Field Evaluation of A New Compaction Monitoring Device

Dr. Heather J. Miller, PI
Dr. Rajib Mallick, Co PI

Prepared for
The New England Transportation Consortium
June 26, 2003

NETCR42 **Project No. NETC 01-6**

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recepient's Catalog No.
NETCR 42	N/A	N/A
4. Title and Subtitle Field Evaluation of A New Compaction Monitoring Device		5. Report Date June 26, 2003 6. Performing Organization Code N/A
7. Author Dr. Heather J. Miller		8. Performing Organization Report No. NETCR 42
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Massachusetts Dartmouth North Dartmouth, MA 02747		10 Work Unit No. (TRAIS) N/A 11. Contract or Grant No. N/A
12. Sponsoring Agency Name and Address New England Transportation Consortium 179 Middle Turnpike University of Connecticut, U-5202 Storrs, CT 06269-5202		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code NETC 01-6 A study conducted in cooperation with the U.S. DOT
15 Supplementary Notes N/A		

16. Abstract

This report documents a research project conducted to verify the effectiveness of the Soil Compaction Supervisor (SCS) as a tool for determining optimum compaction for highway construction applications. The scope of work included testing a number of different materials in a large test frame in a laboratory setting, as well as field testing at several highway construction sites throughout New England. The overall results of this study indicate that the SCS performs well as a QA/QC tool for monitoring compaction of a wide variety of soils, provided that the specifications require a minimum of 95% compaction based upon standard Proctor density (AASHTO T-99, with coarse particle correction). In addition to testing a wide range of soils, use of the SCS with lightweight aggregate and asphalt was also investigated. It was concluded that the SCS is not a viable QA/QC tool for use with lightweight aggregate. A limited amount of testing performed on asphalt indicates that, although the SCS could potentially be used to monitor compaction of that material, it might produce a "stop compaction" signal prematurely in that application. It might be necessary for the manufacturer to make adjustment(s) to the internal data processing in the SCS meter if it is to be used for monitoring asphalt compaction where specifications require a minimum of 98% compaction.

17. Key Words	18. Distribution Statement
compaction, field quality control, soil compaction meter, soil compaction supervisor	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	80	N/A

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

Acknowledgments

The writer wishes to thank the New England Transportation Consortium (NETC) for providing the funds to conduct this research, and MBW, Inc. for providing the Soil Compaction Supervisor. The Co PI, Dr. Rajib Mallick is acknowledged for coordinating the work on the project completed at WPI. The writer would also like to thank several undergraduate students at UMass Dartmouth (Nicholas Yafrate, Paulo Baganha and Eric Rudenauer) and at WPI (Jonathan Gould) for assistance that was provided during the field and laboratory testing. And finally, the advice and support of the NETC technical committee is gratefully acknowledged (Kenneth Cogswell, Chair, Joe Anderson, Christopher Benda, Jeff DiFilippo, Leo Fontaine and Nabil Hourani). Their assistance in developing the work plan, in arranging access to numerous field sites, and in providing technical comments on this report is much appreciated.

TABLE OF CONTENTS

Tables

Figures

1. Abstract

This report documents a research project conducted to verify the effectiveness of the Soil Compaction Supervisor (SCS) as a tool for determining optimum compaction for highway construction applications. The scope of work included testing a number of different materials in a large test frame in a laboratory setting, as well as field testing at several highway construction sites throughout New England. The overall results of this study indicate that the SCS performs well as a QA/QC tool for monitoring compaction of a wide variety of soils, provided that the specifications require a minimum of 95% compaction based upon standard Proctor density (AASHTO T-99, with coarse particle correction). In addition to testing a wide range of soils, use of the SCS with lightweight aggregate and asphalt was also investigated. It was concluded that the SCS is not a viable QA/QC tool for use with lightweight aggregate. A limited amount of testing performed on asphalt indicates that, although the SCS could potentially be used to monitor compaction of that material, it might produce a "stop compaction" signal prematurely in that application. It might be necessary for the manufacturer to make adjustment(s) to the internal data processing in the SCS meter if it is to be used for monitoring asphalt compaction where specifications require a minimum of 98% compaction.

2. Background

In many highway projects, soil must be placed and compacted for roadway base material, for backfill behind retaining walls and abutments, for construction of embankment fills, and for trenching operations. Each layer of soil, or lift, must be properly compacted before the addition of the next lift of soil is placed. There are a number of factors that influence the degree of compaction that can be attained, including soil type and placement moisture content, lift thickness, and characteristics of the compaction equipment (Holtz and Kovacs, 1981). If the soil is not properly compacted, the soil may fail or settle excessively, resulting in poor performance of the roadway and/or associated structures.

To avoid potential shortcomings in the compaction process, quality assurance tools are typically used to monitor the backfilling process. Presently, the nuclear density technique is the predominant method used to monitor the compaction of granular materials on New England highway projects. The nuclear density gauge uses radioactive materials and directs gamma and neutron rays through the soil. The probe is inserted into the ground, and the density of the soil is correlated to the amount of radiation transmitted through the soil. The sampling time is a minimum of 60 seconds, but can be several minutes in some situations.

There are several drawbacks associated with the nuclear density gauge technique. For example, it does not accurately measure density on some granular materials with high proportions of coarse aggregate. Also, because of its radioactive sources, there are many health and safety issues associated with the nuclear density gauge, and considerable expense is involved with the purchase, use, and maintenance of these devices. The nuclear density gauge must be operated by a certified technician, requires an annual federal licensing fee, and must be periodically checked for radiation leakage.

Other techniques are available for quality control during compaction operations; however, those techniques also have drawbacks in terms of reliability and/or time and expense required to perform the testing. The sand cone test is often used in lieu of the nuclear density test for quality control. A small hole is excavated in the compacted lift, and the in-place density of the soil is determined based upon the weight and moisture content of the soil removed from the hole, and the weight of calibrated sand (from the sand cone) required to fill the hole. A major disadvantage of this test is the time required to perform the test, and the fact that compaction equipment cannot be operated while the test is being performed, since vibrations from compaction equipment would adversely affect the test results.

The dynamic cone penetrometer (DCP) test has occasionally been used for quality control during backfilling operations. The DCP, originally developed in South Africa, consists of a steel rod with a cone at one end that is driven into the ground by means of a sliding hammer. The test is conducted by raising the hammer to the top of the drop height and releasing the hammer so it falls freely to impact the anvil. The DCP index is generally defined as the number of millimeters of penetration by the cone under one hammer blow (mm/blow). Although there are no direct correlations with density, the penetration resistance of soils materials (as indicated by the DCP index) has been correlated to other known measurements, such as California Bearing Ratio (CBR). The CBR has been widely used by many highway agencies throughout the world as an indicator of soil strength.

A potential problem with the DCP is that the accuracy of the measurement is affected by the consistency of the operator to make identical blows with the slide hammer. Also, the DCP (as well as the nuclear density test and the sand cone test) must be set up and implemented with each lift if the entire depth of backfill is to be checked. As a result, the time required to complete the overall backfilling operation is increased. Therefore, an economical, reliable and rapid means of assessing the sufficiency of compaction is still sought for quality control on highway construction projects.

The Soil Compaction Meter (SCM) and Soil Compaction Supervisor (SCS) show much promise in this regard. The Soil Compaction Meter was the "first-generation" device developed by Foster-Miller, Inc. and MBW Inc. for the Gas Research Institute (GRI). The SCS is an updated version of the device, which incorporates many improvements. The SCM and SCS operate on the same principals; the main difference in the two devices is that the Soil Compaction Supervisor has internal memory, so it can record data regarding the compaction process, which can later be downloaded to a personal computer. The SCM and SCS consist of a hand-held meter and a disk shaped disposable sensor, which is connected to the meter by a wire (see Figure 1 on page 22). A polymer-based piezoelectric element is bonded to the inside of the top surface of the sensor, as shown in Figure 2 (page 22). The general theory of operation of both the SCM and SCS (which is based upon a mathematical procedure referred to as the "Peak Detect Algorithm") is as follows (Torbin and Heirtzler, 1995).

A sensor is initially placed at the bottom of an uncompacted lift of fill. The meter is turned on as the compactor passes over the sensor and a green "processing" light appears on the meter. The enclosed piezoelectric element within the disk produces a voltage in response to compression waves transmitted through the soil from the compactor. The voltage level is proportional to the amplitude of the pressure wave reaching the sensor and is dependent on several factors (moisture, soil type, compactor characteristics, etc.). The most important factor for the peak detect algorithm is soil density. Initially, the uncompacted soil is at a relatively low density and so the efficiency of transmission of pressure waves through the soil is low. Thus, the corresponding voltage response generated by the sensor is also small. As the soil becomes more compact, the transmission efficiency increases and the voltage produced by the sensor similarly increases. During this process, the visual signal on the meter advances from the green processing signal to a first and then a second level green light signal. Theoretically, when compaction is optimized (i.e., when the soil reaches the maximum achievable density under a given set of conditions), the voltage increases level off. A mathematical algorithm programmed into the hand-held meter filters and manipulates successive voltage readings to determine when that asymptotic value has been achieved. The operator is then notified by a visual "red light" signal from the meter that the lift has been sufficiently compacted. A single sensor can be used to monitor compaction of several successively placed lifts of fill.

The Soil Compaction Meter was initially intended to address "bellhole" type street excavations for utility repair work. As part of the GRI development program, field evaluations were conducted to evaluate several technical and operational issues associated with the Compaction Meter (Torbin and Heirtzler, 1995). Several natural gas utilities from a number of geographic locations participated in these evaluations. Additionally, an extensive verification-testing program (sponsored by the Gas Research Institute) was completed by Dr. David Gress at the University of New Hampshire in 1998 (Cardenas, 2000). Data from those studies show that, for most soils tested, the "optimized compaction" as indicated by the Compaction Meter was correlated to an average percent of Standard Proctor Density ranging from 95% to 99%. Some problems were encountered in tests performed on cohesive soils. The investigators concluded, however, that those problems resulted because the soil was compacted at moisture contents that were too high (relative to optimum).

The research cited above has provided a significant body of data regarding use of the Soil Compaction Meter with "portable" compaction equipment typically used for compacting bellhole excavations (e.g., pneumatic pole tamper, rammer, small vibratory plate compactor, or jackhammer). On the other hand, very little testing has been documented with heavy compaction equipment typically used in highway applications (e.g., vibratory rollers). It is that gap in knowledge that was addressed in this research project.

3. Objectives

The overall objective of this study was to verify the effectiveness of the Soil Compaction Supervisor as a tool for determining optimum compaction for highway construction applications. Initially, a literature review was conducted to identify the operational parameters and current capabilities/limitations of the SCS. Subsequently, testing was performed to evaluate the effective uses of the device in a variety of applications and for a variety of materials. The overall testing plan was divided into two Phases, Phase A and Phase B, to reflect test conditions which were performed in a large-scale test mold in the laboratory at WPI (Phase A) versus testing performed in the field at various highway construction sites (Phase B). Details of the testing conducted under the two different phases are provided in the sections that follow.

During the course of the testing program, several parameters were varied, including soil/material type, moisture content, lift thickness, and the total number of lifts or total height of fill above the sensors. After testing was completed, statistical analysis of the data was performed to evaluate the performance of the SCS. Specifically, the following questions were addressed:

1. Does the SCS "red light" signal correlate well with at least 95% Standard Proctor Density for a variety of soils?
2. Does the SCS give the red light signal at a point of diminishing returns for soil density and/or stiffness?
3. Is the SCS an effective tool for QA/QC for materials other than soil (i.e., lightweight aggregate, and asphalt)?
4. Are there any conditions that limit the use of the SCS in typical highway construction applications?

4. Methodology

4.1 Phase A

The work conducted under this task involved testing materials compacted with a roller in a large-scale test frame (mold). The roller and mold are part of the MMLS Mk3 Accelerated Traffic Loading Machine at Worcester Polytechnic Institute (WPI). The dimensions of the test frame are 9-ft. long by 3-ft. wide by 1-ft. deep. The roller can be operated in either static or vibratory mode, but the vibration frequency cannot be varied. Photographs of the mold and roller are included in Appendix A.

Five different materials were investigated in the WPI test mold:

1. M1: Dense-Graded Aggregate
2. M2: Gravel Borrow
3. M3: Ordinary Borrow
4. M4: Lightweight Aggregate
5. M5: Asphalt

Prior to testing at WPI, sieve analyses and Proctor compaction tests (as appropriate) were performed on the materials at UMass Dartmouth (UMD). Results of those tests are included in Appendix B. For the first three materials, three different target moisture contents were selected for testing (less than optimum, optimum moisture and above optimum). The moisture contents selected were within the range corresponding to 90% - 100% maximum dry unit weight. Each material/moisture content combination was placed, compacted, and tested in the load frame at a given moisture content three times.

Materials M2 and M3 were tested according to the following procedures. Prior to compaction, the moisture content of the soil was measured, and the weight of water necessary to bring the moisture content up to the target value was computed. The calculated weight of water was added to the soil and thoroughly mixed in a cement mixer. A thin layer of soil was initially spread in the bottom of the mold, then an SCS sensor was placed (approximately centered between the sidewalls of the mold), and finally the remaining soil was shoveled into the mold. The M2 and M3 soils were placed in loose lifts approximately 12 inches thick.

The loose soil was then subjected to several passes of the roller, operating in vibratory mode. Throughout the compaction process, the signal on the SCS was recorded (i.e., green light/processing, green light + one, green light + two, red light). After application of each pass with the roller, GeoGauge stiffness measurements were taken at 3 locations along the top of the lift. The GeoGauge, produced by Humboldt Manufacturing Company, is a hand-portable instrument designed to provide a simple, rapid means of measuring soil stiffness. A brief description of the principles of operation of the GeoGauge is included in Appendix D.

Compaction and GeoGauge measurements were repeated until the red light signal on the SCS appeared. At that point, the SCS discontinued processing data for that lift of fill, and a sand cone test was performed to determine the unit weight of the compacted soil. Alternate compaction of the material and GeoGauge measurements continued for 3 to 4 more passes, or until it became apparent that a point of diminishing return had been achieved in terms of GeoGauge stiffness measurements. At that point, a second sand cone test was performed. For each test series, data was recorded and entered on an Excel spreadsheet, as shown in Figure A-3 (Appendix A, page A-2).

For material M1 (dense-graded aggregate), the same testing procedures described for materials M1 and M2 were followed, with the following exceptions. A layer of neoprene rubber (typically used in pavement testing to model the soil subgrade beneath the aggregate base) was placed in the bottom of the WPI test mold. Then six inches of the dense-graded aggregate was placed and compacted in the mold. Since sand cone tests can not be used effectively to measure the in-place unit weight of dense-graded aggregate, nuclear density tests were performed. The nuclear density tests were generally performed after each pass of the roller. Data was recorded in the same manner as for materials M2 and M3.

Material 4 (lightweight aggregate) was of interest because it is often used in highway embankments or as backfill behind abutments, however there are currently no QA/QC standards for that material in terms of a specified percent compaction. This is because, to date, there has been no reliable means developed for determining the dry unit weight of the compacted material in the field. It was hoped that perhaps the SCS might prove to be a useful tool for monitoring compaction of this material.

The gradation selected for the lightweight aggregate was based upon recommendations from the Vermont Agency of Transportation (see Figure B-7, page B-4). The material was placed in loose lifts of about 10 to12 inches and compacted with the roller. The lightweight aggregate was compacted using both static and vibratory modes. In most cases the SCS did not even register a "processing" signal during compaction. In a few instances, the SCS did sporadically produce the processing signal, but did not advance to any level above that. Similarly, the GeoGauge failed to give stiffness measurements on this material. It is likely that both the SCS and the GeoGauge were not able to function as intended due to the open-graded nature of the lightweight aggregate. The void ratio of the lightweight aggregate is quite high and the material retains little to no water in the voids. Thus it is not able to transmit compression waves effectively enough to be compatible with QA/QC tools (like the SCS and the GeoGauge) that produce signals in response to transmission of compression waves through the test material.

One series of tests on an asphalt material (M5) was performed in the mold at WPI. The base of the mold was lined with neoprene rubber sheets, and then a 1.5 inch layer of Frenchville gravel (dense-graded aggregate) was placed as base material. The SCS sensor was placed on top of the aggregate base, and then a 1.5-inch layer of hot mix asphalt (HMA) was placed and compacted in the mold. The HMA was produced using a Gilson 5-Gal bucket mixer and a laboratory Wirtgen foamed asphalt plant (WLB-10) timer and pneumatic controls to obtain the desired amount of asphalt. The target asphalt content was 5.90% and the actual asphalt content was 6.09%. The SCS signal was recorded during each pass of the vibratory roller during compaction of the asphalt. Stiffness measurements were also taken using the GeoGauge after every 3 to 5 passes of the roller. Although the SCS reached the red light/stop compaction signal after 14 passes of the roller, compaction of the asphalt continued for about 38 more passes until the asphalt temperature dropped down to 80°C. During the additional rolling, GeoGauge measurements were taken after every 10 passes. This data, as well as data from the other materials tested during phase A, are included in Appendix B.

4.2 Phase B

During this phase, full-scale field testing with the SCS was conducted at several different highway construction sites throughout New England. A listing of those sites and materials tested is presented in Table 1 (page 16). In the field, materials M1, M2 and M3 were generally tested as follows. The material was typically end dumped in stockpiles on site, and then a full lift thickness was spread with one or more dozers. Lift thicknesses ranged from 12 to 24 inches, depending upon the contract specifications for a given project. After the loose lift was placed the PI and/or research assistant would dig a small hole (down to approximately an inch above the base of the lift) and bury the SCS sensor. A trench (about 3 inches deep) was excavated so that the cable between the sensor and the meter could be buried and run to the edge of the lift. This was necessary so that the PI and/or research assistant could remain out of the way of the heavy equipment during compaction operations.

The soil was then compacted, and the SCS meter was turned on as the compaction equipment made its first pass over the sensor. Throughout the compaction process, the number of passes of the compactor and the signal on the SCS were recorded (i.e., green light/processing, green light + one, green light + two, etc.). The research team was usually unable to obtain GeoGauge measurements in between passes of the compactor because either (a) there was not enough time between successive passes to take a measurement and/or (b) the GeoGauge gave a "sensory overload" signal due to the proximity of the compaction equipment. When the red light signal appeared on the SCS, a unit weight determination was made either via the sand cone method (performed by the research team) or via the nuclear density method (performed by certified state highway personnel).

Some of the sites selected for testing material M2 (gravel borrow) and material M3 (ordinary borrow) were chosen because it was anticipated that very high fills would be placed there. On those sites, the same procedures outlined in the paragraph above were followed for each lift of fill, except that the same sensor (placed near the base of the first lift) was kept in place and used to monitor several lifts, where possible.

Data obtained at each field site (including lift thickness, compactor type, density test results etc.) for materials M1, M2 and M3 are included in Appendix C. Results from sieve analyses as well as laboratory compaction tests for each material that was tested in the field are also included in Appendix C. For QA/QC in the field, it is necessary to compare the unit weight measured in the field to a laboratory maximum value (typically from a standard or a modified Proctor compaction test). The percent compaction (also known as relative compaction, R.C.) is defined as the field dry unit weight divided by the laboratory maximum unit weight; it is usually expressed as a percentage. Most specifications require a minimum of 95% compaction, based upon either the standard (AASHTO T-99) or the modified (AASHTO T-180) Proctor compaction test.

It should be noted that there are many variables encountered in both the field and the laboratory (i.e., corrections for coarse particle content, etc.) that can influence the computed values of percent compaction. One of the most significant variables is the type of laboratory test used as a standard of comparison for field compaction. For example, the major difference between the standard and the modified Proctor compaction tests is the amount of compactive energy applied. Much more compactive energy is applied in the modified test, because it calls for use of a heavier compaction hammer with a greater height of fall. In general, compactive energy affects the moisture-density relationship of soils as follows: an increase in the amount of compactive energy applied results in increased values for maximum dry density (or dry unit weight) and decreased values of optimum moisture content (Holtz and Kovacs, 1981). That general trend can be seen in many of the moisture-density plots included in Appendices B and C. As a result, computed values of percent compaction (R.C.) in excess of 100% are sometimes encountered. For example, on pages C-5 and C-6, it can be seen that R.C. values are less than 100% when calculated based upon the modified Proctor test, but that R.C. values for that same field data are greater than 100% when based upon the standard Proctor test.

Material M4 was not investigated during Phase B since it had been concluded (during Phase A) that lightweight aggregate is not able to transmit compression waves effectively enough to be compatible with QA/QC tools like the SCS.

The SCS was used to test material M5 (asphalt) at three different sites. At sites M5.1 (N. Conway, NH) and M5.2 (Kingston, RI) the SCS was used to monitor compaction of hot-mix asphalt (HMA). At those sites, after the gravel base had been compacted, a small trench was excavated in the gravel with a shovel, and the SCS sensor was buried under about 1 inch of the gravel. A layer of HMA (2.5 inches thick at site M5.1 and 3 inches thick at site M5.2) was then spread and compacted, first with a breakdown roller and then with a finish roller. At site M5.1, both the breakdown roller and the finish roller were operated in static mode because of restrictions imposed due to detrimental effects of vibrations on nearby businesses. At site M5.2, the breakdown roller was operated in static mode and the finish roller was operated in vibratory mode. At both sites, the SCS meter was activated as the finish roller made its first pass over the sensor, and the number of passes of the roller and signal on the SCS were recorded throughout the compaction process. Nuclear density tests were also performed by highway agency personnel during the compaction process. At site M5.1, a core sample of the asphalt was obtained for density determination at the conclusion of the compaction process.

At the third site, M5.3 (Orient, ME), the SCS was used to monitor compaction of foamed asphalt recycled base material. Construction and testing at that site proceeded as follows. The first step was to apply a layer of crusher dust to the roadway. The crusher dust, entire depth of pavement, and base material were pulverized to a minus 2-inch material using a Wirtgen Model WR 2500 milling machine. The roadway was then shaped and compacted to the cross-slopes and grades and a tractor equipped with a spreader evenly applied Portland cement across the entire width of the road. Following the application of the cement, a Wirtgen Model WR 2500 equipped with foaming chambers introduced foamed asphalt into the recycled base material.

The stabilization process involved a train of vehicles: a primary milling vehicle, a truck with a spreader to apply cement, and a secondary milling vehicle with foamed asphalt chambers to work foamed asphalt into the base material up to a depth of 20 inches. Attached to the foaming Wirtgen Model WB 2500 milling machine was a 10,000-liter asphalt tanker capable of maintaining temperature up to 180 degree Celsius, and a water tanker.

The SCS sensor was placed under approx. 8" of foamed material after the Foaming equipment initially went through. To place the sensor, a channel was dug using a spaded shovel and then the sensor and wire were backfilled with the foamed material. The layer was initially compacted with 3 passes of a sheepfoot roller and was then graded to meet slope and grade requirements. The material was once again foamed and then compacted with a 10-ton vibratory drum roller to a minimum percent compaction of 98%.

The SCS was not used during static compaction with the sheepfoot roller. The SCS meter was activated during the first pass of compaction using the10 ton vibratory drum roller. Stiffness measurements were taken with the GeoGauge and nuclear density tests were performed during the compaction process. That data from the SCS, the GeoGauge and the nuclear density tests are included in Appendix C.

5. Test Data and Analysis

The bulk of the data from the Phase A testing and the Phase B testing are included in Appendices B and C, respectively. Summaries of those data are included in Tables 2, 3 and 4 (pages 16-19) of this report. To answer the questions listed in Section 3 of this report, several different statistical analyses were performed.

A hypothesis test is one commonly used method of statistical inference. To conduct a hypothesis test, two opposing hypothetical statements are set up to describe the data (the null hypothesis, H_o, and the alternative hypothesis, H_A). Usually, the alternative hypothesis describes what one is attempting to prove true. There are three kinds of hypothesis tests: left-tail, right-tail and two-tail. If one is trying to show that a sample mean is less than a given value, then a left-tail test is appropriate. Conversely, if one is trying to show that a sample mean is greater than a given value, then a right-tail test is appropriate. If one is attempting to detect a significant change in either direction, then a two-tail test is appropriate.

