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Evaluation of microwave sensor for soil moisture content determination

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For

My Husband ***Pavan***

My Parents ***Rama Devi & Rama Rao***

TABLE OF CONTENTS

LIST OF FIGURES v
LIST OF TABLES viii
ABSTRACT ix
INTRODUCTION 1
- Goal 1
- Objectives 1
- Significance/Benefit 2
- Forecasting 3

BACKGROUND 5
DESCRIPTION OF THE EQUIPMENT 17
- Microwave sensor 17
- Sensor output variables 17
- Filtered Unscaled 18
- Filtering 18
- Sensor Specifications 19
- Hydro-Com 20
- Sensor Page 20
- Logging to File 20
- Working Principle 21
- Theory 21

TEST METHODS 25
- Soil Classification 25
- Specific Gravity 26
- Laboratory Compaction 26
- Microwave sensor testing in the laboratory and Soil moisture content measurement 29
- Sensor Evaluation 31

RESULTS AND DISCUSSION 32
- Test Plan 1 – Developing relationship between microwave values and moisture content 32
  - Test Methods 32
  - Results 32
  - Discussion 38
- Test Plan 2 - A comparison between tests on different molds and extracted samples 39
  - Test Methods 39
  - Results 41
  - Discussion 43
- Test Plan 3 – A comparison between tests on different soil types 44
  - Test Methods 44
  - Results 44

Discussion 46
Test Plan 4 – Comparison of field and laboratory tests 50
Test Methods 50
Results 52
Discussion 54
Test Plan 5 – Study of the effects of change in area and volume and influence of steel plate on microwave readings 55
Test Methods 55
Results 59
Discussion 62
Test Plan 6 – Tests on five different soils – lab and spot tests – model development using statistical software 63
Test Methods 63
Results 73
Discussion 103
Test Plan 7 – Accuracy and Precision Tests 106
Test Method 106
Results 109
Discussion 111
SUMMARY 112
RECOMMENDATIONS 115
REFERENCES 116
ACKNOWLEDGEMENTS 119
APPENDIX A: COMPACTION AND MICROWAVE TEST DATA 120
APPENDIX B: ATTERBERG LIMITS AND GRAIN SIZE DISTRIBUTION TESTS 151
APPENDIX C: STATISTICAL MODELS 188

LIST OF FIGURES

Figure 1. Methods of installation for soil moisture determination (Harms) ... 13
Figure2. Sensor specifications... 19
Figure 3. Sensor page ... 20
Figure 4. Trend graph and logging page ... 20
Figures 5(a-f): Sample preparation and compaction ... 28
Figures 6(a-h): Microwave sensor testing in lab (sample in the mold)... 31
Figure 7. Standard Proctor moisture-density relationships for sand and silt ... 35
Figure 8. Gravimetric moisture content vs. microwave value – sand and silt ... 35
Figure 9. Sand–Gravimetric moisture contents vs. microwave value... 36
Figure 10. Sand –Volumetric moisture contents vs. microwave value... 36
Figure 11. Silt – Gravimetric moisture contents vs. microwave value ... 37
Figure 12. Silt – Volumetric moisture contents vs. microwave value ... 37
Figures 13(a-j): Microwave sensor testing in lab (on extracted samples)... 41
Figure 14. Gravimetric moisture content vs. Microwave value... 43
Figure 15. Gravimetric moisture content vs. Microwave value - Loess ... 47
Figure 16. Volumetric moisture content vs. Microwave value - Loess ... 48
Figure 17. Gravimetric moisture content vs. Microwave value – Glacial Till... 48
Figure 18. Volumetric moisture content vs. Microwave value – Glacial Till... 49
Figure 19. Gravimetric moisture content vs. Microwave value – Comparison graph – Loess and Glacial Till ... 49
Figures 20(a-j): Microwave sensor testing in the field ... 52
Figures 21(a-l): Study of influence of contact area... 58
Figures 22(a-d): Study of influence of steel plate ... 59
Figure 23. Change in microwave value with contact area ... 61
Figure 24. Change in microwave value with volume... 61
Figure 25. Height of sample vs. Microwave value ... 62
Figures 26(a-u): Spot tests... 68
Figures 27(a-t): Laboratory tests ... 72
Figure 28. Moisture density relationships for Edward Till ... 75
Figure 29. Moisture density relationships for Kickapoo Clay ... 75
Figure 30. Moisture density relationships for Kickapoo Topsoil ... 76
Figure 31. Moisture density relationships for FA6 ... 76
Figure 32. Moisture density relationships for CA6G... 77
Figure 33. Gravimetric moisture content vs. Microwave value – Edward Till... 78
Figure 34. Gravimetric moisture content vs. Microwave value – Kickapoo Clay... 78
Figure 35. Gravimetric moisture content vs. Microwave value – Kickapoo Topsoil ... 79
Figure 36. Gravimetric moisture content vs. Microwave value – FA6... 79
Figure 37. Gravimetric moisture content vs. Microwave value – CA6G ... 80
Figure 38. Continuous microwave sled and oven dry spot tests on Edward Till – Wet side... 81
Figure 39. Continuous microwave sled and oven dry spot tests on Edward Till – Dry side ... 82
Figure 40. Continuous microwave sled and oven dry spot tests on Kickapoo Clay – Wet side... 82
Figure 41. Continuous microwave sled and oven dry spot tests on Kickapoo Clay – Dry side ... 83
Figure 42. Continuous microwave sled and oven dry spot tests on Kickapoo Topsoil – Wet

side 83
Figure 43. Continuous microwave sled and oven dry spot tests on Kickapoo Topsoil – Dry side 84
Figure 44. Continuous microwave sled and oven dry spot tests on FA6 – Wet side 84
Figure 45. Continuous microwave sled and oven dry spot tests on FA6 – Dry side 85
Figure 46. Continuous microwave sled tests on Edward Till – Wet side 85
Figure 47. Continuous microwave sled tests on Edward Till – Dry side 86
Figure 48. Continuous microwave sled tests on Kickapoo Clay – Wet side 86
Figure 49. Continuous microwave sled tests on Kickapoo Clay – Dry side 87
Figure 50. Continuous microwave sled tests on Kickapoo Topsoil – Wet side 87
Figure 51. Continuous microwave sled tests on Kickapoo Topsoil – Dry side 88
Figure 52. Continuous microwave sled tests on FA6 – Wet side 88
Figure 53. Continuous microwave sled tests on FA6 – Dry side 89
Figure 54. Distance vs. Microwave value /Moisture Content-Kickapoo Clay-Slow sled movement-1 on air dry bed 89
Figure 55. Time vs. Microwave value -Kickapoo Clay-Slow sled movement-1 on air dry bed... 90
Figure 56. Distance vs. Microwave value/ Moisture content -Kickapoo Clay-Slow sled movement-2 on air dry bed 90
Figure 57. Time vs. Microwave value -Kickapoo Clay-Slow sled movement-2 on air dry bed... 91
Figure 58. Distance vs. Microwave value/ Moisture content -Kickapoo Clay-Slow sled movement-3 on air dry bed 91
Figure 59. Time vs. Microwave value -Kickapoo Clay-Slow sled movement-3 on air dry bed... 92
Figure 60. Distance vs. Microwave value / Moisture content -Kickapoo Clay-Fast sled movement on air dry bed 92
Figure 61. Time vs. Microwave value -Kickapoo Clay-Fast sled movement on air dry bed 93
Figure 62. Distance vs. Microwave value/ Moisture content -Kickapoo Topsoil-Slow sled movement on air dry bed 93
Figure 63. Time vs. Microwave value -Kickapoo Topsoil-Slow sled movement on air dry bed . 94
Figure 64. Distance vs. Microwave value / Moisture content -Kickapoo Topsoil-Fast sled movement on air dry bed 94
Figure 65. Time vs. Microwave value -Kickapoo Topsoil-Fast sled movement on air dry bed... 95
Figure 66. Distance vs. Microwave value/ Moisture content –FA6-Slow sled movement on air dry bed 95
Figure 67. Time vs. Microwave value –FA6-Slow sled movement on air dry bed 96
Figure 68. Distance vs. Microwave value / Moisture content –FA6-Fast sled movement on air dry bed 96
Figure 69. Time vs. Microwave value –FA6-Fast sled movement on air dry bed 97
Figure 70. Moisture content vs. Microwave Value – Edward Till - Spot tests 97
Figure 71. Moisture content vs. Microwave Value – Kickapoo Clay - Spot tests 98
Figure 72. Moisture content vs. Microwave Value – Kickapoo Top soil - Spot tests 98
Figure 73. Moisture content vs. Microwave Value – FA6 - Spot tests 99
Figure 74. Predicted vs. Measured Moisture content– Edward Till 101
Figure 75. Predicted vs. Measured Moisture content– Kickapoo Clay 101
Figure 76. Predicted vs. Measured Moisture content– Kickapoo Top soil 102
Figure 77. Predicted vs. Measured Moisture content– FA6 102

Figure 78. Predicted vs. Measured Moisture content– All soils 103
Figures 79(a-l): Accuracy and Precision tests.. 109
Figure 80. Microwave Value vs. Moisture Content – Loess.. 110
Figure 81. Microwave Value vs. Moisture Content – Edward Till.. 110

LIST OF TABLES

Table 1. Evaluation of volumetric moisture content using TDR measurements 7
Table 2. Slope comparisons 15
Table 4. Atterberg limits 33
Table 5. Gradation analysis 33
Table 6. Soil classifications 33
Table 7. Specific gravities 34
Table 8. Atterberg limits 41
Table 9. Gradation analysis 42
Table 10. Soil classifications 42
Table 11. Gravimetric moisture contents and Microwave values 43
Table 12. Atterberg limits 44
Table 13. Gradation analysis 45
Table 14. Soil classifications 45
Table 15. Specific gravities 45
Table 16. Moisture contents and Microwave values of Loess and Glacial Till 46
Table 17. Atterberg limits 53
Table 18. Gradation analysis 53
Table 19. Soil classifications 53
Table20. Moisture contents and Microwave values - Glacial Till, Loess, and Gumbo 54
Table 21. Moisture contents and Microwave values for Mixed soil at the creek 54
Table 22. Atterberg limits 59
Table 23. Gradation analysis 60
Table 24. Soil classifications 60
Table 25. Moisture contents and Unit weights of samples tested 60
Table 26. Microwave values of sample at different heights placed on steel plate: 62
Table 27 Compaction Processes adopted for Tests 6 69
Table 28. Atterberg limits 73
Table 29. Gradation analysis 73
Table 30. Soil classifications 74
Table 31. Specific gravities 74
Table 32. Significance Tests on Different Models 100
Table 33. Model Coefficients 100
Table 34. Statistical Analysis of Accuracy and Precision Test Data 109

ABSTRACT

Real-time knowledge of soil moisture content and its variability during earthwork construction operations could have tremendous impact on process control (i.e. fill placement, disking, compaction, etc.) and the resulting fill quality. A means of rapidly determining soil moisture content using an off-the-shelf microwave sensor (Hydronix Hydro-Mix VI) is described in this report. The sensor provides an analogue output of 4 to 20 mA and is scaled to report zero in air and 100 in water. The sensor is placed in contact with the soil and has a measure up to about 100 mm. The sampling rate is 25 Hz, but usually takes 2 to 3 seconds to stabilize. The operating temperature is 0 to 60˚C.

The purpose of this phase of the study was to develop relations between the microwave value (MV) and gravimetric moisture content of the soil in the laboratory, although some field tests were also performed. Tests were performed using several different soil types at different compaction efforts and at a wide range of moisture contents on the wet and dry sides of "optimum" moisture contents. The MV values from the sensor are correlated with oven dry moisture contents. In short, low values of standard deviation, standard error and coefficient of variation in the microwave data indicate that the precision in the measurements is high. Microwave sensor proved to be a very useful instrument for fast and accurate soil moisture content determination. The findings are promising and warrant further evaluation and development.

Some of the key findings and observations from the study are as follows:

- The standard laboratory mold dielectric is found to have a significant effect on the MVs and should not be used for laboratory calibration.
- The MV value is sensitive to small changes in contact area of the sensor. The maximum allowable change in surface area of a specimen compacted on the wet of optimum is found to be 3cm^2.
- The height up to which the steel plate dielectric affects a microwave value of an extracted soil specimen resting on the plate is about 50 mm.
- The suitability of the microwave sensor for five different soils, namely Edward Till, Kickapoo Clay, Kickapoo Topsoil and FA6 and CA6G were studied both at ISU

laboratory and in the test beds at Caterpillar's soil mechanic lab. Regression analysis showed that R^2 values from linear relationships ranged from 0.87 to 0.98.

- Statistical models were developed based on soil type using the laboratory data. MV and MV^2 terms proved to be the most significant parameters affecting the models — dry density and various soil index parameters were also considered and in soe cases were significant. Using just the MV terms in the statistical analysis results in predication models can be improved.
- Accuracy and precision tests on Edwards till samples compacted at -3%, 0%, and +2% of standard Proctor optimum moisture content produced standard deviations of 0.4 to 0.6%. The standard error of the mean was 0.06 to 0.08%. For Loess samples compacted at -3%, 0%, and +2% of standard Proctor optimum moisture content, the standard deviations varied from 0.2 and 0.3%and the standard errors are from 0.03 to 0.05. At a 95% confidence interval the predictions are within ±1%, which meeting the target established for this research.

The low values of standard deviation, standard error and coefficient of variation in the microwave data indicate that the precision in the measurements is high. Microwave sensor proved to be a very useful instrument for fast and accurate soil moisture content determination.

INTRODUCTION

Conventional approaches for measuring soil moisture content include gravimetric sampling, time-domain reflectometry (TDR), and neutron probes, all of which are time-consuming and invasive. In this study a non-destructive microwave sensor was evaluated for rapid determination of soil moisture content. This equipment works on the principle of *electromagnetic aquametry*. Microwave/electromagnetic aquametry (measurement of moisture content) is a nondestructive technique for determining moisture content of material. The basic principle of the technique consists of measuring the electrical properties of the material and relating those properties to the moisture content. The moist soil is placed in the path of an electromagnetic wave and a relationship between the propagation constant and the amount of water is determined.

The microwave sensor used in this study is the Hydro Mix-VI model manufactured by Hydronix (http://www.hydronix.com/ hydromix6.html). This sensor was originally developed for use in water content analysis of Portland cement concrete mixtures. The microwave sensor output is an unscaled value of 0 (air) to 100 (water).

Goal

The ultimate goal of the broader research effort of this study is to develop a sensor that can be fitted to a machine and used to rapidly determine soil moisture content during earthwork operations with an accuracy of about ±1% (based on gravimetric moisture content).

Objectives

The specific objectives of this study were to:

- Evaluate the suitability of using the Hydro VI microwave sensor in the laboratory for a range of different soil types to predict gravimetric soil moisture content;
- Develop statistical models for predicting moisture content of individual soil types and a combined model with microwave value and other soil index parameters as variables;

- Test the accuracy and precision of the microwave sensor; and
- Investigate implementation of the sensor for field applications.

Significance/Benefit

Test methods D2216 and D4959 are the most popular standards of ASTM for determination of moisture content of soil. (Moisture Content by oven-drying (D2216) or by direct heating (D4959)). An oven or direct heat are generally used for drying the soil and the difference in the mass of the sample before and after drying will give the moisture content present in the soil sample. The principal objection to the use of the direct heating for moisture content determination is the possibility of overheating the soil, thereby yielding moisture content higher than would be determined by test method D2216. The use of test method D2216 can be time consuming and there are occasions when a more expedient method is desirable. ASTM D 3017 [Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)] is perhaps the most common field method for soil moisture content determination but is limited to spot test measurements and is highly regulated due to the radioactive source. ASTM D4944 [Standard Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester] is another alternative, but requires use of calcium carbide and chemically treating the soil. Only a small value of soil is tested in this method.

Because of the particular properties of microwave radiation (frequencies between 1 and 100 GHz), this method as described in the following has some advantages over the above mentioned conventional methods.

- Contrary to lower frequencies, the direct current (dc) conductivity effect on material properties can be neglected.
- Penetration depth is much larger than that of infrared radiation and permits the probing of a significant volume of material.
- Physical contact between the equipment and the material under test is not required, allowing on-line continuous and remote moisture sensing.

- In contrast to infrared radiation, it is relatively insensitive to environmental conditions, thus dust and water vapor in industrial facilities do not affect the measurement.
- In contrast to ionizing radiation, microwave methods are much safer and faster.
- Water reacts specifically with certain frequencies in the moisture region (relaxation) allowing even small amounts of water to be detected.
- Contrary to chemical methods, it does not alter or contaminate the test material, thus the measurement is non destructive.

These features combined with great potential savings in fuel, energy, manpower and improvement of the quality of earth fill resulting from the application of moisture content measurement and control, created a powerful incentive for research and innovations in equipment development.

Forecasting

Research is done in the past to study the electromagnetic wave interactions with water and aqueous solutions; Impact of dielectric constant on moisture content; Use of elastic and electromagnetic waves to evaluate the water content and mass density of soils; Use of a moisture sensor for monitoring the effect of mixing procedure on uniformity of concrete mixtures. Experiments relating to the microwave dielectric behavior of wet soils are conducted by Martti T. Hallikainen et al. and empirical models were developed. Much work on the use of these sensors particularly in soils is not found. This study prompted some research to evaluate the use of these sensors for soil moisture content determination.

Evaluation of the microwave sensor was performed in seven experimental stages using compacted samples over a wide range of moisture contents. A brief description of the experiments is as follows:

1. In the first stage, relationships between microwave value (MV) and gravimetric and volumetric moisture contents were developed.
2. In the second stage, the effect of the compaction mold dielectric on the MVs was studied. This showed that the material dielectric played some influence on the MVs.

Tests were then performed on the extracted samples to eliminate the material dielectric influence and better simulate the field condition.

3. In the third stage of experiments the suitability and behavior of the sensor in different soil types was studied.
4. The sensor response in the field was compared with its response under laboratory conditions in the fourth stage for a limited number of samples. These comparisons led to insights concerning soil-sensor contact and the effects of voids in the soil surface.
5. The height up to which a steel plate material dielectric influences the MV was studied in the fifth stage. Laboratory and spot microwave tests were carried out on five different soil types and statistical models were developed.
6. In the sixth stage, variables including compaction energy, dry unit weight and some interactive terms were tested for significance. The inclusion of a MV squared term in the model proved better in the case of one soil. Other variables like liquid limit, plastic limit, percent passing no.4 sieve, percent passing no. 10 sieve and percent passing no. 200 sieve were not included in the model due to limited data (five soil types). In the future, if tests are extended to additional soil types, these variables can be tested for inclusion in soil specific MV models.
7. The accuracy and precision of the microwave sensor instrument was evaluated in the seventh stage. Low values of standard deviations, standard error of the means and coefficient of variations for samples compacted at optimum moisture content, -3% and +2% of optimum moisture content demonstrates the potential of this sensor for accurate moisture content measurements.

BACKGROUND

The requirement for any tool or instrument is that it has to be relatively inexpensive, portable, accurate, easy to use, immediate display of results and have a visual display that is easily understood. The use of microwave sensor for soil moisture content measurement is a non-destructive technique. Typical non-destructive techniques for determining moisture content in material consist of measuring the electrical properties of the material in a sample holder and relating these properties to the moisture content. These techniques have their roots at the beginning of the twentieth century when the possibility of rapid determination of moisture content in grain by measuring the direct current (dc) resistance between two metal electrodes inserted into the grain sample was established. This resistance was found to vary with moisture content. Later samples of wet material were placed in the path of an electromagnetic wave between two horn antennas and the simple relationship between propagation constant and the amount of water was easily determined. Many methods of soil moisture have been developed, from simple manual gravimetric sampling to more sophisticated remote sensing and Time Domain Reflectometry (TDR) measurements.

A great deal of work was done using sensor technique to study properties of various materials like concrete, the study of the electromagnetic wave interactions with water and study of the dielectric influence on the moisture content.

Wang and Hu (2005) studied the use of a moisture sensor for monitoring the effect of mixing procedure on uniformity of concrete mixtures. A given concrete mix was subjected to three different mixing procedures. A moisture sensor was installed inside a pan mixer to monitor moisture content during mixing. The moisture sensor used in this case works on the microwave reflection concept. During mixing, the sensor recorded the moisture content of the concrete mixture at a speed of four readings per second. The concrete mixtures were considered as uniformly mixed when stable moisture content was detected by the moisture sensor. The effectiveness of the mixing procedures and their effects on concrete workability, strength and microstructure were also examined in this study. They concluded that the moisture sensor used provided reliable test results describing moisture distribution in concrete mixtures. The sensor readings well captured the subtle changes, such as the loading sequence of concrete materials, in the concrete mixing process.

Another promising technique for moisture content determination is the Purdue TDR method developed by Drnevich and co-workers (Siddiqui and Drnevich 1995; Lin et al. 2000; ASTM D6780-02). The Purdue TDR method utilizes data collected with the Time domain reflectometry (TDR) technique to estimate the soil water content and density. TDR is a technology that was originally developed in electrical engineering for locating breakages in electrical cables. It was later used to measure material dielectric spectra as the signal contains a broad frequency band response of the material under the excitation of a fast rising electrical pulse (Fellner-Fellnegg 1969). Topp et al.1980 established a universal equation which is widely used in engineering practice. Subsequent research has significantly increased the understanding of TDR principles. It involves driving four spikes into the soil surface using a template (Drnevich et al. 2003, Yu and Drnevich 2004). Then, a multiple-rod-head-probe TDR system is placed on the top of the spikes to measure the electromagnetic wave properties. The measurement procedure also includes extracting a soil specimen, placing it in a compaction mold, and measuring electromagnetic wave properties as a way to calibrate the measurements. Based on the two sets of measurements, the water content and the density are calculated.

Using non-destructive techniques like TDR, one can measure conductivity and permittivity of a given soil and for calibrated equations the porosity and volumetric water content may be estimated (Jones et al. 2001; Noborio 2001). That is, if electrical conductivity measurements are used, the results may be correlated to volumetric water content; and if dielectric permittivity is measured, two unknown parameters may be inverted for: porosity and volumetric water content. The major limitation with this analysis is that the dielectric permittivity measurements have been traditionally correlated to volumetric water content (Table 1). The main assumption in this method is that the insitu soil and the compacted soil are the same, and that the water content does not vary throughout the testing site. Such an assumption and the fact that the soil specimens must be removed at regular intervals could limit the applicability of this methodology.

Table 1. Evaluation of volumetric moisture content using TDR measurements

Researcher	Equation
Topp et al. (1981)	$\theta_v = -5.3.10^{-2} + 2.92.10^{-2}.k - 5.5.10^{-4}.k^2 + 4.3.10^{-6}.k^3$
Mixture equation (β~0.5)	$\theta_v = \dfrac{k^{\beta} - (1-n).k_s{}^{\beta} - n.k_a{}^{\beta}}{k_w{}^{\beta} - k_a{}^{\beta}}$
Maliki et al. (1996)	$\theta_v = \dfrac{\sqrt{k} - 0.819 - 0.168.\rho - 0.159.\rho^2}{7.17 + 1.18.\rho}$

Source: Topp et al. (1981); Benson and Bosscher (1999); Jones et al. (2001); Noborio (2001)

Where θv = Volumetric moisture content
ks, kw and ka = relative dielectric permittivity of solid, water and air phases respectively
β = experimentally determined parameter
n = porosity
ρ = soil density

Topp GC, Davis JL and Annan AP studied the electromagnetic determination of soil water content by measurements in coaxial transmission lines. In their study, the dependence of the dielectric constant, at frequencies between 1 MHz and 1 GHz, on the volumetric water content was determined empirically in the laboratory. The effect of varying the texture, bulk density, temperature, and soluble salt content on this relationship was also determined. Time-domain reflectometry (TDR) was used to measure the dielectric constant of a wide range of granular specimens placed in a coaxial transmission line. The water or salt solution was cycled continuously to or from the specimen, with minimal disturbance, through porous disks placed along the sides of the coaxial tube. Four mineral soils with a range of texture from sandy loam to clay were tested. An empirical relationship between the apparent dielectric constant K sub and the volumetric water content theta sub v which is independent of soil type, soil density, soil temperature, and soluble salt content, can be used to determine theta sub v from air dry to water saturated, with an error of estimate of 0.013. Precision of theta sub v to within +0.01 from K sub can be obtained with a calibration for the particular granular material of interest. An organic soil, vermiculite, and two sizes of glass beads were also tested successfully. They concluded that the results of applying the TDR technique on parallel transmission lines in the field to measure theta sub v versus depth were encouraging (Sims-ISWS).

Bashar Alramahi[1], Khalid A. Alshibli[2] and Dante Fratta[3] studied the use of elastic and electromagnetic waves to evaluate the water content and mass density of soils. The approach helps relating volumetric water content to stiffness and hints to the use of the technique for non-destructive evaluation of in situ water content and mass density of soils. This study also presents evidence through a numerical analysis that an alternative procedure may be used to evaluate the mass density and water content by combining dielectric permittivity and P-wave velocity of soils as the water content is increased. They concluded that the evaluation of water content and mass density in soils using new non-destructive methods must be based on solid physical properties in order to properly estimate the required parameters. A solution is obtained even when simulated measurement errors are presented both in the evaluation of volumetric water content and P-wave velocity. However, physically meaningful constraints should be incorporated to facilitate the convergence of the solution for field applications.

Xiong Yu and Vincent P. Drnevich (2004) presented a new method for determining the soil water content and dry density using a single time domain reflectometry test. Promotion of TDR technology for soil moisture monitoring is largely attributed to Topp et al. (1980) who established a relation between soil volumetric water content and soil apparent dielectric constant. Geotechnical applications require the gravimetric water content, w, i.e., mass of water compared to mass of dry soil solids. Gravimetric water content is related to volumetric water content, by the dry density of the soil, which generally is not measured with presently used TDR methods. The method proposed in this study is based on simultaneous measurements of apparent dielectric constant and bulk electrical conductivity on the same soil sample. Calibration equations correlate these two parameters with soil gravimetric water content and dry density, which are simultaneously solved after adjusting field-measured conductivity to a standard conductivity. This method compensates for temperature effects. The test process takes about 3 min and all calculations are automated. Testing may be done in situ using a special probe that provides sufficient sampling volume or in a compaction mold adapted to form a probe.

Use of this new one-step TDR method requires laboratory calibration and field testing procedures. Given below are the equations formulated and used in their study.

$$\left.\begin{aligned} K_{a,20^oC} &= K_{a,f}.TCF \\ EC_{b,adj} &= (f + g.K_{a,20^oC})^2 \end{aligned}\right\} \rightarrow \quad \begin{aligned} w &= \frac{c\sqrt{K_{a,20^oC}} - a\sqrt{EC_{b,adj}}}{b\sqrt{EC_{b,adj}} - d\sqrt{K_{a,20^oC}}} \\ \rho_d &= \frac{d\sqrt{K_{a,20^oC}} - b\sqrt{EC_{b,adj}}}{ad - cd}\rho_w \end{aligned}$$

Where a, b, c, d, f and g = soil specific calibration constants obtained from laboratory compaction tests.
ρ_d = dry density of soil
ρ_w = density of water
w = gravimetric water content
Ka = apparent dielectric constant of the soil
Eb,adj = bulk electrical conductivity of the soil
TCF = Temperature compensation factor

The major limitation for this method is that it cannot be used for certain fine-textured soils such as fat clays at very high water contents because no significant second reflections (reflections from the probe end) are observed and the apparent dielectric constant cannot be measured.

Another common technique is to measure dielectric constant, the capacitive and conductive parts of a soil's electrical response. Through the use of appropriate calibration curves, the dielectric constant measurement can be directly related to soil moisture (Topp et al. 1980). Dielectric constant can be measured in a variety of ways. Soil moisture probes, designed to be buried and left in-situ, are commercially available. Satellites such as RADARSAT, using synthetic aperture radar, can indirectly measure the dielectric constant of the soil due to its direct effect on microwave backscatter (Henderson and Lewis ed. 1998). Because the soil probes and radar both measure dielectric constant, less error is introduced when comparing one to the other. Soil moisture may also be remotely sensed using a passive microwave radiometer such as AMSR-E, which covers a larger footprint than RADARSAT, and uses an algorithm based on a radiative transfer model, rather than dielectric constant to determine the soil moisture (Njoku 1999). Remote sensing instruments can produce measurements of surface (from a few mm to ~5cm depth) soil moisture at a large spatial scale but only at occasional times, while in-situ sensors measure soil moisture at a point, can be installed at depth (>5cm) in the soil matrix, and can sample nearly continuously.

Jeffrey Kennedy, Tim Keefer, Ginger Paige and Frank Barnes evaluated the dielectric constant based soil moisture sensors in a semiarid rangeland. Soil moisture probes (Vitel probes) were used for the study over a twelve month period. Their aim was to assess the accuracy of dielectric constant based soil moisture probes through comparison with gravimetric samples and to investigate soil water redistribution following precipitation events in winter and summer. Their study proved that these probes quickly responded to the changes in soil moisture, and with appropriate calibration and/or correction, accurately measure soil water content.

Peter J. van Oevelen and Dirk H. Hoekman, IEEE studied the radar backscatter inversion techniques for estimation of surface soil moisture. They applied a semi empirical model from Oh et at., 1992 and a numerical inversion of the Integral Equation Model (IEM) model, introduced as "INVIEM" to retrieve soil moisture over bare soil surfaces from active microwave data. The range of soil moisture values estimated by INVIEM model is in agreement with the soil moisture variation found in the field. They presented a general framework to estimate soil moisture from microwave backscatter measurements. This framework consists of five different steps, each describing a different relationship. The first three steps are useful to obtain a soil moisture estimate from microwave backscatter measurements. These steps describe the relationship between surface parameters and backscatter coefficient, the influence of vegetation on this relationship, and the influence of dielectric properties and retrieval of effective water content. The last two steps are necessary for a correct interpretation and application of the soil moisture estimates. They recommended that more research needs to be done to explore the sensing depth at various frequencies under actual field conditions.

Several experimental programs have been conducted over the past several years in order to determine the dielectric behavior of soil-water mixtures in the microwave region. Additionally several attempts have been made to model this dielectric behavior throught the use of dielectric mixing formulas. An examination of these investigations leads to the following observations:

- Inconsistencies exist between experimental measurements reported by different investigators, both in terms of the absolute level of the relative dielectric constant (versus water content) for similar soil textures and in terms of the dependence of dielectric constant on soil texture. Hoekstra and Delaney and Dvis et al., for example conclude that on the basis of their respective measurements, soil textural composition has a very minor influence on the dielectric constant of wet soil. In contrast, the data reported by other investigators, particularly those of Wang, Lundien and Newton, show significant differences in the magnitude of dielectric constant for different soil types (at the same volumetric moisture content). Experimental differences in sample composition, sample preparation, and measurement procedures make it difficult to reconcile these inconsistencies in the data.
- Although each of the reported experimental data sets shows that dielectric constant exhibits an upward trend with increasing soil moisture content, most of the data exhibit a fair amount of scattering about the best-fit curve. Additionally, some of the reported results indicate that the curve for the real part of the complex dielectric constant, as a function of increasing moisture content, has a tendency to level off for large values of moisture content. This behavior has been attributed by Wang to leakage of soil water from the apparatus when the water content approaches the porosity of the soil sample.
- Many microwave dielectric models are developed for soil-water mixtures. The models developed by Martti T. Hallikainen et al. are discussed below.

Martti T. Hallikainen et. al. studied the microwave dielectric behavior of wet soil and presented in two parts. In the first part, they evaluated the microwave dielectric behavior of soil-water mixtures as a function of water content, temperature, and soil textural composition. They presented the results of dielectric constant measurements conducted for five different soil types at frequencies between 1.4 and 18GHz. They considered the soil medium, electromagnetically as a four component dielectric mixture consisting of air, bulk soil, bound water (water molecules contained in the first few molecular layers surrounding the soil particles and are tightly held by the soil particles due to the influence of matric and osmotic forces) and free water (water molecules located several molecular layers away from soil particles). Due to the high intensity of the forces acting upon it, a bound water molecule interacts with an incident electromagnetic wave in a manner dissimilar to that of a free water molecule, thereby exhibiting a dielectric dispersion spectrum that is very different from that of free water. The complex dielectric constants of bound and free water are explained as functions of the electromagnetic frequency f, the physical temperature and the salinity S. The dielectric constant of the soil mixture is hence considered to be a function of f, T and S; the total volumetric water content and the relative fractions of bound and free water, which are related to the soil surface area per unit volume; the bulk soil density; the shape of the soil particles and the shape of the water inclusions.

Their study mainly aimed at conducting dielectric constant measurements with a high degree of accuracy and precision over the 1-to-18GHz region for several soil types and developing a dielectric constant based model based on specific soil physical characteristics. Two measurement techniques were adopted, waveguide transmission technique for the 1-2 and 4-6 GHz bands and free space transmission technique for measurements at frequencies between 4 and 18 GHz. In order to test the comparative accuracy and precision of the two measurement techniques, soil samples were measured using both techniques at 6 GHz and then compared. The dielectric constant behavior is explained as follows. At frequencies less than 5 GHz, the effective ionic conductivity of the soil solution is dominant, whereas at higher frequencies, the dielectric relaxation of water is the principal mechanism contributing to loss. Individual polynomial equations were generated for dielectric constants as a function of volumetric moisture content for each frequency and soil type. Measured and Predicted dielectric constants were compared to evaluate the goodness of fit.

