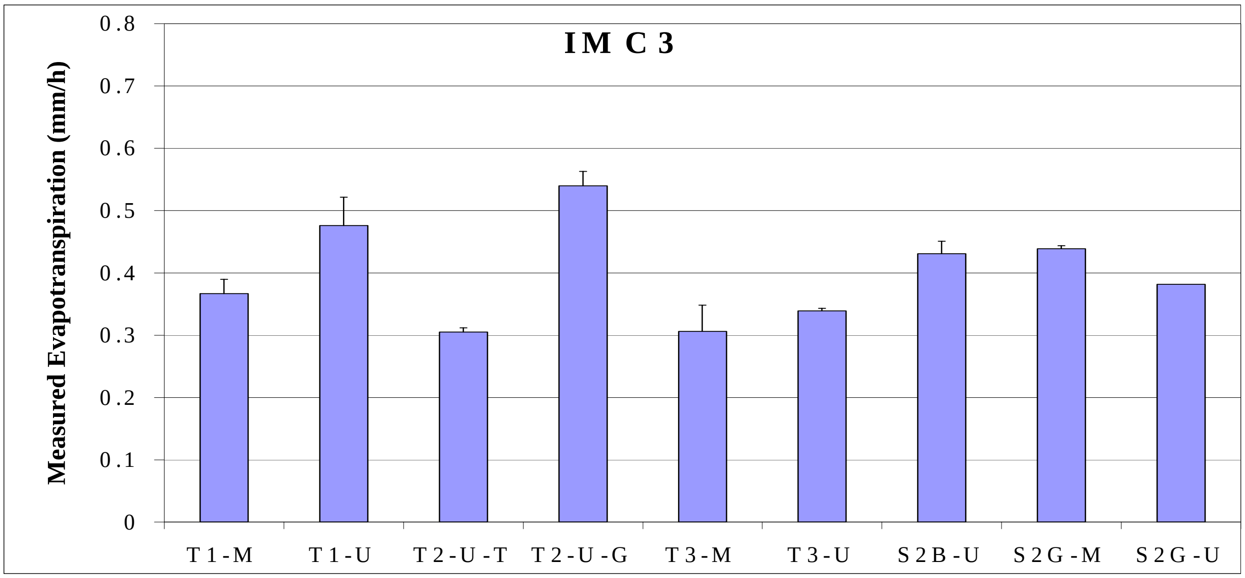

Figure 123. Measured Noontime Evapotranspiration on Six Plots at IMC 3.

Measured ET at noon for this set of measurements was somewhat lower than the first three sets of measurements but not as low as the IMC 2 set. The values are probably low because of the dry soil conditions at the plots. At the top site, the measured ET for the T1 plot was higher than the others (0.48 vs. 0.32 mm/h) while on the side slope the S2B treatment was slightly higher than the S2G plot (0.43 vs. 0.38 mm/h). For the top site, the mowed plots had lower ET rates while on the side slope there was no difference. The highest ET rate was for the small grassy area within T2 plot (T2-U-G). This small area of surviving grass was quite vigorous and might indicate a management problem with the rest of the plot.

All Sites

All the ET measurements from this study are presented in Figure 124. The ET values (ET2000) are scaled from the observed PAR values to a common full-sun value of 2000 μmol/m^2/s to allow comparisons across measurements taken at different times of the year and under different radiation conditions. The relative values of ET2000 are similar to the ET values presented in previous table and figures, but the relative magnitude of the values might have changed slightly.

