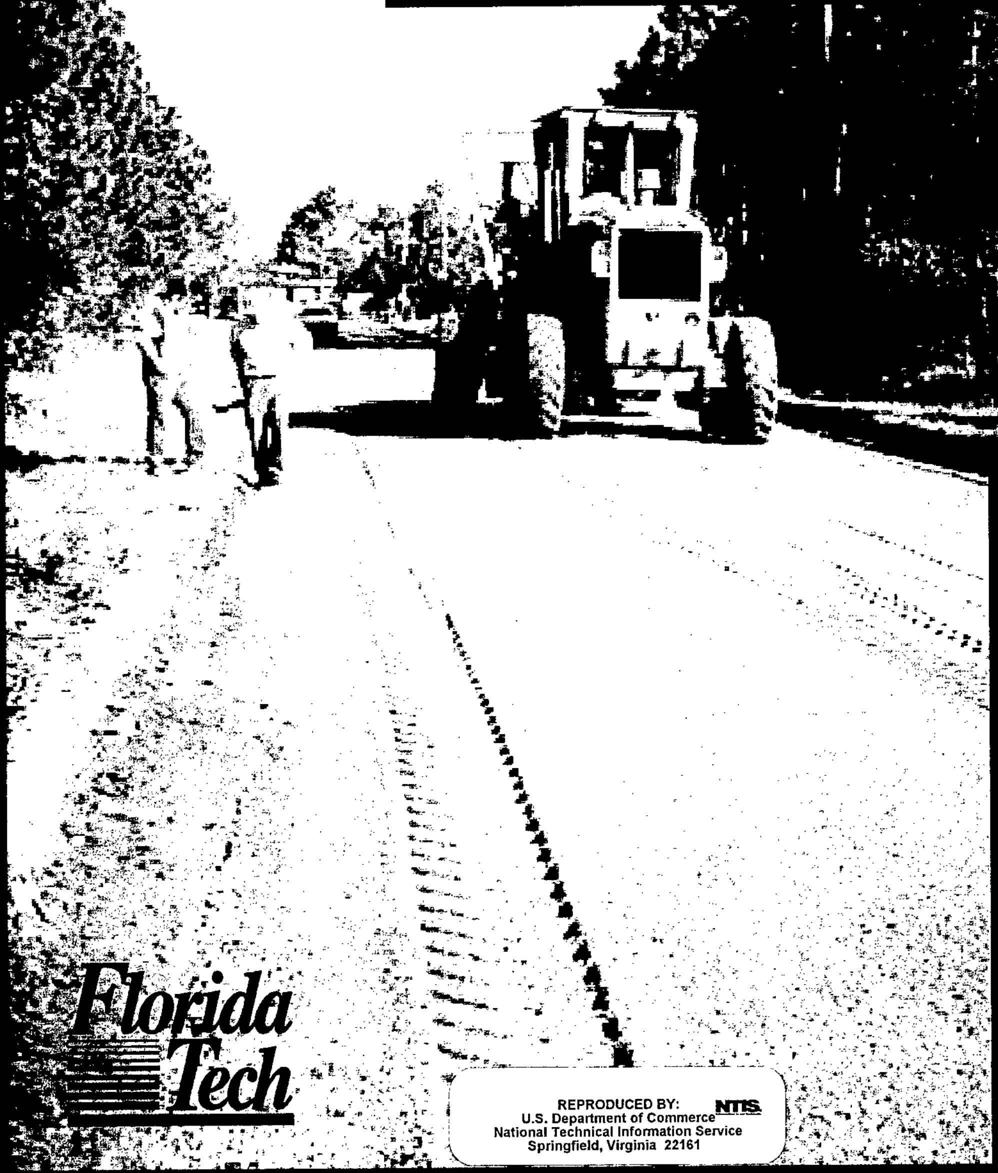
DEVELOPING SPECIFICATIONS FOR WASTE GLASS, MUNICIPAL WASTE COMBUSTOR ASH AND WASTE TIRES AS HIGHWAY FILL MATERIALS (CONTINUATION)

FINAL REPORT

VOLUME 2–WASTE GLASS



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16. Abstract

A two year study was conducted as a continuation project for the Florida Department of Transportation (FDOT) to evaluate Municipal Waste Combustor (MWC) ash, Waste Glass, and Waste Tires for use as general highway fill. Initial studies conducted at Florida Tech concluded that MWC ash and waste glass possess engineering properties required for highway applications and the environmental characteristics were satisfactory for field deployment. The results of these studies are presented in three volumes. Volume I summarizes the findings for MWC Ash, Volume II summarizes findings for Waste Glass and Volume III summarizes findings for Waste Tires.

During this continuation study field demonstration projects using MWC ash and waste glass indicated that conventional construction methods and techniques were applicable. A comprehensive literature review was completed on the waste tires and their use as highway fill by state DOT's. It revealed that waste tires are highly compressible, but with adequate processing they can be used as highway fill.

For the field demonstration project involving the MWC ash a 82 foot (25 m) long, 32 foot (9.8 m) wide, 4 foot (1.2 m) high embankment was constructed using treated combined ash. A runoff and leachate collection system were installed for environmental monitoring. The geotechnical properties showed that combined ash exhibits high strength while being relatively free draining. An environmental analysis of 8 metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) indicated that the leachate and runoff concentrations were below surface water standards and below drinking water standards for all elements except an initial peak of selenium.

Laboratory studies conducted on combined ash from all 12 Florida waste-to-energy facilities indicated it would classify as either a well graded or poorly graded sand (SW or SP according to United Soil Classification System). The combined ash meets engineering criteria established by FDOT for use as a highway subgrade material.

The investigation of the environmental properties of waste glass revealed it can be cleaned to meet EPA drinking water standards at a reasonable cost. An outdoor reactor system was used to evaluate the environmental characteristics of waste glass leachate and waste glass cleaning methods. Prior to handling, the waste glass was crushed at a materials recovery facility. The waste glass was cleaned using two methods; direct rainfall and recirculating rinse water. Leachate from the system was analyzed for BOD5, TKN, and Phosphorus. These techniques produced leachate that initially exceeded drinking water standards, but that became clean within a reasonably short time.

For the field demonstration project involving the waste glass a 300 foot (91.5 m) section of subgrade was stabilized to a depth of 6 inches (2.4 cm) on a residential street using approximately 15% waste glass by volume. The subgrade stabilization was accomplished by mixing the waste glass with both the highly deteriorated pavement surface plus the existing base. Subgrade CBR, density and moisture contents data were collected. The construction process produced an acceptable subgrade.

Shredded tires exhibit engineering properties that are favorable for use in highway construction. They are a lightweight, free draining material, however, they undergo large initial displacements upon loading. The waste tire literature indicated that a major concern with waste tire fills was combustion. Fills in Washington and Colorado have combusted, causing numerous environmental concerns and hazards. Combustion can be avoided by proper sizing and placement. The state wide survey revealed that less than 1% of the nearly 14 million scrap tires generated yearly in Florida are available for use as highway fill. The majority of the tires are burned in either waste-to-energy facilities or in the tire-derived-fuel facility.

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1. INTRODUCTION

An investigation of the environmental engineering and highway engineering properties conducted by Cosentino, et al. (1994), revealed that waste glass had desirable properties for uses as highway fill. Environmental contamination levels could be controlled for a reasonable cost, while excellent drainage and shear strength properties were found. Developmental specifications were proposed for incorporation into Section 180 of the FDOT "Standard Specifications for Road and Bridge Construction."

1.1 Waste Glass Quantities

About 200 million tons of municipal solid waste (MSW) is generated yearly in the United States. Florida produced about 24.3 million tons of MSW in 1995, with about 9.7 million or 40 percent being recycled. Roughly 2.7 percent (by weight) of Florida's municipal waste stream is glass ; this percentage has decreased yearly since 1989 (Department of Environmental Protection [DEP], 1996).

According to the Glass Packaging Institute (1993) 35 percent of all glass containers were recycled, with the total glass recycled being 3.8 million tons. A 1992 estimate indicates that Florida generated approximately 582,000 tons of glass out of which 128,000 was recycled, thereby, matching its typical recycling rate of between 20 and 25 percent (Kynes, 1994). The construction industry in Florida uses over 18 million tons of sand and gravel yearly (U.S. Dept. of Interior, 1990) implying that all of the waste glass produced yearly could be utilized by the construction industry.

Waste glass (WG) is generated by most municipalities within Florida due to state mandated recycling quotas. It is defined as the non-recyclable portion of disposed glass. Very few glass recycling facilities exist in Florida, consequently most glass is recycled out of state. If a shipment is overly contaminated, a recycling facility cannot economically use the WG and will consequently refuse the shipment (Institute of Scrap Recycling Industries, 1994). Transportation costs for recycled glass range from $1.00 to $1.50 per mile and the glass is worth $15 to $50 per ton upon delivery to a recycling center (Heck et al., 1989).

1.2 WG Production

Recycling has become increasingly important as one of today's strategies for solid waste reduction. The practice of recycling glass reduces the quantity of glass disposed of in landfills thereby saving significant landfill space. Approximately 69% of all glass bottles can not be economically recycled due to the contamination resulting from the mixture of amber, flint, and green glass. This nonrecyclable portion is referred to as WG or mixed cullet. The use of WG as an aggregate helps to conserve the naturally occurring aggregates. In aggregate markets, WG would compete with materials ranging from $5 to $10 per ton. According to a report released by the Clean Washington Center, processing glass as an aggregate feedstock costs between $7 and $12 per ton, while sorting glass for the bottle market can cost between $20 and $50 per ton (Dames & Moore, 1993). Highway applications have been proposed where 100% cullet can safely be used. Additional applications that require a mixture of cullet with natural aggregates have also been proposed. According to the Clean Washington Center report, it is less expensive to collect and process glass for recycling than it is to landfill it (Dames & Moore, 1993).

To be recycled curbside, glass must be separated by color into flint, amber, and green. This separation insures color consistency when new containers are manufactured. Current specifications require separated glass to be relatively free of contamination—for example, specifications published by the Institute of Scrap Recycling Industries (1994) require furnace ready flint glass to be 95% pure. However, at present no technology exists which can efficiently color sort glass, although research in this area continues (Glass Packaging Institute, 1993).

1.3 WG Disposal Techniques

Glass is an interesting component of waste; it will not burn, rust, or decay. The current disposal method for glass is limited to sanitary landfilling. Economic considerations have generally dictated whether or not salvage and reclamation operations are feasible—and in the past, processing and transportation costs have generally ruled out this opportunity (Malisch, et al., 1970). In some areas, MSW landfills cannot provide a solution because of the lack of available space. Also, the volume glass bottles take up can be excessive unless they are thoroughly crushed.

1.4 Secondary WG Uses

A growing number of secondary uses are emerging for WG. Uncontaminated WG is used to a limited degree in the fiber glass insulation industry while clear glass is used in the production of glass beads and reflective paints (Menges, 1990). It can also be used as an aggregate in a form of asphalt known as "glasphalt" (Day and Schaffer, 1995). It can be used as a replacement for gravel and crushed stone in road base construction, pipe backfill and storm drains (Glass Packaging Institute, 1993). In the U.S., approximately 575,000 tons per year of recycled glass is used in these secondary applications (Glass Packaging Institute, 1993). However, a recent survey of Florida's largest 30 counties, revealed that there were no cullet stockpiles.

1.5 Objectives

The following objectives were accomplished during this research on Waste Glass.

- Refinement of the developmental specifications proposed for WG for use as highway fill material.
- Evaluation of the engineering and environmental acceptability of waste glass materials through small scale field demonstration projects.

1.6 Approach

To meet the overall project goal of developing specifications for the Florida Department of Transportation (FDOT) for utilizing WG as a highway fill material the following tasks were completed for the WG research.

1. The contamination level was determined of WG leachate in terms of biochemical oxygen demand (BOD), total phosphorous (TP), total kjeldahl nitrogen (TKN), and solids content
2. A method was developed for determining contamination within WG samples
3. The stress-strain and shearing characteristics were determined for using WG as highway fill material
4. Specifications were developed for using WG as highway fill material

2. METHODOLOGY

2.1 Environmental Studies

Potential glass stockpiling problems were identified after the laboratory environmental studies performed during phase 1 of the project. During phase 2, a WG field study was conducted on the Florida Tech campus to simulate worst case conditions at a glass storage area. Florida Department of Transportation proposed draft specifications establish that WG must be processed to reduce leachable materials to acceptable environmental levels at the time of usage. The field study included two stockpiled WG cleaning procedures: (1) Natural Assimilation and (2) Accelerated Cleaning. Results from this testing program were used as the basis for recommended WG environmental clean-up procedures. During WG placement, handling techniques and construction quality control procedures were developed. The information was used to supplement the observations from the test road constructed from WG.

The field evaluation was conducted using 256 ft^3 (7.24 m^3) reactors, filled with Mixed Color Glass Cullet from the West Palm Beach Materials Recovery Facility (WPBMRF). Chemical analyses were performed on the leachate generated, to determine the level of contamination and how long it would take to "clean" glass so that it can be safely used in highway construction. Leachate samples were tested for BOD_5, TKN (Total Nitrogen) and Phosphate content. BOD_5 was selected because it includes a wide range of organic contaminants and oxygen demand from leachate flowing into receiving waters. The additional oxygen demand created by organic contaminants could cause fish kills. Nitrogen and Phosphate are nutrients which can cause algae blooms and accelerated eutrification (natural aging process) in surface water bodies.

2.1.1 Natural Assimilation

To evaluate the reduction of organic and inorganic contaminants from WG leachate due to natural processes, waste glass was placed in reactors and sampled after significant rainfall events occurred. Three identical reactors measuring 8' by 8' by 4' (2.4 by 2.4 by 1.2 m) were constructed and equipped with a plastic inner liner to prevent leakage and allow leachate collection. A leachate sampling base was placed at the center of the reactors which were then filled with WG to approximately 80% of their total volume (See Figure 2.1). Leachate samples were extracted from each reactor once a week or immediately following an adequate rainfall event. The samples were tested for BOD_5, Total Phosphorus (TP) and Total Kjeldahl Nitrogen (TKN) content. The Natural Assimilation Testing sequence was conducted with three reactors operating at the same time, with glass obtained on the same day from WPBMRF. WG contains high levels of contaminants such as organic carbons, nitrogen and phosphorus. As rainwater flows through the WG reactors the food and beverage residue dissolves in the water releasing the contaminants in the leachate.

2.1.2 Accelerated Cleaning

The Accelerated Cleaning test was performed using one 256 ft^3 (7.24 m^3) reactor. In addition to the liner and the sampling base, this reactor was equipped with top-mounted sprinklers and a water pump to re-circulate the WG rinse-water from the bottom and distribute it over the top. The glass samples obtained on 9/9/96, 11/11/96 and 1/16/97 were from the same facilities but represent different conditions and waste history. Tap water was added to the reactor to maintain recirculation during the test, instead of using natural rainwater. The water reaching the reactor bottom was pumped up to the top, and distributed by sprinklers over the top surface of the reactor. The water was allowed to continuously re-circulate through the reactor for 8 hours, with the sprinkler system off during the remainder 16 daily hours. Leachate samples for this part of the study were collected daily, at the end of the 8 hour recirculation cycle. The samples were tested for BOD_5, Total Phosphorus (TP) and Total Kjeldahl Nitrogen (TKN) content.

2.1.3 Laboratory Analyses

A 5-day BOD Test for the leachate from the WG was conducted following 5210 B, Standard Methods (American Public Association, 1989). The Total Phosphorus concentration in the WG leachate was conducted using the single reagent method and persulfate digestion (U.S.EPA, 1974). The Total Kjedahl Nitrogen analysis was performed by Brevard Teaching and Research Labs, Inc. In Palm Bay, Florida. The analysis was performed following Standard Method 351.3 (American Public Association, 1989).

2.2 Laboratory Engineering Studies

2.2.1 Introduction

Waste glass from Southeast Recycling, Brevard County and WPBMRF was considered for the study. The material from the Brevard County facility contained a very high level of debris while glass from WPBMRF contains less contaminants and was therefore assumed to be more suitable for use as base/subbase material (Cosentino, et al., 1994). Therefore, only the WPBMRF materials were evaluated. All debris was left in the cullet because the percentages by weight were in very small quantities: 0.48% of crushed paper, 0.31% of plastics and 0.01% of ceramic and others (Syed, 1994).

The limerock and cemented were obtained from two different companies. Limerock was obtained from Tarmac Corp., Cocoa, Florida and cemented coquina was obtained from Blackhawk Corporation, Palm Bay, Florida. The materials from both sources met the specifications from FDOT of the Standard Specifications for Road and Bridge

Construction (FDOT, 1996). Limerock met the requirements of Section 911 while cemented coquina met the requirements of Section 915.

2.2.2 Sample Preparation

To determine if the cullet has engineering properties suitable for highway applications, a series of tests were performed in accordance with the appropriate ASTM procedures. Waste glass, limerock and cemented coquina samples were sieved through a 3/4 inch (19 mm) mesh. Particles greater than 3/4 inch (19 mm) in diameter were discarded. The particle sizes greater than 3/4 inch (19 mm) represented less than 5% of the total weight in any of the materials used.

It was placed in three 10 gallon containers, one for each material. The second step was mixing the materials in different percentages by weight. Variations of 5 to 10 percent by weight were used. Table 2-1 shows the percentages of aggregate and glass used for the various tests conducted. More mixtures were used for the Specific Gravity, Moisture-Density and California Bearing Ratio-Limerock Bearing Ratio tests than for the other tests.

To ensure complete mixing, WG base mixtures were placed in a mixer and blended for approximately 8 minutes.

2.2.3 Grain Size Distributions

A sieve analysis was performed on each mixture prepared, following ASTM C 136-84a, "Standard Method for Sieve Analysis of Fine and Coarse Aggregates" (ASTM, 1987). The US standard sieves used were the 3/8", #4, #8, #16, #30, #50, and #100. The amount sieved was 2000 grams (4.4 lb) for each sample and a total of eleven samples were sieved.

For each sample, the grain size distribution was plotted and the coefficient D_{10} was calculated.

2.2.4 Specific Gravity

The procedures outlined by ASTM D 854 "Standard Test Method for Specific Gravity of Soils" and ASTM C127 "Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate," were followed. Test method D 854 was used for the fine material passing sieve #4 and test method C 127 was used for the coarse material retained on the 4.75-mm sieve. The specific gravity of WG from these tests were compared to the specific gravity values from Syed (1994) and Dames & Moore (1993).

2.2.5 Moisture-Density Relations

The procedure outlined by ASTM D 1557-78 "Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-lb. Rammer and 18-in. Drop" method C or method D was followed. Samples prepared using method C were made in the 6.0 inch diameter mold, having a capacity of 1/13.333 ft^3, and material passing a 3/4 inch sieve. Method D was used only when the amount of material retained on the 3/4 inch sieve was 10 percent or greater.

2.2.6 Constant Head Permeability Testing

Constant head permeability tests were conducted on the mixes of limerock-base and cemented coquina base. A relative compaction between 87% and 95% of maximum from modified proctor compaction testing (ASTM D-1557), was maintained throughout the twelve constant head permeability experiments to obtain consistent results. Triaxial test samples used a similar compaction method. The equipment used was a modified constant head permeameter (Figure 2-2), a graduated cylinder, rubber tubing and a stop watch.

Syed (1994) made some modifications to the original ASTM D 2434-74 procedure in order to obtain permeability measurements up to 10 cm/sec and to have more accurate head loss readings at different heights of the sample. The original permeameter was modified by increasing the inlet from 1/8 in (3.2 mm) to 1/4 in (6.4 mm), and the outlet from 3/16 in (4.8 mm) to 1/4 in (6.4 mm). The porous stones were replaced by a commercial window screen to assure free draining conditions. The next modification was to increase the height from 4 in (10.2 cm) to 12 in (30.5 cm). Four openings were added to the cylindrical permeameter mold where four pinchcocks were attached. Four piezometers consisting of a 1/8 in (3.2 mm) clear nylon tubing were mounted, each piezometer passed through the wall of the permeameter to the center of the mold. The last 1 in (2.54 cm) of the tubing was sliced in half to allow the water to enter the piezometer.

Water from the outflow was collected in the graduated cylinder during a period of 30 seconds, this procedure was repeated several times volume of water collected from the outflow during set time intervals remained constant. At this time, a final reading of the water flow through the sample was taken, the readings from the four piezometers were also taken.

2.2.7 California Bearing Ratio and Limerock Bearing Ratio Testing

The procedure outlined by the ASTM D 1883-87 "Standard Test Method for The California Bearing Ratio Test" was followed. California Bearing Ratio (CBR) tests were performed on test specimens at the optimum moisture content and at least 95 percent of the maximum density based on ASTM D 1557. Soaked and unsoaked samples were prepared for each material mix. Soaking required submerging the sample for 96 hours under a 10 lb. surcharge. The surcharge was used for both the soaked and unsoaked specimens. Penetration testing was accomplished in a compression machine using a strain rate of 0.05 in./min. while readings of load versus penetration were taken.

FM 5-515 or "Florida Method of Test for Limerock Bearing Ratio" gives the procedure for Limerock Bearing Ratio (LBR) testing. The LBR test procedure was similar to the CBR test procedure except for the size of the mold and spacer disc, and the bearing ratio calculation. The specimen volumes, however, are the same for LBR test and CBR tests. To determine the CBR and LBR values, a single test was conducted, however different calculations were conducted.

2.2.8 Consolidated Drained Triaxial Shear Testing

Because both limerock and cemented coquina are considered granular, and are being evaluated as possible base course when mixed with WG, consolidated drained (CD) triaxial tests were chosen to evaluate the frictional behavior. For a CD triaxial test the saturated soil specimen was subjected to a confining pressure (σ_3). The pore water pressure (u_c) remained at zero because the drainage connection was left open. The principal stress difference ($\Delta\sigma$) was then increased by applying axial load at a deflection rate of 0.005 in/min (0.0127 cm/sec). The drains open to allow complete dissipation of the pore water pressure. The total stress equals the effective stress in the CD test because the excess pore water pressure was kept at zero.

From the results of several experiments, Mohr circles were plotted. By drawing a common tangent to these circles internal friction angle (ϕ) values were obtained, assuming the cohesion was equal to zero.

A total of thirty-three CD triaxial experiments were performed. Fifteen for the glass mixed with cemented coquina and fifteen for the glass mixed with limerock and three for the 100 percent glass samples. Three CD tests were performed on each mixture at confining pressures of 5 psi, 10 psi, and 15 psi to allow for accurate determination of the Mohr-Coulomb envelope.

During all experiments two rubber membranes were used to help ensure that the sharp edges of the glass would not perforate the rubber membrane. Samples were compacted in approximately ten equal layers, with a compaction rod. The number of blows per layer were increased linearly for each succeeding layer to develop a uniform density throughout the specimen (Bishop, 1961). The weight of material used to prepare the sample was determined after compaction.

Once the sample was prepared, the rigid mold around the sample was removed, and sample dimensions were measured with a vernier caliper. Top, bottom, and middle height diameters were measured to the nearest 0.01 in., as well as the height of the specimen. Sample diameter dimensions were corrected for the thickness of the two membranes.

Sample saturation was conducted following procedures recommended by Bishop and Henkel (1974). Load-displacement readings were taken in increments of 0.005 in (0.127 mm) of the loading rate dial reading. Readings were taken until the specimen failed or until the strain reached about 5%. After 5% strain, the stress stayed constant.

2.2.8.1 Elastic moduli

The elastic modulus, defined as the vertical stress divided by the vertical strain, was determined from the stress versus strain curve. The elastic modulus was calculated using both the initial tangent modulus and the secant modulus at 2% strain. The secant modulus was calculated at 2% strain because many of the stress versus strain plots were constant up to this point.

2.2.8.2 Resilient moduli

The resilient modulus was determined from triaxial data for the cemented coquina glass mixtures. The values of the resilient modulus were obtained by unloading and reloading the specimens. Specimens were unloaded at three different displacements: 0.050 in (1.27 mm), 0.100 in (2.54 mm), and 0.150 in (3.81 mm), then reloaded at the three corresponding displacements of: 0.047 in (1.19 mm), 0.097 in (2.46 mm), and 0.147 in (3.73 mm). These three values where chosen because all three fell within the elastic portion of the stress-strain curve. The approximate strain levels at which the three unloading-reloading loops occurred were selected as 0.9%, 1.8%, and 2.7% respectively.

3. ENVIRONMENTAL PROPERTIES OF WASTE GLASS

3.1 Natural Assimilation Procedure

In the Natural Assimilation study (NAS), the removal of leachate from the reactor after rainfall events is a removal mechanism in addition to the following removal methods. In the Accelerated Cleaning study (ACS) leachate is not removed, but recirculated. Only the following mechanisms can cause a decrease in contaminant levels in the ACS.

3.1.1 Carbon

The primary removal mechanisms for carbon are biological oxidation and cellular synthesis. Biological oxidation is a natural process by which organic cells are broken down using oxygen as an electronic acceptor, producing CO_2 and other end products with a release of energy. CO_2 is a gas which leaves the reactor, reducing the organic concentration. Synthesis is the incorporation of organic carbon into bacterial cell mass. Equation 3.1 presents both oxidation and synthesis.

(Equation 3.1)

$$COHNS + O_2 + nutrients \xrightarrow{bacteria} CO_2 + NH_3 + C_5H_7NO_2 + other.end.products$$

In this equation COHNS represents the elements released in the leachate by the food and beverage residue on the glass. $C_5H_7NO_2$ represents an average al composition of new bacteria.

Endogenous Respiration is an oxidative process where existing bacteria cells are utilized by other bacteria as a food source resulting in the formation of CO_2 and the release of energy. Equation 3.2 presents Endogenous Respiration reaction.

(Equation 3.2)

$$C_5H_7NO_2 + 5O_2 \xrightarrow{bacteria} 5CO_2 + 2H_2O + NH_3 + energy$$

All of these processes will ultimately result in a reduction of BOD_5 concentration in the WG leachate due to the release of CO_2 or the incorporation of carbon into insoluble cell mass (biological sludge).

3.1.2 Nitrogen

Three processes which can cause a decrease in Nitrogen levels are synthesis, Ammonia stripping and nitrification/denitrification. The synthesis process generates new bacterial cell mass($C_5H_7NO_2$), as presented in Equation 1. Nitrogen is incorporated into new cell mass at a rate of $\frac{14}{5*12}$ the carbon removal rate.

Ammonia is produced during endogenous respiration, oxidation and synthesis (See Equations 3.1 & 3.2). In water, Ammonia will either be in the dissolved gas form (NH_3) or the ionic form (NH_4^+) (See Equation 3.3). At a neutral pH the primary form is NH_4^+, but there will still exist a small fraction of NH_3 (See Equation 3.4). The atmosphere contains almost no NH_3, therefore, according to Henry's Law, the NH_3 in the water phase will try to reach equilibrium with the NH_3 concentration in the gas phase. Since the gas phase is exposed to the atmosphere, the released Ammonia will disperse resulting in the continuous conversion of NH_4^+ to NH_3 in the liquid phase and the release of NH_3

to the gas phase. This will result in a decrease in the Ammonia concentration in the leachate.

(Equation 3.3)

$$NH_4^+ \Leftrightarrow NH_3 + H^+$$

(Equation 3.4)

$$K_a = \frac{[NH_3][H^+]}{[NH_4^+]}$$

Nitrification is the first step in the removal of nitrogen by the nitrification-denitrification process. Two bacteria genera are responsible for nitrification, *Nitrosomonas* and *Nitrobacter*. *Nitrosomonas* oxidizes ammonia to the intermediate product nitrite. Nitrite is converted to nitrate by *Nitrobacter*. Equations 3.5 & 3.6 describe the Nitrification process.

(Equation 3.5)

$$55NH_4^+ + 76O_2 + 109HCO_3^- \longrightarrow C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3$$

(Equation 3.6)

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \longrightarrow C_5H_7O_2N + 3H_2O + 400NO_3^-$$

Denitrification is the second step in the removal of nitrogen by the nitrification-denitrification process. The denitrification process consists of the removal of nitrogen in the form of nitrate, by conversion to nitrogen gas under anoxic (without oxygen) conditions. Conversion of nitrate-nitrogen to a readily removable form can be accomplished by several genera of heterotroph bacteria capable of dissimilatory nitrate reduction, a two-step process. The first step is the conversion of nitrate to nitrite. This stage is followed by production of nitric oxide, nitrous oxide, and nitrogen gas. Equation 3.7 describes nitrate reduction during this process.

(Equation 3.7)

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$$

3.1.3 Phosphorous

The synthesis process shown in equation 3.1 represents the only removal mechanism for phosphorous. It is not evident in equation 3.1, but in the formation of new cell mass, phosphorous is incorporated a rate of 1/5 the rate of nitrogen. The new cell mass containing the removed phosphorous may accumulate as a sludge in the bottom of the reactor or as a biological film of the surface of the glass particles.

3.2 Experimental Results

The results of the NAS are presented in Figure 3.1 and Tables 3-1, 3-2 and 3-3. The ACS results are presented in Figure 3.2 and Tables 3-4, 3-5 and 3-6.

3.3 NAS Results

Reactor experiments for the NAS were conducted simultaneously on three reactors during March 19, 1996 to July 2, 1996. Leachate was extracted after each rainfall, with 12 extractions occurring during the experimental period. The volume of leachate from each reactor was measured and samples for contaminant concentrations were collected. When a BOD_5 concentration of 10 mg/l was reached, the reactor experiments were stopped.

In addition to leachate measurements, shake extraction experiments were performed on the initiated WG from the three reactors and the final WG after the experiment was stopped. Initial WG samples for shake extraction was randomly sampled from each reactor and mixed together soon after the WG was loaded. This method of sample collection and analysis was used because WG loaded into each reactor was obtained from the same source and considered to have the same properties or characteristics. WG samples obtained after experiments were stopped were collected and analyzed separately from each reactor.

The total mass leached fro the WG is the sum of the products of the concentration of contaminant in the leachate and the volume of leachate extracted after each rainfall event. The relationship of production of leachate, the leachate concentration, and the resultant cumulative contaminant mass extracted from the WG are presented for each contaminant (Figures 3.3 to 3.11).

3.3.1 Removal of BOD

3.3.1.1 BOD_5 reduction in reactor experiments

In Figure 3.1, the decreasing curves in BOD_5 concentration obtained during the NAS for the three reactors are shown. Tables 3.1 through 3.3 provide the results for each leachate sample, including the concentrations of BOD_5, TKN. and phosphate found in the leachate; the ratios between BOD_5 and TKN, and BOD_5, TKN, and phosphate; and the volume of the leachate extracted from each reactor. As can be observed from the figure and tables, the initial concentration of BOD_5 (on day 10 or 3/29/96) in Reactor 1 was 838.3 mg/l. The concentration decreased to 4.46 mg/l at day 105. For Reactor 2, the initial concentration of BOD_5 was 506.0 mg/l, and the concentration finally decreased to 3.90 mg/l For Reactor 3, the initial concentration of BOD_5 was 531.0 mg/l and the concentration decreased to 4.8 mg/l. The target value of 10 mg/l was reached by day 105 for all three experiments. Although the WG loaded into the reactors on the same day were considered as having the same properties and characteristics, their initial concentrations varied.

3.3.1.2 BOD_5 results from the shake extraction experiments

Table 3.7 presents the shake extraction experiment results for BOD_5. As observed in this table, the average initial BOD_5 of 547 mg/l, is reduced to 20.0 mg/l, representing a 96% reduction resulting from the reactor experiments. These results illustrate that the shake extraction procedures using a one to one volume ratio compares well with actual values and is a useful tool for assessing leachate concentration from WG in storage applications. The final BOD_5 indicated that the post-treat WG was not clean in terms of the BOD_5 target value of 10 mg/l, eventhough the target value was reached in the reactor experiments. One possible reason that the final BOD_5 did not reach the target value is thought to be because the BOD_5 concentration was increased by the removal of the bacterial slime layer attached to the waste glass and sludge trapped in the void spaces, but not present in the leachate from the reactors.

3.3.2 Removal of Nitrogen

3.3.2.1 TKN reduction in reactor experiments

Figure 3.1 presents the decreasing curves in TKN for the three reactors. Tables 3.1 through 3.3 provide the reactor experiment results, including concentrations of TKN and the volumes of the leachate extracted from the reactors at every leachate extraction procedure. The initial concentration (at day 10 or 3/29/96) in Reactor 1 was 615.0 mg/l and progressively decreased to 4.09 mg/l at day 105. In Reactor 2, the initial concentration was 543.0 mg/l and progressively decreased to 4.63 mg/l. The initial concentration in Reactor 3 was 446.0 mg/l and progressively decreased to 4.90 mg/l. WG loaded into the reactors at the same day were considered as having the same properties and characteristics, but their initial concentrations varied. The variation was not in the same order as variations in the BOD_5 data, but the amount of variation was similar.

3.3.2.2 TKN results from the shake extraction experiments

Table 3.8 presents the shake extraction experiment results for TKN. As observed in this figure, the average initial TKN, 471 mg/l, was reduced to 6.80 mg/l, the average final TKN, which represents a 98.6% reduction resulting from treatment (storage experiments). The shake extraction procedure proved to be useful at estimating the reactor leachate concentrations.

The average initial and final TKN concentration (534.7 and 4.54 mg/l) from the reactor experiments (Tables 3.1 through 3.3) and initial and average final TKN concentration from the shake extraction experiment were 471 and 6.8 mg/l.

3.3.3 Removal of Phosphorus

Phosphate concentration presented in this study was soluble and insoluble orthophosphate reported as phosphorus. Total phosphorus was not measured.

3.3.3.1 Phosphate reduction in reactor experiments

Figure 3.1 presents the decreasing curves for phosphate in the three reactors. Tables 3.1 through 3.3 provide the reactor experiment results, including the concentrations of phosphate, the BOD_5 to TKN to phosphate ration, and the volume of the leachate extracted from the reactors for every leachate extraction procedure. The initial concentration (at day 10 or 3/29/96) in Reactor 1 is 10.2 mg/l and progressively decreased to 1.8 mg/l at day 105. In Reactor 2 the initial concentration was 7.5 mg/l and progressively decreased to 2.0 mg/l. The initial concentration in Reactor 3 was 11.0 mg/l and progressively decreased to 1.2 mg/l.

3.3.3.2 Phosphate results from the shake extraction experiments

Table 3.9 provides the shake extraction experiment results for phosphate. As observed in this figure the average initial phosphate concentration of 5.49 mg/l was reduced to an average final concentration of 2.85 mg/l. The reduction ratio resulting from the treatment (reactor experiment) was just 47.2%. The shake extraction procedure did not provide as useful an estimate of the phosphorus concentration as it did BOD_5 and TKN.

3.4 ACS Results

In order to allow the contaminants adequate time to dissolve from the glass surfaces, the first sampling time was at the end of the first 8 hour washing cycle. Based on the results from this experiment, significant changes could have occurred during the 8-hour washing ; therefore, initial concentrations measured in reactor experiments #2 and 3 at 30 minutes after washing was started.

WG used in measured reactor experiments were from three different processing days and do not represent a triplicate experiment. They do not represent variations which would be expected to occur for different processing days. Initially, each batch of WG used in the ACS was contaminated at different degrees because the contaminated level of WG is subject to the amount of food residue remaining in bottles or containers discarded by consumers. Rain falling on the bottles or containers at curbside, at the material recovery facility (MRF), or during the transportation and storage conditions at MRF such as length of time, temperature, and/or ventilation would affect contaminant concentrations in

WG leachate. In the case of the Batch #3 WG, it is thought that this WG was washed by rain at curbside during the collection, at MRF during the storage period, and/or during transportation from MRF to the Florida Tech experiment site. According to the weather reports in Florida Today, there were several large rainfall events in West Palm Beach where the WG used in this study originally came from. On the delivery day, the truck carrying the WG was rained on during the trip to the experiment site, according to the truck driver. WG leachate was leaking out of the truck bed when it arrived at the test site.

Every post-treat WG used for shake extraction experiments was collected randomly from the whole reactor after the BOD_5 concentration in the leachate dropped to 10 mg/l. Sludge was observed in the bottom two inches of the reactor. This sludge was quite black and foul smelling. It was most likely composed of food residue, dead and live microorganisms, and inorganic and organic compounds. Every WG sample used for shake extraction experiments contained this sludge to varying degrees.

The contaminants analyzed for reactor experiments and shake extraction experiments in the ACS include BOD_5, TKN, phosphate and TP.

3.4.1 Removal of BOD_5

3.4.1.1 BOD_5 data from reactor experiments

BOD_5 data of wastewater recirculation through the ACS are presented in Tables 3.4 through 3.6. Figure 3.2 presents BOD_5 decreasing curves for reactor experiments #1, 2 and 3 as time elapses. Achieving 10 mg/l of BOD_5 was the target value for this study. In Figure 3.2a, BOD_5 values in experiment 1 are initially high and decreased to 7.6 mg/l in 9 days. In this experiment, the initial BOD_5 (at time zero) was not measured, although it has been mathematically predicted. Average ambient temperature during the experimental period of experiment #1 was 27.1°C. Reactor experiment #1 was conducted during the warmest period of the three experiments. Figure 3.2b presents BOD_5 decreasing curve for the experiment #2. Their initial BOD_5 is 707 mg/l, and the target value was achieved at day 12. Figure 3.2c presents the BOD_5 data for experiment #3. The initial BOD_5 was 85 mg/l (at time zero) and remained close to that level until day 6, after which it decreased to the target level. Experiment #3 took 13 days. This represents the longest required time period to achieve the target value in spite of the lowest initial BOD_5 concentration (85 mg/l). This may have been due to the low ambient temperature causing decreased bacterial activities. The average ambient temperature during reactor experiment #3 was 15.5°C. During the first to third days the temperature dropped below 7°C. The low level of food initially available did not allow for a rapid increase in the microbial population. The combination of highly variable, low initial temperatures and the lack of food availability would explain the delay in microbial activity.

3.4.1.2 BOD data from shake extraction

Shake extraction experiment results for BOD_5 through the ACS are presented in Table 3.10. The initial BOD_5 value of Batch #2 is 277 mg/l and the final is 58.0 mg/l after treatment. For the Batch #3 WG, the initial BOD_5 value is 104.3 mg/l and the final is 78.2 mg/l. In comparison to the initial BOD_5 values (at day zero) obtained from the reactor experiment (Table 3.5), the initial BOD_5 concentrations fro the shake extraction experiment for Batch #2 WG is much lower than that from reactor experiment #2 (277 versus 707 mg/l). The initial BOD_5 obtained from shake extraction experiment of Batch #3 WG is slightly larger than that from reactor experiment #3 (104.3 versus 85 mg/l) (Table 3.6). For all field studies, the shake extraction results performed well estimating the initial BOD_5 results, except for Batch #2 of the ACS. The final BOD_5 values obtained for the shake extraction experiments are 19.4 mg/l for Batch #1, 58.0 mg/l for Batch #2, and 78.2 mg/l for Batch #3. These are higher than the values obtained from the actual leachate from the reactors which were 4.37, 8.74 and 8.2 mg/l for reactor experiments #1, 2 and 3 respectively. The reason for high final BOD_5 values for the shake extraction experiments are thought to be the presence of a sludge or microbial slime on the glass surfaced and trapped within the void spaces.

3.4.1.3 Estimate of clean-up time at various temperatures with modified BOD_5 constants

The time required to clean-up a sample from 1000 mg/l to 10 mg/l of BOD_5 was estimated. 1000 mg/l was chosen since it is a value higher than any measured for this study and should represent a worst case situation. Equation 3.8 is used to predict the clean-up time:

(Equation 3.8)

$$(BOD_5)_t = (BOD_5)_0 * e^{-kt}$$

where

$(BOD_5)_0$ = initial BOD , 1000 mg/l

$(BOD_5)_t$ = BOD at any time t, mg/l

t = time elapsed, days

k = BOD constant which varies with temperature, 1/day

BOD_5 rate constants at 15, 20, 25 and 30°C were estimated using equation 9 and the data obtained from the three experiments.

(Equation 3.9)

$$k_T = k_{std} * \theta^{(T-T_{std})}$$

where

k_T = expected BOD_5 constant at a temperature T, 1/day

k_{std} = standard BOD_5 constant, 1/day

T = ambient temperature, 15, 20, 25, 30°C

T_{std} = standard averaged ambient temperature

θ = temperature coefficient

Using the data from the experiments θ was found to be 1.292, and k_{std} was 0.346 for a temperature of 20.7°C (Table 3.11). The BOD_5 rate constants would be 0.08/day, 0.289/day and 1.041/day at temperatures of 15, 20 and 25°C, respectively (See Table 3.11). The time to reach 10 mg/l would be 58 days, 16 days and 5 days respectively for the different rate constants.

3.4.2 Removal of Nitrogen

3.4.2.1 TKN data from reactor experiments

TKN data obtained from the reactor experiments in the ACS are presented in Tables 3.4 through 3.6. The TKN concentrations versus time are shown in Figure 3.2. TKN analyses were performed everyday on leachate samples during the experiment periods. It is observed in Table 3.4 that the TKN concentration at time 7 hours in reactor experiment #1 was 57.7 mg/l and decreased to 14.5 mg/l at day 13. The TKN data in this experiment did not fall below 10 mg/l during the test period unlike other two experiments. A possible reason for this is that in the denitrification process there was a low availability of carbon relative to nitrogen in the leachate. As presented in Table 3.4 BOD to TKN ratios for experiment #1 during the last seven days remained below 1, which is lower to those for other experiments (Tables 3.5 and 3.6). As Figure 3.2b shows the initial TKN concentration in reactor experiment #2 is 152.0 mg/l and decreased to 7.9 mg/l at day 13. In Figure 3.2c, it is observed that the initial TKN concentration in reactor experiment #3 was 26.0 mg/l and decreased to 5.7 mg/l at day 13.

3.4.2.2 TKN data from shake extraction experiments

Shake extraction experiment results for TKN obtained through the ACS are presented in Table 3.12. Shake extraction experiments were performed for every pre-treat WG and every post-treat WG (initial TKN) except for the pre-treat WG and every post-treat WG (initial TKN) except for the pre-treat WG (final TKN) of Batch #1 WG. WG treated in reactor experiment #1, 2 and 3 are called Batch #1, 2 and 3, respectively. As seen in this table the final TKN of Batch #1 WG was 8.23 mg/l. It is observed in the table that the initial and final TKN of Batch #2 WG was 39.0 mg/l and 17.0 mg/l respectively. Similarly, the initial TKN of Batch #3 WG was 20.9 mg/l and the final TKN was 18.2 mg/l. The initial TKN values for Batch #2 and 3 WG obtained from the shake extraction experiments are less concentrated in comparison with the initial TKN concentrations obtained from reactor experiments (Table 3.12). Thus, TKN values obtained from the reactor experiments should be more concentrated than those from the sake extraction experiments specially in the initial stage.

3.4.3 Removal of Phosphorus

3.4.3.1 Phosphate and TP data from reactor experiments

Phosphate and TP data obtained through the ACS are presented in Tables 3.4 through 3.6. The decrease in concentration of phosphate and TP as time passed is shown in Figure 3.2. Phosphate concentrations were analyzed daily on leachate samples during the experiment periods except for the data at day 0 in reactor experiment #1. It is thought that phosphate concentrations obtained in experiment #1 were higher due to colloidal solids present in the leachate samples. As observed in Figure 3.2a, there seems to be no decrease during days 1 to 13. The procedure applied in sample preparation for analyzing phosphate concentrations in WG leachates obtained from reactor experiments #2 and 3 was changed from that used in reactor experiment #1. Phosphate concentration obtained from the experiment #2 was initially 4.20 mg/l and decreased to 0.03 mg/l during the experimental period. As observed in Figure 3.2c, the initial phosphate concentration obtained from the experiment #3 was 0.21 mg/l and decreased to 0.03 mg/l during the experimental period.

TP concentrations were analyzed everyday on leachate samples obtained from the experiments #2 and 3 during the experimental periods. The initial TP concentration obtained through the experiment #2 was 12.47 mg/l and decreased to 0.17 mg/l during the experimental period as presented in Figure 3.2b. The peak at day 6 in the same figure may be an analytical error. Figure 3.2c shows that the initial TP concentration obtained from experiment #3 was 2.90 mg/l and decreased to 0.39 mg/l during the experimental period. The measured reduction in total phosphorus could only be accomplished by incorporation into new bacterial cell mass. When these cells are attached to the sludge surface or trapped in the void spaces as a sludge, the concentrations measured in the leachate will decrease.

3.4.3.2 Phosphate and TP data from shake extraction

Shake extraction experiment results for phosphate obtained through the ACS are presented in Table 3.13. Shake extraction experiments were performed for every pre-trea WG (initial phosphate) and every post-treat WG (final phosphate) except for the pre-treat WG of Batch #1. WG to be treated in reactor experiments #1, 2 and 3 are called Batch #1, 2 and 3, respectively. As seen in Table 3.13, the final phosphate of Batch 3

WG was 2.45 mg/l. It is observed in the table that the initial and final phosphate of Batch #2 WG were 2.71 and 2.41 mg/l, respectively. There is slight concentration reduction in Batch #2 WG leachate. Similarly, the initial and final phosphate concentrations obtained from Batch #3 WG were 1.13 and 1.50 mg/l. For Batch #3 WG, the final was slightly more concentrated than the initial.

Shake extraction experiment results for TP obtained through the ACS are presented in Table 3.14. Shake extraction experiments for TP were performed for pre-treat and post-treat WG in Batches #2 and 3. As this table shows, the initial and final TP in Batch #2 WG were 4.11 and 4.35 mg/l respectively. Similarly, the initial and final TP in Batch #3 WG were 1.13 and 1.17 mg/l respectively. In both batches, the initial and final concentrations were very close. This should be expected since no removal mechanism exists.

4. ENGINEERING PROPERTIES OF WASTE GLASS COMBINED WITH TYPICAL FLORIDA BASE COURSE SOILS

4.1 Grain Size Results

Experiments were performed using mixtures of particles smaller than 3/4 in (19 mm) mainly for safety reasons. The largest WG particle size was 3/8 in (9.5 mm) and it was easily handled. The average grain size distribution results obtained from several sieve analyses performed on the WG mixed with cemented coquina and limerock in different percentages by weight, are reported in Figures 4.1 and 4.2. All the results were within ±2% of the desired distribution. For example, if the percentages were to be obtained by adding 80% WG and 20% cemented coquina, the resulting curve was within ±2% from the desired values. Sieve analyses performed before and after CD Triaxial shear tests varied less than ±1%. This variation indicates little or no particle degradation during testing.

The AASHTO Soils Classification System was used in describing the materials. The WPBMRF glass was classified as A-1-a. The cemented coquina and limerock was also classified as A-1-a, therefore all the mixtures between WG and cemented coquina were classified as A-1-a.

4.2 Specific Gravity Results

The average specific gravity values for WG, cemented coquina, and limerock are shown in Table 4-1.

The specific gravity of waste glass was about 10 percent lower than the specific gravities of the standard base materials. The value for WPBMRF glass reported by Clean Washington Center (CWC, 1994) was 2.5 for fine cullet.

4.3 Moisture-Density Results

The moisture-density relation of WG mixed with limerock and cemented coquina are shown in Appendix A.

4.3.1 Optimum Moisture Content

All of the optimum moisture content results are summarized in Table 4-2. The optimum moisture content of both 100 percent limerock and 100 percent cemented coquina were about 8 percent, and the results of 100 percent glass was about 4 percent. For all mixtures of glass and aggregate, the optimum moisture contents were between 7 and 9 percent with the exception of 90 percent glass with both materials. The optimum moisture content for these cases was approximately 5 to 6 percent.

4.3.2 Maximum dry density

The maximum dry density results of all materials are summarized in Table 4-2. The maximum dry density versus glass content for all cemented coquina-glass and limerock-glass mixtures are plotted in Figures 4-3 and 4-4. The values of both 100 percent limerock and 100 percent cemented coquina were 129 pcf.(20.2 KN/m^3) and this value decreased to a minimum of 110 pcf. (17.3 KN/m^3) for 100 percent glass. For glass-cemented coquina blends, the values become almost stable at 128-129 pcf (20.1-20.2 KN/m^3) from 0 to 70 percent of glass, and decrease to the lowest at 100 percent glass. For glass-limerock blends, the maximum dry densities range from 116 to 130 pcf (18.2 to 20.4 KN/m^3) and the values become almost stable at 129-130 pcf (20.2-20.4 KN/m^3) from 0 to 50 percent glass. After that the values curve downward until 100 percent glass.

The maximum dry density of 100 percent WPBMRF glass was 111 pcf (17.4 KN/m^3) (Syed 1994). The maximum dry density in the CWC research ranged from 90.9 to 109.3 pcf (14.3 to 17.2 KN/m^3). for 100 percent cullet glass, from 132.3 to 133.2 pcf (20.8 to 20.9 KN/m^3) for 15 percent of cullet content, and from 120.3 to 125.2 pcf (18.9 to 19.6 KN/m^3) for 50 percent of cullet content when the cullet was mixed with crushed rock and a gravely sand (Dames & Moore, 1994). The maximum dry density values of glass mixtures did not decrease until the glass content reached 70 percent for cemented coquina and 50 percent for limerock.

4.4 Permeability Results

The coefficient of permeability (k) results are summarized in Table 4-3. Figure 4-5 is a plot of permeability versus percent glass. Values range from 0.12 cm/sec when testing 100% limerock, to 0.85 cm/sec when testing mixes of 80% glass-20% cemented coquina. Syed (1994) reported k values for 100% glass between 0.3 cm/sec and 5 cm/sec depending upon the density, effective grain size, and uniformity coefficient. The density throughout the permeability testing was kept between 87% and 95% of maximum modified proctor compaction of ASTM D-1557. In this research larger k-values were obtained as the percentage of glass increased.

Permeability values reported by the CWC (1994) varied from 0.014 cm/sec when testing 100% gravely sand to 0.23 cm/sec when testing 100% glass. In Figure 4-5 it can be noted that the coefficient of permeability increased slightly with increasing cullet content.

A discrepancy exists between the permeabilities obtained from Syed's (1994) permeameter and the values reported by Ho (1994), of 10^{-5} cm/sec for 100% cemented coquina and 100% limerock. This discrepancy may be due to either the piezometers allowing a drainage path or to lower densities of samples in the modified permeameter. The modified permeameter developed by Syed (1994) worked very well for coarse grain materials. A disadvantage of using the modified permeameter was that high compaction densities were difficult to achieve because the mold is made of a plastic material which vibrates and may deform while under pressure.