The first question addressed in this study was: Does the SCS "red light" signal correlate well with at least 95% standard Proctor density for a variety of soils? To help answer that question, a series of right-tail t-tests was conducted. In those tests, the null hypothesis, H_o, is that the percent compaction of the soil is less than 95% at the SCS red light signal. If the null hypothesis is rejected, the alternative hypothesis, H_A, is accepted, implying that the percent compaction of the soil is greater than or equal to 95% at the SCS red light signal. Results from those statistical analyses are summarized in Tables 5 and 6 (page 20). For each case analyzed in Tables 5 and 6, an alpha value of 0.05 (95% confidence level) was used. The percent compaction was based upon the standard Proctor compaction test (AASHTO T-99 C), with test adjustment to account for rock content as specified in Note 7 of the AASHTO T 99-97 test specifications (AASHTO, 1998).

As indicated in Table 6, for all soils tested in the field, the correlation between the SCS red light signal and a percent compaction equal to 95% (or greater) is significant at the 95% confidence level. For the soils tested in the mold at WPI (Table 5), the correlation is significant only for material M3 (ordinary borrow). These results are discussed further in the following section of this report.

An alternative method of statistical inference involves construction of a confidence interval for a given data set. The 95% confidence intervals for each of the three general classes of soils tested in the WPI test mold and in the field are presented in Figure 3 (page 23). An example interpretation of these confidence intervals is as follows. For the 21 tests performed on ordinary borrow in the field (data set M3-B), the average percent compaction was 97.88% at the SCS red light signal. Based upon statistical analysis of that data set, there is a 95% chance that the mean percent compaction achieved would fall between 95.34% and 100.41% when the SCS produces a red light signal with that material. The data presented in Figure 3 were based upon standard Proctor density. A similar plot based upon modified Proctor density is presented in Figure 4 (page 24).

The second question addressed in this study was: Does the SCS give the red light signal at a point of diminishing returns for soil density and/or stiffness? That question was addressed through analysis of the Phase A data. During the Phase A testing, the percent compaction was determined when the SCS gave the red light signal, and then again after the soil had been subjected to several additional passes of the roller. Those values are listed in Table 7 (page 21), along with the difference between those two measurements for each test. Ideally, if the SCS gave the red light signal at a point of diminishing returns for soil density, the change in percent compaction would equal zero. Statistical analysis of that data set indicates that the mean change in percent compaction was 1.97%, with a standard deviation of 6.69. The lower and upper limits for a 95% confidence interval are –0.73 and 4.67, respectively.

GeoGauge measurements were taken in an attempt to detect whether the SCS gives the red light signal at a point of diminishing returns with regard to soil stiffness. During the Phase A testing, GeoGauge measurements were generally taken at 3 locations along the top of the lift after each pass of the roller during compaction. The three individual GeoGauge stiffness measurements taken after each roller pass, along with the average, the standard deviation and the coefficient of variation between measurements, is tabulated in Appendix D. It can be seen that the coefficient of variation between the three measurements on any given lift is generally quite high. As such, that data could not reliably be used to determine whether or not a statistically significant difference in stiffness occurred during additional compaction after the SCS red light signal was produced.

The third question addressed in this study was: Is the SCS an effective QA/QC tool for other materials such as lightweight aggregate and asphalt? As noted in Section 4.1, attempts to monitor compaction of lightweight aggregate with the SCS were unsuccessful, so no additional data or analysis is presented here with regard to that material. Data from the asphalt testing at WPI is included in Appendix B, and data from the three field sites where the SCS was used to monitor asphalt compaction is included in Appendix C. Although the data set for that material was not large enough to perform rigorous statistical analyses, results of those tests are discussed in the following section.

6. Results and Conclusions

The overall results of this study indicate that the SCS performs well as a QA/QA tool for monitoring compaction of a wide variety of soils, provided that the specifications require a minimum of 95% compaction based upon standard Proctor density (AASHTO T-99, with coarse particle correction). Analysis of the Phase B (field) data indicates that, for a 95% confidence level, the percent compaction for all soils tested should be greater than or equal to 95% (standard Proctor density) when the SCS produces its red light signal. Although the soils tested during phase B were grouped into three general classes, a wide variety of soils were investigated. Sieve analyses and laboratory compaction tests indicate that a significant variation in soil properties existed, even among soils grouped into the same general material class. As seen in Table 6 (page 20) and Figure 3 (page 23), variations in soil type did not significantly affect the correlations associated with the Phase B data. Furthermore, variations in lift thickness (up to 24 inches), and total height of fill (up to about 4 feet) did not significantly affect the results. While a single sensor may be used to monitor multiple successively placed lifts of soil, a total height of fill of about 4 feet was the approximate upper limit at which measurements could be obtained during this study.

The statistical correlations produced from the Phase A data from material M3 (ordinary borrow) were quite strong, however the correlations for M1 (dense-graded aggregate) and M2 (gravel borrow) were much weaker. Those weaker correlations may possibly be due to artifacts of the test setup rather than to the performance of the SCS. For example, it may not have been prudent to place the neoprene rubber sheets in the mold beneath the dense-graded aggregate. It is possible that this aspect of the test setup may have adversely affected the nuclear density measurements (and thus the computed percent compaction). It is also possible that the roller used in the WPI mold was not capable of applying sufficient energy to properly compact materials such as M1 and M2 that contain a relatively high fraction of large sized particles.

From the data obtained in this study, it is impossible to make a definitive statement with regard to whether or not the SCS gives the red light signal at a point of diminishing returns for soil density and stiffness. In terms of soil density, it appears that slight increases may occur if soils are subjected to additional compaction after the SCS red light signal is produced. Because there was such a high degree of variability between multiple stiffness measurements taken on a given soil lift, the GeoGauge stiffness measurements could not be used to reliably analyze changes in stiffness resulting from successive roller passes.

In terms of testing materials other than soils, two additional materials were investigated: lightweight aggregate and asphalt. It was concluded that the lightweight aggregate is not able to transmit compression waves effectively enough to be compatible with QA/QC tools like the SCS. For QA/QC control during asphalt compaction, data from site M5.1 (N. Conway) indicate that the SCS is not able to function effectively with static compaction equipment. Again, since the SCS relies on the transmission of compression waves through the test material to produce signals, those data are not surprising. It is likely that the magnitude of the compression waves generated by static compaction equipment may be too small for the SCS to process.

The SCS was able to process data during compaction of asphalt with vibratory equipment on the other two sites (M5.2 and M5.3). At those sites, specifications called for a minimum percent compaction of 98%. However, in all three tests conducted at those sites, the SCS gave the red light signal at less than 98% compaction. In all cases, several additional passes of the roller were applied to bring the asphalt up to at least 98% compaction. Although a conclusion would not be justified based upon such a limited data set, it may be necessary for the manufacturer to make adjustment(s) to the internal data processing in the SCS meter if it is to be used for QA/QC of asphalt compaction.

Finally, one of the goals of this project was to identify potential conditions that may limit the use of the SCS for typical highway construction applications. During the course of the Phase B work, the following issues were identified:

- In many highway applications, the SCS sensors must be installed *after* the loose soil is spread and graded. For such cases, a hole should be dug to install the sensor near the bottom of the lift, and the cable should be buried in a trench and run to the outskirts of the lift. Otherwise, compaction and other construction equipment may run over the cable and damage it.

- The standard length of cable currently supplied with the disposable SCS sensors is about 12 feet. That length is insufficient for many highway construction applications. It is possible to change the connector plugs and add an extension cable, as described in Appendix E. Additionally, the manufacturer (MBW) has stated that they will produce sensors with longer cables and/or provide extension cables if a market exists for those items. During the course of this study, cables lengths of 25 to 40 feet were often used with success. Further examination of cable length may be warranted to be sure that SCS meter performance is not significantly affected by the use of longer cable lengths.

- The SCS meter shuts off automatically after 10 minutes of "inactivity." Although this generally does not pose problems in highway applications, it is imperative (if using the SCS) that the compaction of any given lift continues to completion without delay once the process has been initiated. Otherwise (if the meter shuts itself off and is then turned on again during compaction of a given lift), the SCS meter may not calibrate itself properly. The SCM does not have that automatic shutoff feature.

7. Recommendations

Based upon the results of this study, it is strongly recommended that state highway agencies consider use of the SCS as an alternative QA/QC tool for compaction control of soils and dense-graded aggregates compacted with vibratory equipment. The Soil Compaction Supervisor is simple to use and is quite durable (during this project, it was able to withstand rain, snow and other rigorous field conditions without being damaged). The Soil Compaction Supervisor offers several advantages over other soil compaction monitoring techniques, including:

- The SCS does not require a licensed technician to be operated. This makes the SCS more cost-effective than technologies such as nuclear density testing. Furthermore, many highway agencies are currently faced with cuts in funds and staff, resulting in the need for licensed technicians to monitor multiple operations (e.g., concrete and asphalt placement in addition to soil compaction). Since a wider range of personnel could potentially use the SCS, full-time monitoring of compaction activities might be possible even when the availability of technicians licensed to perform nuclear density testing is limited.
- The SCS provides real time feedback to the operator. Conventional QA/QC tests are performed after the compaction process has been completed on a lift (or in many cases, multiple lifts) of fill. If a test does not pass, the field personnel and contractor are then faced with questions regarding remedial compaction, and possible removal and replacement of material if more than one lift of fill has been placed between QA/QC tests. Since the SCS provides feedback during the compaction process itself, the potential for placing multiple lifts of poorly compacted fill is greatly reduced.
- The SCS technology does not depend on a laboratory test (e.g., the Proctor compaction test) to provide a benchmark for quality control. This also helps to reduce the costs associated with monitoring compaction, particularly on sites where the nature of the backfill material is highly variable. For example, in this study at site M3.1, the nature of the backfill varied significantly over relatively short periods of time (see Figures C-10 and C-12 through C-14 in Appendix C, pages C-8 through C-11). It was thus necessary to perform multiple Proctor compaction tests to provide reliable values for percent compaction (based upon nuclear density and/or sand cone tests).

The SCS is expected to give reliable results where project specifications require a minimum of 95% compaction, based upon standard Proctor density (AASHTO T-99, with coarse particle correction). Although the SCS is not currently recommended for use as a QA/QC tool for asphalt (based upon the limited data set collected in this study), its use in asphalt construction may warrant further investigation. The SCS does not appear to be an appropriate QA/QC tool for use with lightweight aggregate materials.

It is important to note that most of the data collected for this project were within the context of guidelines pertaining to soil compaction on specific highway construction projects. In most cases, loose lifts did not exceed 12 inches. In some cases, lifts on the order of 18 to 24 inches were placed and compacted with successful correlations between the SCS red light signal and the percent compaction. While many soils were compacted at moisture contents that were several percent less than optimum, only a small body of data was collected for soils compacted wet of optimum.

It is therefore recommended that, if the SCS is used for QA/QC, qualified personnel should be present on site to monitor the compaction process and to insure that specifications with regard to lift thickness and placement moisture content are adhered to. In particular, it is recommended that the SCS be used with caution in cases where the placement moisture content is significantly wet of optimum. For such cases, it is suggested that confirmatory field density tests (sand cone or nuclear density tests) be performed on a periodic basis.

And finally, as with any QA/QC tool, it is important that all applicable operating instructions are followed. A stand-alone document is included in Appendix E with specific step-by-step instructions for installing sensors, modifying plugs/adding extra lengths of cable (if necessary), and operating the SCS meter during compaction activities. Appendix F includes photographs of a typical SCM sensor installation sequence at one of the test sites.

8. References

AASHTO, *Standard Specifications f Sampling and Testing*, 19th Ed., American Association of State Highway and Transportation Officials, Washington, DC, 1998

Cardenas, R. L., *Soil Compaction Meter Verification Testing – Summary Report*, prepared for Gas Research Institute by Foster-Miller, Inc., Waltham, MA, September 2000

Holtz and Kovacs, *An Introduction to Geotechnical Engineering*, Prentice-Hall, Englewood Cliffs, NJ, 1981

Humboldt Mfg. Co., *GeoGauge User Guide*, version 3.8, Norridge, IL, March 2000

Torbin, R., and Heirtzler, F., *Soil Compaction Meter*, Proceedings of the International Gas Research Conference, Cannes, France 6-9 November 1995

Table 1 Details of Sites where Phase B Testing was Conducted

Site I.D.	Site Location	Material Tested	Type of Construction
M1.1	Madawaska, ME	M1: Dense-Graded Aggregate	Road Base
M2.1	Plymouth, MA	M2: Gravel Borrow	MSE Wall
M2.2	Kingston, RI	M2: Gravel Borrow	Raise grade for roadbed
M2.3	N. Dartmouth, MA	M2: Gravel Borrow	Backfill sewer trench
M3.1	Carver, MA	M3: Ordinary Borrow	Reinforced earth slope
M3.2	N. Dartmouth, MA	M3: Ordinary Borrow	Backfill sewer trench
M5.1	N. Conway, NH	M5: Asphalt	Pavement
M5.2	Kingston, RI	M5: Asphalt	Pavement
M5.3	Orient, ME	M5: Asphalt	Pavement

Table 2 Summary of Test Data from Phase A

Test I.D.	Material Type	RedLight Dry γ (pcf)	RedLight Moisture Content	Final Dry γ (pcf)	Max. Dry γ (pcf)	Opt. % Moisture Content	RedLight Percent Compact.	Final Percent Compact.
M1waT1	M1	125.7	5.7	121.3	130.0	9.0	96.7	93.3
M1waT2	M1	120.0	6.3	121.7	130.0	9.0	92.3	93.6
M1waT3	M1	115.1	5.2	121.0	130.0	9.0	88.5	93.1
M1waT4	M1	115.6	5.3	123.8	130.0	9.0	88.9	95.2
M1wbT1	M1	118.4	5.5	123.8	130.0	9.0	91.1	95.2
M1wbT3	M1	120.7	3.7	121.1	130.0	9.0	92.8	93.2
M1wcT2	M1	127.7	8.8	133.8	130.0	9.0	98.2	102.9
M2waT1	M2	143.6	4.5	113.5	127.9	7.8	112.3	88.7
M2waT2	M2	111.3	2.9	116.0	127.9	7.8	87.0	90.7
M2waT3	M2	118.0	4.3	120.5	127.9	7.8	92.3	94.2
M2wbT1	M2	122.2	6.2	124.6	127.9	7.8	95.5	97.4
M2wbT2	M2	118.1	5.5	120.3	127.9	7.8	92.3	94.1
M2wbT3	M2	123.9	4.9	118.9	127.9	7.8	96.9	93.0
M2wcT1	M2	121.5	7.0	122.6	127.9	7.8	95.0	95.9
M2wcT2	M2	127.6	7.6	121.8	127.9	7.8	99.8	95.2
M2wcT3	M2	120.8	5.3	118.2	127.9	7.8	94.4	92.4
M3waT1	M3	126.6	5.8	138.6	125.4	8.2	101.0	110.5
M3waT2	M3	129.8	5.1	136.2	125.4	8.2	103.5	108.6
M3waT3	M3	124.1	5.2	134.1	125.4	8.2	99.0	106.9
M3wbT1	M3	144.5	7.8	147.3	125.4	8.2	115.2	117.5
M3wbT2	M3	131.7	7.6	129.7	125.4	8.2	105.0	103.4
M3wbT3	M3	142.7	7.7	147.8	125.4	8.2	113.8	117.9
M3wbT4	M3	129.0	4.6	136.7	125.4	8.2	102.9	109.0
M3wbT5	M3	133.4	5.3	141.4	125.4	8.2	106.4	112.8
M3wcT1	M3	128.8	9.9	146.1	125.4	8.2	102.7	116.5
M3wcT2	M3	132.6	9.7	137.2	125.4	8.2	105.7	109.4

Table 3 Summary of Lab Compaction and Field Density Test Data from Phase B

Date	Site I.D.	Test #	Lab Sample I.D.	Max. Dry γ (pcf)	Opt. % Moisture Content	RedLight Dry γ (pcf)	RedLight Moisture Content	RedLight Percent Compact.
6/25/02	M1.1	1	Roller Pattern	136.0		134.2	4.5	98.7
6/25/02	M1.1	2	Roller Pattern	136.0		131.5	3.9	96.7
6/25/02	M1.1	3	Roller Pattern	136.0		136.8	3.9	100.6
6/25/02	M1.1	4	Roller Pattern	136.0		133.4	4.0	98.1
6/25/02	M1.1	5	Roller Pattern	136.0		139.1	3.8	102.3
3/18/02	M2.1	1	UMD~R44~S1	117.0	12.1	113.4	3.0	96.9
3/21/02	M2.1	2	UMD~R44~S1	117.0	12.1	114.7	3.5	98.0
3/22/02	M2.1	3	UMD~R44~S1	117.0	12.1	113.4	3.7	96.9
3/28/02	M2.1	4	UMD~R44~S1	117.0	12.1	112.7	3.2	96.3
4/9/02	M2.1	5	UMD~R44~S2	124.0	12.2	118.3	2.8	95.4
4/9/02	M2.1	6	UMD~R44~S2	124.0	12.2	122.8	2.9	99.0
4/11/02	M2.1	7	UMD~R44~S2	124.0	12.2	117.6	2.5	94.8
4/11/02	M2.1	8	UMD~R44~S2	124.0	12.2	117.1	4.5	94.4
4/17/02	M2.1	9	UMD~R44~S2	124.0	12.2	117.6	3.8	94.8
4/18/02	M2.1	10	UMD~R44~S2	124.0	12.2	118.1	2.8	95.2
4/18/02	M2.1	11	UMD~R44~S2	124.0	12.2			N.A.
4/24/02	M2.1	12	UMD~R44~S1	117.0	12.1	112.0	3.0	95.7
4/24/02	M2.1	13	UMD~R44~S1	117.0	12.1	116.4	2.8	99.5
4/25/02	M2.1	14	UMD~R44~S1	117.0	12.1	112.1	3.1	95.8
4/25/02	M2.1	15	UMD~R44~S1	117.0	12.1	117.2	3.1	100.2
4/25/02	M2.1	16	UMD~R44~S1	117.0	12.1	112.8	2.4	96.4
9/4/02	M2.2	1	UMD~RI 2	118.0	8.0	129.3	6.9	109.6
9/4/02	M2.2	2	UMD~RI 2	118.0	8.0	121.9	8.5	103.3
9/9/02	M2.2	3	UMD~RI 1	117.5	9.0	124.9	3.6	106.3
9/9/02	M2.2	4	UMD~RI 1	117.5	9.0	129.9	3.8	110.6
9/26/02	M2.2	5	UMD~RI 1	117.5	9.0	124.6	8.2	106.0
9/26/02	M2.2	6	UMD~RI 1	117.5	9.0	124.1	7.8	105.6
9/30/02	M2.2	7	UMD~RI 1	117.5	9.0	128.2	4.5	109.1
10/29/02	M2.3	1	UMD~RR 1	121.5	9.2	113.6	12.6	93.5
10/29/02	M2.3	2	UMD~RR 1	121.5	9.2	118.6	6.8	97.6
10/3/02	M3.1	1	UMD~R44~F2	119.5	10.8	119.1	6.0	99.7
10/3/02	M3.1	2	UMD~R44~F2	119.5	10.8	117.6	4.2	98.4
10/3/02	M3.1	3	UMD~R44~F2	119.5	10.8	134.0	7.4	112.1
10/3/02	M3.1	4	UMD~R44~F2	119.5	10.8	119.6	8.6	100.1
10/7/02	M3.1	5	UMD~R44~F2	119.5	10.8	107.1	3.5	89.6
10/7/02	M3.1	6	UMD~R44~F2	119.5	10.8	113.9	6.4	95.3
10/7/02	M3.1	7	UMD~R44~F3	125.0	10.2	126.4	8.4	101.1
10/8/02	M3.1	8	UMD~R44~F2	119.5	10.8	111.0	3.9	92.9
10/8/02	M3.1	9	UMD~R44~F2	119.5	10.8	110.3	5.3	92.3
10/8/02	M3.1	10	UMD~R44~F2	119.5	10.8	114.5	4.8	95.8
10/8/02	M3.1	11	UMD~R44~F3	125.0	10.2	131.6	5.1	105.3
10/8/02	M3.1	12	UMD~R44~F3	125.0	10.2	127.6	4.0	102.1
10/22/02	M3.1	13	UMD~R44~F2	119.5	10.8	116.9	6.3	97.8

Table 3 (continued) Date	Site I.D.	Test #	Lab Sample I.D.	Max. Dry γ (pcf)	Opt. % Moisture Content	RedLight Dry γ (pcf)	RedLight Moisture Content	RedLight Percent Compact.
10/22/02	M3.1	14	UMD~R44~F2	119.5	10.8	116.0	6.0	97.1
10/22/02	M3.1	15	UMD~R44~F2	119.5	10.8	114.5	5.7	95.8
10/24/02	M3.1	16	UMD~R44~F2	119.5	10.8	119.2	7.5	99.7
10/28/02	M3.1	17	UMD~R44~F4	106.0	14.6	100.0	6.9	94.3
10/29/02	M3.1	18	UMD~R44~F2	119.5	10.8	110.7	7.8	92.6
10/29/02	M3.1	19	UMD~R44~F2	119.5	10.8	121.8	10.0	101.9
10/29/02	M3.1	20	UMD~R44~F4	106.0	14.6	93.3	4.9	88.0
10/29/02	M3.2	1	UMD~RR 2	120.0	9.0	124.0	5.9	103.3

Table 4 Summary of Lift Thickness Data from Phase B

Date	Site I.D.	Test #	# Passes To get SCS Red Light	# Lifts Above Sensor	Approx. Lift Thickness (in)	Thickness Fill Above Sensor (ft)	RedLight Percent Compact.
6/25/02	M1.1	1	4	1	12	1.0	98.7
6/25/02	M1.1	2	5	1	12	1.0	96.7
6/25/02	M1.1	3	9	1	12	1.0	100.6
6/25/02	M1.1	4	7	1	12	1.0	98.1
6/25/02	M1.1	5	9	1	12	1.0	102.3
3/18/02	M2.1	1	4	1	12	1.0	96.9
3/21/02	M2.1	2	4	1	24	2.0	98.0
3/22/02	M2.1	3	5	1	24	2.0	96.9
3/28/02	M2.1	4	4	1	18	1.5	96.3
4/9/02	M2.1	5	7	1	12	1.0	95.4
4/9/02	M2.1	6	7	1	12	1.0	99.0
4/11/02	M2.1	7	8	2	18	3.0	94.8
4/11/02	M2.1	8	***Note 1***	3	18	4.5	94.4
4/17/02	M2.1	9	10	1	18	1.5	94.8
4/18/02	M2.1	10	8	2	18	3.0	95.2
4/18/02	M2.1	11	***Note 2***	3	18	4.5	N.A.
4/24/02	M2.1	12	***Note 3***	4	12	4.0	95.7
4/24/02	M2.1	13	***Note 3***	4	12	4.0	99.5
4/25/02	M2.1	14	2	1	12	1.0	95.8
4/25/02	M2.1	15	2	1	12	1.0	100.2
4/25/02	M2.1	16	4	2	12	2.0	96.4

Table 4
(continued)

Date	Site I.D.	Test #	# Passes To get SCS Red Light	# Lifts Above Sensor	Approx. Lift Thickness (in)	Thickness Fill Above Sensor (ft)	RedLight Percent Compact.
9/4/02	M2.2	1	8	1	12	1.0	109.6
9/4/02	M2.2	2	4	1	12	1.0	103.3
9/9/02	M2.2	3	***Note 4***	1	12	1.0	106.3
9/9/02	M2.2	4	***Note 4***	1	12	1.0	110.6
9/26/02	M2.2	5	7	1	12	1.0	106.0
9/26/02	M2.2	6	8	1	12	1.0	105.6
9/30/02	M2.2	7	***Note 4***	1	12	1.0	109.1
10/29/02	M2.3	1	4	1	12	1.0	93.5
10/29/02	M2.3	2	4	1	12	1.0	97.6
10/3/02	M3.1	1	8	2	12	2.0	99.7
10/3/02	M3.1	2	8	2	12	2.0	98.4
10/3/02	M3.1	3	10	3	12	3.0	112.1
10/3/02	M3.1	4	9	3	12	3.0	100.1
10/7/02	M3.1	5	10	1	12	1.0	89.6
10/7/02	M3.1	6	10	1	12	1.0	95.3
10/7/02	M3.1	7	4	2	12	2.0	101.1
10/8/02	M3.1	8	11	3	12	3.0	92.9
10/8/02	M3.1	9	7	4	12	4.0	92.3
10/8/02	M3.1	10	10	4	12	4.0	95.8
10/8/02	M3.1	11	10	3	12	3.0	105.3
10/8/02	M3.1	12	10	3	12	3.0	102.1
10/22/02	M3.1	13	10	1	12	1.0	97.8
10/22/02	M3.1	14	11	2	12	2.0	97.1
10/22/02	M3.1	15	16	1	12	1.0	95.8
10/24/02	M3.1	16	11	2	12	2.0	99.7
10/28/02	M3.1	17	16	1	12	1.0	94.3
10/29/02	M3.1	18	11	1	12	1.0	92.6
10/29/02	M3.1	19	9	1	12	1.0	101.9
10/29/02	M3.1	20	4	4	12	4.0	88.0
10/29/02	M3.2	1	4	1	12	1.0	103.3

4/11/02	Note #1	No signal on SCS; Nuclear density test taken after 8 passes
4/18/02	Note #2	No signal on SCS; No Nuclear density test taken
4/24/02	Note #3	No signal on SCS; Nuclear density test taken after 6 passes

9/9/02 and 9/30/02

Note #4: For these sensors, the SCS only indicated "processing + 2 Green Lights" after several passes, even though soil appeared to be well compacted. Since the contractor stopped compacting the soil at that point, the density test was performed (even though the "Red Light" signal had not been reached).