They concluded that soil texture has an effect on dielectric behavior over the entire frequency range and is most pronounced at frequencies below 5GHz. The dielectric data as measured at room temperature are summarized at each frequency by polynomial expressions dependent upon both the volumetric moisture content and the percentage of sand and clay contained in the soil.

In Part-II, two dielectric mixing models are presented to account for the observed behavior: a semi empirical refractive mixing model that accurately describes the data and only requires volumetric moisture content and soil texture as inputs, and a theoretical four-component mixing model that explicitly accounts for the presence of bound water.

T.E.Harms studied the various Soil Moisture monitoring devices for incorporating successful irrigation management. For this study, five soil moisture monitoring devices were tested at 10 sites within the eastern irrigation district. The soil moisture instruments were chosen to represent variation in methods of determining soil moisture and installation (Figure 1). The five instruments tested were the Hydrosense, Theta Probe, R.F. Soil Moisture Sensor (name has been changed to AP Moisture Probe), AM400 and Watermark.

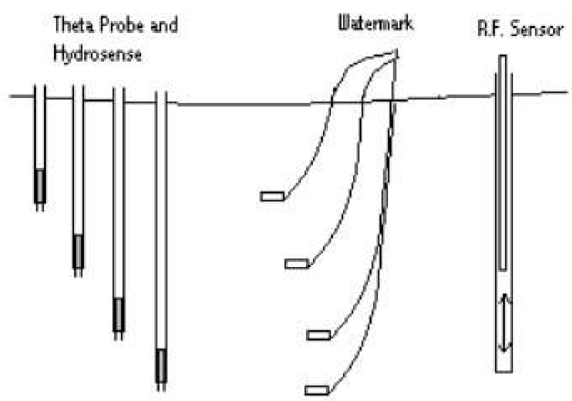


Figure 1. Methods of installation for soil moisture determination (Harms)

The Hydrosense probe manufactured by Campbell Scientific Inc. uses a soil property called dielectric permittivity to estimate volumetric moisture content. A high frequency electromagnetic wave pulse travels the length of a pair of rods (either 12 or 20 cm) inserted in the soil and returns to a sensor. The time it takes for the wave to complete the travel is an indication of the dielectric permittivity of the soil. The readout of the Hydrosense can be either in volumetric moisture content percentage (VMC%) or relative water content when calibrated for field capacity and wilting point. The readout displays relative water content from 0 to 100% of available and also how much additional water (mm) is required to bring the depth of monitoring up to field capacity; sometimes referred to as deficit. A major disadvantage with this probe is that the values for VMC% at field capacity and wilting point are required to convert VMC% reading to percent available moisture.

The ThetaProbe manufactured by Delta-T uses a similar concept as the Hydrosense probe by sensing the apparent dielectric constant of the soil to estimate volumetric water content. The ThetaProbe has a configuration of 3 rods surrounding a center rod, all of which are inserted into the soil. The difference between voltage at a crystal oscillator (enclosed in the body of the probe) and that reflected by the rods is used to determine the dielectric constant of the soil. The readout from the Theta Probe is VMC%. It has the same disadvantage as Hydrosense probe.

The R.F. soil moisture sensor, also termed the AP Moisture Probe manufactured by AquaPro measures the dielectric coefficient of the soil using radio frequency waves. Soil moisture measurements can be taken at any number of locations to any depth. This unit is a profiling probe meaning it is lowered into a polycarbonate tube that has previously been inserted into the soil. The polycarbonate tubes come in 1 meter lengths but can be extended to 2 meter or greater lengths by connecting them together. The readout from the R.F. sensor is percent available moisture. It has installation difficulty in clay-textured soils.

The Watermark™ sensor manufactured by Irrometer works on the principle of electrical conductivity of moist gypsum, which is strongly dependent on the water tension. The sensor consists of a matrix of granular material and two electrodes embedded in gypsum. As water is "pulled" from the matrix, the electrical resistance between the two electrodes increases. The probes are buried and two leads from the electrodes are connected to a handheld meter during readout. The readout is in centibars (a unit of soil tension) and to properly convert or interpret this value as VMC% or percent available, a soil water characteristic curve must be constructed for the specific soil.

The AM400 is not a soil probe but a data logger that uses the Watermark™ sensor as the soil probe component. The Watermark™ sensors are buried into the soil and the leads are connected to the AM400. The logger records soil moisture readings from the Watermark™ sensors (up to 6 individual sensors can be connected to the logger) every eight hours and graphically displays the readings from the sensors showing five weeks of soil moisture readings. The logger displays soil tension in centibars and similar to the Watermark™, a soil water characteristic curve is required to convert soil tension to volumetric moisture content. The conversion of the readings from centibars to available moisture content percentage is quite difficult. A soil characteristic curve has to be constructed to relate soil tension readings to the corresponding VMC%.

Comparisons were made between the weekly neutron probe readings and weekly soil moisture sensor readings at the various locations. Average difference in slope of the least squares regression line of the natural logarithm of weekly available soil moisture percentages between the neutron probe and the various instruments is shown in Table 2.

Table 2. Slope comparisons

Sensor	Average difference in slope compared to neutron probe.
Hydrosense	0.11
ThetaProbe	0.07
R.F. Sensor (AP Moisture Probe)	0.01
Watermark	0.12

Gurdev Singh, Braja M.Das and M.K.Chong studied the measurement of moisture content with a penetrometer. The basic principle described by them is that an increase in volumetric water content causes an increase in the dielectric constant (the ratio of the capacitance of a device whose plates are separated by a given substance to capacitance of a similar device whose plates are separated by a vacuum) of the soil. Because the dielectric constant of water is much higher than that of dry soil, the dielectric constant of moist soil increases markedly with the volume fraction of water present. At low frequencies (below 1 MHz), the dielectric constant is dependent on conductivity. The conductivity though increases with water content, is much more dependent on soil type and therefore not a satisfactory parameter for determining moisture content. They concluded that with the incorporation of a dielectric probe into a penetrometer, it is possible to determine the insitu moisture content of soils from the capacitance change measured at very high frequencies. The method presents particular promise because the moisture content versus capacitance relationship is independent of soil type.

From the above discussion on the works done by various researchers, it is understood that much work was done using sensor technique to study the moisture content of various materials like concrete. Some subjects like the dielectric influence on the soil moisture content and the electromagnetic wave interactions with water in the soil are also established by various researchers.

The present study was motivated by the limitations previously outlined upon the current usage of the sensors as soil moisture monitoring tools. The research done by Wang and Hu on the use of Hydromix sensors for determining the moisture content and monitoring the effect of mixing procedures on the uniformity of concrete mixtures prompted working towards the development of such sensors with a similar working technique in soils.

DESCRIPTION OF THE EQUIPMENT

Microwave sensor

The sensor used for this study is the Hydromix VI, manufactured by Hydronix. It was originally developed for using in water content analysis during mixing of Portland cement concrete. The Hydro-Mix VI digital microwave moisture sensor with integral signal processing provides a linear output (both analogue and digital). The sensor may be easily connected to any control system and is ideally suited to measure the moisture of materials in mixer applications as well as other process control environments.

The sensor reads at 25 times per second, this enables rapid detection of changes in moisture content in the process, including determination of homogeneity. The sensor may be configured remotely when connected to a PC using dedicated Hydronix software. A large number of parameters are selectable, such as the type of output and the filtering characteristics.

Sensor output variables

These define which sensor readings the analogue output will represent. The Filtered/Unscaled output is a reading which is proportional to moisture and ranges from 0 – 100. This is the recommended setting**.** The Filtered Moisture output is the alternative setting. This is derived from the unscaled reading by scaling it with a set of material calibration coefficients. These are the A, B, C and SSD (saturated surface dry) values in the configuration which in nearly all cases are not set for the specific material being measured. If A, B and C values are not specifically set for the material, then the Filtered Moisture output will not represent actual moisture.

The sensor may be configured to output a linear value between 0-100 unscaled units with the recipe calibration being performed in the control system. Alternatively it is also possible to internally calibrate the sensor to output a real moisture value. In this study the sensor is set to filtered/unscaled output.

Filtered Unscaled

The Filtered Unscaled is derived from the raw unscaled processed using the filtering parameters in the 'Signal Processing' frame in the configuration page. An unscaled value of 0 is the reading in air and 100 would relate to a reading in water.

Filtering

In practice, the raw output, which is measured 25 times per second, contains a high level of 'noise' due to irregularities in the signal from pockets of air. As a result, this signal requires a certain amount of filtering to make it usable for moisture control. The default filtering settings are suitable for most applications; however they can be customized if required to suit the application. The ideal filter is one that provides a smooth output with a rapid response. The raw moisture % and raw unscaled settings should not be used for control purposes. To filter the raw unscaled reading, the following parameters are used:

Slew rate filters

These filters set rate limits for large positive and negative changes in the raw signal. It is possible to set limits for positive and negative changes separately. The options for both the 'slew rate +' and the 'slew rate –' filters are: None, Light, Medium and Heavy. The heavier the setting, the more the signal will be 'dampened' and the slower the signal response.

Filtering time

This smoothes the slew rate limited signal. Standard times are 0, 1, 2.5, 5, 7.5, and 10 seconds, although it is possible also to set this to 100 seconds for specific applications. A higher filtering time will slow the signal response. In this study the filtering time is set to 1 second.

Sensor Specifications

Dimensions: The sensor is circular in shape with a diameter of 108mm and length 125mm (200 including connector). The recommended minimum hole size for the sensor is 127mm.

Construction: The body of the sensor is made of stainless steel. It has a ceramic face plate and a hardened steel wear ring.

Penetration of field: Approximately 75-100mm dependent upon material.

Operating temperature range: 0-60°C (32-140°F). This sensor will not work in frozen materials.

Power supply voltage: 15-30VDC. 1 A minimum required for start up (normal operating power is 4W).

The sensor specifications are shown in figure2.

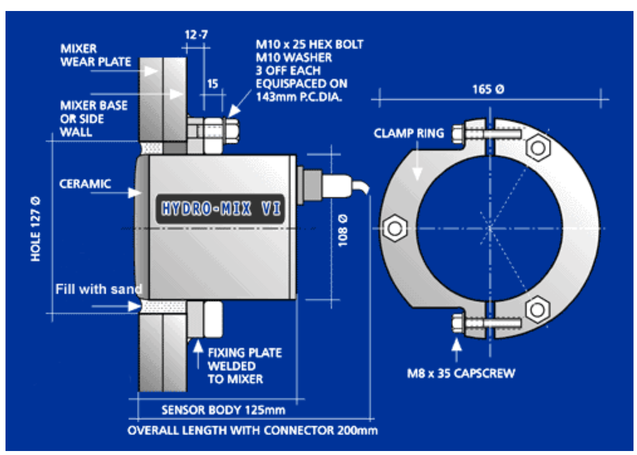


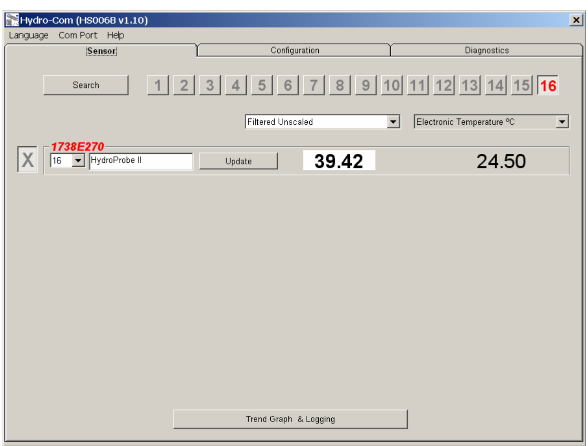
Figure2. Sensor specifications

Hydro-Com

Hydro-Com is a software tool used to configure, maintain and calibrate systems incorporating Hydronix microwave moisture sensors. The program is designed for use on PC-compatible machines running Microsoft Windows 98SE, ME, and XP.

Sensor Page

The sensor page is the default display when Hydro-Com is started. This page shows the status of all connected sensors, allows configuration of the network by renaming and readdressing sensors, and allows the readings of up to six sensors to be read simultaneously (Figure 3). This page also contains a further link to a trend graph and logging page (Figure 4) which can be used to observe long-term trends and recording sensor readings into a formatted text file.



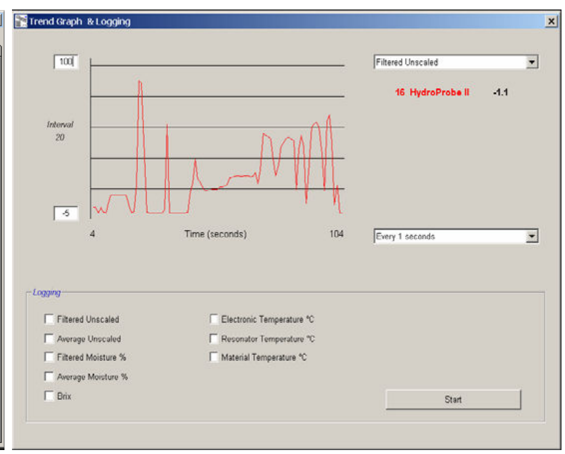


Figure 3. Sensor page

Figure 4. Trend graph and logging page

Logging to File

Sensor data can be saved to file using the ‘Start’ and ‘Stop’ buttons within the ‘Logging’ box. The specified data is logged to a text file with the file extension ‘.log’. The data in this file is formatted with tab separators so that it can be imported into a suitable program like Microsoft Excel, for further graphical analysis. Before pressing the 'Start' button the user must select which output variables to log to the file using the check boxes provided. When the start button is pressed a 'Save As' box will appear where the file name and location should be specified. Data will then be logged at the specified time interval, against both system clock time and elapsed time.

Working Principle

The Hydro-Mix VI uses the unique Hydronix digital microwave technique that provides a more sensitive measurement compared with analogue techniques. The Hydromix sensor, when placed on a soil sample, the faceplate will contact the soil. It radiates a microwave electromagnetic field of energy. Water molecules react to this field 100 times more than dry material. The sensor measures this absorbed energy and converts it into an electrical signal, which is input to the Hydro control IV, thus giving an accurate assessment of the quantity of water present in the material. Improvements in the HM05 sensor have extended the accuracy of these measurements to approximately 20% moisture content. The advantage of this technique is that it minimizes the effects of changes in density, particle size and temperature in the material.

Theory

Electromagnetic wave interactions with water and aqueous solutions

Liquid water is a regular tetrahedron structure with oxygen atom at the center, with two protons at two of its vertices, and with lone pair electrons in orbitals directed towards both other vertices.

The water molecule, due to electronic and atomic displacement polarizabilities, possesses a permanent electric dipole moment;

H-O bond --- Covalent bond

H-O-H bond --- Hydrogen bond

Only the molecules which, at a time, are non- or single- hydrogen bonded are able to rotate the direction of their permanent electric dipole moment into the direction of an external electric field and thus contribute to orientational polarization.

Microwave measurement of moisture content is an inverse problem; we measure over a more or less broad frequency range the resulting permittivity ε (v) of a composite dielectric and we want to calculate from it the volume fraction $v_1=1-v_2$ of one of the constituents, namely the water.

The moisture content of material (on a wet basis) is defined as mass of water, m_w, to the mass of moist material, m_m,

$$\xi = \frac{m_w}{m_m} = \frac{m_w}{m_w + m_d}$$

(On a dry basis) is defined as mass of water in the material to the mass of dry material, m_d,

$$\eta = \frac{m_w}{m_d} = \frac{m_m - m_d}{m_d}$$

The moisture content is related to a certain volume of material, v as follows:

$$\xi = \frac{m_w/\upsilon}{m_w/\upsilon + m_d/\upsilon} = \frac{k}{k+g} = \frac{k}{\rho}$$

k – partial density of water
g – partial density of dry material
ρ – density of moist material

$\xi = \eta / (1+ \eta)$
$\eta = \xi / (1- \xi)$
$k = m_w/v = \rho\, \xi$
$g = m_d/v = \rho\, (1-\xi) = \rho / (1+ \eta)$

Interaction of an electromagnetic wave with moist material can be expressed in terms of a complex value of the propagation constant of the wave in a dielectric medium as

$$\gamma = \alpha + j\beta = j\left(\frac{2\pi}{\lambda}\right)\sqrt{\varepsilon - p} \quad \ldots\ldots(1)$$

where ε = ε' - j ε" is the relative permittivity of the medium where,
ε' - dielectric constant

ε" - loss factor
$p = (\lambda / \lambda_c)^2$

where λ – free space wave length
λ_c – wave guide cut-off wave length

Eq.1 can be solved for two components of the propagation constant being expressed as:

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon' - p}{2}\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon' - p}\right)^2} - 1} \qquad \text{[Np/m]}$$

for the attenuation constant

And for the phase constant

$$\beta = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon' - p}{2}\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon' - p}\right)^2} + 1} \qquad \text{[rad/m]}$$

In free space, where p = 0, the following approximate expressions can be used to relate the electromagnetic wave propagation to the properties of moist materials, assuming that ε'2>> ε"2 which is valid in most practical situations,

The two components of the propagation constant are:

Attenuation constant: $\alpha \cong \frac{\pi}{\lambda}\frac{\varepsilon''}{\sqrt{\varepsilon'}}$

Phase constant: $\beta = \frac{2\pi}{\lambda}\sqrt{\varepsilon'}$

Voltage reflection coefficient from the surface of the moist material:

$$|\Gamma| = \frac{\sqrt{\varepsilon'} - 1}{\sqrt{\varepsilon'} + 1}$$

It is clear from the above that the parameters of the electromagnetic wave are affected by the material relative permittivity which in turn is related to the water content in the material.

The components of the propagation constant, α and β are dependant upon the relative permittivity of the moist material. Since relative permittivity in turn depends on moisture content ξ, density ρ, and temperature T,

$\alpha = \psi_1 (\xi, \rho, T)$ and $\beta = \psi_2 (\xi, \rho, T)$ ………………………………………………………… (2)

The attenuation of the material sample in decibels,

$$A = 20\log|\tau| = 868\alpha d \qquad [dB]$$

Phase shift,

$$\phi = (\beta - \beta_o)d = \frac{2\pi}{\lambda}\left(\sqrt{\varepsilon'} - 1\right) + 360n \qquad [deg]$$

β_0 – phase constant in free space
n – an integer to be determined when the thickness 'd' of the material layer is greater than the wavelength in the material.
$|\tau|$ – Transmission coefficient = exp(-α d)

A= φ_1 (k,g,T) and = φ_2(k,g,T) ………………………………………………………… (3)

Solving (2) and (3), partial densities of water and dry material can be expressed in terms of measured variables:

k= ψ_1 (A, ϕ ,T) and g = ψ_2 (A, ϕ ,T)

In general, this operation known as an inverse problem can be very complex and uncertain, but in the case of moisture content in most materials, it can be quite simple.
The moisture content can be expressed as:

$$\xi = \frac{\Psi_1(\alpha,\phi,T)}{\Psi_1(A,\phi,T) + \Psi_2(A,\phi,T)}$$

which contains only the wave variables, A and ϕ, and temperature T, determined experimentally.

The test methods adopted for evaluation of the Hydromix VI microwave moisture sensor in soil moisture monitoring are presented in the next section.

TEST METHODS

The objective of this research is to develop a sensor that can be used to determine the moisture content of a soil sample with an accuracy of ±1%. The microwave sensor used in this study is the Hydro Mix-VI model manufactured by Hydronix (http://www.hydronix.com/hydromix6.html), originally developed for using in water content analysis during mixing of Portland cement concrete. The systems incorporating Hydronix microwave moisture sensors are configured, maintained and calibrated using Hydro-Com, a software tool. The program is designed for use on PC-compatible machines running Microsoft Windows 98SE, ME, and XP. The sensor has a ceramic faceplate with a diameter of 165mm which when placed on a soil records the microwave value / moisture content on to the PC attached. All Hydronix sensors may be configured to output either a real moisture % or a linear unscaled value of 0-100 unscaled units (scaleable). A linear unscaled value enables a simple material calibration in any 3rd part control system.

The evaluation of the microwave moisture sensor for its suitability and accuracy is carried out on compacted soil specimens. The purpose of a laboratory compaction test is to determine the proper amount of mixing water to be used when compacting the selected soil in the field construction to obtain the specified degree of denseness.

By using this Hydro-Com Sensor, the moisture content can be directly read in the field. For this study, Proctor Standard compaction tests are conducted on different soil types for different moisture contents and correlated with the microwave values obtained from the sensor. Grain size distribution, Atterberg limits and Specific gravity tests are conducted on all the soils used for this study. The test procedures adopted are discussed below.

Soil Classification

Gradation analysis and Atterberg limit tests were performed on each soil sample according to ASTM D 2487 [Test Method for Classification of Soils for Engineering Purposes] and ASTM D 4318 [Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils] (ASTM 2000), respectively.

Standard sized sieves, conforming to specification E11 are used for sieve analysis. Test Practices in ASTM D421-85 and ASTM D422-63 are followed for Particle – size distribution and test methods of ASTM D4318-05 are followed for determining the Atterberg limits. Wet sieve analysis is performed. The dispersion tube invented by Dr. Handy at Iowa State University is used for air-jet dispersion in Hydrometer analysis. Hydrometer 152H conforming to specifications E100 was used for testing. 125ml of sodium hexametaphosphate is used as a dispersing agent (40g/litre of solution). The dispersion agent soaking period adopted was 16h as per ASTM standards. Hygroscopic and Combined moisture Corrections are evaluated and applied. Liquid Limit is determined by Method-A, Multipoint method using Casagrande apparatus as described in ASTM D4318-05. Each soil was classified according to the Unified Soil Classification System (USCS), the AASHTO classification system, and the United States Department of Agriculture (USDA) textural classification system.

Specific Gravity

Test Practices in ASTM D854-05 [2] are followed for determining the Specific Gravity of the finer fraction. Over size fraction is excluded from the test material and corrections to dry unit weight are applied for that. Test Practices in ASTM C127 are followed for determining the over size fraction specific gravity and results are reported. * Instead of oven dry soil, soil dried by using microwave is used in this test. Procedure for oven dried specimens- Method B is followed for the specific gravity determination using a Water pycnometer. *In the deairing process, agitation time of at least 2hr is deviated and the specimen is agitated for 30min. *The pycnometers are not allowed to thermally equilibrate for 3hr. as specified in the standard. For mass determinations during specific gravity evaluation, same instrument is used in order to eliminate any variations among instruments.

Laboratory Compaction

Proctor Compaction is done on all the soils according to test specifications ASTM D698-00a$^{\epsilon 1}$ [Standard Test Method for Determining the Moisture-Density Relations of Soils and

Soil-Aggregate Mixtures] (ASTM 2000) using mechanical rammer. Based on the material gradation, suitable methods were adopted. Air dry soil is used for testing. *Corrections for the dry unit weights and for water contents of oversize fractions are not applied. The sample preparation and Compaction procedure adopted is discussed in steps (a) to (f) below.

(a) Oven dried soil was taken and sieved through #4 sieve and mixed at the selected water content. This soil was sealed to prevent loss of moisture and mellowed for 24 hours.

(b) The Proctor mold was cleaned and fitted tightly to an automatic and calibrated compaction testing machine

(c) After 24 hours, the foil was removed and the soil was mixed again thoroughly

(d) The soil was placed into the Proctor mold of given dimensions and compacted (in 3 layers of equal thickness with each layer compacted by 25 blows of a 5.5lb rammer dropped from a distance of 12-in., subjecting the soil to a compactive effort of about 12,375 ft-lbf/ft^3 - ASTM D 698, Method A for 4” mold; in 3 layers of equal thickness with each layer compacted by 56 blows of a 5.5lb rammer dropped from a distance of 12in., subjecting the soil to a compactive effort of about 12,375 ft-lbf/ft^3 - ASTM D 698, Method C for 6” mold)

(e) The mold was detached from the machine and the collar removed. The surface was trimmed with a straight edge repeatedly scraped across the top of the mold to form a plane surface with the top of the mold.

(f) Holes at the surface were filled with trimmed soil from the specimen and scraped with the straight edge again.

The same process was adopted for all soils. For soils which required the Method-C compaction, same test procedure was followed with soils compacted in 6” mold according to the standards. Microwave testing followed is same as mentioned above for all tests.

(5a)

(5b)

(5c)

(5d)

(5e)

(5f)

Figures 5(a-f): Sample preparation and compaction

Microwave sensor testing in the laboratory and Soil moisture content measurement

(a) Sensor Installation: The Hydro-mix sensor was connected to the PC according to the directions given in the manual.

(b) The bottom surface of the sensor was cleaned and free of soil particles. The top of the mold was also clean and leveled.

(c) The sensor was carefully placed on the compacted soil so that the sensor bottom completely rested on the top smooth surface of the soil. Because the microwave sensor contact plate slightly protrudes from the holding ring, the soil is in direct contact with the microwave sensor.

(d) After placing the sensor on the compacted soil, the sensor data was recorded.

(e) The sensor page displayed on the PC detects the selected sensor (No.16). The filtered unscaled value is noted after the trend and logging graph stabilizes (~ 2 seconds).

(f) The sensor was removed and the mass of the mold with soil was immediately measured and recorded for dry unit weight determination.

(g) For water content determination, a sample of the soil was taken from the top 2 to 3 cm to correlate this water content to the microwave value (since readings of microwave were taken from the top surface).

(h) The container with soil sample was weighed and kept in the oven maintained at a temperature of 110°C. After 24 hours the dry soil sample with container was weighed and gravimetric and volumetric moisture contents were determined. The dry densities were calculated and OMC and MDD were determined from the compaction curves.

(6a)

(6b)

(6c)

(6d)

(6e)

(6f)

(6g)

(6h)

Figures 6(a-h): Microwave sensor testing in lab (sample in the mold)

Sensor Evaluation

The sensor is evaluated in six different steps. In the first step, the relationship between the microwave values and gravimetric and volumetric moisture contents are studied ; in the second step effect of the material dielectric on the sensor readings is studied by testing the samples in the mold (4" and 6") and extracted samples , in the next step the sensor suitability in different soil types is tested by choosing two soil types ; in the fourth step, the sensor is tested for its suitability in the field ; in the fifth step the causes for the differences in laboratory and field measurements are evaluated by studying the influence of contact area and the depth of influence of a steel plate dielectric on the sensor readings ; The sensor is finally evaluated for its suitability on six different soil types laid in a row in a trench prepared for this purpose. The soils in the trench are divided into three different soil moisture zones, the wet, dry and air dry moistures. The microwave value measurements are made as discussed above. Models are developed for all soil types and are tested for significance using statistical software (Refer to Results and Discussion section). The Accuracy and Precision of the microwave sensor is also tested. Details of each test method are presented with the results and discussion chapter for a better understanding of the test plans.

RESULTS AND DISCUSSION

The evaluation of the microwave sensor is done in the form of various tests on different soil types. The properties like gradation, atterberg limits and specific gravity of the materials used for each task are presented. The moisture and density relationships of the materials are also shown. The suitability of the sensor for various soils like sand, silt, loess, glacial till, gumbo, Edward till, Kickapoo Clay, Kickapoo topsoil, FA6 and CA6G is tested. In the following section, the methods adopted for various test plans and the results obtained are presented followed by a discussion.

Test Plan 1 – Developing relationship between microwave values and moisture content

Test Methods

This preliminary test presents data from the initial laboratory trial involving tests on two soil types - sand and silt. These soils were compacted at different moisture contents varying from 0-30% and the microwave values were obtained by using Microwave sensor. The evaluation is being carried out by developing relationships between the microwave sensor measurement values and moisture content (gravimetric and volumetric).

Results

Material Properties

Gradation analysis and Atterberg limit tests were performed on each soil sample according to ASTM D 2487 [Test Method for Classification of Soils for Engineering Purposes] and ASTM D 4318 [Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils] (ASTM 2000), respectively. The Atterberg limits and gradation parameters for each soil are provided in Tables 4 and 5.

Table 4. Atterberg limits

Soil Type	LL	PL	PI
Silt	29	23	6
Sand	—	—	NP

Table 5. Gradation analysis

Soil Type	Gravel (> 4.75 mm)	Sand (≤ 4.75 and > 0.75 mm)	Silt (≤ 0.075 and > 0.002 mm)	Clay (≤ 0.002 mm)
Silt	0	2.9	90.9	6.2
Sand	3.0	97.0	0	0

Each soil was classified according to the Unified Soil Classification System (USCS), the AASHTO classification system, and the United States Department of Agriculture (USDA) textural classification system. Soil classifications are provided in Table 6.

Table 6. Soil classifications

	USCS		AASHTO	
Soil Type	Group Symbol	Group Name	Classification	GI*
Silt	ML	Silt	A-4	(6)
Sand	SP	Poorly-graded Sand	A-3	(0)

* Group Index = $(F_{200} - 35)\,[0.2 + 0.005\,(LL - 40)] + 0.01\,(F_{200} - 15)\,(PI - 10)$

Specific Gravity

The specific gravity was determined for each soil type. The tests were performed according to ASTM C 128 [Specific Gravity and Absorption of Fine Aggregate] (ASTM 2002). Specific gravities are provided in Table 7.

Table 7. Specific gravities

Soil Type	G_s
Silt	2.70
Sand	2.65

Moisture and Density Properties

The moisture-density relationship was developed with the standard Proctor test, performed according to ASTM D 698, Method A [Standard Test Method for Determining the Moisture-Density Relations of Soils and Soil-Aggregate Mixtures] (ASTM 2000). The moisture - density relationships are shown in Figure 7. The sand exhibits a bulking phenomenon with increasing water content due to capillary tension. The maximum dry density and optimum moisture content for the silt are about 1710 kg/m^3 and 17%, respectively.

Microwave Tests

- The microwave value is plotted against the gravimetric moisture contents for both soils (sand and silt) in Figure 8.
- The 95% confidence levels and best fit lines have been determined using sigma plot. The linear equations are shown in Figures 9-12.
- The time taken for the microwave value to stabilize was about 2 seconds.