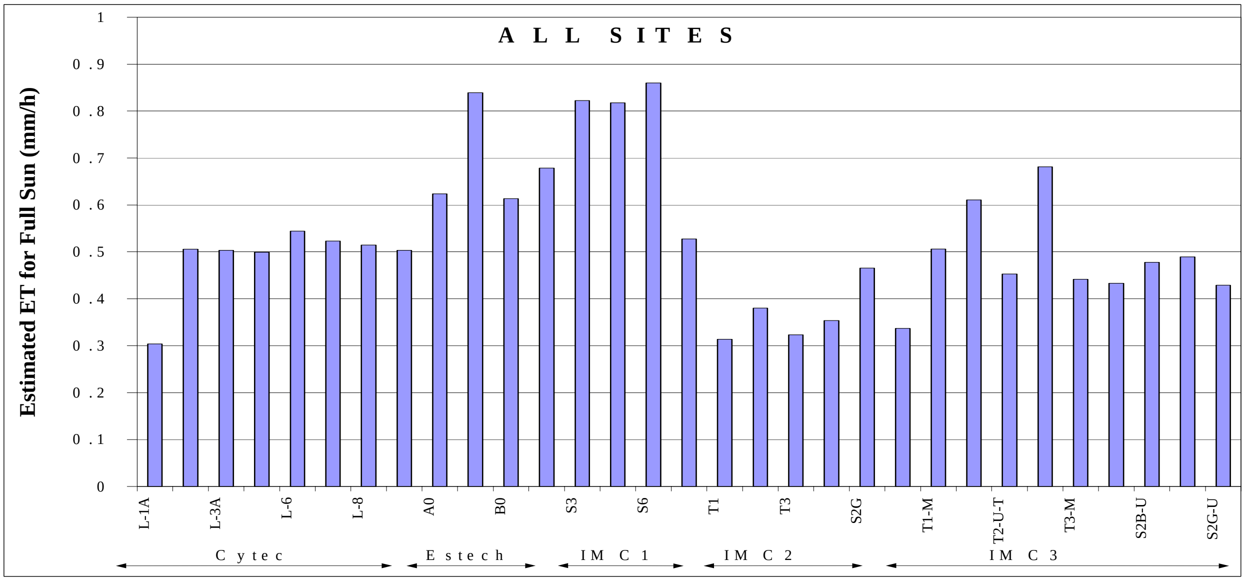

Figure 124. Estimated Full Sun Evapotranspiration on All Plots.

The ET2000 values were then ranked and plotted in Figure 125 to permit an evaluation of the conditions, other than radiation, likely to maximize ET. Seven of the highest nine ET2000 values were taken under moist soil conditions. In contrast, most of the IMC 2 and IMC 3 plots fall in the lowest 50% of the ET2000 values, a manifestation of the moderate to low soil moisture conditions that were present for these measurements. These observations highlight the importance of soil moisture in regulating ET.

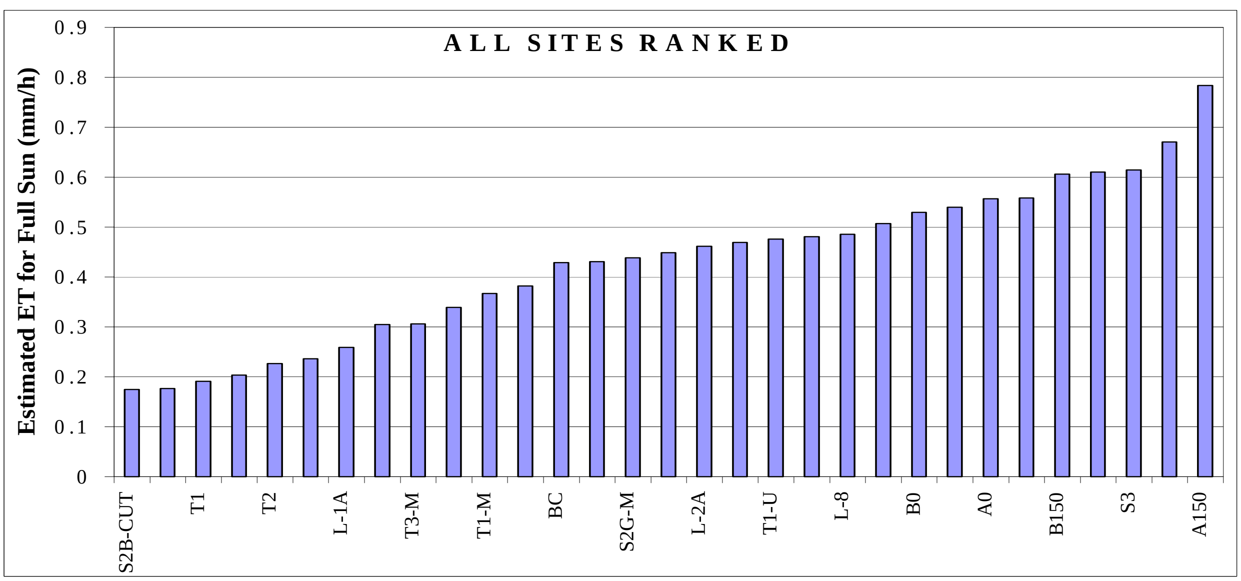

Figure 125. Ranked Estimated Full Sun Evapotranspiration on All Plots.