Table 5 Phase A Data: Right-Tail t-Test

Material	Sample Size	Average % Compaction @ Red Light	Standard Deviation	Lower Limit*	Greater or Equal
M1: Dense-Graded Aggregate	7	92.66	3.67	89.96	No
M2: Gravel Borrow	9	96.17	6.99	91.83	No
M3: Ordinary Borrow	10	105.52	5.23	102.48	Yes

* Lower Limit from 95% Confidence Level (Right-Tail t-Test)

Table 6 Phase B Data: Right-Tail t-Test

Material	Sample Size	Average % Compaction @ Red Light	Standard Deviation	Lower Limit*	Greater or Equal
M1: Dense-Graded Aggregate	5	99.28	2.19	97.19	Yes
M2: Gravel Borrow	19	99.20	5.02	97.20	Yes
M3: Ordinary Borrow	21	97.88	5.57	95.78	Yes

* Lower Limit from 95% Confidence Level (Right-Tail t-Test)

Table 7 Changes in Percent Compaction during Phase A Testing

Test I.D.	Material Type	Red Light Percent Compaction	Final Percent Compaction	Change in Percent Compaction
M1waT1	Dense-Graded Aggregate	96.7	93.3	-3.4
M1waT2	Dense-Graded Aggregate	92.3	93.6	1.3
M1waT3	Dense-Graded Aggregate	88.5	93.1	4.5
M1waT4	Dense-Graded Aggregate	88.9	95.2	6.3
M1wbT1	Dense-Graded Aggregate	91.1	95.2	4.2
M1wbT3	Dense-Graded Aggregate	92.8	93.2	0.3
M1wcT2	Dense-Graded Aggregate	98.2	102.9	4.7
M2waT1	Gravel Borrow	112.3	88.7	-23.5
M2waT2	Gravel Borrow	87.0	90.7	3.7
M2waT3	Gravel Borrow	92.3	94.2	2.0
M2wbT1	Gravel Borrow	95.5	97.4	1.9
M2wbT2	Gravel Borrow	92.3	94.1	1.7
M2wbT3	Gravel Borrow	96.9	93.0	-3.9
M2wcT1	Gravel Borrow	95.0	95.9	0.9
M2wcT2	Gravel Borrow	99.8	95.2	-4.5
M2wcT3	Gravel Borrow	94.4	92.4	-2.0
M3waT1	Ordinary Borrow	101.0	110.5	9.6
M3waT2	Ordinary Borrow	103.5	108.6	5.1
M3waT3	Ordinary Borrow	99.0	106.9	8.0
M3wbT1	Ordinary Borrow	115.2	117.5	2.2
M3wbT2	Ordinary Borrow	105.0	103.4	-1.6
M3wbT3	Ordinary Borrow	113.8	117.9	4.1
M3wbT4	Ordinary Borrow	102.9	109.0	6.1
M3wbT5	Ordinary Borrow	106.4	112.8	6.4
M3wcT1	Ordinary Borrow	102.7	116.5	13.8
M3wcT2	Ordinary Borrow	105.7	109.4	3.7

Note: Percent Compaction based upon Standard Proctor Compaction Test

95% Confidence Interval for Data Set

Sample Size	Mean Change in % Compaction	Standard Deviation	Lower Limit**	Upper Limit**
26	1.97	6.69	-0.73	4.67

Figure 1 Soil Compaction Supervisor (SCS)

Figure 2 Piezoelectric Element Inside SCS Sensor

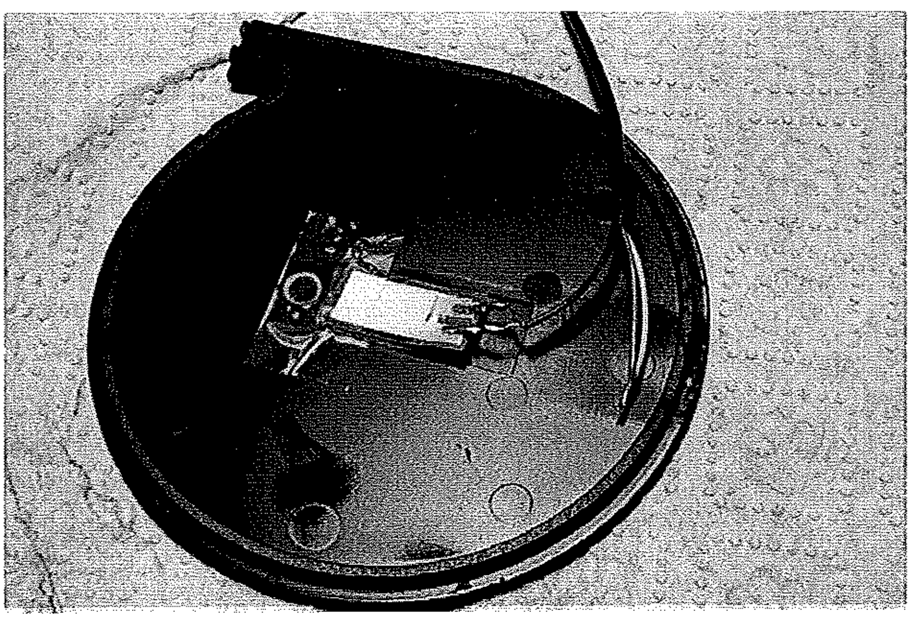
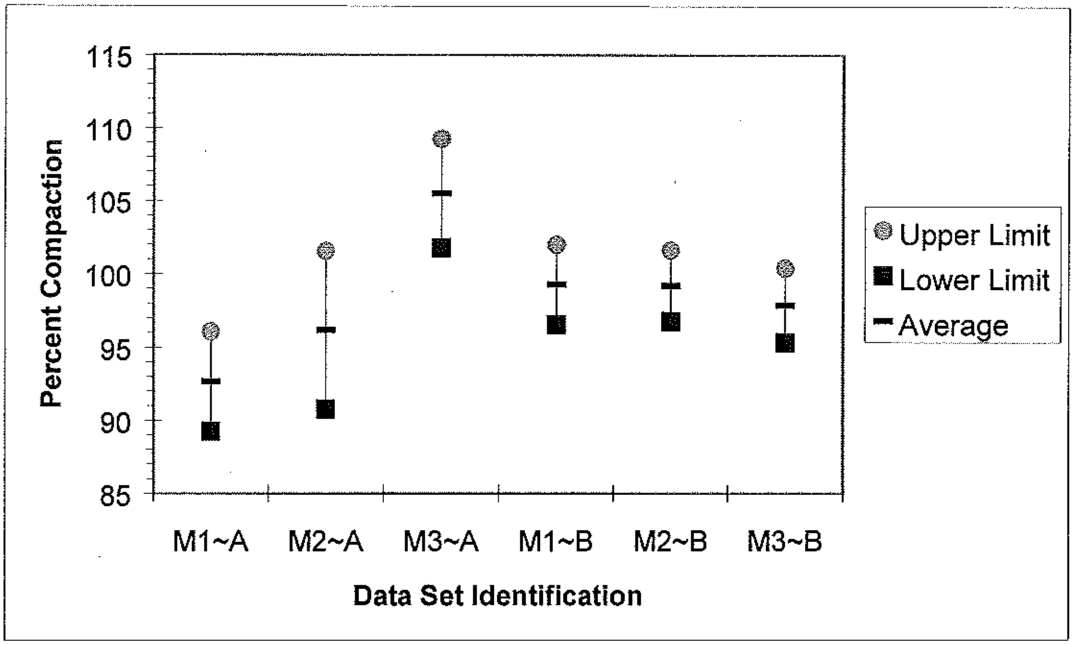


Figure 3 95% Confidence Interval (Based upon Standard Proctor Density)



M1~A: Dense-Graded Aggregate tested in WPI mold (Phase A)

M2~A: Gravel Borrow tested in WPI mold (Phase A)

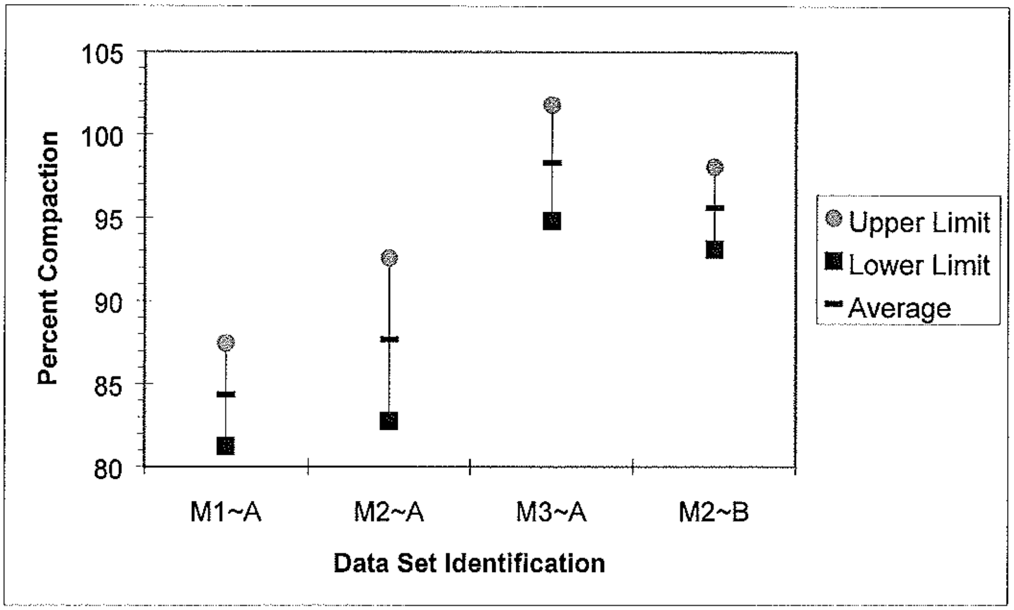
M3~A: Ordinary Borrow tested in WPI mold (Phase A)

M1~B: Dense-Graded Aggregate tested in Field (Phase B)

M2~B: Gravel Borrow tested in Field (Phase B)

M3~B: Ordinary Borrow tested in Field (Phase B)

Figure 4 95% Confidence Interval (Based upon Modified Proctor Density)



M1~A: Dense-Graded Aggregate tested in WPI mold (Phase A)

M2~A: Gravel Borrow tested in WPI mold (Phase A)

M3~A: Ordinary Borrow tested in WPI mold (Phase A)

M2~B: Gravel Borrow tested in Field (Phase B)

Appendix A: Equipment and Sample Data Sheets used in Phase A Testing

Figure A-1 Empty MMLS Mk3 Mold and Roller

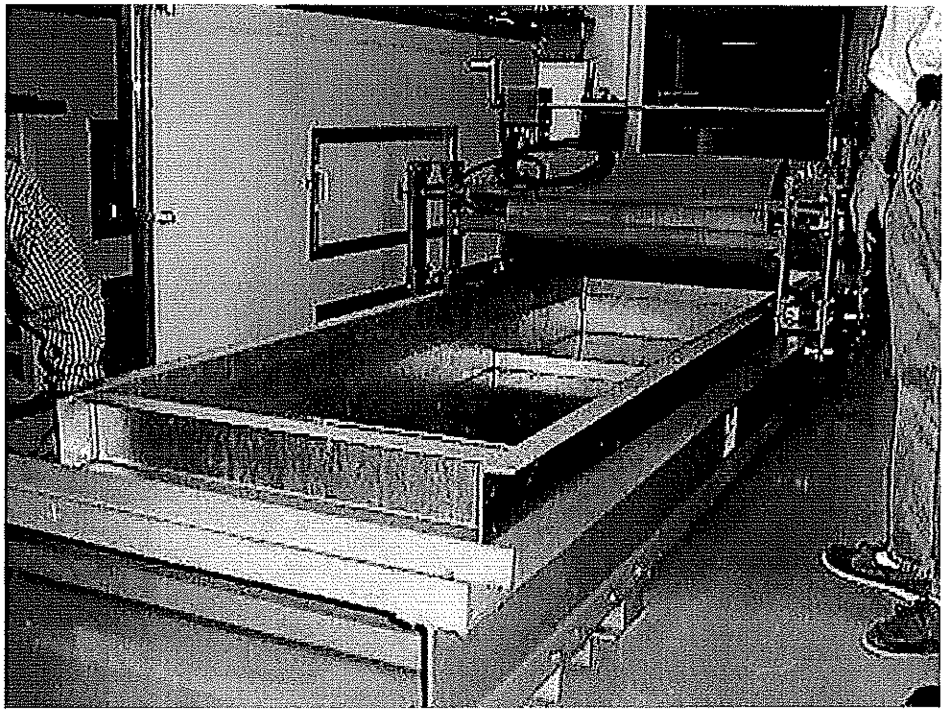


Figure A-2 Compacting Soil in Mold at WPI

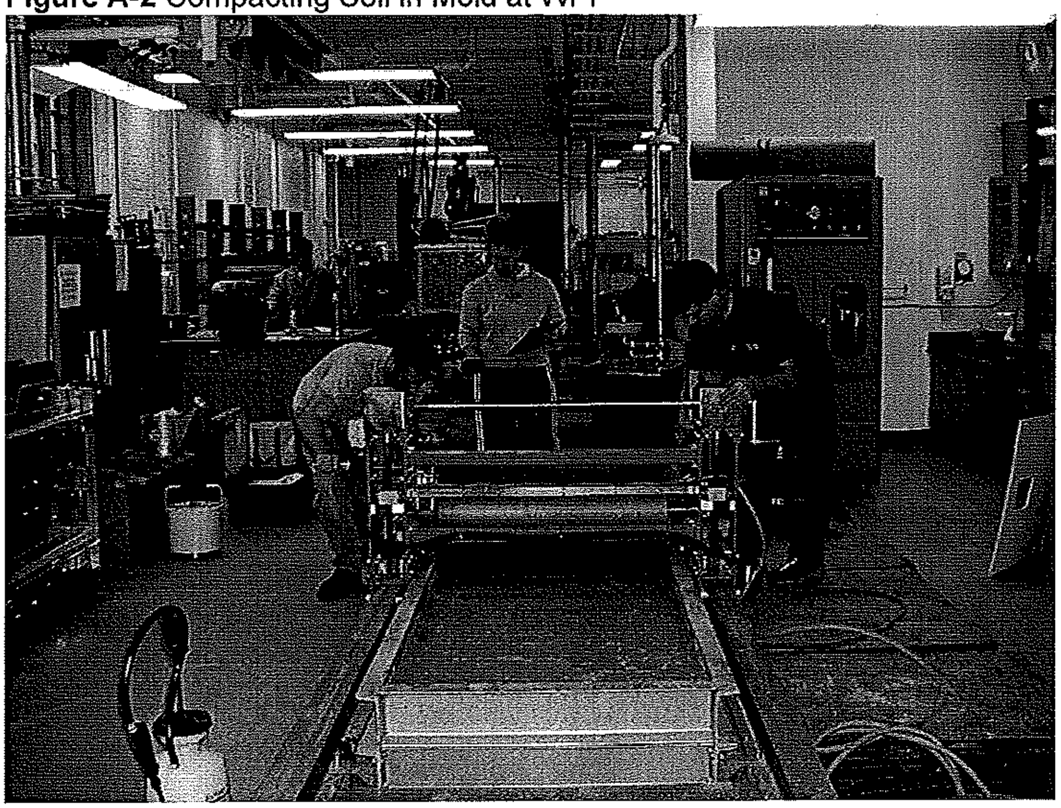
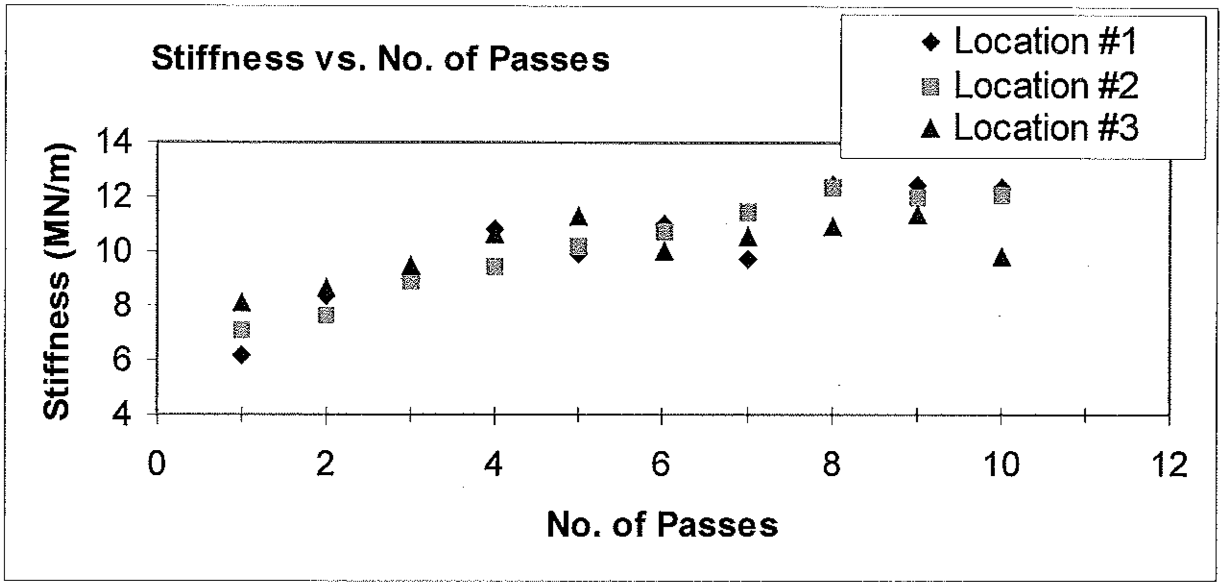


Figure A-3 Sample Spreadsheet (Phase A Data: Test M3waT3)

Date:	2/26/2002						Soil Compaction Meter
Material:	Ordinary Borrow				Material #:	3	0 = Processing
Target w (%):	less then opt				w (a, b, c):	a	1 = Indicator #1
					Test (1,2,3):	3	2 = Indicator #2
							3 = Red Stop Light
Tested by:	Nick, Eric						
		ID/Target:	Snr	5d	StiF	ID #	
Soil Compaction Meter Signal	Pass #	Geo-Gauge Test #	Signal Noise Ratio (dB)	Standard Deviation	Stiffness (MN/m)	StorEd	Comments
0	1	1	33.78	1.63	6.15	1	
		2	30.75	1.57	7.11	2	
		3	29.85	1.63	8.12	3	
0	2	1	19.93	1.69	8.32	4	
		2	30.41	1.79	7.65	5	
		3	30.13	1.42	8.65	6	
0	3	1	27.89	2.12	8.96	7	
		2	29.54	2.25	8.94	8	
		3	24.03	1.43	9.45	9	
1	4	1	23.60	2.42	10.83	10	
		2	27.85	1.80	9.45	11	
		3	30.09	1.86	10.64	12	
2	5	1	22.80	1.84	9.87	13	
		2	28.56	1.50	10.20	14	
		3	26.31	1.66	11.24	15	
3	6	1	28.74	1.98	11.00	16	
		2	26.74	1.39	10.69	17	
		3	28.72	1.60	9.96	18	Sand Cone #1
	7	1	29.42	1.58	9.73	1	
		2	27.82	1.77	11.46	2	
		3	16.74	1.73	10.55	3	
	8	1	27.56	2.51	12.42	4	
		2	26.31	2.18	12.37	5	
		3	24.64	1.33	10.89	6	
	9	1	25.90	2.15	12.48	7	
		2	27.19	2.05	12.03	8	
		3	27.28	1.51	11.34	9	
	10	1	27.17	2.13	12.37	10	
		2	26.41	1.94	12.05	11	
		3	22.32	1.70	9.80	12	Sand Cone #2

Figure A-4 Sample Spreadsheet (Plots with Stiffness Measurements at 3 Locations)