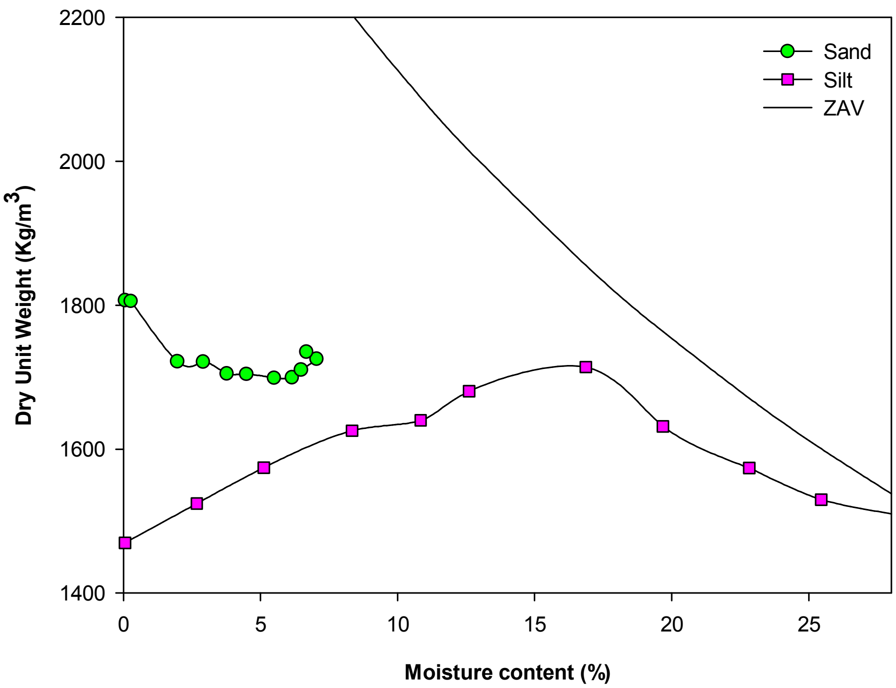


Figure 7. Standard Proctor moisture-density relationships for sand and silt

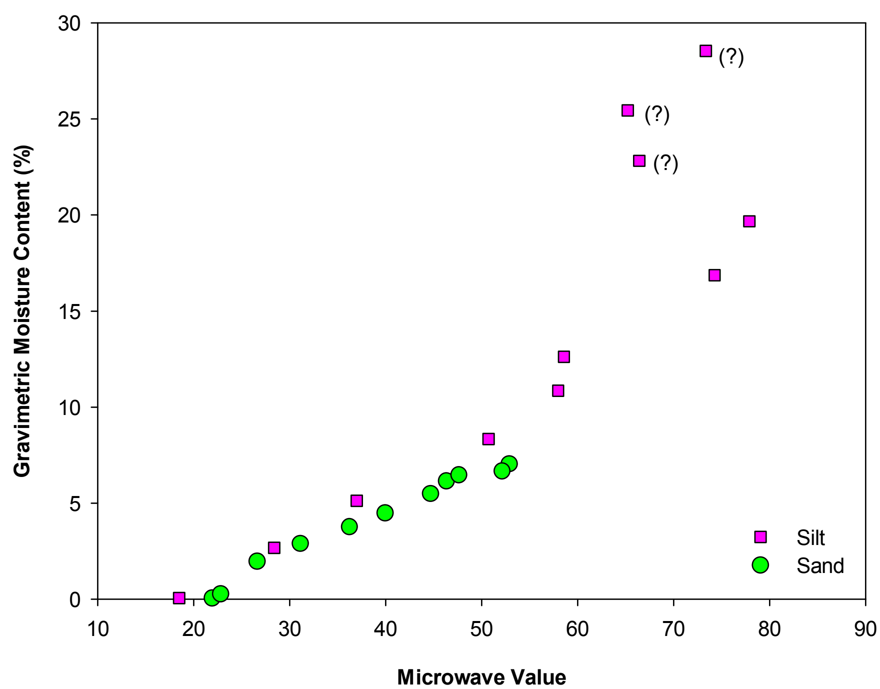


Figure 8. Gravimetric moisture content vs. microwave value – sand and silt

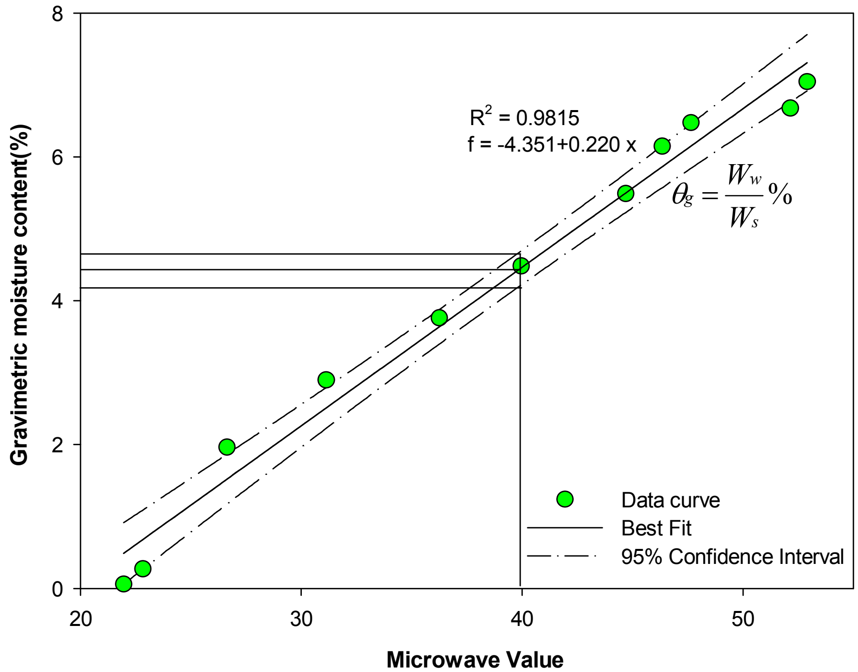


Figure 9. Sand–Gravimetric moisture contents vs. microwave value

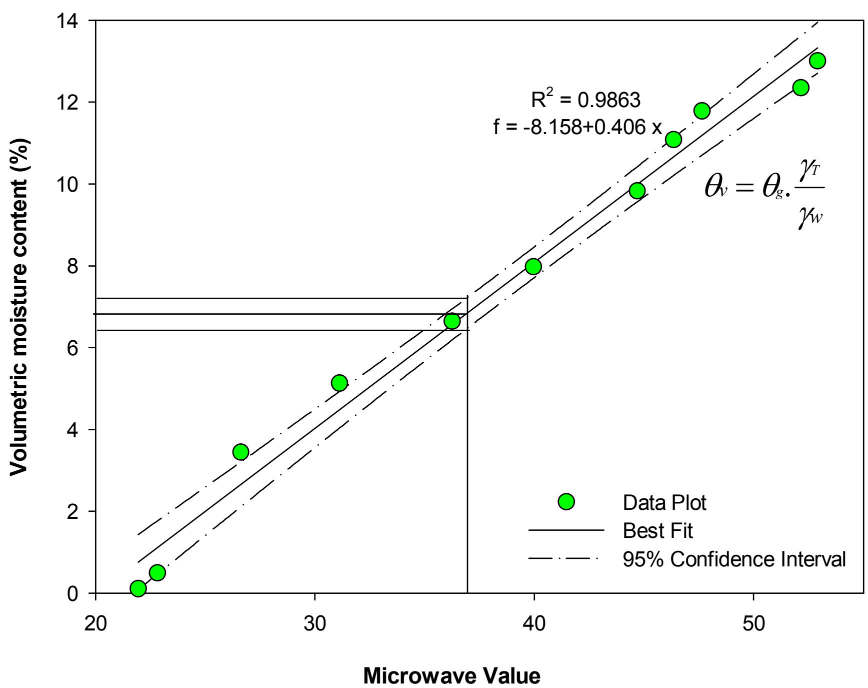


Figure 10. Sand –Volumetric moisture contents vs. microwave value

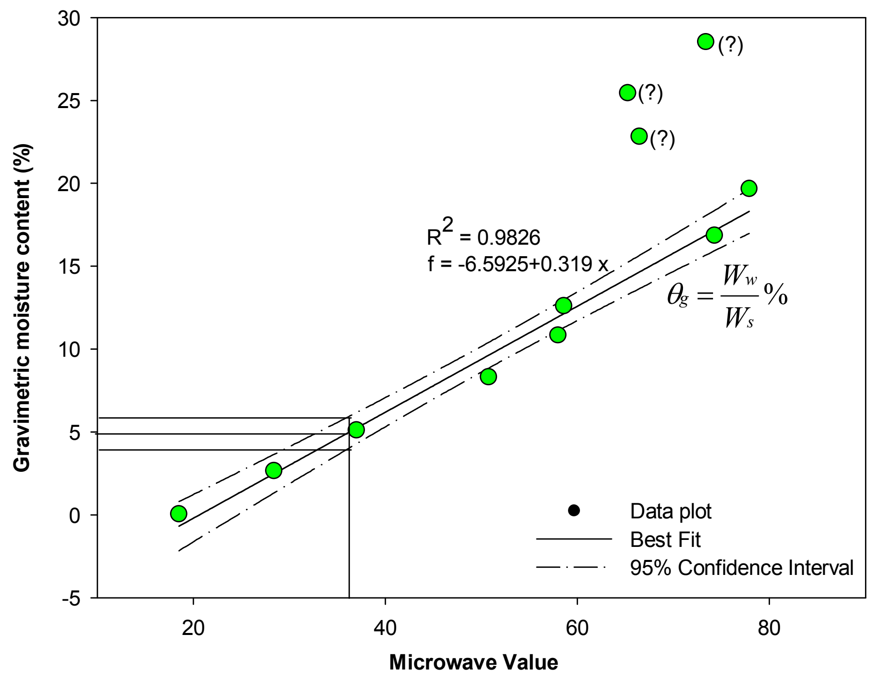


Figure 11. Silt – Gravimetric moisture contents vs. microwave value

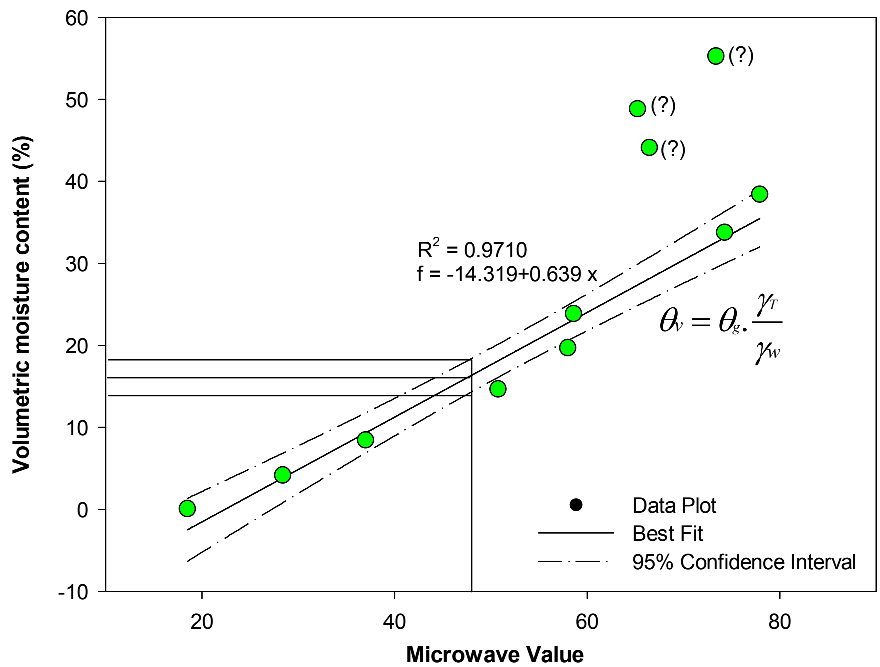


Figure 12. Silt – Volumetric moisture contents vs. microwave value

Discussion

The microwave values show a linear relationship with the moisture content with the exception of moisture contents above about 20% (gravimetric).

The regression equations developed for sand and silt are shown below:

Sand:
$\Theta_g = -4.351+0.220x$ (Gravimetric)
$R^2 = 0.9815$

$\Theta_v = -8.158+0.406x$ (Volumetric)
$R^2 = 0.9863$

Silt:
$\Theta_g = -6.592+0.319x$ (Gravimetric)
$R^2 = 0.9826$

$\Theta_v = -14.319+0.639x$ (Volumetric)
$R^2 = 0.9710$

For understanding the variation with the predictions from the regression models, the 95% confidence intervals were determined. For sand, the 95% confidence interval for gravimetric moisture content at a microwave value of 40 is ± 0.2%. Similarly, for volumetric moisture content values at a microwave value of 36, the confidence interval is ± 0.4%. For silt, the confidence interval for gravimetric moisture content at a microwave value 36 produced is ± 1%. For volumetric moisture content values at a microwave value of 48, the confidence interval level is ± 2%. For silt the trend was found to deviate from linear at moisture contents above 21%. At this moisture content and higher, the microwave sensor was visibly wet after testing.

Test Plan 2 - A comparison between tests on different molds and extracted samples

Test Methods

This test compares the results of laboratory microwave sensor tests conducted on Loess samples compacted in different molds (4" and 6" molds) and on the extracted samples of each. The influence of the mold material dielectric is studied in this test. The microwave sensor tests on soil samples in the mold are conducted as discussed in the test methods section. Microwave sensor tests on extracted samples are conducted as follows.

(a) Soil sample is compacted as discussed in the above section. The collar is removed and the surface is planed.

(b) The sides and bottom of the mold are cleaned.

(c) The mass of the soil in the mold is noted for dry density evaluation.

(d) The soil sample is extracted from the mold using a lab extruder.

(e) The bottom surface of the sensor was cleaned and free of soil particles.

(f) The sensor was carefully placed on the compacted soil so that the sensor bottom completely rested on the top smooth surface of the soil.

(g) After placing the sensor on the compacted soil, the sensor data was recorded.

(h) For water content determination, a sample of the soil was taken from the top 2 to 3 cm to correlate this water content to the microwave value.

(i,j) The container with soil sample was weighed and kept in the oven (110°C). After 24 hours the dry soil sample with container was weighed and gravimetric and volumetric moisture contents were determined. The dry densities were calculated and OMC and MDD were determined from the compaction curves.

(13a)

(13b)

(13c)

(13d)

(13e)

(13f)

(13g)

(13h)

(13i)

(13j)

Figures 13(a-j): Microwave sensor testing in lab (on extracted samples)

Results

Material Properties

The Atterberg limits and gradation parameters for loess are provided in Tables 8 and 9.

Table 8. Atterberg limits

Soil Type	LL	PL	PI
Loess	32	25	7

Table 9. Gradation analysis

Soil Type	Gravel (> 4.75 mm)	Sand (≤ 4.75 and > 0.75 mm)	Silt (≤ 0.075 and > 0.002 mm)	Clay (≤ 0.002 mm)
Loess	0	3	83	14

Loess was classified according to the Unified Soil Classification System (USCS), the AASHTO classification system, and the United States Department of Agriculture (USDA) textural classification system. Soil classifications are provided in Table 10.

Table 10. Soil classifications

Soil Type	USCS		AASHTO	
	Group Symbol	Group Name	Classification	GI*
Loess	ML	Silt	A-4	(7)

Specific Gravity

Specific gravity of loess used in this test is found to be 2.62

Microwave Tests

- The microwave value is plotted against the gravimetric moisture contents for loess samples tested in 4" and 6" molds and the extracted samples.
- Considerable variation was observed in microwave values of soil tested in the mold and extracted soil samples.
- A difference was observed in the microwave values of the same soil tested in 4" mold and 6" mold compacted at almost same moisture contents.
- The time taken for the microwave value to stabilize was about 2 seconds.

Table 11. Gravimetric moisture contents and Microwave values

Tested in 4" mold			Tested in 6" mold		
Gravimetric moisture content	Microwave value		Gravimetric moisture content	Microwave value	
	In mold	Extract		In mold	Extract
9.085	52	42.910	9.285	48.640	53.540
11.68	61.96	54.720	12.046	59.180	61.15
14.651	60.93	63.13	14.996	68.97	64.12

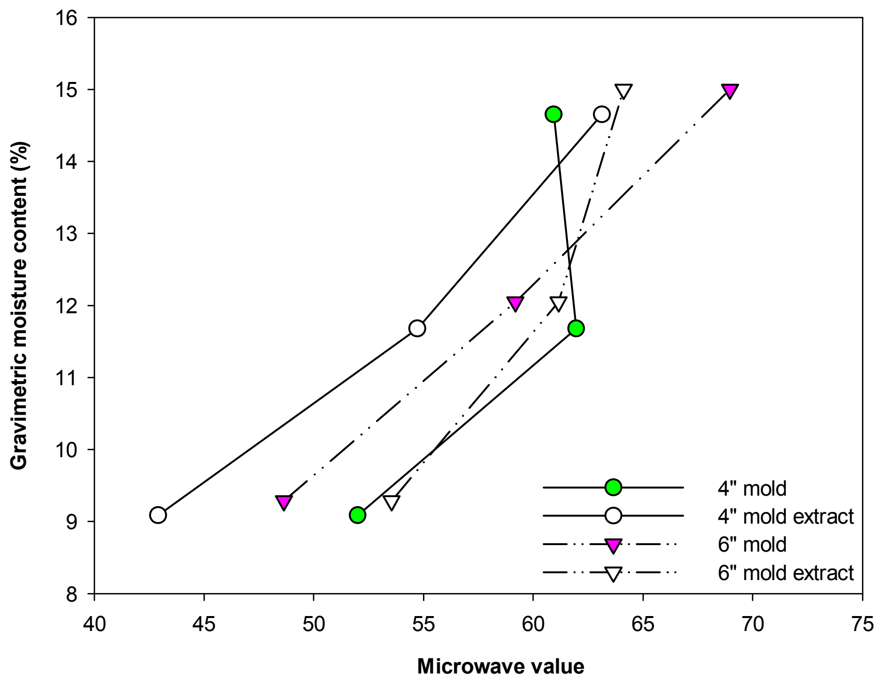


Figure 14. Gravimetric moisture content vs. Microwave value

Discussion

The variation in microwave values between the sample in the mold and extracted sample can be understood as below:

- In the case of sample tested in the 4” mold, the edge of the microwave sensor rested on the mold. The dielectric constant of the mold may have some influence on the reading. Whereas, for extracted sample the sensor showed a reduction in the microwave value.

This may be considered to be the true moisture content of the soil without any external influence.

- For the soil tested in 6” mold, the sensor does not rest on the mold in either extracted sample or sample tested with the mold. The variation in the values in this case explains the need for further study in this aspect.
- In the plot between Moisture content and Microwave values (Figure 14), soil sample compacted at 15% water content showed an abnormal trend. Much more study is carried out to understand the sensor response at higher moisture contents.

Test Plan 3 – A comparison between tests on different soil types

Test Methods

In this test, the suitability of Microwave sensors for different soil types is evaluated by developing relationship between moisture content and microwave values. This test compares the results of laboratory tests conducted on two soil types – Loess and Glacial Till compacted in a 4” mold and on the extracted samples. Microwave tests on extracted samples are conducted following the same procedure as mentioned in Test plan 2.

Results

Material Properties

The Atterberg limits and gradation parameters for Loess and Glacial Till are provided in Tables 12 and 13.

Table 12. Atterberg limits

Soil Type	LL	PL	PI
Loess	32	25	7
Glacial Till	21	16	5

Table 13. Gradation analysis

Soil Type	Gravel (> 4.75 mm)	Sand (≤ 4.75 and > 0.75 mm)	Silt (≤ 0.075 and > 0.002 mm)	Clay (≤ 0.002 mm)
Loess	0	3	83	14
Glacial Till	3	5	65	27

Soil classifications are provided in Table 14.

Table 14. Soil classifications

	USCS		AASHTO	
Soil Type	Group Symbol	Group Name	Classification	GI*
Loess	ML	Silt	A-4	(7)
Glacial Till	CL-ML	Silty clay	A-4	(2)

Specific Gravity

The Specific gravities of loess and glacial till soils used in this test are shown in Table15.

Table 15. Specific gravities

Soil Type	G_s
Loess	2.62
Glacial Till	2.65

Microwave Sensor tests

- The microwave value is plotted against the gravimetric and volumetric moisture contents for both soil samples – loess and glacial till tested in 4" mold and the extracted samples.
- There was a reverse in trend at moisture contents above 15% in both the soils.
- At higher moisture contents, a considerable increase was observed in the microwave values on the extracted sample against the same soil tested in 4" mold at same moisture contents.

- A comparison graph is plotted for the two soil types to observe the trend in microwave value with gravimetric moisture content.
- The time taken for the microwave value to stabilize was about 2 seconds.

Table 16. Moisture contents and Microwave values of Loess and Glacial Till

Loess				Glacial Till			
Gravimetric moisture content	Volumetric moisture content	Microwave value		Gravimetric moisture content	Volumetric moisture content	Microwave value	
		In 4" Mold	Extract			In 4" mold	Extract
0.06	0.09	17.54	14.46				
3.90	6.29	35.15	25.15	4.04	7.36	33.43	30.4
9.51	17.16	54.46	47.43	8.80	16.94	50.84	44.62
14.03	27.39	62.62	63.77	13.97	29.01	64.28	63.25
19.18	37.74	77.14	79.86	17.93	36.70	72.21	76.12
23.69	45.41	66.96	89.77	23.69	46.03	72.62	85.62
28.45	53.62	74.66	89.27	28.34	51.97	70.98	90.74

Discussion

The variation in microwave values between the sample in the mold and extracted sample for the two soil types tested in this case can be understood as below:

- In the case of sample tested in the 4” mold, the edge of the microwave sensor rested on the mold. The dielectric constant of the mold may have some influence on the reading. Whereas, for extracted sample the sensor showed a reduction in the microwave value. This may be considered to be the true moisture content of the soil without any external influence.
- In the plot between Moisture content and Microwave values (Figures 15-18), soil samples compacted at 15% water content and above showed that there is a considerable increase in microwave values of extracted samples in both soils. This behavior at higher moisture contents explains the difference between samples tested in lab and open field. This also

shows that there is some effect of material dielectric on the microwave readings at higher moisture contents.

The comparison graph plotted for both the soil types shows a similar trend of microwave value with gravimetric moisture content for both the soils (Figure 19).

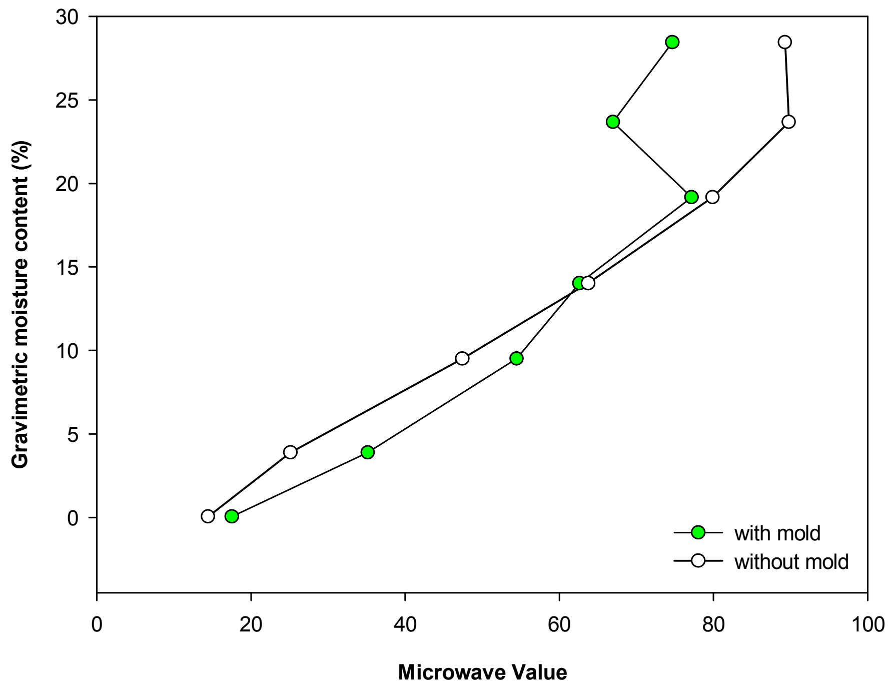


Figure 15. Gravimetric moisture content vs. Microwave value - Loess

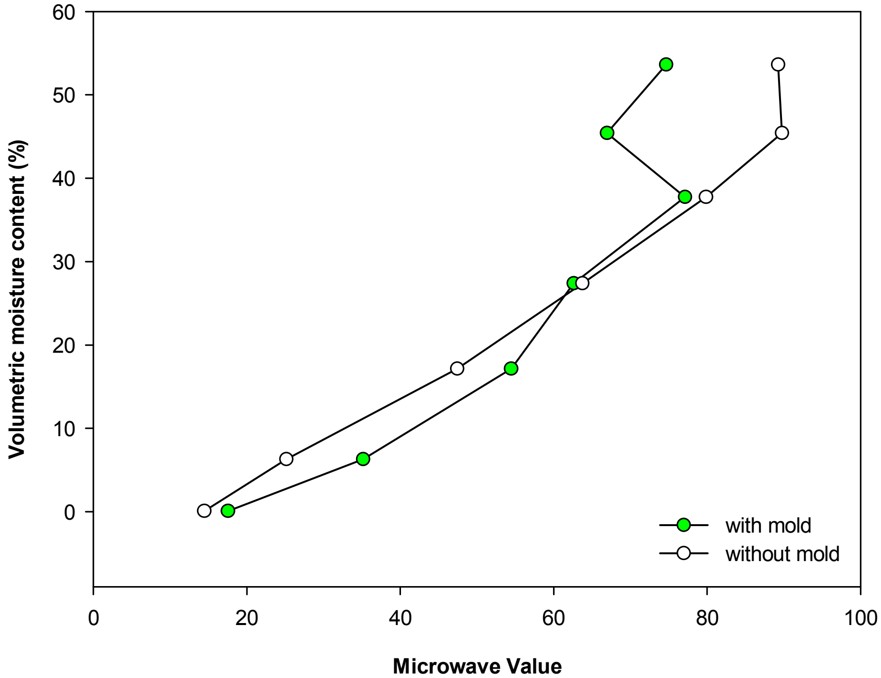


Figure 16. Volumetric moisture content vs. Microwave value - Loess

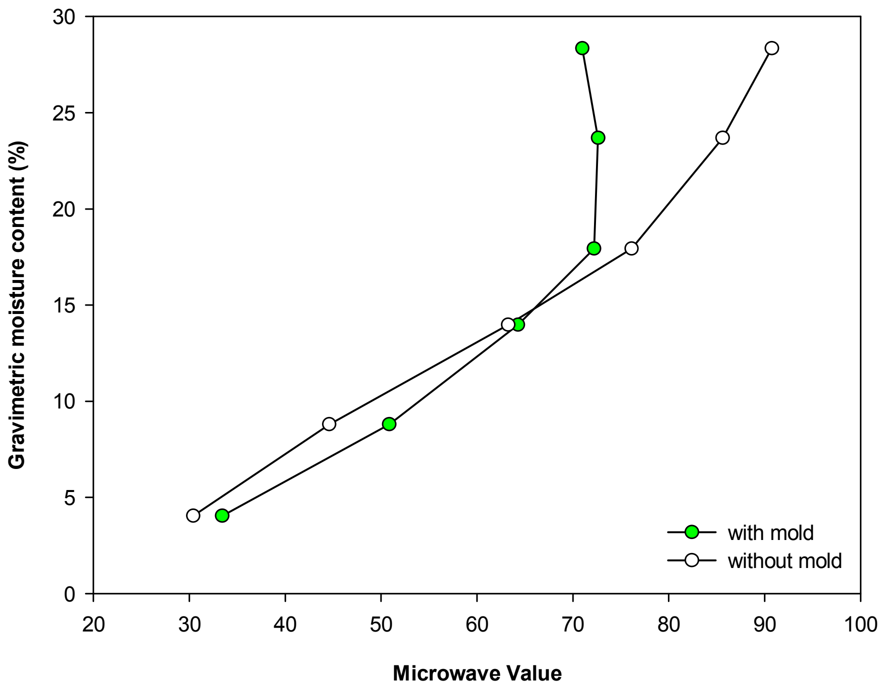


Figure 17. Gravimetric moisture content vs. Microwave value – Glacial Till

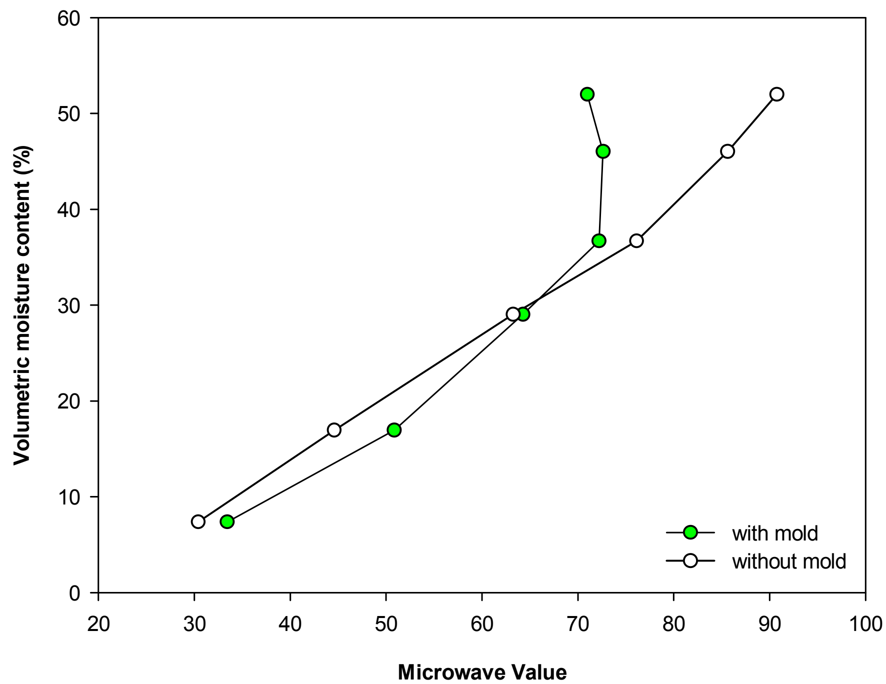


Figure 18. Volumetric moisture content vs. Microwave value – Glacial Till

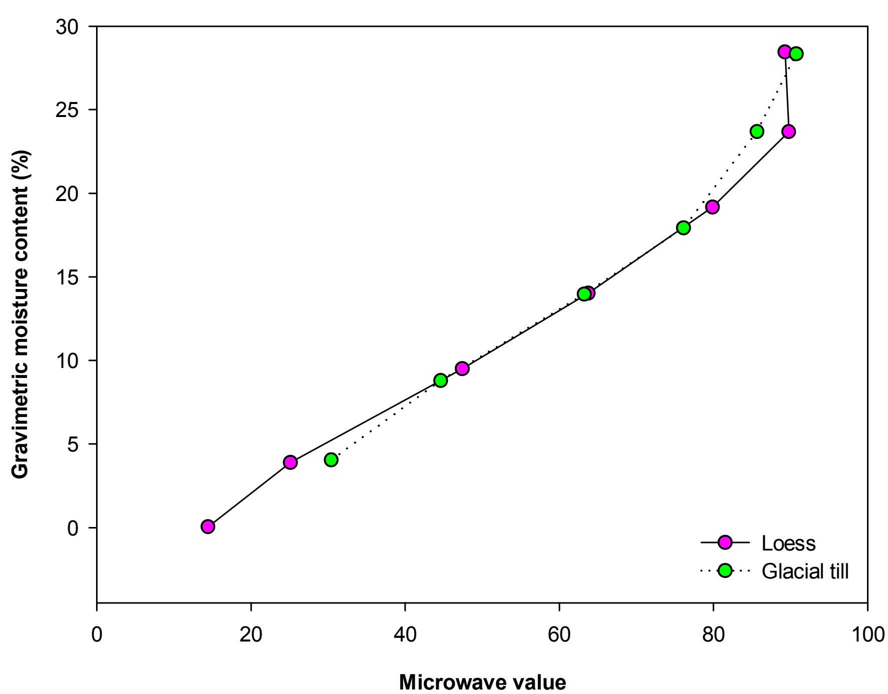


Figure 19. Gravimetric moisture content vs. Microwave value – Comparison graph – Loess and Glacial Till

Test Plan 4 – Comparison of field and laboratory tests

Test Methods

This plan deals with the tests done on three different soils in the field and laboratory using Microwave sensors. The tests were carried out on Glacial Till, Loess and Gumbo soil spreads near the bypass construction project in Fairfield, IA. Laboratory microwave sensor test procedures are as mentioned in the above test plans on extracted samples. For comparison of laboratory and the field study, testing was conducted in open field compacted by rollers. The procedure adopted is explained below.

(a) The microwave sensor test platform is prepared. This is done by selecting suitable area of soil to be tested.

(b) The soil surface is then planed by using a shovel.

(c) It is ensured that there are no voids or gaps on the surface

(d) The microwave sensor surface is also cleaned

(e) The sensor is placed carefully on the soil.

(f) Readings of microwave values are produced on a computer attached to the sensor. The microwave value is noted after the reading stabilizes and it takes only a few seconds for the reading to stabilize.

(g) The sensor is then removed and the soil core below the sensor is collected and wrapped carefully to prevent loss of moisture.

(h) The collected soil sample is taken to the mobile lab and the density evaluated.

(i) The sample is extracted from the mold.

(j) The microwave test is done on that extracted sample in the mobile lab following procedure mentioned above to compare field and lab data.

(20a)

(20b)

(20c)

(20d)

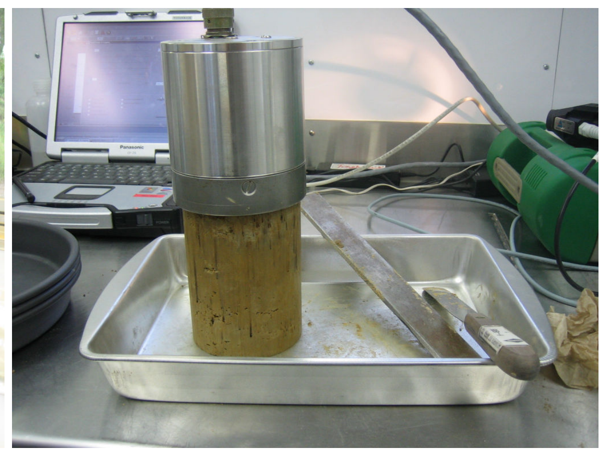
(20e)

(20f)

(20g)

(20h)

(20i)



(20j)

Figures 20(a-j): Microwave sensor testing in the field

Results

Material Properties

The Atterberg limits and gradation parameters for loess and Glacial Till soils in the field are not provided in this report due to the non-availability of material from field. The properties of the material Gumbo from the field used for this test are provided in Tables 17 and 18.

Table 17. Atterberg limits

Soil Type	LL	PL	PI
Gumbo	65	34	31

Table 18. Gradation analysis

Soil Type	Gravel (> 4.75 mm)	Sand (≤ 4.75 and > 0.75 mm)	Silt (≤ 0.075 and > 0.002 mm)	Clay (≤ 0.002 mm)
Gumbo	0	8	75	17

Loess was classified according to the Unified Soil Classification System (USCS), the AASHTO classification system, and the United States Department of Agriculture (USDA) textural classification system. Soil classifications are provided in Table 19.

Table 19. Soil classifications

	USCS		AASHTO	
Soil Type	Group Symbol	Group Name	Classification	GI*
Gumbo	MH	Elastic Silt	A-7-5	(35)

Specific Gravity

Specific gravity of Gumbo used in this test is found to be 2.70

Microwave Tests

- The microwave values obtained at the field and lab for the three soils- Glacial Till, Loess and Gumbo are presented in table 20.
- The microwave values for the soils tested at creek are presented in table 21.
- The time taken for the microwave values to stabilize was about 10 seconds.