4.5 CBR and LBR Test Results

CBR and LBR values are functions of dry density. In order to determine variations of these bearing ratios with density, cemented coquina, limerock, and cullet glass mixes were compacted using 10, 25 and 56 blows per layer in five layers at the optimum moisture content. Bearing ratio tests were conducted on these samples after soaking, and a plot of dry density versus soaked CBR values was developed (Figure 4-6). Figure 4-6 shows that a 1 pcf decrease of the dry density of cemented coquina and limerock caused about 10 percent decrease in CBR values. WPBMRF glass CBR values showed less sensitivity to density changes.

No specimen expansion occurred during the 4-day soaking period. All CBR values were based on the stress at 0.2 inch piston penetration (Appendix B) because the CBR values at 0.1 inch penetration were always lower than the CBR values at 0.2 inch penetration. The LBR values were always based on the stress at 0.1 inch penetration according to FM

5-515. The CBR and LBR values were slightly different in soaked and unsoaked conditions. A correlation was developed by plotting CBR versus LBR (Figure 4-7). The correlation coefficients were nearly 1.00 for both sets of data. This relationship indicated that glass-limerock and glass-cemented coquina mixes have LBR values very similar to CBR values. Therefore, FDOT can confidently use the LBR test on glass base course mixes.

The CBR and LBR values of cemented coquina and limerock combined with waste glass in different percentages for soaked and unsoaked conditions are shown in the Figure 4.8 and 4.9, respectively. Based on the FDOT aggregate base specifications, soil mixtures were compacted to a maximum of about 98% relative compaction based on ASTM D1557 methods. For cemented coquina and glass blends, CBR and LBR values remained well over 100 from 0 to 20 percent glass, and then varied between 70 and 115 from 30 to 80 percent glass. Between 80 and 100 percent glass the bearing ratios decreased to a minimum of about 30 (Figure 4.8).

The CBR and LBR values for limerock and cullet glass blends had larger variations than the glass-coquina mixes for the 10 to 30 percent range. These variations resulted in several unsoaked bearing ratios below 100. Excluding these points, the bearing ratios from 0 to 40 percent exceeded 100, while the ratio from 50 to 60 were above a bearing ratio of 40. The values from 70 to 100 percent decreased from 35 to about 25 (Figure 4.9). FDOT specifications (Sections 911-6 and 915-3) state that Limerock and Cemented Coquina is acceptable as a base material if the LBR exceeds 100. Similarly Section 160-6 indicates that all material with LBR-values in excess of 40 are acceptable subbases. Both, Figures 4.8 and 4.9, have these specified cut-offs labeled, showing when the mixes would be acceptable base or subbase materials.

Typically unsoaked specimens have higher CBR values than soaked specimens, because drier specimens exhibit higher and more brittle failures than specimens nearing saturation. For this reason, the CBR of soaked specimens are the design value used for pavement design. In cemented coquina-glass mixes, most specimens had unsoaked CBR values higher or almost equal to the values under soaked conditions. Most of the soaked CBR values were higher than the unsoaked in the limerock-glass material. A possible explanation for the non-typical unsoaked and soaked values for the cemented coquina mixtures was that the cementing action would have occurred during soaking but not for the unsoaked specimens. This action increased the strength for the soaked specimens as is seen in Figure 4.8

4.6 Triaxial Test Results

The CD Triaxial shear test results are summarized in Table 4-4. Assuming zero cohesion, only friction angles are reported for each mixture. The relative compaction obtained for every test reported was at least 90% of maximum based on ASTM D-1557. The graphs showing the Mohr circle diagram are presented in Appendix C.

4.6.1 Angle of Internal Friction

The friction angles obtained ranged from 39° when testing 100% glass to 44° when testing 100% limerock base; the angle obtained when testing 100% cemented coquina was 41°. The values reported for 100% limerock base and 100% cemented coquina are very close to the ones reported by FDOT (1994) which were about 44° for both limerock base and cemented coquina.

Angle of internal friction values were plotted against the percentage of glass in Figure 4-10. From this figure it can be noted that the friction angle only reduces by 3° when glass was added to the base materials at different percentages.

CWC (1994) reported friction angles between 42° and 46° when performing CD Triaxial shear test on mixes of glass and aggregate, and between 50° and 53° when performing direct shear test. The small variation in the friction angle when performing CD Triaxial shear test is probably due to the different base material used in mixtures.

Cosentino (1994) reported angles of friction for waste glass between 42° and 44° when performing CD Triaxial shear test. These values increased to 45° when performing direct shear tests. Values reported by Das (1994) show an angle of friction between 40° and 45° for dense angular sands. Figure 4-10 indicates that the addition of glass does not significantly affect the frictional characteristics of cemented coquina or limerock.

For several reasons, the cohesion value was reported as zero for all types of mixtures. First, the friction angles calculated assuming zero cohesion (Table 4.4) are very high. Second, the actual Mohr envelope is slightly curved in a concave downward shape, and a straight line approximation is often used. Therefore, the straight line envelope was drawn through zero. CWC (1994) reported a cohesion value of zero when testing 100% glass as well as when testing 100% crushed rock. Cohesion values of the Florida base materials tested are usually less than 9 psi (62 kPa) as reported by FDOT (1994). By adding a small percent (i.e. 20%) of glass to the base materials the cohesion value quickly drops to a value close to zero. Since the cohesion values in the mixes were generally less than 1 psi (6.9 kPa) in most cases, the plots were drawn approximating the cohesion to a zero value. Therefore, it was concluded that the cohesion can be neglected for the glass/base course mixes.

4.6.2 Elastic Modulus Results

Elastic moduli from CD tests are reported in Table 4-5, calculated using the initial tangent method. These values as well as the elastic modulus values at 2% strain were plotted versus the percent cullet in cemented coquina and limerock base in Figures 4-11 to 4-14, respectively. From these figures, it was determined that the 2% strain elastic modulus does not vary significantly with percent glass but it is difficult to determine a clear trend from the initial elastic modulus because it does not maintain constant values. Initial elastic moduli vary from 500 psi (3448 kPa) to 8000 psi (55160 kPa) for cemented coquina, and from 2000 psi (13790 kPa) to 8000 psi (55160 kPa) for limerock base.

4.6.3 Resilient Modulus Results

The resilient moduli results are summarized in Table 4-6. The resilient modulus was calculated only from CD tests performed on cemented coquina mixes. The unload-reload procedure was performed at 0.9%, 1.8%, and 2.7% axial strains. At each of these strain levels an unload-reload loop was conducted over 0.05% resilient strain. Table 4-6 also shows the three deviator stress levels at which resilient moduli were found, along with the values for the stress invariant (q). The stress invariant for the triaxial test is calculated by adding the principal stress difference (Δs) plus three times the confining pressure (σc). The values of the resilient modulus at 5 psi (34.47 kPa), 10 psi (68.95 kPa), and 15 psi (103.43 kPa), versus the percent of cullet content in the cemented coquina are shown in Figures 4-15, 4-16, and 4-17. The resilient moduli in each figure corresponds to the percent strain at which the unloading-reloading procedure was performed. In Figure 4-18 the average values of the resilient modulus obtained from the three different strain levels at which the unload-reload loops were conducted are plotted versus the percent of waste glass content. Values obtained for the resilient modulus vary from 14 ksi (96.5 MPa) to 28 ksi (193 MPa), which are excellent values for structural design purposes. Resilient moduli reported by AASHTO (1986) in the "Guide for Design of Pavement Structures" indicate that poor roadbed values for resilient modulus are less than 3.7 ksi (25.5 MPa), while very good values are about 9.5 ksi (65.5 MPa). Resilient moduli reported from CWC (1994), ranged from 19.8 ksi (136.5 MPa) when testing 100% glass to 40 ksi (275.8 MPa) when testing 100% crushed rock.

Two additional graphs of the resilient modulus were plotted. One of log Mr versus the stress invariant and the other of Mr versus the deviator stress, Figures 4-19 and 4-20, respectively. These type plots are often used to develop relationships between stress and resilient modulus for pavement designs. In both of the figures the resilient modulus obtained from the three different percent strains were combined to compare the results. In Figure 4.19 semi-log plot yielded the equation $Mr = K_1\theta^{K_2}$, where $K_1 = 1.319$ and $K_2 = 0.726$.

This equation represents the resilient modulus at any percentage of mixture between waste glass and the cemented coquina. Both graphs indicate that the amount of glass in the mixture changes the resilient modulus by a maximum of 5 ksi (34.5 MPa), having a peak value of 20.3 ksi (140 MPa) at 0.9% strain with 40% of glass in the mixture. The arithmetic plot of Mr versus deviator stress yielded a linear equation of $Mr = 9.28 + 0.67\sigma_d$.

4.7 Predicted Layer Coefficient

The layer coefficient is an empirical value used to determine the layer thickness in several pavement design procedures. Van Til, et al., (1972) developed correlations between resilient moduli and layer coefficients. The coefficients used by FDOT (1994) in their design process are of 0.18 for both cemented coquina and limerock base. Layer coefficient values were estimated only for the cemented coquina, because no resilient modulus was obtained for limerock. Based on the range of average resilient moduli (Table 4.6) the layer coefficient obtained in this research ranged from 0.06 to 0.14. The values obtained in this research are lower than the ones reported by FDOT (1994), because the relative compaction in this research varied from 90% to 95% while FDOT used 95% to 98%. It was also found that layer coefficient decreased with the increase of glass percent as did the resilient modulus.

5. WG FIELD DEMONSTRATION

5.1 Description

A WG road construction project took place on Dalhart Road in Palm Bay, Florida, on January 22, 1997. The project was organized by Florida Tech in coordination with the City of Palm Bay highway department and consisted of a 300 ft road section modified with WG (15% by volume) and reclaimed subgrade as subgrade materials. Reclaimed material is a mixture of *in situ* soils mixed with the base and asphalt on-site mixed with a reclaimer to create the subgrade. Cone penetrometer, pressuremeter, *in situ* densities and field CBR tests were performed.

5.2 Construction Procedure

Approximately 26 cubic yards of WG were transported from Florida Tech using 12 cubic yard trucks to the Palm Bay site on the morning of January 22. The WG was supplied by WPBMRF and had been used in the environmental characteristics experiments on campus. The WG was clean of organics and deposited directly on the existing road subgrade. When handling glass, the use of gloves is highly recommended.

5.2.1 Material Spreading

A CHAMPION 710-A Series III Mechanical Grader (Figure 5.1) was used to spread the WG over a 300 foot long section of the road at a specified depth of 1 to 2 inches. During spreading, WG would topple over the spreading blade as a result of the WG high friction angle. WG depths were measured after spreading at nine locations within the 300 foot test section with the results summarized in Table 5.1.

5.2.2 Material Mixing

The WG and reclaimed material were mixed together at a depth of 6 inches using a Caterpillar RM-350 Re-claimer as shown in Figure 5.2. The reclaimer, operated at a mixing rate of 100-120 feet/minute, distributed the WG in the upper 6 inches of the reclaimed material base over the 300 ft section in about 30 minutes. Figure 5.3 shows a quarter in a tire track of the reclaimer after mixing the WG with the soil cement.

5.2.3 Material Compaction

Compaction of the WG/reclaimed material subgrade was performed with a Hamm 12-ton vibratory compactor after the required mixing (Figure 5.4). Excessively high moisture conditions caused difficulties during field compaction. Soil pumped beneath the roller during compaction. Table 5.2 summarizes the moisture contents found by the oven method before and after mixing. This 3% decrease was most likely due to the combination of the additional WG, plus the handling of the material by construction equipment. Approximately 12 passes were made with the vibratory roller to meet 98% of the modified Proctor density (ASTM D-1557). The required density based on 95% of the maximum density from ASTM D-698, was 120.6 pcf, however, the extreme moisture conditions prevented this from being achieved (Table 5.3). Speedy moisture contents were slightly lower than the others shown. Excluding these values an average of about 9.5% moisture was present during compaction. The compacted subgrade was left to dry and proof rolling was performed prior to placement of the asphalt-concrete surface. The excessive moisture was present prior to placement of the WG, and the WG did not help or hinder the compaction process.

5.3 Testing Program

Reclaimed material and WG /reclaimed material samples were taken at specific locations within the 300 foot test section for moisture content determinations. Samples were taken before the WG was mixed, after the WG was mixed, and at the locations where nuclear densometer tests were performed. The locations and determined moisture contents are shown in Table 5.2. These samples were used to verify the percentage of WG in the subbase by sorting the WG in the laboratory. The approximate content of the WG in the subbase was approximately 12.5 ± 3.4% by weight.

Reclaimed subgrade samples were also taken from the side of the road for grain size distribution analysis and laboratory determination of moisture density relationships. Figure 5.5 shows the moisture density curve (ASTM D-698) for both the reclaimed material and the recalimed material with 15% WG.

Field CBR, Clegg Impact , and field density tests were performed at different locations within the 300 foot test section. A 20 pound surcharge load was used for field CBR testing. Refer to Tables 5.3 and 5.4 for the results of each test. One field CBR and one field density test were performed at the center and east edge of the road 300 foot from the south edge. These tests were performed for comparison purposes since the WG content at this location was observed to be very low. No road section without WG was prepared for testing. Physical observations of the surficial soil conditions revealed the east side was softer than the west side of the road as expected. The CBR results showed much lower values on the east side of the road. This was due to slightly higher moisture contents on the east side.

6. CONCLUSIONS

WG is an acceptable highway fill material. It can be cleaned at a reasonable cost so that no environmental harm will occur and it has excellent highway engineering properties. WG was successfully mixed with limerock, cemented coquina and reclaimed subgrade. All mixes exhibited adequate highway engineering characteristics.

Stockpiling WG for 3 months was sufficient to allow leachate contaminte concentrations to be reduced to a level that could be discharged. Large redfuctions in BOD, nitrogen, and phosphorus occured. The reductions occured due to washing as well as biodegradation.

Acelerated cleaning of WG can occur by recirculating the leacahte over the WG. Clean up times are reduced to less than 2 weeks. Large reductions, greater than 90%, in BOD occur. The nitrogen and phosphorus are reduced to a lesser extent. The nitrogen can be assimilated into new cell mass or oxidized and reduced un the nitrification/ denitrification process. The only process available to remove phosphorus is assimilation. Since the leachate is carbon limited, phosphorus reduction is minimal.

The shake extraction procedure developed to genrate a leachate from WG is useful to determine when the WG is clean or for predicting the leachate concentrations which could be expected from stockpiled WG.

The roadway demonstration project confirmed the WG's potential as highway fill. The only concern arises from interpreting field moisture data.

The study performed during this research provided valuable information regarding the shear and deformation characteristics of cemented coquina and limerock base mixed with

WG. WG is useful in the construction of highways and the following conclusions can be drawn regarding the use of cullet as base/subbase material.

- The coefficient of permeability is very low for 100% limerock base or cemented coquina. The permeability increases significantly with the increase of WG content in the mix.
- The elastic modulus values of the mixes increased very little compared to the values obtained for 100% limerock base or cemented coquina. These values are very good for base course materials.
- The resilient modulus values remained almost constant as the percent of WG content increased. The values obtained are excellent for drainage purposes.

7. RECOMMENDATIONS

WG should be used in a large or full scale highway project. This project should be located near a WG facility to help defray hauling costs. An ideal use would be as drainage material behind a retaining structure. A careful examination of the quantities of WG should be undertaken before FDOT considers using WG on a large scale.

The following is a list of recommendations for additional research to obtain more valuable information regarding the use of waste glass as base/subbase material.

- Perform additional shear strength experiments with other types of base/subbase materials that need drainage improvements. Compare the results to the results from this research to determine if the improvements to other base/subbase materials (if any) are the same as the ones reported here or if the waste glass behaves in a different manner when combined with other types of base/subbase materials
- Perform additional experiments with glass and cemented coquina mixtures with respect to time, because pozzolonic activity may be occurring causing the mixture to increase or decreasing in strength with time.
- Perform more permeability experiments in waste glass mixes with cemented coquina and limerock base at various densities to see how the density relates to the permeability.

8. DEVELOPMENTAL SPECIFICATIONS FOR USING WG IN HIGHWAY APPLICATIONS

Based on the results from this study the following developmental specifications are proposed. These specifications have been formatted to fit into the general section on Earthwork and Related Operations in "Standard Specifications for Road and Bridge Construction" (1996) from the Florida Department of Transportation. Section number 180 was developed such that any new specifications for reused waste materials could be added at the end of the section as they were approved.

DEVELOPMENTAL SPECIFICATION SECTION 180
REUSE OF DISCARDED MATERIALS AND BYPRODUCTS

180-1 Description

Discarded materials and byproducts shall consist, in general of municipal waste combustor bottom ash and waste glass generated from state mandated recycling quotas. The specification requirements for various discarded materials as contained in this Section are to govern their use only when these materials are used as a source of borrow material.

Sources of supply shall be approved by the Department.

180-3 Waste Glass

180-3.1 Composition: Waste glass shall consist of collected glass, available from recycling facilities or programs.

180-3.2 Gradation: Waste glass for borrow applications shall meet the following gradation requirements:

Passing the 1/2-inch sieve	Minimum 97% (max. dimension , 1-inch)
Passing the No. 200 sieve	Maximum 2 % (by weight)

180-3.3 Characteristics: Waste glass shall contain no more than 1 percent by weight of paper, plastics or other deleterious materials.

180-3.4 Furnishing of Material: Except as might be specifically shown otherwise, all waste glass material and sources thereof shall be furnished by the contractor.

180-3.5 Storage of Material: Waste glass shall be stockpiled for a sufficient time period to allow reduction of leachable materials to acceptable environmental levels.

180-3.6 Chemical Properties: Prior to usage, leachate from waste glass stockpiles must meet treated domestic waste water standards for land application. In addition, the contractor must comply with regulatory issues of other environmental regulatory agencies.

180-3.7 Construction Methods: The contractor must comply with construction methods specified in DOT Standard Specifications for constructing embankments Section 120-8. Waste glass shall not be placed in contact with synthetic liners, geogrids or geotextiles.

180-3.7.1 *Support of Vegetation:* Areas to be covered with grass shall be covered with a minimum of six inches of topsoil over the waste glass. Prior to planting trees and shrubs, the depth of the topsoil shall be adjusted to accommodate the root system.

180-3.7.2 *Compaction Requirements:* Waste glass shall be compacted to a minimum density of 100 pcf unless otherwise approved by the Engineer.

180-3.8 Waste Glass Mixtures: The work specified in this Section consists of the construction of a mix of waste glass and base materials as described in Section 200 Base Courses, uniformly mixed, moistened, shaped, and compacted in reasonably lose conformity with test specifications and in reasonably close conformity with the lines, grades thickness, and notes shown on the plans or established by the Engineer.

180-3.8.1 *Construction Methods for Waste Glass Mixtures.*

180-3.8.1.1 *Preparation:* Prior to mixing with waste glass, the subgrade shall have been constructed to an elevation which will provide a subgrade surface conforming to the plans and specifications upon completion of mixing. No appreciable quantity of roots, sticks, or other deleterious material shall remain in the area to be treated. Prior to mixing, the surface of the subgrade shall be scarified as directed. Water shall be applied as required when soil conditions are such that prewetting will be beneficial to pulverization and mixing. Windrows shall be constructed along each side of the area to be treated to prevent loss of glass. Drain openings shall be cut through the windrows at sufficient intervals to prevent ponding of water on the subgrade and the windrowed material shall be moved, when necessary, to permit the subgrade to dry.

180-3.8.1.2 *Application:* The waste glass shall be uniformly spread dry. Waste glass shall be applied through the use of mechanical spreaders which are able to provide a uniform distribution of waste glass across the full width of the subgrade being treated or by other methods approved by the Engineer.

The quantity of waste glass spread on any section shall not vary more than ± 5% from the quantity ordered.

180-3.8.1.3 *Mixing:* Immediately after the waste glass has been spread over a section to be processed, the soil-waste glass mixture shall be scarified over the full width and to the depth required. Water shall then be applied in liberal amounts as necessary and the waste glass and water incorporated uniformly into the soil to be treated by means of a rotary type mixer or other equipment which may be approved by the Engineer. Addition of water prior to and in conjunction with mixing shall be controlled such that the moisture content does not exceed the optimum moisture content of the mixture by more than five percentage points.

180-3.8.1.3 *Compaction:* Compaction operations shall begin as soon as possible after completion of the mixing operation. The full depth and width receiving waste glass shall be compacted to not less than 100% of the maximum density as determined by AASHTO T99. Shaping may be required prior to and during compaction operations in order to obtain uniform compaction and the required cross section and elevation.

180-3.8.1.4 *Finishing:* After compaction of a section has been completed, the surface shall be shaped to the required lines, grades, and cross sections. In order to prevent the formation of surface laminations, the surface shall be lightly scarified with a spring tooth harrow, spike drag, or other approved device such that the surface is uniformly loosened. The surface shall then be sealed by rolling with a traffic roller.

180-3.8.1.4 *Thickness Assurement:* During various stages of construction test holes shall be dug in the mixture to assure the correct construction of designed layers with waste glass mixtures.

180-3.9 Safety and Health: The contractor must comply with the requirements of Section 7-1.4 of the Florida DOT Standard Specifications.

Proper precautions shall be taken for protection of the workers' eyes and bodies while working with waste glass.

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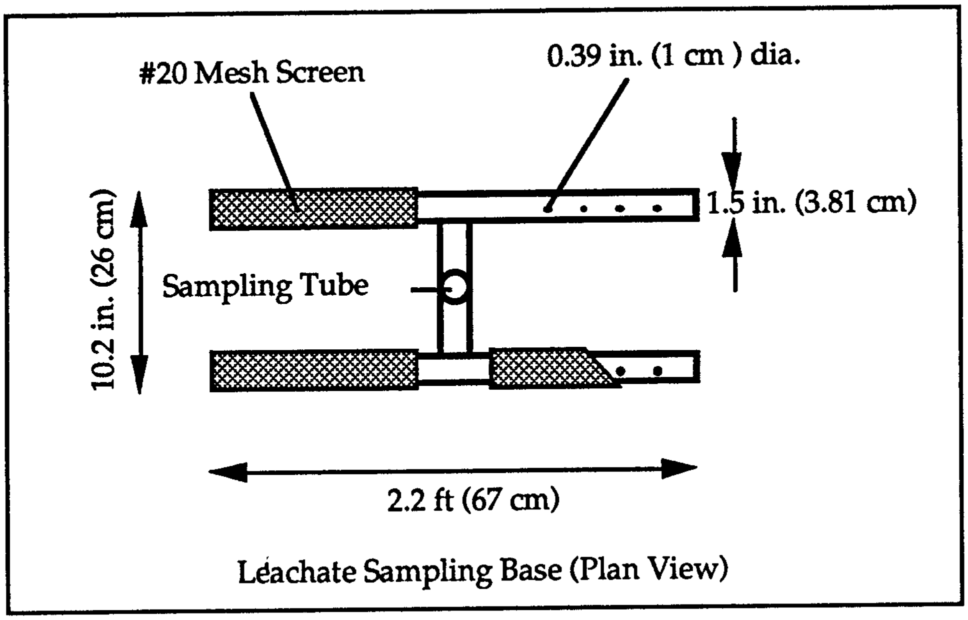
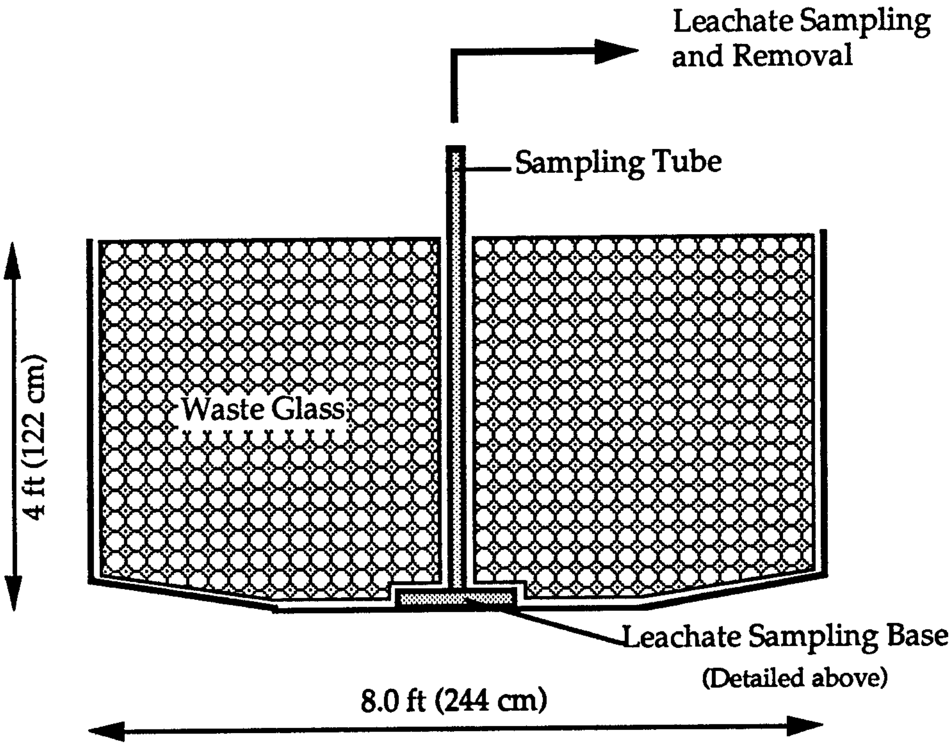


Leachate Sampling Base (Plan View)



Cross-section

Figure 2.1 WG reactor used for NAS

Table 2-1: Percentages by weight of the materials in each sample

Test Description			
Specific Gravity Moisture-Density CBR-LBR		Grain Size Permeability Triaxial Layer Coefficient	
Aggregate (%)	Glass (%)	Aggregate (%)	Glass (%)
100	0	100	0
95	10		
85	15		
80	20	80	20
70	30		
60	40	60	40
50	50		
40	60	40	60
30	70		
20	80	20	80
10	90		
0	100	0	100

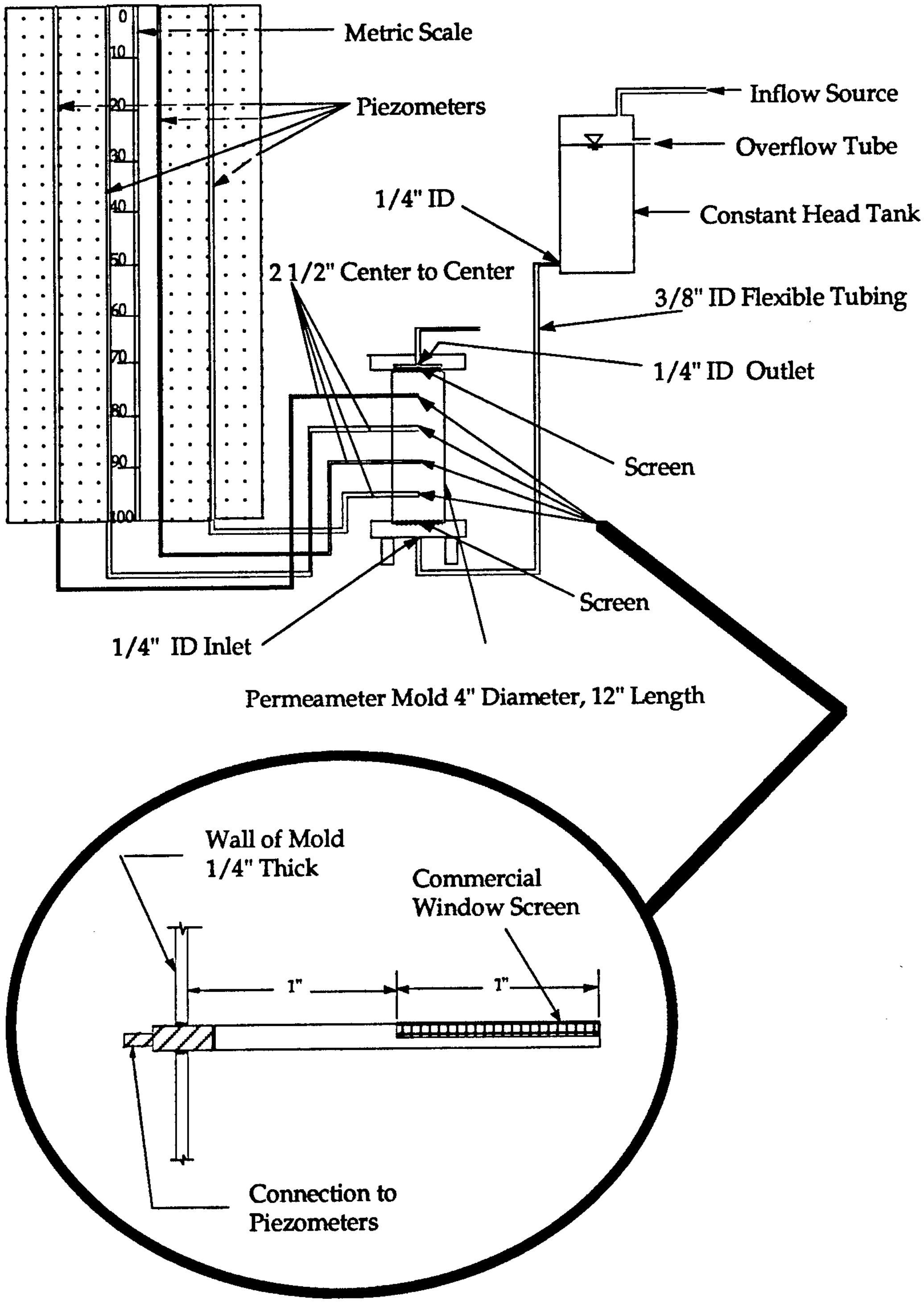


Figure 2.2 Modified permeameter with detail of piezometric head entrance (from Syed, 1994)

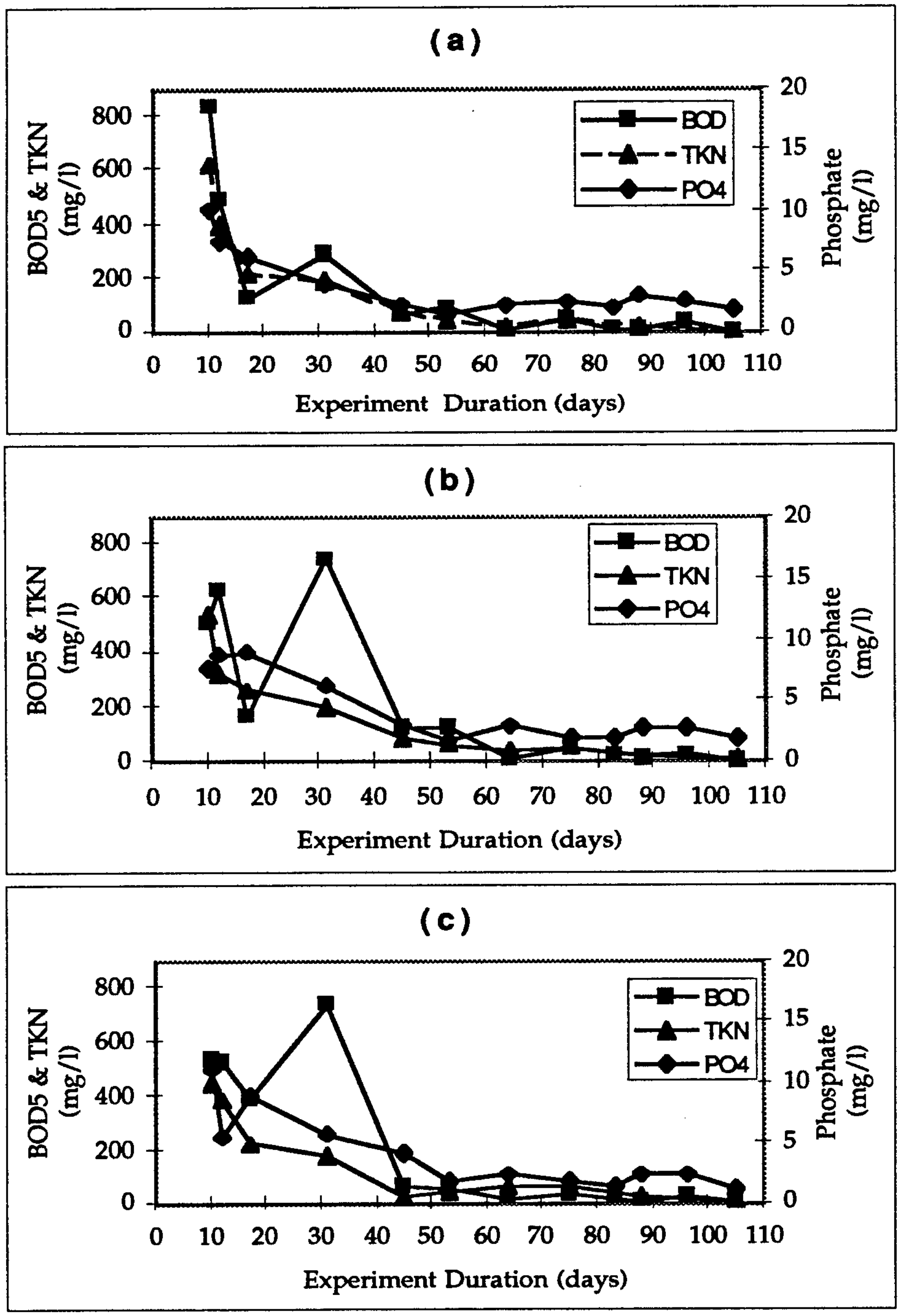
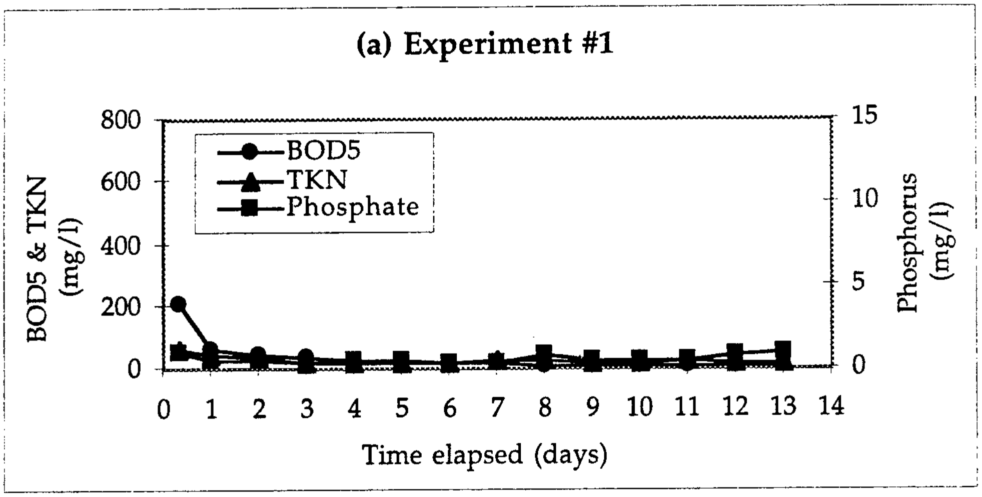
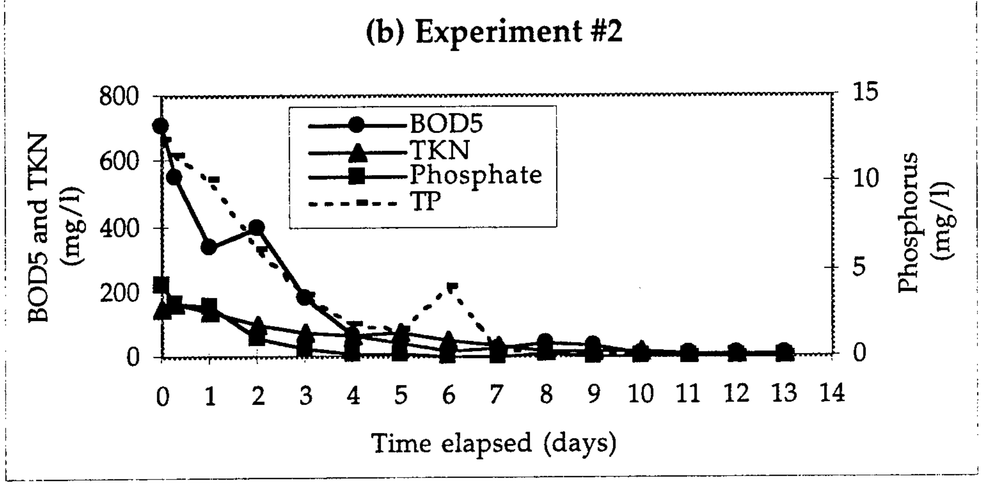


Figure 3.1 Contaminant concentrations through NAS, (a) Reactor 1, (b) Reactor 2, (c) Reactor 3


(a) Experiment #1


(b) Experiment #2

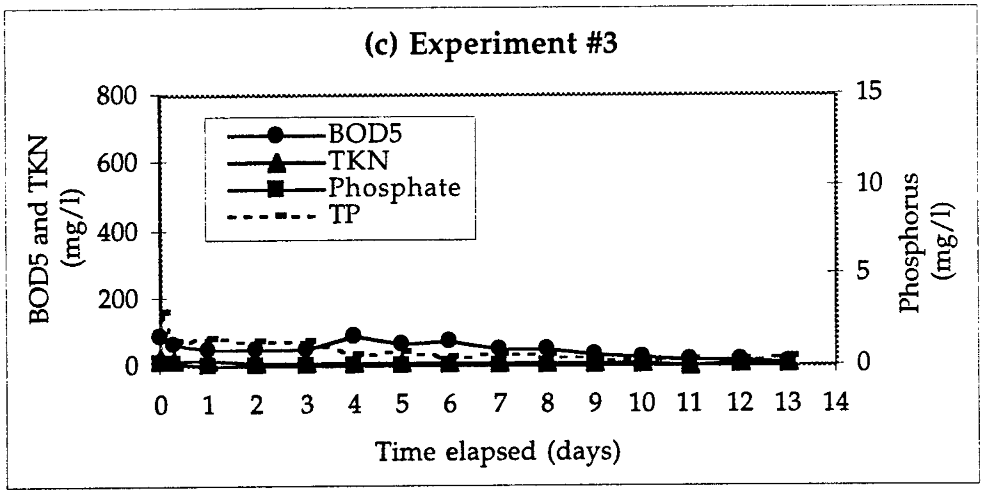

(c) Experiment #3

Figure 3.2 Contaminant concentrations through ACS, (a) Reactor 1, (b) Reactor 2, (c) Reactor 3

Table 3.1 NAS results for Reactor 1

Date	Time	Concentrations			C: N ratio	C : N : P' ratio	Leachate Extracted	Cum. Leachate Volume	Cumulative Mass Released		
		BOD$_5$	TKN	Phospate					BOD$_5$	TKN	Phospate
	t	C	N	P'							
	(days)	(mg/l)	(mg/l)	(mg/l)			(l)	(l)	(g)	(g)	(g)
3/19/96	0	BOD$_5$	TKN	Phosphate	NA	NA	NA	Cum. Volume	Cum. Mass Extracted	Cum. Mass Extracted	Cum. Mass Extracted
3/29/96	10	838.3	615.0	10.2	1.36 : 1	82.6 : 60.6 : 1	21	21	17.6	12.9	0.2
3/31/96	12	488.7	396.0	7.4	1.23 : 1	66.2 : 53.6 : 1	117	138	74.7	59.2	1.1
4/5/96	17	126.0	221.0	6.2	0.57 : 1	20.2 : 35.4 : 1	122	259	90.0	86.0	1.8
4/19/96	31	288.3	195.0	3.9	1.48 : 1	73.1 : 49.4 : 1	33	292	99.4	92.4	2.0
5/3/96	45	60	68.7	2.2	0.87 : 1	27.7 : 31.7 : 1	74	366	103.8	97.5	2.1
5/11/96	53	88.3	42.8	1.5	2.06 : 1	58.9 : 28.5 : 1	35	401	106.9	98.9	2.2
5/22/96	64	5.3	21.8	2.2	0.24 : 1	2.4 : 9.9 : 1	52	452	107.2	100.1	2.3
6/1/96	75	41.3	44.9	2.4	0.92 : 1	17.2 : 18.7 : 1	110	563	111.7	105.0	2.6
6/10/96	83	11.7		2.1		5.6 : NA : 1	104	666	112.9	105.0	2.8
6/15/96	88	12.8	18.6	3.0	0.69 : 1	4.3 : 6.2 : 1	224	890	115.8	109.2	3.4
6/23/96	96	32.54		2.6		12.5 : NA : 1	626	1515	136.1	109.2	5.1
7/2/96	105	4.46	4.09	1.8	1.09 : 1	2.4 : 2.2 : 1	305	1820	137.5	110.4	5.6
Total							**1820.3**		**137.5**	**110.4**	**5.6**

Table 3.2 NAS results for Reactor 2

Date	Time	Concentrations			C: N ratio	C : N : P' ratio	Leachate Extracted	Cum. Leachate Volume	Cumulative Mass Released		
		BOD$_5$	TKN	Phospate					BOD$_5$	TKN	Phospate
	t	C	N	P'							
	(days)	(mg/l)	(mg/l)	(mg/l)			(l)	(l)	(g)	(g)	(g)
3/19/96	0	BOD$_5$	TKN	Phosphate	NA	NA	NA	Cum. Volume	Cum. Mass Extracted	Cum. Mass Extracted	Cum. Mass Extracted
3/29/96	10	506.0	543.0	7.5	0.9 : 1	67.5 : 72.4 : 1	10	10	4.8	5.2	0.1
3/31/96	12	628.4	326.0	8.8	1.9 : 1	71.7 : 37.2 : 1	103	112	69.2	38.6	1.0
4/5/96	17	164.0	262.0	8.9	0.6 : 1	18.4 : 29.4 : 1	117	229	88.3	69.1	2.0
4/19/96	31	743.0	203.0	6.2	3.7 : 1	120.1 : 32.8 : 1	45	273	121.4	78.1	2.3
5/3/96	45	126	90.3	2.9	1.4 : 1	43.9 : 31.5 : 1	66	339	129.7	84.1	2.5
5/11/96	53	120.3	58	1.7	2.1 : 1	71.8 : 34.6 : 1	39	378	134.4	86.3	2.5
5/22/96	64	8.7	42.8	2.9	0.2 ; 1	3.0 : 14.7 : 1	54	432	134.9	88.7	2.7
6/1/96	75	54.7	48.2	2.0	1.1 : 1	26.9 : 23.7 : 1	92	524	139.9	93.1	2.9
6/10/96	83	25.0		2.0		12.5 : NA : 1	98	622	142.3	93.1	3.1
6/15/96	88	15.3	21.2	2.7	0.7 : 1	5.6 : 7.8 : 1	210	832	145.6	97.5	3.7
6/23/96	96	27.06		2.8		9.7 : NA : 1	626	1458	162.5	97.5	5.4
7/2/96	105	3.90	4.63	2.0	0.8 : 1	2.0 : 2.4 : 1	298	1756	163.6	98.9	6.0
Total							**1755.8**		**163.6**	**98.9**	**6.0**

Table 3.3 NAS results for Reactor 3

Date	Time	Concentrations			C: N ratio	C:N:P' ratio	Leachate Extracted	Cum. Leachate Volume	Cumulative Mass Released		
		BOD$_5$	TKN	Phospate					BOD$_5$	TKN	Phospate
	t (days)	C (mg/l)	N (mg/l)	P' (mg/l)			(l)	(l)	(g)	(g)	(g)
3/19/96	0	BOD$_5$	TKN	Phosphate	NA	NA	NA	Cum. Volume	Cum. Mass Extracted	Cum. Mass Extracted	Cum. Mass Extracted
3/29/96	10	531.0	446.0	11.0	1.2 : 1	48.3 : 40.5 : 1	10	10	5.3	4.5	0.1
3/31/96	12	522.3	383.0	5.6	1.4 : 1	92.7 : 68 : 1	71.8	81.8	42.8	32.0	0.5
4/5/96	17	392.0	222.0	8.9	1.8 : 1	43.9 : 24.9 : 1	116.4	198.2	88.4	57.8	1.6
4/19/96	31	735.7	175.0	5.7	4.2 : 1	128.0 : 30.5 : 1	37.05	235.25	115.7	64.3	1.8
5/3/96	45	62.0	24.6	4.1	2.5 : 1	15.2 : 6.0 : 1	64.85	300.1	119.7	65.9	2.0
5/11/96	53	50.3	41.2	1.7	1.2 : 1	29.2 : 23.9 : 1	39.15	339.25	121.7	67.5	2.1
5/22/96	64	21.3	58.2	2.4	0.4 : 1	8.9 : 24.2 : 1	62.4	401.65	123.0	71.1	2.2
6/1/96	75	36.0	64.5	1.8	0.6 : 1	19.5 : 35.0 : 1	103.7	505.35	126.8	77.8	2.4
6/10/96	83	18.9		1.5		12.8 : NA : 1	65.1	570.45	128.0	77.8	2.5
6/15/96	88	12.9	22.6	2.5	0.6 : 1	5.2 : 9.1 : 1	210.2	780.65	130.7	82.6	3.1
6/23/96	96	22.34		2.3		9.7 : NA : 1	625.5	1406.15	144.7	82.6	4.5
7/2/96	105	4.78	4.9	1.2	1.0 : 1	4.0 : 4.1 :1	285	1691.15	146.0	84.0	4.8
Total							1691.2		146.0	84.0	4.8

Table 3.4 Reactor experiment results in ACS in Experiment #1

Date	Time	BOD$_5$	TKN	Phosphate	TP	BOD$_5$: N ratio	BOD$_5$: N : P ratio	Ambient Temperature
	t (days)	C (mg/l)	N (mg/l)	P' (mg/l)	P (mg/l)			T (°C)
		BOD$_5$	TKN	Phosphate	TP			
9/9/96	0				NA	NA	NA	26.9
9/9/96	0.333	205	57.7	1.02	NA	3.55 : 1	201 : 57 : 1	26.9
9/10/96	1	57.13	41.2	0.46	NA	1.39 : 1	124 : 90 : 1	26.9
9/11/96	2	43.33	36.3	0.48	NA	1.19 : 1	90 : 76 : 1	26.9
9/12/96	3	36.07	18.3	0.35	NA	1.97 : 1	103 : 52 : 1	26.9
9/13/96	4	27.23	18.3	0.41	NA	1.49 : 1	66 : 45 : 1	27.8
9/14/96	5	21.8	16.9	0.42	NA	1.29 : 1	52 : 40 : 1	26.4
9/15/96	6	17.07	16.5	0.32	NA	1.03 : 1	53 : 52 : 1	26.9
9/16/96	7	15.2	25.0	0.35	NA	0.61 : 1	43 : 71 : 1	27.5
9/17/96	8	12.3	22.7	0.86	NA	0.54 : 1	14 : 26 : 1	29.2
9/18/96	9	7.57	19.7	0.48	NA	0.38 : 1	16 : 41 : 1	28.1
9/19/96	10	6.93	20.8	0.52	NA	0.33 : 1	13 : 40 : 1	26.4
9/20/96	11	6.33	23.5	0.55	NA	0.27 : 1	12 : 43 : 1	26.1
9/21/96	12	5.47	15.4	0.86	NA	0.36 : 1	6 : 18 : 1	26.4
9/22/96	13	4.37	14.5	1.03	NA	0.30 : 1	4 : 14 : 1	26.4

Table 3.5 Reactor experiment results in ACS in Experiment #2

Date	Time t (days)	BOD$_5$ C (mg/l)	TKN N (mg/l)	Phosphate P' (mg/l)	TP P (mg/l)	BOD$_5$: N ratio	BOD$_5$: N : P ratio	Ambient Temperature T (°C)
		BOD$_5$	TKN	Phosphate	TP			
11/11/96	0	706.5	152.0	4.20	12.47	4.65 : 1	168 : 36 : 1	14.7
11/11/96	0.29	549.25	164.0	3.03	11.65	3.35 : 1	181 : 54 : 1	14.7
11/12/96	1	338	140.0	2.87	10.24	2.41 : 1	118 : 49 : 1	16.1
11/13/96	2	397	97.8	1.03	6.15	4.06 : 1	384 : 95: 1	22.2
11/14/96	3	180	73.7	0.45	3.63	2.44 : 1	396 : 162 : 1	22.5
11/15/96	4	70.1	69.2	0.22	1.89	1.01 : 1	326 : 322 : 1	23.3
11/16/96	5	42.04	75.8	0.18	1.51	0.55 : 1	238 : 428 : 1	22.2
11/17/96	6	16.8	45.9	0.07	4.05	0.37 ; 1	258 : 706 : 1	23.1
11/18/96	7	25.73	29.9	0.06	0.36	0.86 : 1	408 : 475 : 1	22.5
11/19/96	8	37.17	15.6	0.12	0.23	2.39 : 1	320 : 134 : 1	20.6
11/20/96	9	31.17	14.3	0.08	0.19	2.17 : 1	405 : 186 : 1	20.8
11/21/96	10	11.35	12.8	0.04	0.18	0.89 : 1	324 : 365 : 1	22.8
11/22/96	11	10.47	9.1	0.04	0.18	1.16 : 1	299 : 259 : 1	20.6
11/23/96	12	8.47	11.3	0.03	0.21	0.75 : 1	339 : 451 : 1	16.7
11/24/96	13	8.74	7.9	0.03	0.17	1.11 : 1	273 : 247 : 1	21.4

Table 3.6 Reactor experiment results in ACS in Experiment #3

Date	Time t (days)	BOD$_5$ C (mg/l)	TKN N (mg/l)	Phosphate P' (mg/l)	TP P (mg/l)	BOD$_5$: N ratio	BOD$_5$: N : P ratio	Ambient Temperature T (°C)
		BOD$_5$	TKN	Phosphate	TP			
1/16/97	0	85	26.60	0.21	2.90	3.20 : 1	405 : 127 : 1	21.9
1/16/97	0.29	59.8	17.80	0.08	1.40	3.36 : 1	748 : 223 : 1	21.9
1/17/97	1	50.5	14.80	0.06	1.50	3.41 : 1	841 : 247 : 1	7.2
1/18/97	2	46.2	11.20	0.04	1.30	4.13 : 1	1154 : 280 : 1	6.4
1/19/97	3	43.7	10.10	0.03	1.30	4.33 : 1	1457 : 337 : 1	6.1
1/20/97	4	89.4	9.18	0.03	0.66	9.74 : 1	2982 : 306 : 1	9.4
1/21/97	5	66.6	8.82	0.02	0.68	7.55 : 1	3330 : 441 : 1	12.5
1/22/97	6	73	8.15	0.02	0.41	8.96 : 1	3649 : 408 : 1	16.7
1/23/97	7	45	7.04	0.02	0.66	6.39 : 1	2251 : 352 : 1	17.2
1/24/97	8	45	6.89	0.02	0.60	6.53 : 1	2252 : 345 : 1	20.0
1/25/97	9	30.3	5.08	0.02	0.31	5.96 : 1	1517 : 254 : 1	20.8
1/26/97	10	20.6	5.17	0.06	0.27	3.98 : 1	344 : 86 : 1	17.2
1/27/97	11	16.6	0.04	0.02	0.29	NA	NA	20.6
1/28/97	12	15.4	5.85	0.03	0.23	2.63 : 1	513 : 195 : 1	19.4
1/29/97	13	8.2	5.72	0.03	0.39	1.43 : 1	273 : 191 : 1	21.1