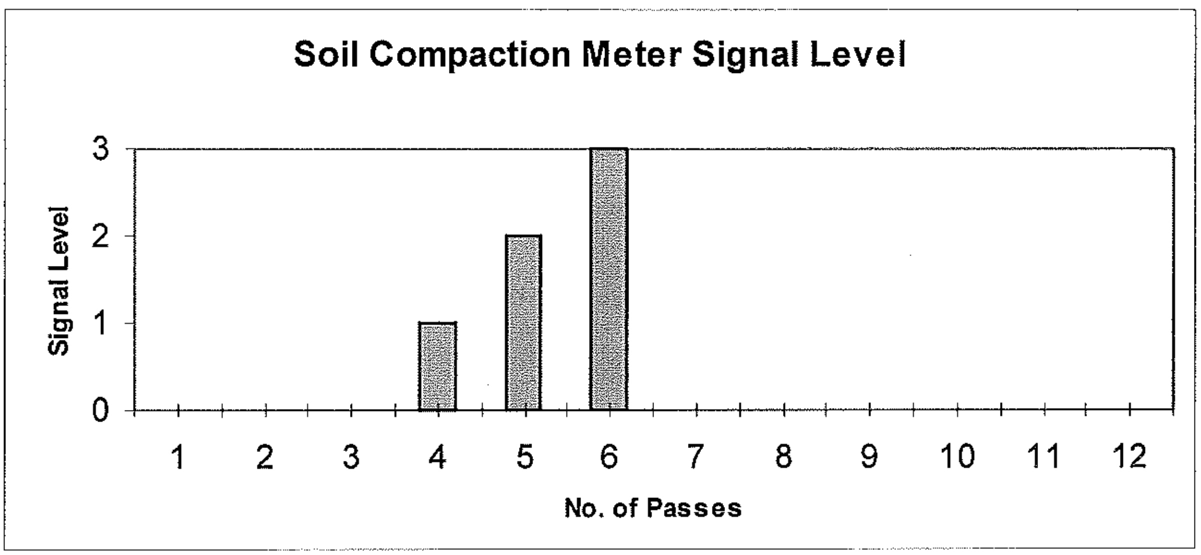
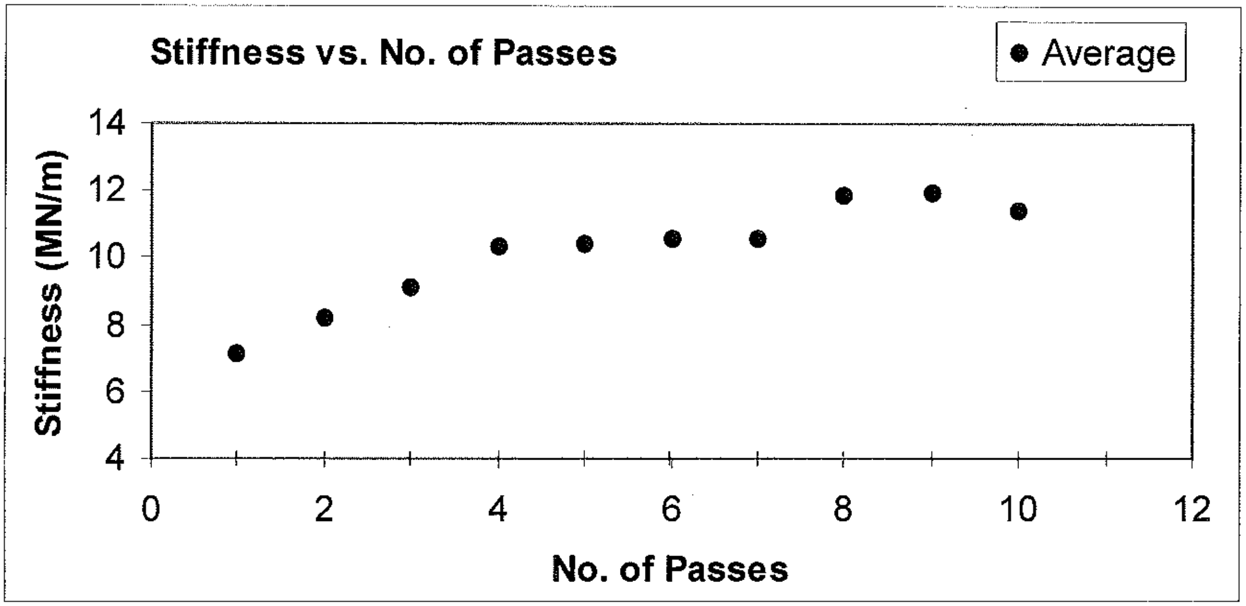
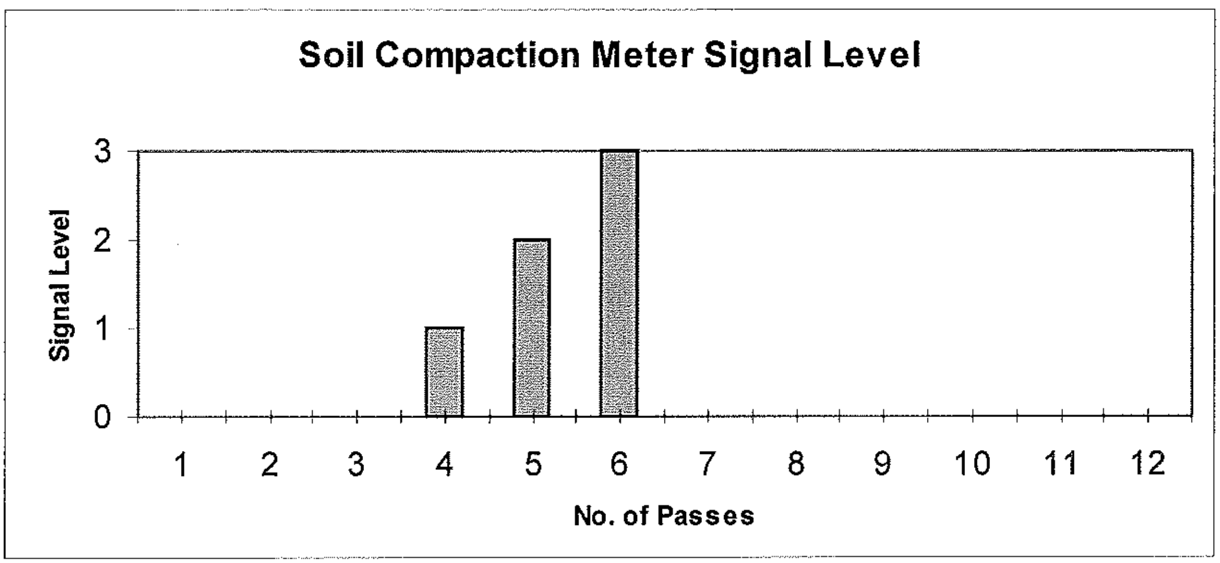


Figure A-5 Sample Spreadsheet (Plots with Average Stiffness Measurements)





Appendix B: Summary Data from Phase A Testing

Figure B-1 Target Gradation and Sample Gradation for Material 1 (Dense-Graded Aggregate)

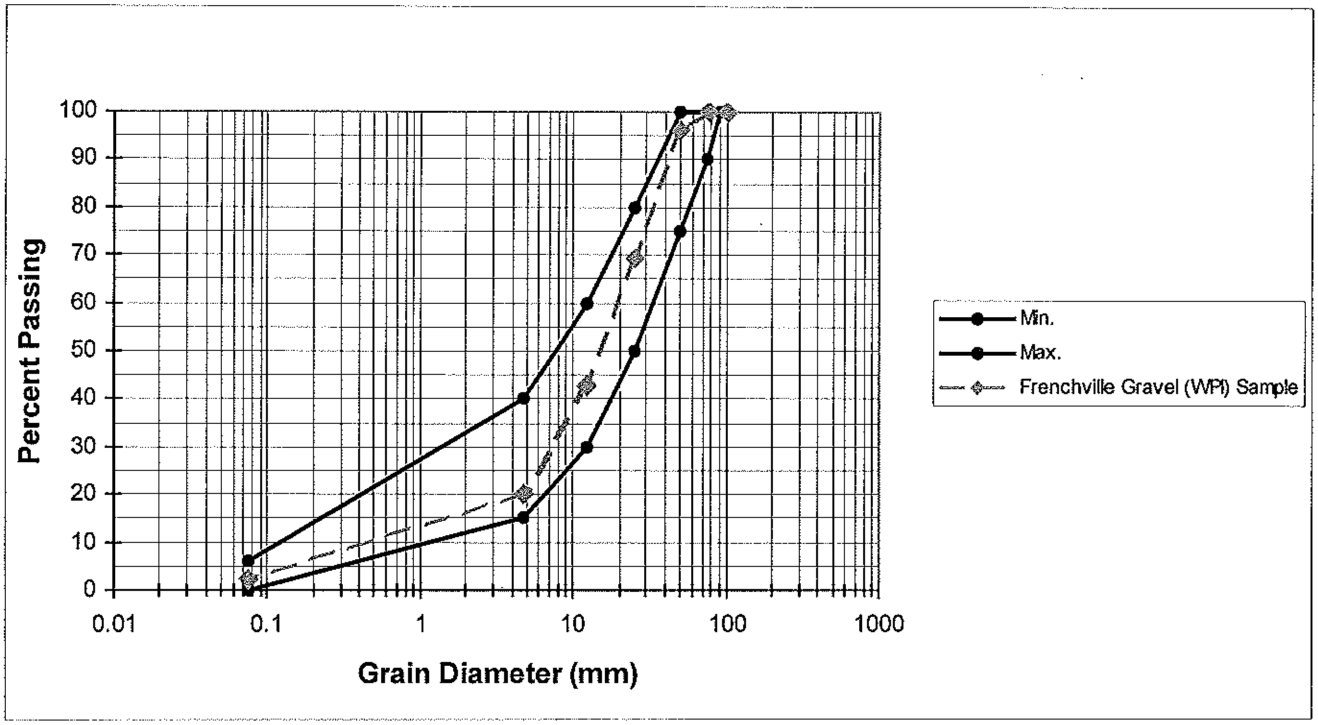


Figure B-2 Proctor Compaction Curves and WPI Compaction Data for Material 1

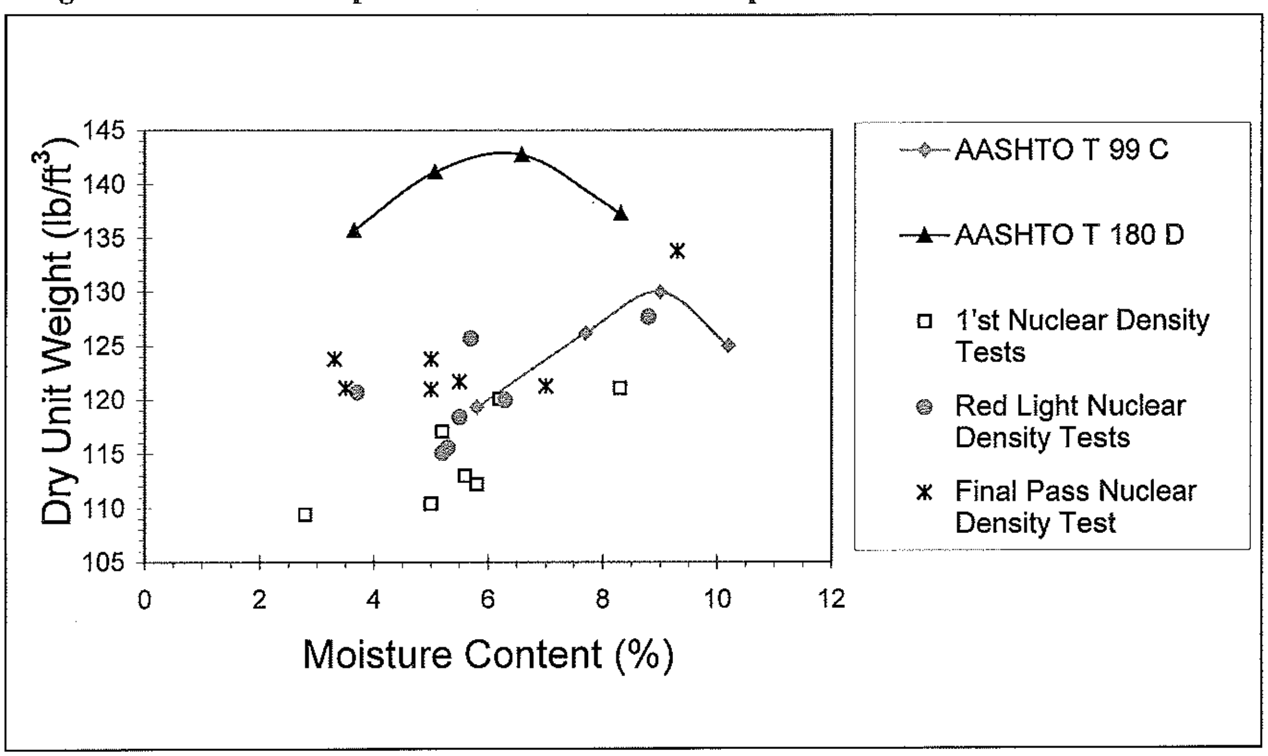


Figure B-3Target Gradation and Sample Gradation for Material 2 (Gravel Borrow)

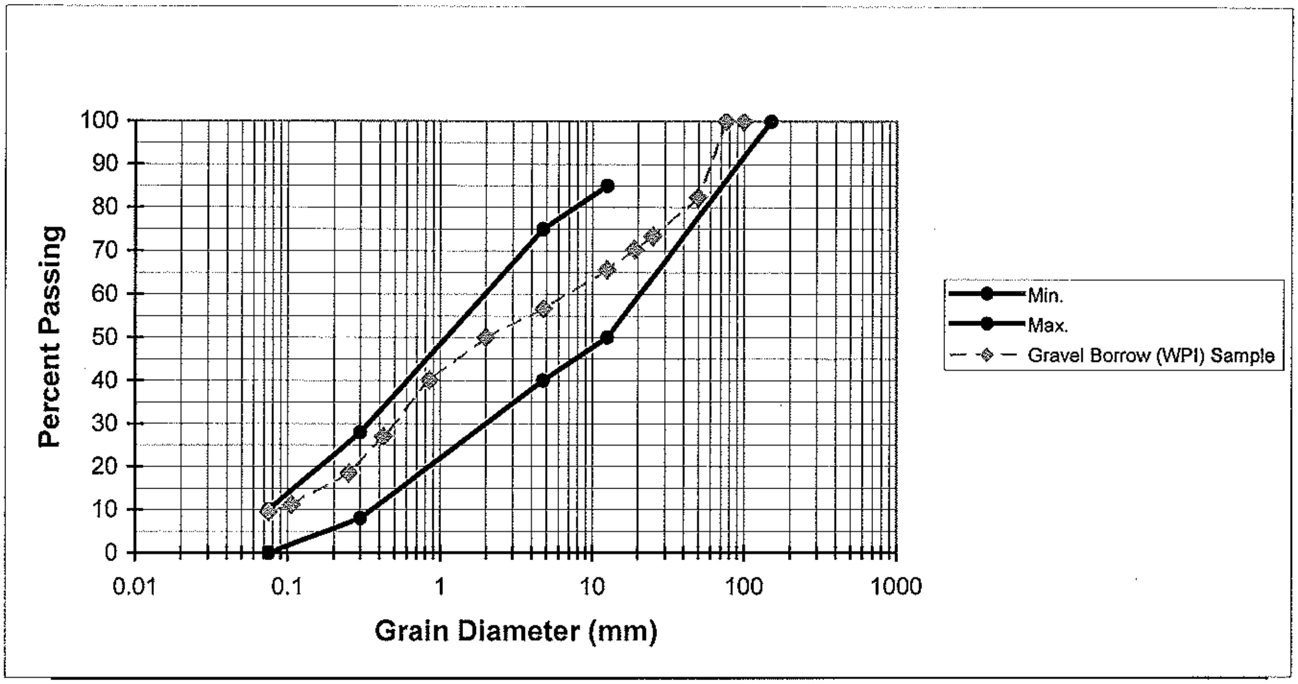


Figure B-4 Proctor Compaction Curves and WPI Compaction Data for Material 2

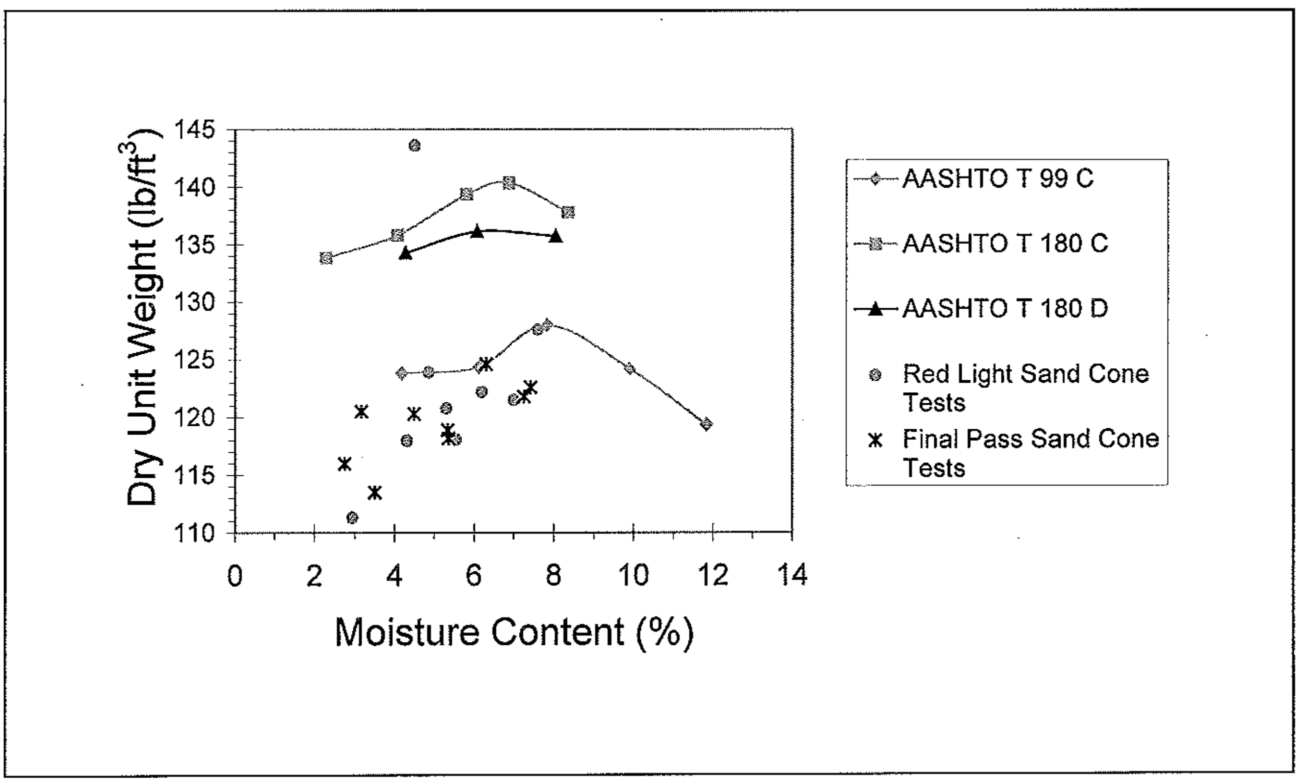


Figure B-5 Grain Size Distribution Curve for Material 3 (Ordinary Borrow)

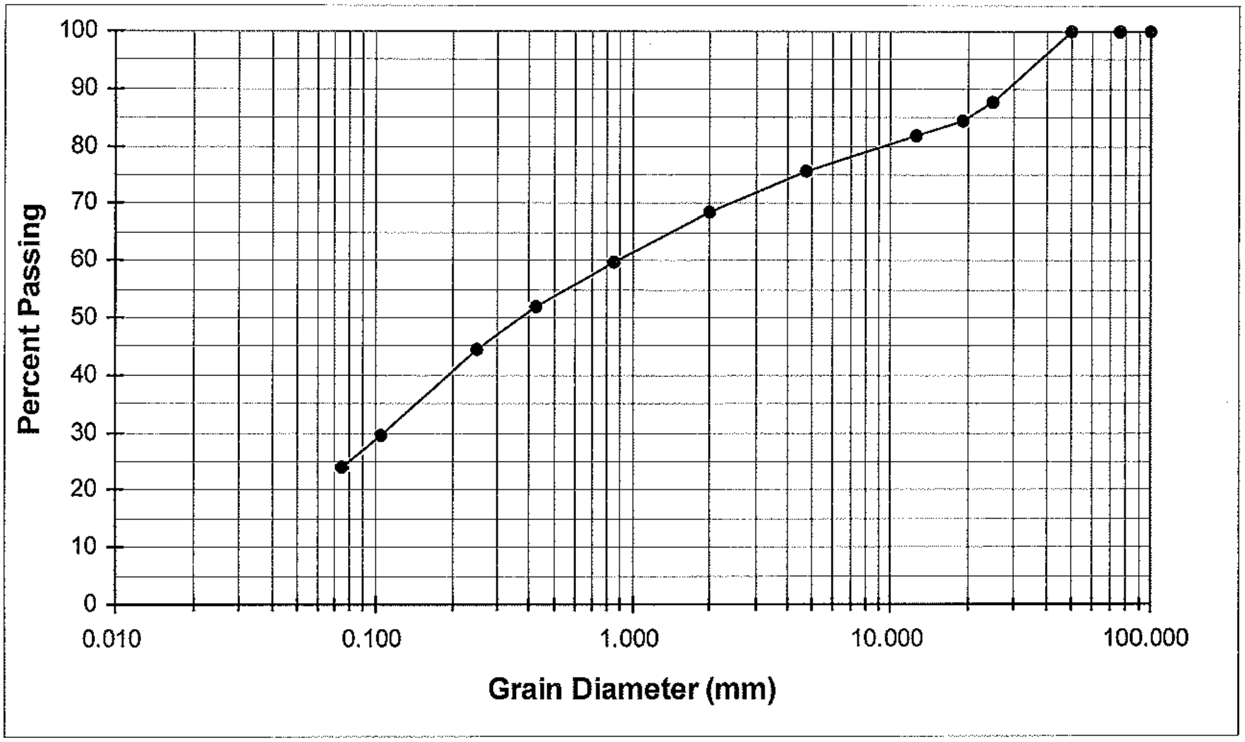


Figure B-6 Proctor Compaction Curves and WPI Compaction Data for Material 3

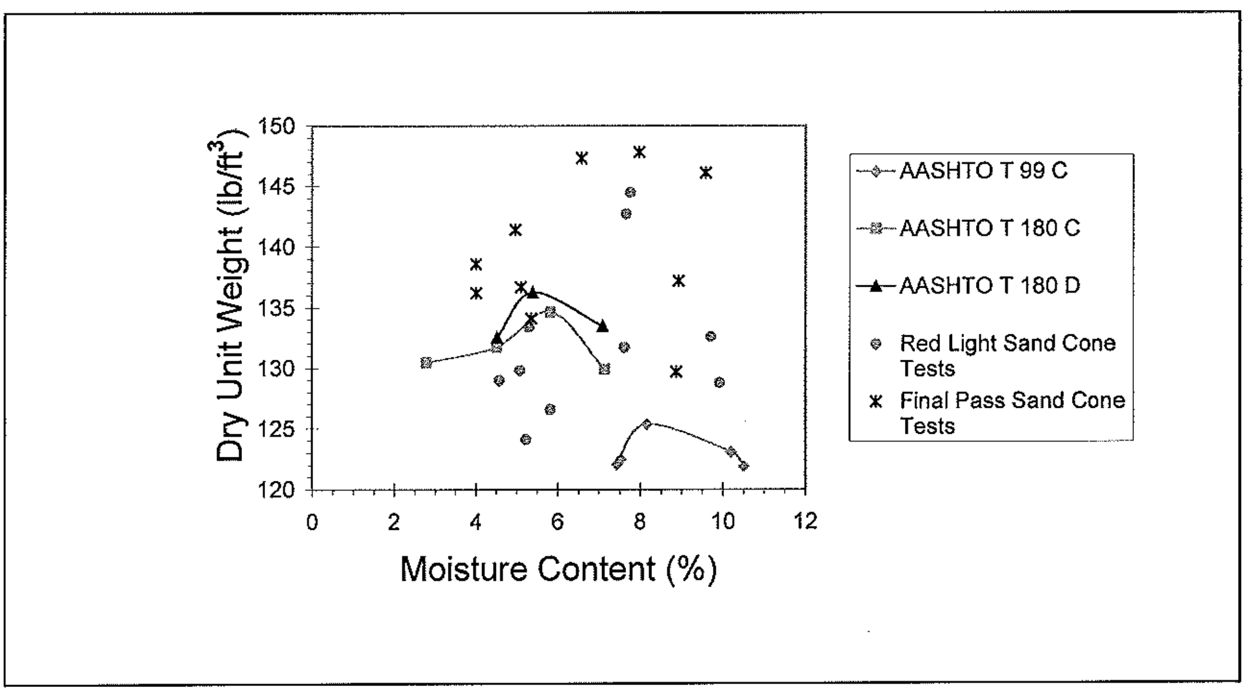


Figure B-7 Target Gradation and Sample Gradation for Material 4 (Lightweight Aggregate)

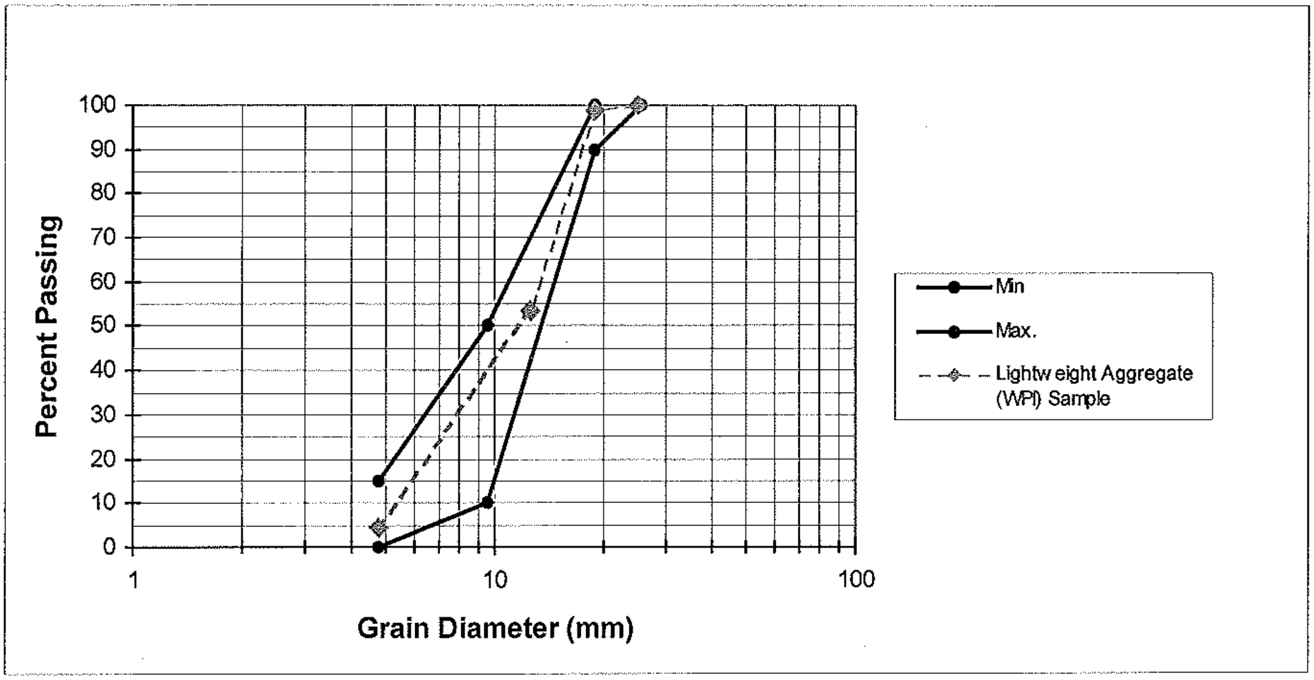


Figure B-8 WPI Compaction Data for Material 5 (HMA)

Date:	8/27/2002
Material:	Hot Mix Asphalt
Material Depth:	1.5"
Target AC (%):	5.90%
Compaction:	Vib. Roller (lab)
Base Material:	FrenchVille
Base Depth:	1.5" {on top of 6" D60 Neoprene Rubber
Tested by:	JSG #503

Material #:	M5 - HMA
AC (%)	6.09
Thickness:	1.5"

SCM Signal	
0	Processing
1	Indicator #1
2	Indicator #2
3	Red Stop Light

SCM Soil Compaction Meter Signal	Pass #	Snr Signal Noise Ratio (dB)	5d Standard Deviation	StiF Stiffness (MN/m)
0	0			
0	1			
0	2			
0	3	28.70	1.06	3.44
0	4			
0	5			
0	6			
1	7			
2	8	20.00	1.07	3.39
2	9			
2	10			
2	11	31.94	1.05	3.22
2	12			
2	13			
3	14			
	15			
	16	31.55	1.03	2.81
	17			
	18			
	19			
	20			
	21			
	22	29.37	1.07	3.24
	32	30.6	1.0	2.96
	42	31.4	1.1	2.28
	52	30.6	1.1	2.18

Appendix C: Summary Data from Phase B Testing

Note:

The percent compaction (also known as relative compaction, R.C.) is defined as the field dry unit weight divided by the laboratory maximum unit weight; it is usually expressed as a percentage. Most specifications are based upon either the standard (AASHTO T-99) or the modified (AASHTO T-180) Proctor compaction test performed in the laboratory.