Table20. Moisture contents and Microwave values - Glacial Till, Loess, and Gumbo

Glacial Till			Loess			Gumbo		
Gravimetric moisture content (%)	Microwave value		Gravimetric moisture content (%)	Microwave value		Gravimetric moisture content (%)	Microwave value	
	In the field	In the lab		In the field	In the lab		In the field	In the lab
12.314	34.11	38.85	25.24	32.91	77.22	25.5	63.04	79.75
14.393	31.57	64.06	26.898	39.83	81.37	25.242	65.43	75.12

Table 21. Moisture contents and Microwave values for Mixed soil at the creek

Gravimetric moisture content (%)	26.465	20.969	23.187	19.462	29.943	24.401
Filtered Average from Hydro Com sensor	46.74	62.64	64.19	52.11	59.55	71.58

Discussion

- Considerable variation is observed in microwave values of the same soil when tested at field and at the lab. This can be due to a variety of differences in the field and laboratory conditions. For instance, in the laboratory, perfect plane surface can be achieved on the sample top, whereas, in the field it was difficult to achieve. Also, it was observed in the field that, even small voids on the prepared surface led to a considerable change in the microwave values and that variation range was 2-75, which is an important point to be observed.

- Other factors like vibration on the nearby ground and temperature differences can be possible reasons for the variation. When there is some vibration around the sensor, the contact surface of the sensor will disturb and this will give scope for air to fill in the gaps and thus the microwave value may vary. Further research is carried out to understand this variation in detail.

Test Plan 5 – Study of the effects of change in area and volume and influence of steel plate on microwave readings

Test Methods

Under this plan, Microwave sensor tests were carried out on oxidized Glacial till sample to study the sensitivity of Microwave sensor values to the changes in contact area and the volume of the specimen under test. Considerable differences in field and laboratory microwave sensor values were observed in previous testing's which can be attributed to the variability in test conditions in the field and laboratory. As a first step to understand this behavior in detail, microwave sensor tests were conducted on oxidized Glacial till sample compacted at particular moisture content and the change in microwave readings with changes in contact area and volume are observed. The effect of steel plate on the sensor readings has also been observed in this case. Details of the test methods adopted are given below.

Study of influence of Contact Area on the Microwave values

(a) Oxidized Glacial till sample is compacted on the wet side of optimum moisture content. The top surface of the sample is planed.

(b) Microwave sensor is placed carefully on the sample after ensuring a surface free of voids and the microwave value is noted.

(c) The mold is marked for making equidistant holes on the surface.

(d) Pocket penetrometer shown in figure is taken to establish equal voids on the surface of the soil sample. The influence depth of the microwave sensor is assumed to be 1 cm below the sample top. A mark of 1cm depth is made on the penetrometer to ensure same penetration depth throughout

(e) The penetrometer is pushed into the soil to make a void of 0.63cm diameter and 1cm depth.

(f) The sensor is placed on the sample and the microwave value is taken.

(g-l) 25 Voids/holes of same volume are made on the sample in increments of one number to form concentric circles and the microwave values at each area/ volume change are noted.

Soil samples are collected for moisture content determination as mentioned in previous methods. The change in microwave value with contact area is studied at two moisture contents.

(21a)

(21b)

(21c)

(21d)

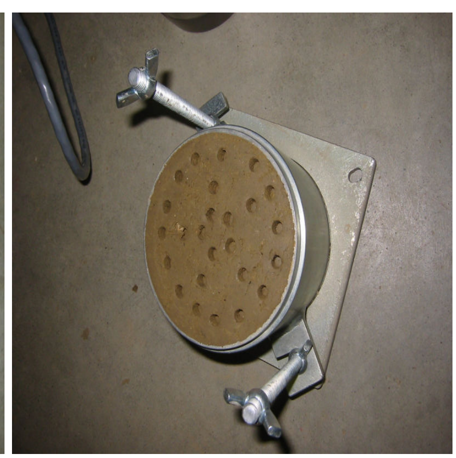

(21e)


(21f)


(21g)


(21h)


(21i)


(21j)

(21k)

(21l)

Figures 21(a-l): Study of influence of contact area

Study of influence of steel plate on the Microwave values

Oxidized Glacial till soil compacted at optimum moisture content is extracted from the mold and the sample is placed on a steel plate. After ensuring a plane surface, the microwave sensor is placed on the sample and the microwave value is noted. The sample is then placed on the ground and the microwave value is taken. The sample is cut by 1/2”from the top and the microwave values when placed on steel plate and on ground are noted. The sample is cut in 1/2” increments from the top to bottom and the microwave values after each cut are noted. The sensor is placed on the steel plate and on the ground directly and the microwave values are taken. Samples of the soil are collected for moisture content and dry unit weight determination. The same test is done at two moisture contents. The influence of steel plate on microwave values is presented and discussed in the results and discussion section. Figures below show the method described above at 2 inches and 0.5 inches height of specimen. (Figures 22(a-d)).

(22a) Cutting specimen height to 2" **(22b) Sensor reading on steel plate**

(22c) Specimen cut to 0.5" **(22d) Sensor reading on steel plate at 0.5" specimen height**

Figures 22(a-d): Study of influence of steel plate

Results

Material Properties

The Atterberg limits and gradation parameters of the Glacial Till soil are provided in Tables 22 and 23.

Table 22. Atterberg limits

Soil Type	LL	PL	PI
Glacial Till	21	16	5

Table 23. Gradation analysis

Soil Type	Gravel (> 4.75 mm)	Sand (≤ 4.75 and > 0.75 mm)	Silt (≤ 0.075 and > 0.002 mm)	Clay (≤ 0.002 mm)
Glacial Till	3	5	65	27

Soil classifications are provided in Table 24.

Table 24. Soil classifications

Soil Type	USCS		AASHTO	
	Group Symbol	Group Name	Classification	GI*
Glacial Till	CL-ML	Silty clay	A-4	(2)

Specific Gravity

The Specific gravity of the glacial till soil used in this test is 2.65.

Microwave Tests

- The moisture content and dry density values of samples tested are shown in Table 25.
- The curves showing the change in microwave values with contact area and volume are presented in Fig. 23 and 24.
- Microwave values of samples placed on steel plate and on ground are shown in Table26.
- The change in microwave value of samples on steel plate and on ground with height is shown in Fig.25.

Table 25. Moisture contents and Unit weights of samples tested

Sample No.	1	2
Moisture Content (%)	13.97	17.93
Dry Density (Kg/m^3)	1891.027	1839.105

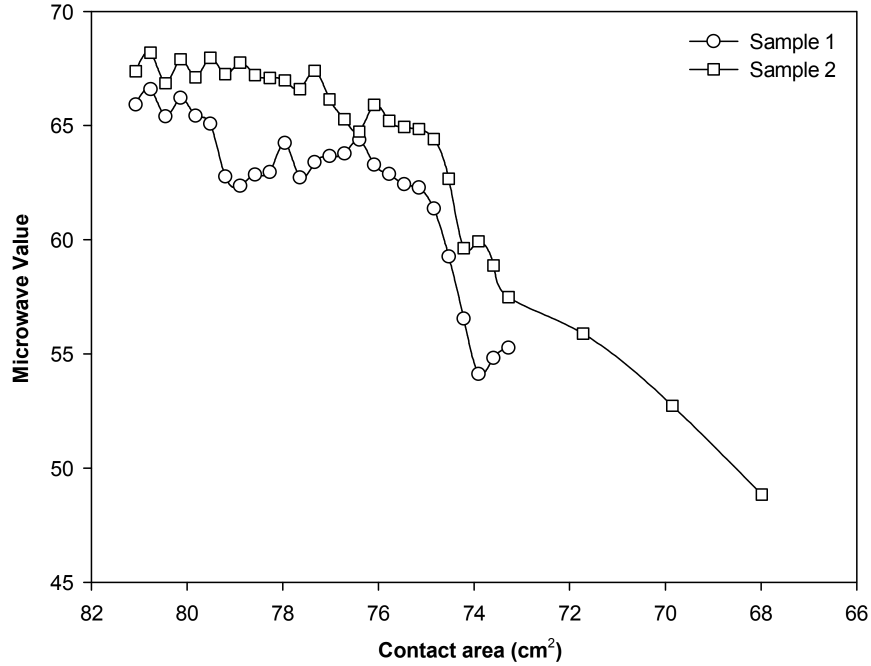


Figure 23. Change in microwave value with contact area

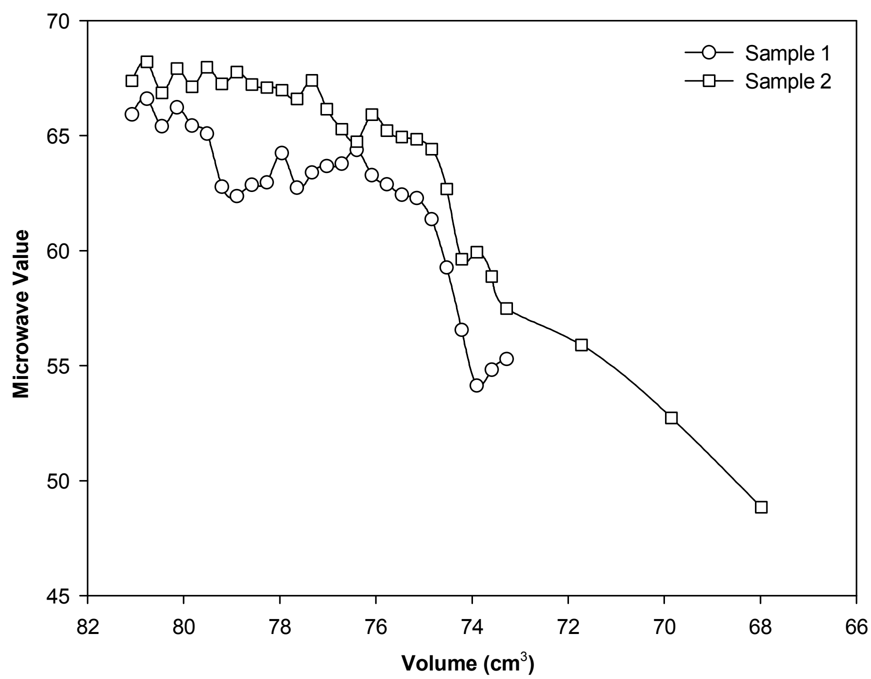


Figure 24. Change in microwave value with volume

Table 26. Microwave values of sample at different heights placed on steel plate:

Sample No.	1		2	
Moisture content (%)	10.74		11.92	
Dry Unit Weight (Kg/m^3)	2006.372		1965.297	
Microwave value for	Sample placed		Sample placed	
Height of the sample	on steel plate	on ground	on steel plate	on ground
41/2"	61.32		65.35	65.91
4"	59.80	60.18	66.23	66.56
31/2"	59.17	59.88	65.15	65.97
3"	58.47	59.33	64.11	65.68
21/2"	58.27	58.75	63.86	65.57
2"	59.74	59.63	64.77	65.28
11/2"	60.14	59.14	66.34	64.79
1"	63.18	59.35	67.44	63.87
3/4"	60.36	56.36		
1/2"	65.50	56.86	67.34	62.97
(0") sensor placed directly	91.26	37.76	91.26	37.76

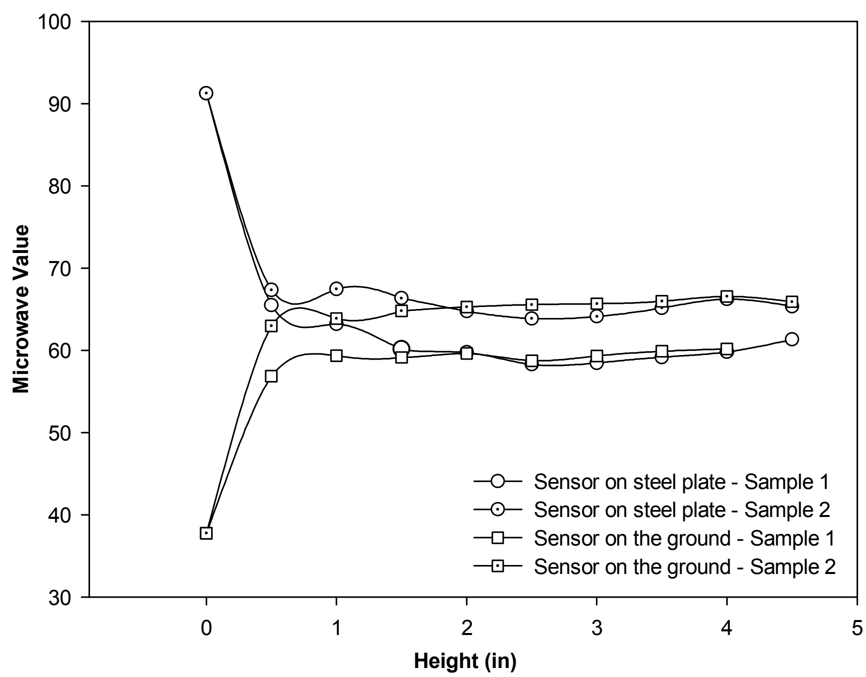


Figure 25. Height of sample vs. Microwave value

Discussion

- It can be observed from Figure 23 that a change in area from 81cm^2 to 78cm^2 does not show significant change in the microwave values. Beyond this change in area, the microwave values change significantly. Hence the maximum allowable change in surface area of the sample compacted at moisture contents at wet of optimum shall be permissible to 3 cm^2.

- From Figure 24, we can infer that the maximum permissible volume change is 3cm^3 with the assumption that the influence depth of the sensor is 1cm.
- From the tests on a steel plate (Figure25), it can be inferred that a steel plate placed under the sample has effect on the microwave values only within 2" height of the soil sample. Beyond that point the microwave values on steel plate and on ground are almost the same.

Test Plan 6 – Tests on five different soils – lab and spot tests – model development using statistical software

Test Methods

This section presents data from the laboratory microwave tests and spot tests conducted at Caterpillar laboratory. The statistical models developed are also presented in this section. Five soil types namely, Edward Till, Kickapoo Clay, Kickapoo Top soil, FA6 and CA6G are tested using Microwave sensors. These soils are compacted at three different compactive efforts (Sub-standard, Standard and Modified) and at moisture contents varying from 0-30% and the microwave values are obtained by using Microwave sensor.

The evaluation was carried out by developing relationships between the microwave sensor measurement values and oven dry moisture contents. Using this data, statistical models are developed one for each soil type and two combined models are developed, one for sandy soils (FA6 and CA6G) and one for clayey soils (Edward till, Kickapoo clay and Kickapoo topsoil). Details of the methods adopted are given below.

Microwave sensor testing in the trench prepared for the purpose at CAT lab and Testing at ISU laboratory

Spot Tests

At the Caterpillar laboratory, Peoria, a trench is prepared for the purpose of these tests. The trench is spread with four different soils, Edward Till, Kickapoo Clay, Kickapoo Top Soil and FA6. The width of each soil spread in the trench varies from 8 feet to 10 feet. Points are marked on the bed at every 1 feet distance (Edward Till- 8 points, Kickapoo Clay- 10 points, Kickapoo Top soil- 8 points and FA6- 9 points).

Initially, the trench is air dried. The surface is compacted by the movement of a sled consisting of roller. Microwave sensor is placed on the air dry soils at all the points marked and the microwave values are recorded. The sensor is placed on a steel plate and tied to a rope and is moved across the bed with hand and the microwave values are taken. Samples are collected at every point tested for determining the oven dry moisture content. The hydro com sensor has an inbuilt feature of plotting the trend graph of time versus Microwave value. These plots are analyzed for all soils.

(26a)Trench prepared for testing; (26b) Microwave sensor on air dry compacted soil bed


(26c) Sensor on air dry bed; (26d) Sample collection for oven dry test


(26e) Sensor placed on steel plate;(26f) Sensor:hand-pulled across the bed

In the second stage, the sensor is pulled with machine on all soil beds in the trench and the variations of microwave values with time are noted.

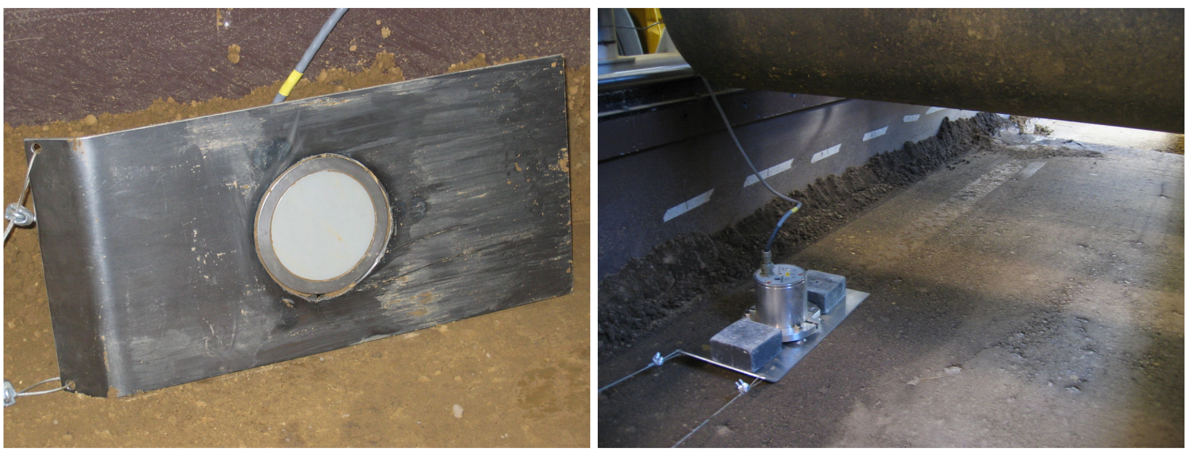

(26g) Sensor base cleaned before testing; (26h) Sensor: Tied to a sled

(26i,26 j) Sensor: Machine pulled across the trench

In the next stage of testing, the trench is divided into two parts, one side prepared wet of optimum moisture content and the other side prepared dry of optimum moisture content. The soil beds are compacted thoroughly with a roller. The microwave sensor is placed on the soil and moved along the whole trench. The sensor speed is controlled by hooking it up to a sled. The sensor is tested at varying speeds of the sled at slow and fast movements (Speed 1- 0.0524ft/sec; Speed 2- 1.348ft/sec). The microwave values are recorded continuously by placing the computer connected to the sensor on one side of the sled. The same procedure is adopted on wet and dry sides of the soil beds and for all four soils in the trench.

(26k,26 l) Wet and dry sides of the trench, being compacted thoroughly

(26m, 26n) Preparation of wet and dry sides of the trench



(26o) Sensor base during sled movement; (26p) Sensor movement along the wet side

(26q, 26r) Sensor: Machine pulled along the wet side of the soil bed

(26s) Sensor: during movement with the sled; (26t) PC set-up

At the end, Microwave sensor is placed with hand on the wet and dry side points and the microwave readings are noted. Samples are collected on the wet and dry sides of the soil bed at all the points for oven dry testing.

(26u) Spot tests on wet and dry sides

Figures 26(a-u): Spot tests

Laboratory Test Methods

The above four soil types which are spot tested, and another soil, CA6G are brought to the Olson soil laboratory at ISU. These five soils are compacted at a wide range of moisture contents (wet, dry and at optimum) and at different compactive efforts (Sub Standard, Standard and Modified Proctor). Methods mentioned in test plans 1 and 2 may be referred for detailed test methods. The compaction processes adopted are shown in Table 27 below.

Table 27 Compaction Processes adopted for Tests 6

Mold Diameter (inches)	Compaction Method	Number of blows per layer	Number of layers	Weight of rammer (lbf)	Height of fall (in)	Compactive Energy (ft-lbf/ft^3)
4	Sub Standard	12	3	5.5	12	6200
	Standard	25	3	5.5	12	12,400
	Modified	25	5	10	18	56,000
6	Sub Standard	28	3	5.5	12	6200
	Standard	56	3	5.5	12	12,400
	Modified	56	5	10	18	56,000

The samples are extracted from the mold to eliminate any effects of the mold material dielectric on the sensor readings. Some of the samples spilled off and could not be extracted due to dry conditions at very low moisture contents. Such samples are tested in 6" mold to prevent contact of the sensor with the mold material and microwave testing is carried out in the mold itself. For extracted samples, microwave sensor tests are done on the bottom side of the sample, as moisture at the bottom is preserved better from losses than at the top. Microwave sensor is placed on the sample and the microwave values are noted. Samples are collected for oven dry moisture content determination by the above mentioned methods. Some pictures taken during this testing are presented below.

(27a) Soil sample mixed and mellowed

(27b) Mold cleaned and fitted to the compactor

(27c,27d) Automatic Compactor set-up

(27e) Mixing soil uniformly just before testing

(27f) Placing in the mold in layers

(27g) Adjusting blow count

(27h) Compacted sample

(27i) Clean sensor surface **(27j) Sensor placement on the soil sample**

(27k,27l) Dry soil – zero percent moisture, compacted in 6” mold and planed (spilled soil)

(27m) Dry compacted soil tested in the mold (27n)Wet soil - oozing water at the side of the mold


(27o, 27p) Wet sample extracted- moisture can be seen clearly on the surface and sides


(27q) Bottom side of sample tested **(27r) Very wet sample – collapsed on extraction**


(27s) Sensor testing at very high moisture content (27t) Moisture seen on the sensor base

Figures 27(a-t): Laboratory tests

Statistical models

Spot microwave data and oven dry moisture data are analyzed and discussed in the following section. The Laboratory microwave sensor and oven dry moisture data is also analyzed. The laboratory test data is used to develop statistical models for moisture content from microwave values of all the five soils tested. Model details are presented in the results and discussion sections.

Results

Material Properties

Gradation analysis and Atterberg limit tests were performed on each soil type according to ASTM D 2487 [Test Method for Classification of Soils for Engineering Purposes] and ASTM D 4318 [Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils] (ASTM 2000), respectively. The Atterberg limits and gradation parameters for all soils are provided in Tables 28 and 29.

Table 28. Atterberg limits

Soil Type	LL	PL	PI
Edward Till	30	17	13
Kickapoo Clay	39	24	15
Kickapoo Topsoil	35	25	10
FA6	-	-	NP
CA6G	-	-	NP

Table 29. Gradation analysis

Soil Type	Gravel (> 4.75 mm)	Sand (≤ 4.75 and > 0.75 mm)	Silt (≤ 0.075 and > 0.002 mm)	Clay (≤ 0.002 mm)
Edward Till	3	30	49	18
Kickapoo Clay	0	5	73	22
Kickapoo Topsoil	0	3	78	19
FA6	9	75	15	1
CA6G	45	45	8	2

The soils are classified according to the Unified Soil Classification System (USCS), the AASHTO classification system, and the United States Department of Agriculture (USDA) textural classification system. They are shown in Table 30.

Table 30. Soil classifications

Soil Type	USCS Group Symbol	USCS Group Name	AASHTO Classification	AASHTO GI*
Edward Till	CL	Sandy lean clay	A-6	(6)
Kickapoo clay	CL	Lean clay	A-6	(16)
Kickapoo Topsoil	ML	Silt	A-4	(11)
FA6	SM	Silty sand with gravel	A-1-b	(0)
CA6G	SW-SM	Well-graded sand with silt and gravel	A-1-a	(0)

Specific Gravity analysis

The specific gravity tests were performed according to ASTM C 128 [Specific Gravity and Absorption of Fine Aggregate] (ASTM 2002). Specific gravities of the five soils tested are provided in Table 31.

Table 31. Specific gravities

Soil Type	G_s
Edward Till	2.72
Kickapoo Clay	2.71
Kickapoo Topsoil	2.64
FA6	2.73
CA6G	2.74

Moisture and Density Properties

The moisture-density relationships of the samples compacted in the laboratory at substandard, standard and modified efforts were developed with the Proctor test, performed according to ASTM (test methods). These relationships are shown in Figures 28-32. The FA6 soil sample (sand) exhibits a bulking phenomenon with increasing water content due to capillary tension. The zero air void line (ZAV) is also indicated on these figures.

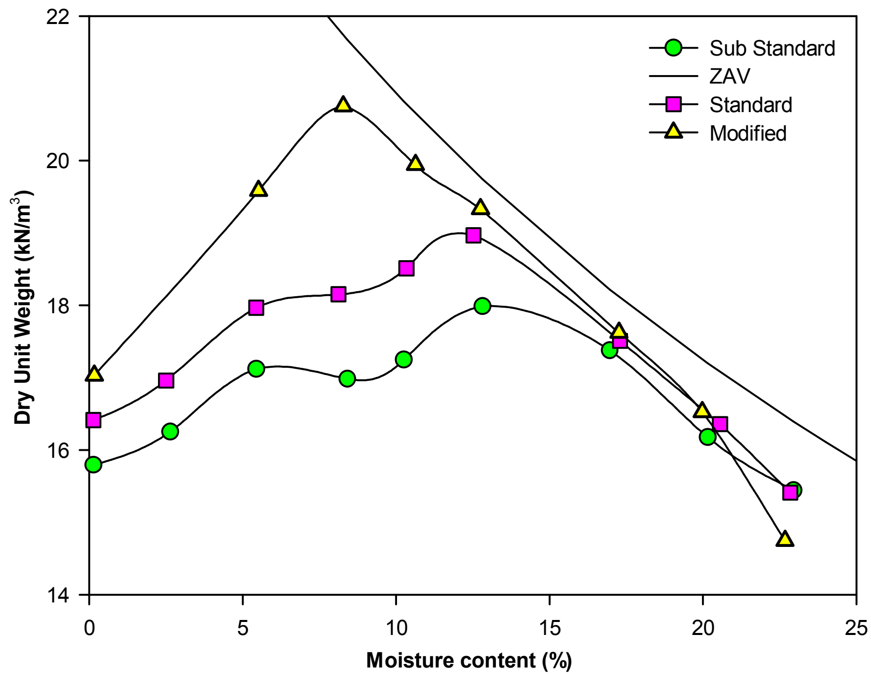


Figure 28. Moisture density relationships for Edward Till

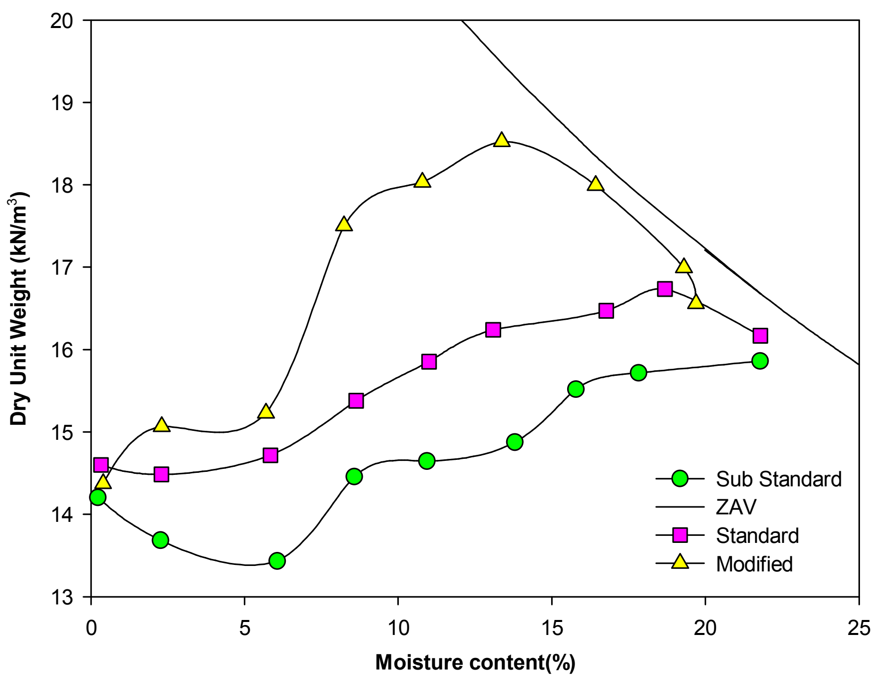


Figure 29. Moisture density relationships for Kickapoo Clay

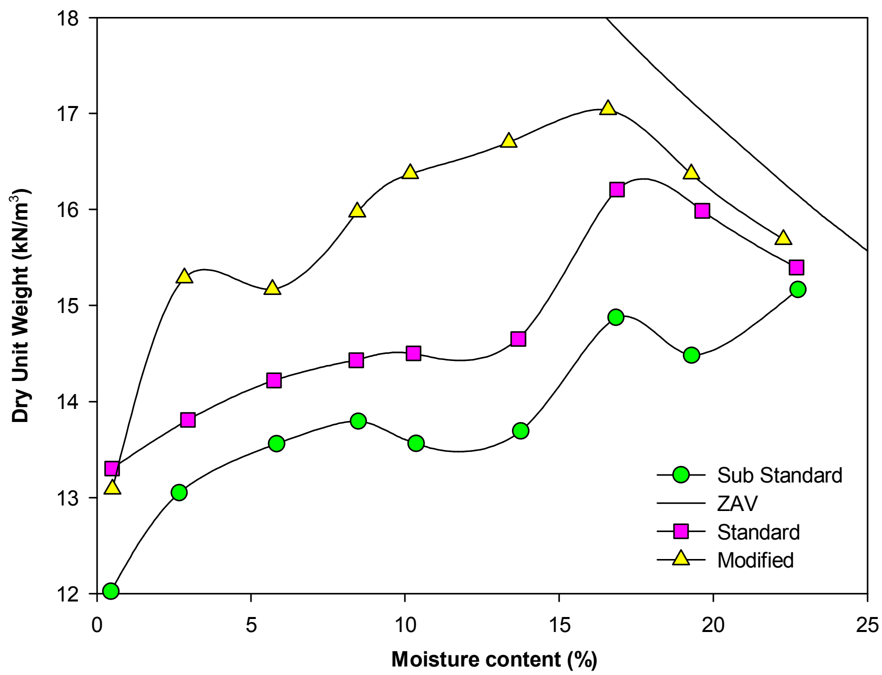


Figure 30. Moisture density relationships for Kickapoo Topsoil

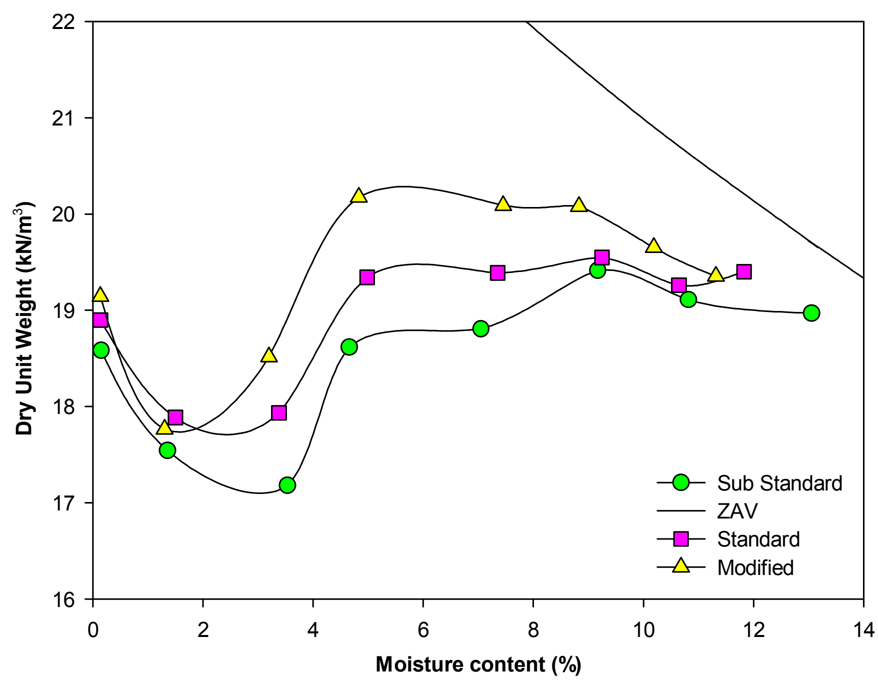


Figure 31. Moisture density relationships for FA6

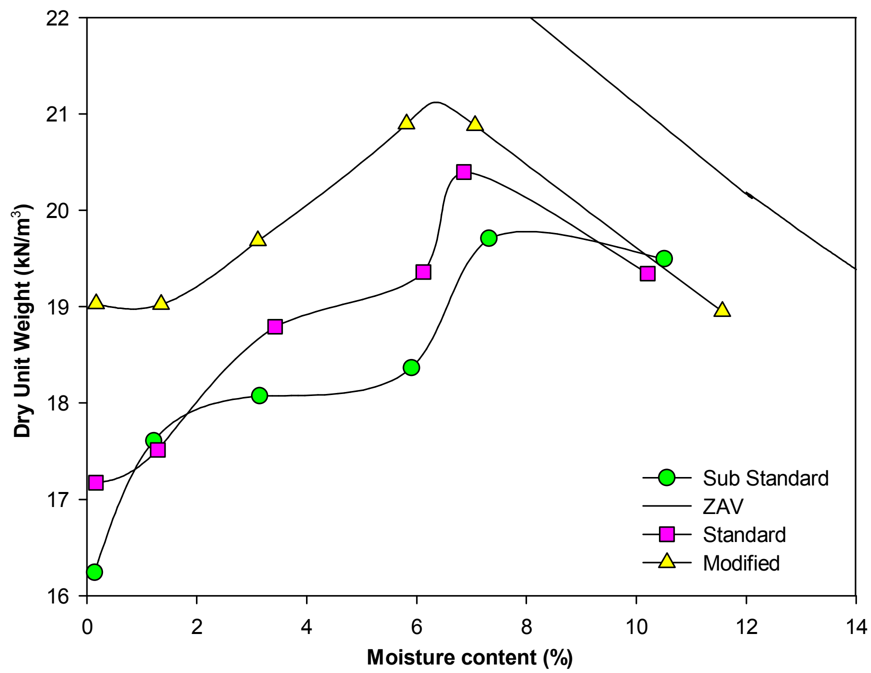


Figure 32. Moisture density relationships for CA6G

Laboratory Tests

Laboratory microwave sensor tests are done over a range of moisture contents on the five soils, Edward Till, Kickapoo Clay, Kickapoo Topsoil, Fa6 and CA6G compacted at three different compactive efforts. This information was useful to study the effect of compactive effort on the microwave values. Further, statistical models were developed for the moisture content with the microwave value as a variable. Plots of gravimetric moisture content vs. microwave value are prepared. The best fit and 95% confidence and prediction intervals are plotted for all the data in the plot. The microwave value is plotted against the gravimetric moisture contents for all five soils in Figures 33-37.