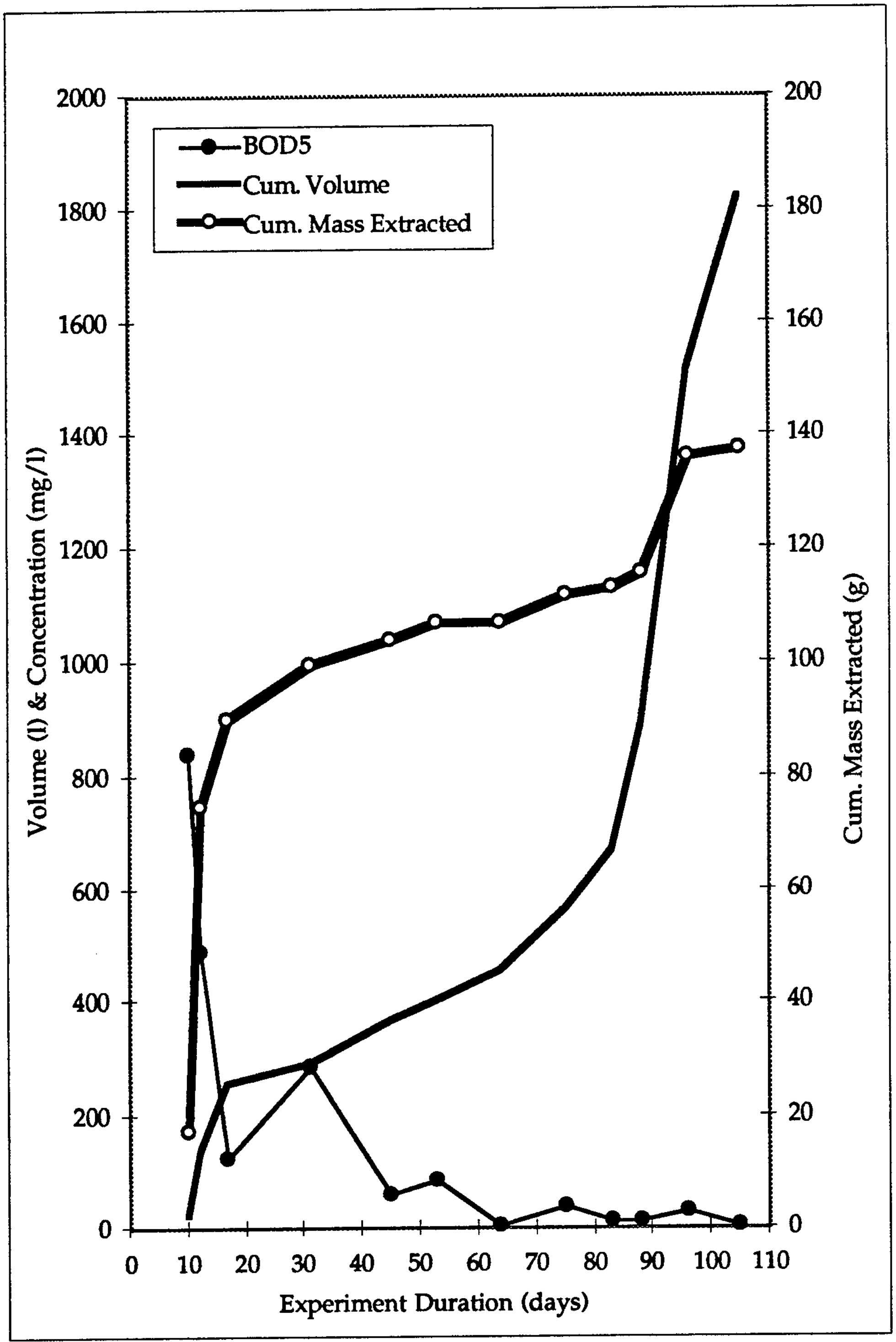


Figure 3.3 Relationship between leachate generation, BOD_5, and cumulative BOD_5 mass extracted for Reactor 1

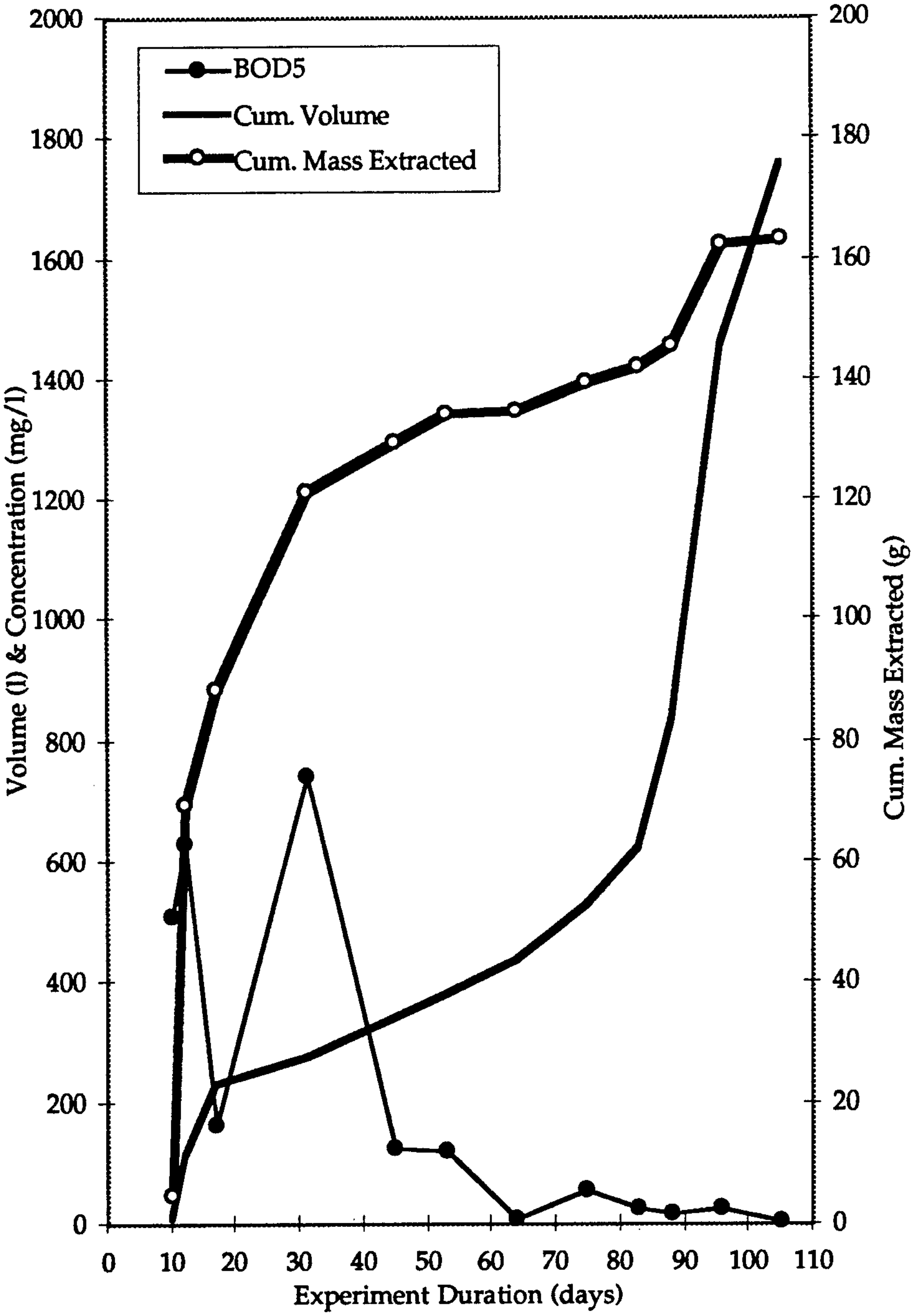


Figure 3.4 Relationship between leachate generation, BOD_5, and cumulative BOD_5 mass extracted for Reactor 2

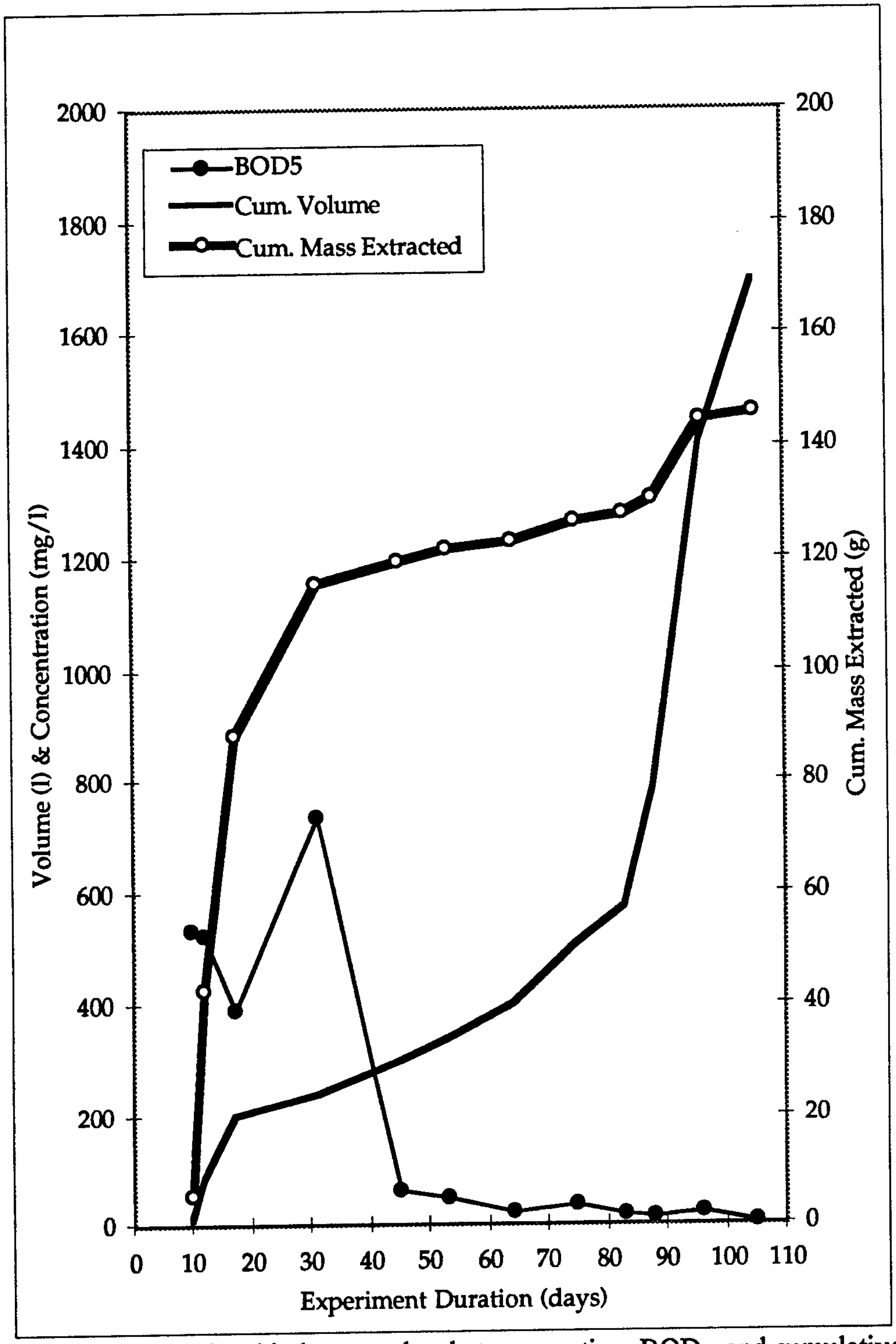


Figure 3.5 Relationship between leachate generation, BOD_5, and cumulative BOD_5 mass extracted for Reactor 3

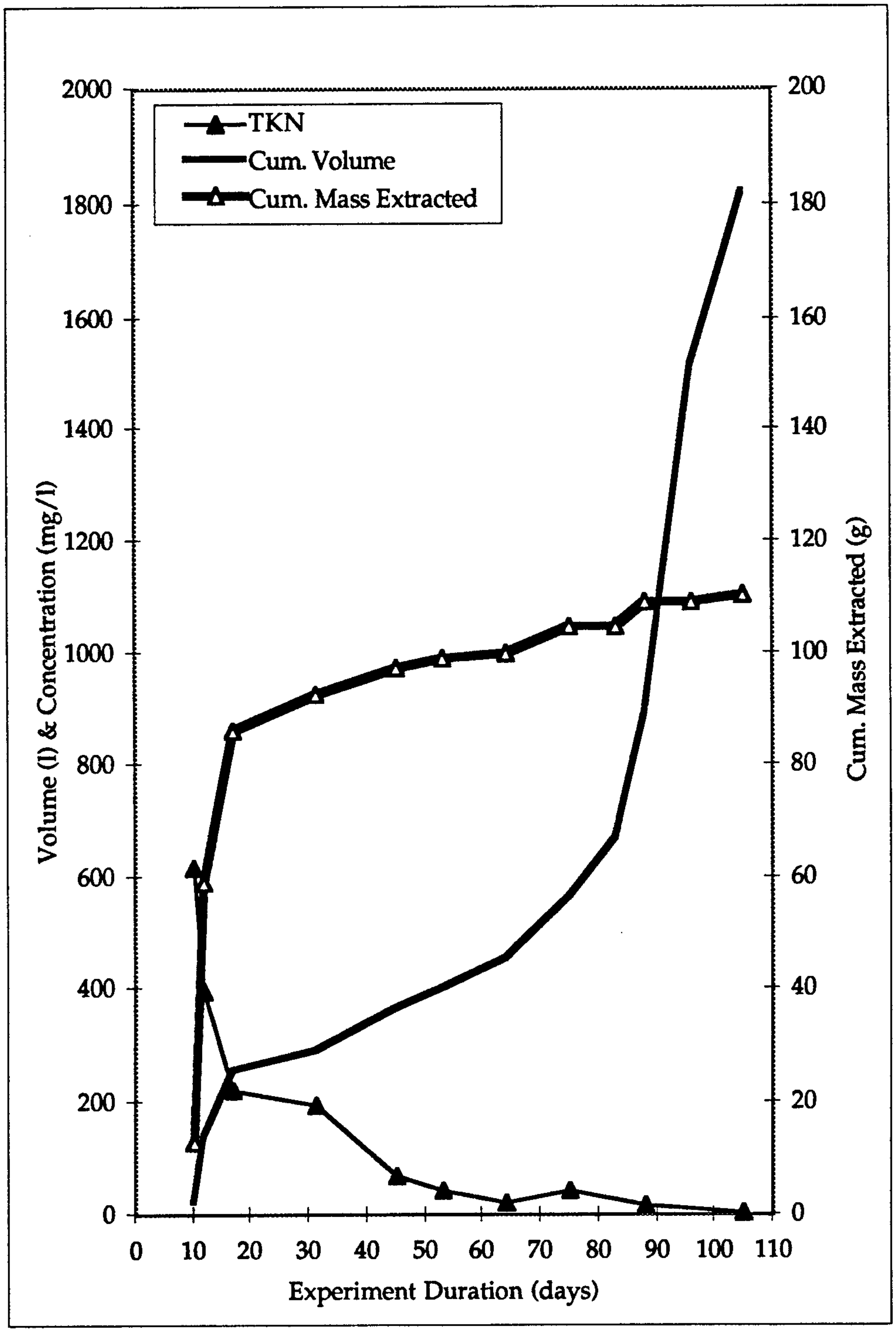


Figure 3.6 Relationship between leachate generation, TKN, and cumulative TKN mass extracted for Reactor 1

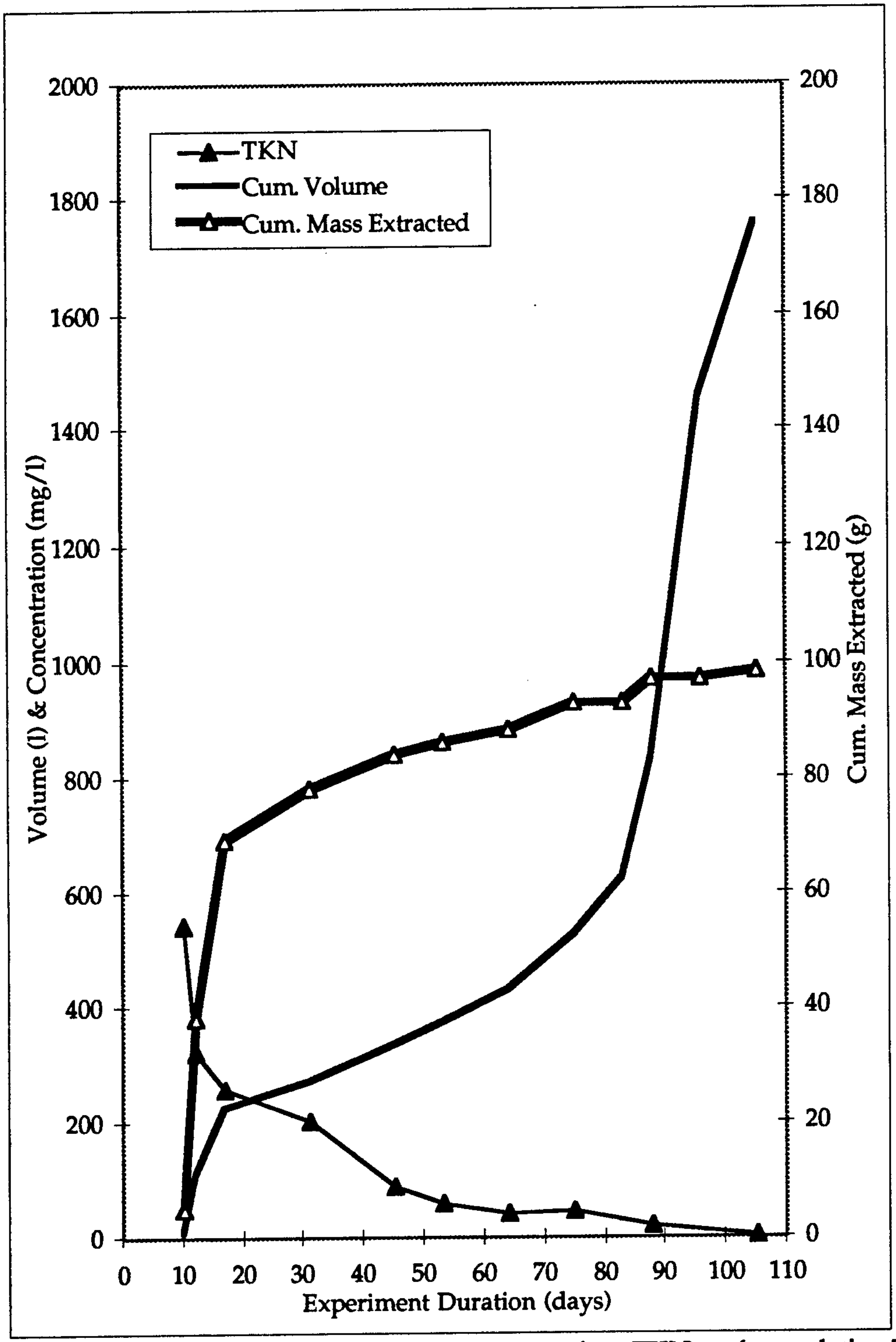


Figure 3.7 Relationship between leachate generation, TKN, and cumulative TKN mass extracted for Reactor 2

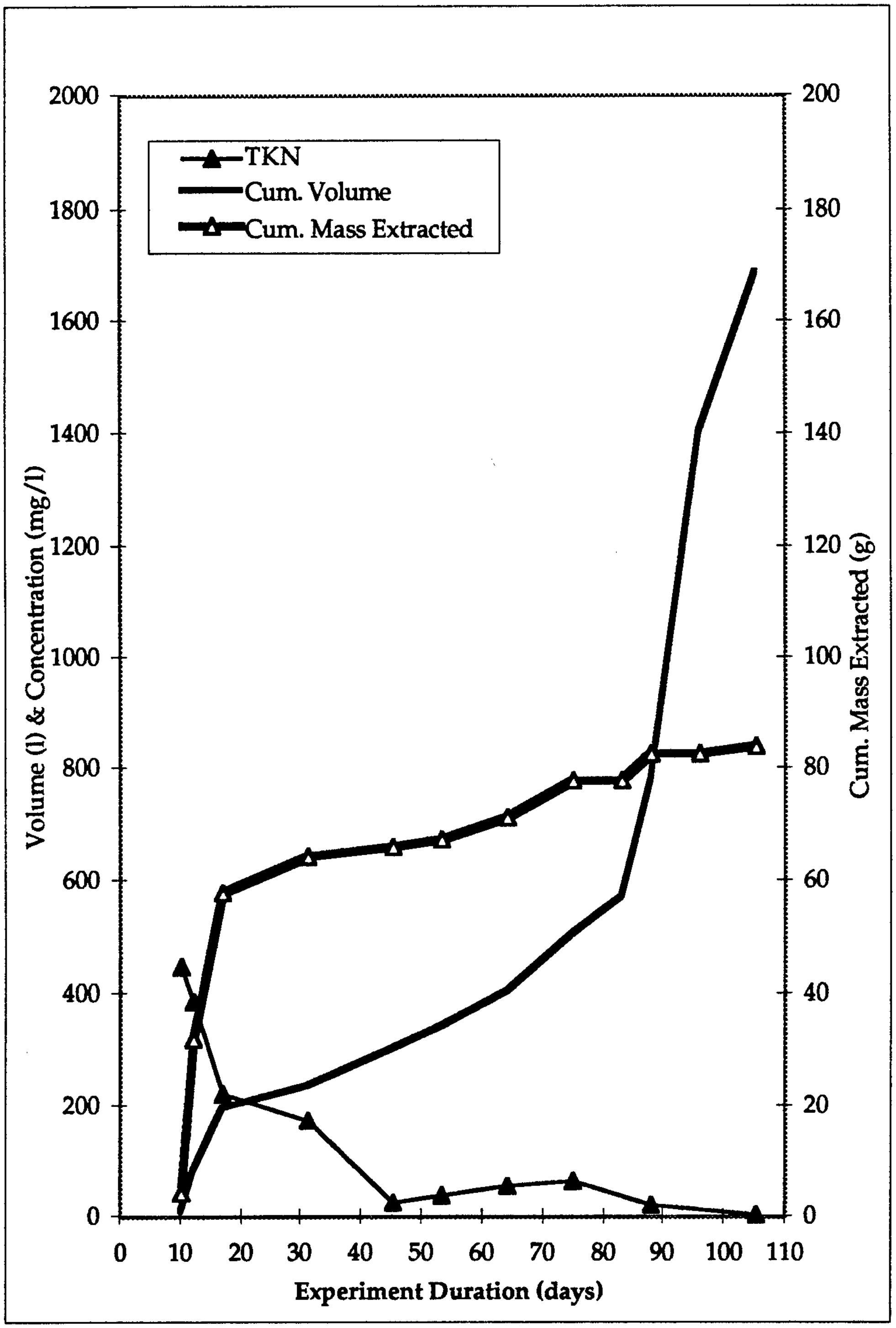


Figure 3.8 Relationship between leachate generation, TKN, and cumulative TKN mass extracted for Reactor 3

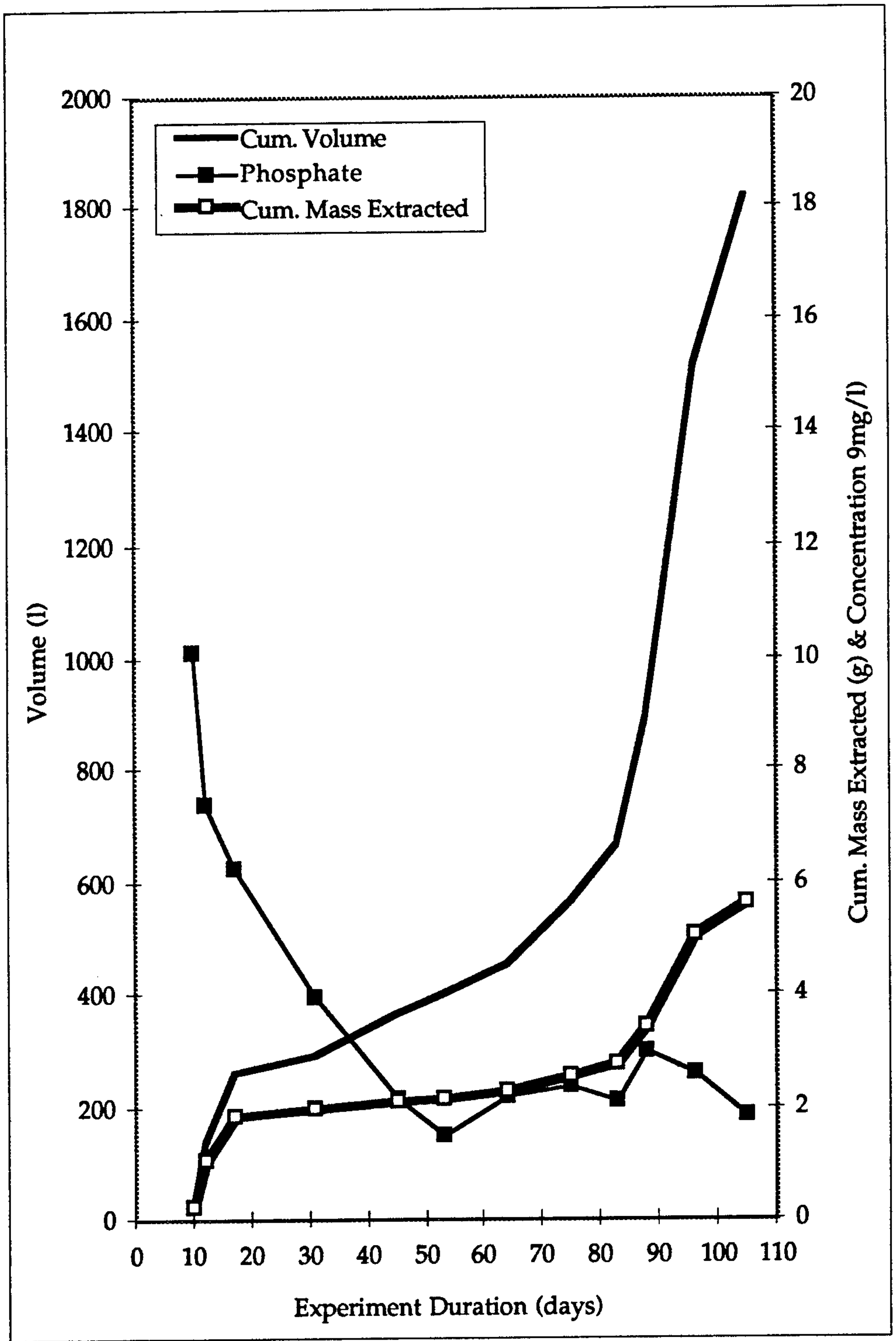


Figure 3.9 Relationship between leachate generation, phosphate, and cumulative phosphate mass extracted for Reactor 1

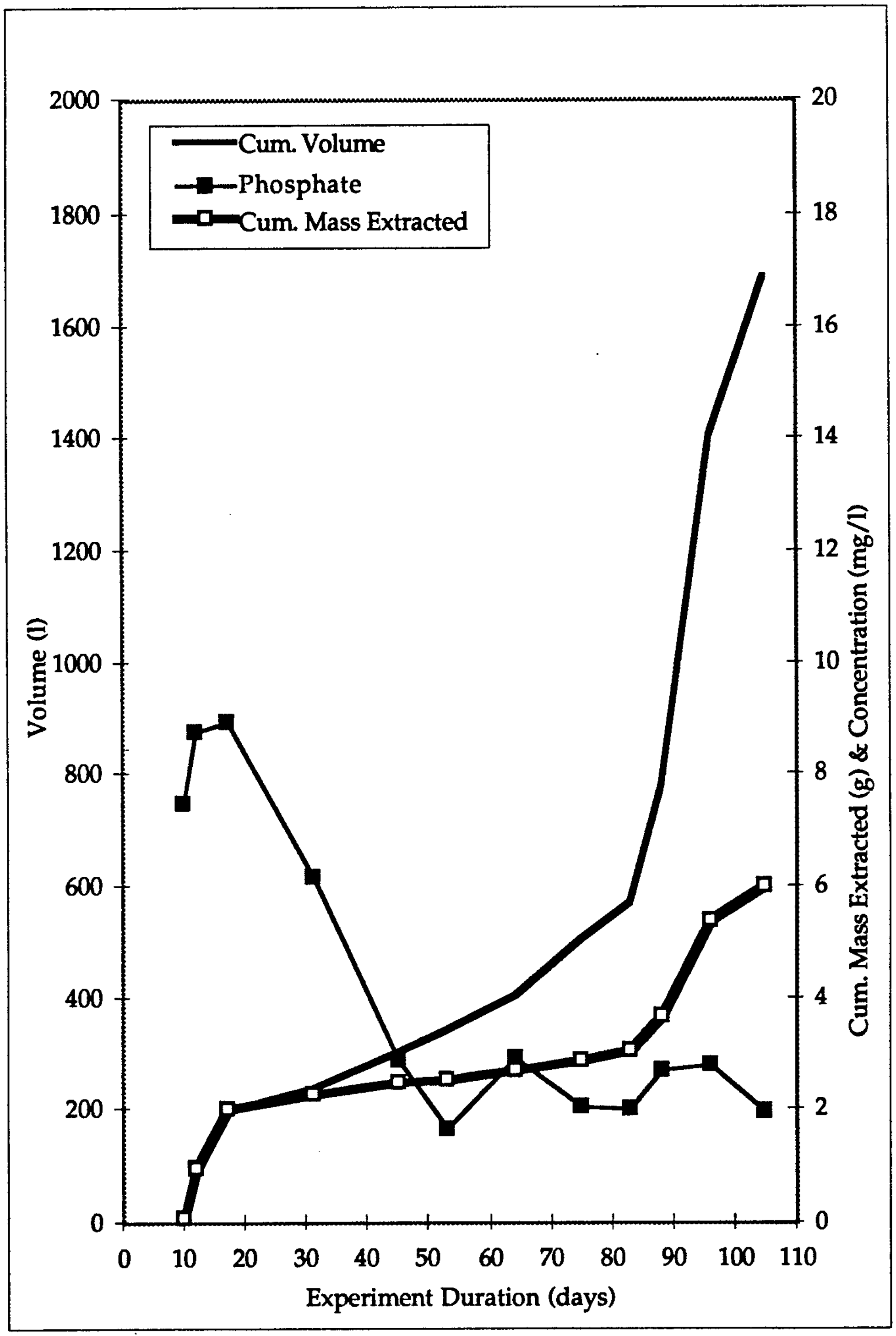


Figure 3.10 Relationship between leachate generation, phosphate, and cumulative phosphate mass extracted for Reactor 2

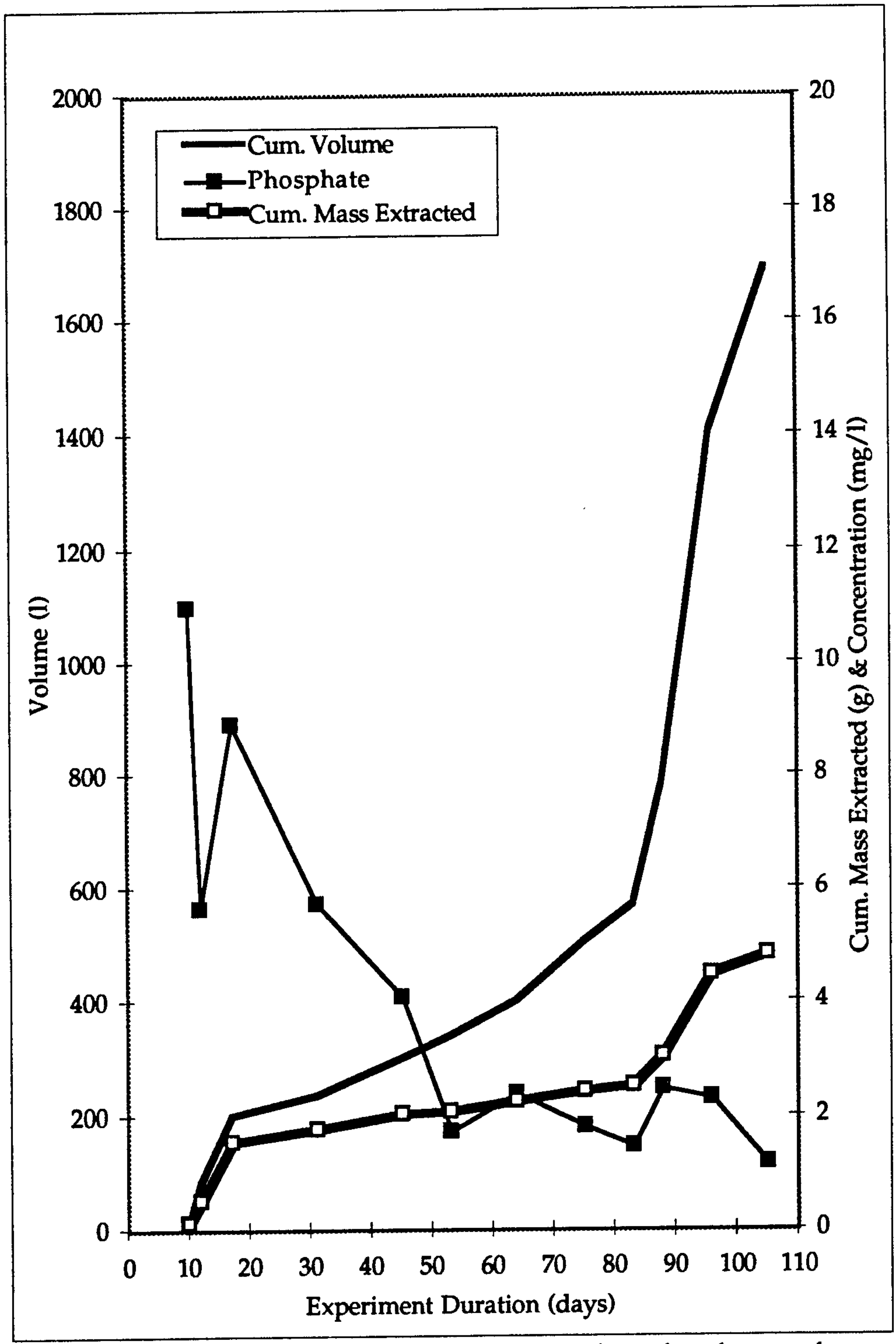


Figure 3.11 Relationship between leachate generation, phosphate, and cumulative phosphate mass extracted for Reactor 3

Table 3.7 Shake extraction results for BOD_5 for NAS

	Initial BOD_5 (pre-treat WG) (mg/l)	**Final BOD_5** (post-treat WG) (mg/l)	**Reduction Ratio** (%)
Batch 1	546.9*	24.2	95.6
Batch 2	546.9*	17.7	96.8
Batch 3	546.9*	18.1	96.7
Average	546.9	20.0	96.3

* WG analyzed here was common among Reactor 1, 2 and 3.

Table 3.8 Shake extraction results for TKN for NAS

	Initial TKN (pre-treat WG) (mg/l)	**Final TKN** (post-treat WG) (mg/l)	**Reduction Ratio** (%)
Batch 1	471*	7.6	83.9
Batch 2	471*	5.6	88.1
Batch 3	471*	7.1	84.9
Average	471*	6.8	85.6

* WG analyzed here was common among Reactor 1, 2 and 3.

Table 3.9 Shake extraction results for phosphate for NAS

	Initial Phosphate (pre-treat WG) (mg/l)	Final Phosphate (post-treat WG) (mg/l)	Reduction Ratio (%)
Batch 1	5.49*	2.72	50.5
Batch 2	5.49*	2.70	50.8
Batch 3	5.49*	3.12	43.2
Average	5.49	2.85	47.2

* WG analyzed here was common among Reactor 1, 2 and 3.

Table 3.10 Shake extraction experiment results for BOD_5

	Initial BOD_5 (pre-treat WG) (mg/l)	Final BOD_5 (post-treat WG) (mg/l)
Batch 1	NM	19.4
Batch 2	276.7	58.0
Batch 3	104.3	78.2
Average	190.5	51.8

NM: Not Measured

Table 3.11 Estimate of clean-up times at varying temperature with an initial BOD_5 of 1000 mg/l

Elapsed Time	BOD5 Concentrations			
	T=30(℃) ke=3.746	T=25(℃) ke=1.040	T=20(℃) ke=0.289	T=15(℃) ke=0.080
(days)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
0	1000.0	1000.0	1000.0	1000.0
1	23.6	353.4	749.1	922.9
2	0.6	124.9	561.1	851.7
3		44.1	420.3	786.0
4		15.6	314.8	725.4
5		5.5	235.8	669.4
6			176.6	617.8
7			132.3	570.2
8			99.1	526.2
9			74.2	485.6
10			55.6	448.2
11			41.7	413.6
12			31.2	381.7
13			23.4	352.3
14			17.5	325.1
15			13.1	300.0
16			9.8	276.9
17				255.5
18				235.8
19				217.6
20				200.8
21				185.4
22				171.1
23				157.9
24				145.7
25				134.5
26				124.1
27				114.5
28				105.7
29				97.5
30				90.0
31				83.1
32				76.7
33				70.7
34				65.3
35				60.3
36				55.6
37				51.3
38				47.4
39				43.7
40				40.3
41				37.2
42				34.4
43				31.7
44				29.3
45				27.0
46				24.9
47				23.0
48				21.2
49				19.6
50				18.1
51				16.7
52				15.4
53				14.2
54				13.1
55				12.1
56				11.2
57				10.3
58				9.5

Table 3.12 Shake extraction experiment results for TKN

	Initial TKN (pre-treat WG) (mg/l)	**Final TKN** (post-treat WG) (mg/l)
Batch 1	NM	8.23
Batch 2	39.0	17.0
Batch 3	20.9	18.2
Average	21.0	14.5

NM: Not Measured

Table 3.13 Shake extraction experiment results for phosphate

	Initial Phosphate (pre-treat WG) (mg/l)	**Final Phosphate** (post-treat WG) (mg/l)
Batch 1	NM	2.45
Batch 2	2.71	2.41
Batch 3	1.13	1.5
Average	1.92	2.12

NM: Not Measured

Table 3.14 Shake extraction experiment results for TP

	Initial TP (pre-treat WG) (mg/l)	**Final TP** (post-treat WG) (mg/l)
Batch 1	NM	NM
Batch 2	4.11	4.35
Batch 3	3.13	3.17
Average	3.62	3.76

NM: Not Measured

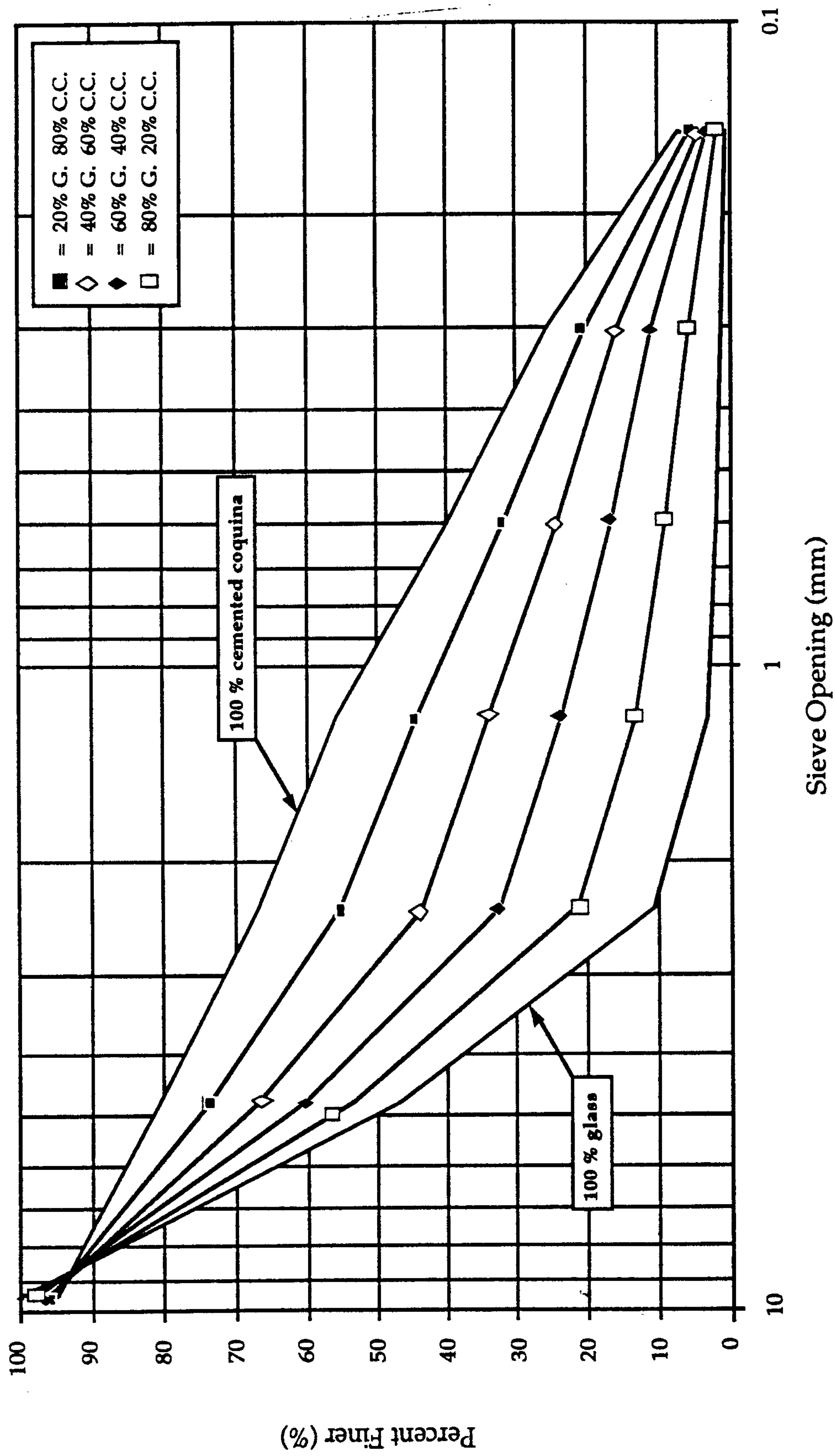


Figure 4.1 Grain size distribution for WG mixtures ranging from 100% glass to 100% cemented coquina

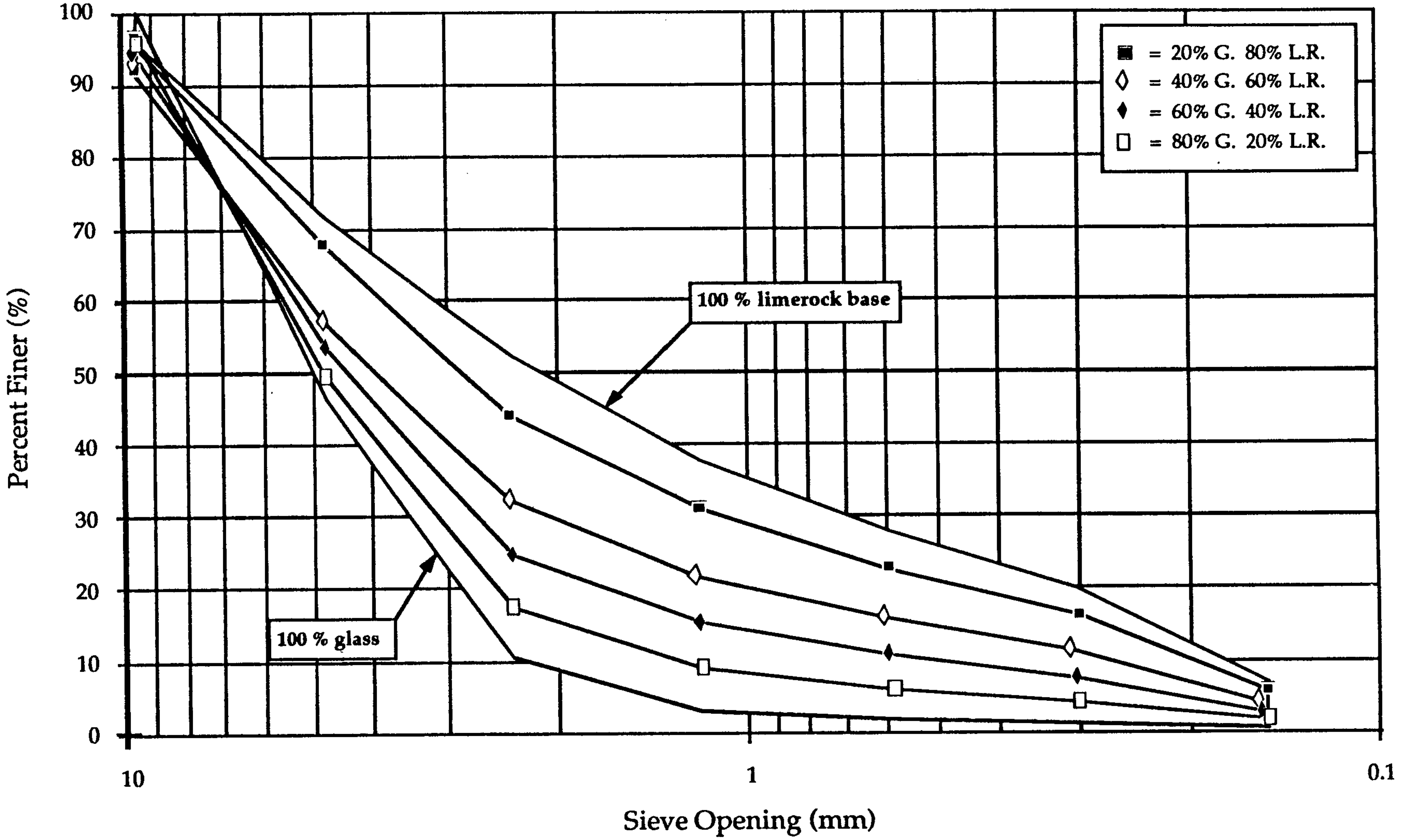


Figure 4.2 Grain size distribution for WG mixtures ranging from 100% glass to 100% limerock

Table 4-1 The specific gravity of materials

Materials	Specific Gravity (ASTM D 854)	Specific Gravity (ASTM C 127)	Average Specific Gravity
Cemented Coquina	2.72	2.61	2.66
Limerock	2.69	2.61	2.66
WPBMRF Glass	2.49	2.52	2.5

Table 4.2 Maximum dry density and optimum moisture content of WG-cemented coquina-limerock mixtures

Mixtures			Compaction Test (ASTM D1557)	
Glass (%)	Cemented Coquina (%)	Limerock (%)	Maximum Dry Density (pcf)	Optimum Water Cont. (%)
0	100	-	129	8
10	90	-	128	8
15	85	-	130	7
20	80	-	129	7
30	70	-	129	8
40	60	-	129	8
50	50	-	129	8
60	40	-	128	9
70	30	-	128	9
80	20	-	122	8
90	10	-	117	5
100	0	0	110	4
0	-	100	129	8
10	-	90	129	8
15	-	85	129	8
20	-	80	130	8
30	-	70	130	8
40	-	60	130	9
50	-	50	130	9
60	-	40	122	8
70	-	30	119	7
80	-	20	116	7
90	-	10	113	6

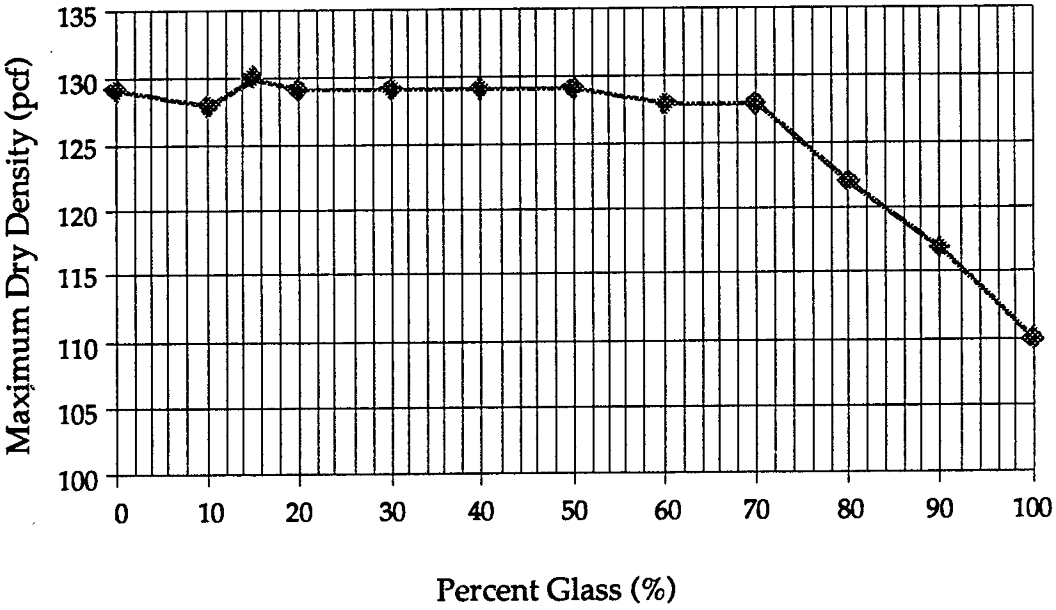


Figure 4.3 Maximum dry density versus the percentage of glass in the cemented coquina-WG mix (1 pcf=0.157KN/m^3)