It should be noted that there are many variables encountered in both the field and the laboratory (i.e., corrections for coarse particle content, etc.) that can influence the computed values of percent compaction. One of the most significant variables is the type of laboratory test used as a standard of comparison for field compaction. For example, the major difference between the standard and the modified laboratory compaction tests is the amount of compactive energy applied. Much more compactive energy is applied in the modified test, because it calls for use of a heavier compaction hammer with a greater height of fall. In general, compactive energy affects the moisture-density relationship of soils as follows: an increase in the amount of compactive energy applied results in increased values for maximum dry density (or dry unit weight) and decreased values of optimum moisture content (Holtz and Kovacs, 1981). That general trend can be seen in many of the moisture-density plots included in Appendices B and C. As a result, computed values of percent compaction (R.C.) in excess of 100% are sometimes encountered. For example, on pages C-5 and C-6, it can be seen that R.C. values are less than 100% when calculated based upon the modified Proctor test, but that R.C. values for that same field data are greater than 100% when based upon the standard Proctor test.

Figure C-1 Gradation of Samples from Site M1.1 (M1: Dense-Graded Aggregate)

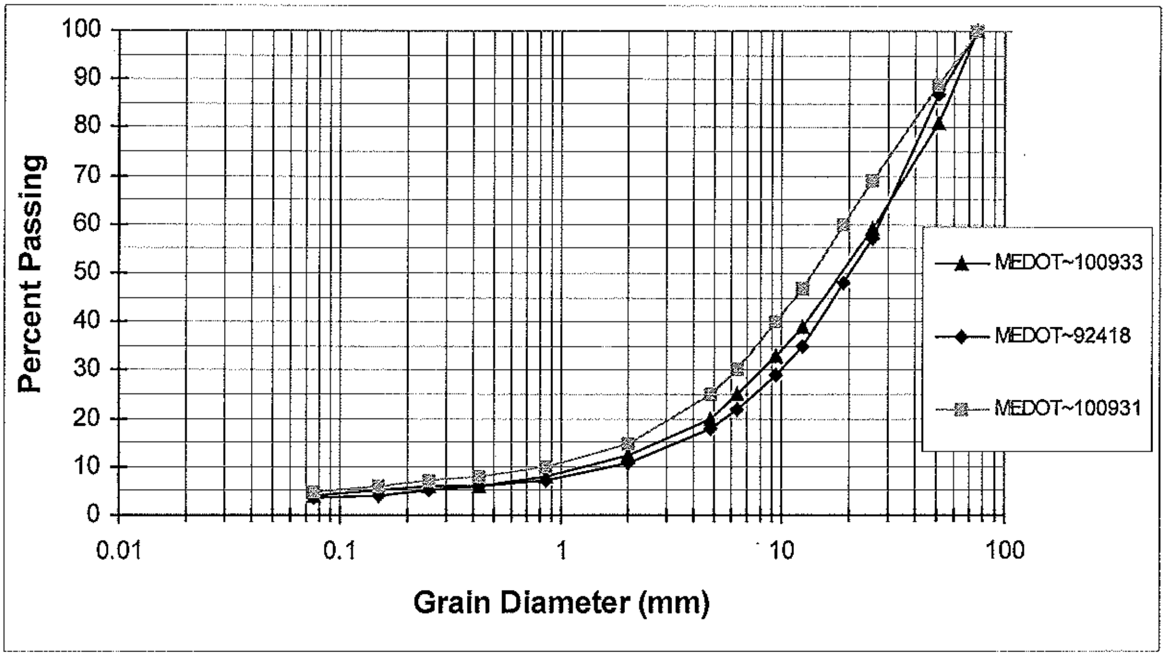


Table C-1 Field Data from Site M1.1 (M1: Dense-Graded Aggregate)

Test #	# Passes Red Light	Field Water Content (%)	R.C. (%)
1	4	4.5	98.7
2	5	3.9	96.7
3	9	3.9	100.6
4	7	4.0	98.1
5	9	3.8	102.3

NOTE: Percent compaction based upon **max. dry unit weight = 136 pcf** **(@ avg. moisture content = 3.8%)** obtained from roller pattern tests

For each test, **1 lift** of aggregate, approximately **12 inches** thick, was compacted over sensor.

A 25-ton vibratory roller was used at this site.

Figure C-2 Gradation of Samples from Site M2.1 (M2: Gravel Borrow)

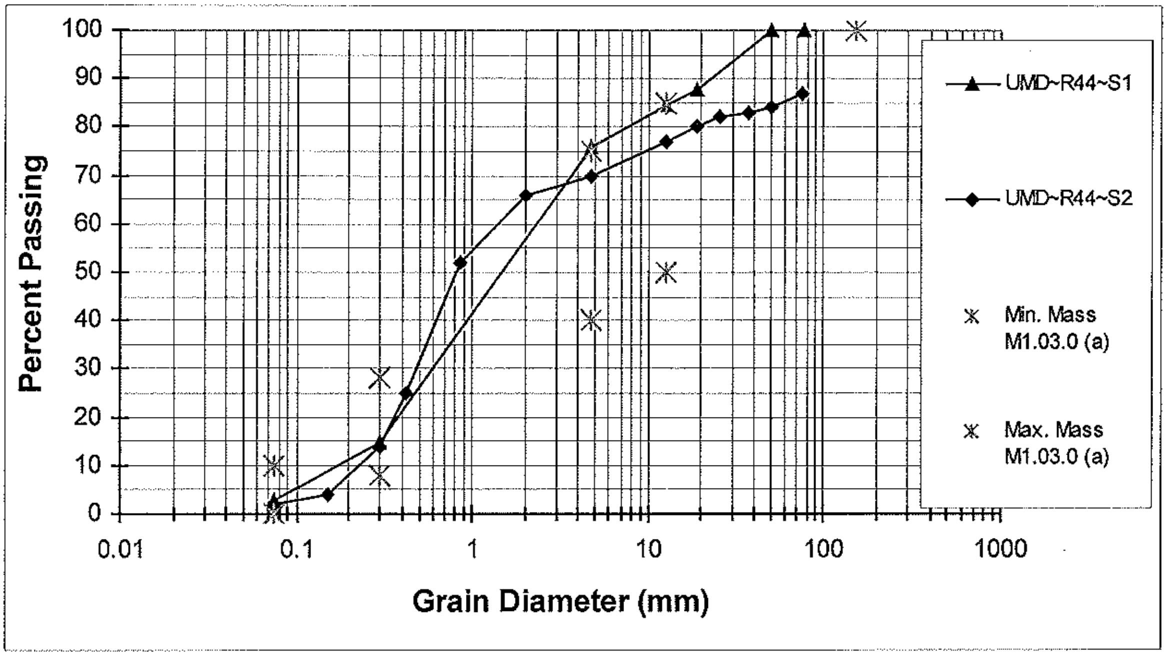


Figure C-3 Gradation of Samples from Site M2.2 (M2: Gravel Borrow)

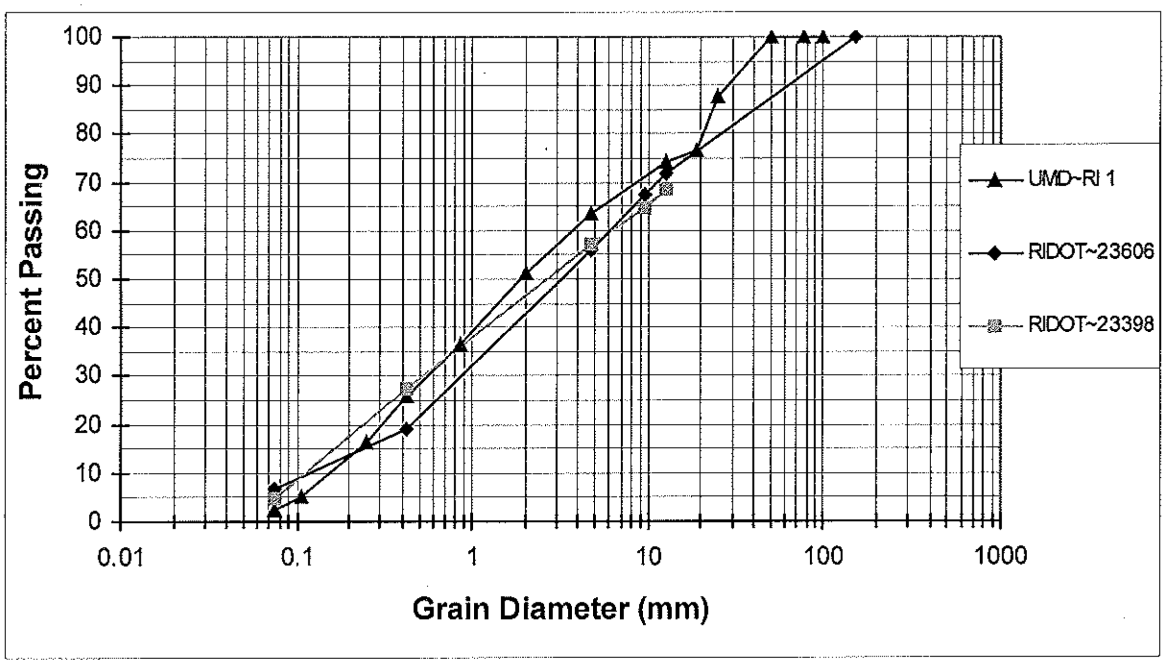
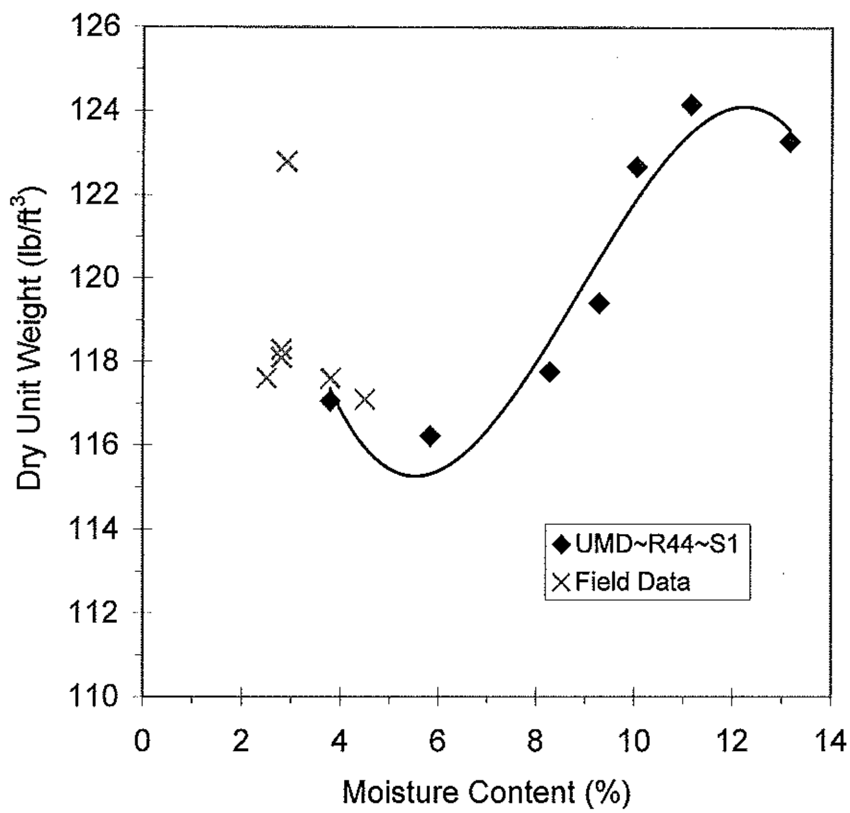


Figure C-4 Site M2.1: Field Data and Standard Proctor Compaction Test for Sample UMD~R44~S1 (M2: Gravel Borrow)



Note 1:
All compaction at Site M2.1 was performed with a CAT CS-563 D vibratory drum roller.

Table C-2 Site M2.1: Field Data from Sample UMD~R44~S1

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	# Lifts Above Sensor	Approx. Lift Thickness (in.)	Thickness Fill Above Sensor (ft.)
3/18/02	4	117.0	113.4	3.0	96.9	1.0	12.0	1.0
3/21/02	4	117.0	114.7	3.5	98.0	1.0	24.0	2.0
3/22/02	5	117.0	113.4	3.7	96.9	1.0	24.0	2.0
3/28/02	4	117.0	112.7	3.2	96.3	1.0	18.0	1.5
4/24/02	***Note 2***	117.0	112.0	3.0	95.7	4.0	12.0	4.0
4/24/02	***Note 2***	117.0	116.4	2.8	99.5	4.0	12.0	4.0
4/25/02	2	117.0	112.1	3.1	95.8	1.0	12.0	1.0
4/25/02	2	117.0	117.2	3.1	100.2	1.0	12.0	1.0
4/25/02	4	117.0	112.8	2.4	96.4	2.0	12.0	2.0

Note 2: No signal on SCM; Nuclear density test taken after 6 passes

Figure C-5 Site M2.1: Field Data and Standard Proctor Compaction Test for Sample UMD~R44~S2 (M2: Gravel Borrow)

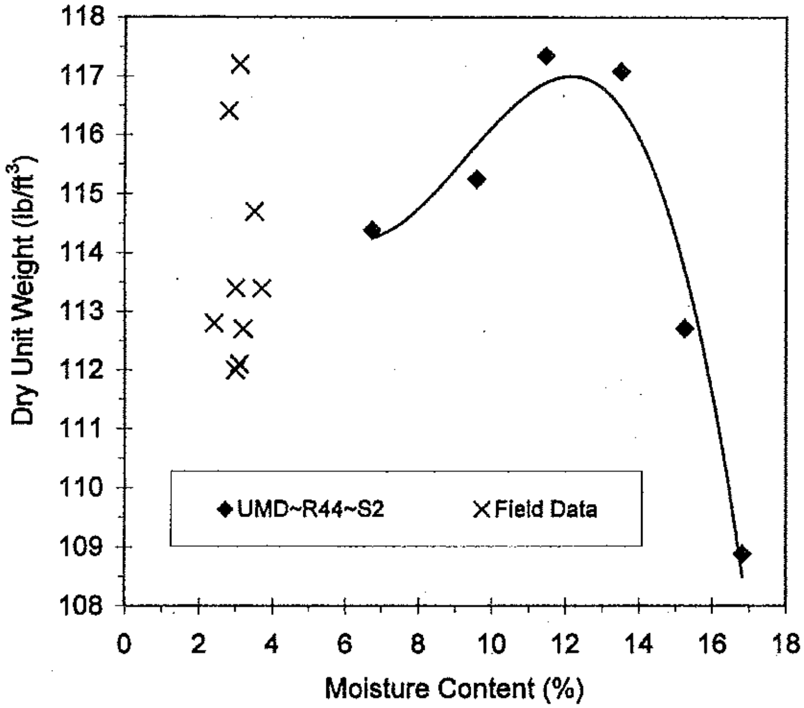


Table C-3 Site M2.1: Field Data from Sample UMD~R44~S2

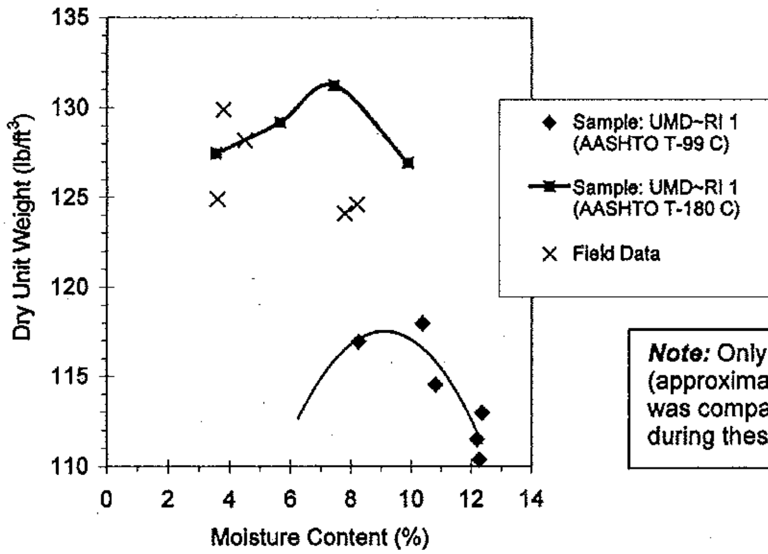
	A	B	C	D	E	F	G	H	I
1	Date	# Passes	Max Lab	Field	Field	R.C.	# Lifts	Approx.	Thickness
2		Red	Dry	Dry	Water		Above	Lift	Fill
3		Light	Unit	Unit	Content		Sensor	Thickness	Above
4			Weight	Weight					Sensor
5			(pcf)	(pcf)	(%)	(%)		(in.)	(ft.)
6	4/9/02	7	124.0	118.3	2.8	95.4	1.0	12.0	1.0
7	4/9/02	7	124.0	122.8	2.9	99.0	1.0	12.0	1.0
8	4/11/02	8	124.0	117.6	2.5	94.8	2.0	18.0	3.0
9	4/11/02	***Note 1***	124.0	117.1	4.5	94.4	3.0	18.0	4.5
10	4/17/02	10	124.0	117.6	3.8	94.8	1.0	18.0	1.5
11	4/18/02	8	124.0	118.1	2.8	95.2	2.0	18.0	3.0
12	4/18/02	***Note 2***				N.A.	3.0	18.0	4.5

Note 1:
No signal on SCM; Nuclear density test taken after 8 passes

Note 2:
No signal on SCM; No Nuclear density test taken

Note 3: All compaction at Site M2.1 was performed with a CAT CS-563 D vibratory drum roller.

Figure C-6 Site M2.2: Field Data and Proctor Compaction Tests for Sample UMD~RI 1 (M2: Gravel Borrow)



Note: Only one lift of soil (approximately 12 inches thick) was compacted above sensors during these field tests.

Table C-4 Site M2.2: Field Data from Sample UMD~RI 1

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	Type/Model Compactor
Percent Compaction (R.C.) Based Upon Standard Proctor Test (AASHTO T-99 C)						
9/9/02	***Note ****	117.5	124.9	3.6	106.3	Ingersoll Rand 100 PAC
9/9/02	***Note ****	117.5	129.9	3.8	110.6	Ingersoll Rand 100 PAC
9/26/02	7	117.5	124.6	8.2	106.0	Svedala Dynapac CA 250
9/26/02	8	117.5	124.1	7.8	105.6	Svedala Dynapac CA 250
9/30/02	***Note ****	117.5	128.2	4.5	109.1	Svedala Dynapac CA 250
Percent Compaction (R.C.) Based Upon Modified Proctor Test (AASHTO T-180 C)						
Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	Type/Model Compactor
9/9/02	***Note ****	131.0	124.9	3.6	95.3	Ingersoll Rand 100 PAC
9/9/02	***Note ****	131.0	129.9	3.8	99.2	Ingersoll Rand 100 PAC
9/26/02	7	131.0	124.6	8.2	95.1	Svedala Dynapac CA 250
9/26/02	8	131.0	124.1	7.8	94.7	Svedala Dynapac CA 250
9/30/02	***Note ****	131.0	128.2	4.5	97.9	Svedala Dynapac CA 250

Note *: For these sensors, the SCM only indicated "processing + 2 Green Lights" after several passes, even though soil appeared to be well compacted. Since the contractor stopped compacting the soil at that point, the density test was performed (even though the "Red Light" signal had not been reached).