- The 95% confidence levels, 95% prediction levels and best fit lines have been determined using sigma plot. The linear equations are shown in Figs. 33-37.
- The time taken for the microwave value to stabilize was about 2 seconds.

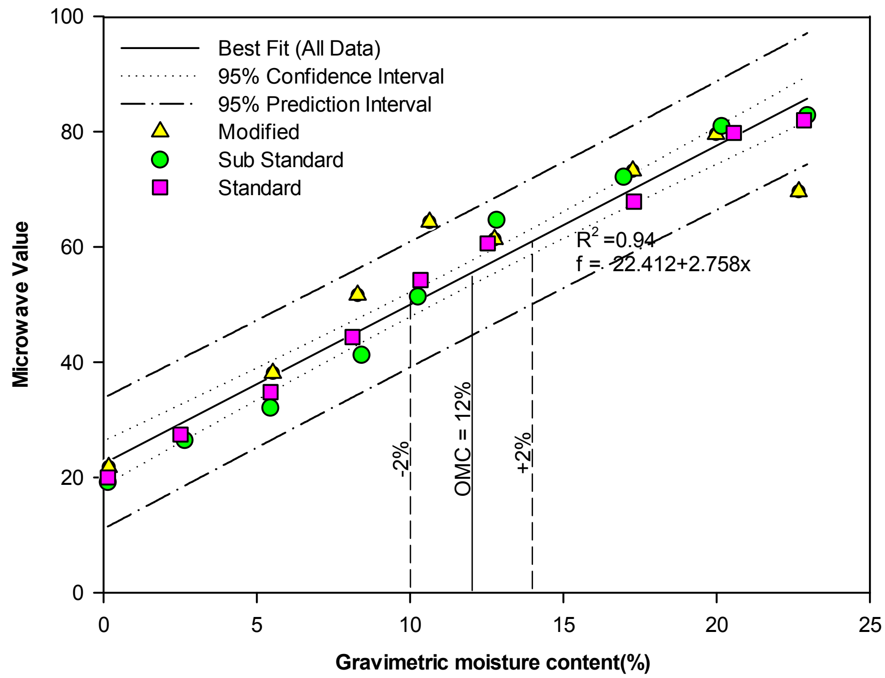


Figure 33. Gravimetric moisture content vs. Microwave value – Edward Till

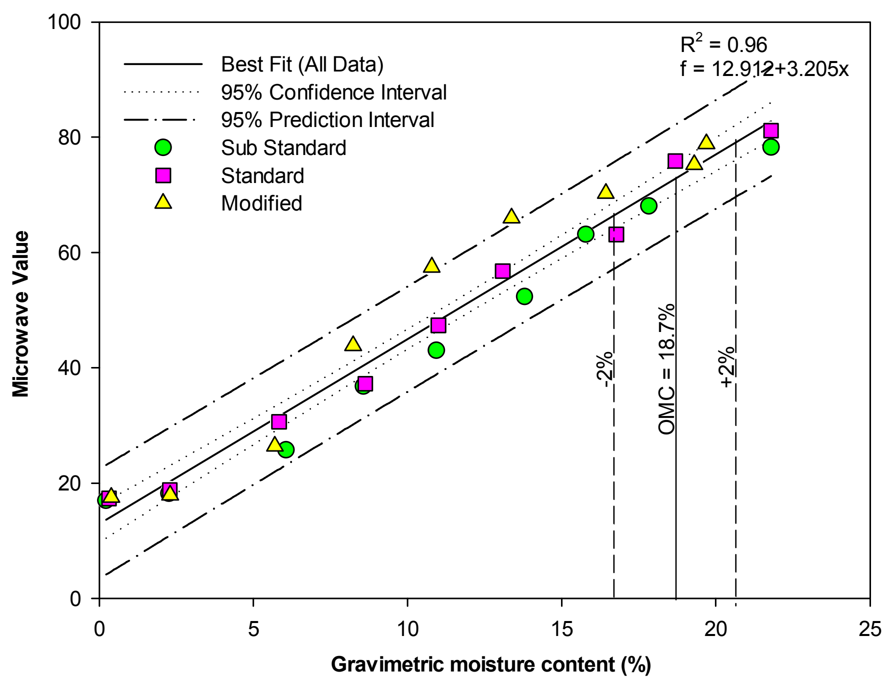


Figure 34. Gravimetric moisture content vs. Microwave value – Kickapoo Clay

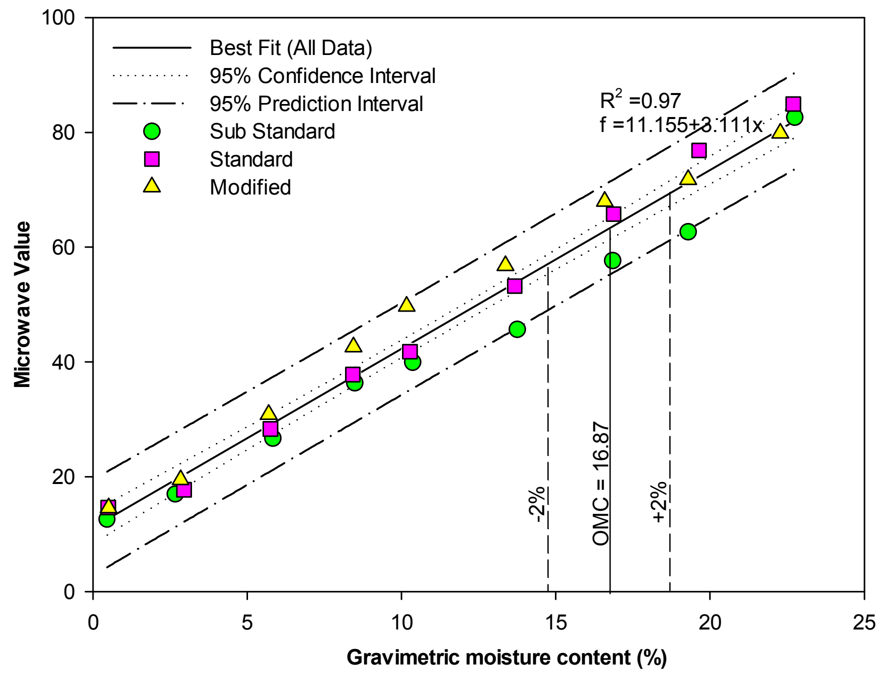


Figure 35. Gravimetric moisture content vs. Microwave value – Kickapoo Topsoil

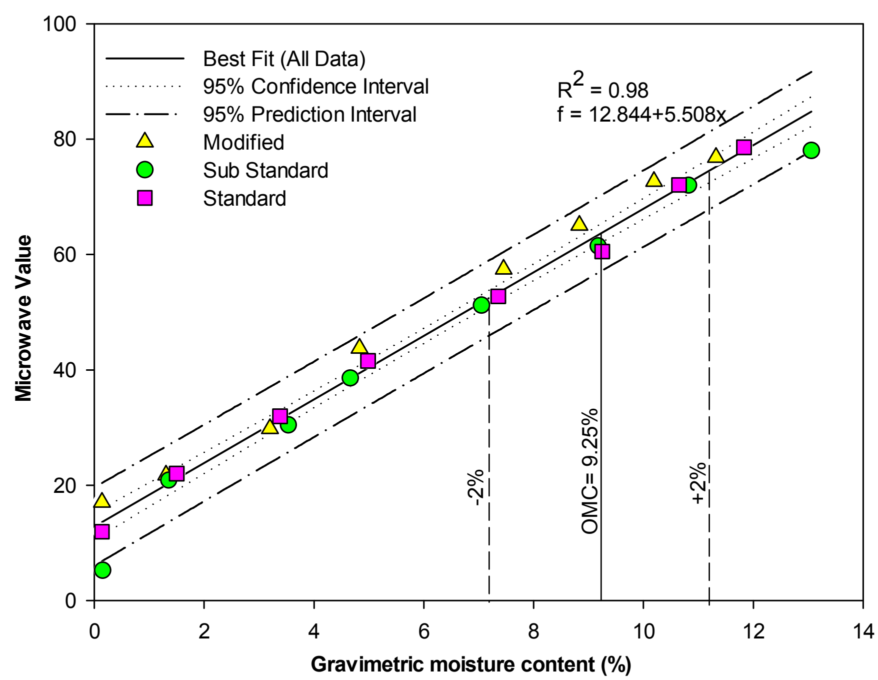


Figure 36. Gravimetric moisture content vs. Microwave value – FA6

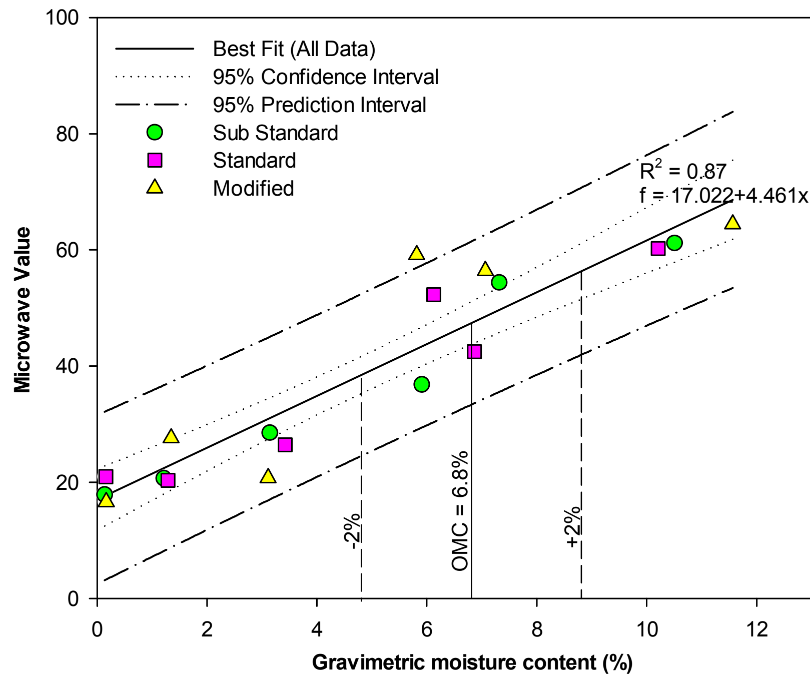


Figure 37. Gravimetric moisture content vs. Microwave value – CA6G

Spot Tests

Microwave sensor suitability tests were carried out at Caterpillar laboratory on a test bed prepared for this purpose. The test bed was made of four different soil types, Edward Till, Kickapoo Clay, Kickapoo Top soil and FA6 laid in a row, each soil extending up to 10feet on the ground. The Microwave sensor was placed on a sled which moved at constant speed and the microwave values were recorded. Trials of slow speed and fast speed sled movements were made. Tests were carried out in air dry, wet and dry conditions to optimum. Samples were collected for oven dry moisture content determination from all three locations at all points of spot tests on all soil types.

The plots of distance vs. microwave value and oven dry moisture contents taken at the spot on wet and dry sides are shown in figures 38-45. Time versus microwave value plots for these tests on all soils are shown in figures 46-53. Results of slow speed and fast speed sled movements on air dry soil beds are also presented in this section. The plots of distance vs. microwave value/moisture content and time vs. microwave value for slow and fast sled movements on air dry soil beds are shown in figures 54-69. This slow and fast sled movement data is available for Kickapoo clay, Kickapoo top soil and FA6 soils. Slow sled movement was done on Kickapoo clay three times and all the results obtained are plotted and shown below (figures 54-69). The plots of gravimetric moisture content vs. microwave value for all soils tested in air dry, wet and dry sides of the test bed are shown in figures 70-73.

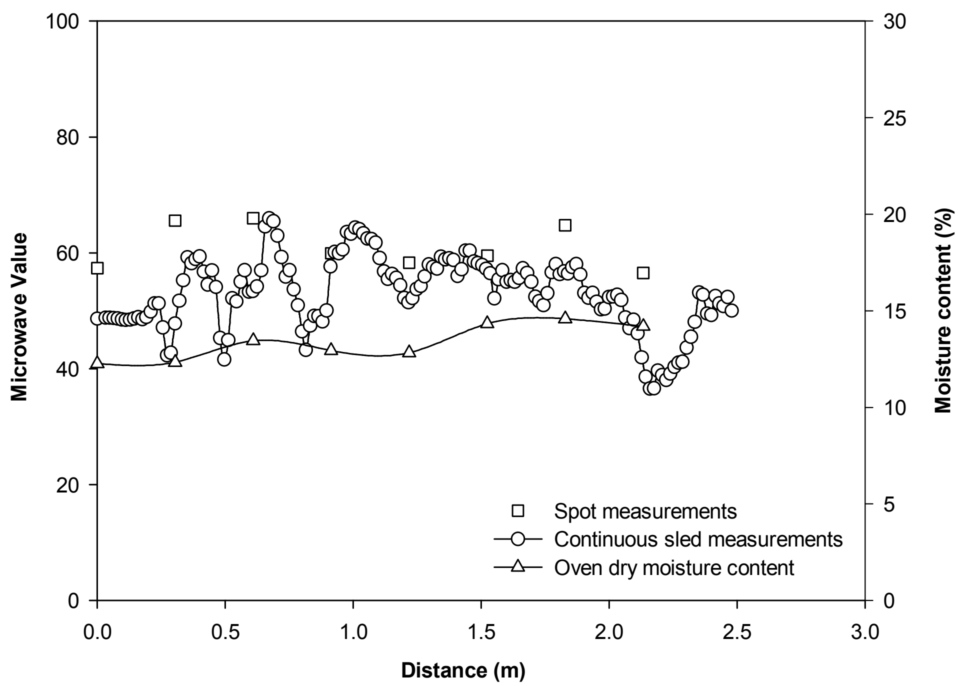


Figure 38. Continuous microwave sled and oven dry spot tests on Edward Till – Wet side

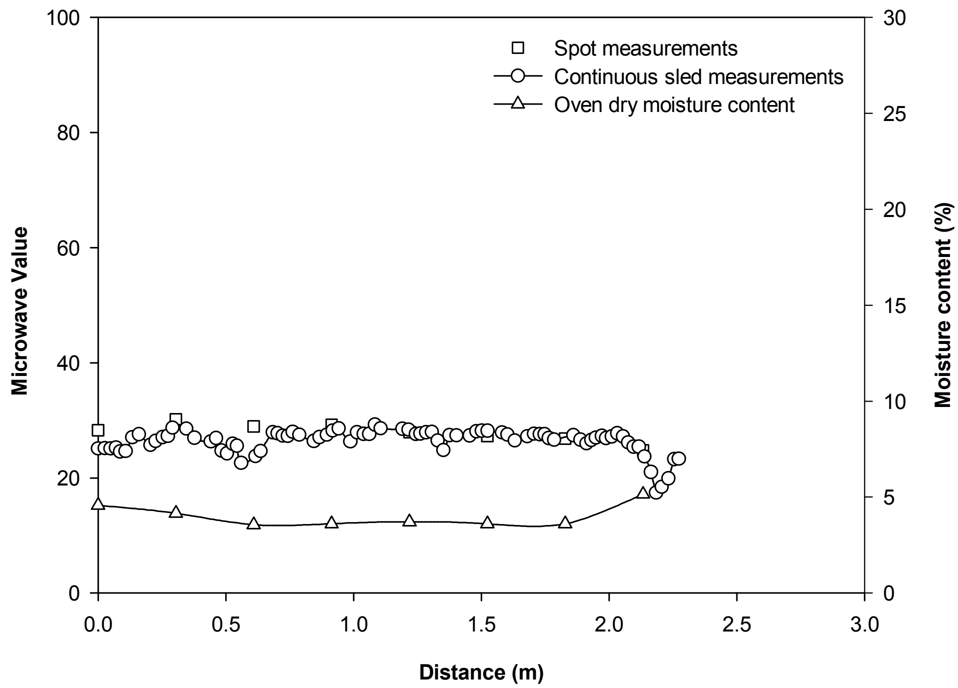


Figure 39. Continuous microwave sled and oven dry spot tests on Edward Till – Dry side

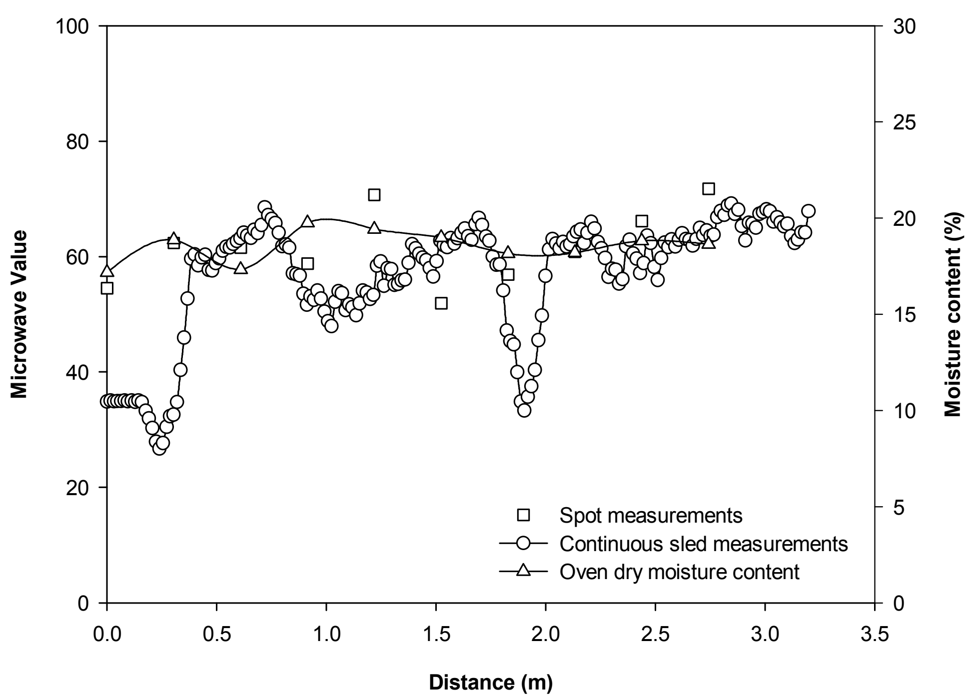


Figure 40. Continuous microwave sled and oven dry spot tests on Kickapoo Clay – Wet side

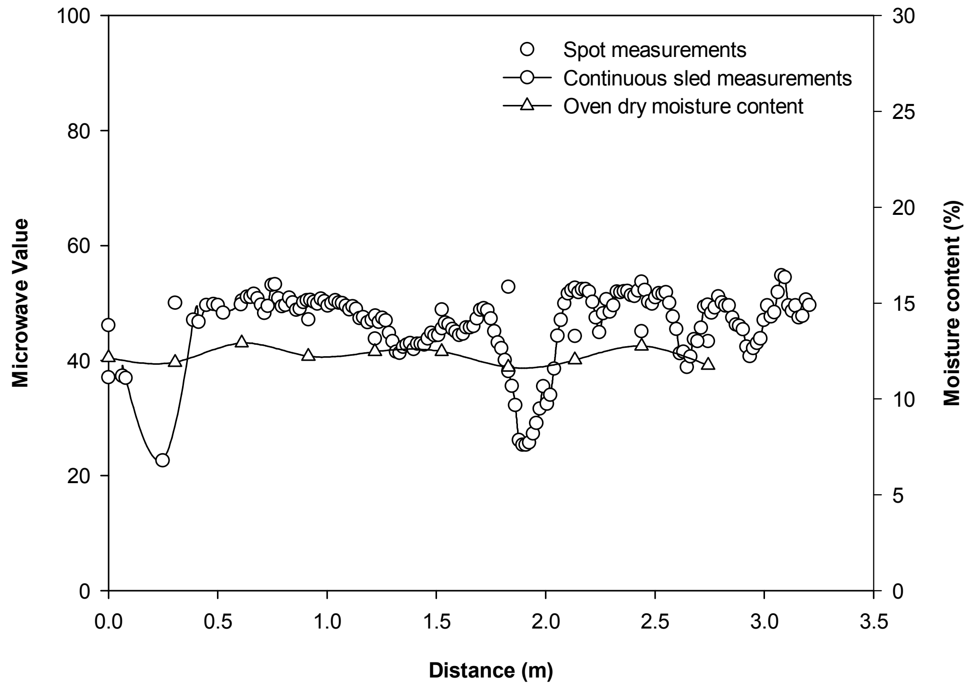


Figure 41. Continuous microwave sled and oven dry spot tests on Kickapoo Clay – Dry side

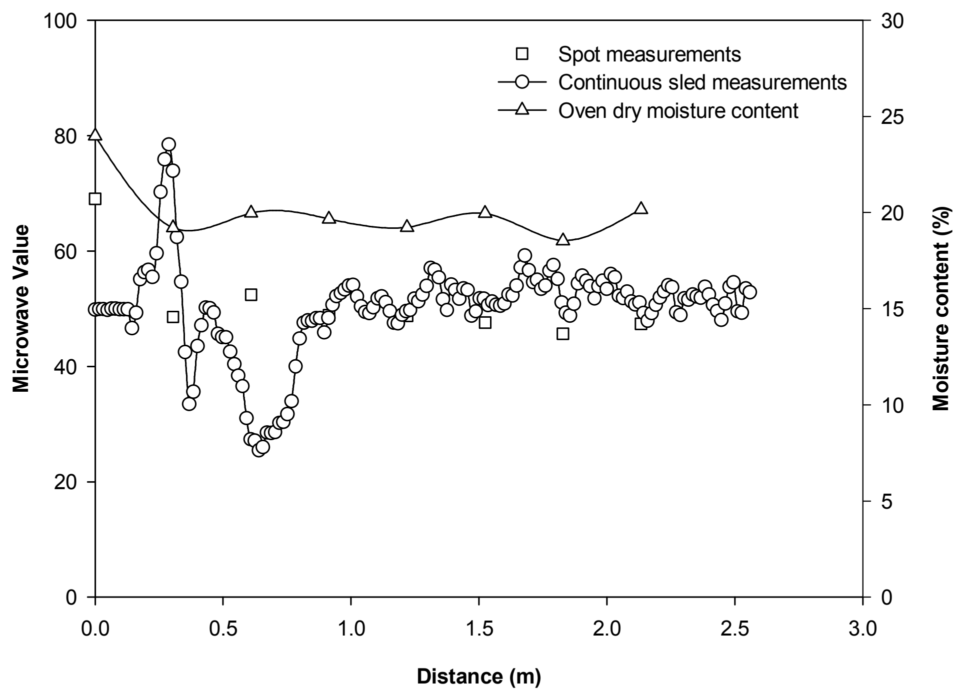


Figure 42. Continuous microwave sled and oven dry spot tests on Kickapoo Topsoil – Wet side

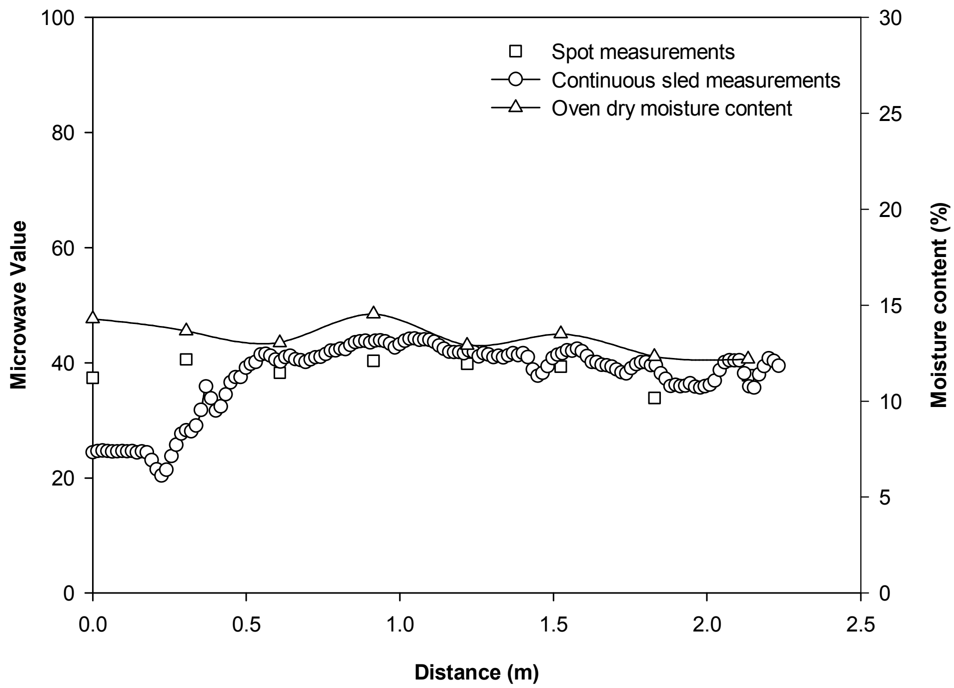


Figure 43. Continuous microwave sled and oven dry spot tests on Kickapoo Topsoil – Dry side