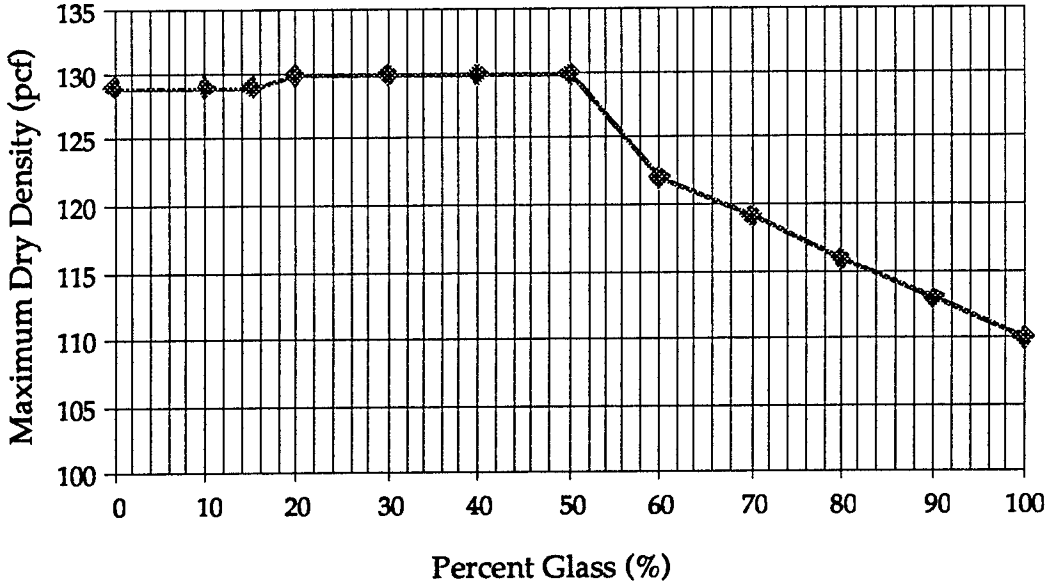


Figure 4.4 Maximum dry density versus the percentage of glass in the limerock-WG mix (1 pcf=0.157KN/m^3)

Table 4.3 Coefficient of permeability results for WG, cemented coquina, and limerock mixes

Glass (% by weight)	Cemented coquina (% by weight)	k (cm/sec)	Density (lb/cu.ft)	Relative Compaction (ASTM D1557)
0	100	0.17	123	95
20	80	0.52	119	92
40	60	0.67	115	89
60	40	0.74	110	87
80	20	0.85	106	90
100*	0*	0.3 - 2*	94 - 106*	85 - 95*

Glass (% by weight)	Limerock Base (% by weight)	k (cm/sec)	Density (lb/cu.ft)	% Max. Density ASTM-D1557
0	100	0.12	121	93
20	80	0.12	116	89
40	60	0.26	117	90
60	40	0.66	111	87
80	20	0.71	103	87
100*	0*	0.3 - 2*	94 - 106*	85 - 95*

* from Syed (1994)

(1 cm/sec = 0.394 in/sec)

(1 PCF = 0.157 KN/m^3)

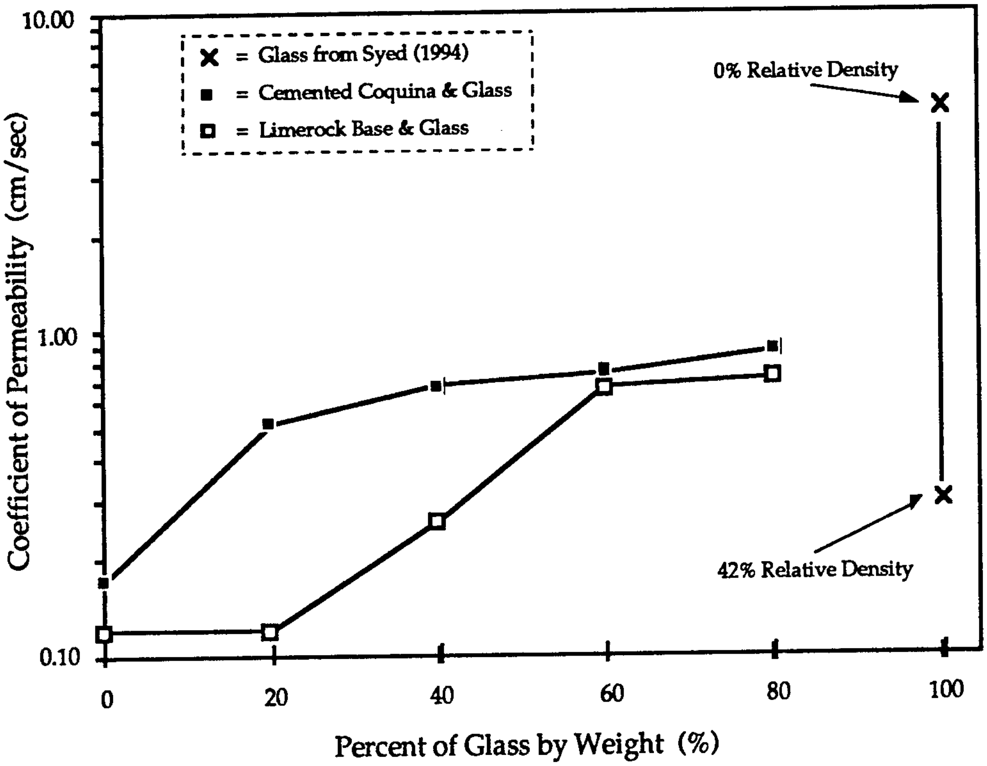


Figure 4.5 Coefficient of permeability versus percent of WG by weight for cemented coquina and limerock base mixes (1 cm/sec=0.394 in/sec)

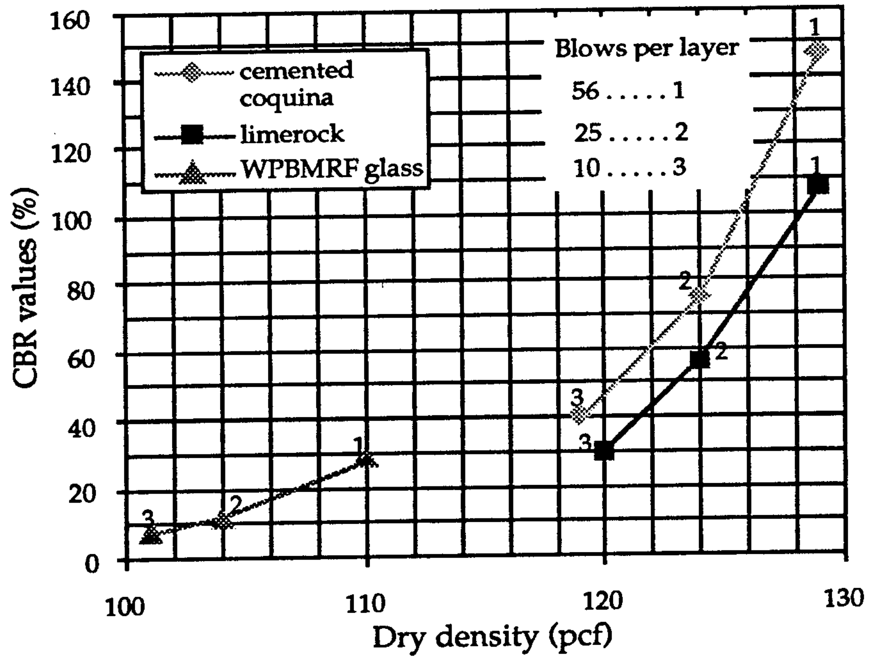


Figure 4.6 Soaked CBR versus dry density

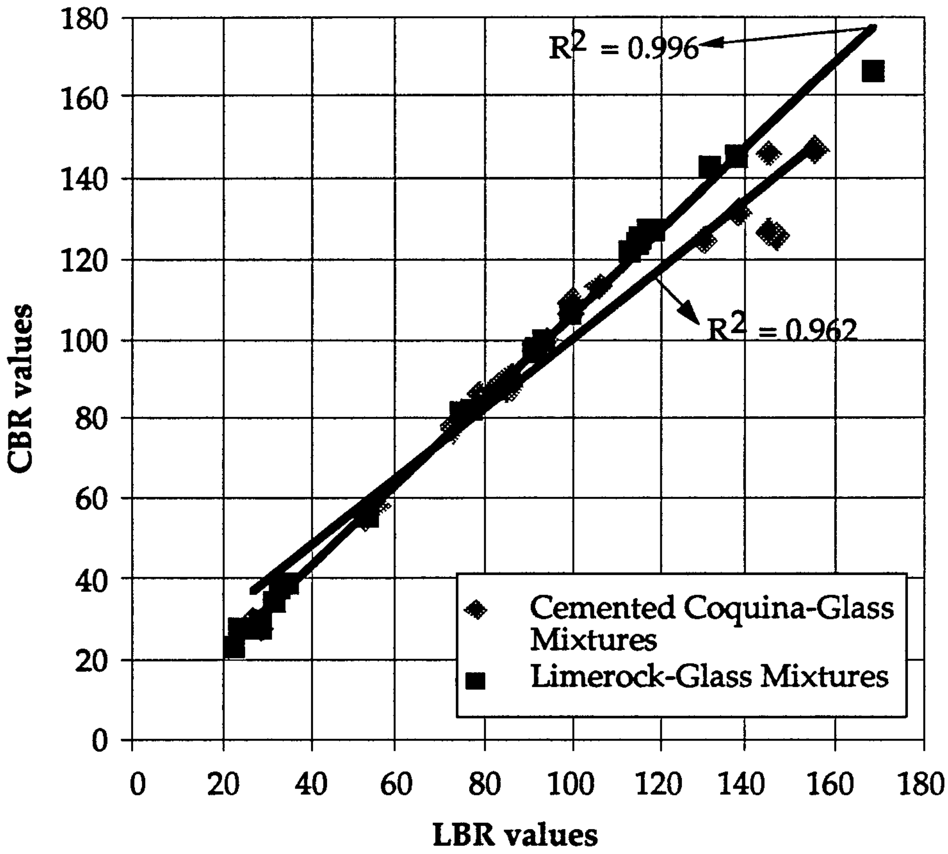


Figure 4.7 Correlation between CBR and LBR values for mixtures of WG with cemented coquina and limerock

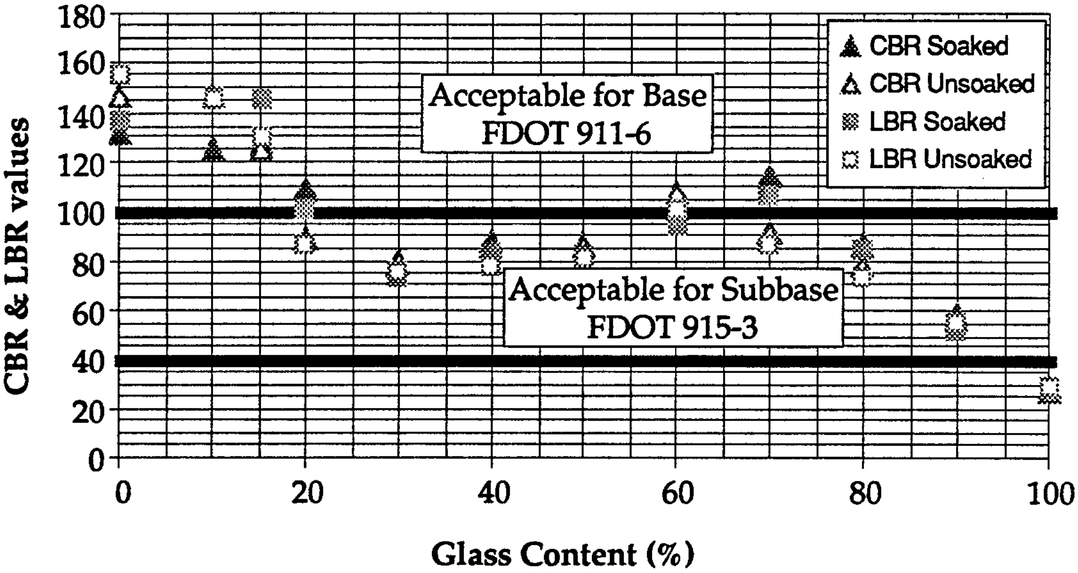


Figure 4.8 CBR and LBR values versus percentages of WG in cemented coquina-WG content (98±2% relative compaction ASTM D-1557)

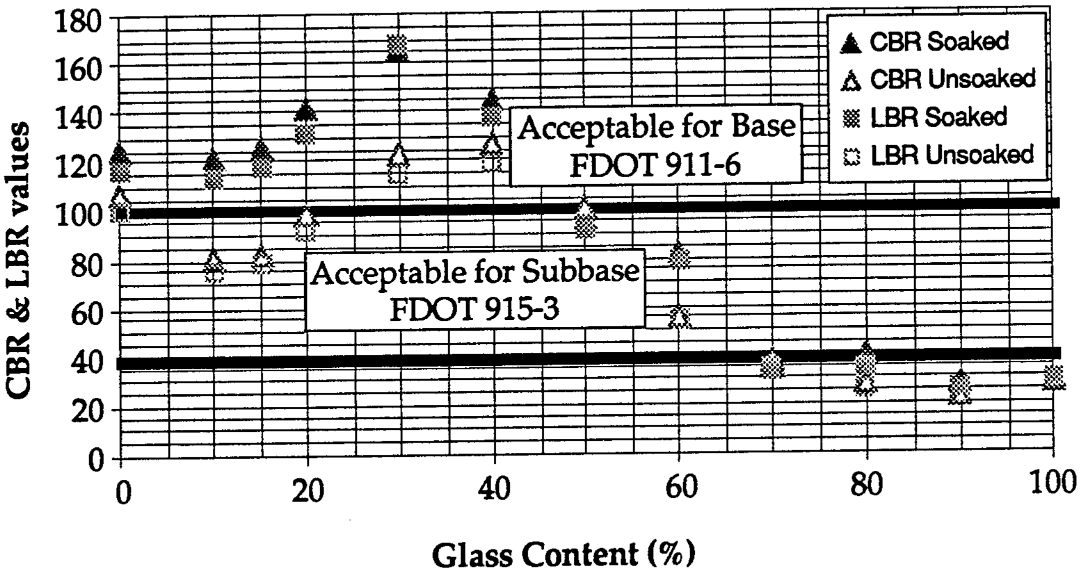


Figure 4.9 CBR and LBR values versus percentages of WG in limerock-WG content (98±2% relative compaction ASTM D-1557)

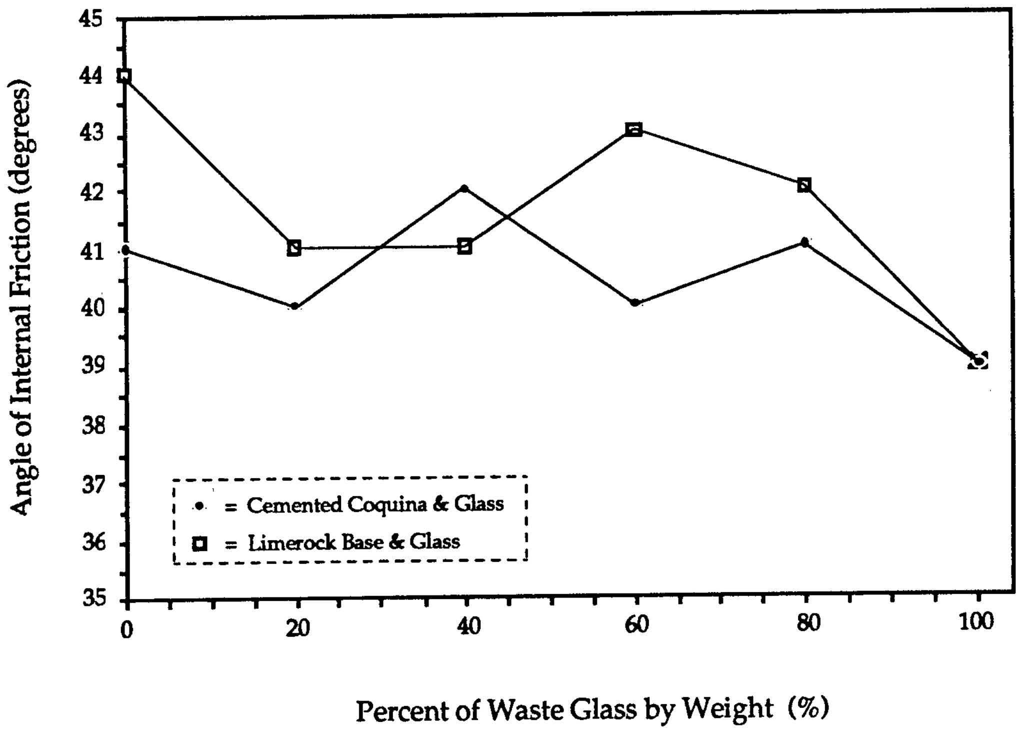


Figure 4.10 Angle of internal friction versus percent glass by weight for limerock base and cemented coquina

Table 4.4 CD triaxial shear results for WG, cemented coquina, and limerock mixes

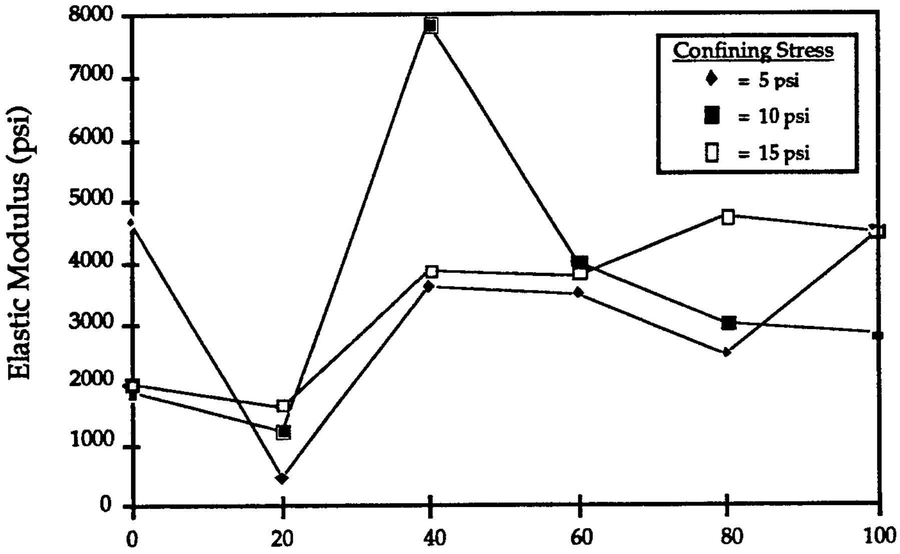
Mixtures			Maximum Compaction D 1557	Relative Compaction D 1557	Friction * angle
glass	cemented coquina	limerock base			
(%)	(%)	(%)	(PCF)	(%)	(deg)
100	0	0	112	95	39
0	100	-	130	91	41
20	80	-	128	90	40
40	60	-	129	95	42
60	40	-	129	91	40
80	20	-	118	94	41
0	-	100	129	97	44
20	-	80	130	93	41
40	-	60	130	90	41
60	-	40	127	90	43
80	-	20	118	93	42

* Friction angles based on zero cohesion assumption

(1 PCF = 0.157 KN/m^3)

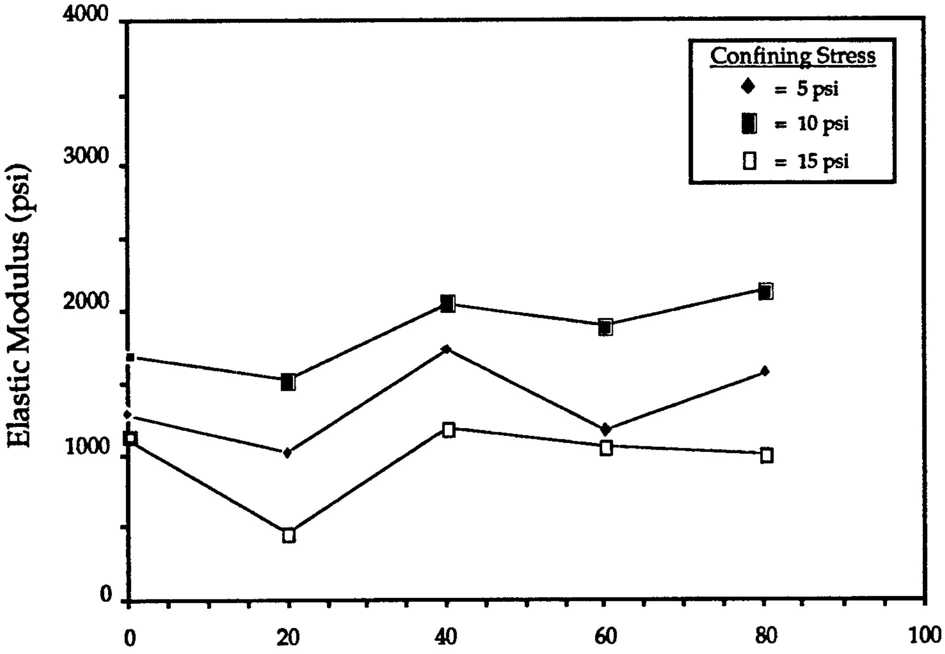
Table 4.5 Elastic modulus results for WG, cemented coquina, and limerock mixtures

Mixtures			Confining Pressure		Relative Compaction (ASTM-D1557)	Elastic Modulus initial tangent method	
glass	cemented coquina	limerock					
(%)	(%)	(%)	(psi)	(kPa)	(%)	(psi)	(kPa)
100	0	0	5	34.5	95	4500	31028
			10	69.0		2800	19306
			15	103.4		4480	30890
0	100	-	5	34.5	91	4680	32269
			10	69.0		1850	12756
			15	103.4		2000	13790
20	80	-	5	34.5	90	450	3103
			10	69.0		1200	8274
			15	103.4		1630	11239
40	60	-	5	34.5	95	3610	24891
			10	69.0		7850	54126
			15	103.4		3900	26891
60	40	-	5	34.5	91	3500	24133
			10	69.0		4000	27580
			15	103.4		3800	26201
80	20	-	5	34.5	94	2500	17238
			10	69.0		3000	20685
			15	103.4		4760	32820
0	-	100	5	34.5	97	3410	23512
			10	69.0		2000	13790
			15	103.4		3280	22616
20	-	80	5	34.5	93	2100	14480
			10	69.0		1900	13101
			15	103.4		2300	15859
40	-	60	5	34.5	90	2000	13790
			10	69.0		4850	33441
			15	103.4		5410	37302
60	-	40	5	34.5	90	2700	18617
			10	69.0		6210	42818
			15	103.4		8200	56539
80	-	20	5	34.5	93	2390	16479
			10	69.0		4400	30338
			15	103.4		4000	27580



Percent of Glass by Weight (%)

Figure 4.11 Elastic modulus calculated using the initial tangent method versus percent glass mixed with cemented coquina (1 psi=6.895 kPa)



Percent of Glass by Weight (%)

Figure 4.12 Elastic modulus at 2% strain versus percent glass mixed with cemented coquina (1 psi=6.895 kPa)

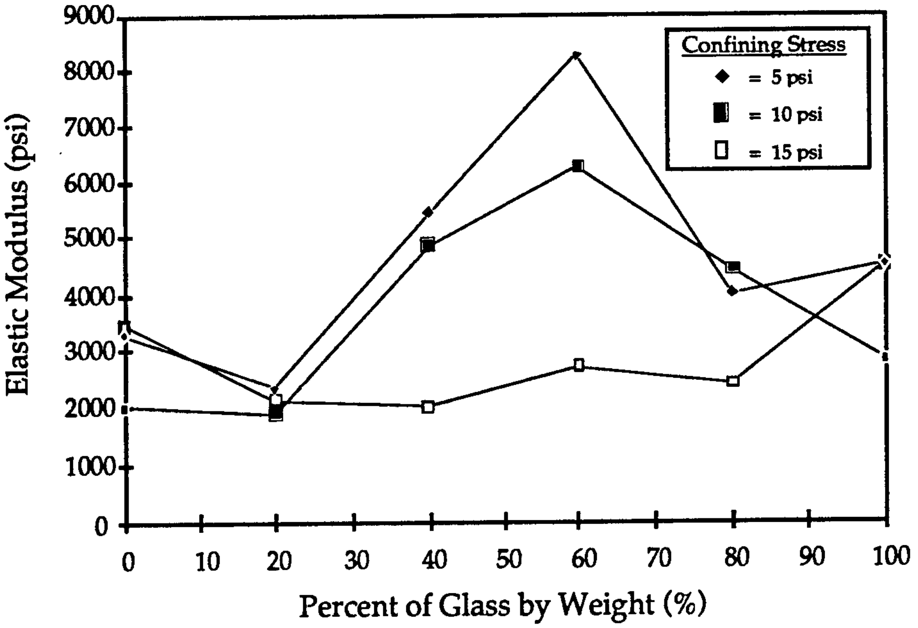


Figure 4.13 Elastic modulus calculated using the initial tangent method versus percent glass mixed with limerock base (1 psi=6.895 kPa)

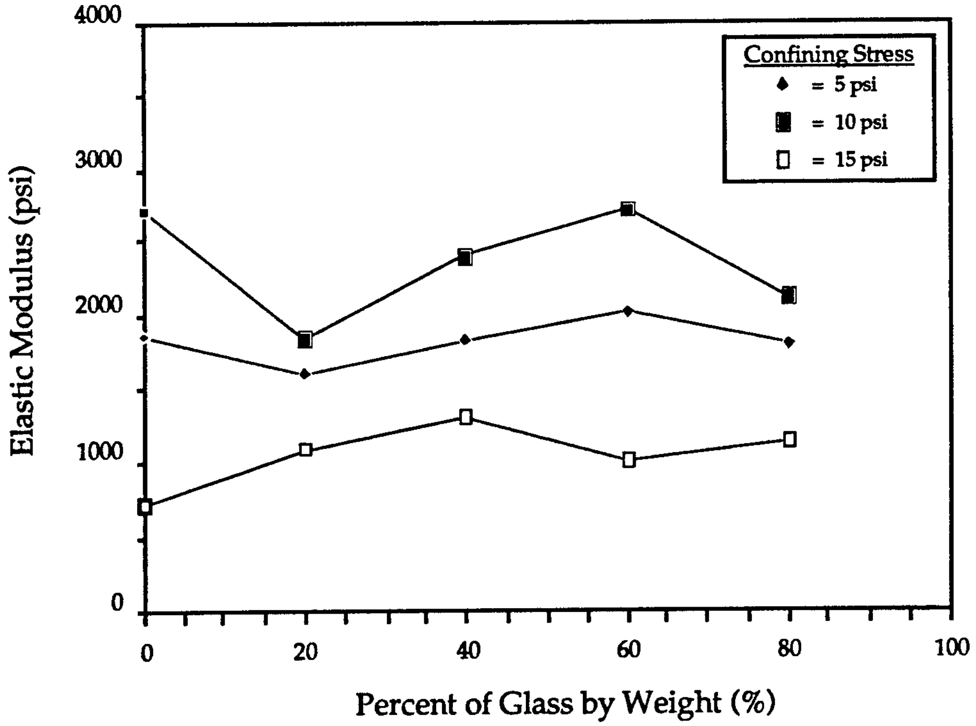


Figure 4.14 Elastic modulus at 2% strain versus percent glass mixed limerock base (1 psi=6.895 kPa)

Table 4.6 Resilient modulus results for WG, cemented coquina, and limerock mixes

Mixture			Confining	Relative	Deviator	Deviator	Deviator	Stress	Stress	Stress	Resilient Modulus		Resilient Modulus		Resilient Modulus	
glass	cemented coquina	limerock base	Pressure	Compaction	Stress	Stress	Stress	Invariant	Invariant	Invariant		Average		Average		Average
(%)	(%)	(%)	(psi)	(%)	(psi) σ1	(psi) σ2	(psi) σ3	(psi) θ1	(psi) θ2	(psi) θ3	(ksi) Mr1	(ksi) Mr1a	(ksi) Mr2	(ksi) Mr2a	(ksi) Mr3	(ksi) Mr3a
100	0	0	5	95	-	-	-	15.00	15.00	15.00	-	-	-	-	-	-
			10		-	-	-	30.00	30.00	30.00						
			15		-	-	-	45.00	45.00	45.00						
0	100	-	5	91	14.74	18.12	18.41	29.74	33.12	33.41	17.4	19.9	18.5	25.0	20.1	29.0
			10		9.19	18.80	23.50	39.19	48.80	53.50	17.6		23.5		25.0	
			15		13.00	21.81	30.89	58.00	66.81	75.89	24.8		33.1		42.0	
20	80	-	5	90	1.80	5.08	7.81	16.80	20.08	22.81	7.2	14.1	11.5	19.0	13.8	23.5
			10		8.64	12.72	18.86	38.64	42.72	48.86	13.8		19.0		20.4	
			15		8.05	20.50	28.14	53.05	65.50	73.14	21.2		26.4		36.6	
40	60	-	5	95	12.91	17.39	19.58	27.91	32.39	34.58	16.8	20.3	20.7	26.9	19.8	27.5
			10		22.46	27.34	31.00	52.46	57.34	61.00	21.2		29.0		26.7	
			15		14.96	29.65	37.50	59.96	74.65	82.50	22.8		30.9		36.0	
60	40	-	5	91	10.70	15.85	18.65	25.70	30.85	33.65	16.0	19.0	15.2	20.7	16.1	23.2
			10		12.68	17.31	20.44	42.68	47.31	50.44	15.0		16.7		23.9	
			15		15.57	27.22	34.63	60.57	72.22	79.63	26.0		30.2		29.6	
80	20	-	5	94	10.17	14.08	15.70	25.17	29.08	30.70	13.0	18.0	16.0	23.6	20.9	24.0
			10		15.24	22.83	28.61	45.24	52.83	58.61	20.6		25.4		22.2	
			15		23.10	32.76	39.51	68.10	77.76	84.51	20.4		29.5		28.8	
0	-	100	5	97	-	-	-	15.00	15.00	15.00	-	-	-	-	-	-
			10		-	-	-	30.00	30.00	30.00						
			15		-	-	-	45.00	45.00	45.00						
20	-	80	5	93	-	-	-	15.00	15.00	15.00	-	-	-	-	-	-
			10		-	-	-	30.00	30.00	30.00						
			15		-	-	-	45.00	45.00	45.00						
40	-	60	5	90	-	-	-	15.00	15.00	15.00	-	-	-	-	-	-
			10		-	-	-	30.00	30.00	30.00						
			15		-	-	-	45.00	45.00	45.00						
60	-	40	5	90	-	-	-	15.00	15.00	15.00	-	-	-	-	-	-
			10		-	-	-	30.00	30.00	30.00						
			15		-	-	-	45.00	45.00	45.00						
80	-	20	5	93	-	-	-	15.00	15.00	15.00	-	-	-	-	-	-
			10		-	-	-	30.00	30.00	30.00						
			15		-	-	-	45.00	45.00	45.00						

Mr1 = Resilient Modulus @ 0.9 % strain
Mr2 = Resilient Modulus @ 1.8 % strain
Mr3 = Resilient Modulus @ 2.7 % strain
a = average

Conversion Factors:
1 psi = 6.895 kPa
1 ksi = 6.895 MPa
1 PCF = 0.157 KN/m^3

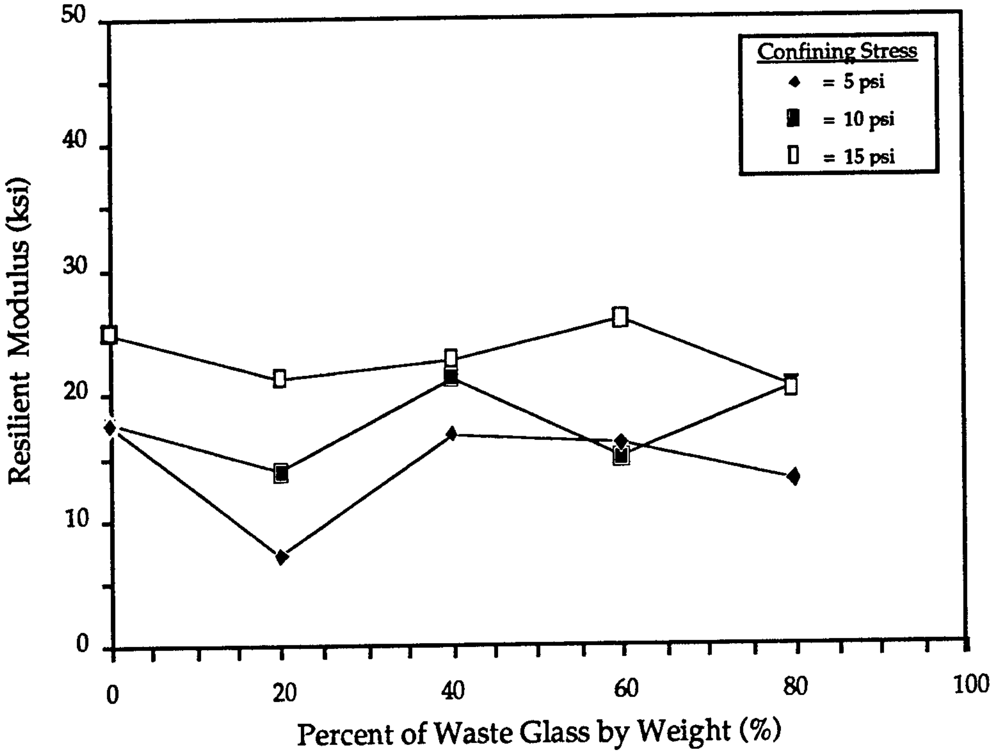


Figure 4.15 Resilient modulus at 0.9% strain versus percent of glass content mixed with cemented coquina (1 ksi=6.895 Mpa)

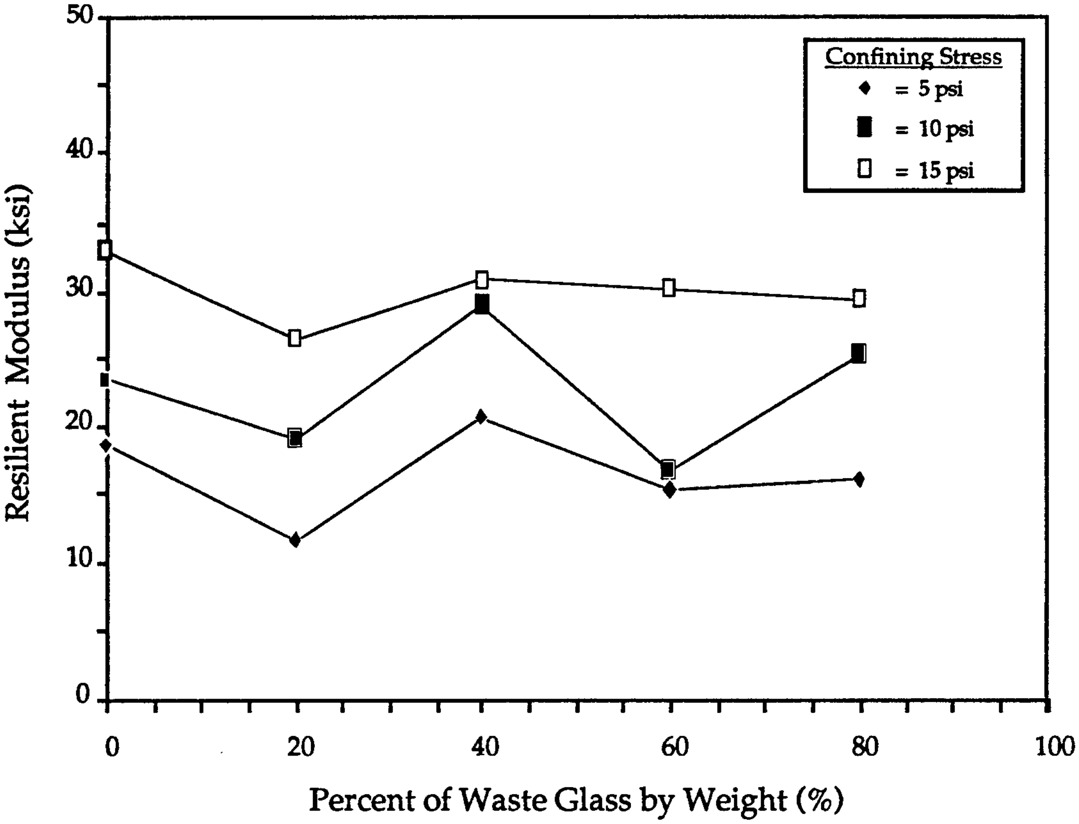


Figure 4.16 Resilient modulus at 1.8% strain versus percent of glass content mixed with cemented coquina (1 ksi=6.895 Mpa)

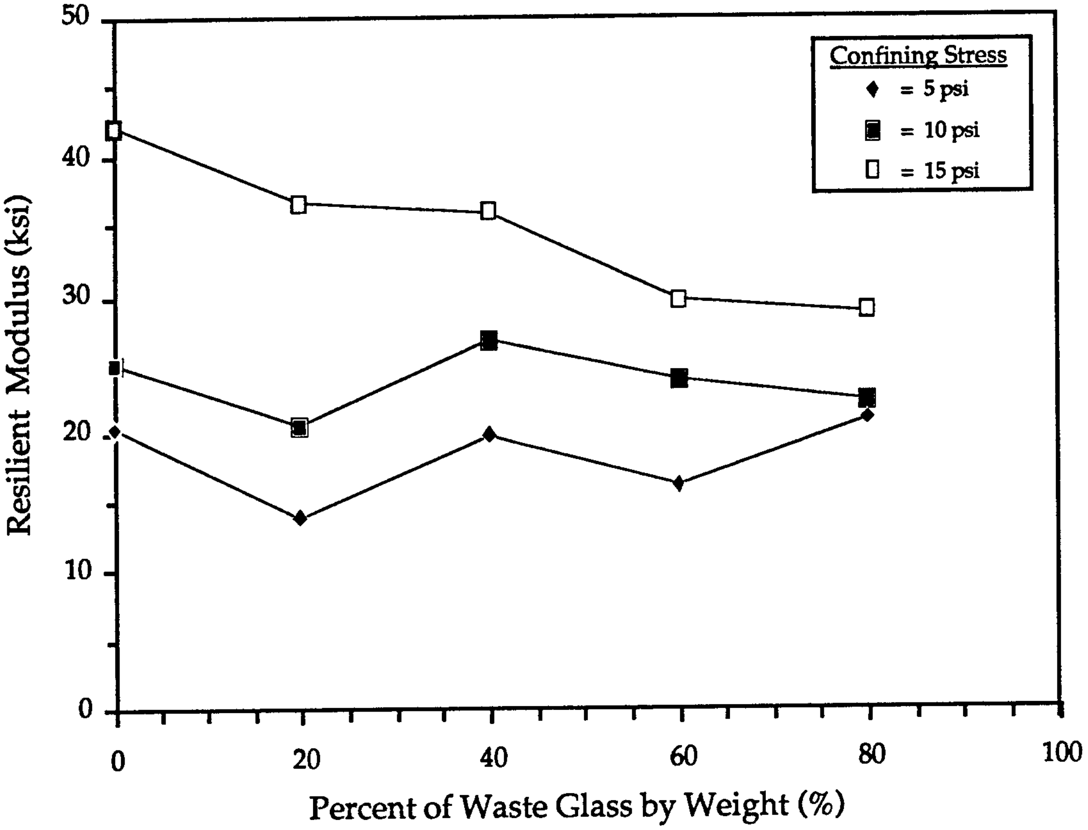


Figure 4.17 Resilient modulus at 2.7% strain versus percent of glass content mixed with cemented coquina (1 ksi=6.895 Mpa)

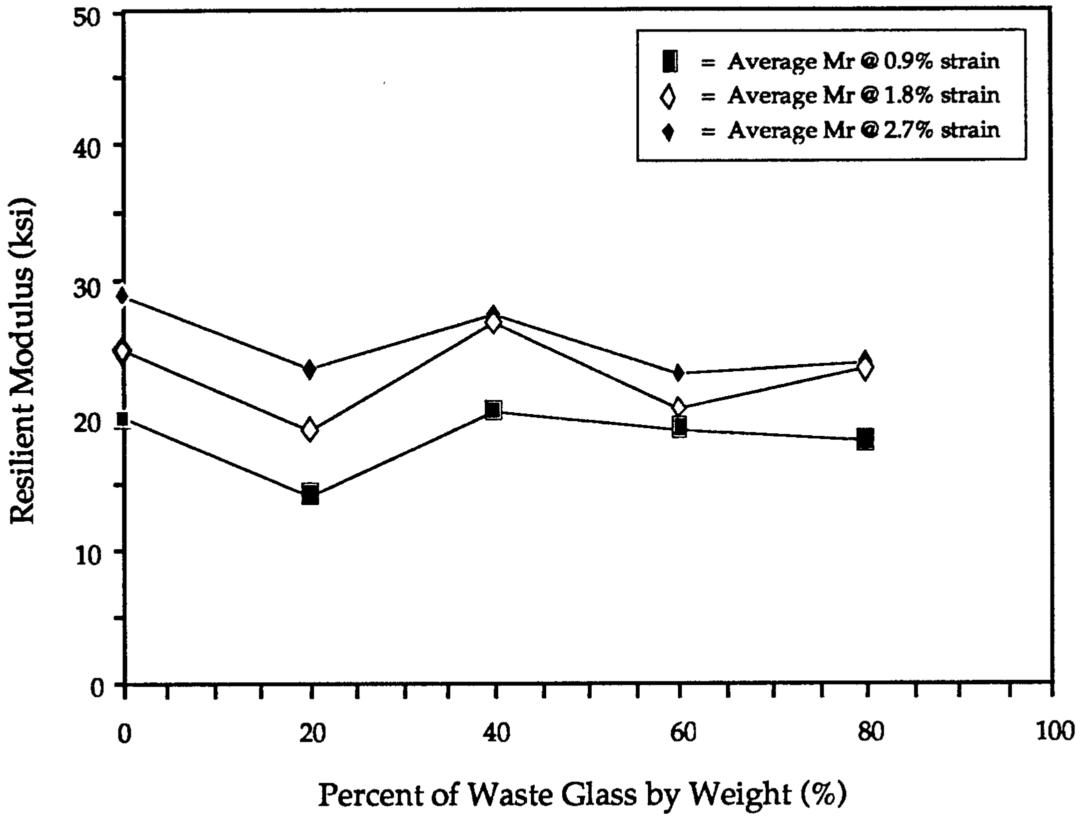


Figure 4.18 Average resilient modulus from CD triaxial tests versus percent glass content mixed with cemented coquina (1 ksi=6.895 Mpa)

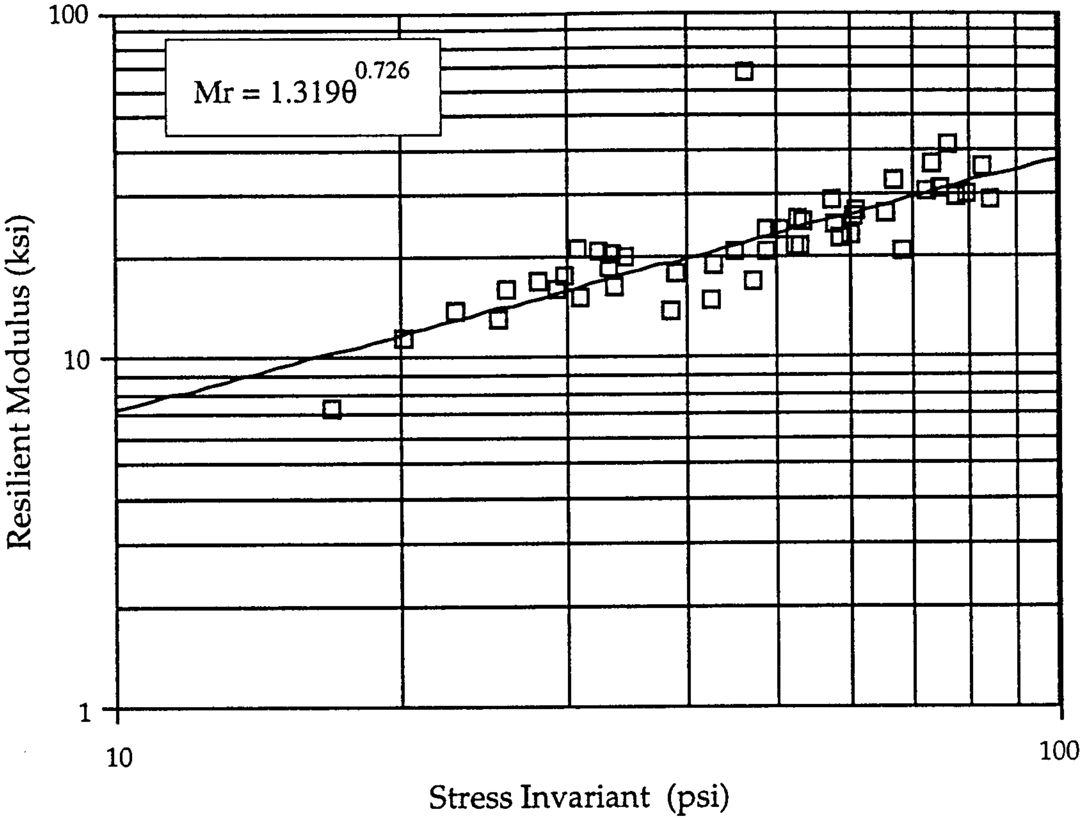


Figure 4.19 Resilient moduli over 0.05% resilient or unload strain versus stress invariant from CD triaxial tests (1 psi=6.895 kPa)

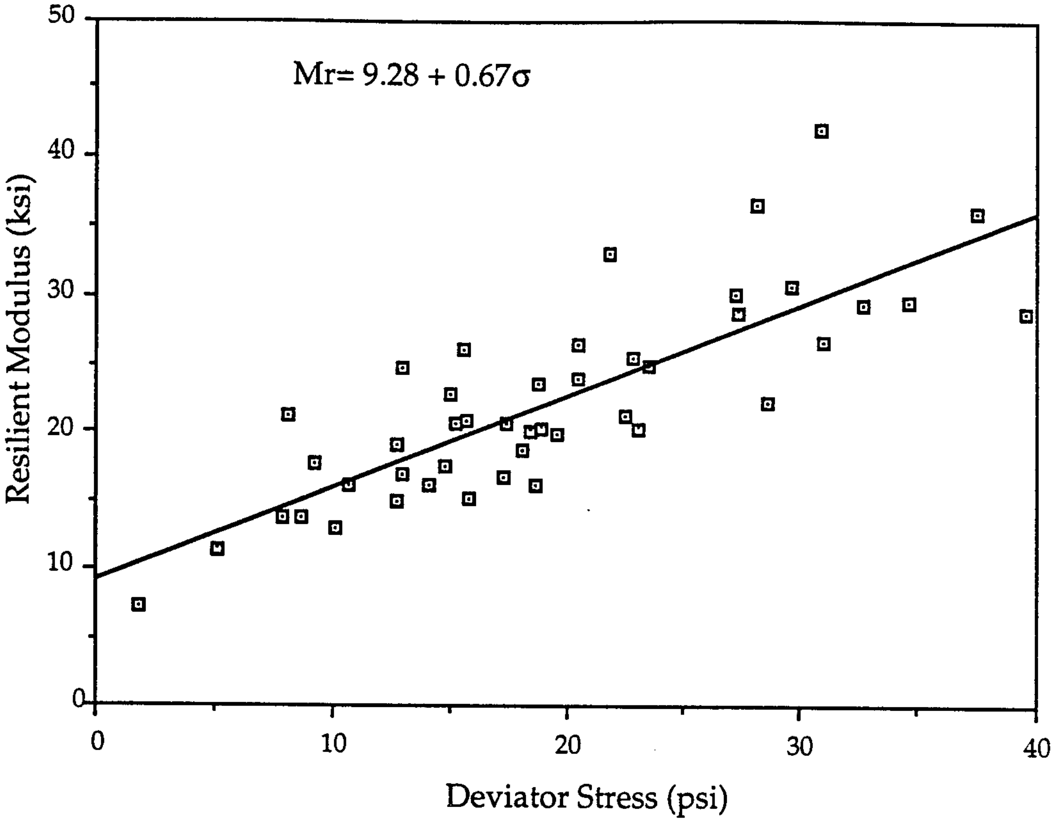


Figure 4.20 Resilient moduli over 0.05% resilient or unload strain versus deviator stress from CD triaxial tests (1 ksi=6.895 Mpa)