Three of the highest nine ET2000 values are soil surface amendment treatments illustrating the importance of soil moisture storage. Two of the highest five ET2000 values are high nitrogen treatments showing the importance of nitrogen fertilization. The bare soil plots are in the middle of the ranking showing that soil moisture can dominate the lack of vegetative cover since, under moist conditions, E overwhelms T. Another observation is the very high ranking of the good condition segment of one of the top plots for the IMC 3 data. Management for healthy grass cover is obviously very important to maximize ET.

DISCUSSION

Bare plots measured at Cytec and IMC 1 had significantly lower ET rates than the vegetated ones. This result can be attributed to lower radiation absorption by a bare soil versus a fully vegetated canopy. In addition, a bare surface loses water via E only and this only occurs from the upper soil layer. Vegetating the PG stack will definitely remove more water from the gypsum-soil matrix. ET rates from the bare plot were about 60-70% of the vegetated ones.

The ratio of non-vegetated to vegetated ET rates would be expected to be higher soon after a rainfall and lower with drier soils. After a recent rainfall, where the soil surface layer is wet, the ET from a bare soil surface will be similar to a vegetated one. The vegetated plots continue to extract water effectively with declining moisture content. There was no measurable decline in ET rate at the Cytec plots until the soil moisture content was about 20% of the wetter plots. Even though T from these plots is low (see later in discussion), the grass must be able to extract some extra water from the deeper soil until the soil become very dry.

Slightly lower ET rates were observed for increased soil slope at Cytec. Transpiration from these plots is low (see later in discussion); a greater effect might be seen under cooler conditions more favorable to photosynthesis and T. The observed effect of slope on ET is probably due to the increased runoff and less infiltration into the soil layer, but reduced solar angle can also reduce absorbed solar radiation. Increasing the slope will increase runoff, decrease soil moisture, and reduce ET. The slope effect on soil moisture only occurs at the highest slope (50%), probably due to the subtle effect of moisture mentioned above. Although ET could be lower at higher slope, infiltration is also likely to be lower, so that there will be less infiltrated water to export via ET. The net effect of slope on deep percolation of water is unclear.

From the Estech results, we can see that the Alamo switchgrass had higher ET than the bermudagrass and had a larger N fertilization effect. Inadequate mixing associated with the larger chamber used for the taller Alamo switchgrass was evaluated. Fortunately, the larger Alamo switchgrass canopy was fairly open and allowed good penetration of the wind created by the fans, therefore the inadequate mixing explanation was discarded. The Alamo switchgrass probably has higher ET due to larger leaf area and greater height than bermudagrass.

At the IMC 1 site, the ET increased with a six-inch surface layer of overburden soil. This increase makes sense since the greater overburden depth should allow deeper root penetration, more uptake of water and more T. Given that the role of T for these measurements on the bermudagrass is small, an even greater effect might be seen under conditions more favorable to photosynthesis and T.

There is no clear interpretation of the differences in ET for the IMC 2 and IMC 3 sets of measurements made on the plots created for the study by Ardaman (1997). The plots with soil cover had lower ET than plots without soil on the top site but the reverse was true on the side slope site. The most likely explanation is that the soil has higher infiltration rates but lower available moisture capacity than the gypsum. This would limit ET on the top sites where infiltration rate is less critical and would enhance infiltration, soil moisture storage, and ET on the side slope plots.

During maturation, N moves from the leaves to the seed and roots, and photosynthesis is markedly reduced. Mowing was suggested as a possible management practice to induce new growth and prevent senescence.