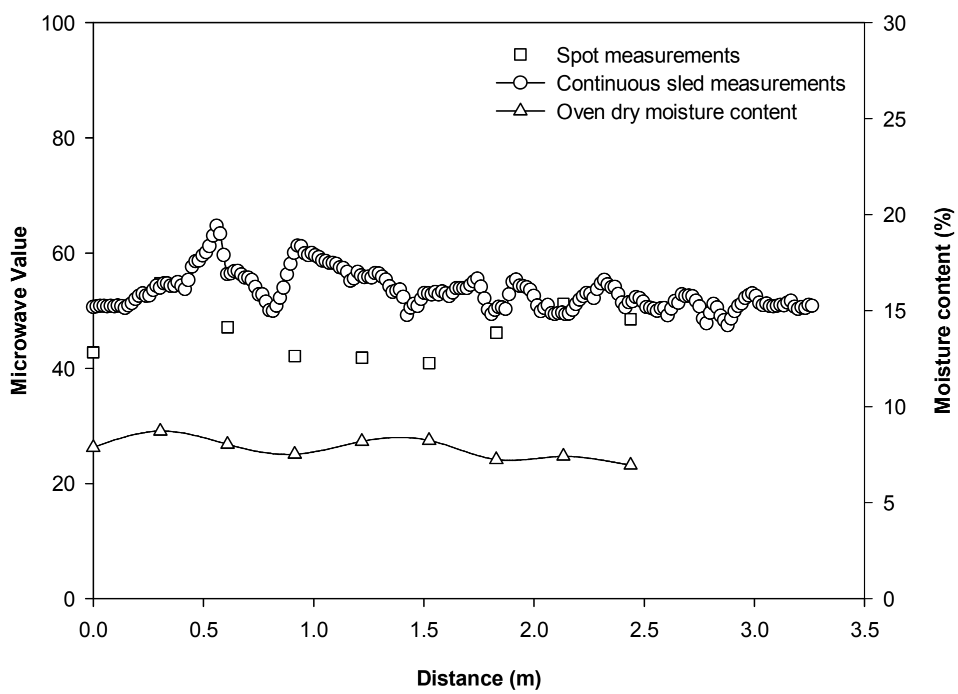


Figure 44. Continuous microwave sled and oven dry spot tests on FA6 – Wet side

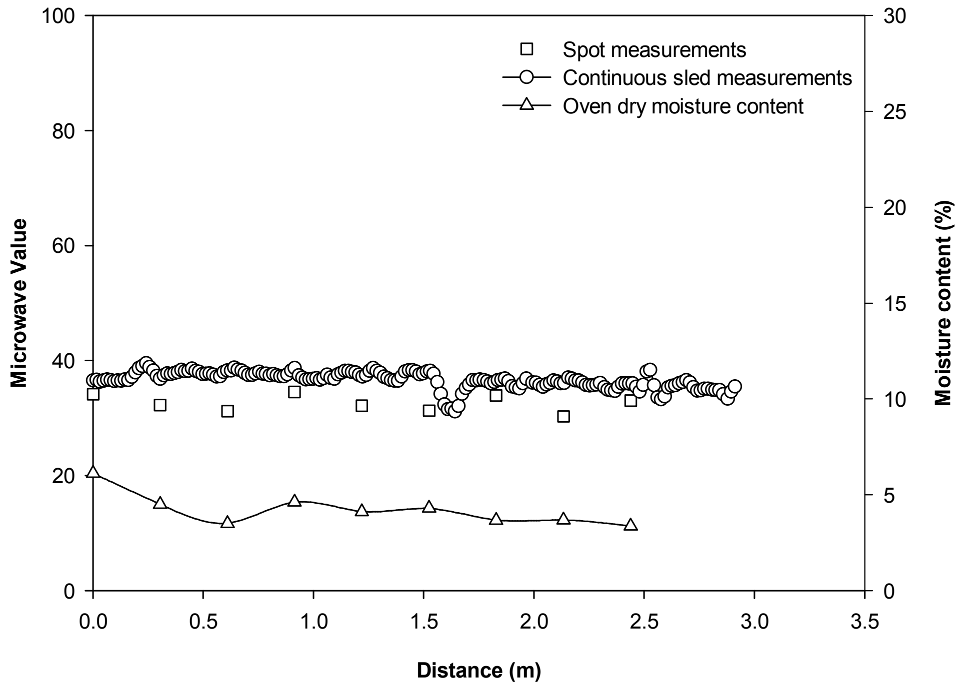


Figure 45. Continuous microwave sled and oven dry spot tests on FA6 – Dry side

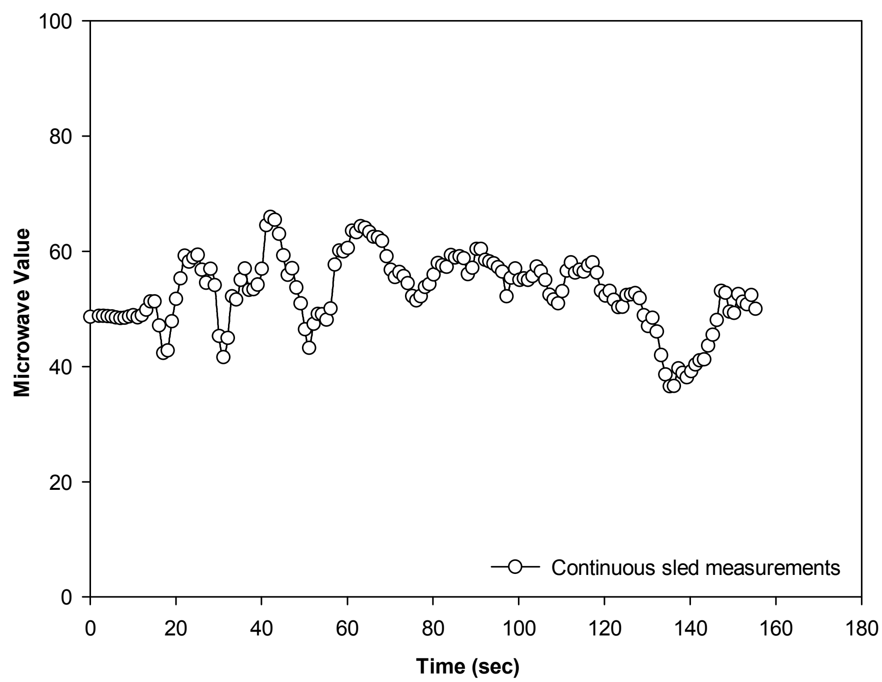


Figure 46. Continuous microwave sled tests on Edward Till – Wet side

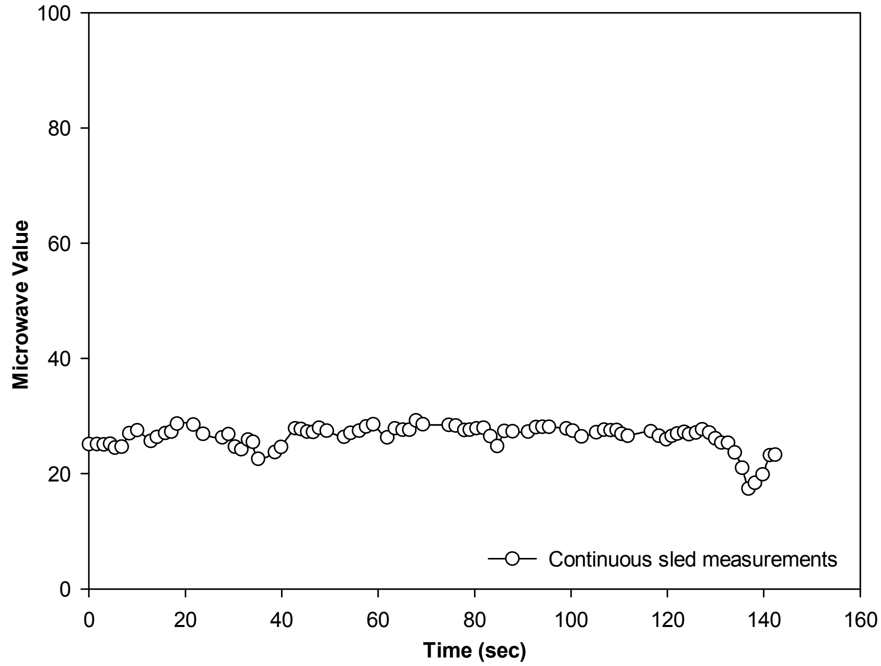


Figure 47. Continuous microwave sled tests on Edward Till – Dry side

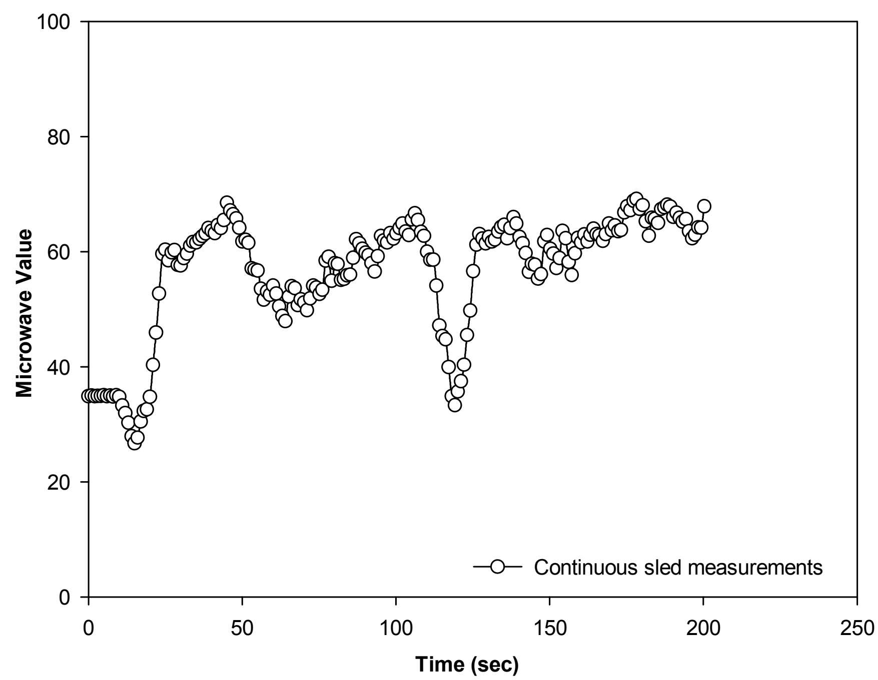


Figure 48. Continuous microwave sled tests on Kickapoo Clay – Wet side

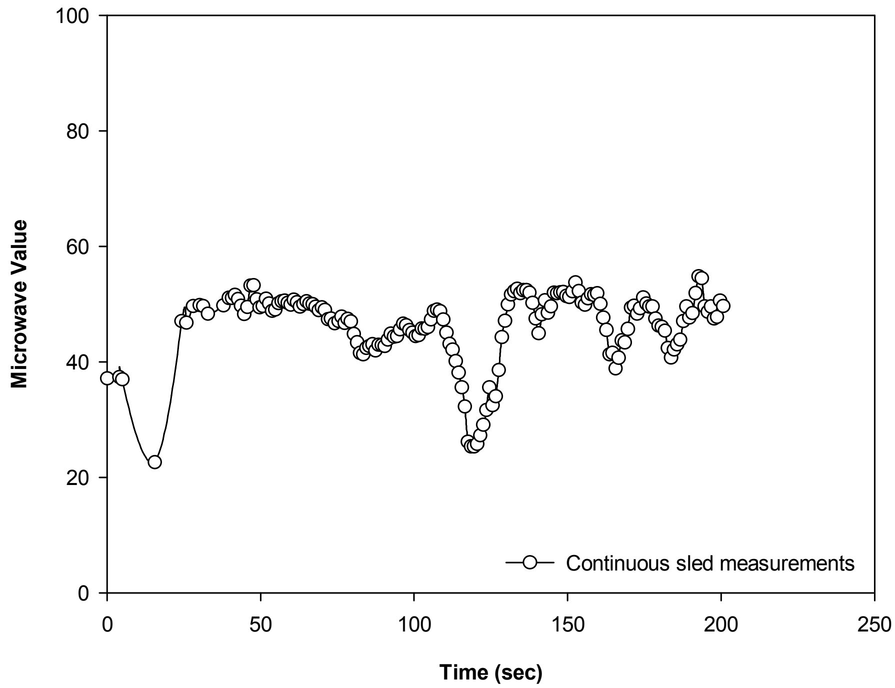


Figure 49. Continuous microwave sled tests on Kickapoo Clay – Dry side

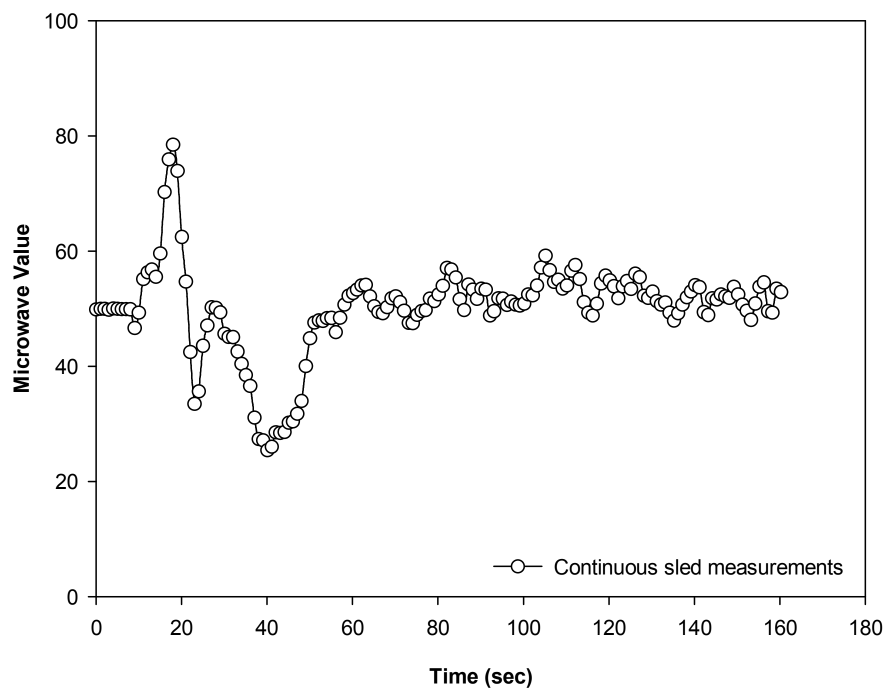


Figure 50. Continuous microwave sled tests on Kickapoo Topsoil – Wet side

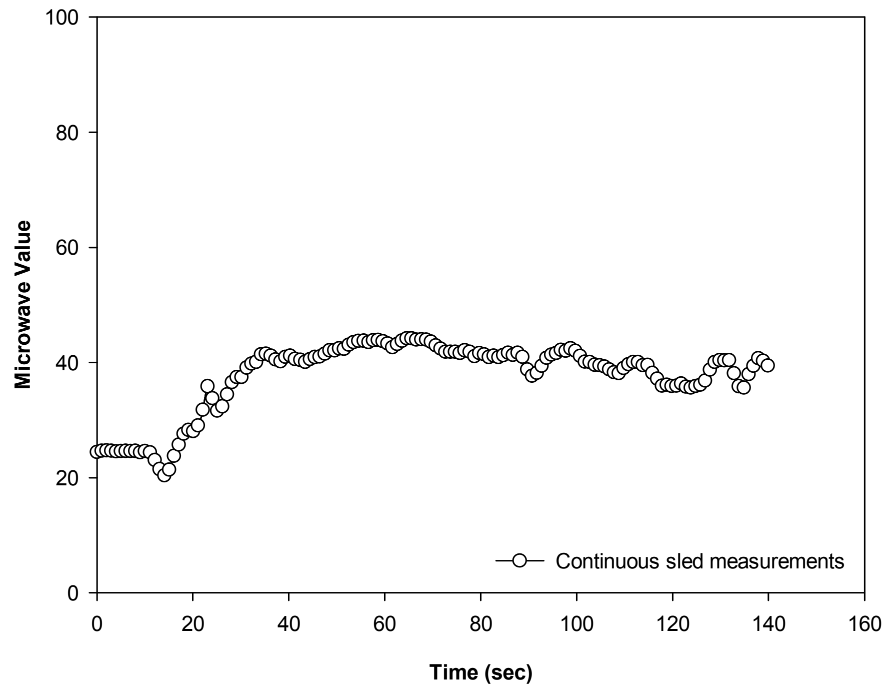


Figure 51. Continuous microwave sled tests on Kickapoo Topsoil – Dry side

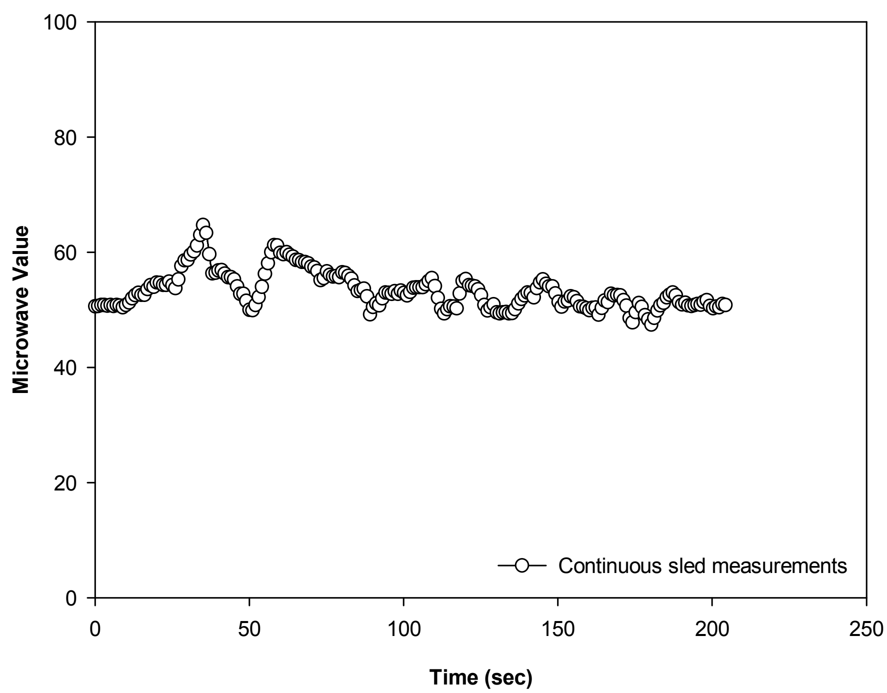


Figure 52. Continuous microwave sled tests on FA6 – Wet side

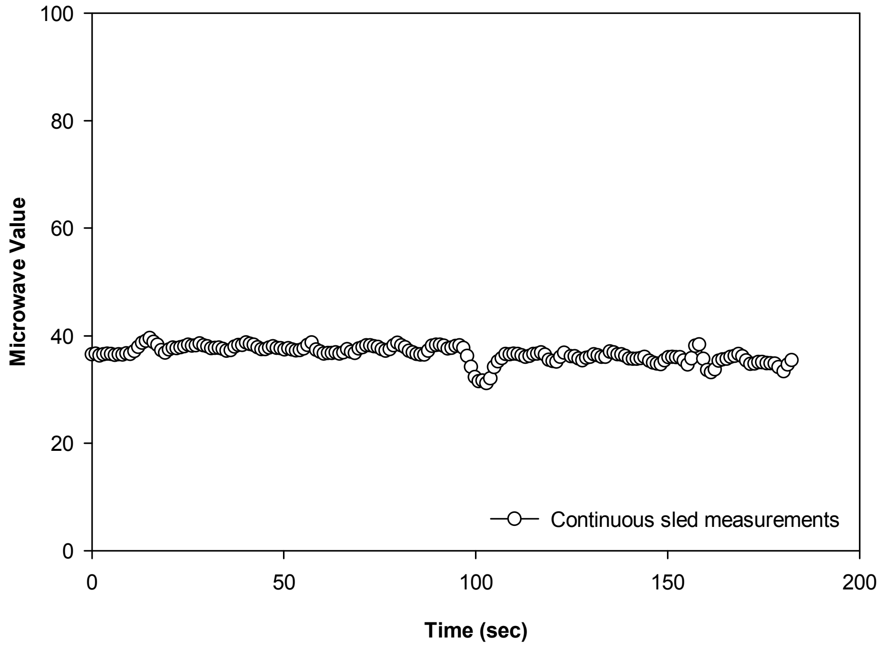


Figure 53. Continuous microwave sled tests on FA6 – Dry side

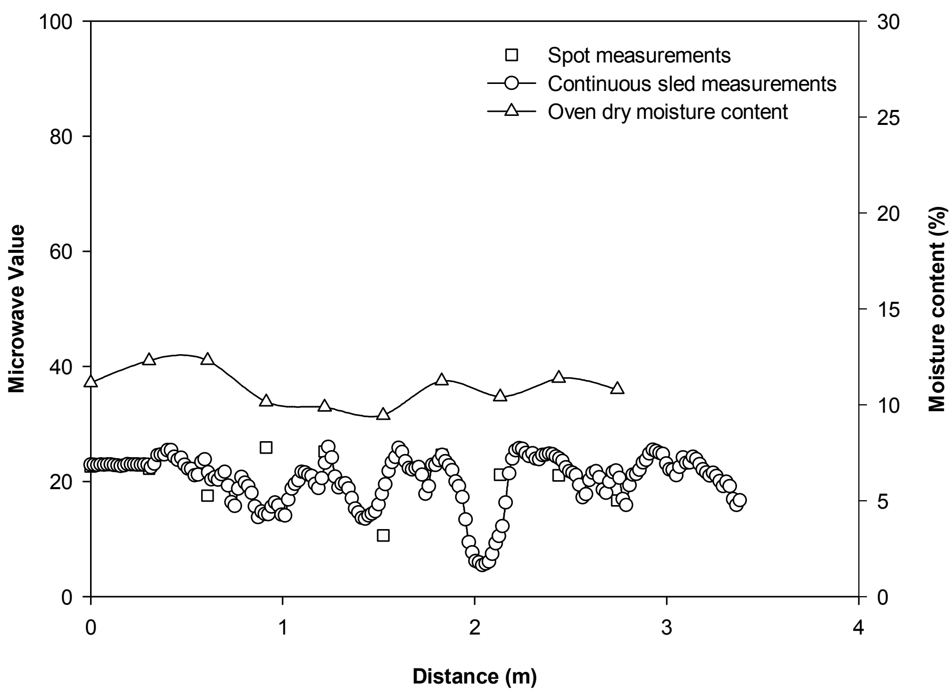


Figure 54. Distance vs. Microwave value /Moisture Content-Kickapoo Clay-Slow sled movement-1 on air dry bed

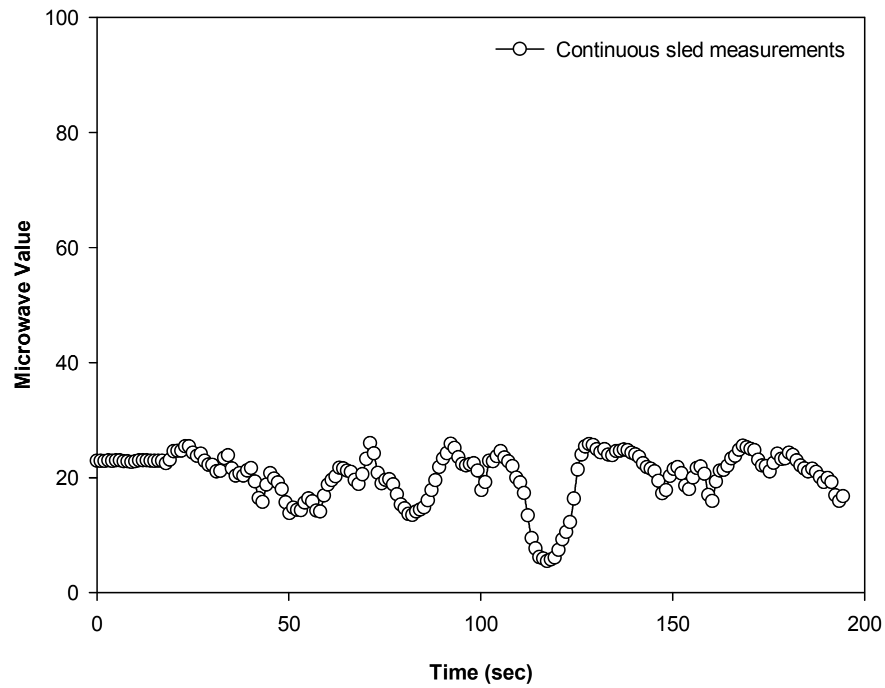


Figure 55. Time vs. Microwave value -Kickapoo Clay-Slow sled movement-1 on air dry bed

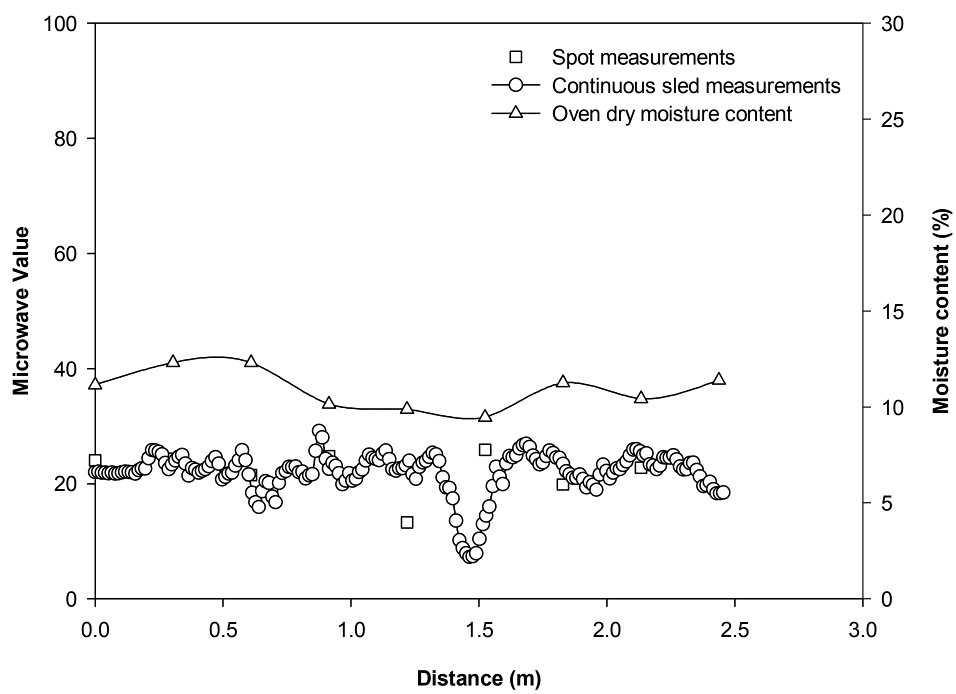


Figure 56. Distance vs. Microwave value/ Moisture content -Kickapoo Clay-Slow sled movement-2 on air dry bed

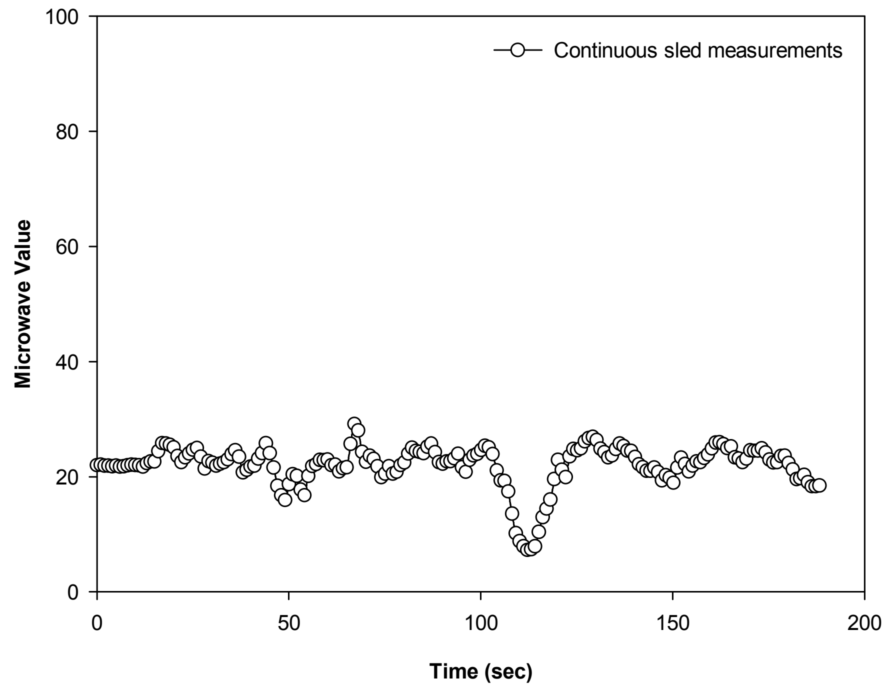


Figure 57. Time vs. Microwave value -Kickapoo Clay-Slow sled movement-2 on air dry bed

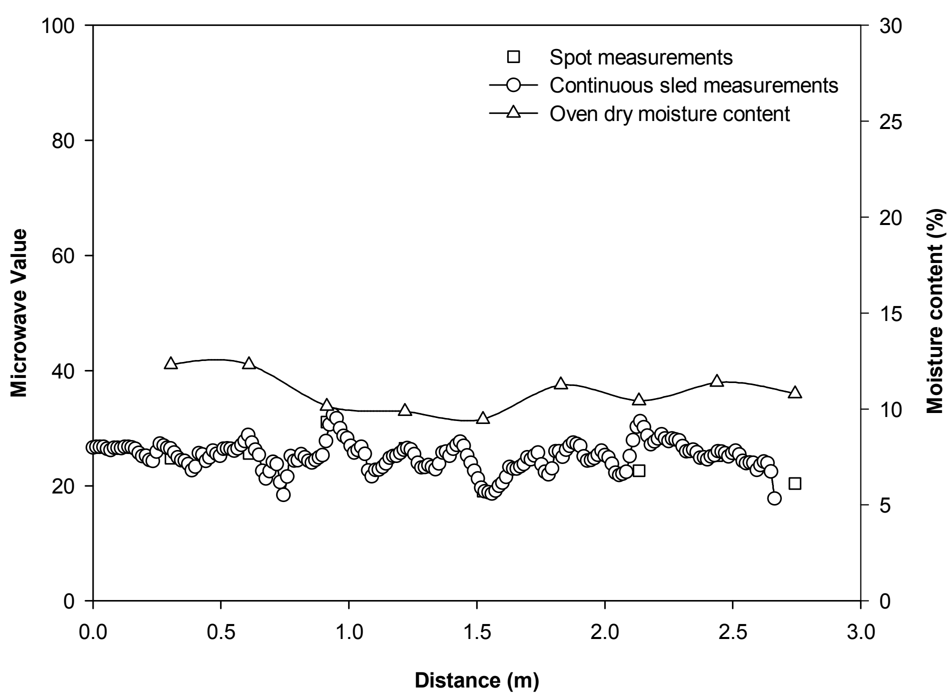


Figure 58. Distance vs. Microwave value/ Moisture content -Kickapoo Clay-Slow sled movement-3 on air dry bed

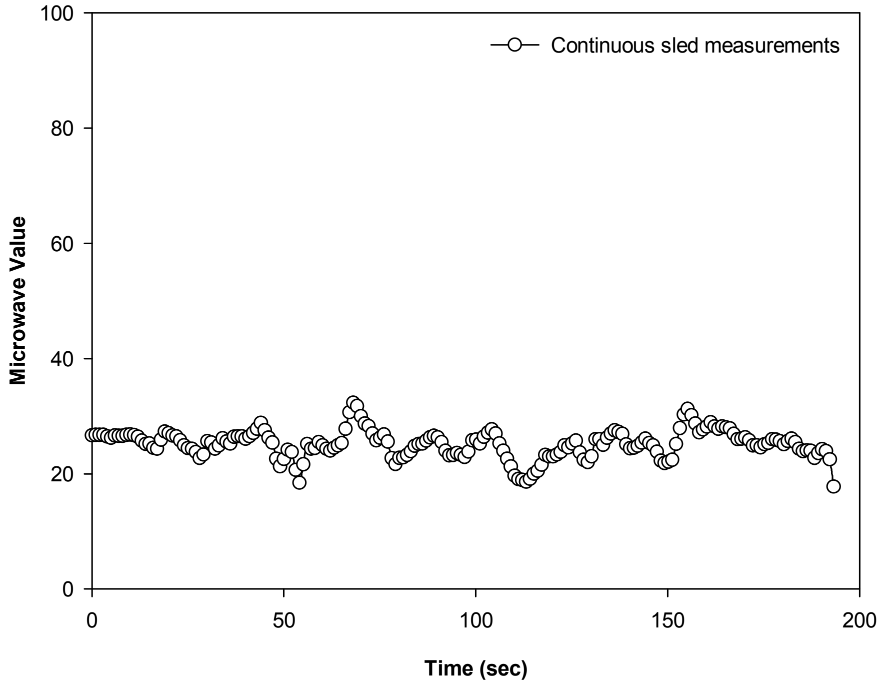


Figure 59. Time vs. Microwave value -Kickapoo Clay-Slow sled movement-3 on air dry bed

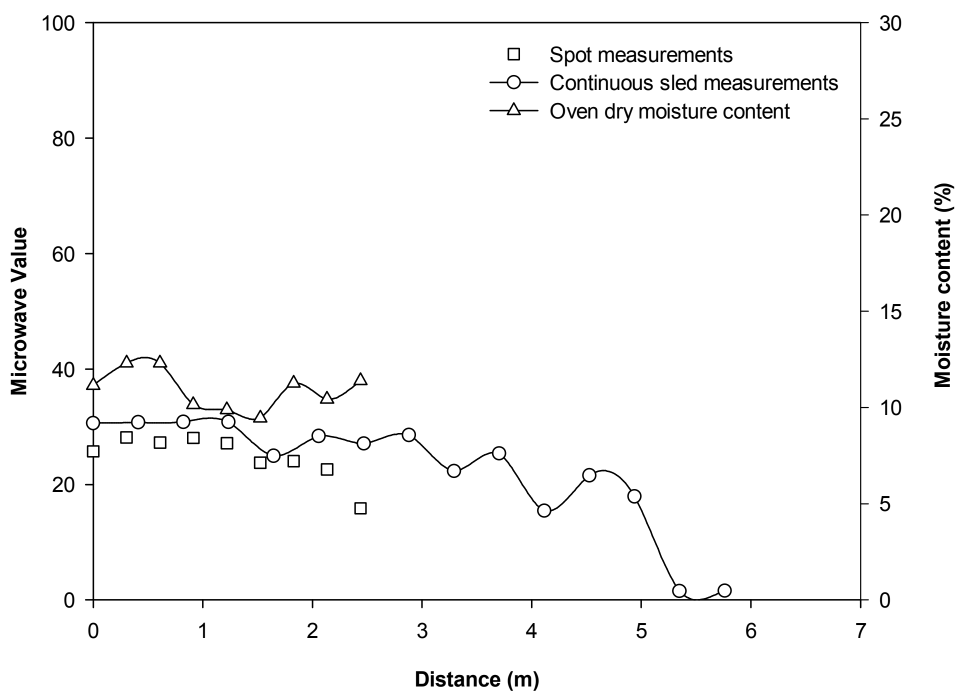


Figure 60. Distance vs. Microwave value / Moisture content -Kickapoo Clay-Fast sled movement on air dry bed

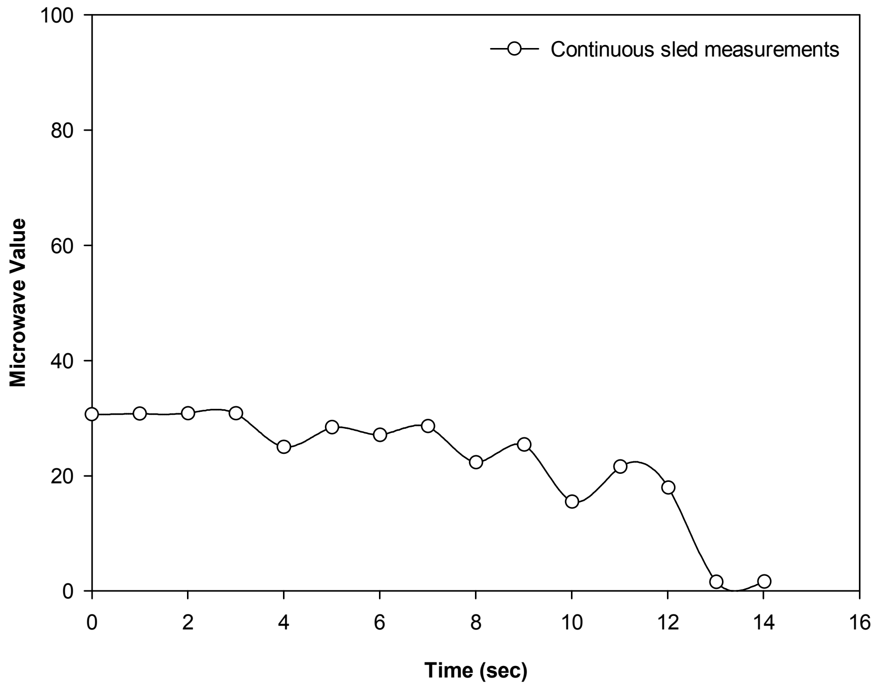


Figure 61. Time vs. Microwave value -Kickapoo Clay-Fast sled movement on air dry bed

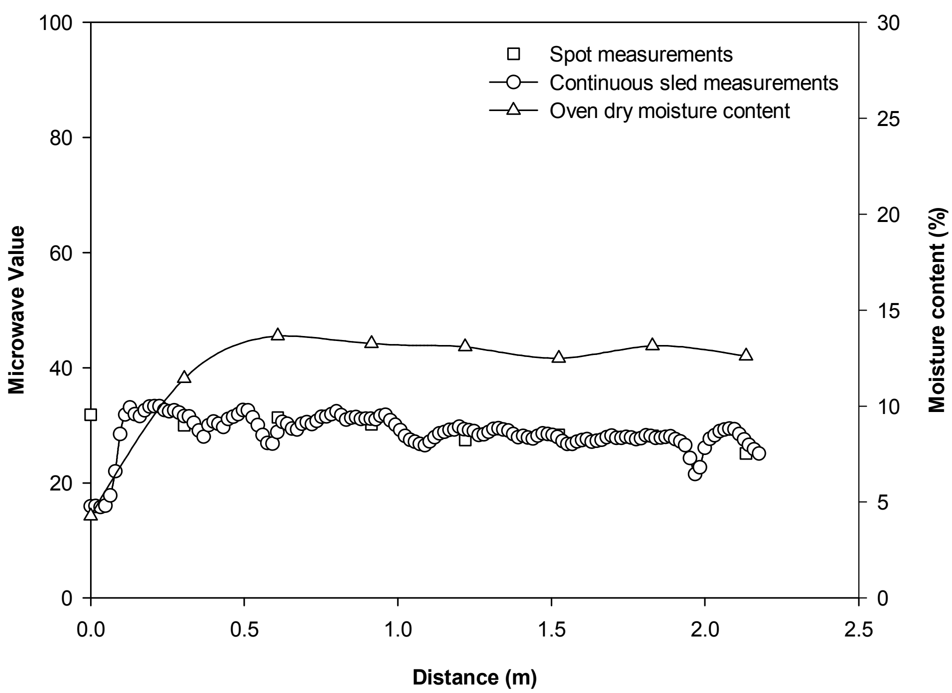


Figure 62. Distance vs. Microwave value/ Moisture content -Kickapoo Topsoil-Slow sled movement on air dry bed