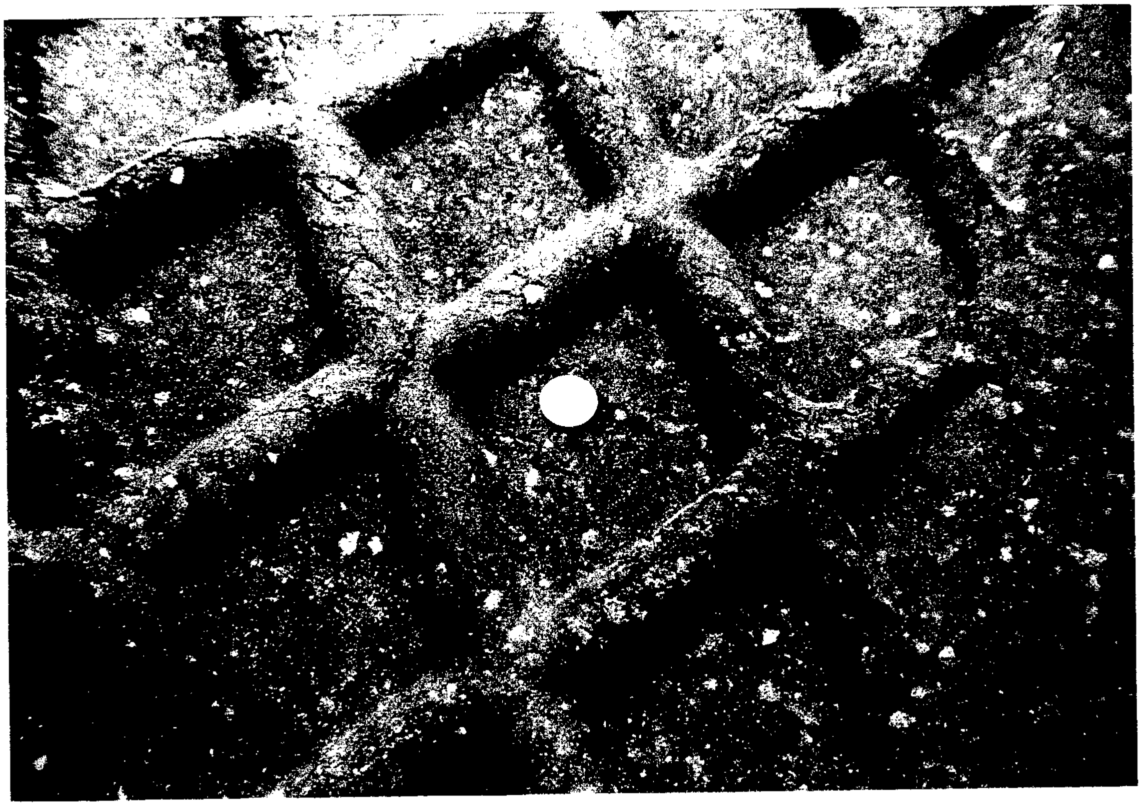


Figure 5.3 WG and reclaimed material after mixing

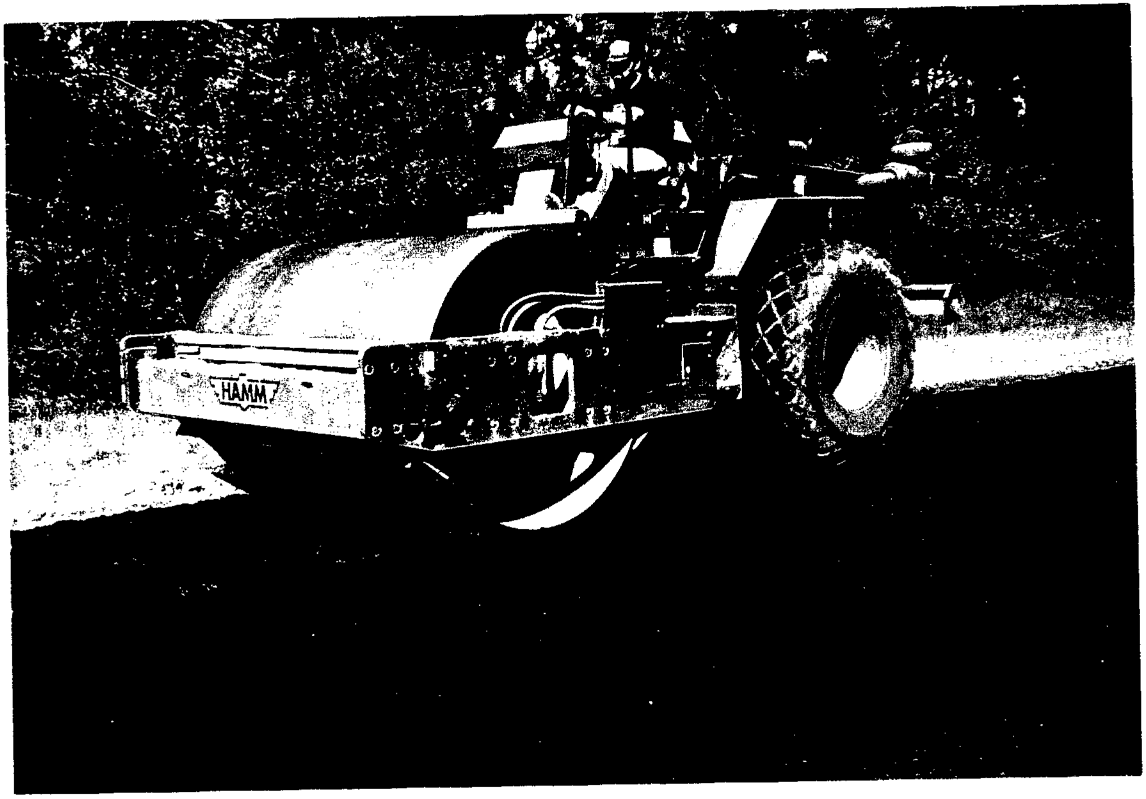


Figure 5.4 Compaction with the vibratory compactor

Table 5.3 Test results after mixing as measured from the nuclear densometer and oven methods

Optimum Moisture (ASTM D-698)	9.3%
Maximum Dry Density (ASTM D-698)	127 pcf

Location	Dry Density (PCF)	Moisture Content (FDOT oven)	Moisture Content (speedy)	Moisture Content (nuclear)	Moisture Content (Florida Tech oven)
50 feet from south edge (east)	119.2	9.6	8.4	11.8	8.4
75 feet from south edge (center)	120.6	9.3	_	11.6	9.6
125 feet from south edge (east)	119.2	9.8	8.0	11.8	9.2
150 feet from south edge (east)	121.6	9.2	_	11.1	8.5
175 feet from south edge (center)	122.3	8.8	5.6	10.5	8.7
200 feet from south edge (center)	124.1	8.3	_	9.5	7.9
225 feet from south edge (east)	120.4	9.2	7.6	10.5	9.0
250 feet from south edge (center)	120.4	8.2	_	9.5	16.5
300 feet from south edge (west)	118.4	_	_	12.8	_
Average	120.7	9.0	7.4	11.0	9.7

Table 5.4 CBR and Clegg Impact test results

Location	CBR Value	Clegg Impact Value
50 feet from south edge (center)	19.3	17
75 feet from south edge (east)	10.8	12
125 feet from south edge (center)	22.1	14
150 feet from south edge (center)	26.0	12
175 feet from south edge (east)	9.5	8
200 feet from south edge (east)	8.9	6
225 feet from south edge (center)	21.4	10
250 feet from south edge (east)	16.0	9
300 feet from south edge (center)	16.3	9
Average	16.7	11

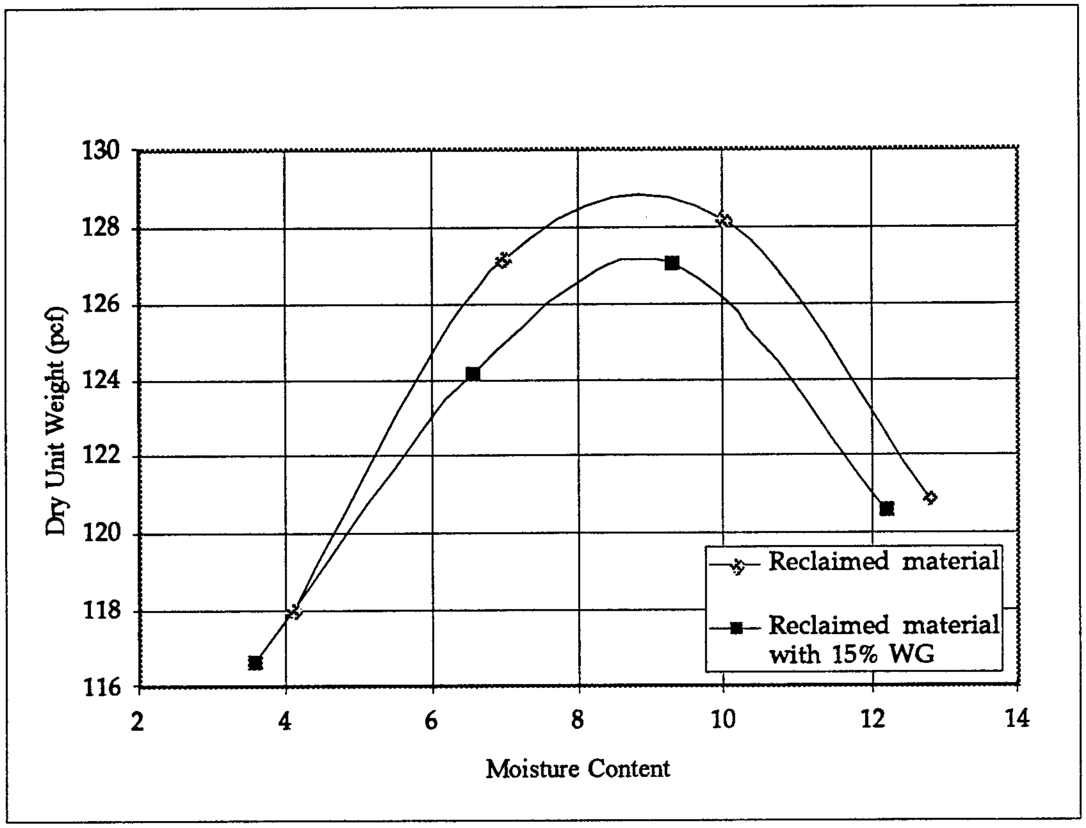


Figure 5.5 Moisture density curves (ASTM D-698) for reclaimed material and reclaimed material with 15% WG

APPENDIX A

The Moisture-Dry Density Relations

The Optimum Moisture Content, The Maximum Dry Density

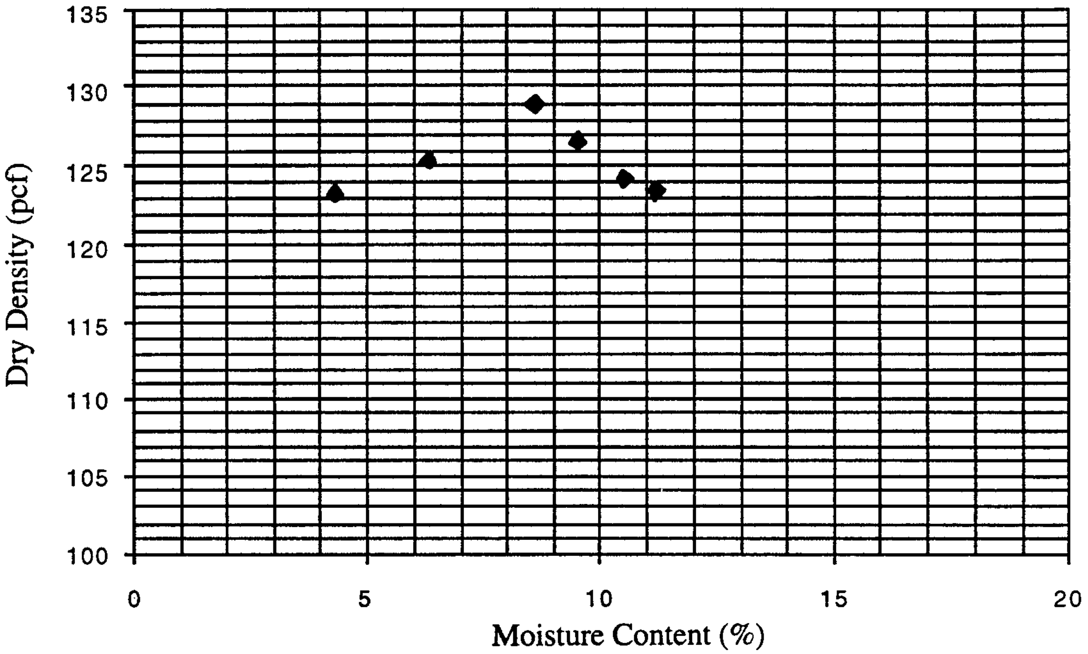


Figure A-1. The Optimum Moisture Content of 100% Cemented Coquina Base

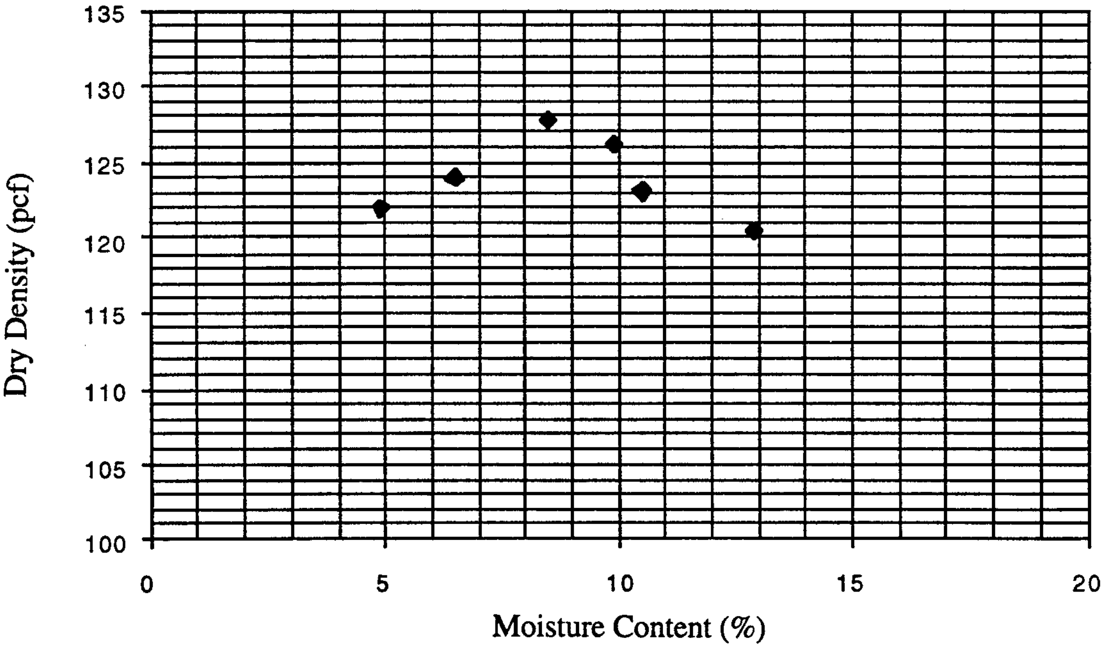


Figure A-2. The Optimum Moisture Content of 90% Cemented Coquina and 10% WPBMRF Glass Blend

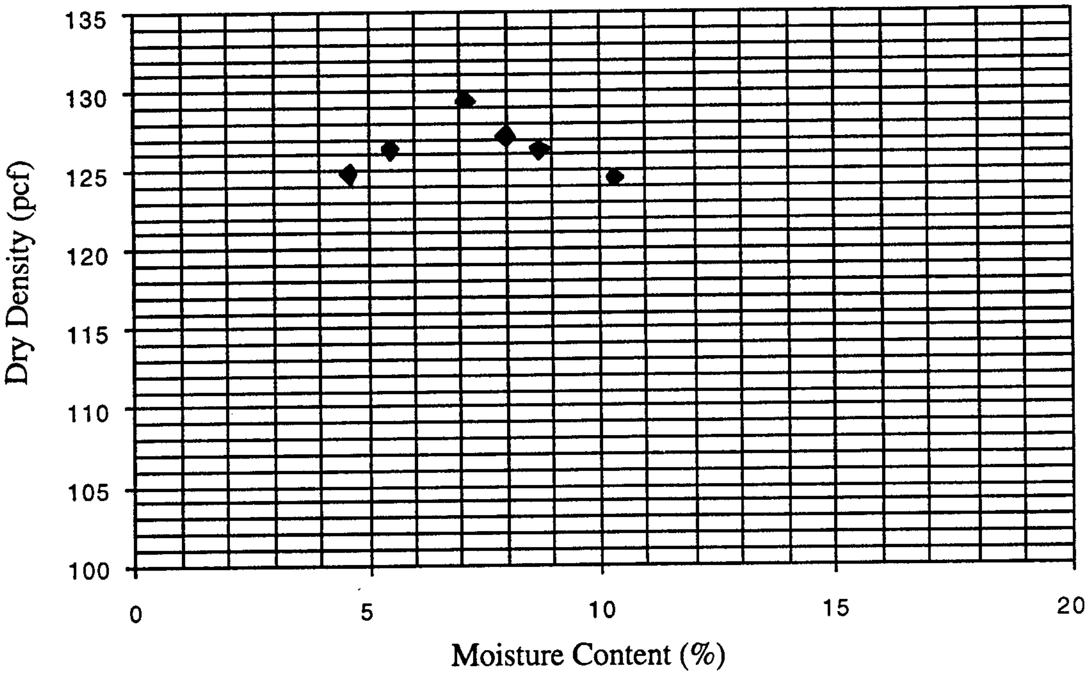


Figure A-3. The Optimum Moisture Content of 85% Cemented Coquina and 15% WPBMRF Glass Blend

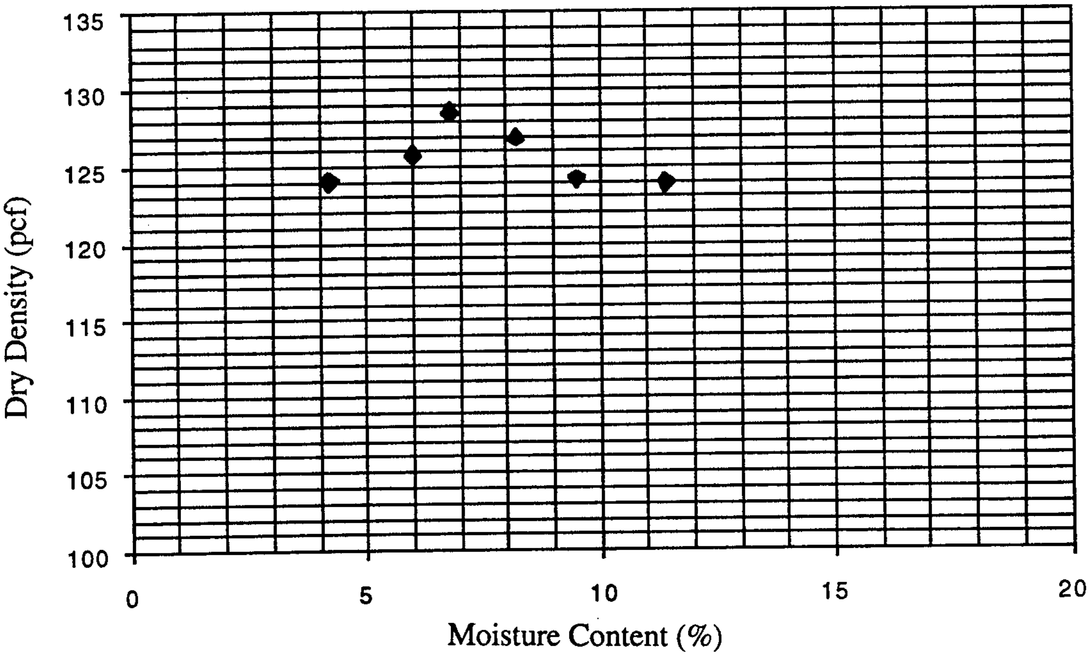


Figure A-4. The Optimum Moisture Content of 80% Cemented Coquina and 20% WPBMRF Glass Blend

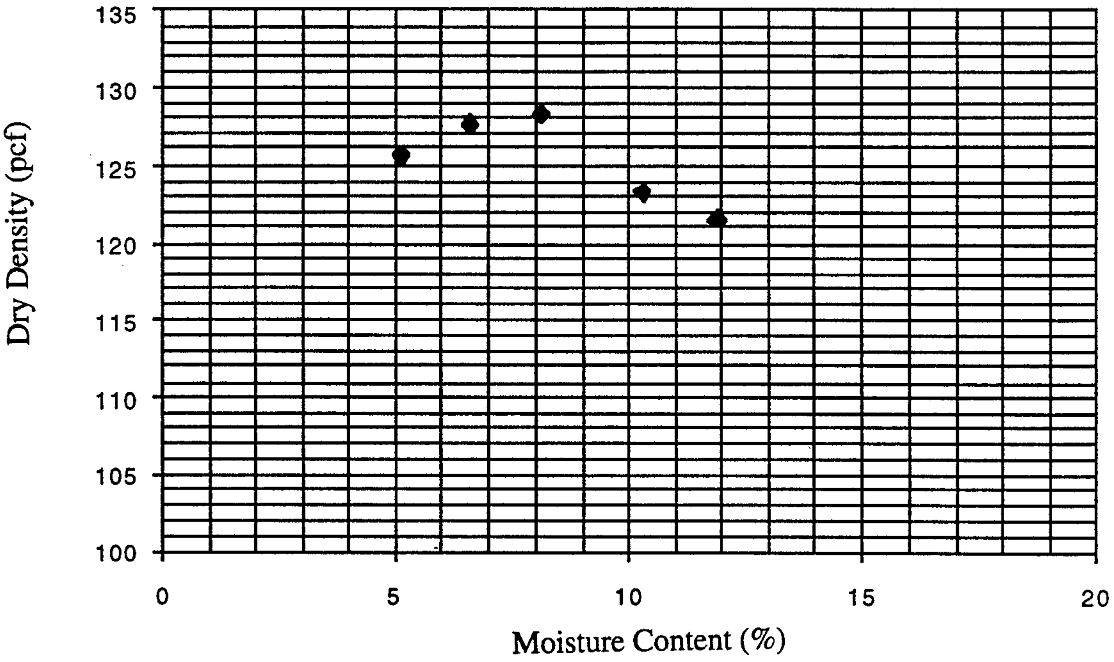


Figure A-5. The Optimum Moisture Content of 70% Cemented Coquina and 30% WPBMRF Glass Blend

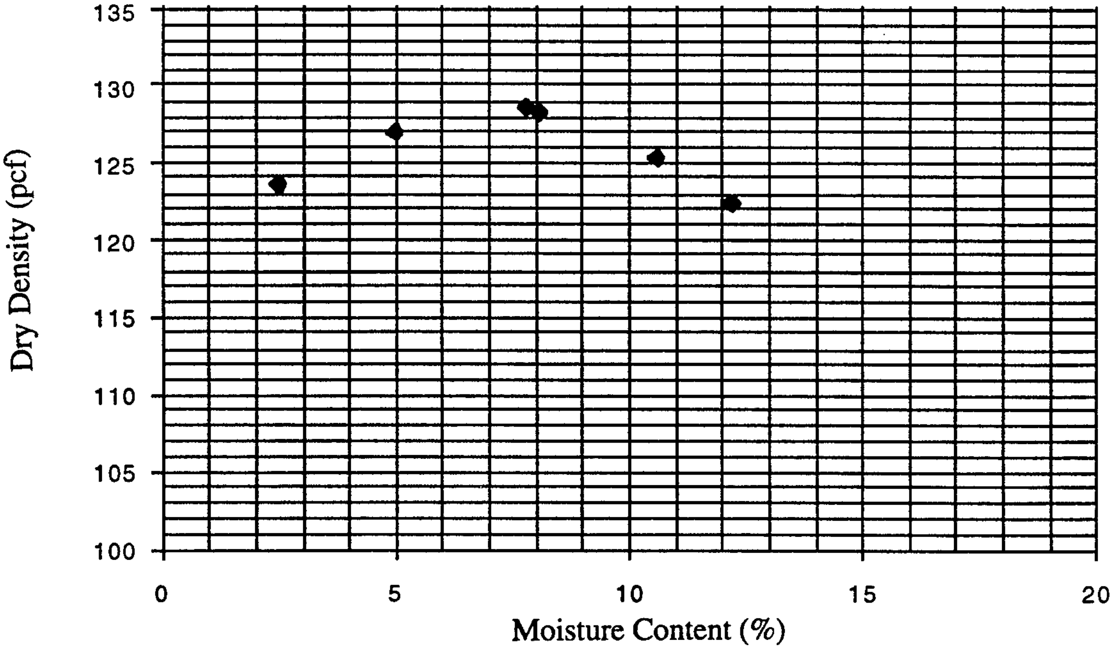


Figure A-6. The Optimum Moisture Content of 60% Cemented Coquina and 40% WPBMRF Glass Blend

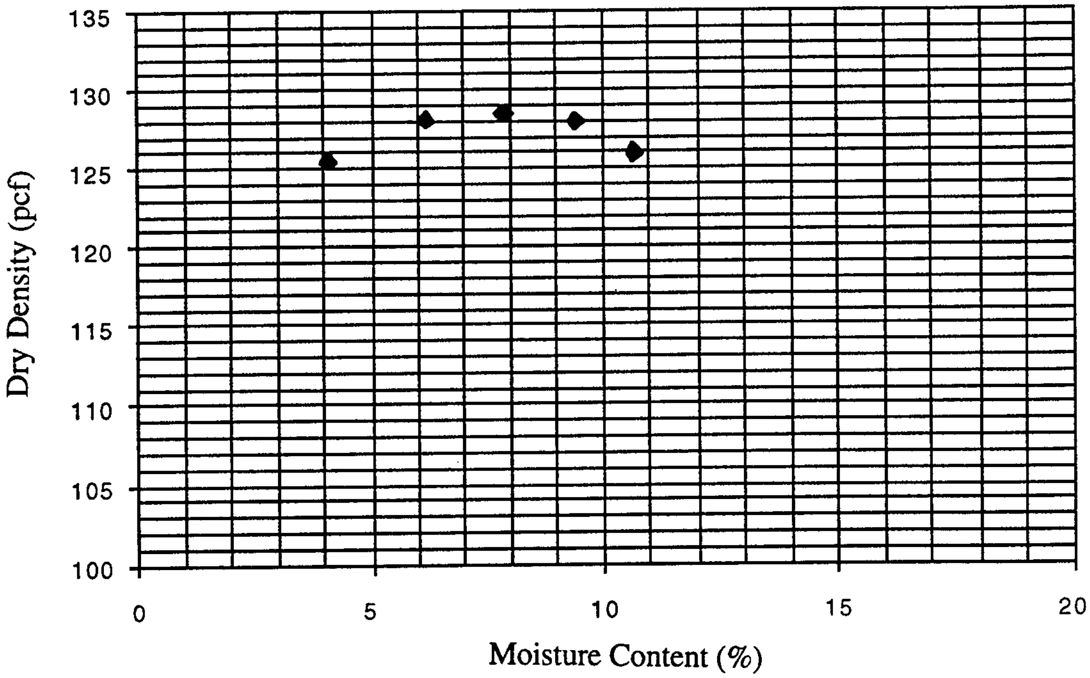


Figure A-7. The Optimum Moisture Content of 50% Cemented Coquina and 50% WPBMRF Glass Blend

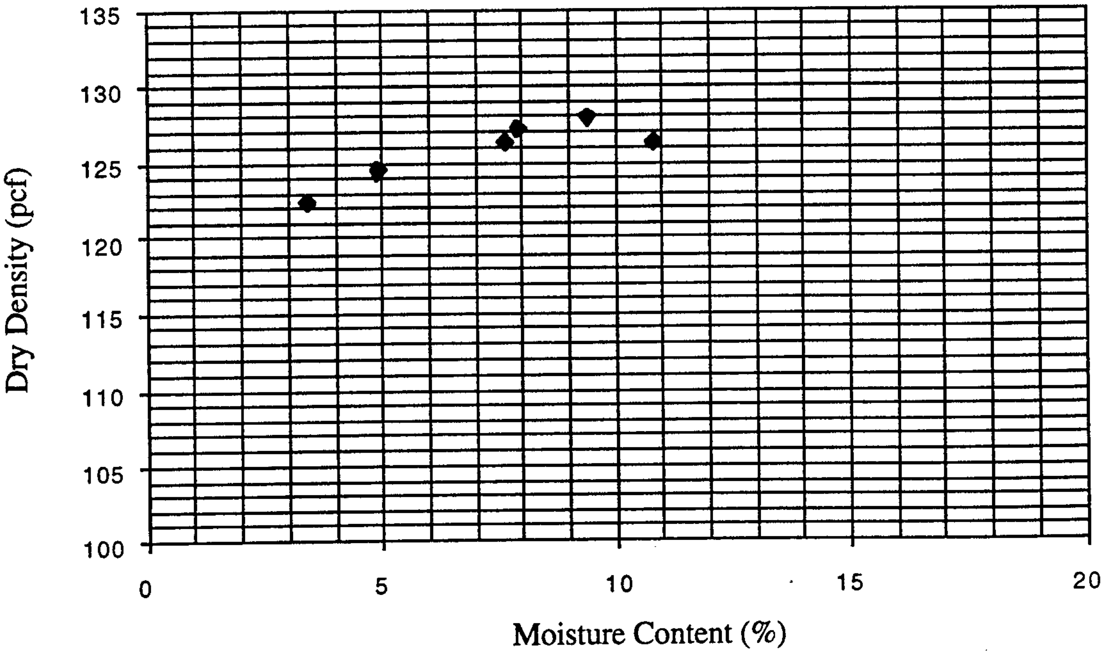


Figure A-8. The Optimum Moisture Content of 40% Cemented Coquina and 60% WPBMRF Glass Blend

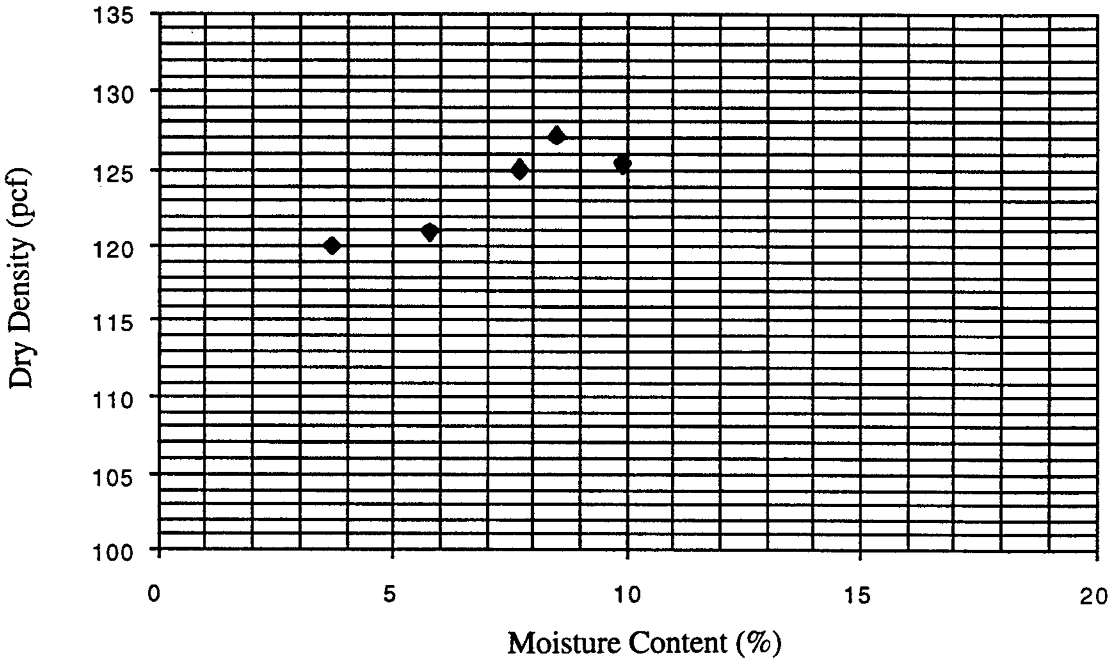


Figure A-9. The Optimum Moisture Content of 30% Cemented Coquina and 70% WPBMRF Glass Blend

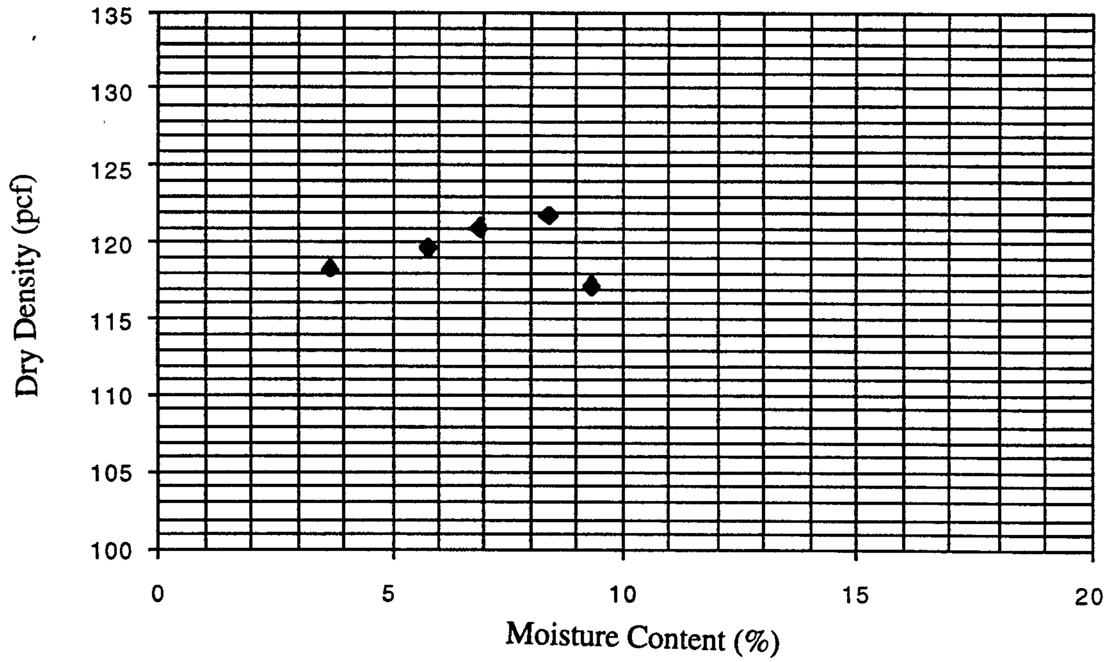


Figure A-10. The Optimum Moisture Content of 20% Cemented Coquina and 80%WPBMRF Glass Blend

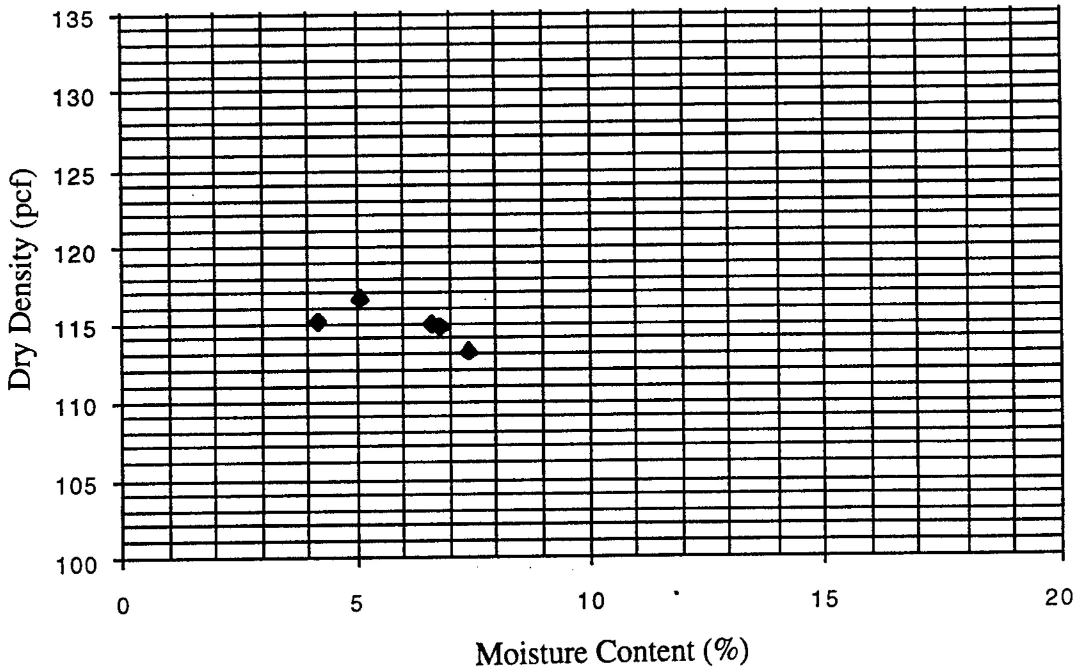


Figure A-11. The Optimum Moisture Content of 10% Cemented Coquina and 90% WPBMRF Glass Blend

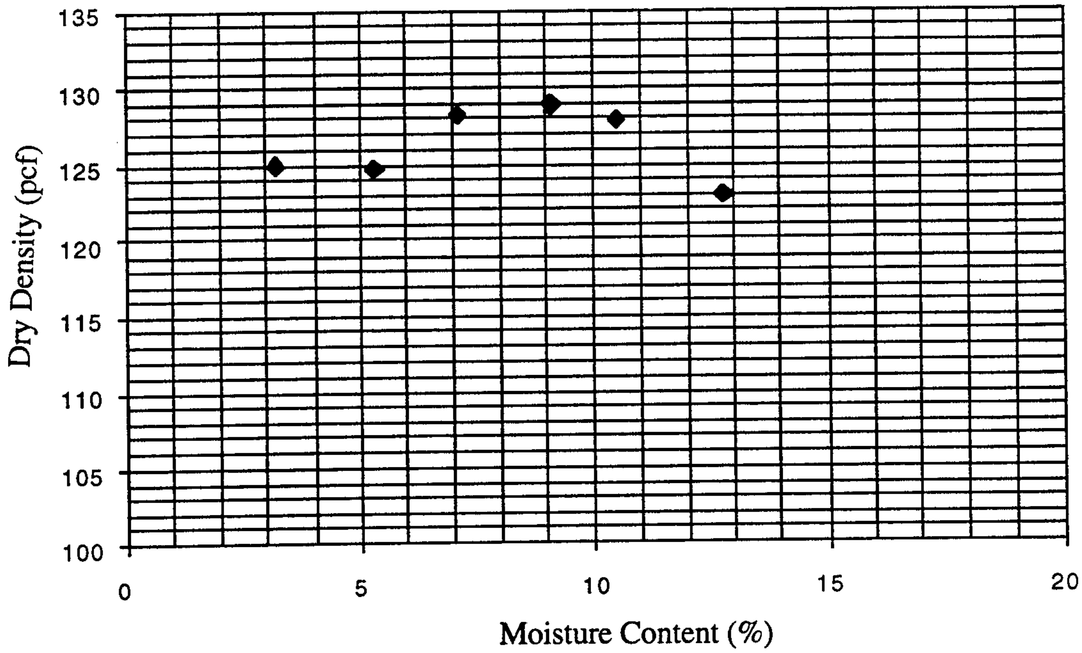


Figure A-12. The Optimum Moisture Content of 100% Limerock Base

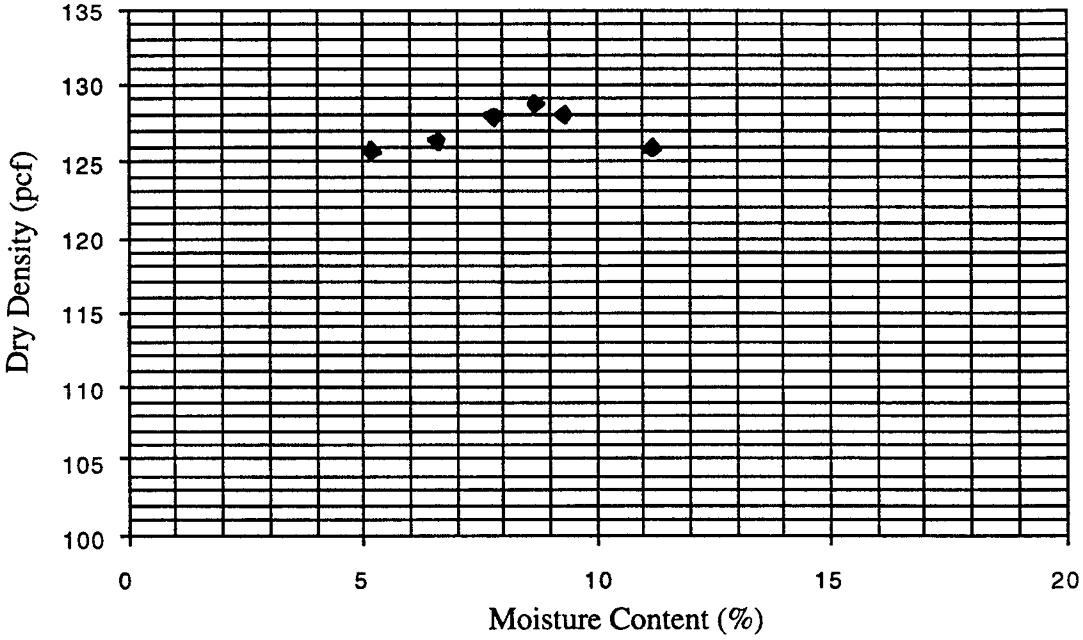


Figure A-13. The Optimum Moisture Content of 90% Limerock and 10% WPBMRF Glass Blend

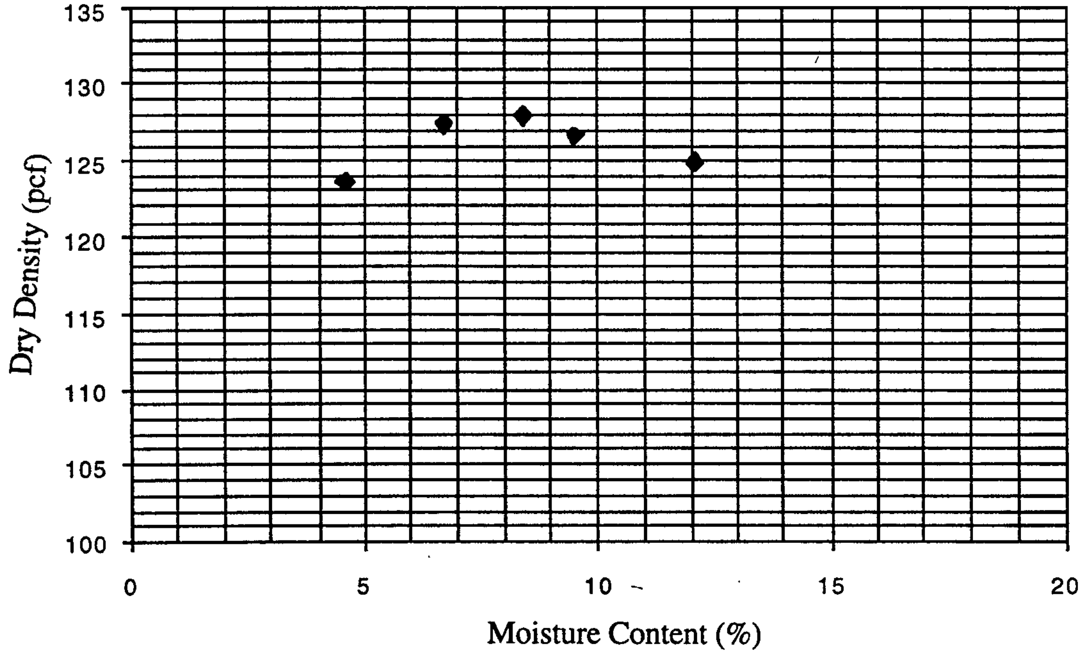


Figure A-14. The Optimum Moisture Content of 85% Limerock and 15% WPBMRF Glass Blend

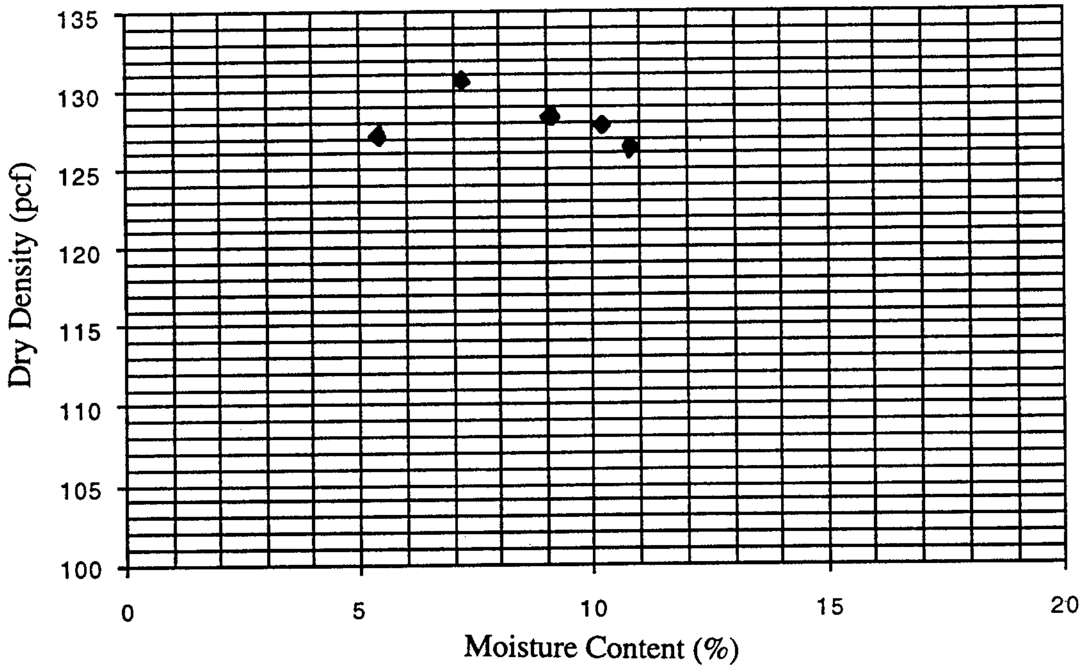


Figure A-15. The Optimum Moisture Content of 80% Limerock and 20% WPBMRF Glass Blend

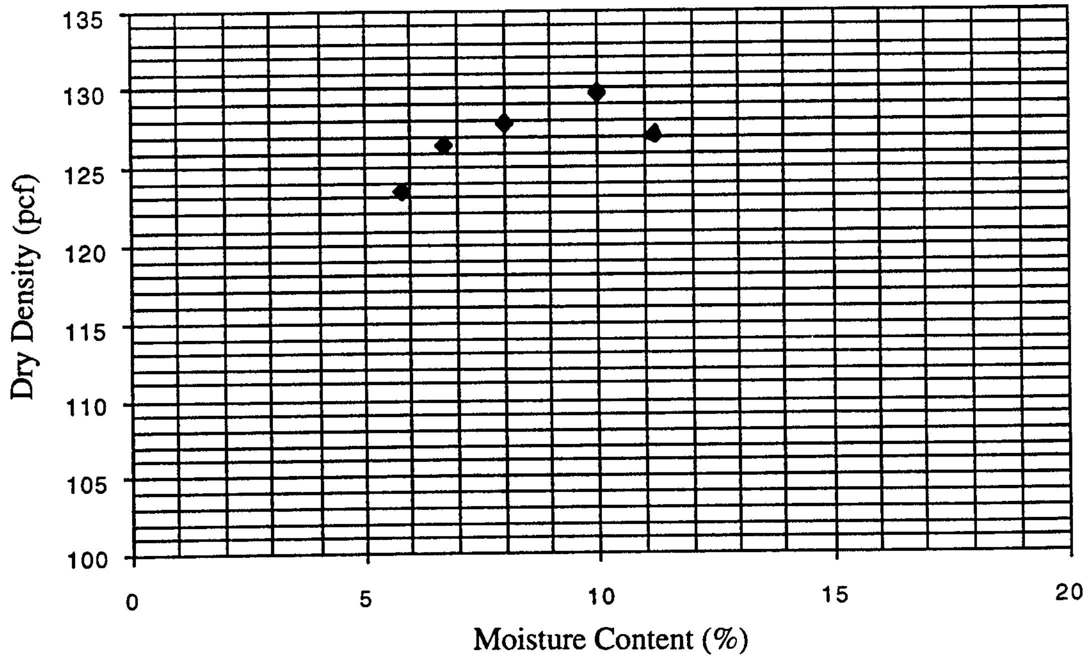


Figure A-16. The Optimum Moisture Content of 70% Limerock and 30% WPBMRF Glass Blend

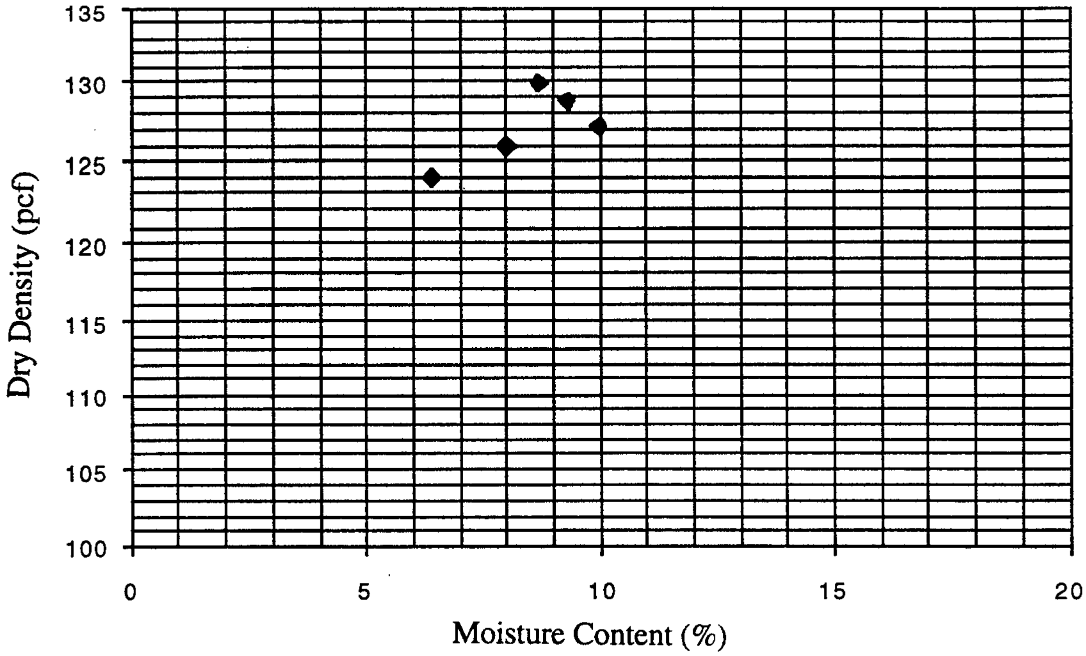


Figure A-17. The Optimum Moisture Content of 60% Limerock and 40% WPBMRF Glass Blend