The effect of mowing to rejuvenate growth and enhance ET was investigated for the IMC 2 and IMC 3 measurements. In general, however, the expected effect was not observed; i.e., the mowed plots had lower ET values than the unmowed ones. The moisture condition of the plots was moderate (IMC 2) to dry (IMC 2) and the plots were mowed a couple of weeks prior to measurement to allow the grass time to grow back. The reduced leaf area of the mowed plots probably reduced radiation capture and reduced the measured ET. Mowing during a dry period or without proper management to enhance growth will probably yield a period of reduced ET. However, a yearly mowing in the middle of the winter during a period of limited heat or moisture stress could be a suitable alternative.

CONCLUSIONS

- The bare plots had significantly lower ET rates (60-70%) than the vegetated ones. Vegetating the PG stack will definitely remove more water from the gypsum-soil matrix.
- Alamo switchgrass had slightly higher ET than bermudagrass.
- Evapotranspiration rate is increased by increased nitrogen fertilization for both grasses, but the effect was greater for Alamo switchgrass than bermudagrass.
- Evapotranspiration rate was decreased at low soil moisture content (< 2% mass).
- Evapotranspiration rates were consistently slightly lower for steeper soil slopes even though the differences were not statistically different. Although ET could be lower at higher slope, infiltration is also likely to be lower, so that there will be less infiltrated water to export via ET. The net effect of slope on deep percolation of water is unclear.
- Evapotranspiration rate was increased with soil overburden on side slope plots but decreased on top plots. The most likely explanation is that the soil has higher infiltration rates but lower available moisture capacity than the

gypsum, thus limiting ET on the top sites where infiltration rate is less critical and enhancing infiltration and ET on the side slope plots.

- Mowing during the growing season reduced ET in two instances, probably because of reduced leaf area. Winter mowing seems to be a suitable alternative.

RECOMMENDATIONS

The above conclusions of this study suggest a number of recommendations for maximizing ET losses from phosphogypsum stacks:

- Plant a hardy, long-season, cover crop like bermudagrass on the entire stack.
- Combine bermudagrass and Alamo switchgrass to maximize both hot and cool season ET.
- Incorporate soil or overburden containing significant organic nitrogen to ensure good crop establishment.
- Increase depth of root penetration by tilling organic matter into the gypsum.
- Use different soils on the stack top (high water holding capacity) versus side slope (high infiltration rate). [The goal is to minimize deep percolation of water. Increasing infiltration on the side slopes may not help this, although it might promote greater grass vigor and hence better erosion control.]
- Annually apply slow-release nitrogen fertilizer in the spring using the lowest possible recommended fertilization rate. This low rate should be sufficient for grass maintenance while minimizing cost and environmental impact. [Fertilizer rate should be high enough to promote good grass vigor.]
- Annually mow grass during the winter.
- Use an appropriate pest management program to maintain grass health.

The preliminary results from the ET study indicate the importance of cover crop management for maximizing ET rates. It is clear that plant health needs to be maintained through pest management, fertilization, and mowing practices. The past experimental design was too limited to address specific management recommendations in detail.

Although some clear results were obtained from this study, the results were inconclusive in addressing several cover crop management issues. Therefore, we recommend that an additional study be developed that will better address the management issues that affect ET rates. The following issues should be addressed:

- Pest management. The goal of this investigation would be to define the appropriate management practices that keep the grass healthy so that seasonal ET rates would be maximized.
- Mowing frequency. This study would define the appropriate mowing frequency that promotes grass vigor and reduces dormancy periods so that seasonal ET rates can be maximized.
- Double cropping. This analysis could investigate using a combination of grasses that are adapted to different seasons. A possibility would be to

combine bermudagrass and Alamo switchgrass to maximize both hot and cool season ET.

- Additional soil amendments. The goal of this investigation is similar to the pest management goal, defining the appropriate management practices that keep the grass healthy so that seasonal ET rates would be maximized.