Figure C-7 Site M2.2: Field Data and Proctor Compaction Tests for Samples UMD~RI 2 and RIDOT~23398 (M2: Gravel Borrow)

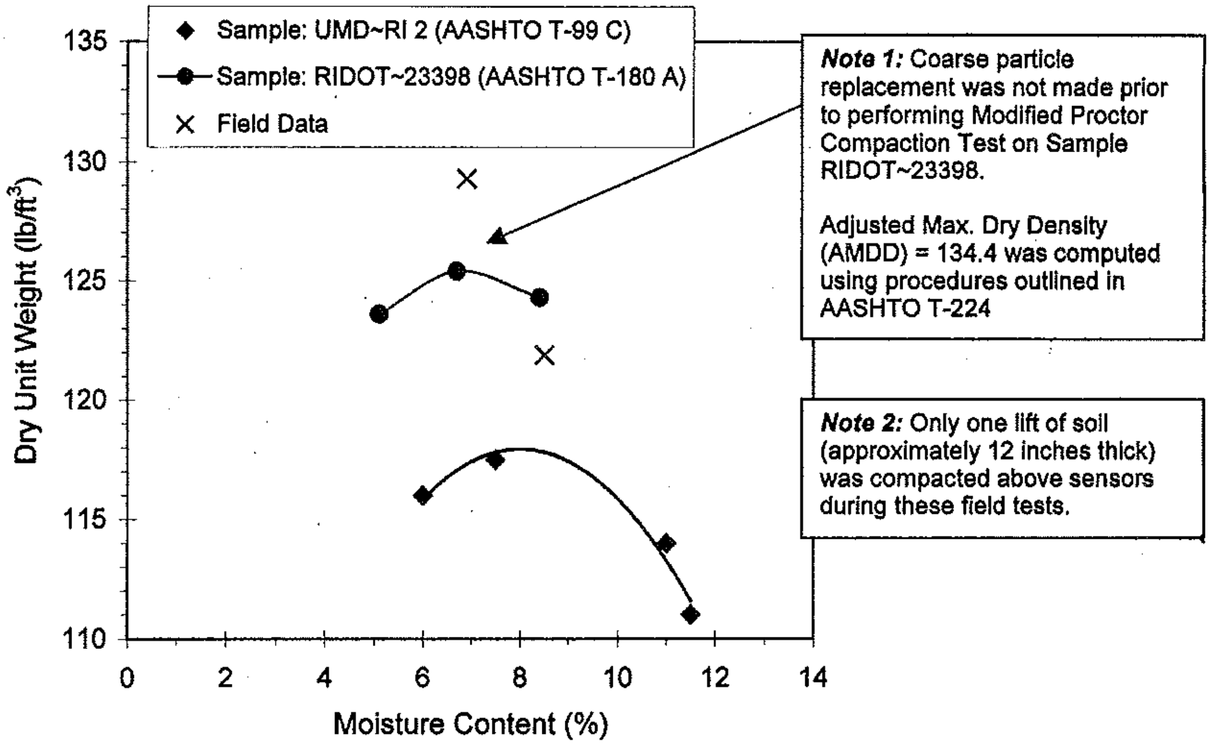


Table C-5 Site M2.2: Field Data from Samples UMD~RI 2 and RIDOT~23398

Percent Compaction (R.C.) Based Upon Standard Proctor Test (AASHTO T-99 C)						
Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	Type/Model Compactor
9/4/02	8	118.0	129.3	6.9	109.6	Ingersoll Rand 100 PAC
9/4/02	4	118.0	121.9	8.5	103.3	Ingersoll Rand 100 PAC
Percent Compaction (R.C.) Based Upon Modified Proctor Test (AASHTO T-180 A)						
Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	Type/Model Compactor
9/4/02	8	134.4	129.3	6.9	96.2	Ingersoll Rand 100 PAC
9/4/02	4	134.4	121.9	8.5	90.7	Ingersoll Rand 100 PAC

Figure C-8 Gradation of Sample UMD~RR 1 from Site M2.3 (M2: Gravel Borrow)

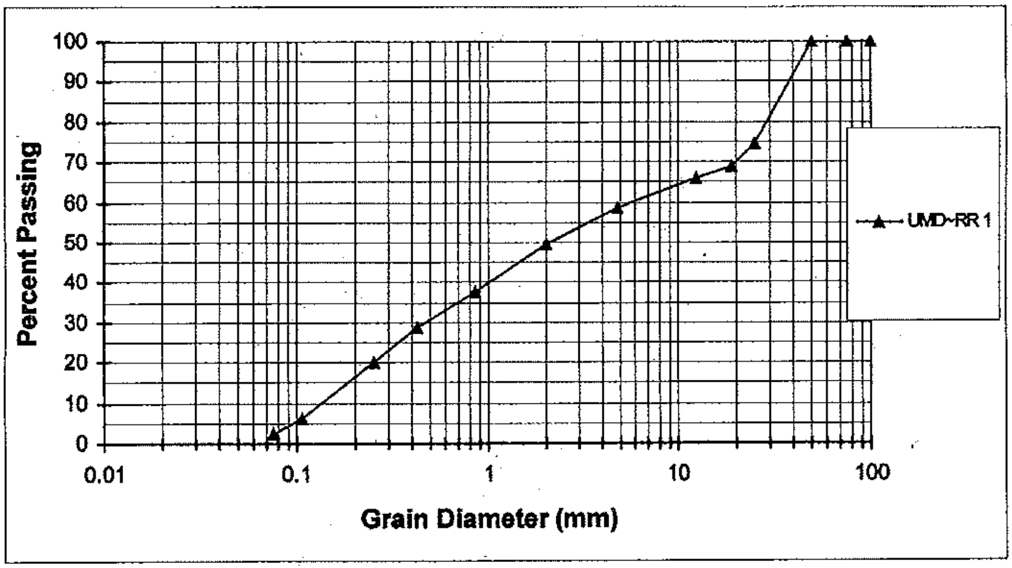
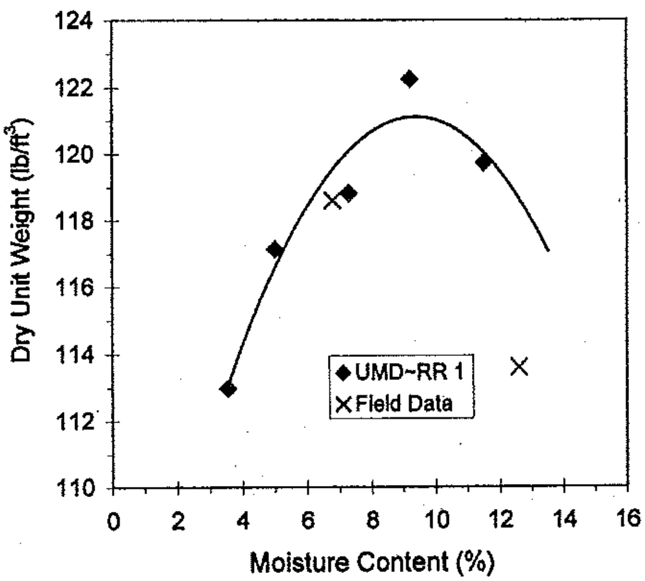


Figure C-9 Site M2.3: Field Data and Standard Proctor Compaction Test for Sample UMD~RR 1 (M2: Gravel Borrow)



Note 1: Compaction at Site M2.3 was performed with a Wacker (sheepsfoot vibratory roller).

Note 2: Only one lift of soil (approximately 12 inches thick) was compacted above sensors during these field tests.

Table C-6 Site M2.3: Field Data from Sample UMD~RR 1

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)
10/29/02	4	121.5	113.6	12.6	93.5
10/29/02	4	121.5	118.6	6.8	97.6

Figure C-10 Gradation of Samples from Site M3.1 (M3: Ordinary Borrow)

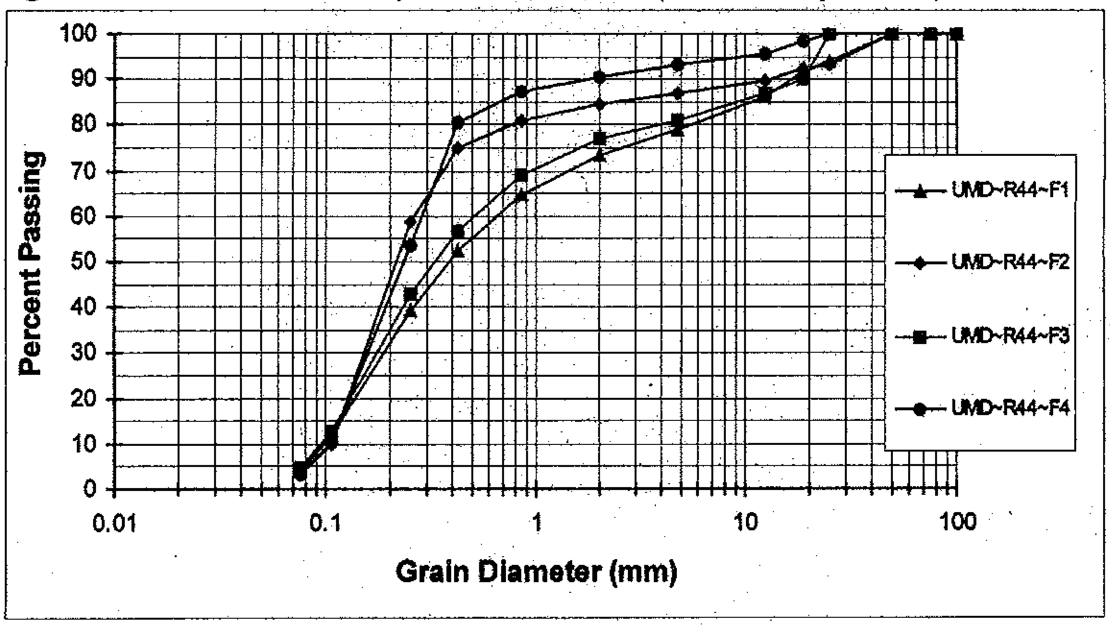


Figure C-11 Gradation of Sample UMD~RR 2 from Site M3.2 (M3: Ordinary Borrow)

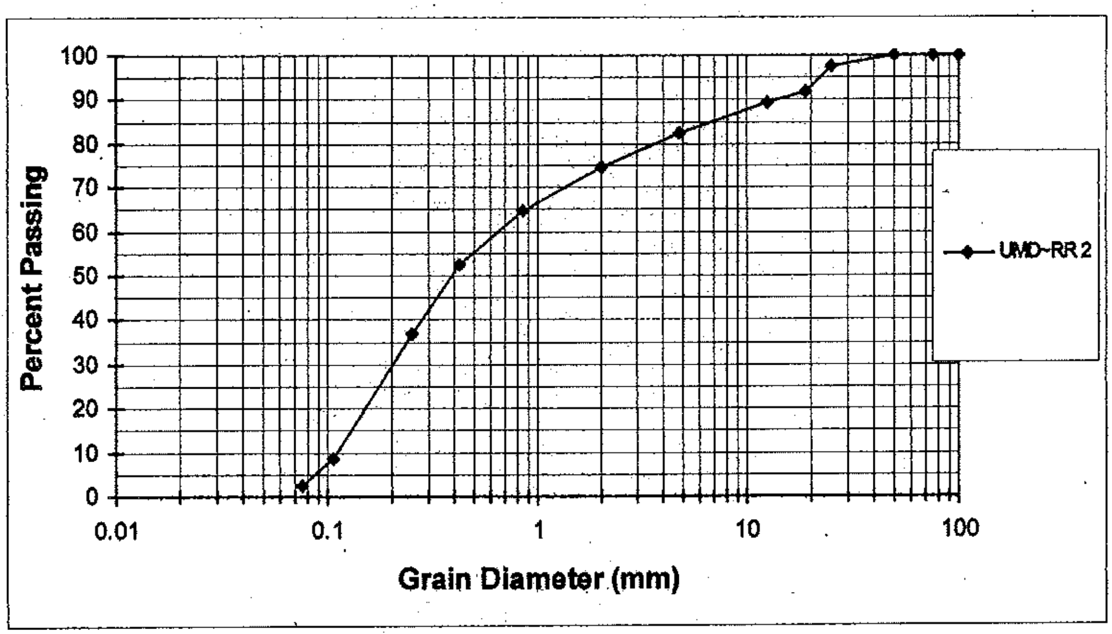
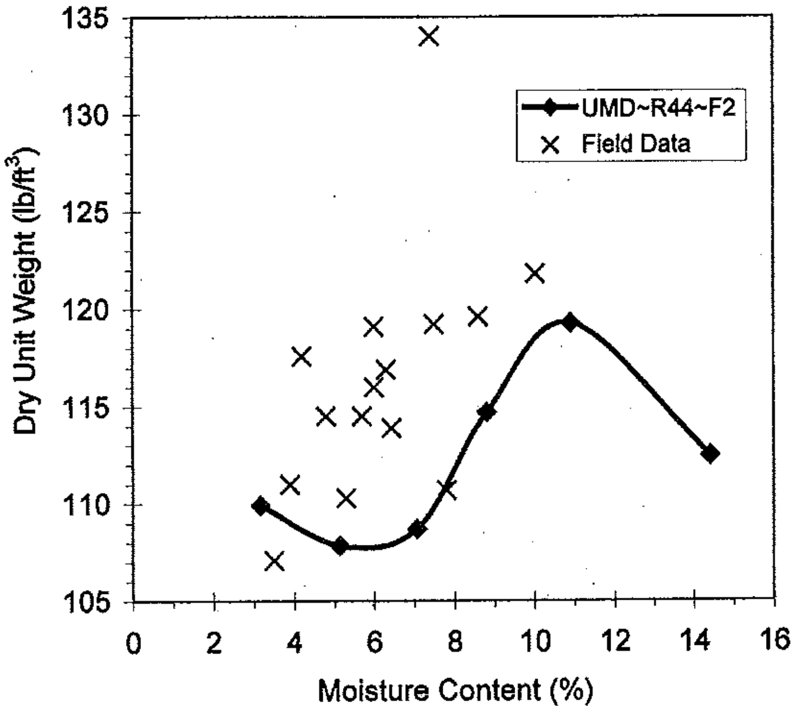


Figure C-12 Site M3.1: Field Data and Standard Proctor Compaction Test for Sample UMD~R44~F2 (M3: Ordinary Borrow)

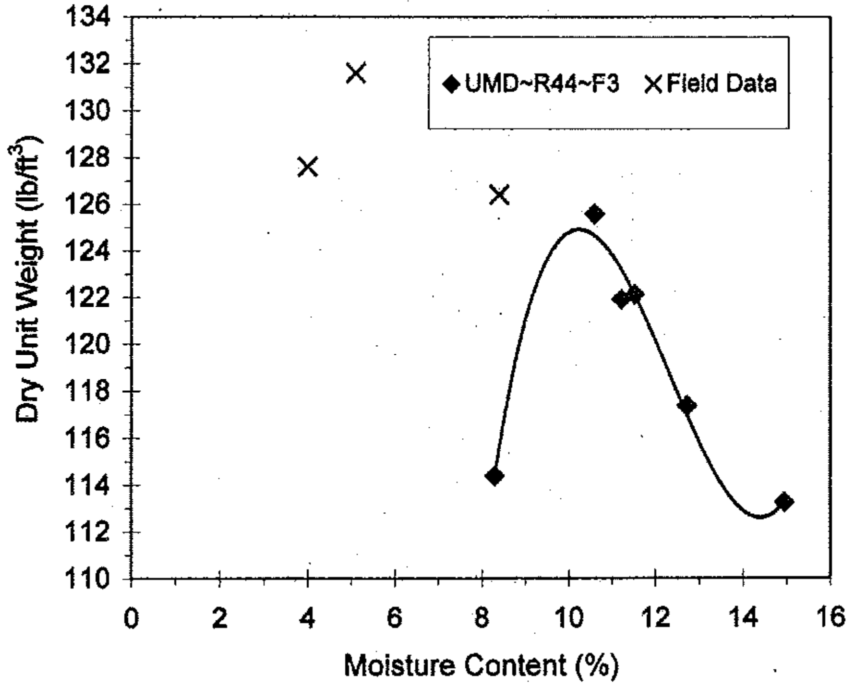


Note 1:
All compaction at Site M3.1 was performed with a CAT CS-563 D vibratory drum roller.

Table C-7 Site M3.1: Field Data from Sample UMD~R44~F2

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	# Lifts Above Sensor	Approx. Lift Thickness (in.)	Thickness Fill Above Sensor (ft.)
10/3/02	8	119.5	119.1	6.0	99.7	2	12	2.0
10/3/02	8	119.5	117.6	4.2	98.4	2	12	2.0
10/3/02	10	119.5	134.0	7.4	112.1	3	12	3.0
10/3/02	9	119.5	119.6	8.6	100.1	3	12	3.0
10/7/02	10	119.5	107.1	3.5	89.6	1	12	1.0
10/7/02	10	119.5	113.9	6.4	95.3	1	12	1.0
10/8/02	11	119.5	111.0	3.9	92.9	3	12	3.0
10/8/02	7	119.5	110.3	5.3	92.3	4	12	4.0
10/8/02	10	119.5	114.5	4.8	95.8	4	12	4.0
10/22/02	10	119.5	116.9	6.3	97.8	1	12	1.0
10/22/02	11	119.5	116.0	6.0	97.1	2	12	2.0
10/22/02	16	119.5	114.5	5.7	95.8	1	12	1.0
10/24/02	11	119.5	119.2	7.5	99.7	2	12	2.0
10/29/02	11	119.5	110.7	7.8	92.6	1	12	1.0
10/29/02	9	119.5	121.8	10.0	101.9	1	12	1.0

Figure C-13 Site M3.1: Field Data and Standard Proctor Compaction Test for Sample UMD~R44~F3 (M3: Ordinary Borrow)

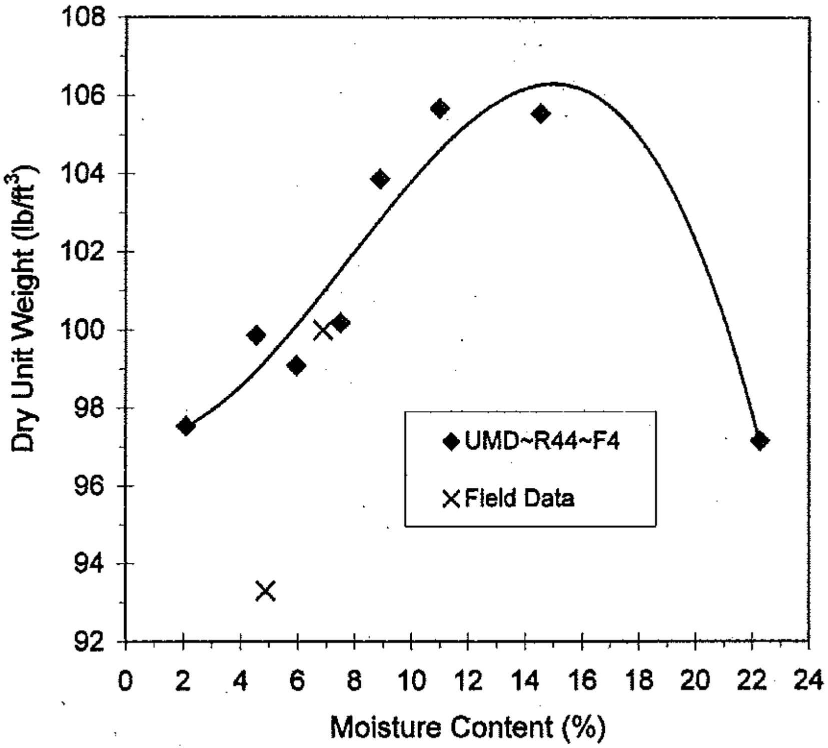


Note 1:
All compaction at Site M3.1 was performed with a CAT CS-563 D vibratory drum roller.

Table C-8 Site M3.1: Field Data from Sample UMD~R44~F3

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	# Lifts Above Sensor	Approx. Lift Thickness (in.)	Thickness Fill Above Sensor (ft.)
10/7/02	4	125.0	126.4	8.4	101.1	2	12	2.0
10/8/02	10	125.0	131.6	5.1	105.3	3	12	3.0
10/8/02	10	125.0	127.6	4.0	102.1	3	12	3.0

Figure C-14 Site M3.1: Field Data and Standard Proctor Compaction Test for Sample UMD~R44~F4 (M3: Ordinary Borrow)

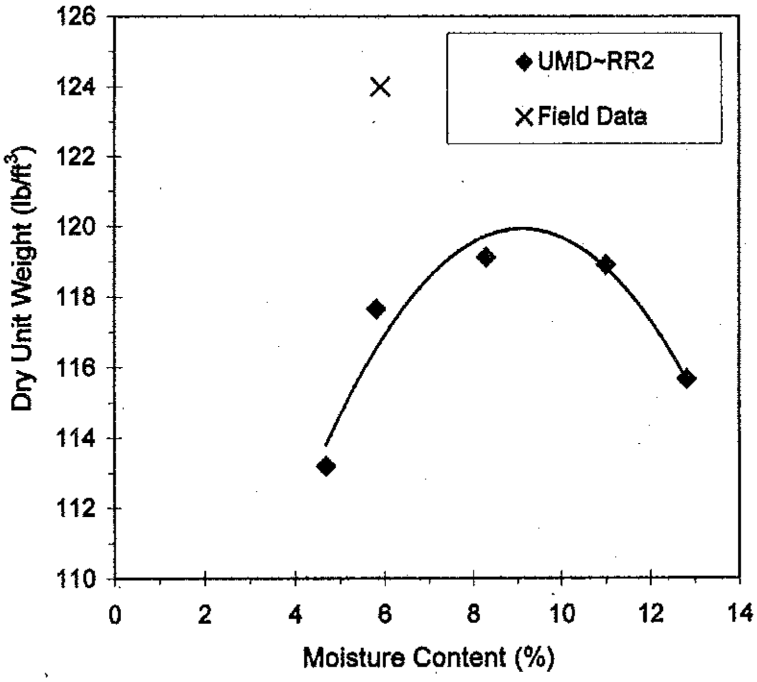


Note 1:
All compaction at Site M3.1 was performed with a CAT CS-563 D vibratory drum roller.

Table C-9 Site M3.1: Field Data from Sample UMD~R44~F4

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)	# Lifts Above Sensor	Approx. Lift Thickness (in.)	Thickness Fill Above Sensor (ft.)
10/28/02	16	106.0	100.0	6.9	94.3	1	12	1.0
10/29/02	4	106.0	93.3	4.9	88.0	4	12	4.0

Figure C-15 Site M3.2: Field Data and Standard Proctor Compaction Test for Sample UMD~RR 2 (M3: Ordinary Borrow)



Note 1: Compaction at Site M3.2 was performed with a Wacker (sheepsfoot vibratory roller).

Note 2: Only one lift of soil (approximately 12 inches thick) was compacted above sensors during these field tests.

Table C-10 Site M3.2: Field Data from Sample UMD~RR 2

Date	# Passes Red Light	Max Lab Dry Unit Weight (pcf)	Field Dry Unit Weight (pcf)	Field Water Content (%)	R.C. (%)
10/29/02	4	120.0	124.0	5.9	103.3

Table C-11 Field Data from Site M5.1

Date & Site:	N. Conway, NH 5/22/02					Soil Compaction Meter
Compaction Equipment:	Svedala Dynapac CA 250					0 = Processing
Material:	Asphalt					1 = Indicator #1
No. of Lifts above Sensor:	1					2 = Indicator #2
Approx. Thickness (this Lift):	2.5 inches					3 = Red Stop Light
Approx. Thickness (Material above Sensor):	2.5 inches					
Tested by:	Heather Miller					
		ID/Target:	**Snr**	**5d**	**StiF**	
Soil Compaction Meter Signal	Pass #	Geo-Gauge Test #	Signal Noise Ratio (dB)	Standard Deviation	Stiffness (MN/m)	Comments (Density Test, etc.)
Not Running	0	1				
		2				
		3				
No Signal	1	1				
		2				
		3				
No Signal	2	1				Nuclear Density Test
		2				Percent Compction
		3				= 78.51%
No Signal	3	1				
		2				
		3				
0	4	1				Nuclear Density Test
		2				Percent Compction
		3				= 85.39%
No Signal	5	1				
		2				
		3				
0	6	1				Nuclear Density Test
		2				Percent Compction
		3				= 87.28%
No Signal	7	1				Nuclear Density Test
		2				Percent Compction
		3				= 88.7 %
No Signal	8	1				Nuclear Density Test
		2				Percent Compction
		3				= 91.3 %

After final pass, core sample was taken. Percent Compaction = 94.1%

Table C-12 Field Data from Site M5.2

Date & Site:	Rt 403 Relocation Kingston, RI 9/5/02					Soil Compaction Meter
Compaction Equipment:	CAT CB-534 C					0 = Processing
Material:	Asphalt (Sensor #1)					1 = Indicator #1
No. of Lifts above Sensor:	1					2 = Indicator #2
Approx. Thickness (this Lift):	3 inches					3 = Red Stop Light
Approx. Thickness (Material above Sensor):	3 inches					
Tested by:	Heather Miller					
		ID/Target:	**Snr**	**5d**	**StiF**	
Soil Compaction Meter Signal	Pass #	Geo-Gauge Test #	Signal Noise Ratio (dB)	Standard Deviation	Stiffness (MN/m)	Comments (Density Test, etc.)
Not Running	0	1				
		2				
		3				
0	1	1				
		2				
		3				
1	2	1				
		2				
		3				
2	3	1				
		2				
		3				
3	4	1				Nuclear Density Test
		2				Percent Compction
		3				= 95.3%
	5	1				
		2				
		3				
	6	1				
		2				
		3				
	7	1				Nuclear Density Test
		2				Percent Compction
		3				= 97.5%
		1				
		2				
		3				