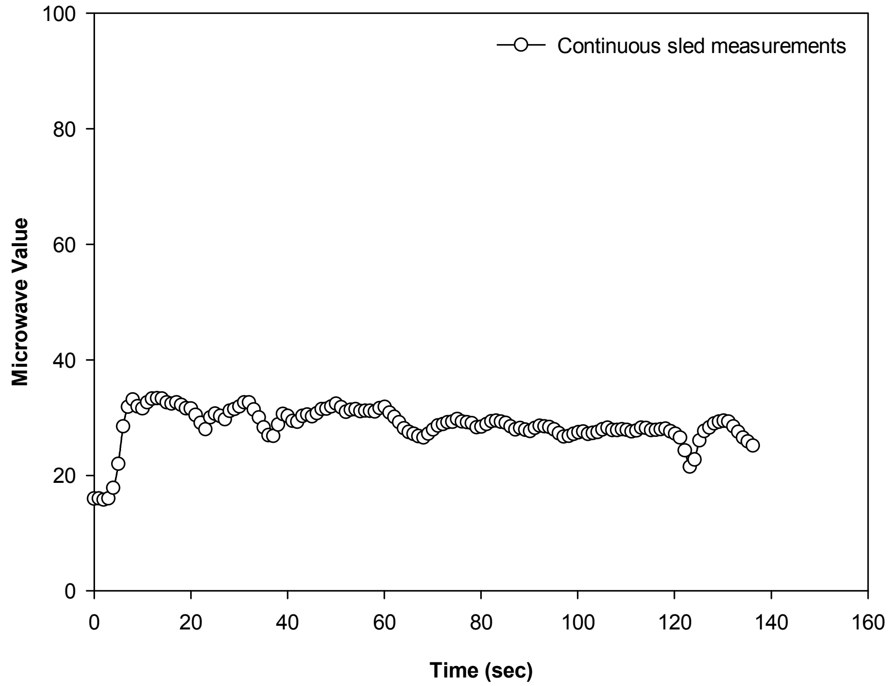


Figure 63. Time vs. Microwave value -Kickapoo Topsoil-Slow sled movement on air dry bed

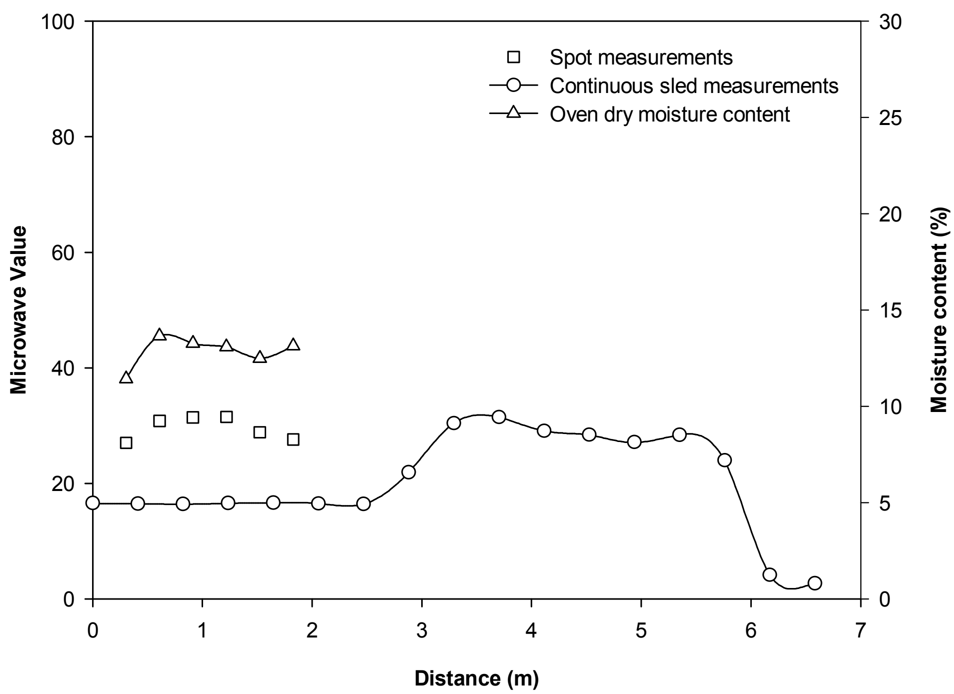


Figure 64. Distance vs. Microwave value / Moisture content -Kickapoo Topsoil-Fast sled movement on air dry bed

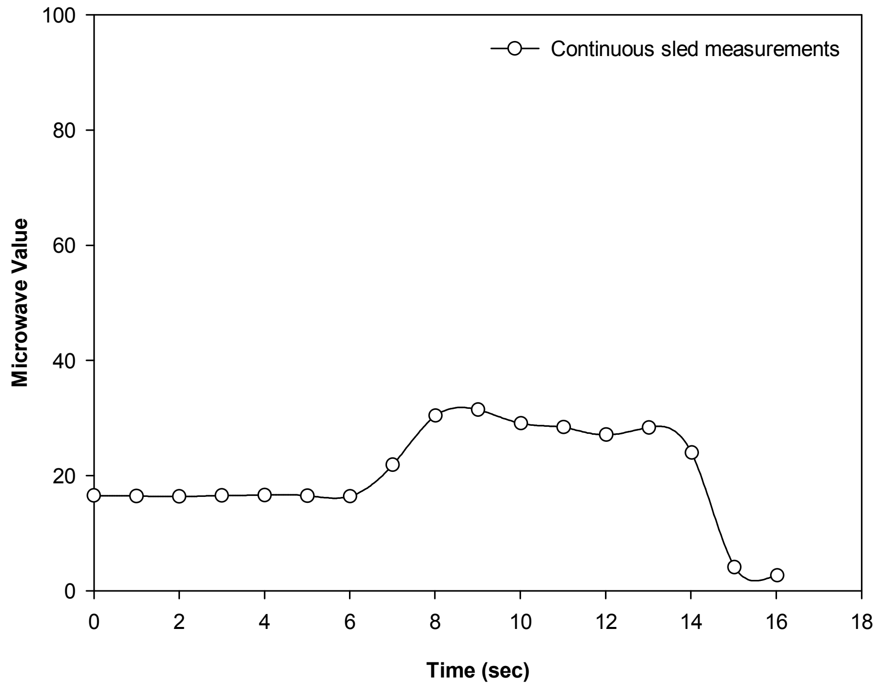


Figure 65. Time vs. Microwave value -Kickapoo Topsoil-Fast sled movement on air dry bed

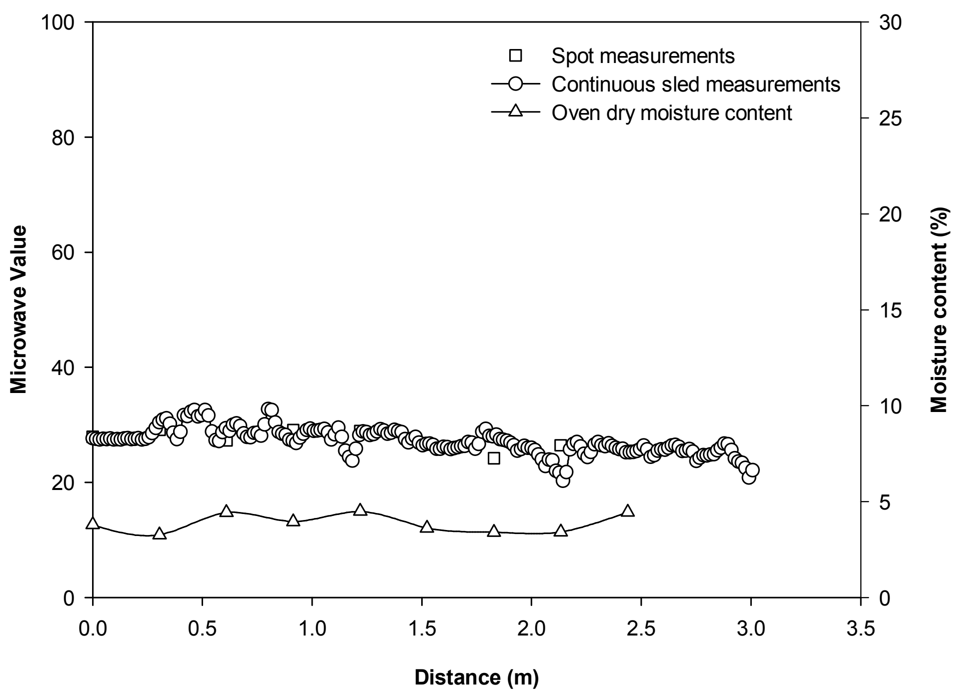


Figure 66. Distance vs. Microwave value/ Moisture content –FA6-Slow sled movement on air dry bed

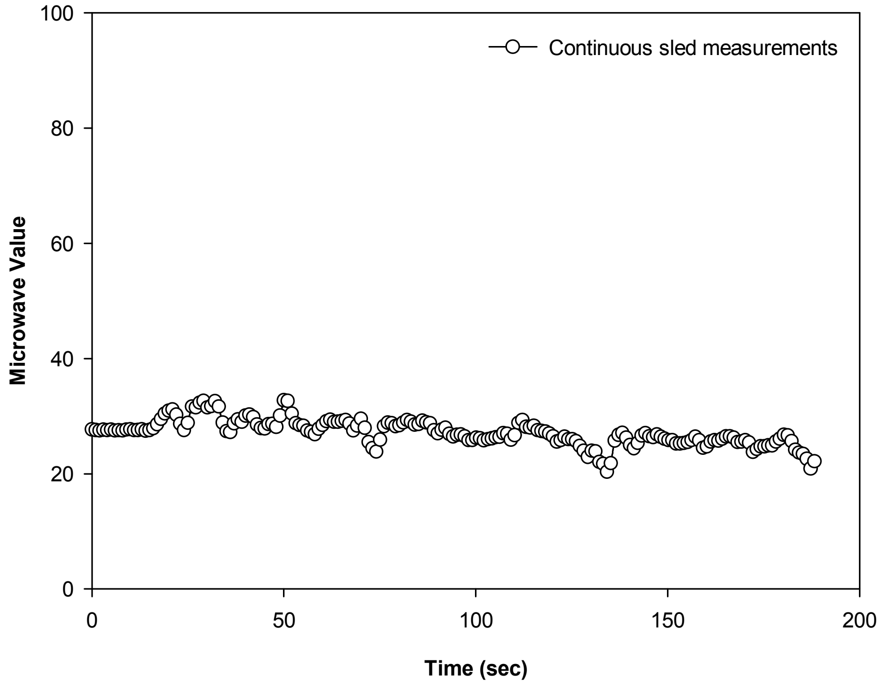


Figure 67. Time vs. Microwave value –FA6-Slow sled movement on air dry bed

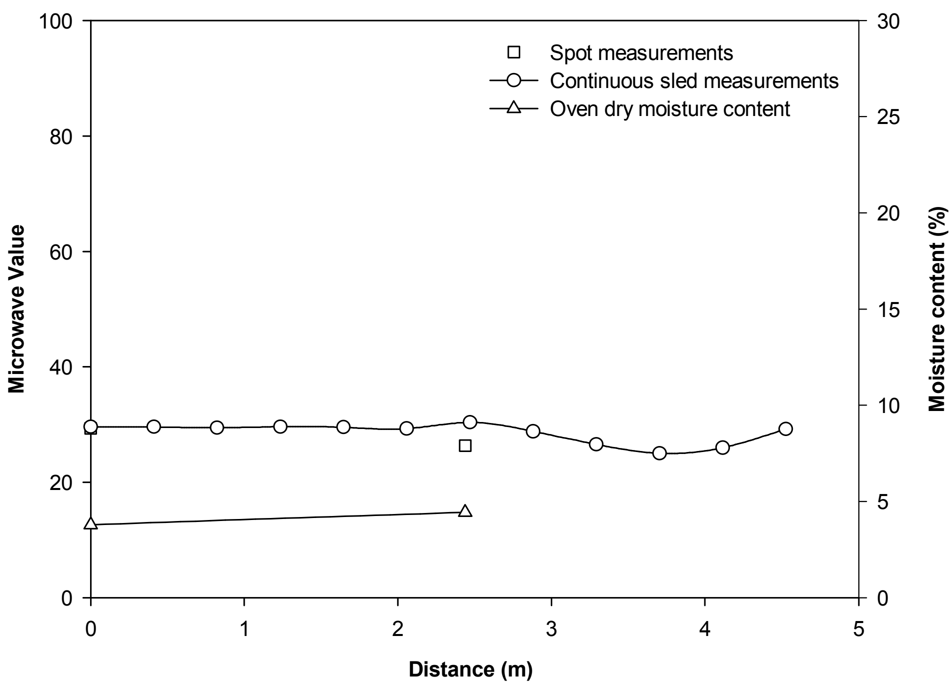


Figure 68. Distance vs. Microwave value / Moisture content –FA6-Fast sled movement on air dry bed

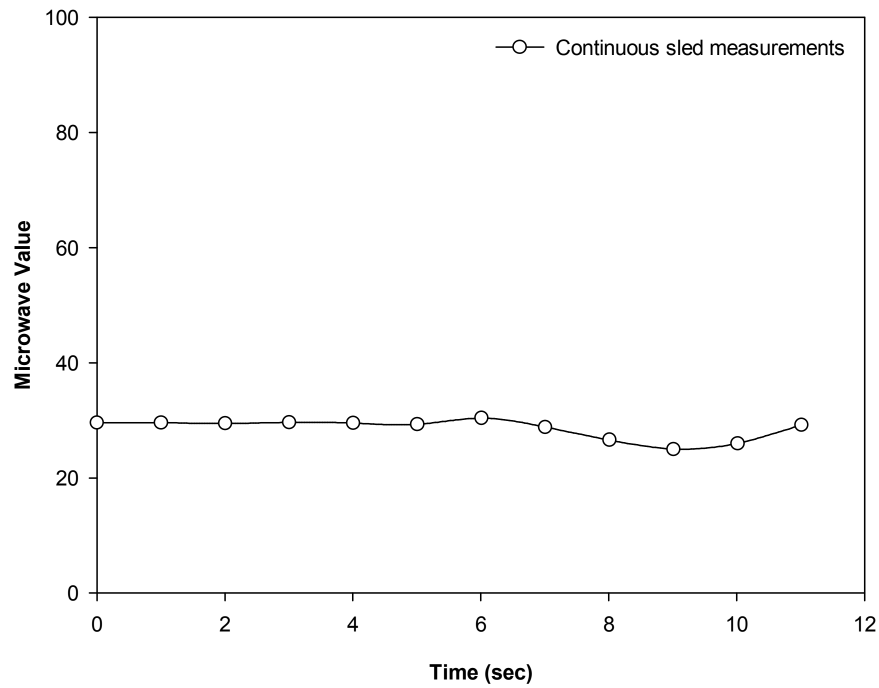


Figure 69. Time vs. Microwave value –FA6-Fast sled movement on air dry bed

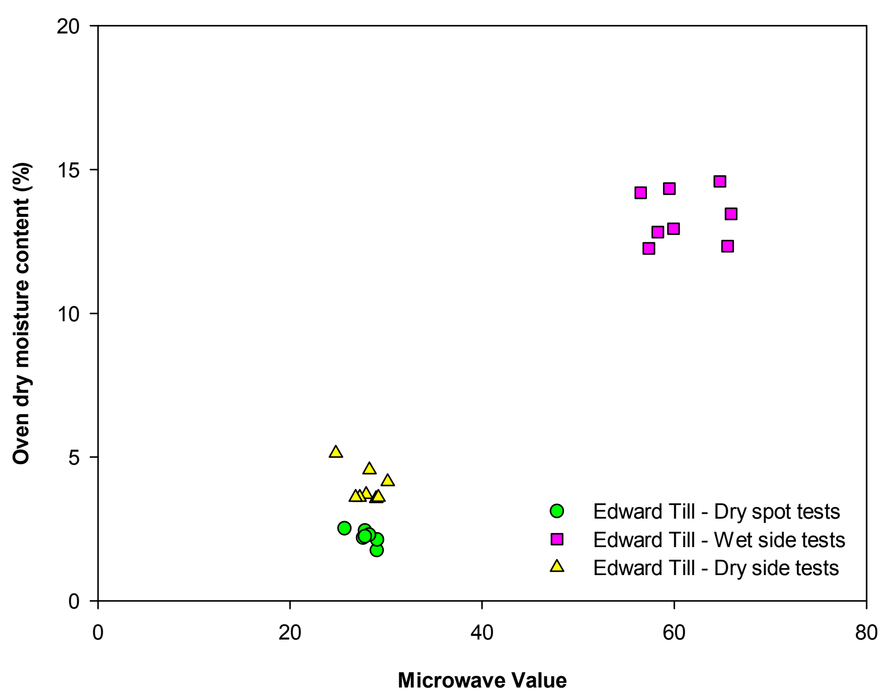


Figure 70. Moisture content vs. Microwave Value – Edward Till - Spot tests

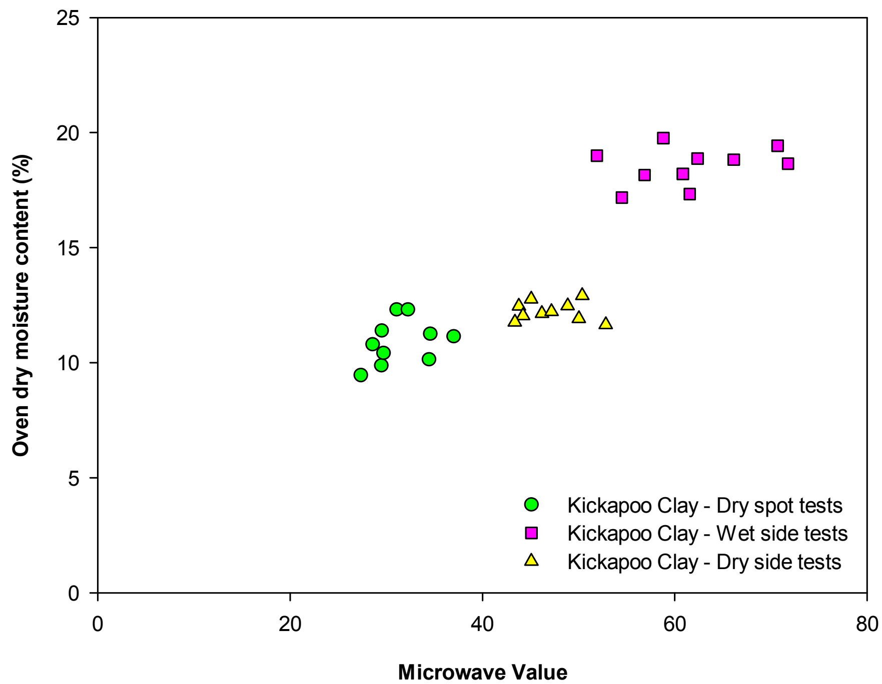


Figure 71. Moisture content vs. Microwave Value – Kickapoo Clay - Spot tests

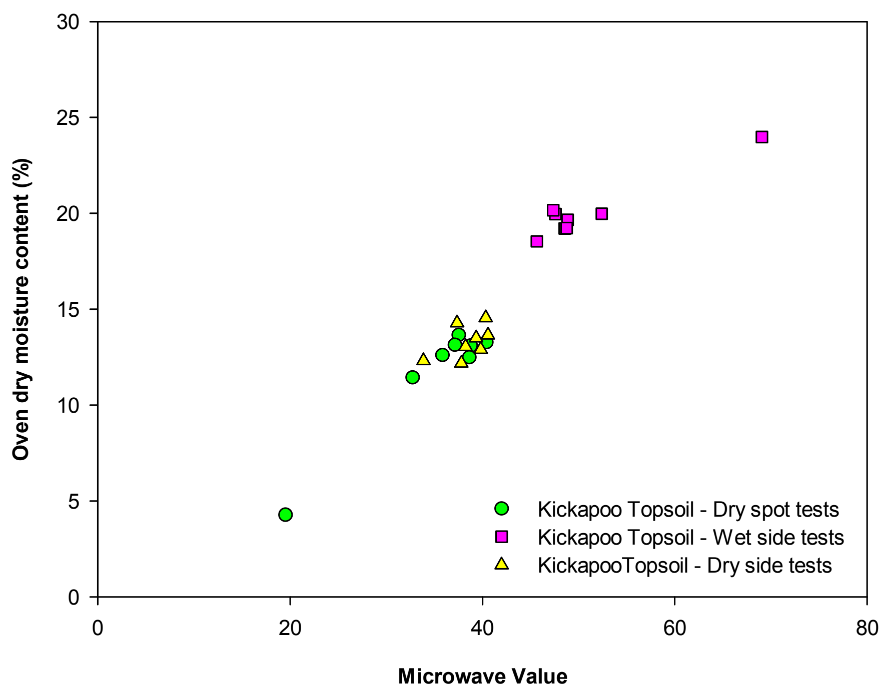


Figure 72. Moisture content vs. Microwave Value – Kickapoo Top soil - Spot tests

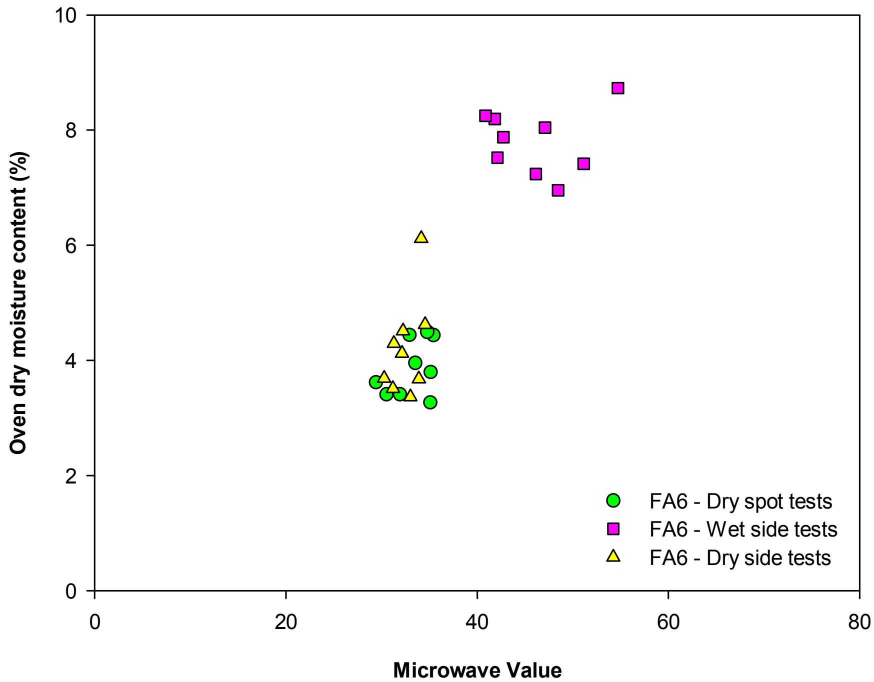


Figure 73. Moisture content vs. Microwave Value – FA6 - Spot tests

Model Development

Microwave Sensor models are developed using the statistical software. These models are evolved after studying various trials considering different variables and their interactions. Significance tests like p-test and t-test are performed to check the significance of different variables and/or their combination and the most suitable model for that particular soil type is chosen. The results of the significance tests are summarized in Table 32. The coefficients of the best suitable model for each soil type are presented in Table 33.

Table 32. Significance Tests on Different Models

Soil Type	Edward Till	Kickapoo Clay	Kickapoo Topsoil	FA6	CA6G
Model Type (Variables used)					
Linear Regr.(MV)	√	√	√	√	√
Multiple Regr.(MV+DD)	√	√	√	X	X
Multiple Regr.(MV+MV^2)	X	X	X	√	X
Multiple Regr.(MV+DD+MV^2)	√	√	√	X	X

*Abbrevations :-
Regr. – Regression ; MV – Microwave Value ; DD- Dry Density
√ - Significant ; X – Not significant (From p-test and t-test)

Table 33. Model Coefficients

Soil Type	Edward Till	Kickapoo Clay	Kickapoo Topsoil	FA6	CA6G
Model Variables	MV	MV	MV	MV+MV^2	MV
Coefficients (Term)					
β_o (Intercept)	-6.9710	-3.4823	-3.1764	-1.3926	-2.7153
β_1 (Microwave Value)	0.3411	0.3004	0.3124	0.1311	0.1953
β_2 (Microwave Value)^2	-	-	-	0.0005	-

*MV – Microwave Value

Using the statistical models developed from laboratory test data as described above and the spot test microwave data, predicted moisture content values are obtained for all soil types. These predicted moisture contents are plotted against the measured moisture content obtained from the oven dry spot tests. These plots are shown in figures 74-77. All the spot test data are plotted on the measured vs. predicted plots in figure 78 and a 1:1 line is drawn through them.

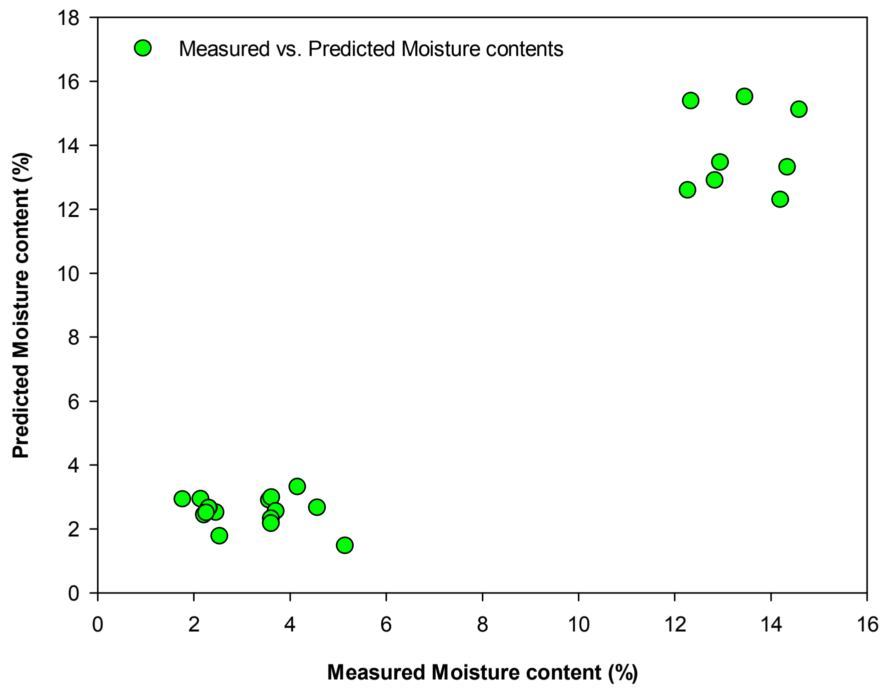


Figure 74. Predicted vs. Measured Moisture content– Edward Till

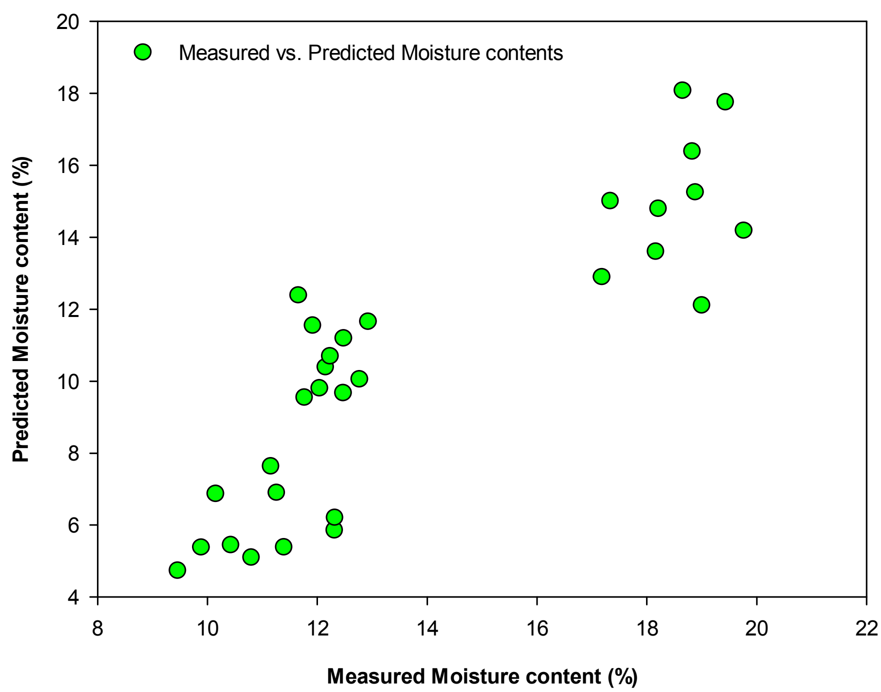


Figure 75. Predicted vs. Measured Moisture content– Kickapoo Clay

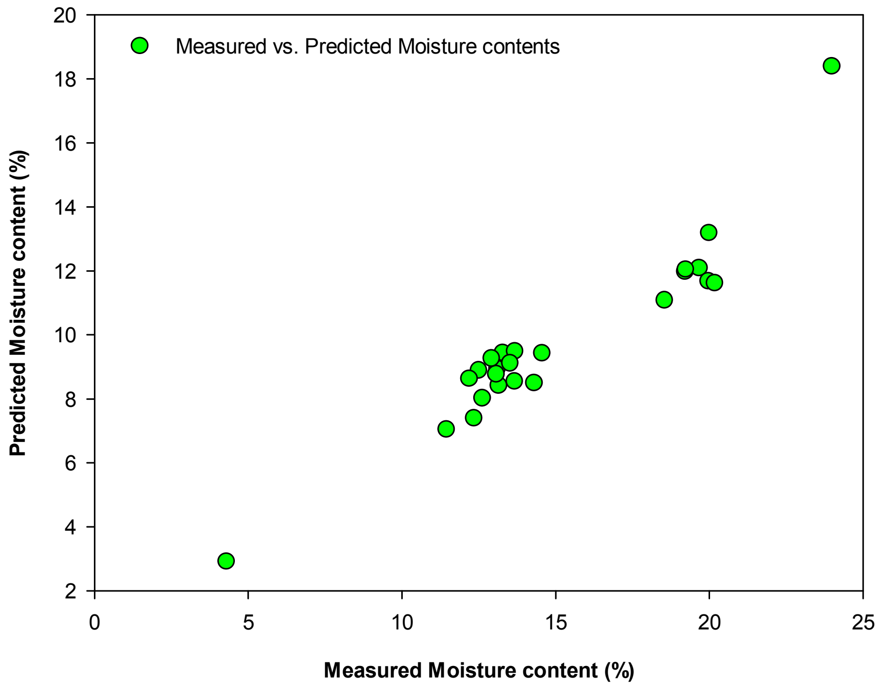


Figure 76. Predicted vs. Measured Moisture content– Kickapoo Top soil

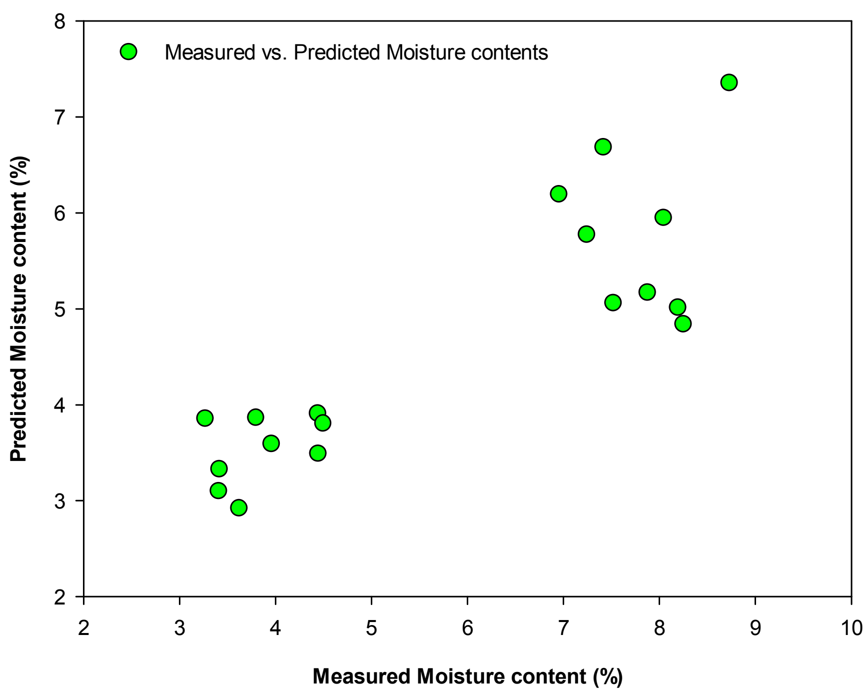


Figure 77. Predicted vs. Measured Moisture content– FA6

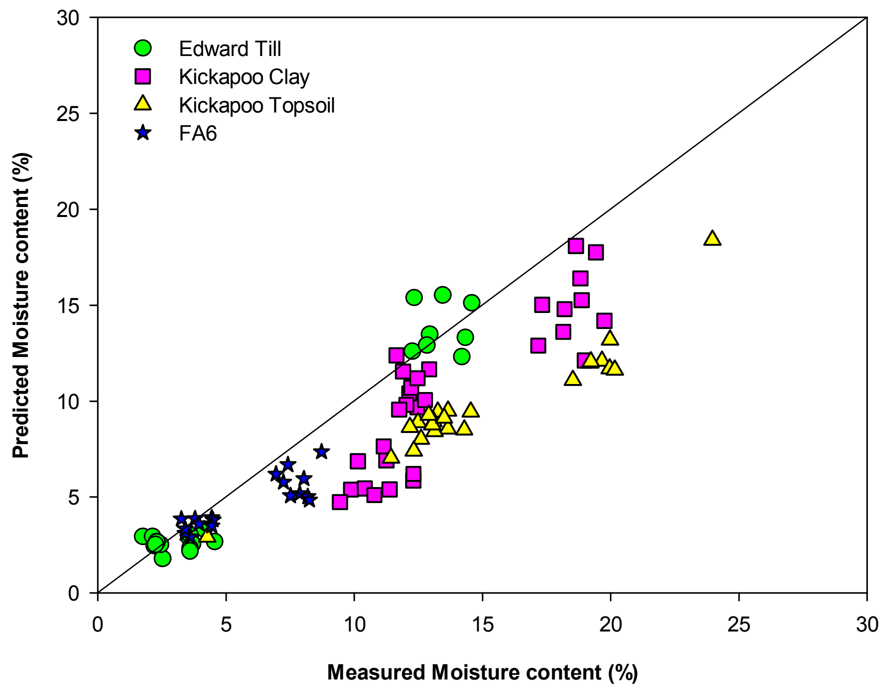


Figure 78. Predicted vs. Measured Moisture content– All soils

Discussion

Test Plan 6 is conducted to study the suitability of Microwave sensor for five different soils, namely Edward Till, Kickapoo Clay, Kickapoo Topsoil and FA6 and CA6G. The material properties of these soils (Tables 28-31) classify these soils broadly into cohesive and cohesionless soils, the Edward Till, Kickapoo Topsoil and Kickapoo Clay as cohesive and FA6 and CA6G behave as non-cohesive soils. The Atterberg limits could not be determined for FA6 and CA6G soils. Hence, they are defined as non-plastic. The specific gravities were also determined and range from 2.64-2.74. As an initial step, the Proctor moisture density relationships are determined for all the five soils at standard, substandard and modified compactive efforts. These tests are performed over a wide range of moisture contents involving wet and dry sides of optimum. Microwave sensor tests are done at all the three compactive efforts on all these five soils.