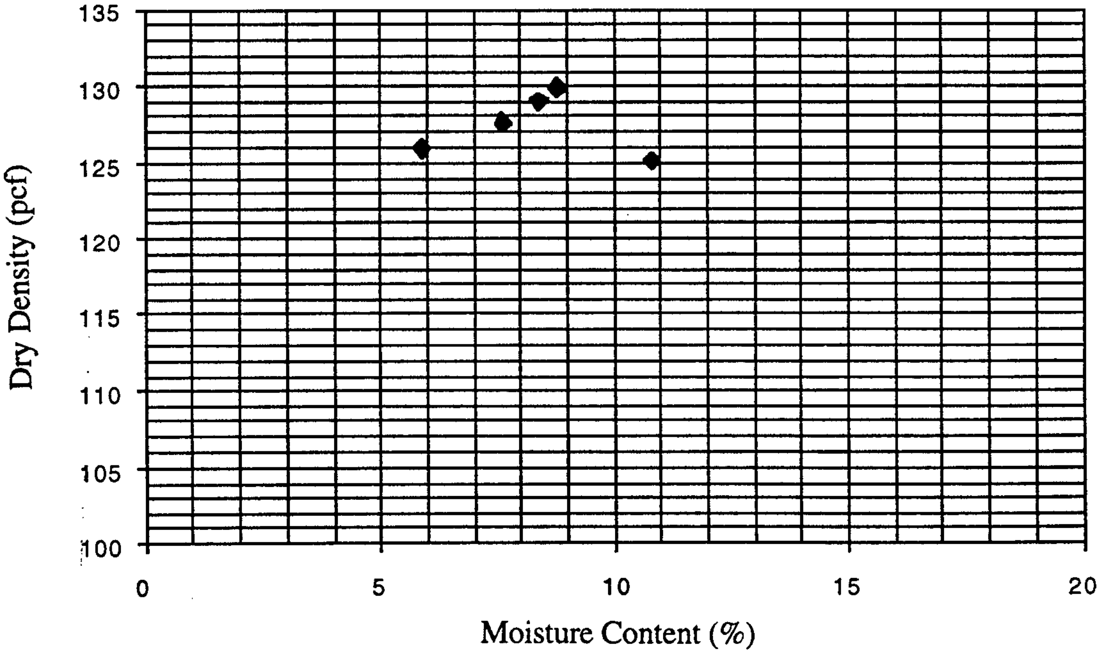


Figure A-18. The Optimum Moisture Content of 50% Limerock and 50% WPBMRF Glass Blend

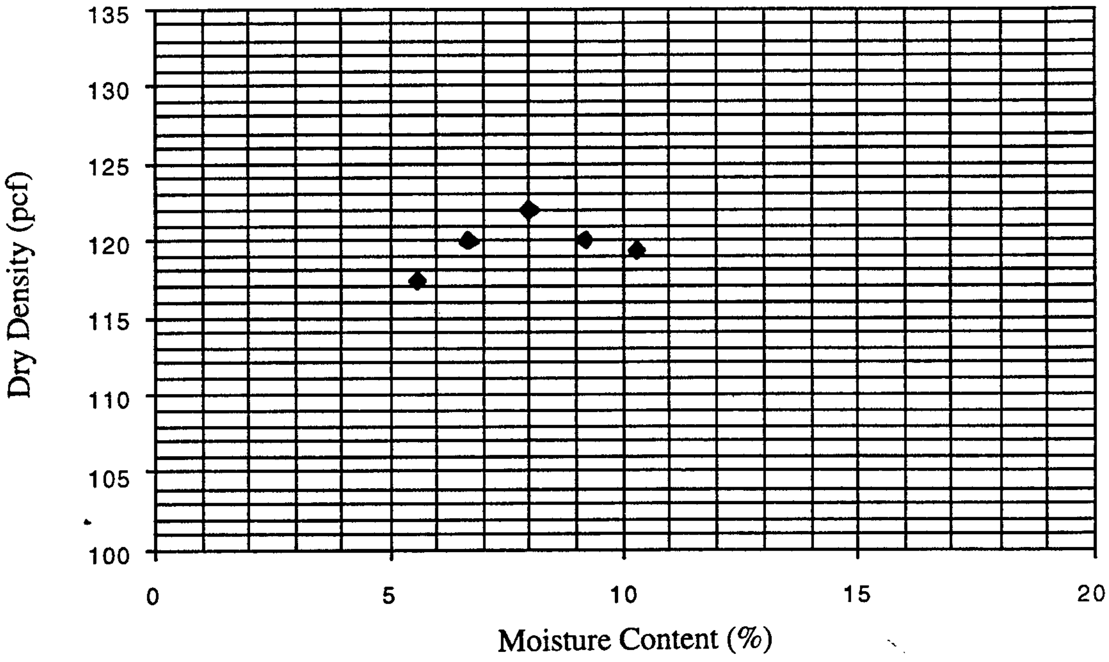


Figure A-19. The Optimum Moisture Content of 40% Limerock and 60% WPBMRF Glass Blend

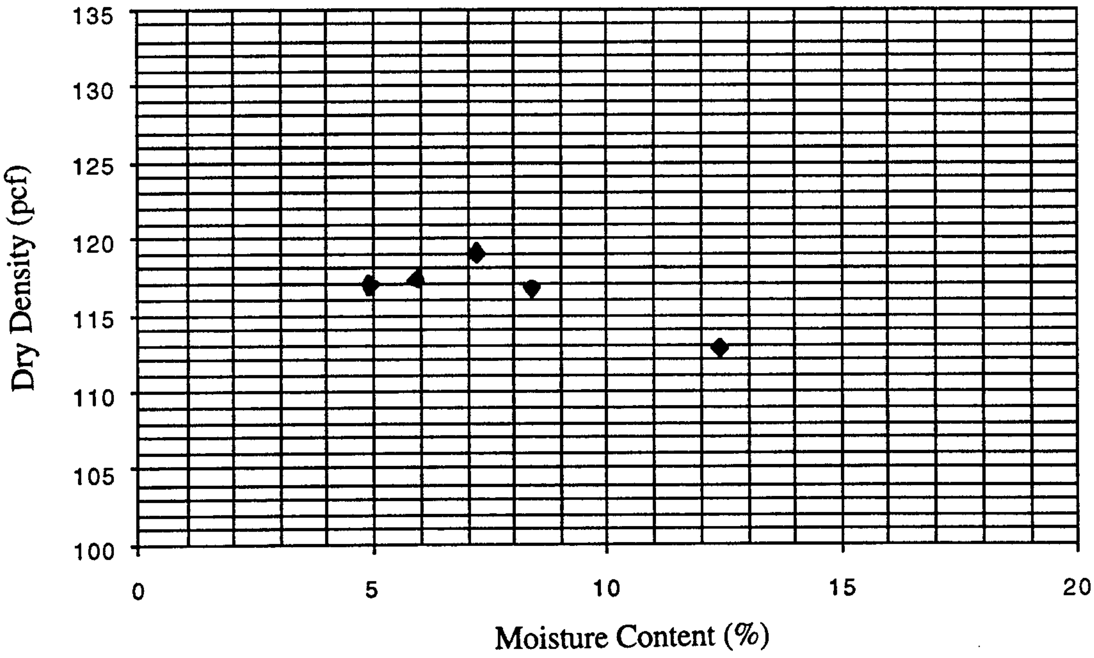


Figure A-20. The Optimum Moisture Content of 30% Limerock and 70% WPBMRF Glass Blend

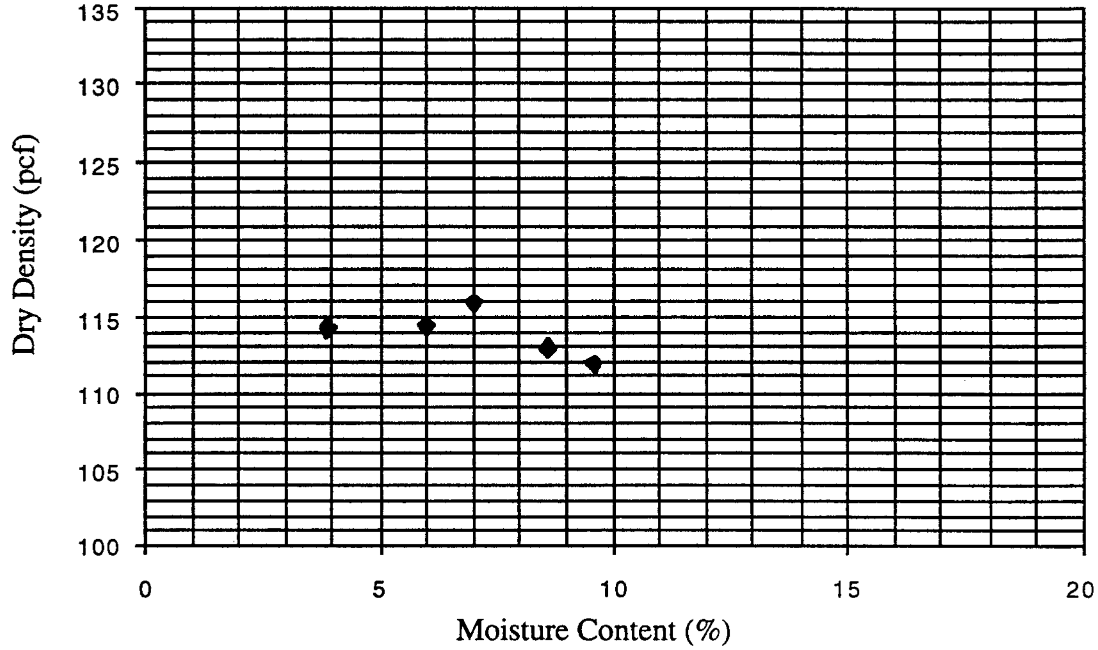


Figure A-21. The Optimum Moisture Content of 20% Limerock and 80% WPBMRF Glass Blend

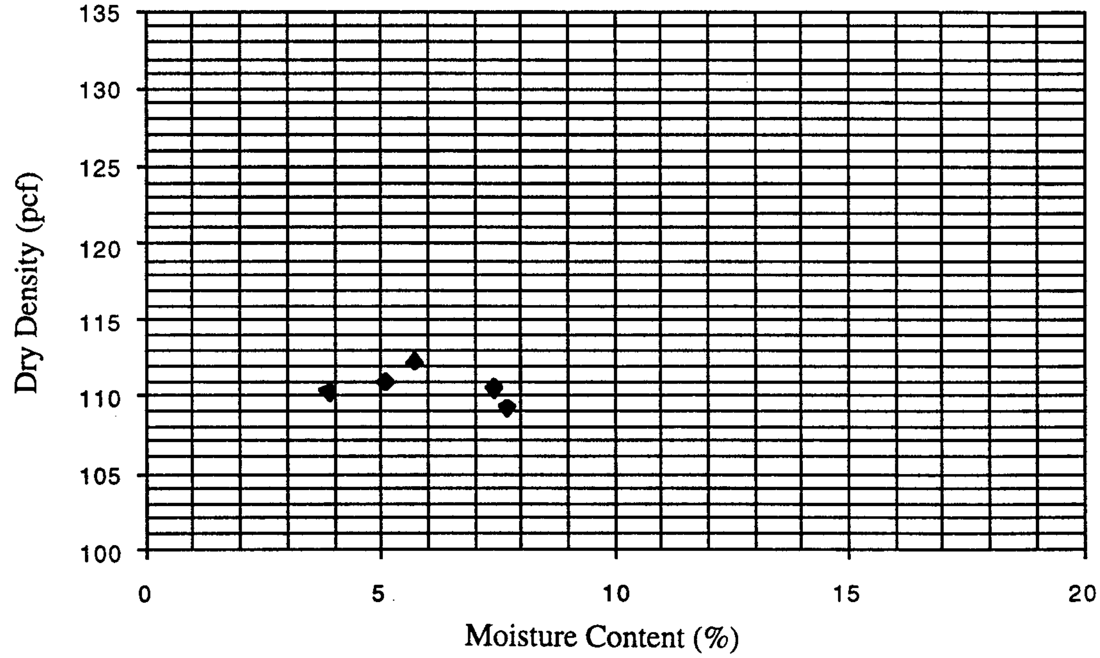


Figure A-22. The Optimum Moisture Content of 10% Limerock and 90% WPBMRF Glass Blend

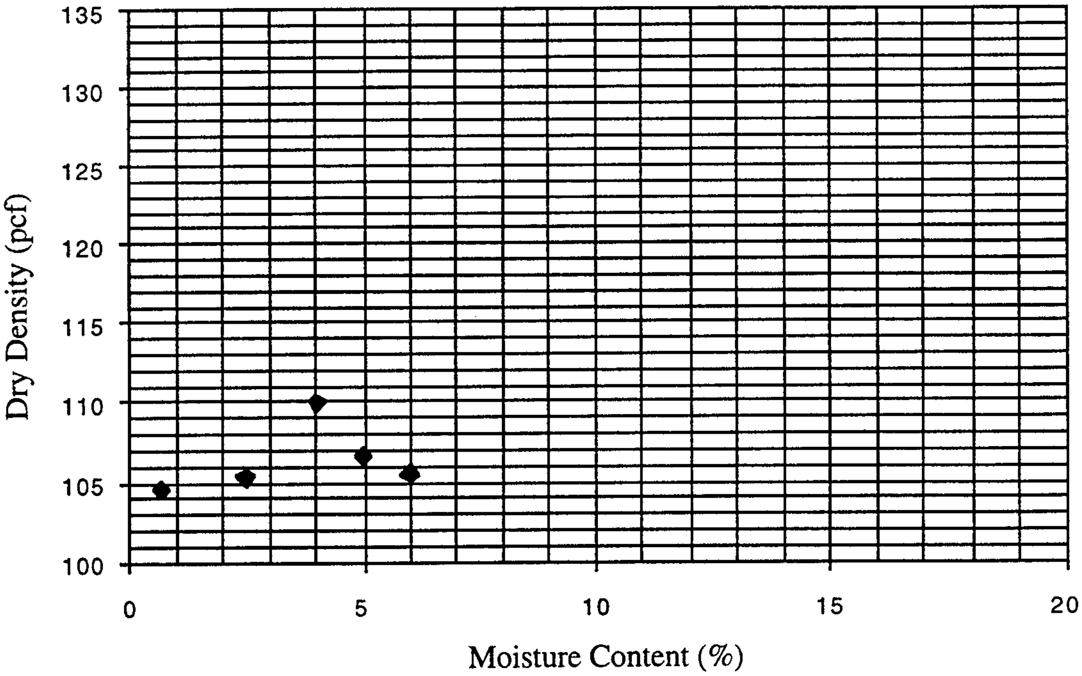


Figure A-23. The Optimum Moisture Content of 100% WPBMRF Glass Blend

APPENDIX B

The Penetration Test for Determining CBR and LBR values

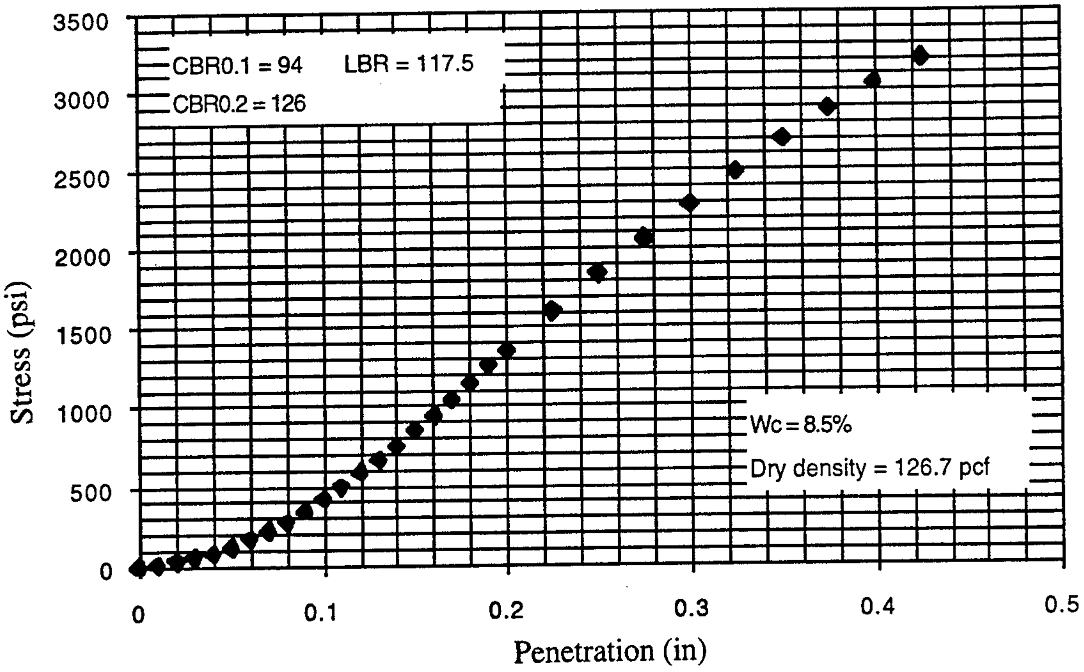


Figure B-3. The Penetration Test of 85% Limerock and 15% WPBMRF Glass Blend (Soaked)

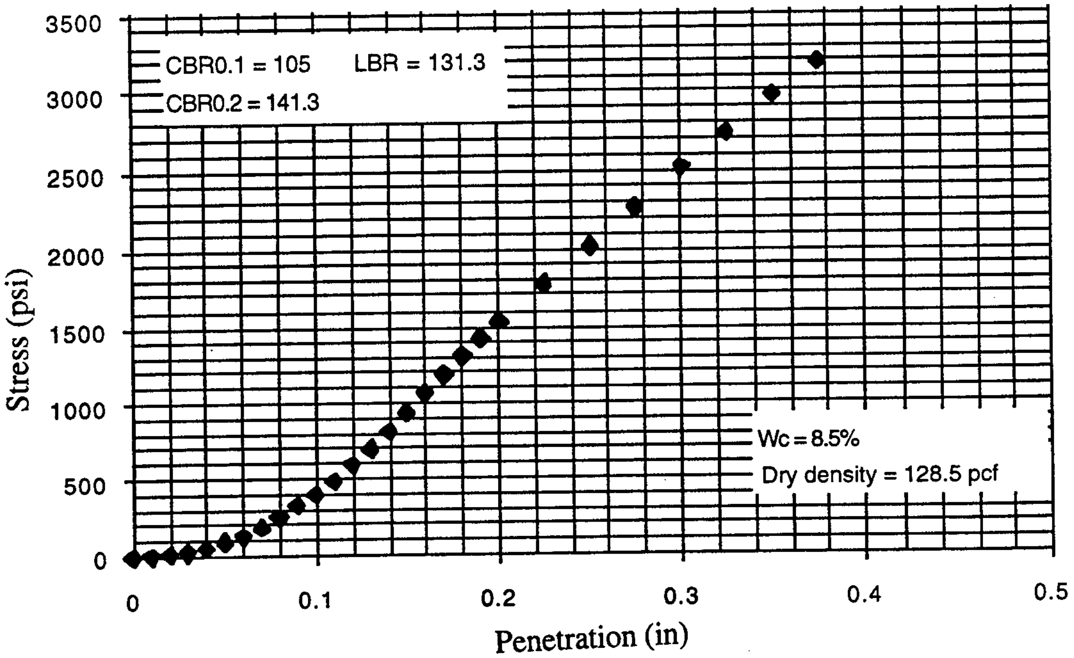


Figure B-4. The Penetration Test of 80% Limerock and 20% WPBMRF Glass Blend (Soaked)

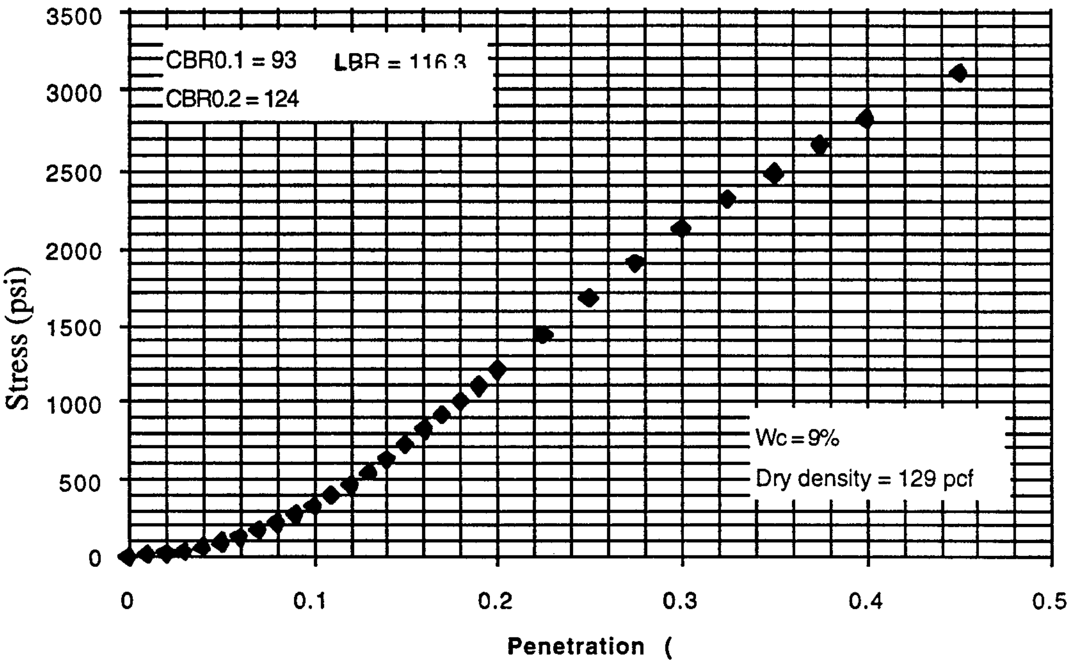


Figure B-1. The Penetration Test of 100% Limerock Base (Soaked)

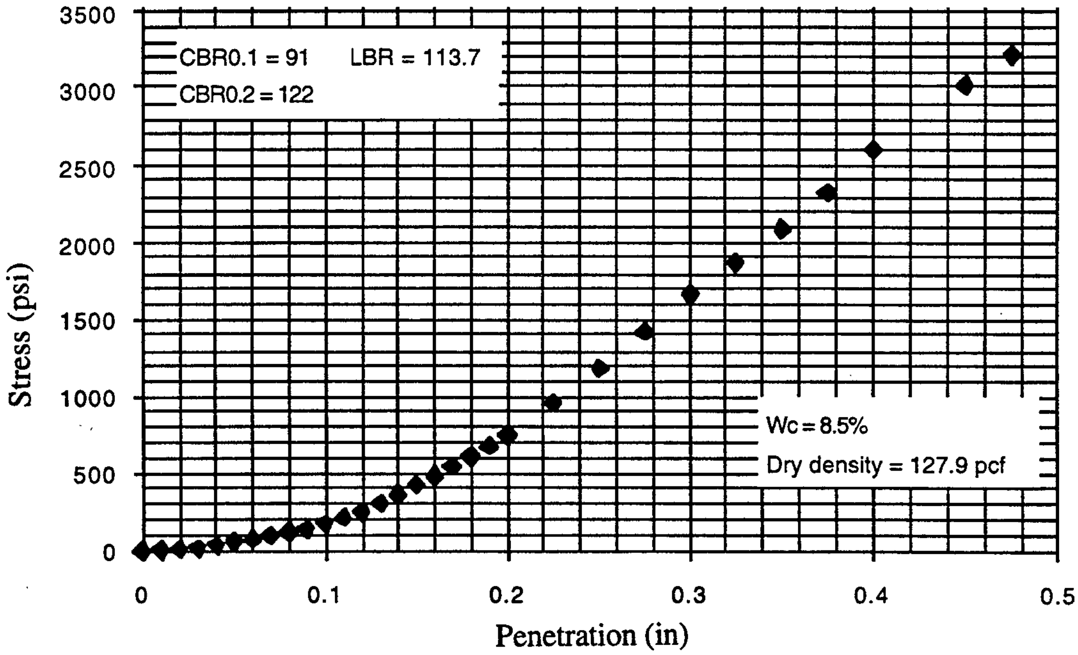


Figure B-2. The Penetration Test of 90% Limerock and 10% WPBMRF Glass Blend (Soaked)

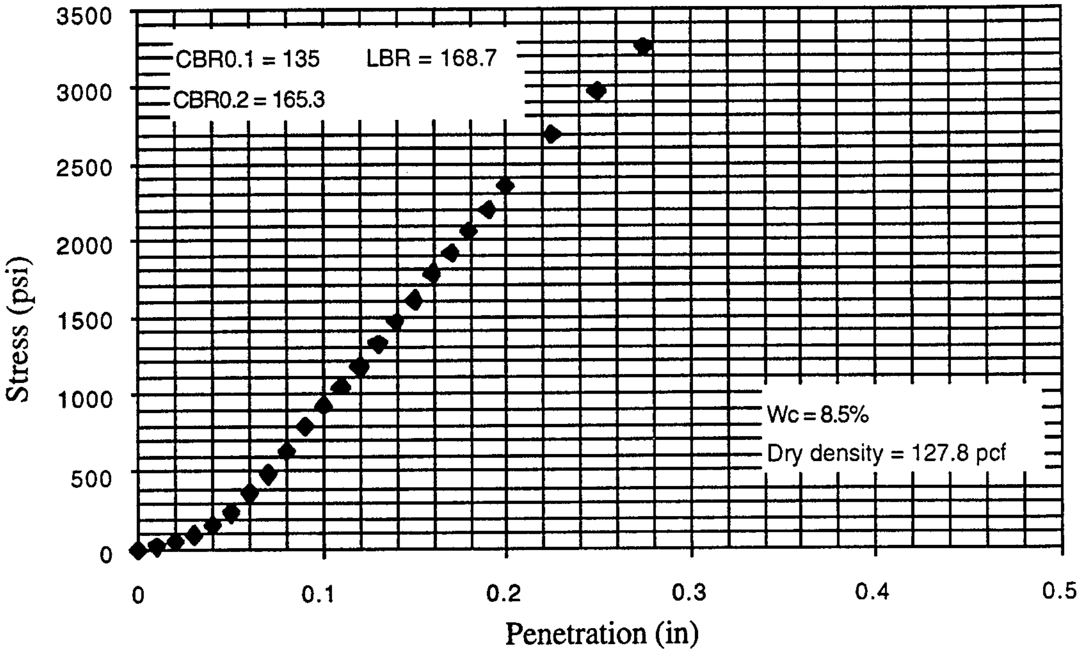


Figure B-5. The Penetration Test of 70% Limerock and 30% WPBMRF Glass Blend (Soaked)

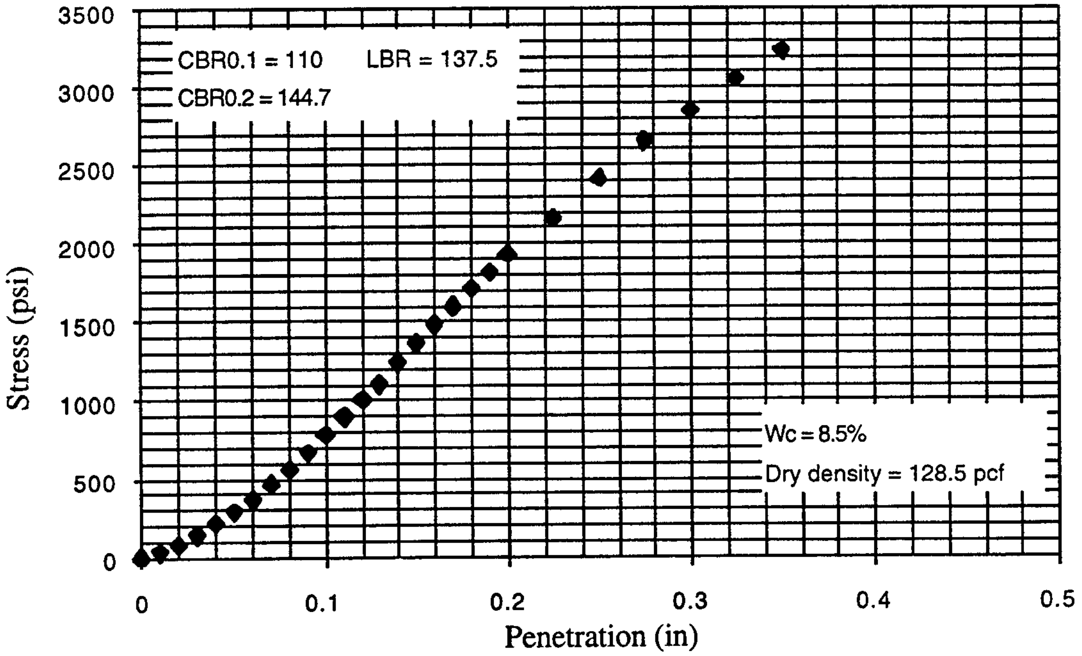


Figure B-6. The Penetration Test of 60% Limerock and 40% WPBMRF Glass Blend (Soaked)

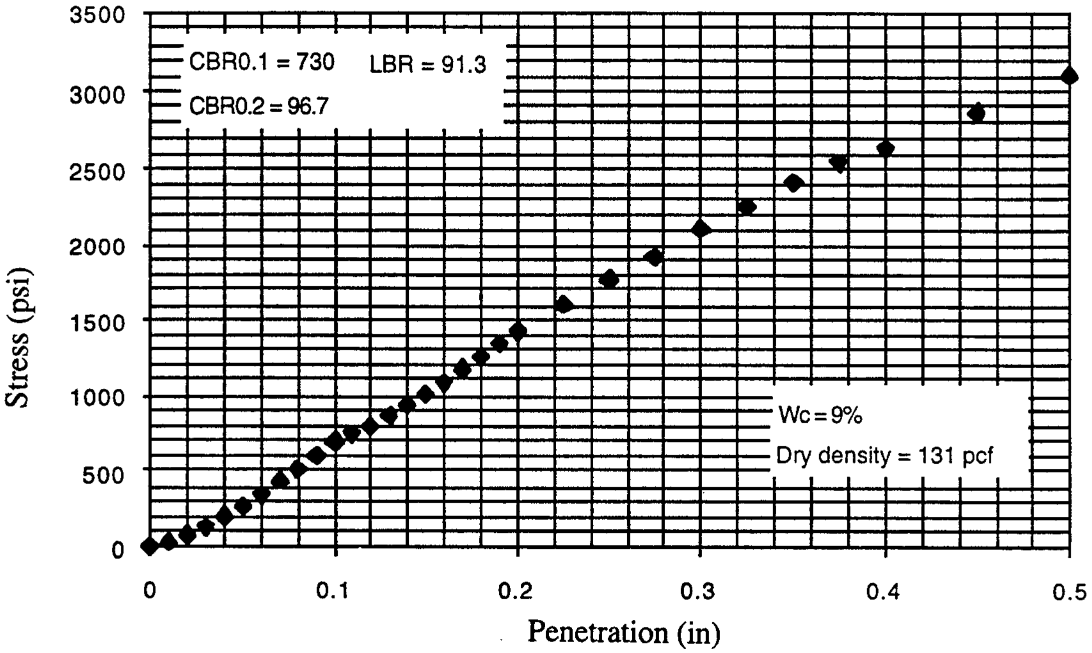


Figure B-7. The Penetration Test of 50% Limerock and 50% WPBMRF Glass Blend (Soaked)

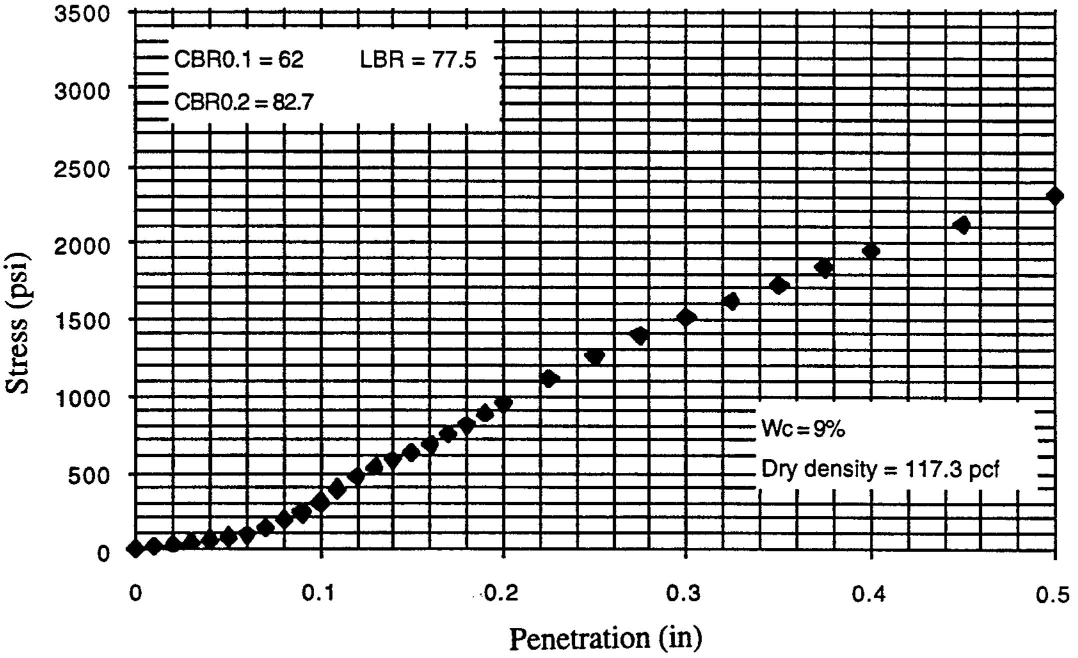


Figure B-8. The Penetration Test of 40% Limerock and 60% WPBMRF Glass Blend (Soaked)

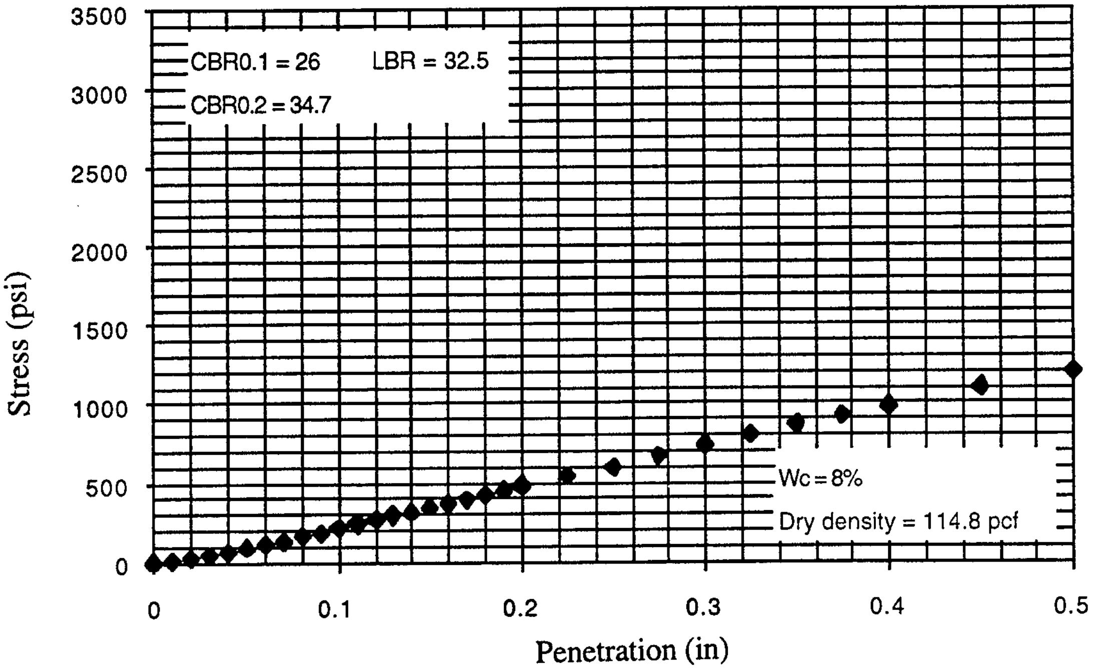


Figure B-9. The Penetration Test of 30% Limerock and 70% WPBMRF Glass Blend (Soaked)

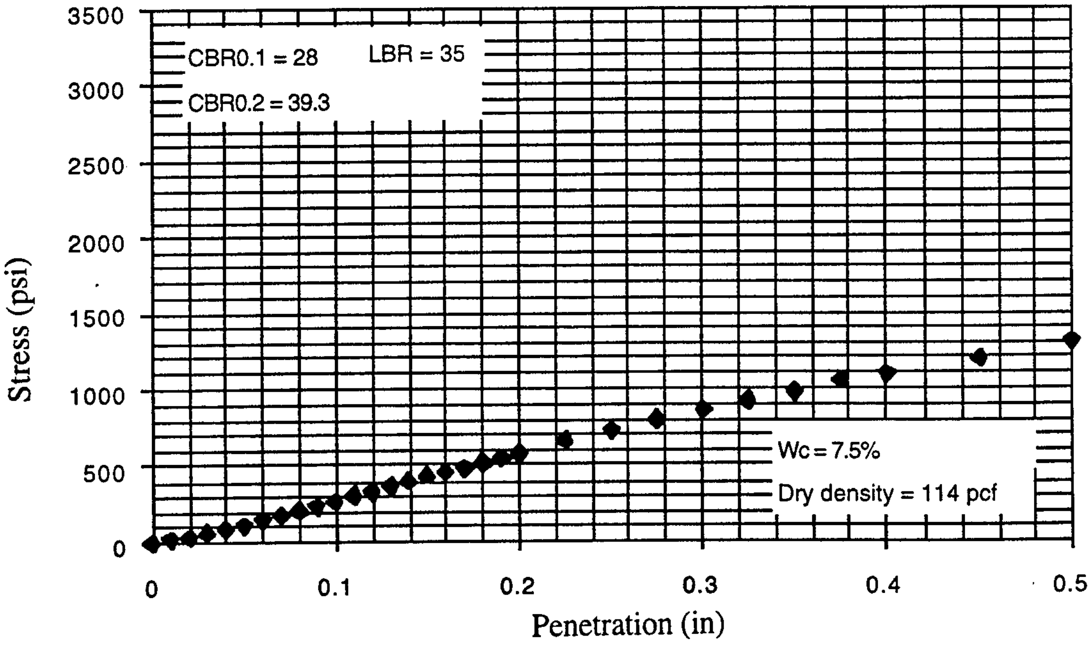


Figure C-10. The Penetration Test of 20% Limerock and 80% WPBMRF Glass Blend (Soaked)

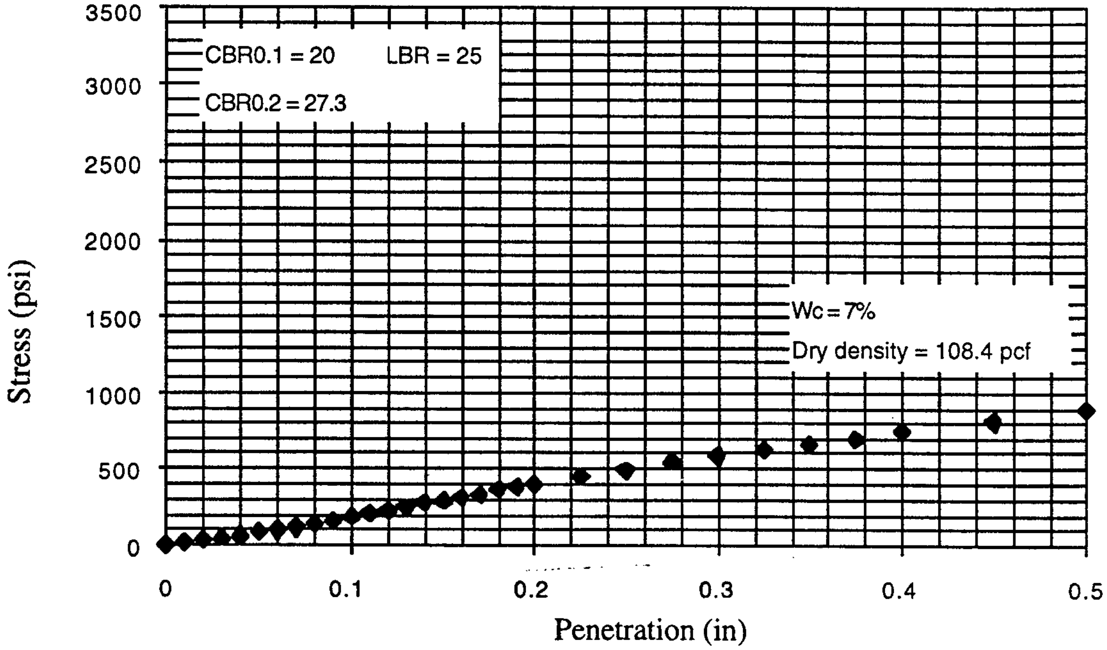


Figure B-11. The Penetration Test of 10% Limerock and 90% WPBMRF Glass Blend (Soaked)

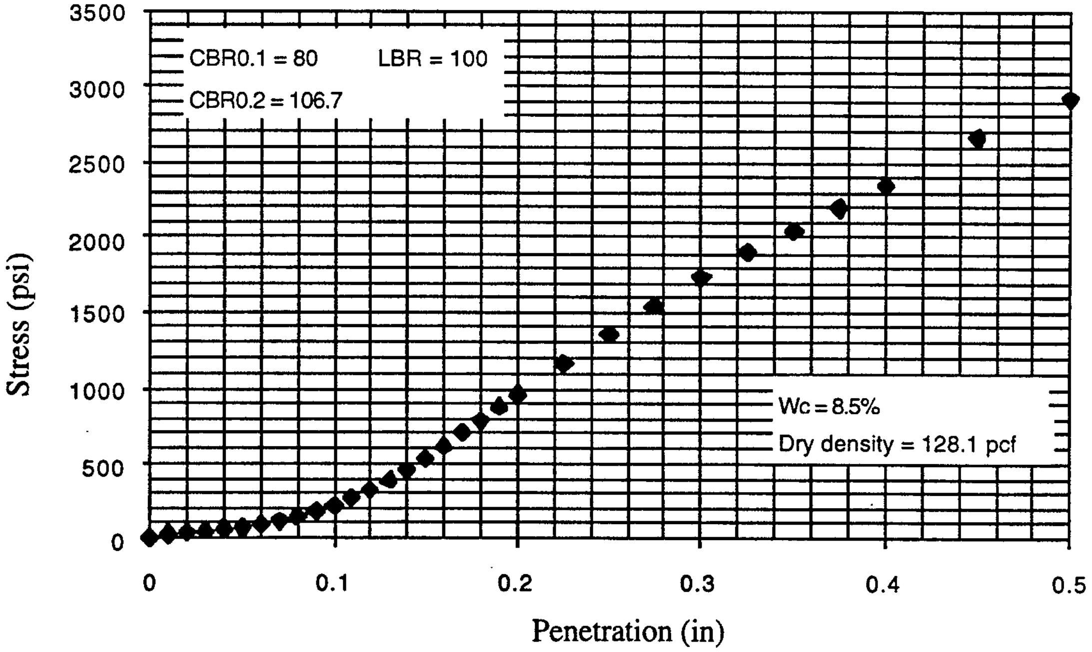


Figure B-12. The Penetration Test of 100% Limerock Base (unsoaked)

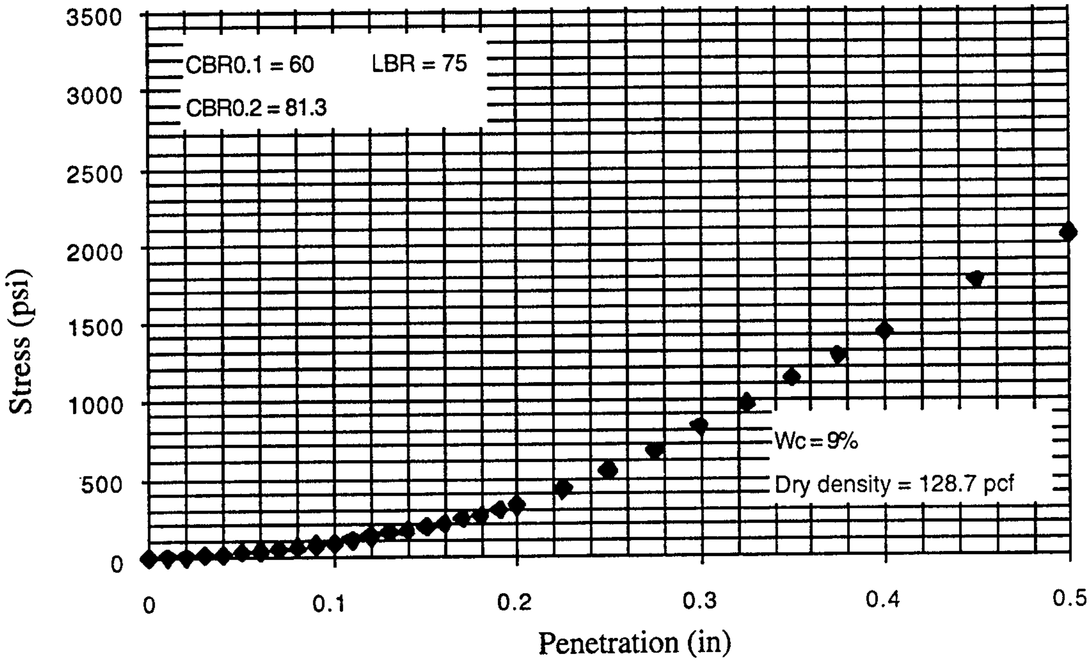


Figure B-13. The Penetration Test of 90% Limerock and 10% WPBMRF Glass Blend (Unsoaked)

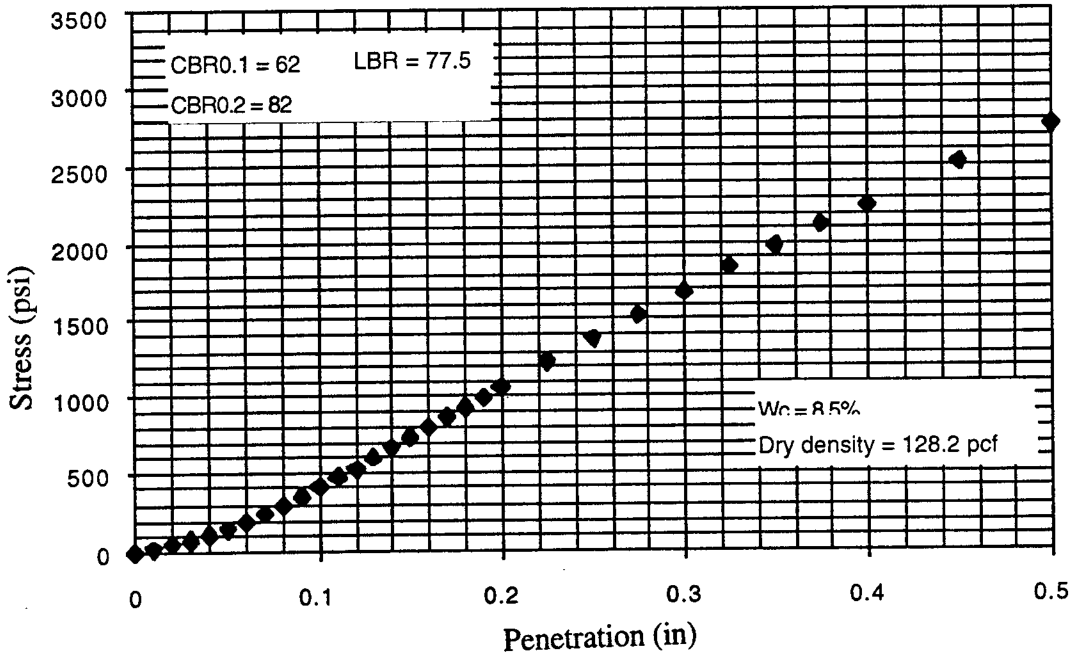


Figure B-14. The Penetration Test of 85% Limerock and 15% WPBMRF Glass Blend (Unsoaked)

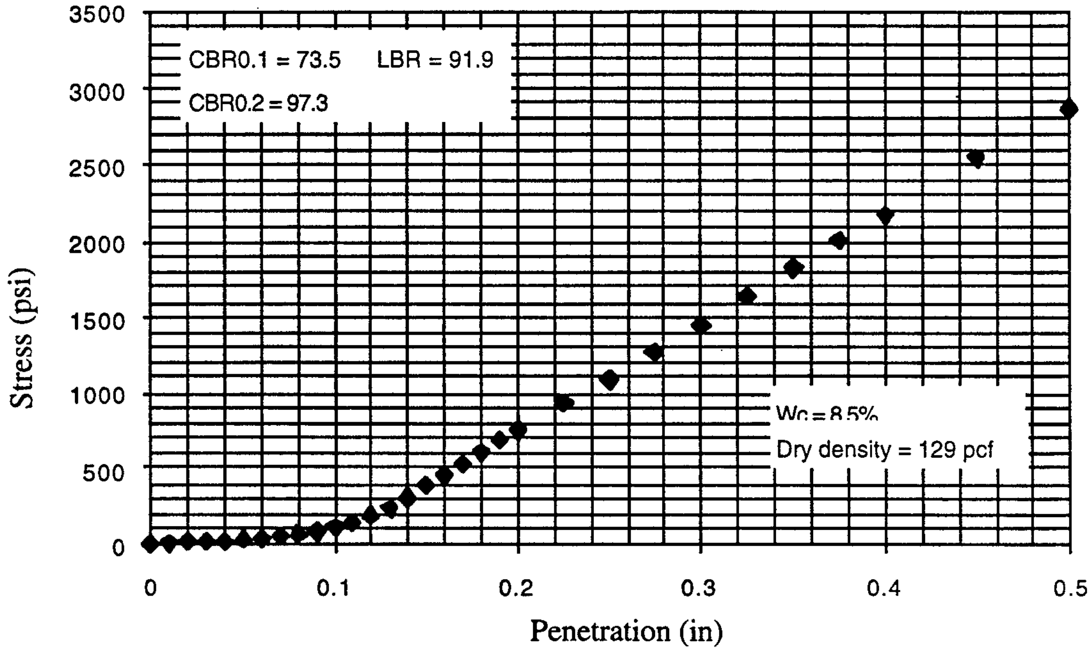


Figure B-15. The Penetration Test of 80% Limerock and 20% WPBMRF Glass Blend (Unsoaked)

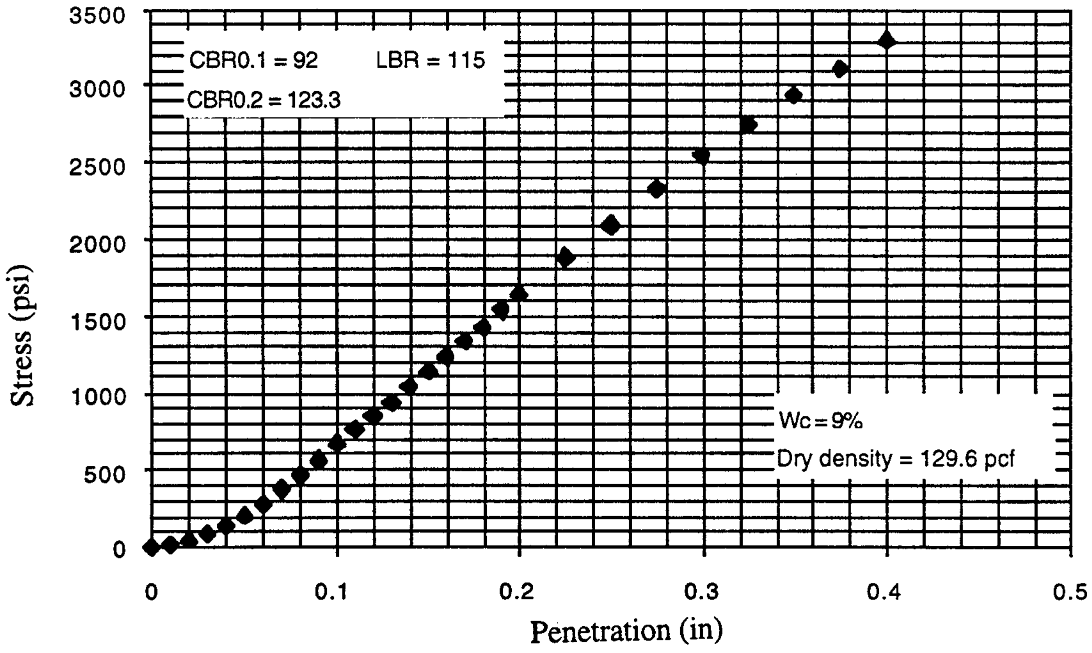


Figure B-16. The Penetration Test of 70% Limerock and 30% WPBMRF Glass Blend (Unsoaked)