Table C-13 Field Data from Site M5.2

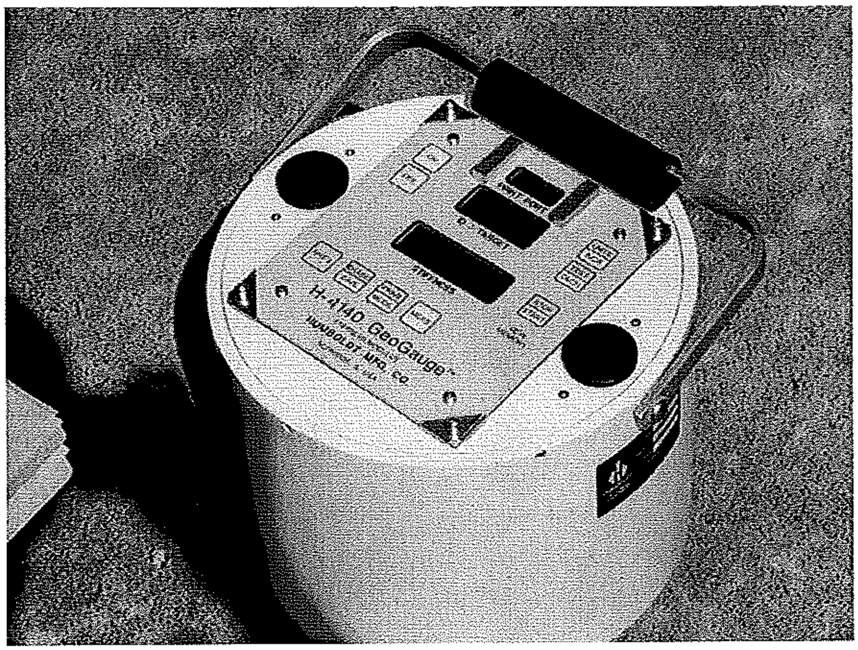
Date & Site:	Rt 403 Relocation Kingston, RI 9/5/02					Soil Compaction Meter
Compaction Equipment:	CAT CB-534 C					0 = Processing
Material:	Asphalt (Sensor #2)					1 = Indicator #1
No. of Lifts above Sensor:	1					2 = Indicator #2
Approx. Thickness (this Lift):	3 inches					3 = Red Stop Light
Approx. Thickness (Material above Sensor):	3 inches					
Tested by:	Heather Miller					
		ID/Target:	**Snr**	**5d**	**StiF**	
Soil Compaction Meter Signal	Pass #	Geo-Gauge Test #	Signal Noise Ratio (dB)	Standard Deviation	Stiffness (MN/m)	Comments (Density Test, etc.)
Not Running	0	1				
		2				
		3				
0	1	1				
		2				
		3				
0-1-2	2	1				
		2				
		3				
2	3	1				
		2				
		3				
2	4	1				
		2				
		3				
3	5	1				Nuclear Density Test
		2				Percent Compction
		3				= 90.8%
	6	1				
		2				
		3				
	7	1				Nuclear Density Test
		2				Percent Compction
		3				= 94.1%
	10	1				Nuclear Density Test
		2				Percent Compction
		3				= 94.8%

Table C-14 Field Data

Date & Site:		6/13/02 Rt. 1 Orient, ME				Soil Compaction Meter
Compaction Equipment:		Steel Drum Roller (10 Ton)				0 = Processing
Material:		Cement 1.5% - Foam 2.5%				1 = Indicator #1
No. of Lifts above Sensor:		1				2 = Indicator #2
Approx. Thickness (this Lift):		8"				3 = Red Stop Light
Approx. Thickness (Material above Sensor):				8"		
Tested by: JSG #503						
		ID/Target	**Snr**	**5d**	**StiF**	
Soil Compaction Meter Signal	Pass #	Geo-Gauge Test #	Signal Noise Ratio (dB)	Standard Deviation	Stiffness (MN/m)	Comments (Density Test, etc.)
Not Running	0	1	~	~	~	
		2				
		3				
0	1	1	n/a			
		2				
		3				
1	2	1	28.5	1.2	7.16	
		2				
		3				
2	3	1	26.7	1.2	7.77	
		2				
		3				
3	4	1	28.4	1.2	7.54	Nuclear Density Test
		2				Percent Compction
		3				= 95.0%
	5	1	22.4	1.2	8.70	
		2				
		3				
	6	1	~	~	~	
		2				
		3				
	7	1	27.7	1.3	8.63	
		2				
		3				
	8	1	~	~	~	
		2				
		3				
	9	1	25.3	1.4	9.84	
		2				
		3				
	10	1				Nuclear Density Test
		2				Percent Compction
		3				= 98.2%

Appendix D: GeoGauge Background Information and Measurements from Phase A Testing

The GeoGauge (formerly known as the Soil Stiffness Gauge), is a hand-portable instrument produced by Humboldt Manufacturing Co. The GeoGauge (shown in the photograph below) weighs about 11.4 kg, is 28 cm in diameter, 25.4 cm tall, and rests on the soil surface via a ring–shaped foot.



The principal of operation of the GeoGauge is as follows (Humboldt, 2000). The foot bears directly on the soil and is provided with rubber isolators to support the weight of the GeoGauge. A shaker is attached to the foot as well as sensors that measure the force and displacement-time history of the foot. The GeoGauge vibrates, producing small changes in force, P, that produce small deflections. The soil deflects an amount, d, which is proportional to the foot geometry, Young's modulus, and Poisson's ratio of the soil. The GeoGauge indicates the stiffness of soil, as measured by the ratio of the force to displacement: $K=P/d$. It is a dynamic equivalent to a plate load test; the soil stress and strain levels produced by the GeoGauge are typical of those applied in pavement applications.

The detailed procedure for using the GeoGauge is described in detail in the manufacturers User Guide (Humboldt, 2000) and is summarized here. To make a measurement, the GeoGauge is generally placed on the soil with little or no preparation of the soil surface. Typically, a slight push on or rotation of the GeoGauge is needed to obtain the recommended 60% minimum contact area between the foot and the soil. On particularly hard or rough surfaces, seating of the foot is enhanced by the use of a thin layer of moist sand or local fines. Once the GeoGauge is properly seated, the unit is turned on, and it performs a short self-test. A measurement of soil stiffness is then obtained by simply pressing the "Meas" button on the top of the unit. An individual test takes about one to two minutes.

Since both the SCS and the GeoGauge function based upon the transmission of compression waves through the soil, it was decided to use the GeoGauge as a complimentary tool to examine changes in soil stiffness that occur with compaction. In particular (during the Phase A testing), GeoGauge measurements were taken in an attempt to detect whether the SCS gives the red light signal at a point of diminishing returns with regard to soil stiffness. During that testing, GeoGauge measurements were taken at 3 locations along the top of the lift after each pass of the roller during compaction. The three individual GeoGauge stiffness measurements taken after each roller pass, along with the average, the standard deviation and the coefficient of variation between measurements, is tabulated in the following pages of this Appendix. It can be seen that the coefficient of variation between the three measurements on any given lift is generally quite high. As such, that data could not reliably be used to determine whether or not a statistically significant difference in stiffness occurred during additional compaction after the SCS red light signal was produced.

Soil Compaction Meter								
0 = Processing								
1 = Indicator #1								
2 = Indicator #2								
3 = Red Stop Light								
Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements				Std. Dev.	Coeff. Of Variation (%)
			1	2	3	Avg.		
M1waT1	0	1						
	1	5	4.04	3.59	3.49	3.71	0.29	7.90
	3	6	2.81	3.43	3.78	3.34	0.49	14.71
		7	3.89	4.11	4.13	4.04	0.13	3.29
		8	3.28	3.76	3.59	3.54	0.24	6.87
		9	3.67	3.90	3.06	3.54	0.43	12.25
		10	3.48	3.89	3.14	3.50	0.38	10.72
M1waT2	0	1	3.31	2.91	3.51	3.24	0.31	9.42
	0	2	3.83	3.14	3.62	3.53	0.35	10.02
	2	3	3.96	2.98	3.58	3.51	0.49	14.09
	3	4	3.28	3.42	3.41	3.37	0.08	2.32
		5	4.20	3.48	3.83	3.84	0.36	9.38
		6	3.30	3.56	3.88	3.58	0.29	8.11
		7	3.63	3.94	3.83	3.80	0.16	4.14
		8	3.47	3.57	3.57	3.54	0.06	1.63
M1waT3	0	1	3.94	2.86	3.20	3.33	0.55	16.57
	2	2	3.35	3.19	3.38	3.31	0.10	3.09
	3	3	3.59	3.91	3.35	3.62	0.28	7.77
		4	3.66	3.93	3.44	3.68	0.25	6.68
		5	3.54	4.38	3.78	3.90	0.43	11.09
		6	3.51	3.36	3.50	3.46	0.08	2.43
		7	3.52	4.26	3.92	3.90	0.37	9.50
M1waT4	0	1	2.76	3.01	2.97	2.91	0.13	4.61
	2	2	3.09	2.85	3.19	3.04	0.17	5.74
	3	3	2.93	2.68	3.06	2.89	0.19	6.68
		4	3.73	3.85	4.04	3.87	0.16	4.04
		5	2.96	3.18	4.04	3.39	0.57	16.82
		6	2.95	3.40	4.35	3.57	0.71	20.04
		7	3.53	3.74	3.75	3.67	0.12	3.38

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements				Std. Dev.	Coeff. Of Variation (%)
			1	2	3	Avg.		
M1wbT1	0	1	3.08	4.13	3.40	3.54	0.54	15.22
	1	2	2.46	4.18	4.02	3.55	0.95	26.74
	2	3	3.24	4.14	3.99	3.79	0.48	12.72
	3	4	3.02	4.71	3.51	3.75	0.87	23.21
		5	3.36	4.27	3.54	3.72	0.48	12.94
		6	2.70	4.34	3.94	3.66	0.86	23.36
		7	2.83	3.85	3.35	3.34	0.51	15.26
		8	2.40	4.25	3.66	3.44	0.95	27.50
M1wbT3	0	1	4.09	4.00	3.76	3.95	0.17	4.32
	0	2	3.58	3.35	3.76	3.56	0.21	5.77
	1	3	3.75	4.44	3.48	3.89	0.50	12.73
	2	4	4.35	3.89	4.12	4.12	0.23	5.58
	3	5	4.38	5.10	4.07	4.52	0.53	11.70
		6	3.82	4.40	3.56	3.93	0.43	10.95
		7	4.13	4.63	3.64	4.13	0.50	11.98
		8	4.11	4.26	4.47	4.28	0.18	4.23
		9	4.48	5.31	4.01	4.60	0.66	14.31
M1wcT1	0	1	1.81	3.04	2.66	2.50	0.63	25.16
	1	2	3.16	3.74	3.35	3.42	0.30	8.65
	2	3	2.85	2.92	3.03	2.93	0.09	3.09
	3	4	3.12	3.94	2.82	3.29	0.58	17.60
		5	3.17	3.64	1.70	2.84	1.01	35.68
		6	2.89	3.57	2.89	3.12	0.39	12.60
		7	3.13	3.29	2.40	2.94	0.47	16.14
		8	3.13	3.52	3.08	3.24	0.24	7.43
M1wcT2	0	1	2.74	3.19	2.62	2.85	0.30	10.54
	1	2	2.75	2.64	3.14	2.84	0.26	9.24
	3	3	2.59	3.76	3.07	3.14	0.59	18.73
		4	2.53	3.34	2.68	2.85	0.43	15.12
		5	2.47	3.73	2.29	2.83	0.78	27.72
		6	2.30	3.93	1.56	2.60	1.21	46.70
		7	2.49	3.57	1.27	2.44	1.15	47.10

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements 1	2	3	Avg.	Std. Dev.	Coeff. Of Variation (%)
M2waT2	0	1	5.97	6.78	5.79	6.18	0.53	8.53
	0	2	6.36	6.74	5.78	6.29	0.48	7.68
	0	3						
	1	4	7.33	6.58	5.65	6.52	0.84	12.91
	2	5	6.37	6.50	5.97	6.28	0.28	4.40
	3	6	7.57	6.27	4.78	6.21	1.40	22.49
		7	7.64	6.37	5.92	6.64	0.89	13.43
		8	7.19	7.60	6.15	6.98	0.75	10.71
M2waT3	0	1						
	0	2	7.43	7.10	7.18	7.24	0.17	2.38
	0	3						
	0	4	8.16	8.33	6.96	7.82	0.75	9.55
	2	5	7.38	6.98	6.35	6.90	0.52	7.52
	3	6	7.56	7.07	6.50	7.04	0.53	7.53
		7	7.42	7.84	6.71	7.32	0.57	7.80
		8	8.02	8.06	7.45	7.84	0.34	4.35
M2wbT1	0	1	5.89	6.33	6.09	6.10	0.22	3.61
	1	2	6.66	7.19	6.25	6.70	0.47	7.03
	2	3	6.69	7.88	7.08	7.22	0.61	8.41
	3	4	7.20	9.18	7.72	8.03	1.03	12.78
		5	7.42	9.01	7.89	8.11	0.82	10.08
		6	7.56	9.43	7.65	8.21	1.05	12.84
		7	7.21	9.06	7.74	8.00	0.95	11.90
M2wbT2	0	1	6.92	5.89	5.03	5.95	0.95	15.91
	0	2	6.77	7.29	5.94	6.67	0.68	10.21
	0	3	7.28	8.01	6.78	7.36	0.62	8.41
	1	4	8.31	8.62	7.57	8.17	0.54	6.61
	2	5	8.45	10.00	7.70	8.72	1.17	13.46
	3	6	8.37	9.04	7.75	8.39	0.65	7.69
		7	8.19	9.93	8.20	8.77	1.00	11.42
		8	7.67	9.58	7.41	8.22	1.18	14.42
		9	7.96	9.87	7.60	8.48	1.22	14.39
		10	8.57	9.82	7.90	8.76	0.97	11.12

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements				Std. Dev.	Coeff. Of Variation (%)
			1	2	3	Avg.		
M2wbT3	0	1	7.29	8.88	7.70	7.96	0.83	10.37
	0	2	7.77	9.66	7.94	8.46	1.05	12.36
	0	3	7.89	9.00	7.85	8.25	0.65	7.91
	1	4	8.43	10.33	8.01	8.92	1.24	13.85
	2	5	8.76	9.54	7.34	8.55	1.12	13.05
	3	6	8.46	10.51	7.67	8.88	1.47	16.51
		7	8.83	8.35	7.47	8.22	0.69	8.39
		8	7.75	10.78	8.03	8.85	1.67	18.91
		9	8.76	9.61	7.95	8.77	0.83	9.46
		10	9.09	10.93	8.26	9.43	1.37	14.50
M2wcT1	0	1	4.48	6.36	6.01	5.62	1.00	17.80
	0	2	6.59	8.13	7.11	7.28	0.78	10.77
	0	3	6.80	7.57	6.92	7.10	0.41	5.84
	1	4	7.38	7.81	7.08	7.42	0.37	4.94
	2	5	6.68	7.69	6.92	7.10	0.53	7.44
	3	6	7.60	8.18	7.07	7.62	0.56	7.29
		7	7.00	7.94	6.98	7.31	0.55	7.51
		8	6.58	6.52	6.76	6.62	0.12	1.89
		9	6.37	7.68	6.36	6.80	0.76	11.16
		10	7.47	7.56	6.38	7.14	0.66	9.20
M2wcT2	0	1	6.42	6.50	6.42	6.45	0.05	0.72
	0	2	6.72	6.92	6.86	6.83	0.10	1.50
	0	3	6.56	8.26	6.53	7.12	0.99	13.91
	1	4	7.29	8.89	6.74	7.64	1.12	14.62
	2	5	6.86	9.13	7.12	7.70	1.24	16.13
	3	6	6.68	8.95	6.73	7.45	1.30	17.39
		7	6.12	8.00	7.02	7.05	0.94	13.34
		8	6.65	8.19	6.45	7.10	0.95	13.42
		9	6.08	8.47	7.04	7.20	1.20	16.71
		10	6.63	9.41	6.62	7.55	1.61	21.29

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements				Std. Dev.	Coeff. Of Variation (%)
			1	2	3	Avg.		
M2wcT3	0	1	6.00	8.12	6.00	6.71	1.22	18.25
	0	2	6.66	8.49	6.11	7.09	1.25	17.58
	0	3	7.28	7.46	6.10	6.95	0.74	10.63
	0	4	6.70	9.78	7.19	7.89	1.66	20.98
	2	5	7.50	9.00	6.53	7.68	1.24	16.21
	0	6	6.68	10.39	7.63	8.23	1.93	23.41
	3	7	7.41	10.32	7.51	8.41	1.65	19.64
		8	6.92	10.75	6.78	8.15	2.25	27.64
		9	7.11	11.32	6.79	8.41	2.53	30.07
		10	5.93	10.24	7.13	7.77	2.22	28.64
		11	7.45	10.50	6.86	8.27	1.95	23.62
		12	6.74	9.08	7.15	7.66	1.25	16.32
M3waT1	0	1	8.87	8.14	10.39	9.13	1.15	12.57
	0	2	9.57	10.08	8.16	9.27	0.99	10.73
	0	3	10.73	10.09	9.18	10.00	0.78	7.79
	1	4	11.37	10.07	11.41	10.95	0.76	6.96
	3	5	9.94	10.99	9.84	10.26	0.64	6.21
		6	11.50	11.65	10.47	11.21	0.64	5.73
		7	12.00	10.62	10.01	10.88	1.02	9.37
		8	12.39	12.35	10.17	11.64	1.27	10.92
		9	12.23	11.27	10.81	11.44	0.72	6.34
M3waT2	0	1	7.13	8.12	7.95	7.73	0.53	6.85
	0	2	8.12	9.40	10.12	9.21	1.01	10.99
	0	3	8.18	9.18	10.59	9.32	1.21	13.00
	2	4	9.55	8.71	10.76	9.67	1.03	10.65
	3	5	9.14	11.14	10.08	10.12	1.00	9.89
		6	10.46	11.97	10.82	11.08	0.79	7.12
		7	9.51	12.01	9.88	10.47	1.35	12.89
		8	12.23	12.63	12.85	12.57	0.31	2.50
		9	9.65	10.94	9.44	10.01	0.81	8.11

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements 1	2	3	Avg.	Std. Dev.	Coeff. Of Variation (%)
M3waT3	0	1	6.15	7.11	8.12	7.13	0.99	13.82
	0	2	8.32	7.65	8.65	8.21	0.51	6.21
	0	3	8.96	8.94	9.45	9.12	0.29	3.17
	1	4	10.83	9.45	10.64	10.31	0.75	7.26
	2	5	9.87	10.20	11.24	10.44	0.72	6.85
	3	6	11.00	10.69	9.96	10.55	0.53	5.06
		7	9.73	11.46	10.55	10.58	0.87	8.18
		8	12.42	12.37	10.89	11.89	0.87	7.31
		9	12.48	12.03	11.34	11.95	0.57	4.80
		10	12.37	12.05	9.80	11.41	1.40	12.28
M3wbT1			GeoGauge not working properly					
M3wbT2	0	1	4.63	5.38	6.54	5.52	0.96	17.44
	0	2	5.63	6.23	7.05	6.30	0.71	11.31
	1	3	6.52	7.63	6.64	6.93	0.61	8.79
	2	4	6.32	7.38	6.20	6.63	0.65	9.79
	3	5	5.14	7.15	6.13	6.14	1.01	16.37
		6	5.30	6.28	6.56	6.05	0.66	10.94
		7	5.58	7.67	7.96	7.07	1.30	18.37
		8	6.06	8.44	8.05	7.52	1.28	16.98
		9	6.10	8.13	7.33	7.19	1.02	14.23
M3wbT3	0	1	5.04	4.43	5.85	5.11	0.71	13.95
	0	2	5.48	5.37	6.21	5.69	0.46	8.03
	0	3	6.87	6.57	6.64	6.69	0.16	2.34
	1	4	7.93	7.57	7.37	7.62	0.28	3.72
	2	5	7.63	8.06	6.98	7.56	0.54	7.20
	2	6	7.35	6.13	6.81	6.76	0.61	9.04
	3	7	6.19	7.45	6.94	6.86	0.63	9.24
		8	6.18	5.44	5.94	5.85	0.38	6.45
		9	7.71	7.36	8.91	7.99	0.81	10.17
		10	7.17	6.98	7.88	7.34	0.47	6.46

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements				Std. Dev.	Coeff. Of Variation (%)
			1	2	3	Avg.		
M3wbT4	0	1	9.32	10.95	10.19	10.15	0.82	8.03
	0	2	10.44	13.75	8.92	11.04	2.47	22.38
	0	3	11.25	12.24	10.99	11.49	0.66	5.74
	1	4	10.02	12.38	10.55	10.98	1.24	11.27
	2	5	11.35	13.87	10.57	11.93	1.72	14.46
	3	6	11.90	8.80	11.02	10.57	1.60	15.11
		7	11.35	13.12	10.50	11.66	1.34	11.47
		8	15.63	11.98	11.38	13.00	2.30	17.70
		9	9.43	13.13	11.30	11.29	1.85	16.39
		10	11.75	13.00	11.31	12.02	0.88	7.29
M3wbT5	0	1	6.68	10.18	8.22	8.36	1.75	20.98
	0	2	7.47	10.06	10.11	9.21	1.51	16.39
	0	3	9.11	11.57	10.14	10.27	1.24	12.03
	1	4	10.40	10.26	10.92	10.53	0.35	3.30
	2	5	9.11	13.24	9.97	10.77	2.18	20.23
	3	6	12.46	12.00	11.22	11.89	0.63	5.27
		7	10.36	13.76	9.36	11.16	2.31	20.67
		8	12.96	12.80	10.71	12.16	1.26	10.33
		9	10.91	13.21	11.04	11.72	1.29	11.02
		10	12.70	12.43	11.16	12.10	0.82	6.80
M3wcT1	0	1	4.98	8.13	7.80	6.97	1.73	24.84
	0	2	5.65	8.63	8.04	7.44	1.58	21.21
	0	3	6.13	8.53	8.49	7.72	1.37	17.81
	1	4	6.80	9.58	8.54	8.31	1.40	16.91
	2	5	6.60	10.12	7.43	8.05	1.84	22.86
	3	6	7.70	10.88	6.44	8.34	2.29	27.44
		7	7.87	11.28	6.21	8.45	2.58	30.58
		8	7.51	10.62	7.47	8.53	1.81	21.18
		9	6.79	9.77	6.77	7.78	1.73	22.20
		10	6.27	9.98	6.02	7.42	2.22	29.87

Test I.D.	SCM Signal	No. of Passes	GeoGauge Measurements				Std. Dev.	Coeff. Of Variation (%)
			1	2	3	Avg.		
M3wcT2	0	1	6.33	9.16	7.89	7.79	1.42	18.19
	0	2	7.60	10.38	8.01	8.66	1.50	17.32
	0	3	7.62	9.58	8.66	8.62	0.98	11.38
	2	4	8.83	11.16	8.47	9.49	1.46	15.39
	3	5	7.23	9.49	5.83	7.52	1.85	24.57
		6	6.55	10.08	6.32	7.65	2.11	27.55
		7	6.18	9.05	5.31	6.85	1.96	28.58
		8	5.62	8.96	5.95	6.84	1.84	26.89
		9	4.27	6.97	5.88	5.71	1.36	23.30

Appendix E:
Instructions for Operating the
Soil Compaction Meter (SCM) and
Soil Compaction Supervisor (SCS)

E.1 Introduction

The "Soil Compaction Meter" (SCM) and "Soil Compaction Supervisor" (SCS) are relatively easy to use instruments that can assist in monitoring soil compaction. The SCM and SCS operate on the same principals; the main difference in the two devices is that the Soil Compaction Supervisor has internal memory, so it can record data regarding the compaction process, which can later be downloaded to a personal computer.

The system consists of a battery powered hand-held meter, a disposable sensor, and, for the SCS, a reusable data key. The sensor is connected to the meter by way of a plug-in cable. The length of cable currently supplied by the manufacturer is about 12 feet. In many highway construction applications, a longer cable may be required. In such cases, the cable can be modified to accept an extension, as discussed in the section E.3.1.c.

In use, the sensor is placed at the bottom of an uncompacted lift of soil and its cable is connected to the meter. As the lift is compacted, the sensor sends a signal to the meter, which is processed internally to determine when the maximum compaction has been achieved under the current conditions. When the lift has been compacted to the optimum level, a red "STOP" light appears on the meter. A single sensor may be used to monitor multiple successively placed lifts of fill, however the maximum working depth for the sensors is approximately 3.5 to 4 feet (depending on the compactor and soil type). Therefore, multiple sensors may need to be used to monitor deeper fills.

The SCM and SCS, manufactured by MBW, Inc., were initially developed to address backfilling of bellhole type utility excavations. The manufacturers operating instructions have been incorporated in this document (with permission) and modified as appropriate for utilization of these devices in highway construction applications.

E.2 Operating the SCM and SCS:

A schematic of the Soil Compaction Supervisor is included in Figure E-1. Before use, it is important to become familiar with a few basic operational tasks.

E.2.1 Power on/off

- To turn the SCS on, press and release the "Power" button. To turn the SCM on, move the toggle switch to the ON position.
- To turn the SCS off, press and hold the "Power" button for about four seconds. Release the button when the READY light turns off. To turn the SCM off, move the toggle switch to the OFF position.