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Appendix

SUMMARY OF MIDDAY

MEASUREMENTS AT ALL SITES

SUMMARY OF MIDDAY MEASUREMENTS AT ALL SITES

Date	Site	TMT	PAR (µmol/ m2/s)	ET (mm/h)	PNET (µmol/ m2/s)	RESP (µmol/ m2/s)	PGROSS (µmol/ m2/s)	ET2000 (mm/h)	PGROSS 2000 (µmol/ m2/s)	PET (mm/h)	ET/PET (%)
11-Jul-95	Cytec	L-1A	1705.7	0.26	-1.3	-	-	0.30	-	0.77	33.5
11-Jul-95	Cytec	L-2A	1825.2	0.46	-3.0	-	-	0.51	-	0.79	58.4
11-Jul-95	Cytec	L-3A	1864.0	0.47	-3.0	-	-	0.50	-	0.82	57.3
11-Jul-95	Cytec	L-4B	1925.9	0.48	-2.9	-	-	0.50	-	0.84	57.1
11-Jul-95	Cytec	L-6	2052.0	0.56	-3.9	-	-	0.54	-	0.91	61.6
11-Jul-95	Cytec	L-7	1939.3	0.51	-3.2	-	-	0.52	-	0.86	59.2
11-Jul-95	Cytec	L-8	1888.2	0.49	-3.2	-	-	0.51	-	0.92	52.8
11-Jul-95	Cytec	BC	1703.0	0.43	-2.3	-	-	0.50	-	0.83	52.0
25-Aug-98	Estech	A0	1785	0.56	4.8	-	-	0.62	-	-	-
25-Aug-98	Estech	A150	1868	0.78	7.8	-	-	0.84	-	-	-
25-Aug-98	Estech	B0	1728	0.53	-3.2	-	-	0.61	-	-	-
25-Aug-98	Estech	B150	1787	0.61	-2.5	-	-	0.68	-	-	-
26-Aug-98	IMC1	S3	1494	0.61	-4.5	-	-	0.82	-	-	-
26-Aug-98	IMC1	SDOL	1494	0.61	-3.5	-	-	0.82	-	-	-
26-Aug-98	IMC1	S6	1560	0.67	-6.8	-	-	0.86	-	-	-
26-Aug-98	IMC1	BI	1701	0.45	-2.0	-	-	0.53	-	-	-

SUMMARY OF MIDDAY MEASUREMENTS AT ALL SITES (CONT.)

Date	Site	TMT	PAR (µmol/ m2/s)	ET (mm/h)	PNET (µmol/ m2/s)	RESP (µmol/ m2/s)	PGROSS (µmol/ m2/s)	ET2000 (mm/h)	PGROSS 2000 (µmol/ m2/s)	PET (mm/h)	ET/PET (%)
30-Nov-99	IMC2	T1	1217.6	0.19	4.2	-2.4	6.6	0.31	10.8	-	-
30-Nov-99	IMC2	T2	1190.5	0.23	5.2	-4.1	9.2	0.38	15.5	-	-
30-Nov-99	IMC2	T3	1260.3	0.20	5.9	-2.6	8.5	0.32	13.5	-	-
30-Nov-99	IMC2	S2B	999.1	0.18	0.2	-2.1	2.4	0.35	4.7	-	-
30-Nov-99	IMC2	S2G	1013.3	0.24	9.1	-4.5	13.6	0.47	26.9	-	-
30-Nov-99	IMC2	S2B-CUT	1038.5	0.17	1.5	-1.9	3.4	0.34	6.5	-	-
14-Sep-00	IMC3	T1-M	1450.0	0.37	1.6	-	-	0.51	-	-	-
14-Sep-00	IMC3	T1-U	1559.2	0.48	3.5	-	-	0.61	-	-	-
14-Sep-00	IMC3	T2-U-T	1345.9	0.30	-1.1	-	-	0.45	-	-	-
14-Sep-00	IMC3	T2-U-G	1584.3	0.54	0.9	-	-	0.68	-	-	-
14-Sep-00	IMC3	T3-M	1385.2	0.31	1.1	-	-	0.44	-	-	-
14-Sep-00	IMC3	T3-U	1565.5	0.34	0.4	-	-	0.43	-	-	-
14-Sep-00	IMC3	S2B-U	1803.7	0.43	0.0	-	-	0.48	-	-	-
14-Sep-00	IMC3	S2G-M	1792.8	0.44	0.9	-	-	0.49	-	-	-
14-Sep-00	IMC3	S2G-U	1778.9	0.38	1.3	-	-	0.43	-	-	-