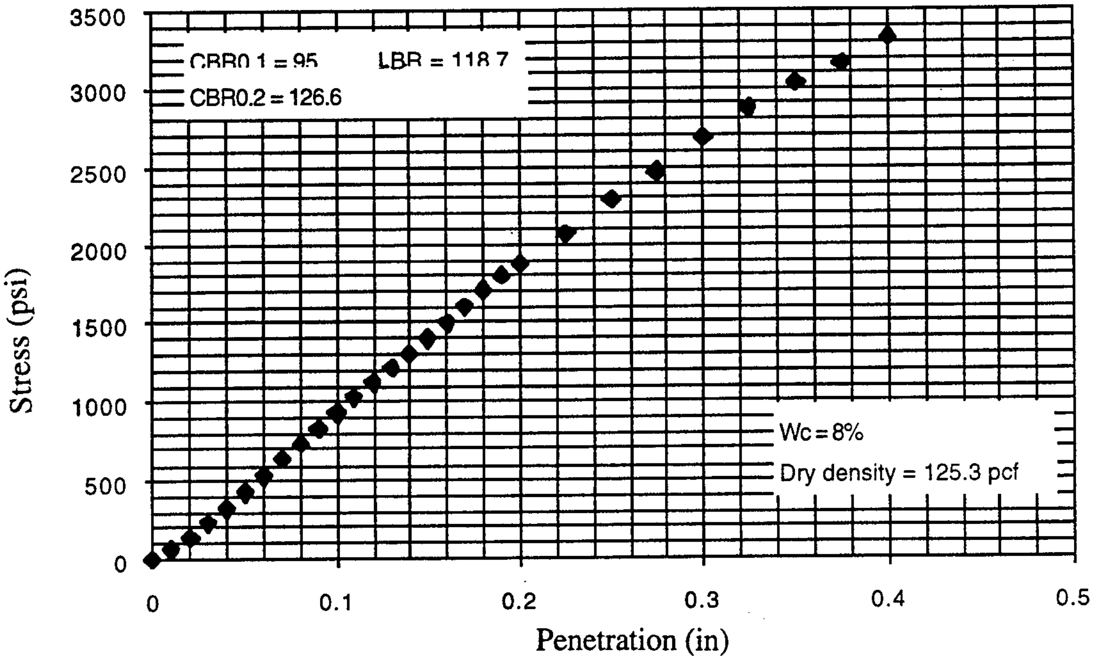


Figure B-17. The Penetration Test of 60% Limerock and 40% WPBMRF Glass Blend (Unsoaked)

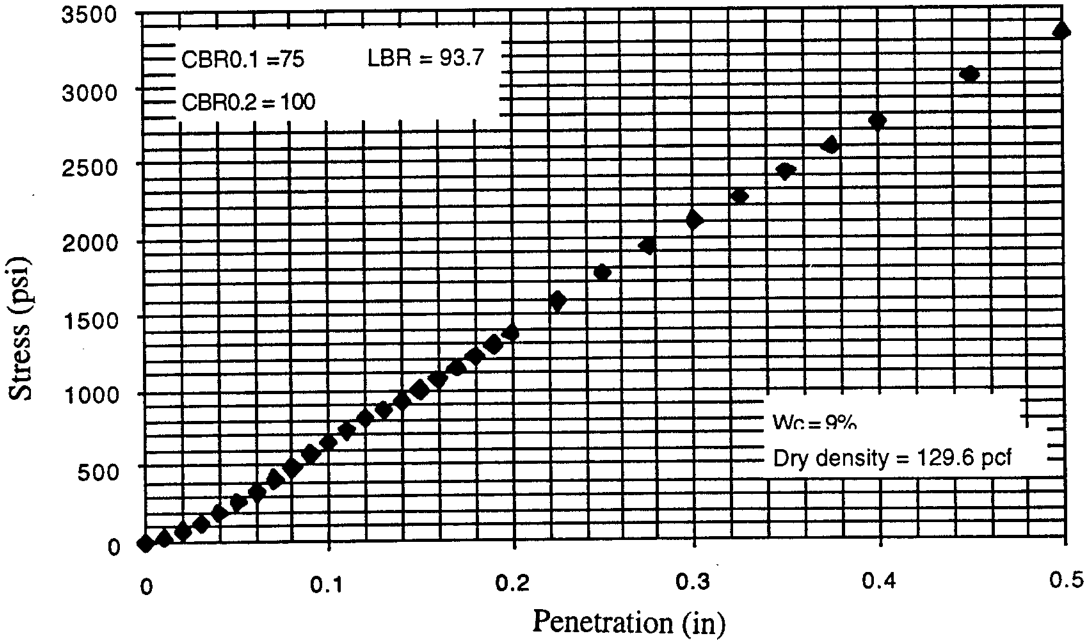


Figure B-18. The Penetration Test of 50% Limerock and 50% WPBMRF Glass Blend (Unsoaked)

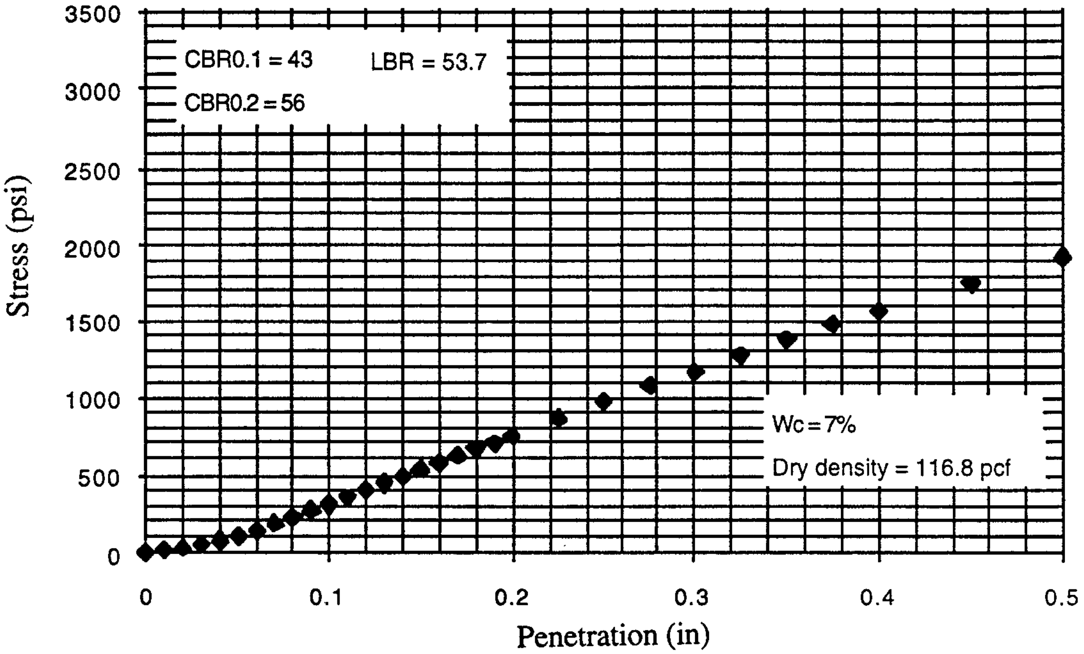


Figure B-19. The Penetration Test of 40% Limerock and 60% WPBMRF Glass Blend (Unsoaked)

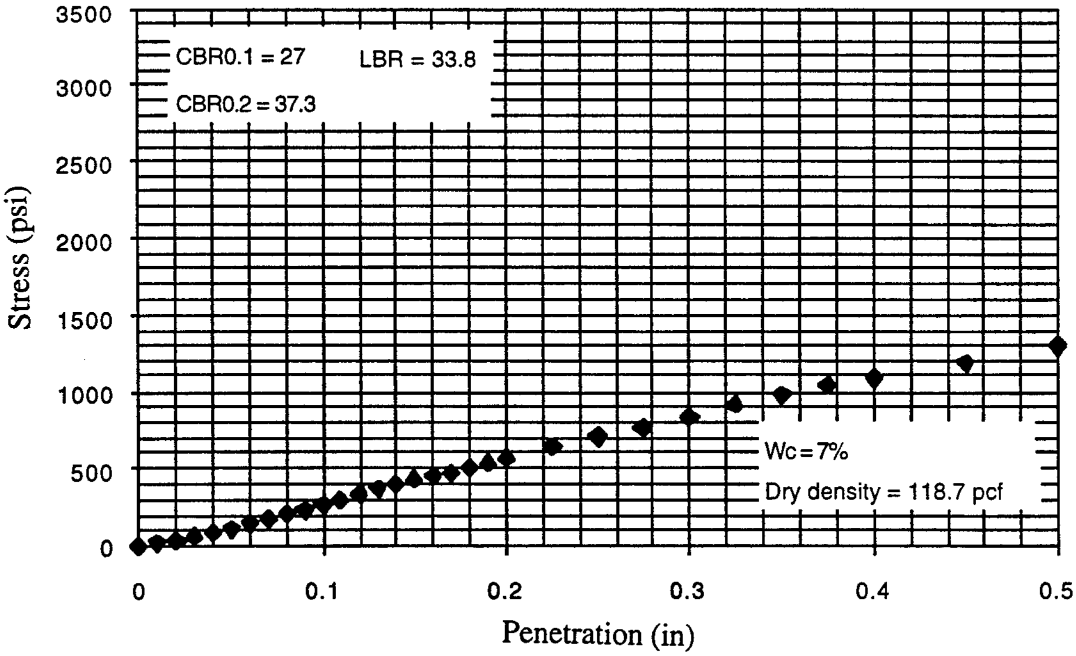


Figure B-20. The Penetration Test of 30% Limerock and 70% WPBMRF Glass Blend (Unsoaked)

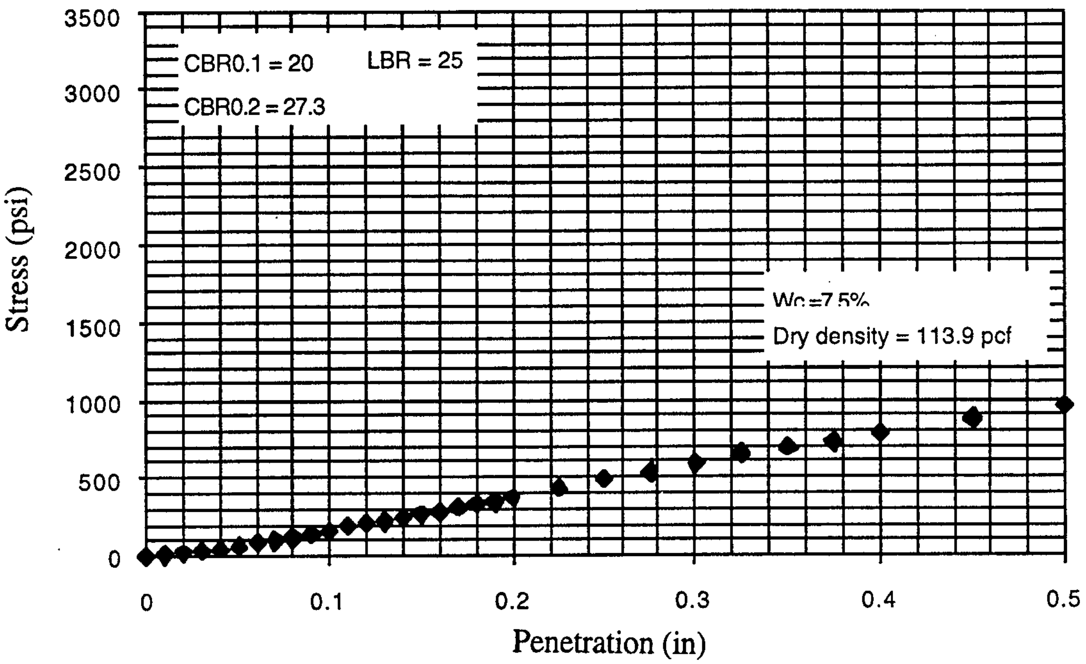


Figure B-21. The Penetration Test of 80% Limerock and 20% WPBMRF Glass Blend (Unsoaked)

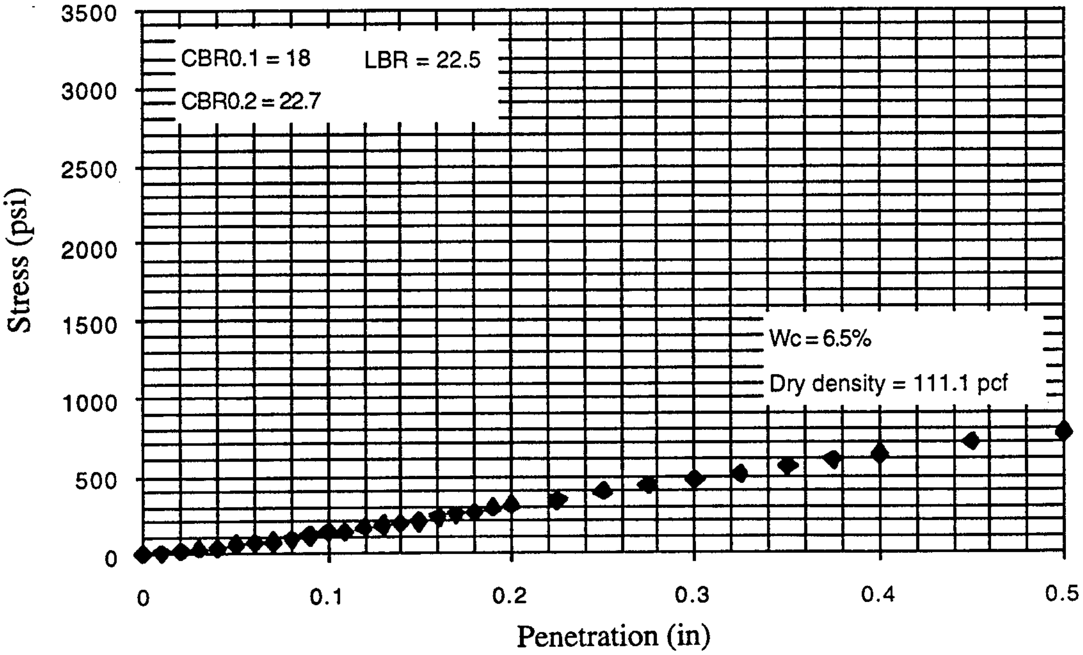


Figure B-22. The Penetration Test of 10% Limerock and 90% WPBMRF Glass Blend (Unsoaked)

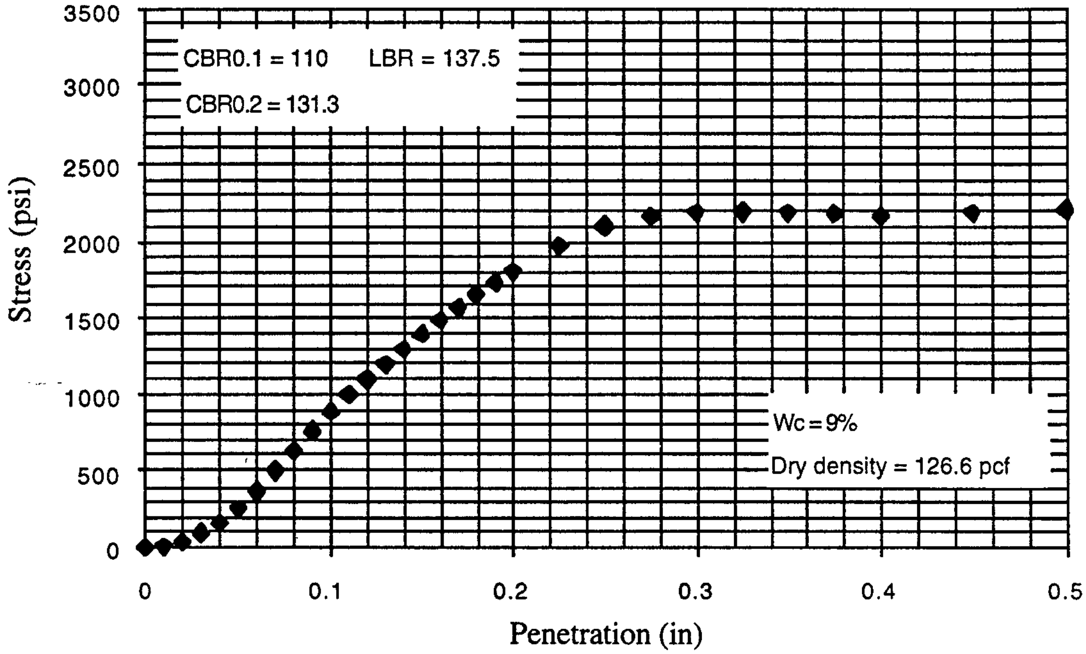


Figure B-23. The Penetration Test of 100% Cemented Coquina Base (Soaked)

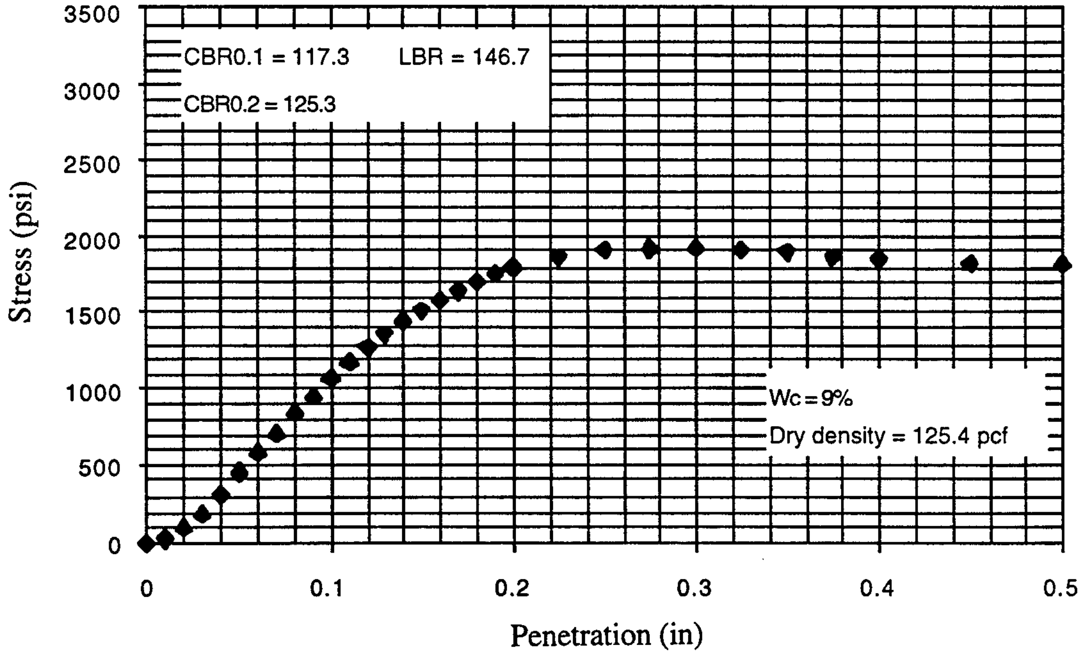


Figure B-24. The Penetration Test of 90% Cemented Coquina and 10% WPBMRF Glass Blend (Soaked)

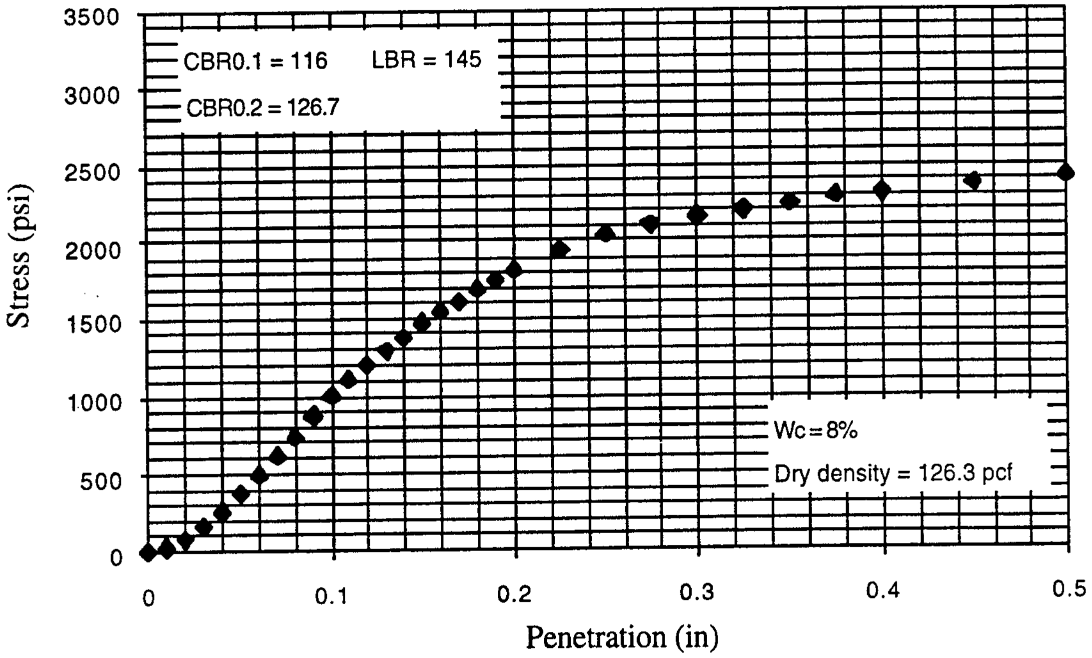


Figure B-25. The Penetration Test of 85% Cemented Coquina and 15% WPBMRF Glass Blend (Soaked)

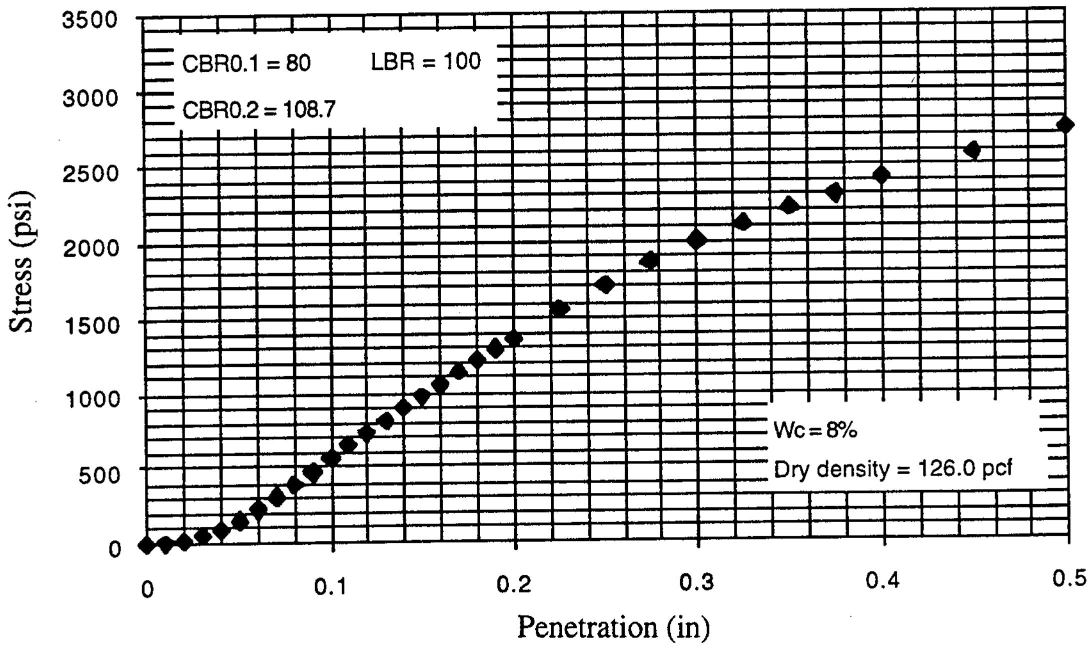


Figure B-26. The Penetration Test of 80% Cemented Coquina and 20% WPBMRF Glass Blend (Soaked)

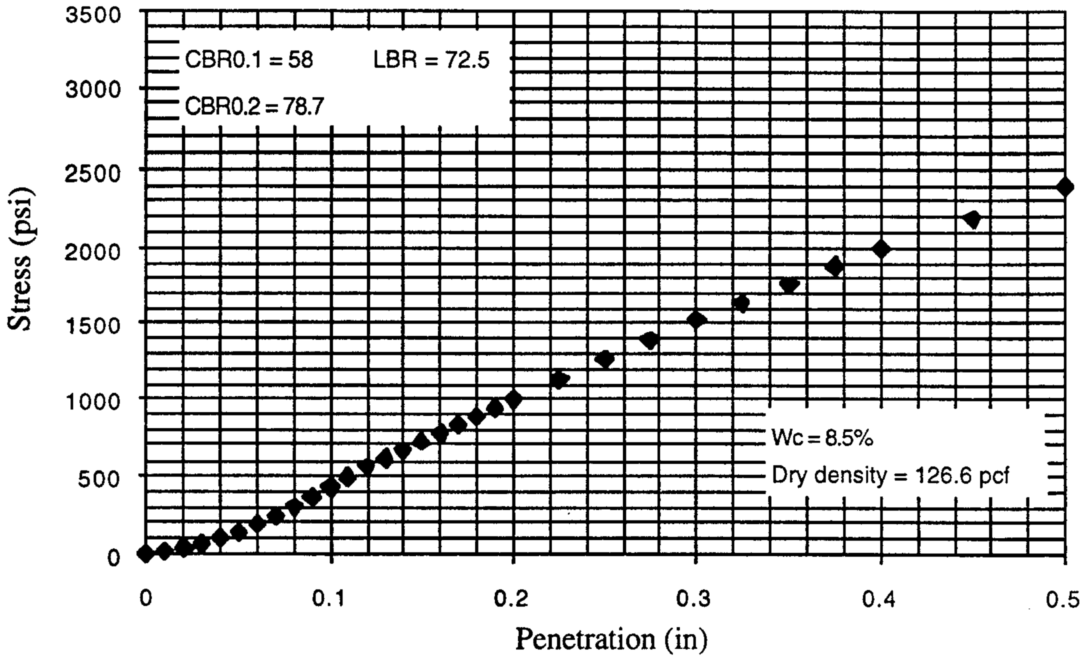


Figure B-27. The Penetration Test of 70% Cemented Coquina and 30% WPBMRF Glass Blend (Soaked)

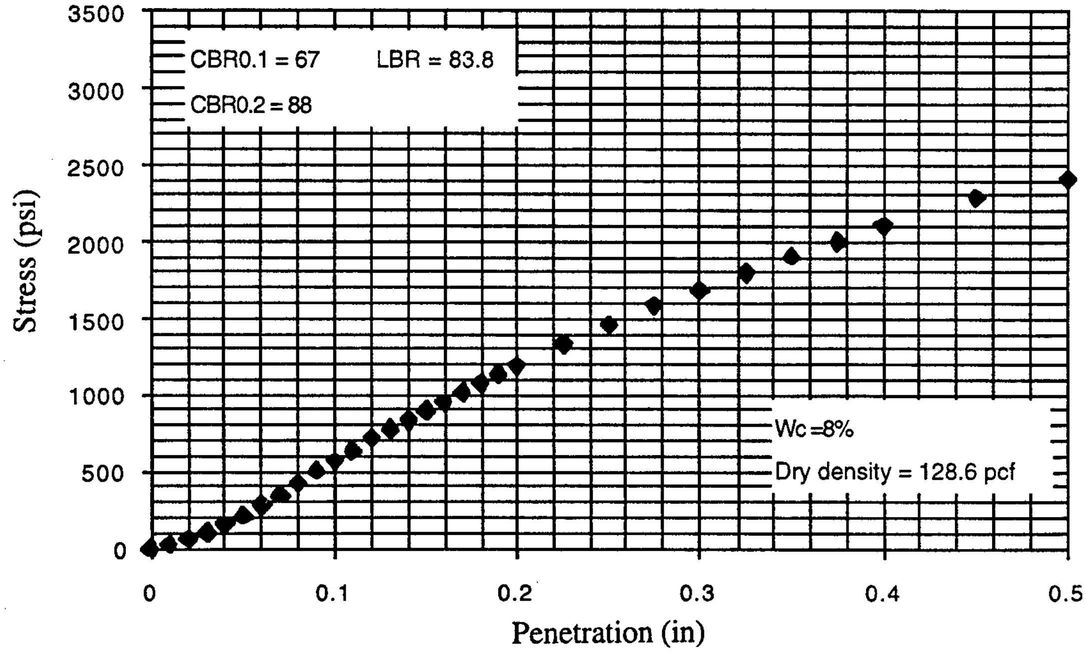


Figure B-28. The Penetration Test of 60% Cemented Coquina and 40% WPBMRF Glass Blend (Soaked)

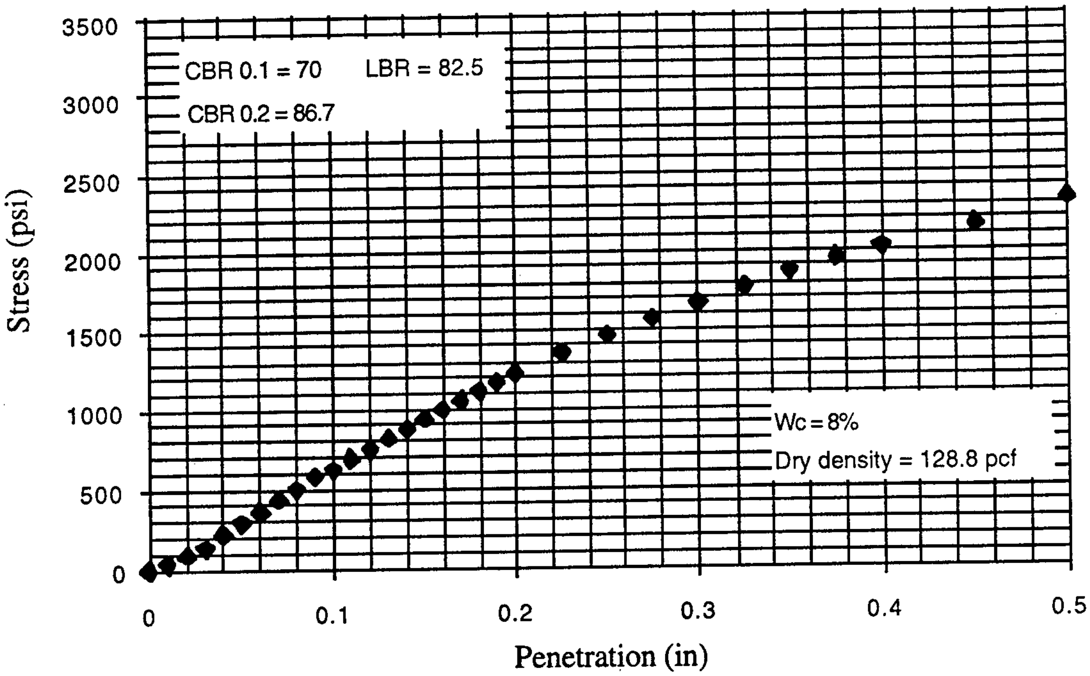


Figure B-29. The Penetration Test of 50% Cemented Coquina and 50% WPBMRF Glass Blend (Soaked)

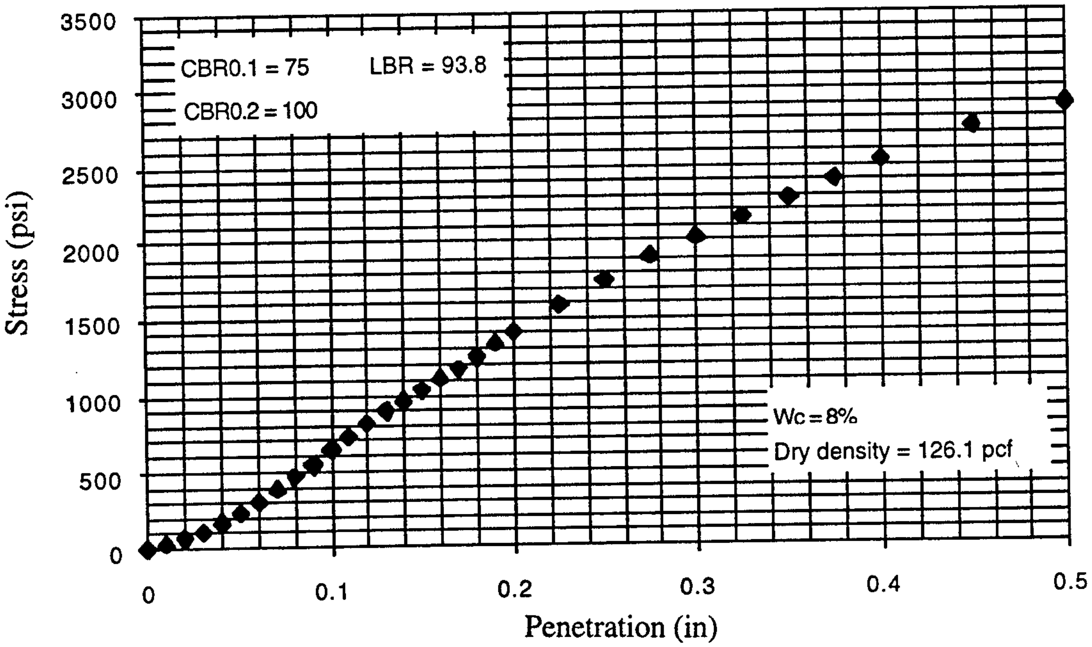


Figure B-30. The Penetration Test of 40% Cemented Coquina and 60% WPBMRF Glass Blend (Soaked)

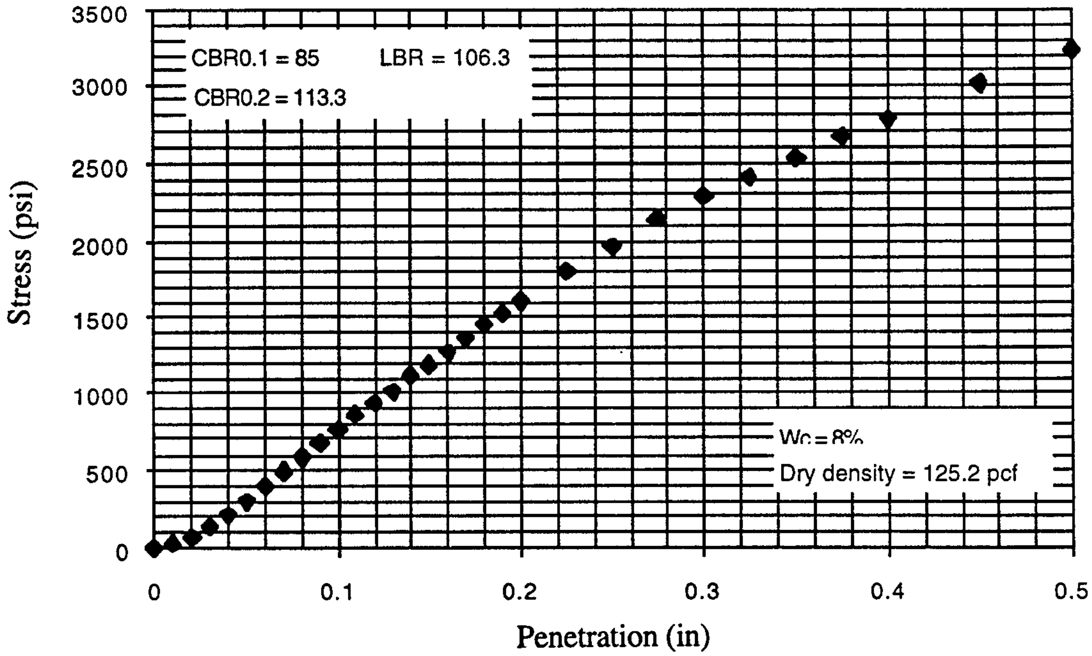


Figure B-31. The Penetration Test of 30% Cemented Coquina and 70% WPBMRF Glass Blend (Soaked)

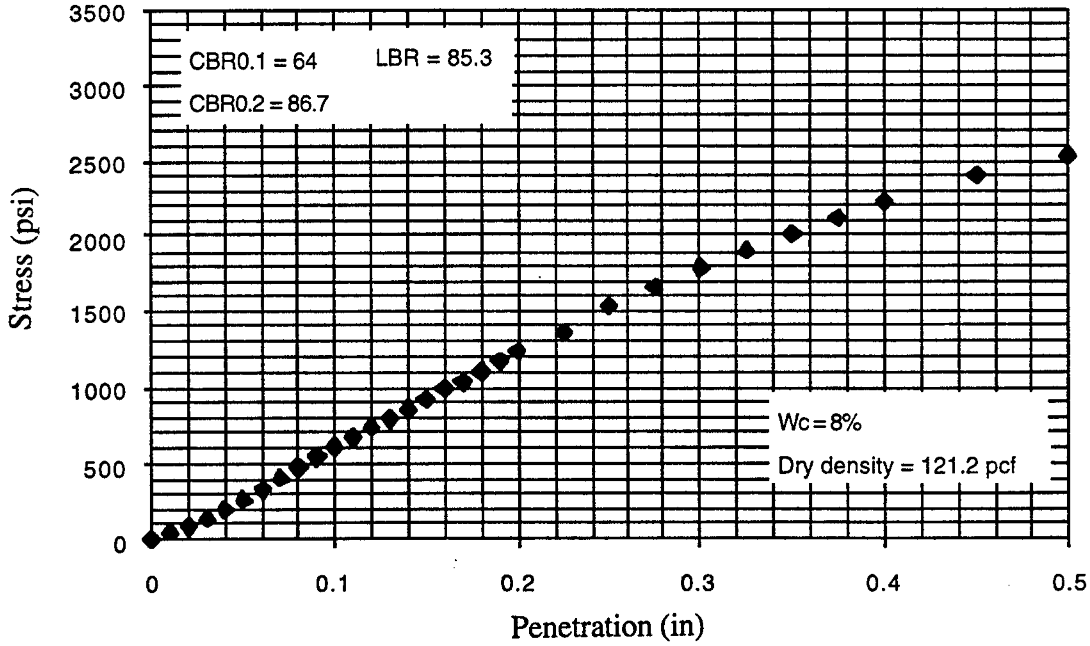


Figure B-32. The Penetration Test of 80% Cemented Coquina and 20% WPBMRF Glass Blend (Soaked)

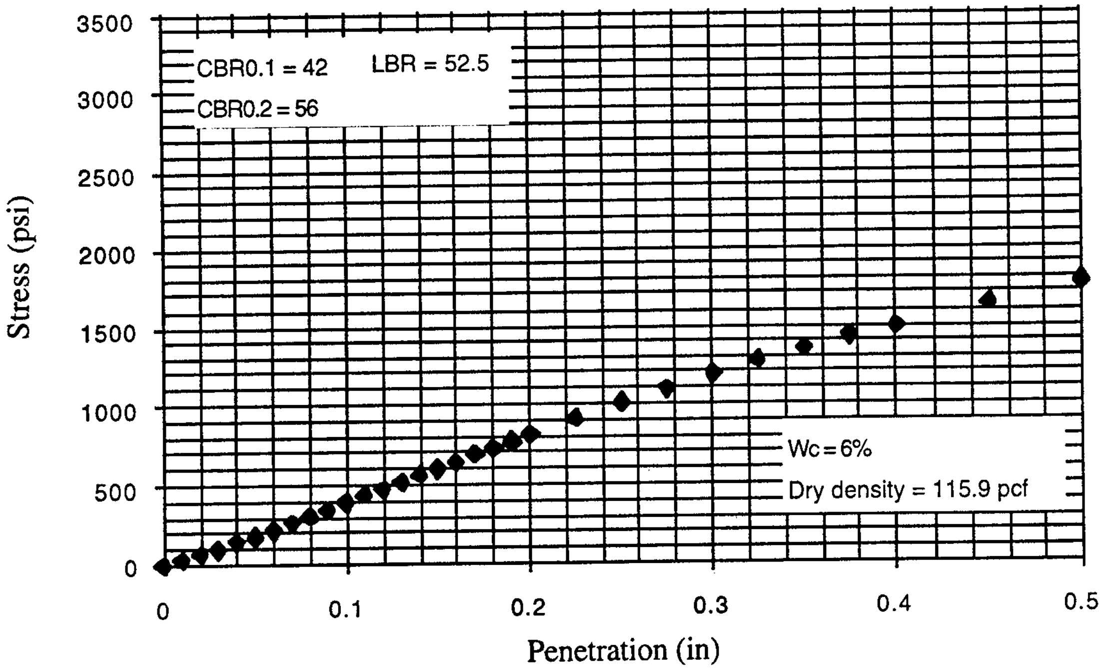


Figure B-33. The Penetration Test of 10% Cemented Coquina and 90% WPBMRF Glass Blend (Soaked)

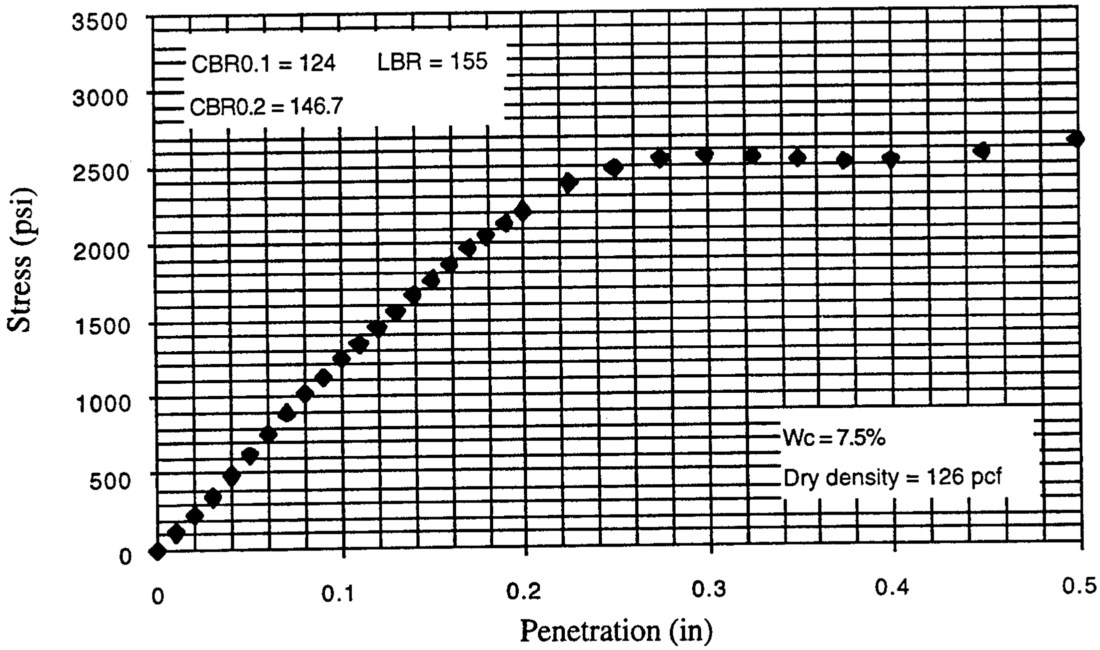


Figure B-34. The Penetration Test of 100% Cemented Coquina Base (Unsoaked)

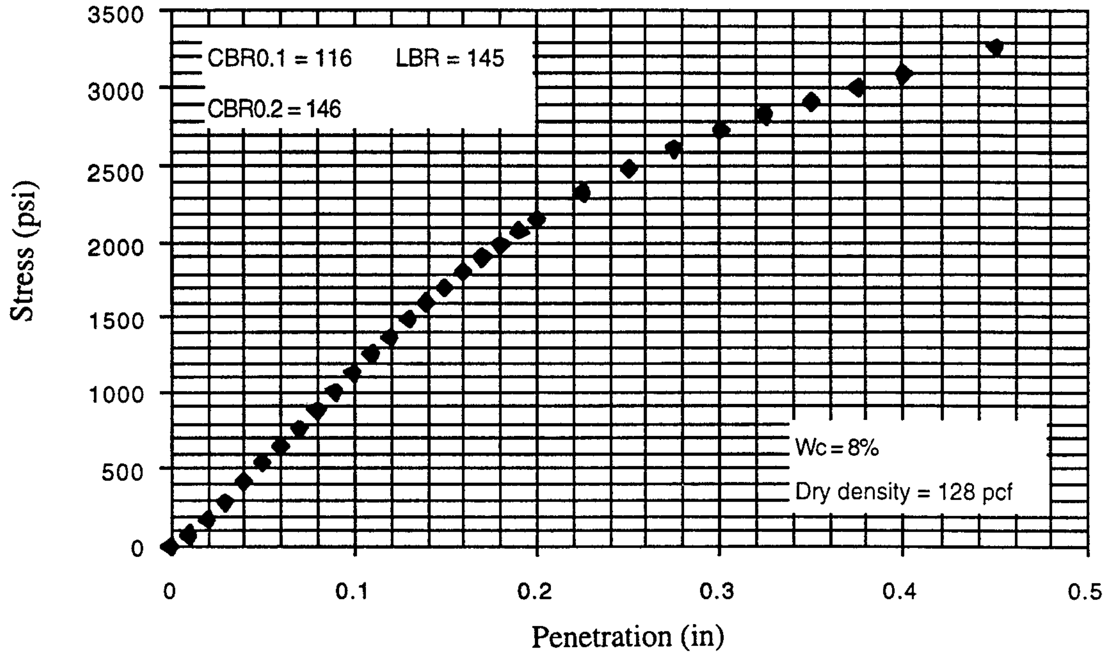


Figure B-35. The Penetration Test of 90% Cemented Coquina and 10% WPBMRF Glass Blend (Unsoaked)

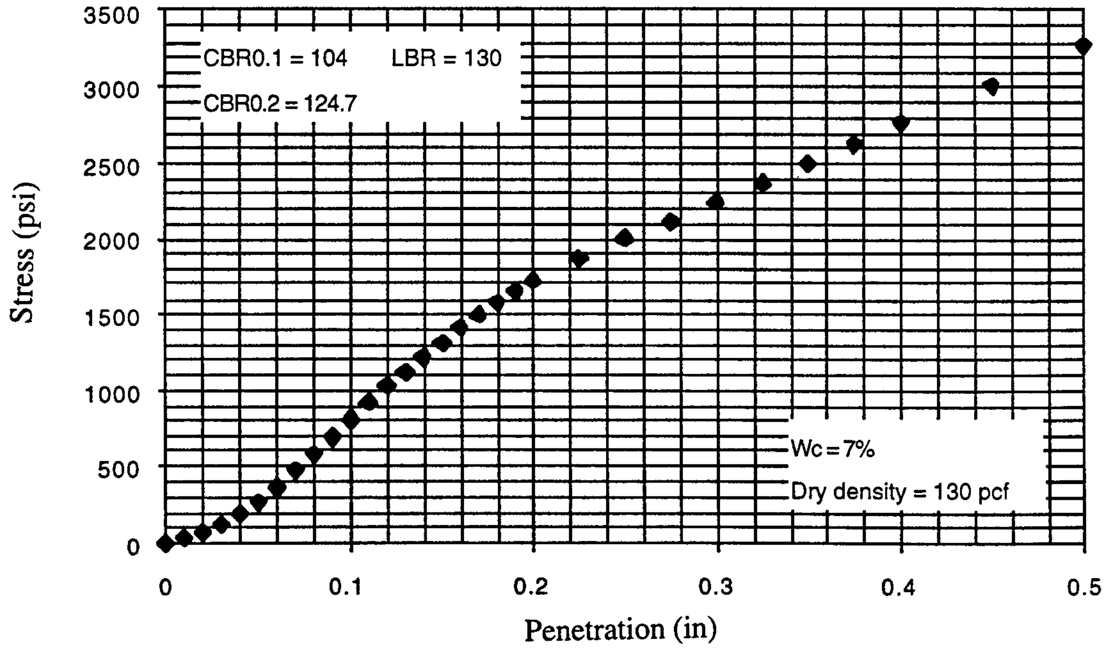


Figure B-36. The Penetration Test of 85% Cemented Coquina and 15% WPBMRF Glass Blend (Unsoaked)

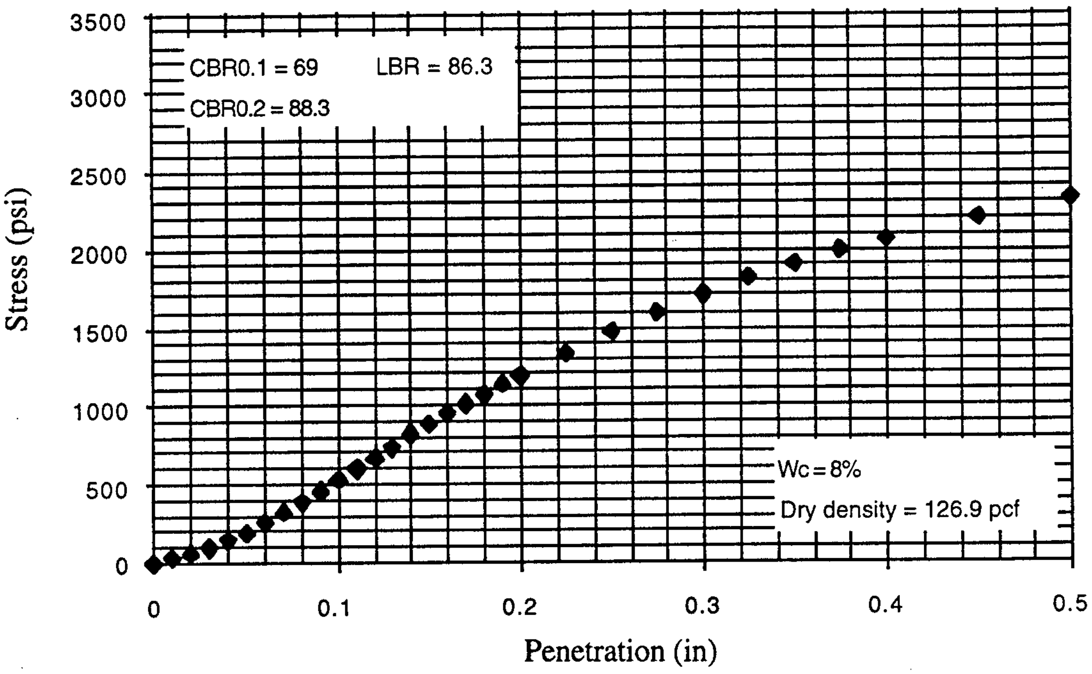


Figure B-37. The Penetration Test of 80% Cemented Coquina and 20% WPBMRF Glass Blend (Unsoaked)