  The Soil Compaction Supervisor performs a short self-test immediately following power up. These tests include: data transfer to the key (if inserted), memory level check, and sensor check. If all the tests pass, the READY light will turn on. If any of the tests fail, an error will be signified by the flashing STOP light, possibly along with other flashing lights. See Table 1 for error codes and solutions for the SCS.

Table E-1 Error Codes and Solutions

Flashing Light(s)	Error	Possible Solution
Data Transferred Light *and* Stop Light	Error reading/writing data key.	Rotate key to fully locked position. Use a different data key.
Memory Light *and* Stop Light	No additional data can be recorded.	Transfer data from meter to key. Use a different data key.
Ready Light *and* Stop Light	No signal from sensor.	Plug in sensor. Replace sensor.
Data Transferred *and* Memory Light *and* Stop Light	Key has insufficient capacity to store the data from the meter.	Use a data key with more capacity.
Stop Light Only	Low Battery.	Replace batteries.

E.2.2 Installing and/or Replacing Batteries

- Slide the battery cover (located on the back of the meter) in the direction of the "open" arrow. Lift cover off.
- Remove old batteries and dispose of properly.
- Insert four new batteries making sure the positive side is on the same side as the positive sign in the battery compartment.
- Put the battery cover back on the meter.

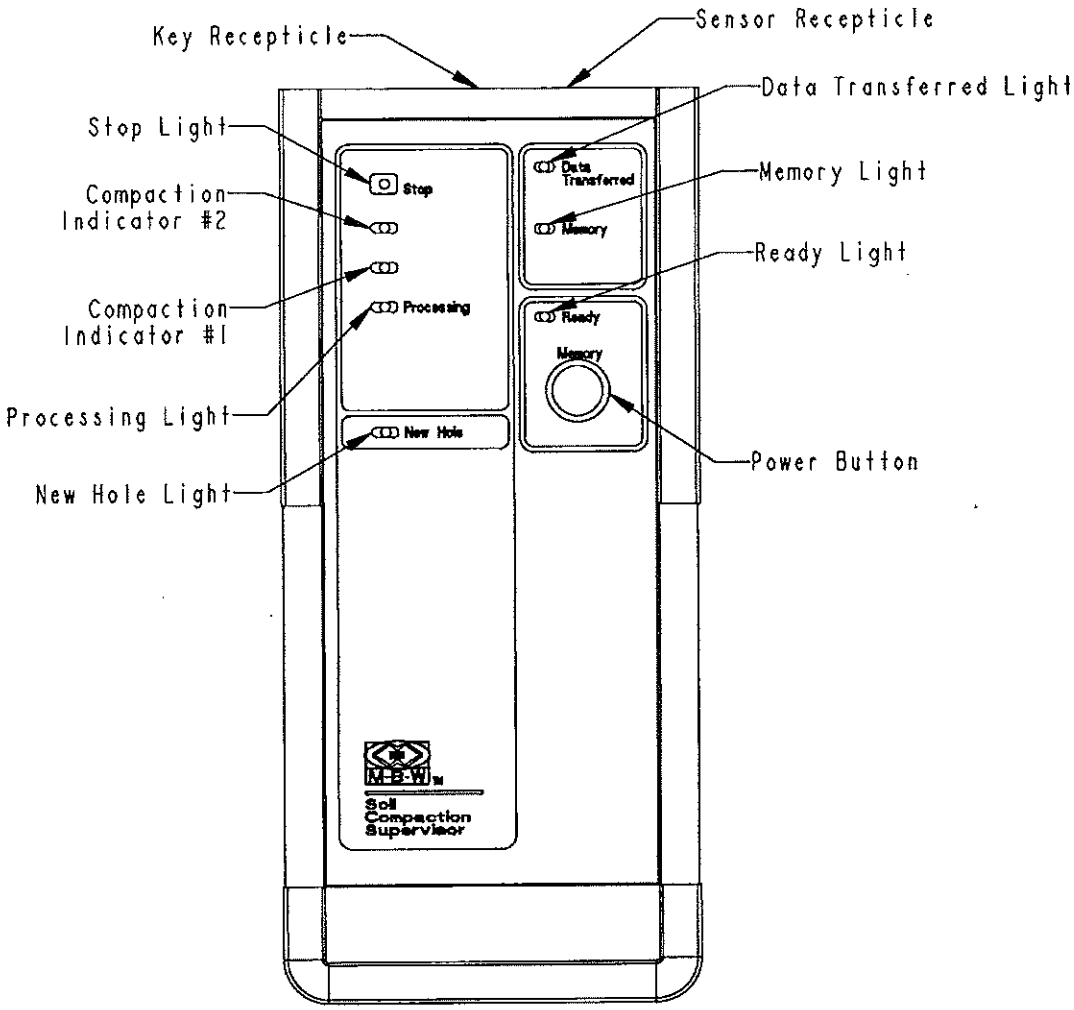
E.2.3 Attaching/Removing Sensor

- To attach the sensor, insert the plug end of the cable into the rectangular receptacle on top of the meter. The plug can only be inserted one way and will "click" when it is inserted all the way.
- To remove the sensor, depress the tang on the plug and gently pull away from the meter.

E.2.4 Inserting and removing data key (for SCS)

- To insert the key, push it into the middle slot on the top of the Soil Compaction Supervisor and turn it clockwise 90°.
- To remove the key, turn it counter clockwise 90° and pull it out of the Soil Compaction Supervisor.

Figure E-1 Soil Compaction Supervisor Layout



E.3 Monitoring Compaction

E.3.1 Installation of Sensors

E.3.1.a For Placing & Compacting Backfill in Trenches

- Place sensor on a firm flat surface at the bottom of the excavation at least 12" away from any sidewalls, if possible. Cover the sensor with a small pile of soil to keep it in place and protect it from the initial backfill.

  NOTE: The words "THIS SIDE UP" (molded into the sensor) should face the top of the excavation.

- Route the cable up the sidewall of the excavation.
- Backfill the excavation to a depth of 6-12 inches.
- Position the sensor cable so it will not get damaged during compaction.
- Plug the sensor into the top of the SCM/SCS meter.

E.3.1.b For Placing & Compacting Fills over a Large Area

- In most highway applications, the SCM/SCS sensors must be installed *after* the loose soil is spread and graded. A hole should be dug to install the sensor near the bottom of the lift, with the words "THIS SIDE UP" (molded into the sensor) facing the top of the lift.
- A small trench (about 2 to 3 inches deep) should be excavated from the sensor location to a safe location near the outskirts of the lift. The sensor cable must be buried in such a trench because: (a) the SCM/SCS operator must remain safely away from construction equipment during the compaction process, and (b) the compaction and other construction equipment will generally damage the cable if they run directly over it.
- Plug the sensor into the top of the SCM/SCS meter.

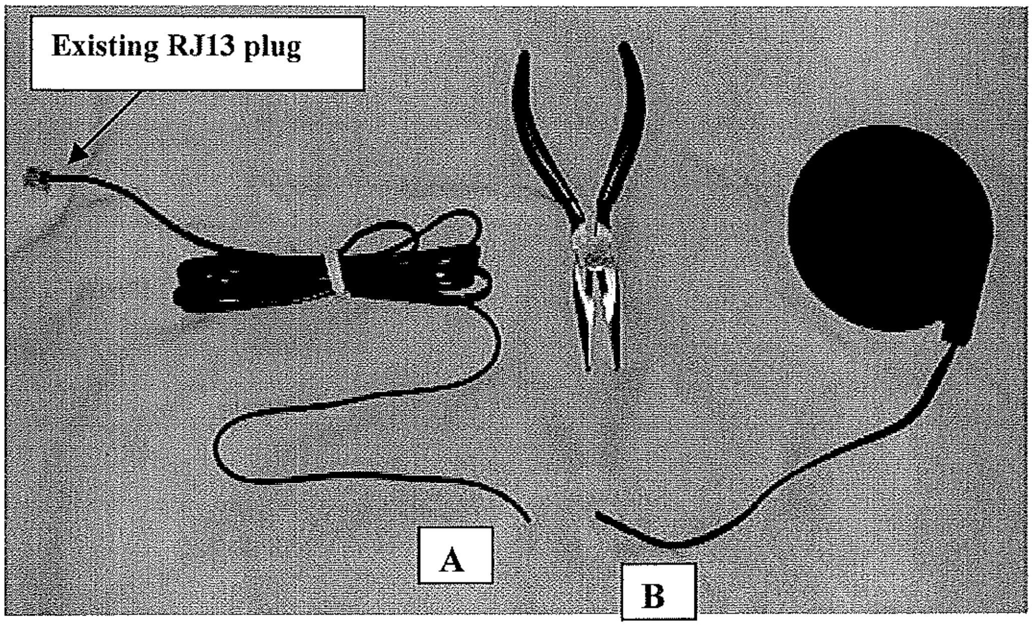
E.3.1.c Modifying Sensor Cable to Add Extension Cable (if necessary)

The length of cable currently supplied with the disposable sensors is about 12 feet. In many highway construction applications, a longer cable may be required. In such cases, the cable can be modified to accept an extension cable. It will be necessary to have the following tools and supplies:

- scissors or wire cutter
- modular crimping tool (for use with RJ11 plugs)
- RJ11 modular plugs
- 4-wire in-line coupler (single-line RJ-11)
- modular phone extension cord

The cables attached to the disposable sensors are supplied with an RJ13 plug, which is inserted into the SCM/SCS meter. Since the RJ13 plug is not compatible with the standard couplers used with modular phone extension cord, the cable must be modified using the following procedure:

Figure E-2 Modification of Cable for Extension



- Using scissors or a wire cutter, cut off a section of the cable attached to the disposable sensor, as shown in Figure E-2. Be sure to cut the ends of the cable straight across (not diagonally).

  Also be sure to leave the existing RJ13 plug in place on the end of the cable. This end of the cable will ultimately be plugged into the SCM/SCS meter.

- Place one end of the cut cable into the stripper blade of the crimping tool, and then squeeze the crimping tool together until it stops. Pull the cable away from the tool to strip about 1/4 inch of the cable's outer insulation. Be careful not to remove or break the inner conductor's colored insulation. Do the same for the other end of the cut cable.

- Hold a RJ-11modular plug with the spring clip facing up, then insert the cut end A of the prepared cable into the plug so the black wire is on the left, as shown in Figure E-4(A). Be sure that the conductors are flush with the tip of the plug and touching the small teeth-like gold conductors. Without moving the cable out of position, insert the end of the plug into the modular plug cavity. Squeeze the crimping tool together until it stops.
- Connect a modular plug to end B of the cable, using the same procedure as above, except be sure to insert the cable into the plug so the black wire is on the right as shown in Figure E-4(B).
- A length of standard modular phone extension cord with 4-wire in-line couplers (single-line RJ-11) can now be installed between ends A and B to extend the length of the cable.

Figure E-3 Crimping Tool

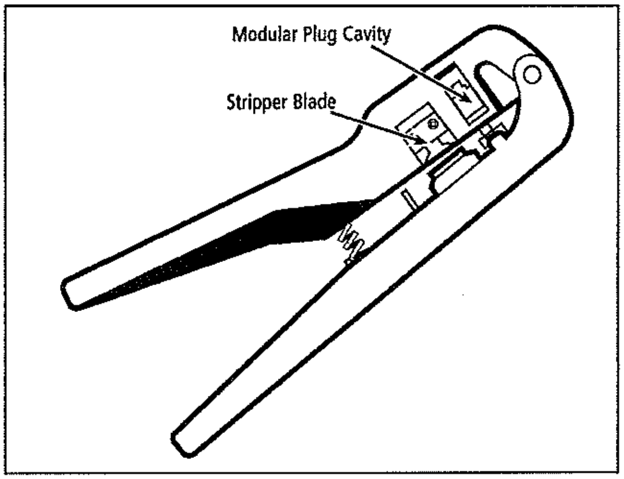
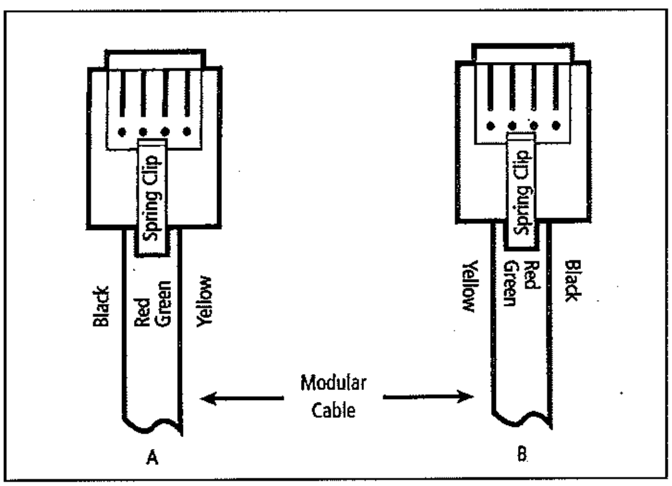


Figure E-4 Wiring Diagram



E.3.2 Compaction of Fill

1. Ideally, one should begin compaction within a short distance (8 to 10 feet) from the sensor. It is important to turn the SCM/SCS on only when the compactor approaches to within 2 to 4 feet of the sensor on its first pass. The compactor must approach and pass over the sensor at normal operating speed. The SCM and SCS will calibrate themselves in about 5 and 2 seconds, respectively. Upon calibration, the green PROCESSING light will begin to flash slowly for percussion machinery or quickly for a vibratory compactor.

   In highway construction applications, and when used in conjunction with heavy compaction equipment, it may be necessary to turn the SCM/SCS on at a slightly greater distance (between 2 and 6 ft) from the sensor. Again, it is important to pass over the sensor at normal operating speed. If the PROCESSING light fails to flash, the process should be repeated, turning the meter on at a slightly greater distance before passing over the sensor. If the green PROCESSING light still fails to appear as the compactor is moving over the sensor, it may be that the equipment is moving too quickly. If so, it may be necessary for the QA/QC personnel to request that the contractor operate the roller more slowly (at least during the initial pass over the sensor).

2. Continue to compact the lift, keeping note of how many passes the compactor makes over the sensor. The meter will continue to monitor the compaction as consecutive passes are made over sensor. The PROCESSING light will continue to flash as long as the Soil Compaction Supervisor is receiving data from the sensor. The COMPACTION INDICATOR lights (#1 and then #2) will illuminate, indicating the approximate stage of compaction as additional passes are made over the lift.

   NOTE: The SCS meter shuts off automatically after 10 minutes of "inactivity." Therefore, for the SCS, it is imperative that compaction of the soil over the sensor continues to completion without delay once the process has been initiated. The SCM does not have that automatic shutoff feature.

3. When the lift has been compacted to the optimum level under the given conditions, a red "STOP" light appears on the meter.

   - For the SCS, the DATA TRANSFERRED light will also come on at this point, indicating the data has been stored to the data key (if inserted) or to the Soil Compaction Supervisor's internal memory.
   - The SCS will automatically turn off 30 seconds after the STOP light comes on. The SCM must be turned off manually by moving the toggle switch to the OFF position.

   At this point, the soil above the sensor has now been compacted to the optimum level under the given conditions, and the compactor may move to the next section of the lift. For proper compaction of the entire lift, it is important that the field personnel observe the process and make sure that the compaction equipment makes an equivalent number of passes over all sections of the lift.

4. Add the next lift of material and repeat steps 1 through 3 until backfill is completed, or until the thickness of fill above the sensor reaches about 3.5 feet. The maximum working depth for the sensors is approximately 3.5 to 4 feet (depending on the soil type). Therefore, multiple sensors may need to be used to monitor deeper fills.

E 3.3 Error Lights and Troubleshooting

The STOP light will blink if the meter encounters an error during start-up or during the compaction process. The SCM/SCS will stop all functions when displaying the error code. The error codes are represented by additional lights flashing in unison with the STOP light. The errors and possible solutions for the SCS are described in Table E-1.

E.4 Data Management (Applicable to Soil Compaction Supervisor Only)

As noted previously, the Soil Compaction Supervisor has internal memory, so it can record data during the compaction process, which can later be downloaded to a personal computer. The following data is recorded by the Soil Compaction Supervisor: compaction start date/time, compaction time in minutes and seconds, job number, lift number, machine type, and completion status. The only data the user defines is new hole or new lift. Using the appropriate setting is important for managing: compaction start date/time, compaction time in minutes and seconds, job number, lift number, machine type, and completion status. The only data the user defines is new hole or new lift. Using the appropriate setting is important for managing data. The Soil Compaction Supervisor defaults to "new hole" when it is turned on. The user may need to toggle this setting if it does not describe the correct compaction process.

E.4.1 Toggling New Hole/New Lift

To Toggle between a "new hole" and a "new lift" press the "Power" button any time when the READY light is on. When the NEW HOLE light is on the Soil Compaction Supervisor is set for "new hole". If the NEW HOLE light is off the Soil Compaction Supervisor is set for "new lift.

E.4.2 Example of Data Management

The following example will describe the proper way to use the Soil Compaction Supervisor to record the data for two bellhole excavations that will require two lifts each to be completely backfilled. This example does not describe all of the steps required to operate the Soil Compaction Supervisor. See Section E.3, "Monitoring Compaction," for complete instructions.

Example:

- As the first lift of the first hole is being compacted the Soil Compaction Supervisor should be powered on and the NEW HOLE light should be toggled "on" to signify the first lift of a hole. After the first lift is complete, the data is saved as Hole #1, Lift #1.
- The second lift is added to the first hole and compaction is started. After the Soil Compaction Supervisor is powered on, the NEW HOLE light should be toggled "off". The data for this lift will be saved as Hole #1, Lift #2.
- As the compaction of the first lift of the second hole is started, the Soil Compaction Supervisor should be powered on and the NEW HOLE light should be toggled "on". The data from this lift will be recorded as Hole #2, Lift #1.
- When monitoring the compaction of the second lift of the second hole, the NEW HOLE light should be toggled "off". The data for this lift will be saved as Hole #2 Lift #2.

E 4.3 Data Location – Key vs. Meter

Compaction data can be stored in the Soil Compaction Supervisor's internal memory or on data keys. The memory in the Soil Compaction Supervisor allows about 90 records to be stored. The capacity of the key is about 200 records. The Soil Compaction Supervisor functions the same regardless of where the data is stored.

- To use the key to store the data insert the key into the Soil Compaction Supervisor before monitoring the first compaction. Then follow the instructions in Section E.3, "Monitoring Compaction."
- To use the Soil Compaction Supervisor to store the data, do not insert the data key. Follow the instructions in Section E.3, "Monitoring Compaction."

E 4.4 Transferring Data from the Soil Compaction Supervisor to the Key

- Turn the Soil Compaction Supervisor power off.
- Insert a data key into the Soil Compaction Supervisor.
- Turn on the Soil Compaction Supervisor.
- The Soil Compaction Supervisor will perform the self-test, check to see if there is room on the key for the data, and then immediately transfer the data in the Soil Compaction Supervisor to the key.

  NOTE: The DATA TRANSFERRED light will flash when transferring the data to the key. If the key contains data, the data from the Soil Compaction Supervisor will be appended after the original data on the key.
- When the data transfer is complete, the READY light will come on to signal the Soil Compaction Supervisor is ready to monitor compaction.

E.4.5 Downloading Data from the SCS Key to a Computer

To download data from the SCS key to a personal computer, a data key reader is required. The procedure for downloading data is outlined in a separate "Operator's Manual for the Compaction Supervisor Key Reader" (produced by the manufacturer).

E.4.6 Updating the Date and Time in the Soil Compaction Supervisor

The procedure for updating the date and time in the SCS requires a blank data key and a data key reader. The procedure is outlined in the separate "Operator's Manual for the Compaction Supervisor Key Reader" (produced by the manufacturer).

E.5 Disclaimer

The use of the Soil Compaction Supervisor does not, in any way, lessen the importance of following good soil reinstatement practices. Backfill soils **MUST** be acceptable for specific backfill purposes. Lift thickness **MUST** be controlled relative to soil type and capacity of the compaction device. Soils **MUST** have moisture contents in a reasonable range relative to optimum. The compaction equipment **MUST** be in good operating condition. Failure to consistently apply the accepted principles of good soil reinstatement can result in failure, with or without the use of quality control instrumentation. As such, the New England Transportation Consortium (NETC) assumes no liability resulting from the use or misuse of the SCM or the SCS.

Appendix F: Photographs of Typical SCS Sensor Installation Sequence

Figure F-1: Overview of Site M2.1 (MSE wall construction; Plymouth, MA)

Figure F-2: End dumping lift of fill

Figure F-3: Spreading fill to approximately 12-inch lift thickness with dozer

Figure F-4: Hole and trench excavated to place sensor near bottom of lift and to route cable away from compaction activities

Figure F-5: Covering sensor and cable with soil

Figure F-6: At this site, the cable was generally routed through gaps in the MSE wall panels so that the operator could stand outside the face of the wall at the top of the slope (thus remaining safely away from heavy equipment during the compaction operations.

Figure F-1

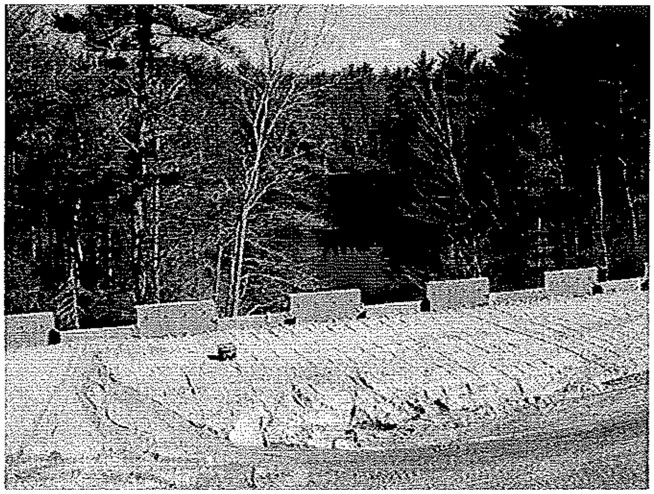


Figure F-2

Figure F-3

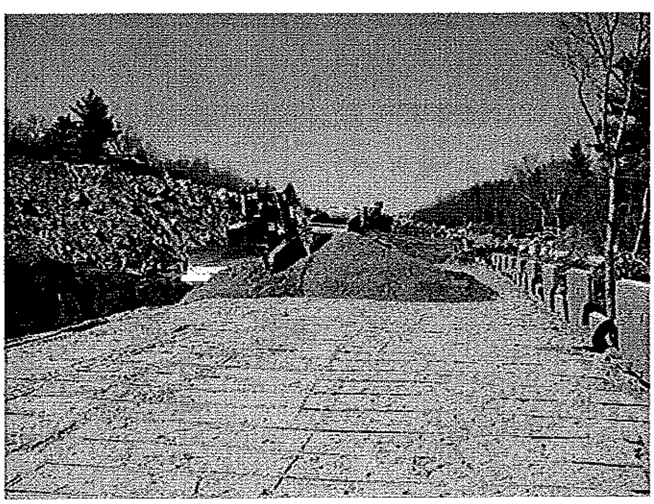


Figure F-4

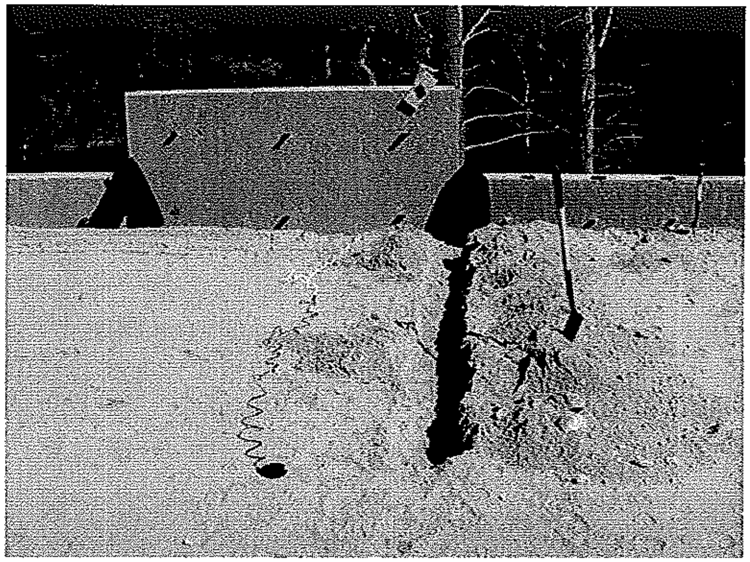


Figure F-5

Figure F-6