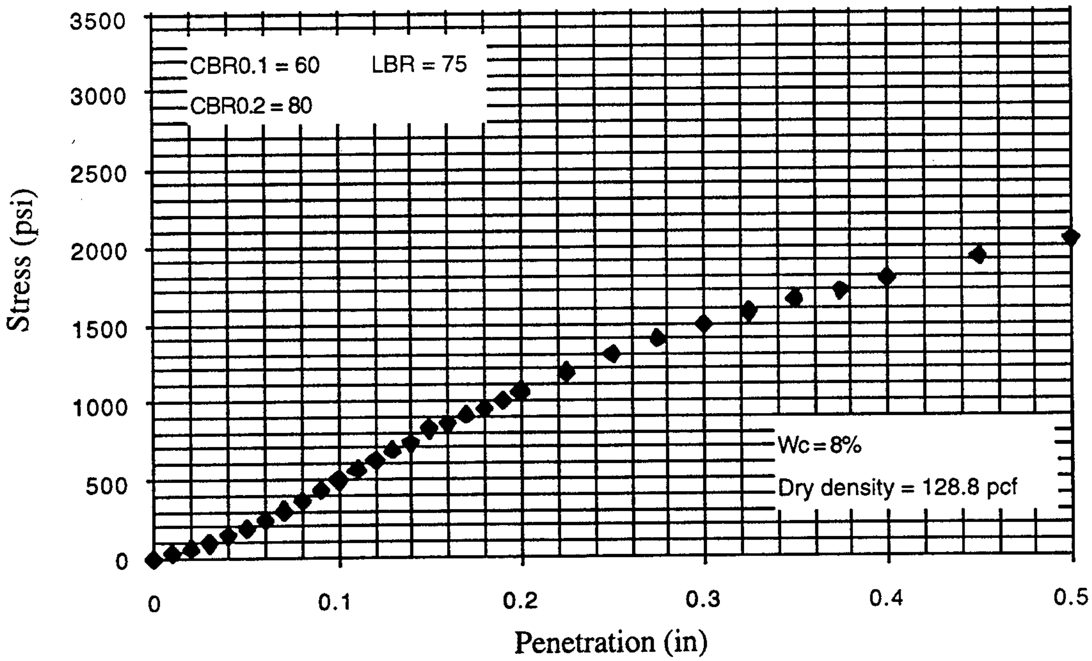


Figure B-38. The Penetration Test of 70% Cemented Coquina and 30% WPBMRF Glass Blend (Unsoaked)

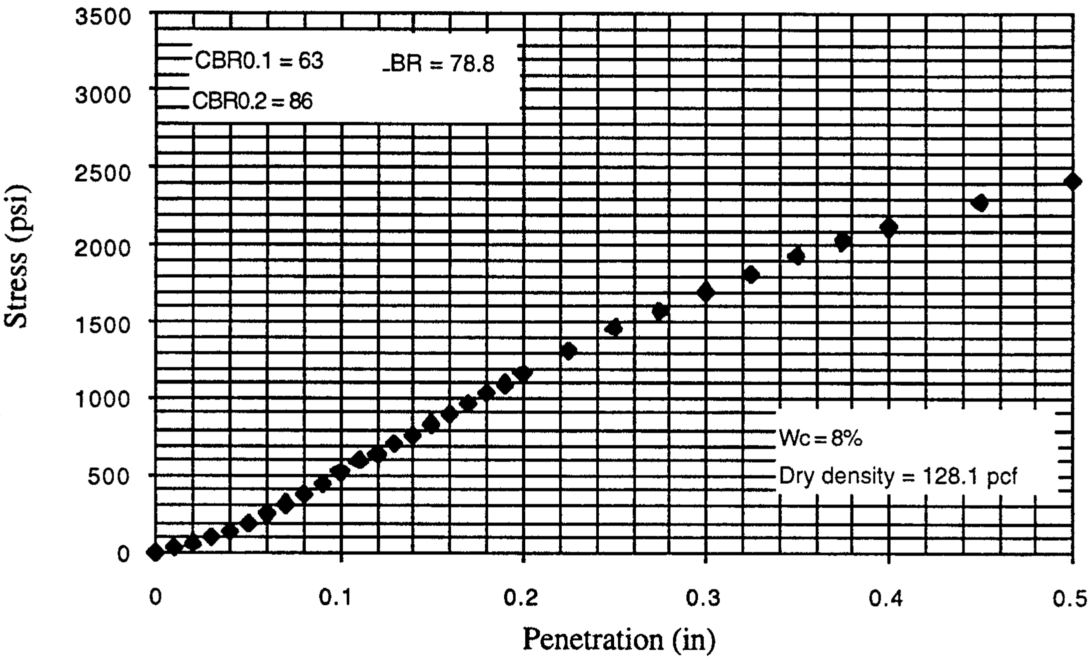


Figure B-39. The Penetration Test of 60% Cemented Coquina and 40% WPBMRF Glass Blend (Unsoaked)

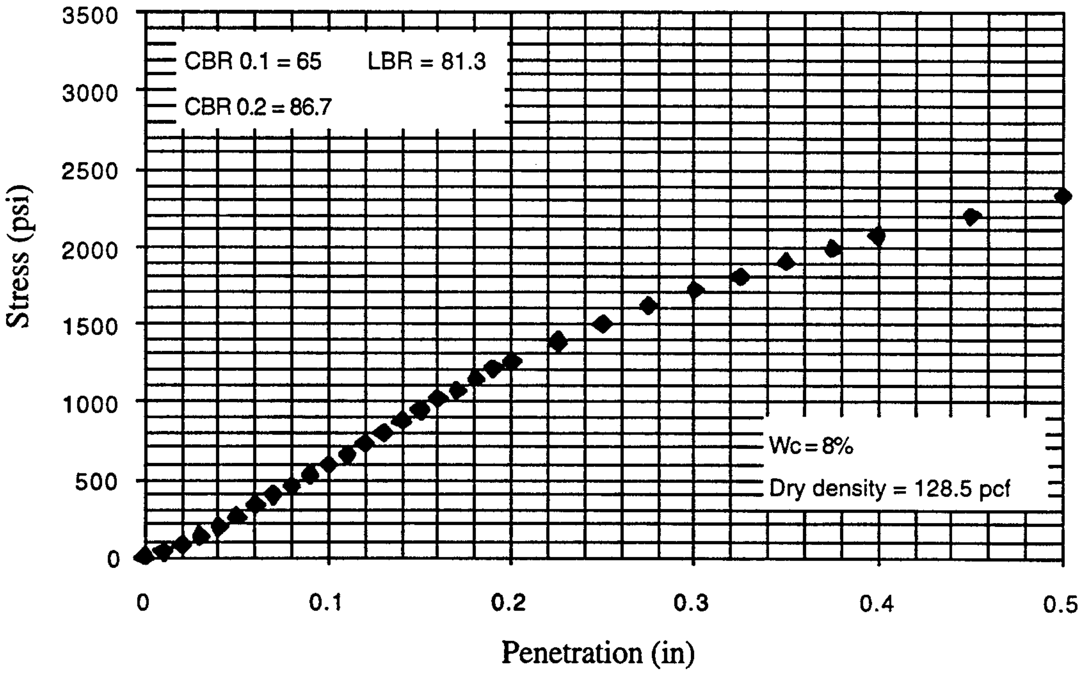


Figure B-40. The Penetration Test of 50% Cemented Coquina and 50% WPBMRF Glass Blend (Unsoaked)

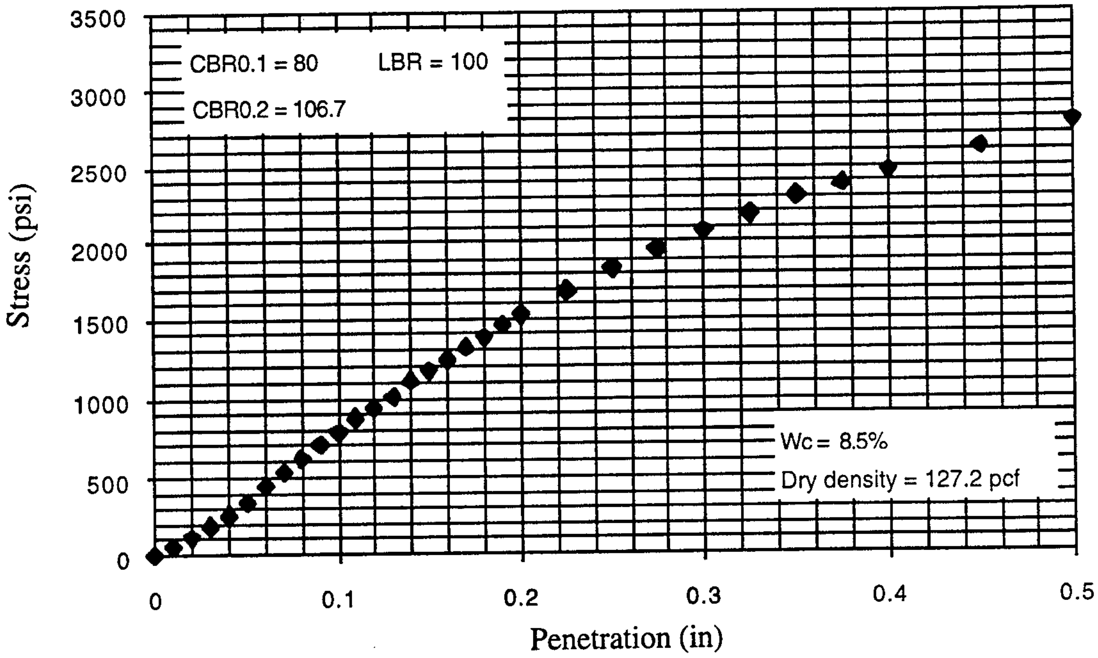


Figure B-41. The Penetration Test of 40% Cemented Coquina and 60% WPBMRF Glass Blend (Unsoaked)

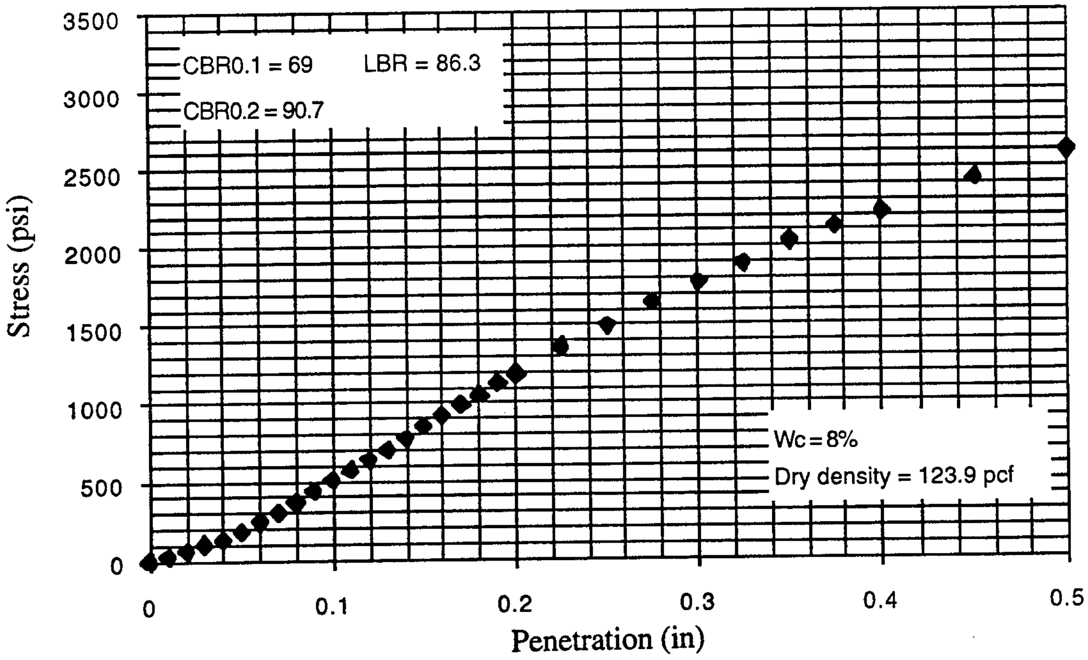


Figure B-42. The Penetration Test of 30% Cemented Coquina and 70% WPBMRF Glass Blend (Unsoaked)

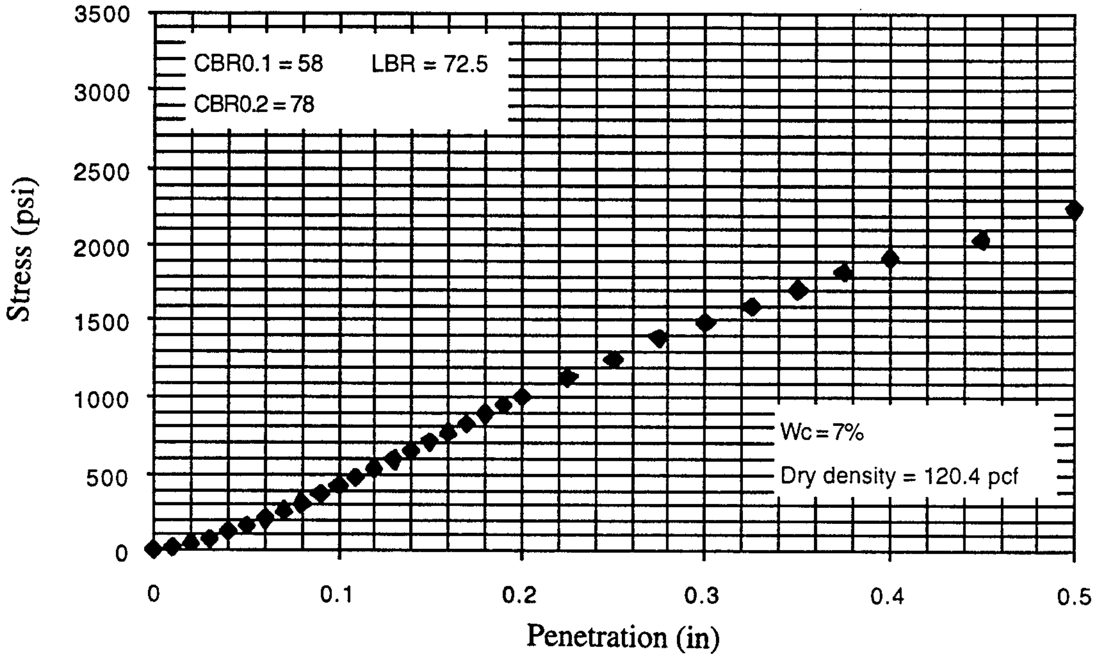


Figure B-43. The Penetration Test of 20% Cemented Coquina and 80% WPBMRF Glass Blend (Unsoaked)

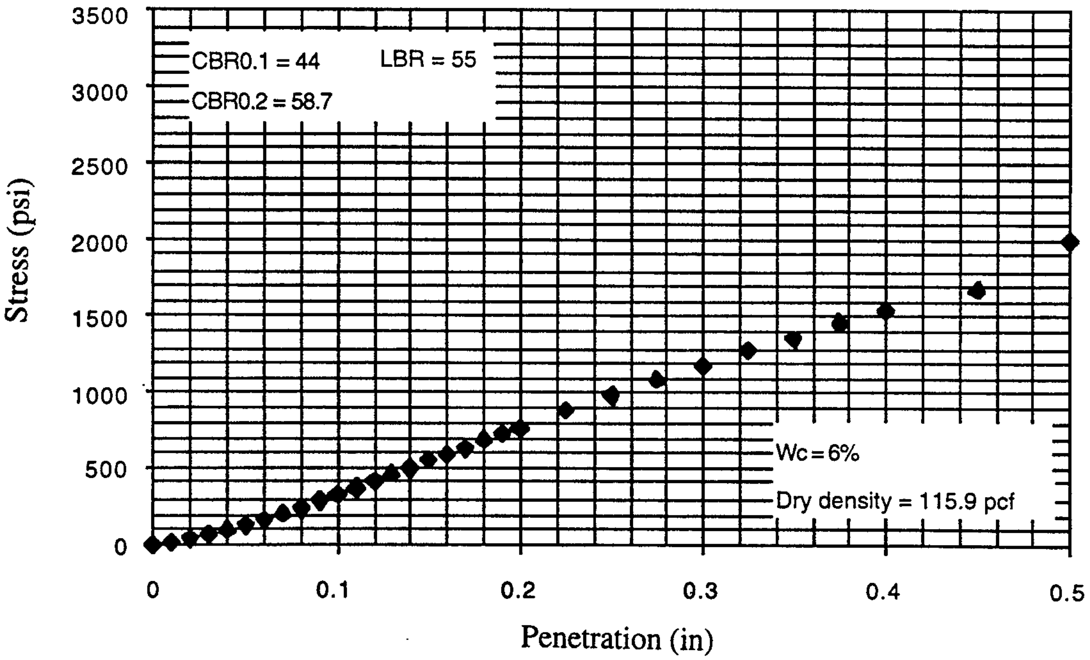


Figure B-44. The Penetration Test of 10% Cemented Coquina and 90% WPBMRF Glass Blend (Unsoaked)

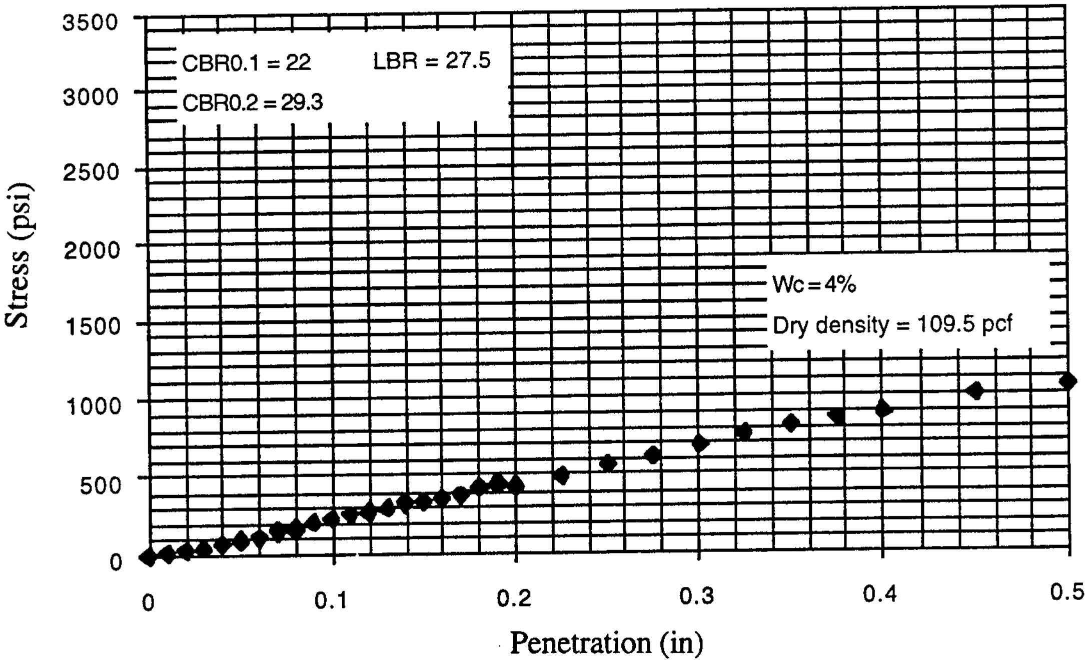


Figure B-45. The Penetration Test of 100% WPBMRF Glass (Soaked)

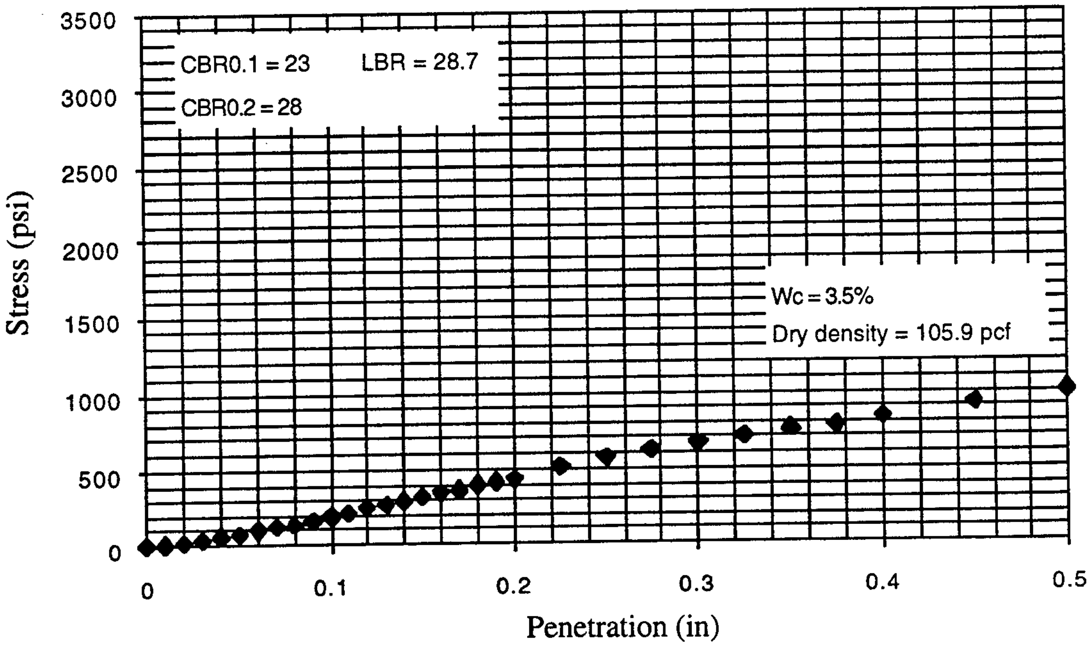


Figure B-46. The Penetration Test of 100% WPBMRF Glass (Unsoaked)

APPENDIX C

The CD Triaxial Test Mohr Cicle Diagrams

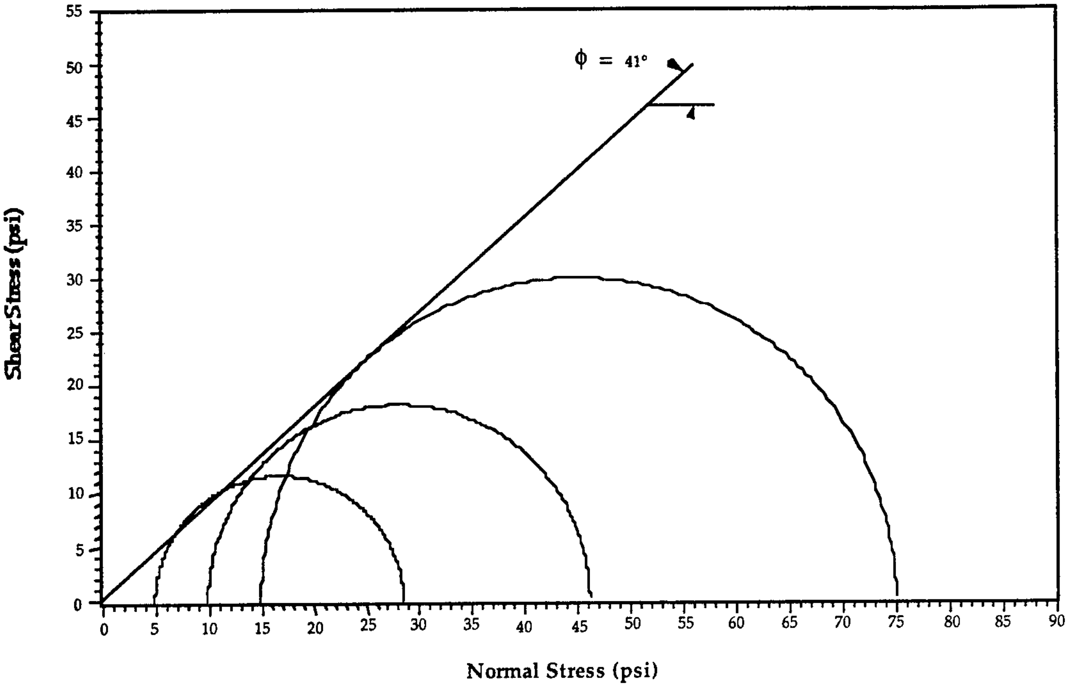


Figure C-1: Mohr failure envelope for the consolidated drained triaxial test on 100 % cemented coquina

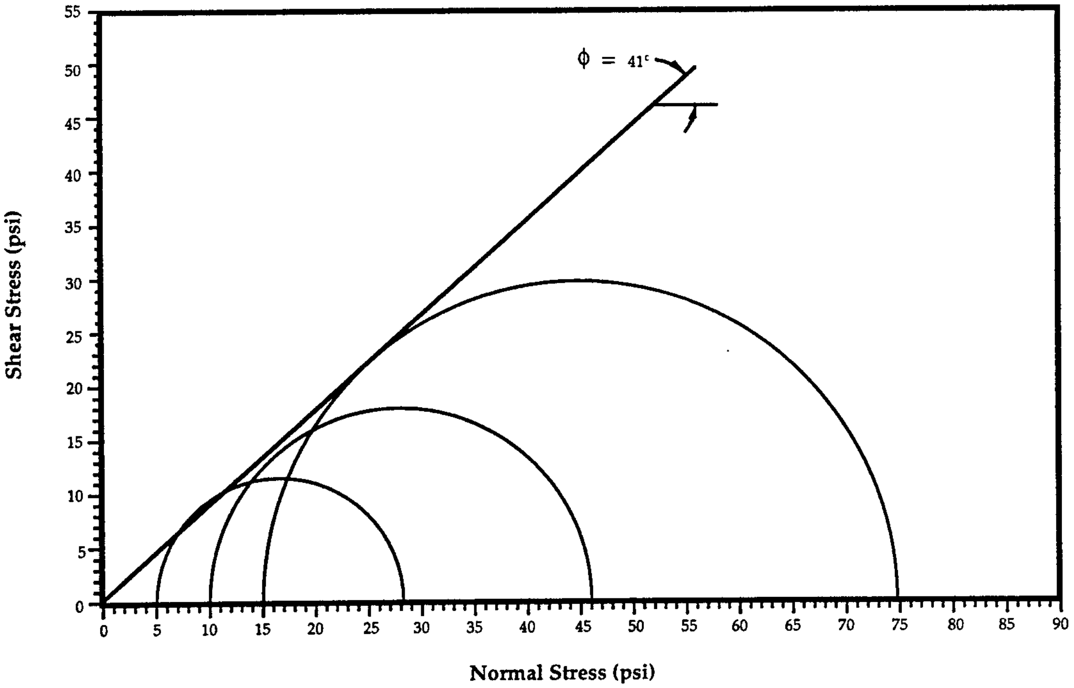


Figure C-2: Mohr failure envelope for the consolidated drained triaxial test on 100 % cemented coquina with a relative compaction dry of optimum of 91 % (1 psi = 6.895 kPa)

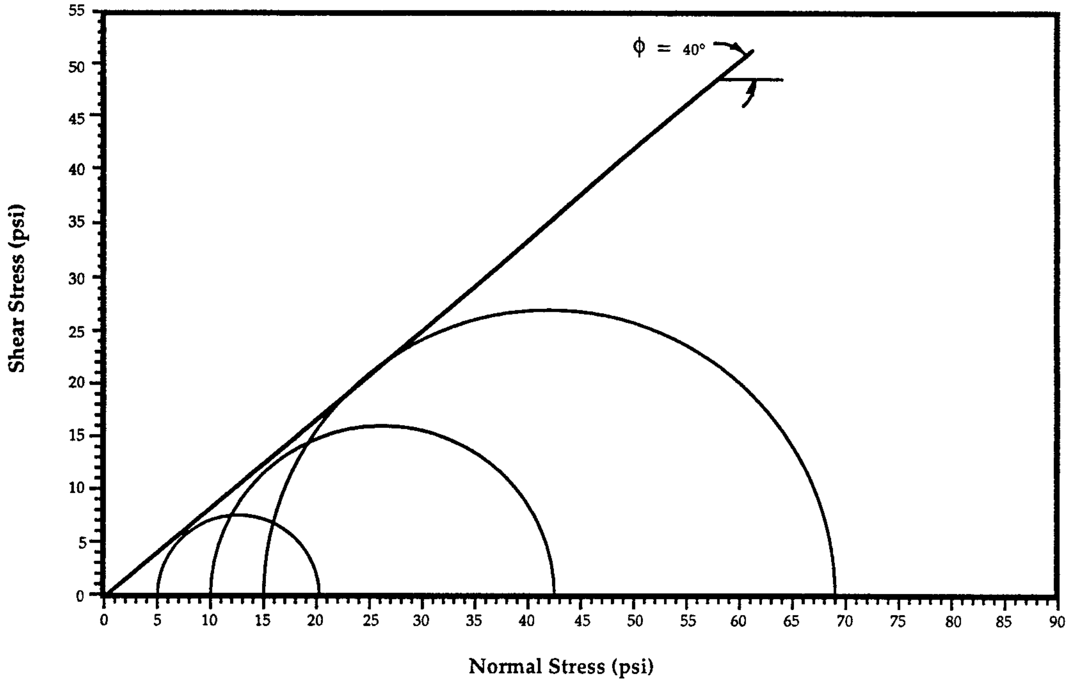


Figure C-3 Mohr failure envelope for the consolidated drained triaxial test on 20 % glass - 80 % cemented coquina mix with a relative compaction dry of optimum of 90 % (1 psi = 6.895 kPa)

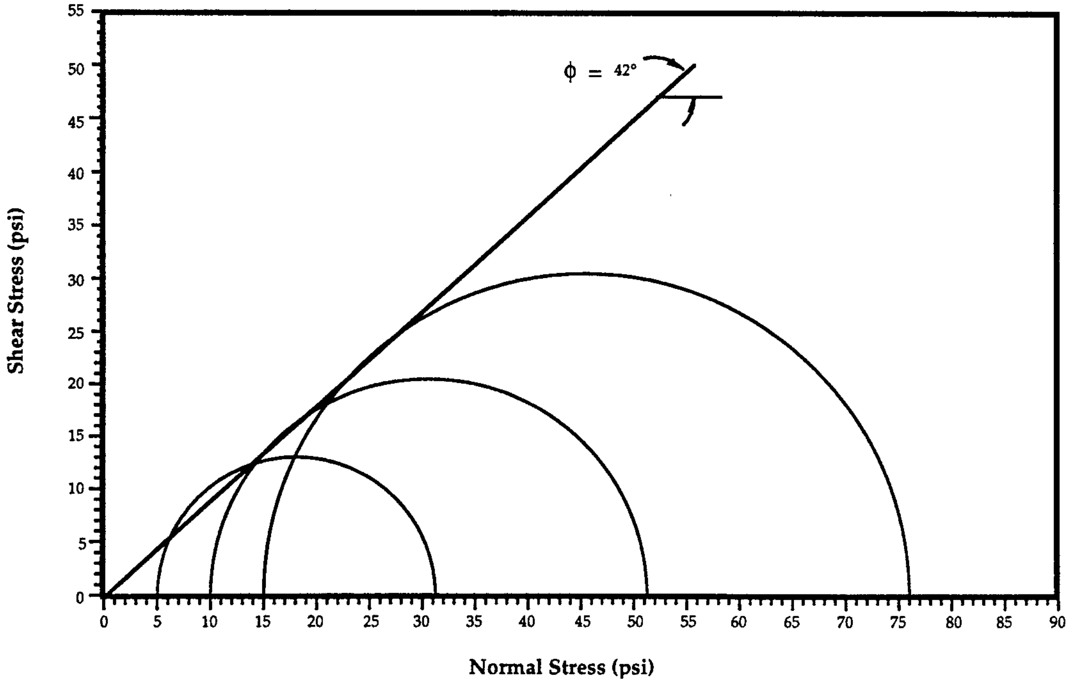


Figure C-4: Mohr failure envelope for the consolidated drained triaxial test on 40 % glass - 60 % cemented coquina mix with a relative compaction dry of optimum of 95 % (1 psi = 6.895 kPa)

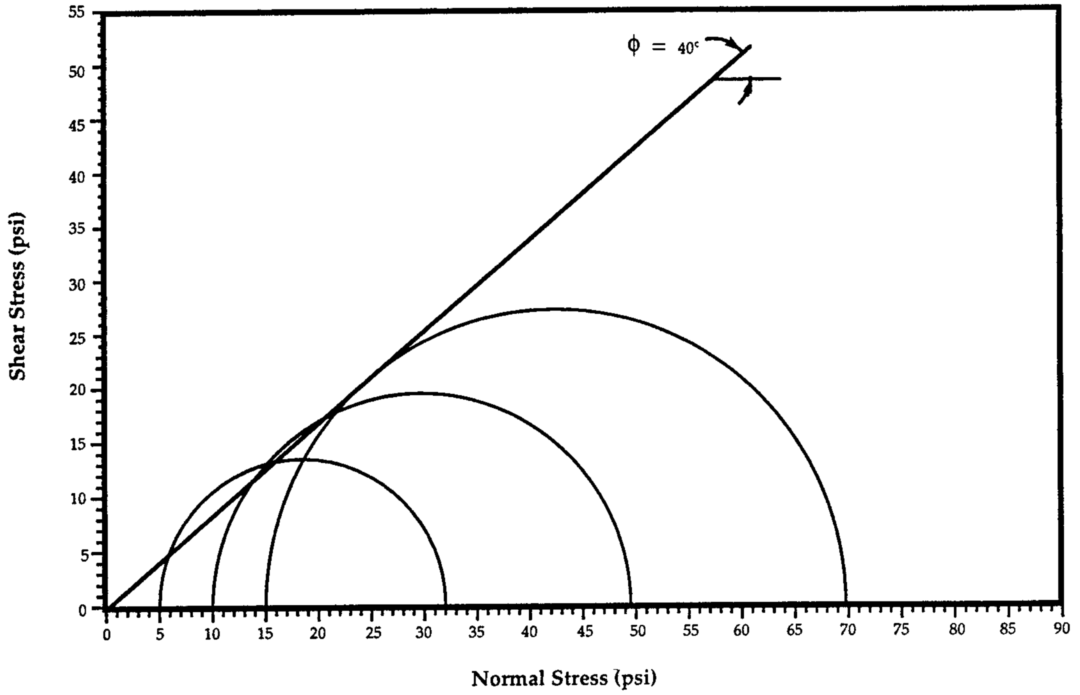


Figure C-5: Mohr failure envelope for the consolidated drained triaxial test on 60 % glass - 40 % cemented coquina mix with a relative compaction dry of optimum of 91 % (1 psi = 6.895 kPa)

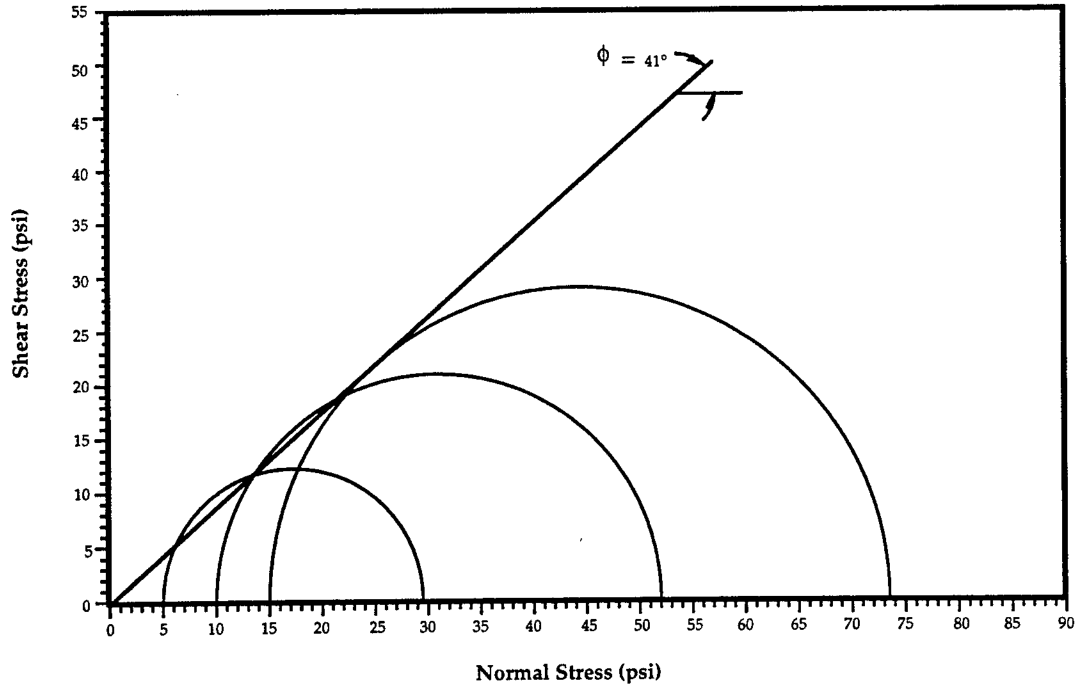


Figure C-6: Mohr failure envelope for the consolidated drained triaxial test on 80 % glass - 20 % cemented coquina mixwith a relative compaction dry of optimum of 94 % (1 psi = 6.895 kPa)

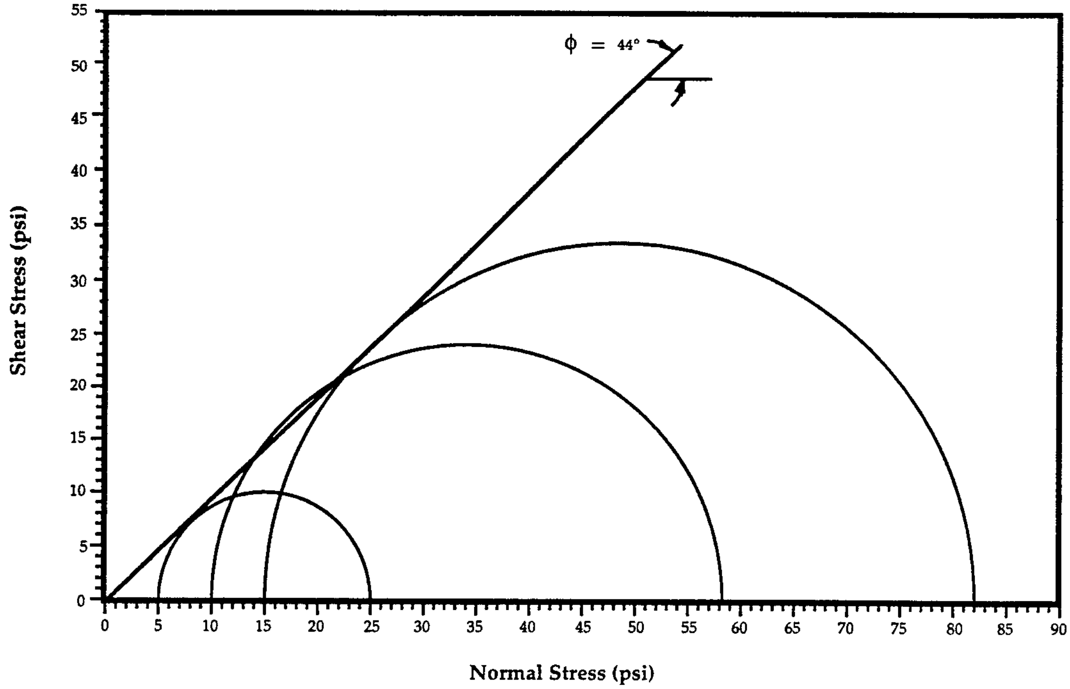


Figure C-7: Mohr failure envelope for the consolidated drained triaxial test on 100 % limerock base with a relative compaction dry of optimum of 97 % (1 psi = 6.895 kPa)

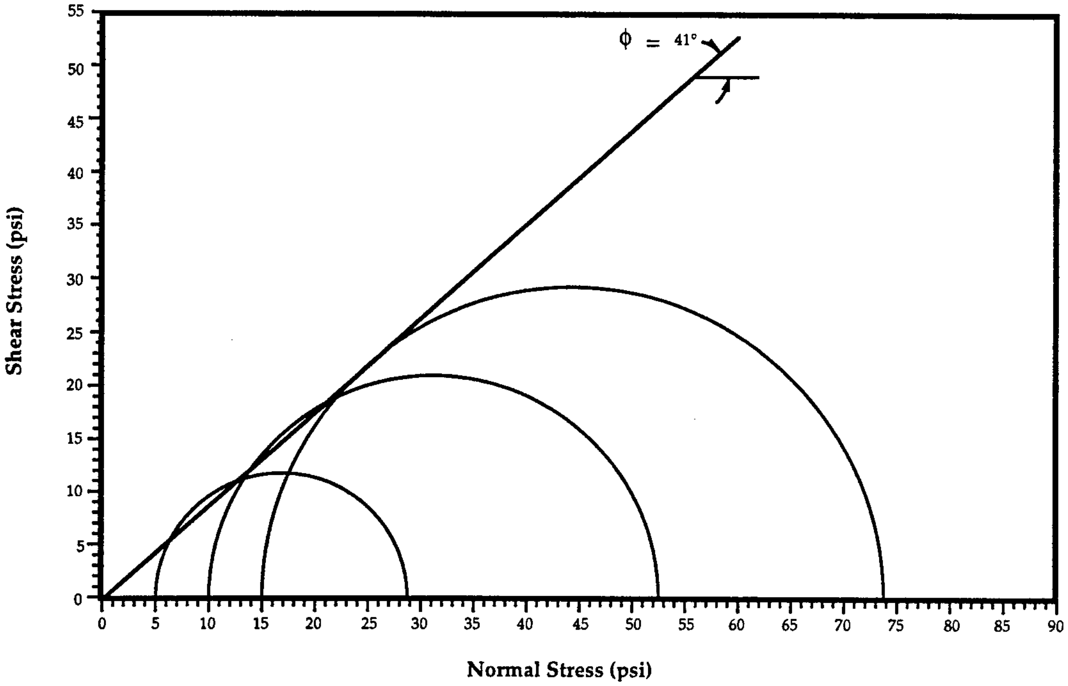


Figure C-8: Mohr failure envelope for the consolidated drained triaxial test on 20 % glass - 80 % limerock base mix with a relative compaction dry of optimum of 93 % (1 psi = 6.895 kPa)

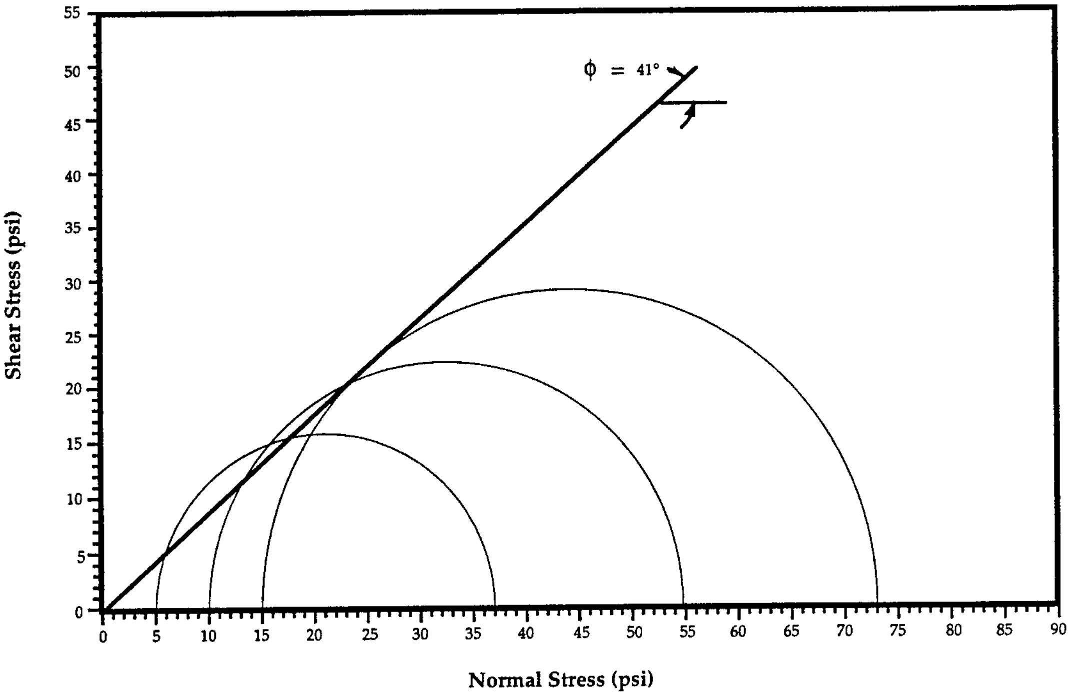


Figure C-9: Mohr failure envelope for the consolidated drained triaxial test on 40 % glass - 60 % limerock base mix with a relative compaction dry of optimum of 90 % (1 psi = 6.895 kPa)

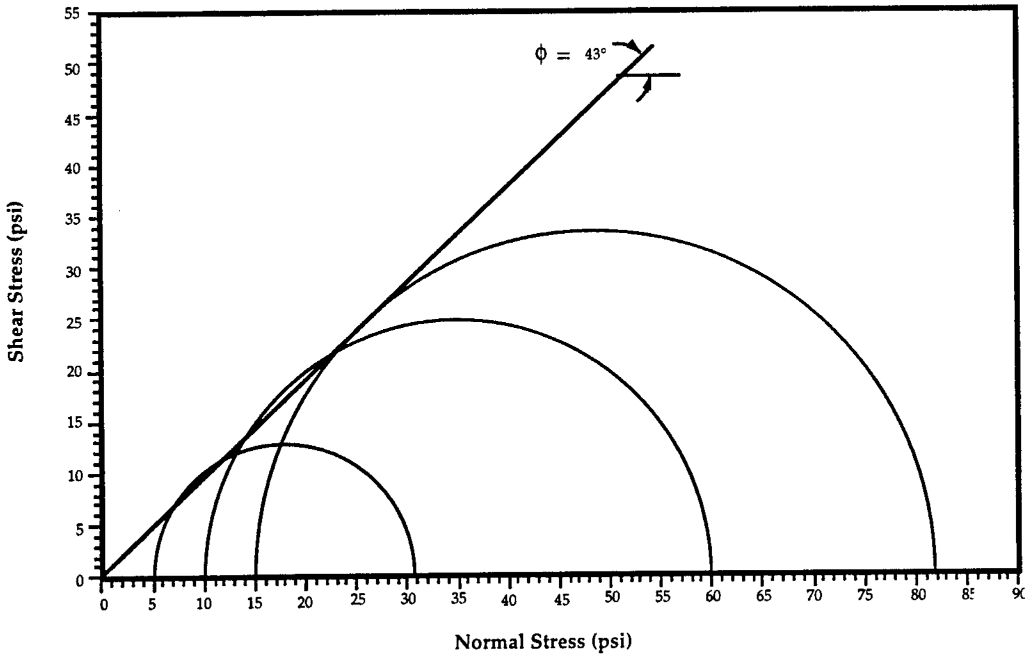


Figure C-10: Mohr failure envelope for the consolidated drained triaxial test on 60 % glass - 40 % limerock base mix with a relative compaction dry of optimum of 90 % (1 psi = 6.895 kPa)

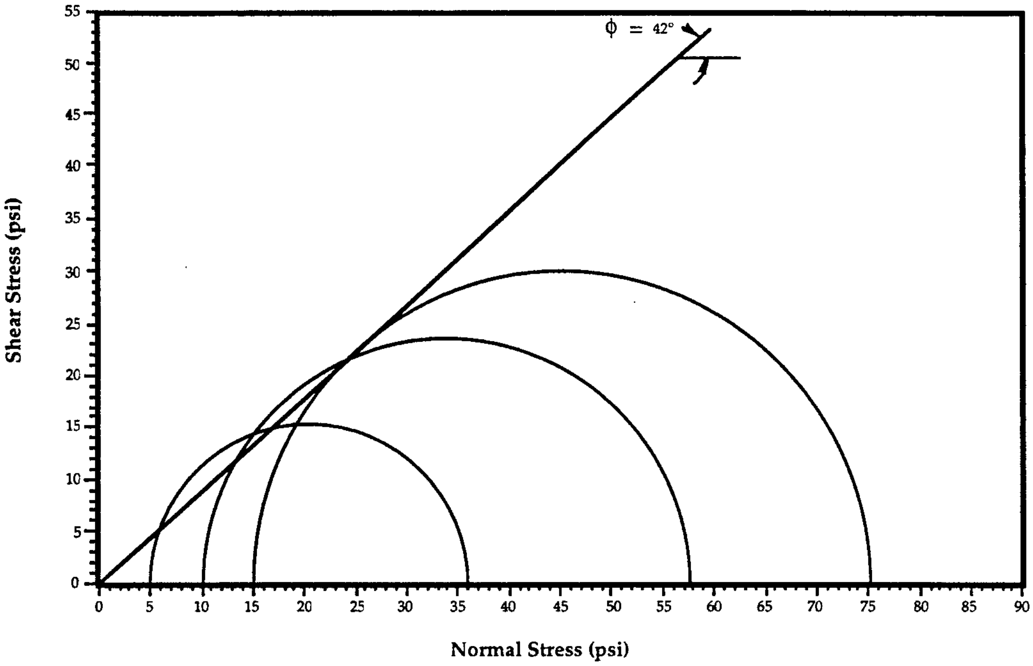


Figure C-11: Mohr failure envelope for the consolidated drained triaxial test on 80 % glass - 20 % limerock base mix with a relative compaction dry of optimum of 93 % (1 psi = 6.895 kPa)