The plots of microwave values against the gravimetric moisture contents show R^2 values of 0.94 for Edward Till, 0.96 for Kickapoo Clay, 0.97 for Kickapoo Topsoil, 0.98 for FA6 and 0.87 for CA6G. The microwave values also correlate well to the moisture content as seen from these plots. Hence, microwave values can be considered to be very useful and significant in predicting the moisture content. The optimum moisture content obtained from the Standard Proctor curves are shown on these plots. The 95% confidence and prediction intervals are shown on these plots. The forecast of y for given x values can be interpreted in two ways. The resulting value can be the long-run average y value that results from averaging infinitely many observations of y when the x's have the specified values. The alternative interpretation is that this is the predicted y value for one individual case having the given x values. In brief, a forecast interval for the mean value is called a *confidence interval* and the forecast interval for an individual value is called a *prediction interval*. Because the prediction interval is an interval for the value of a single new measurement from the process, the uncertainty includes the noise that is inherent in the estimates of the regression parameters and the uncertainty of the new measurement. This means that the interval for the new measurement will be wider than the confidence interval for the value of the regression function. The 95% confidence interval gives a narrower range than the 95% prediction interval. The best fit equations are also presented.

Another variable that was tested for significance in the model is dry density. From the significance tests (p and t tests) performed using statistics (Table 32), dry density played a significant role in the case of cohesive soils, Edward Till, Kickapoo Clay and Kickapoo Topsoil, whereas, it did not show any effect in cohesionless soils like FA6 and CA6G. This can be attributed to greater void ratios in cohesionless soils than cohesive soils, which tend to reduce the effect of density in the moisture content model.

Other probable variables affecting the model might be percent passing #200 sieve, percent passing #4 sieve, liquid limit, plastic limit, percent gravel and percent fines in the sample. These models could not be developed with the available data of five soil types as the number of variables are more and the available soil data is insufficient with constant values of these variables for each soil type. Here the data set will consist of 5 points for each of these variables which are insufficient. More soils can be included in the testing program and checked for these variables in the future.

Although the model with microwave value and density proved better in cohesive soils, the residual plots showed some trend in the data, which cropped up doubts of insufficiency in the model. Hence the (microwave value) ^{2} term was introduced into the model. This term was also introduced in cohesionless soil models and tested for significance. This proved to slightly improve the model for FA6 soil only and was not significant for other soils. Hence this model was chosen in the case of FA6 soils only.

Combined model with microwave value, dry density and (microwave value)^2 has also been developed for all the soils. Though this model proved significant in cohesive soils, this was not implemented due to lack of dry density data at the spot. All these models developed are shown in the appendix section.

Spot tests were conducted at the Caterpillar laboratory on a test bed prepared for the purpose of evaluating the sensor. The sensor was placed on the sled and the sled was moved at different speeds and the microwave data noted. The distance versus microwave values are plotted for a continuous microwave sled movement on the wet and dry sides of optimum. The spot measurements taken at some points are also plotted on the same graph and the oven dry moisture contents at those spots are also shown. It can be seen that in the continuous sled measurements there is more variation in the data. This is due to the movement of the sensor along with the sled. In the course of this movement, the sensor encountered some dips in the test trench at which the sensor lost contact with the soil; this led to erroneous data at those points. This can also be caused due to some void spaces in the way of the sensor movement. The spot test data falls well within the continuous data range for all soils on both wet and dry sides. The oven dry moisture content plotted shows the same trend as the microwave values. The variation is very small in these test data. FA6 soil shows some variation in the data from the three methods. But, in general, the microwave data correlates well with the moisture content as seen from these plots. The time versus microwave value plots showed some variation on the wet side but on the dry side they are mostly stable in the case of Edward Till. In the case of Kickapoo clay, some variations are seen on the wet and dry sides. In the Kickapoo topsoil initially up to 60 seconds variations were seen, after which the readings were stable. The plots of time versus microwave values of FA6 soil were stable throughout.

The plots of distance versus microwave value / moisture contents and plots of time versus microwave values on the air dry soil beds also showed similar trends as the wet and dry sides of optimum moisture content. These aspects are studied at different speeds of the sled, slow, medium and fast and the plots are shown.

The statistical models chosen for each soil (Table 33) are used to evaluate the predicted values from the spot test microwave data. The measured versus predicted moisture content plot for all the soils is shown in figure 78. A 1:1 line drawn through the data showed that the predicted results are an under- estimation of the actual moisture content. At the end of this study, the accuracy and precision of the sensor is tested. It is discussed in the following test plan-7.

Test Plan 7 – Accuracy and Precision Tests

It is very important to define the accuracy and precision of any instrument in the course of its evaluation. This testing is carried out for the microwave sensor used for this study also. The closer a system's measurement to the accepted value, the more accurate the system is considered to be. In other words, accuracy is the degree of veracity while precision is the degree of reproducibility. Precision is measured with respect to detail and accuracy is measured with respect to reality. The test methods described below are carried out for accuracy and precision testing on two soil types, Loess and Edward Till.

Test Method

Each of the soils was mixed at optimum moisture content, -3% optimum moisture content and +2% optimum moisture content. Three samples are prepared at same moisture content of each soil type. They are mixed thoroughly to ensure uniformity. They are compacted using the Proctor Standard procedure described in method 1. These samples are extracted and placed on the ground with the bottom facing upwards. The sensor is placed on the soil sample and microwave reading is noted. The sensor is then lifted up and cleaned of any soil particles sticking to the sensor base. The sensor is again placed on the sample and the microwave reading is taken. The same procedure is repeated 15 times on each sample. The sample is cut at the tested portion and is taken for oven dry moisture test. Dry density of the sample is also evaluated. Sample preparation and compaction are done by the same person throughout and microwave sensor testing is done by the same person for all samples to eliminate methodical errors from person to person. Also, entire testing (18 samples) is done on a single day. Figures 79 (a-l) illustrate the test procedure followed. The precision is evaluated by calculating the mean and standard deviation of the measurements. The results are presented and discussed below.


(79a) Sample preparation, equal amounts weighed (79b) Mixer Used


(79c, 79d) Samples packed in plastic bags after mixing required moisture and left for mellowing


(79e) Compaction in a 4”split mold (79f) Planing the top after compaction


(79g) Planing the top of the sample (79h) Mold surface cleaned and dry density determined


(79i) Sample extraction (79j) Extracted sample resting on top, placed on the ground

(79k) Clean sensor base (79l) Sensor placed on the sample

Figures 79(a-l): Accuracy and Precision tests

Results

The microwave values are plotted against the moisture contents (Figures 80-81). Statistical analysis of the data gives the following results as shown in Table 34.

Table 34. Statistical Analysis of Accuracy and Precision Test Data

Soil Type	Moisture Content (%)	N	Mean	Standard Deviation	Standard Error Mean	Variance	Coefficient of Variation
Loess	11	45	45.37	0.37	0.05	0.14	0.83
	14	45	56.25	0.26	0.03	0.07	0.47
	16	45	64.24	0.30	0.04	0.09	0.47
Edward Till	9	60	44.26	0.64	0.08	0.41	1.46
	12	45	63.63	0.43	0.06	0.18	0.68
	14	45	70.17	0.52	0.07	0.27	0.74

N – Number of samples tested

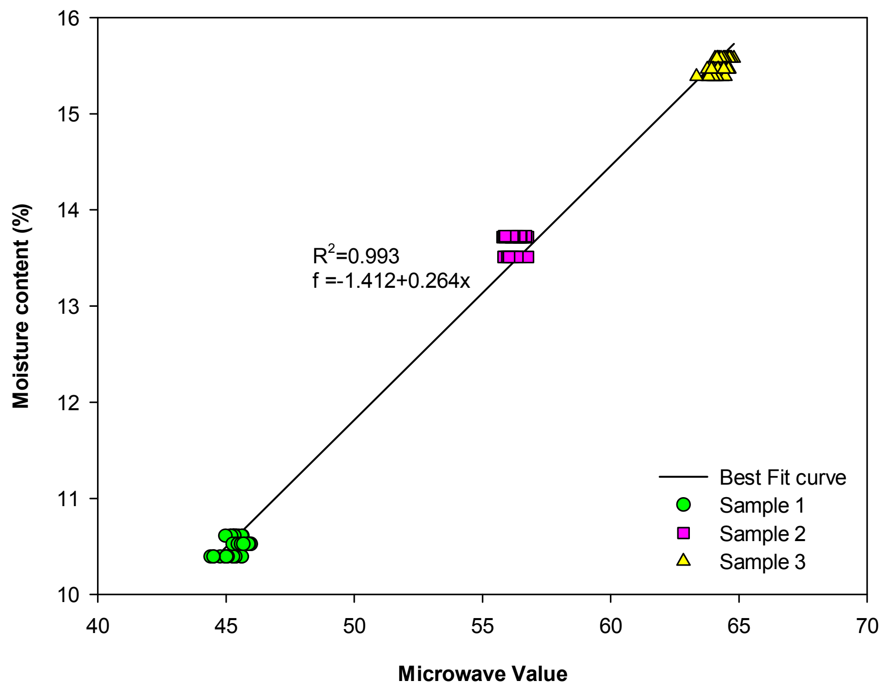


Figure 80. Microwave Value vs. Moisture Content – Loess

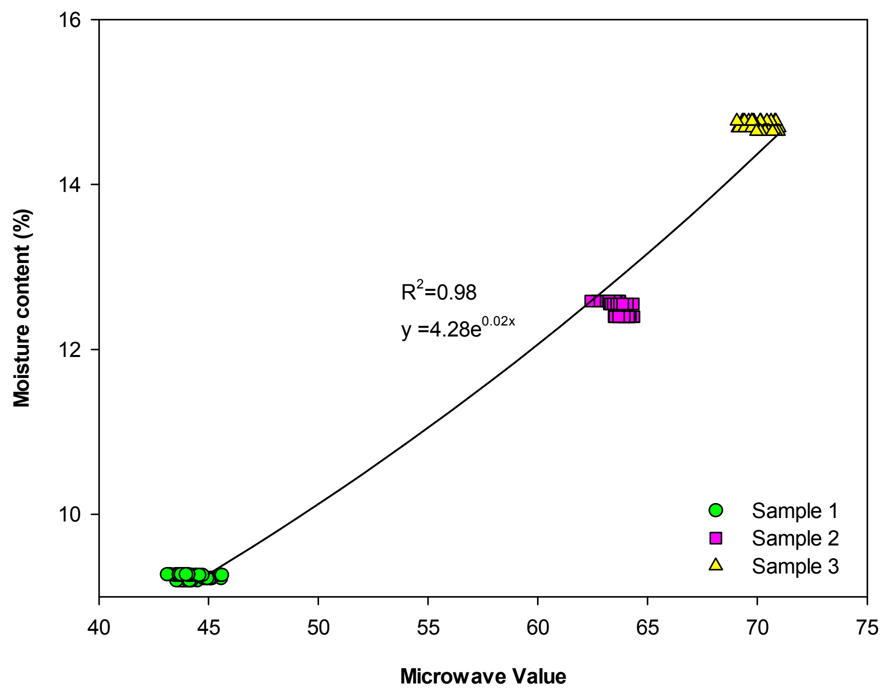


Figure 81. Microwave Value vs. Moisture Content – Edward Till

Discussion

The moisture content versus microwave value plot for Loess (Figure 80) shows a linear fit of the data. Also, all the values are well correlated with the best fit line. The standard deviation ranges from 0.26 to 0.37. Standard error of the mean is less than or equal to 0.05 at all three moisture contents tested. The coefficient of variation is also very less (maximum of 0.83).

The moisture content versus microwave value plot for Edward Till (Figure 81) shows a linear trend on the dry of optimum. The data at optimum moisture content and wet of optimum does not appear to fall on the best fit line. This might be attributed to the non-linear behavior at higher moisture contents. The same trend is seen at higher moisture contents in the preliminary tests. The standard deviation ranges from 0.43 to 0.64. Standard error of the mean lies between 0.06 and 0.08. The coefficient of variation ranges from 0.68 to 1.46.

It can be seen that the sensor predicts the moisture contents with very low standard deviation, standard error and low coefficient of variation. These results prompt us to conclude that the sensor has high precision and accuracy in the evaluation of the soil moisture content. This testing can be done on a wide range of moisture contents and for different soils and the precision can be prescribed.

SUMMARY

- In this study, the Hydronix VI microwave sensor is evaluated for soil moisture content determination.
- Microwave sensor tests were done on different soil types compacted at different energies and at a wide range of moisture contents and the microwave values (sensor output) are correlated with the oven dry moisture content.
- The sensor reading stabilizes in 2 -3 seconds when tested in the lab and in 8-10 seconds in the field.
- Microwave sensor values of silt and sand were correlated with gravimetric and volumetric moisture contents.
- The regression analysis for sand showed low variation in values of microwave sensor which is of the order of ± 0.2% for gravimetric determination. For the silt sample the variability was higher, but still within the target of ± 1.0%.
- For sand and silt, high r^2 values (0.97+) are obtained using linear regression models to predict moisture content from the microwave sensor values.
- For silt, at high moisture contents (in this case 21% (+4% OMC)), the microwave sensor value was relatively high, but variable.
- The Microwave values at different moisture contents for the same soil (Loess and/or Glacial till) tested on 4" mold, 6" mold and extracted samples were studied.
- For the same soil tested, variation was observed in the microwave values when the test medium differed. This may be due to the influence of the dielectric constants.
- At higher moisture contents (15%, in this case-loess), the microwave values showed abnormal trend.
- Variation is observed in field and Lab microwave values. Factors effecting microwave values in the field are studied in detail. The variation in the field is expected due to the loss of contact area of the sensor with the ground.
- Tests were conducted to study the effect of contact area on microwave values and the maximum allowable change in surface area is determined. This study is carried out only

for moisture contents wet of optimum. The sensitivity of the microwave sensor readings to the change in contact area at various moisture contents needs to be studied in detail.

- Maximum allowable change in surface area of a specimen compacted on the wet of optimum is $3cm^2$
- Extracted samples were placed on a steel plate and the effects of steel plate dielectric at various heights of the sample were studied. It was found that the steel plate dielectric affects Microwave values of soil samples that are below 2" height.
- The suitability of Microwave sensor for five different soils, namely Edward Till, Kickapoo Clay, Kickapoo Topsoil and FA6 and CA6G were studied both at ISU laboratory and at the spot (Trench prepared for the purpose at Caterpillar laboratory).
- The laboratory and spot test data are comparable. In general, the microwave data correlates well with the moisture content as seen from the plots of moisture content versus microwave value.
- The plots of microwave values against the gravimetric moisture contents show R^2 values of 0.94 for Edward Till, 0.96 for Kickapoo Clay, 0.97 for Kickapoo Topsoil, 0.98 for FA6 and 0.87 for CA6G.
- The time versus microwave value plots showed some variation on the wet side but on the dry side they are mostly stable in the case of Edward Till. In the case of Kickapoo clay, some variations are seen on the wet and dry sides. In the Kickapoo topsoil initially up to 60 seconds variations were seen, after which the readings were stable. The plots of time versus microwave values of FA6 soil were stable throughout.
- Statistical models were developed based on laboratory data. The microwave value and microwave value squared terms proved to be significant parameters affecting the models.
- Dry density played a significant role in the case of cohesive soils, Edward Till, Kickapoo Clay and Kickapoo Topsoil, whereas, it did not show any effect in cohesionless soils like FA6 and CA6G. But, this variable was not included in the models due to the insufficiency in data.
- Statistical significance tests showed that a combined cohesive soil model and a cohesionless soil model can also be useful. This led to the development of a cohesive soil

model and a cohesionless soil model. However, individual soil models proved to be more significant than the combined models.

- The models are applied to the spot test microwave data and the predicted moisture contents are obtained.
- These predicted moisture contents are plotted against the measured moisture contents from oven dry tests. A 1:1 line drawn through the plot shows that the microwave sensor gives an under-estimation of the moisture content.
- The accuracy and precision of the sensor was tested on Edward Till and Loess soils.
- The Standard deviation was between 0.43 and 0.64, the standard error varied from 0.06-0.08 and the precision or coefficient of variation ranged from 0.47-0.83 for Edward Till.
- The Standard deviation was between 0.26 and 0.37, the standard error varied from 0.03-0.05 and the precision or coefficient of variation ranged from 0.68-1.46 for Loess.
- These results show that the microwave sensor used in this study is fairly accurate and precise with a very minor standard deviation in the data. The coefficient of variation is also very less indicating high precision in the measurements.

RECOMMENDATIONS

- From this research, it was found that a slight change in contact area influenced the microwave value greatly. The permissible change is evaluated in this research by testing soil samples only on the wet side of optimum. In the future, the sensitivity of the microwave sensor readings to the change in contact area at various moisture contents and for different soil types needs to be studied in detail.

- In this research, the laboratory and spot tests were done on five different soil types and at three different compactive efforts and over a wide moisture range. In order to develop statistical models of individual soil types with only a single variable, as in this case, this data set is sufficient, but in order to incorporate other variables in the moisture content model, this data was insufficient. Hence, in the future, more soil types can be tested and other soil properties like Atterberg Limits, Plasticity Index, Percent passing # 4 sieve, percent passing # 200 sieve can all be included in the model.

- Dry density is another variable which showed some significance in the model. Sufficient dry density data can also be collected and used for model development.

- It is understood from the literature review that much work has been done on the study of dielectric behavior of various materials. The sensor used for this research can further be tested for understanding the dielectric influence on microwave values.

- It is also understood that the microwave dielectric behavior of wet soil is influenced by the soil texture. The effect of soil texture on the microwave values can also be studied in the future.

- The accuracy and precision of the equipment needs to be established for different soils at a wide moisture range.

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APPENDIX A: COMPACTION AND MICROWAVE TEST DATA

Data of Test Plan 1: Compaction and Microwave sensor tests on Sand and Silt

Date	2/22/2006
Soil Type	**Sand**
Test No.	1
Specific Gravity	2.65

Water Content Evaluation

Sample No.	1	2	3	4	5	6	7	8	9	10	11
Tare No.	D	M	A	N	C	H	I	B	L	J	G
Mass of wet soil+tare(1)	394.65	302.17	232.65	250.14	269.63	297.34	298.12	295.72	343.96	347.3	316.71
Mass of dry soil+tare(2)	394.45	301.49	229.12	244.5	261.69	286.77	285.20	281.50	326.05	327.75	299.98
Mass of tare (3)	50.28	49.79	49.33	49.84	50.43	50.79	49.71	50.17	49.34	50.23	49.31
Mass of dry soil (4)=(2)-(3)	344.17	251.70	179.79	194.66	211.26	235.98	235.49	231.33	276.71	277.52	250.67
Mass of moisture(5)=(1)-(2)	0.20	0.68	3.53	5.64	7.94	10.57	12.92	14.22	17.91	19.55	16.73
Water Content,w%(6) = [(5)/(4)]*100	0.058	0.270	1.963	2.897	3.758	4.479	5.486	6.147	6.472	7.045	6.674

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	0.058	0.270	1.963	2.897	3.758	4.479	5.486	6.147	6.472	7.045	6.674
Mass of soil+mold, g (7)	5988.5	5991.4	5939.5	5954.1	5952	5963	5973.9	5985	6000.9	6025.6	6029.4
Mass of mold,g (8)	4281.7	4281.7	4281.7	4281.7	4281.7	4281.7	4281.7	4281.7	4281.7	4281.7	4281.7
Mass of soil,g (9)= (7)-(8)	1706.8	1709.7	1657.8	1672.4	1670.3	1681.3	1692.2	1703.3	1719.2	1743.9	1747.7
Wet unit weight,kg/m^3 (10) = (9) *1.059	1807.501	1810.572	1755.61	1771.072	1768.848	1780.497	1792.04	1803.795	1820.633	1846.79	1850.8143
Dry Unit weight,kg/m^3 (11) = (10)/{1+ [(6)/100]}	1806.451	1805.694	1721.804	1721.202	1704.775	1704.164	1698.834	1699.335	1709.956	1725.254	1735.0173
Zero aid void line density, kg/m^3	2645.925	2631.163	2518.939	2461.041	2409.972	2368.824	2313.622	2278.791	2262.017	2233.121	2251.747
Gravimetric moisture content (%)	0.058	0.270	1.963	2.897	3.758	4.479	5.486	6.147	6.472	7.045	6.674
Volumetric moisture content (%)	0.105	0.489	3.447	5.131	6.648	7.975	9.832	11.088	11.784	13.010	12.353

Filtered Average from Hydro Com sensor	21.95	22.83	26.63	31.13	36.25	39.96	44.7	46.35	47.65	52.91	52.15

Date	2/28/2006
Soil Type	**Silt**
Test No.	1
Specific Gravity	2.70

Water Content Evaluation

Sample No.	1	2	3	4	5	6	7	8	9	10	11
Tare No.	M	B	G	I	J	N	P	A	L	C	D
Mass of wet soil+tare(1)	283.59	281.96	246.85	228.16	205.19	215.03	231.1	277.9	280.79	342.36	433.49
Mass of dry soil+tare(2)	283.45	275.92	237.23	214.43	190.03	196.53	204.95	240.32	237.78	283.14	348.42
Mass of tare (3)	49.79	50.18	49.3	49.71	50.23	49.85	49.89	49.33	49.34	50.43	50.28
Mass of dry soil (4)=(2)-(3)	233.66	225.74	187.93	164.72	139.8	146.68	155.06	190.99	188.44	232.71	298.14
Mass of moisture(5)=(1)-(2)	0.14	6.04	9.62	13.73	15.16	18.50	26.15	37.58	43.01	59.22	85.07
Water Content,w%(6) = [(5)/(4)]*100	0.060	2.676	5.119	8.335	10.844	12.612	16.864	19.676	22.824	25.448	28.534

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	0.060	2.676	5.119	8.335	10.844	12.612	16.864	19.676	22.824	25.448	28.534
Mass of soil+mold, g (7)	5670.1	5759.2	5843.8	5944.2	5997.7	6068.3	6172.8	6125	6106.4	6093.3	6109.9
Mass of mold,g (8)	4281.3	4281.3	4281.3	4281.3	4281.3	4281.3	4281.3	4281.3	4281.3	4281.3	4281.3
Mass of soil,g (9)= (7)-(8)	1388.8	1477.9	1562.5	1662.9	1716.4	1787	1891.5	1843.7	1825.1	1812	1828.6
Wet unit weight,kg/m^3 (10) = (9) *1.059	1470.739	1565.096	1654.688	1761.011	1817.668	1892.433	2003.099	1952.478	1932.781	1918.908	1936.4874
Dry Unit weight,kg/m^3 (11) = (10)/{1+ [(6)/100]}	1469.859	1524.311	1574.11	1625.518	1639.842	1680.482	1714.036	1631.464	1573.615	1529.644	1506.6004
Zero aid void line density, kg/m^3	2695.639	2518.087	2372.144	2203.983	2088.507	2014.118	1855.237	1763.250	1670.529	1600.384	1525.073
Gravimetric moisture content (%)	0.060	2.676	5.119	8.335	10.844	12.612	16.864	19.676	22.824	25.448	28.534
Volumetric moisture content (%)	0.088	4.188	8.470	14.679	19.711	23.868	33.781	38.418	44.114	48.832	55.255

Filtered Average from Hydro Com sensor	18.51	28.4	37	50.75	57.98	58.58	74.28	77.9	66.46	65.24	73.38

Data of Test Plan 2: Compaction of Loess samples in 4” mold and 6” mold

Date	6/1/2006
Soil Type	Loess
Test No.	2 (In 4” mold)
Specific Gravity	2.62

Water Content Evaluation

Sample No.	1	2	3
Tare No.	I	M	G
Mass of wet soil+tare(1)	224.71	191.6	190.26
Mass of dry soil+tare(2)	210.14	176.77	172.25
Mass of tare (3)	49.76	49.8	49.32
Mass of dry soil (4)=(2)-(3)	160.38	126.97	122.93
Mass of moisture(5)=(1)-(2)	14.57	14.83	18.01
Water Content,w%(6) = [(5)/(4)]*100	9.085	11.680	14.651

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	9.085	11.680	14.651
Mass of soil+mold, g (7)	5987.8	6074.5	6150.5
Mass of mold,g (8)	4309	4309	4309
Mass of soil,g (9)= (7)-(8)	1678.8	1765.5	1841.5
Wet unit weight,kg/m3 (10) = (9) *1.059	1777.849	1869.665	1950.149
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}	1629.788	1674.128	1700.949
Zero aid void line density	2116.285	2006.104	1893.274
Gravimetric moisture content (%)	9.085	11.680	14.651
Volumetric moisture content (%)	16.151	21.838	28.571

Microwave values

Sample in mold	52	61.96	60.93
Extracted sample	42.91	54.72	63.13

Date	6/1/2006
Soil Type	Loess
Test No.	2 (In 6" mold)
Specific Gravity	2.62

Water Content Evaluation

Sample No.	1	2	3
Tare No.	J	H	D
Mass of wet soil+tare(1)	275.74	273.64	241.98
Mass of dry soil+tare(2)	256.58	249.68	217
Mass of tare (3)	50.23	50.78	50.42
Mass of dry soil (4)=(2)-(3)	206.35	198.9	166.58
Mass of moisture(5)=(1)-(2)	19.16	23.96	24.98
Water Content,w%(6) = [(5)/(4)]*100	9.285	12.046	14.996

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	9.285	12.046	14.996
Mass of soil+mold, g (7)	9541.5	9728.2	9997.8
Mass of mold,g (8)	5735.7	5735.7	5735.7
Mass of soil,g (9)= (7)-(8)	3805.8	3992.5	4262.1
Wet unit weight,kg/m3 (10) = (9) *0.4714	1794.054	1882.065	2009.154
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}	1641.626	1679.721	1747.154
Zero aid void line density	2107.342	1991.469	1880.981
Gravimetric moisture content (%)	9.285	12.046	14.996
Volumetric moisture content (%)	16.658	22.672	30.129

Microwave values

Sample in mold	48.64	59.18	68.97
Extracted sample	53.54	61.15	64.12

Data of Test Plan 3: Compaction of Loess and Glacial Till samples in 4” mold and on extracted samples

Date	7/26/2006
Soil Type	**Loess**
Test No.	3
Specific Gravity	2.62

Water Content Evaluation

Sample No.	1	2	3	4	5	6	7
Tare No.	TDRI	D2	RR	ST3	DAV2	DIST.	S9
Mass of wet soil+tare(1)	110.91	181.37	120.54	185.15	146.65	219.55	248.26
Mass of dry soil+tare(2)	110.85	175.2	111.5	164.43	125.8	180.68	196.88
Mass of tare (3)	16.67	17.09	16.4	16.76	17.09	16.57	16.31
Mass of dry soil (4)=(2)-(3)	94.18	158.11	95.1	147.67	108.71	164.11	180.57
Mass of moisture(5)=(1)-(2)	0.06	6.17	9.04	20.72	20.85	38.87	51.38
Water Content,w%(6) = [(5)/(4)]*100	0.064	3.902	9.506	14.031	19.179	23.685	28.454

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	0.064	3.902	9.506	14.031	19.179	23.685	28.454
Mass of soil+mold, g (7)	5703.8	5958.4	6012.6	6151.4	6166.3	6118.6	6087.7
Mass of mold,g (8)	4308.3	4435.7	4308.3	4308.3	4308.3	4308.3	4308.3
Mass of soil,g (9)= (7)-(8)	1395.5	1522.7	1704.3	1843.1	1858	1810.3	1779.4
Wet unit weight,kg/m^3 (10) = (9) *1.059	1477.835	1612.539	1804.854	1951.843	1967.622	1917.108	1884.385
Dry Unit weight,kg/m^3 (11) = (10)/{1+ [(6)/100]}	1476.894	1551.976	1648.181	1711.673	1650.974	1549.988	1466.968
Zero aid void line density, kg/m^3	2615.634	2376.975	2097.592	1915.737	1743.758	1616.729	1500.999
Gravimetric moisture content (%)	0.064	3.902	9.506	14.031	19.179	23.685	28.454
Volumetric moisture content (%)	0.094	6.293	17.157	27.387	37.738	45.407	53.619

Filtered Average from Hydro Com sensor

With mold	17.54	35.15	54.46	62.62	77.14	66.96	74.66
Without mold	14.46	25.15	47.43	63.77	79.86	89.77	89.27

Date	7/27/2006
Soil Type	**Glacial till**
Test No.	3
Specific Gravity	2.65

Water Content Evaluation

Sample No.	1	2	3	4	5	6
Tare No.	S9	TDRI	Z6	TDR7	RR	DIST.
Mass of wet soil+tare(1)	108.92	182.74	185.88	173.2	229.15	207
Mass of dry soil+tare(2)	105.32	169.31	165.2	149.41	188.4	164.95
Mass of tare (3)	16.32	16.66	17.15	16.76	16.39	16.56
Mass of dry soil (4)=(2)-(3)	89	152.65	148.05	132.65	172.01	148.39
Mass of moisture(5)=(1)-(2)	3.6	13.43	20.68	23.79	40.75	42.05
Water Content,w%(6) = [(5)/(4)]*100	4.045	8.798	13.968	17.934	23.690	28.337

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	4.045	8.798	13.968	17.934	23.690	28.337
Mass of soil+mold, g (7)	6153.6	6126.5	6269.4	6240.6	6143	6040
Mass of mold,g (8)	4435.7	4308.3	4308.3	4308.3	4308.3	4308.3
Mass of soil,g (9)= (7)-(8)	1717.9	1818.2	1961.1	1932.3	1834.7	1731.7
Wet unit weight,kg/m^3 (10) = (9) *1.059	1819.256	1925.474	2076.805	2046.306	1942.947	1833.87
Dry Unit weight,kg/m^3 (11) = (10)/{1+ [(6)/100]}	1748.529	1769.771	1822.266	1735.122	1570.814	1428.944
Zero aid void line density, kg/m^3	2393.444	2148.978	1934.082	1796.291	1627.966	1513.470
Gravimetric moisture content (%)	4.045	8.798	13.968	17.934	23.690	28.337
Volumetric moisture content (%)	7.359	16.940	29.009	36.699	46.029	51.967

Filtered Average from Hydro Com sensor

With mold	33.43	50.84	64.28	72.21	72.62	70.98
Without mold	30.4	44.62	63.25	76.12	85.62	90.74

Data of Test Plan 4: Compaction of Glacial Till, Loess and Gumbo samples in field and in the laboratory

Test Date	8/16/2006
Soil Type	**Glacial Till**
Test No.	4
Specific Gravity	2.70

Water Content Evaluation

Sample No.	1	2
Tare No.	AA	BB
Mass of wet soil+tare(1)	1031.98	845.09
Mass of dry soil+tare(2)	962.73	789.28
Mass of tare (3)	400.37	401.52
Mass of dry soil (4)=(2)-(3)	562.36	387.76
Mass of moisture(5)=(1)-(2)	69.25	55.81
Water Content,w%(6) = [(5)/(4)]*100	12.314	14.393

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	12.314	14.393
Mass of soil+mold, g (7)		2720.52
Mass of mold,g (8)		700.21
Mass of soil,g (9)= (7)-(8)		2020.31
Wet unit weight,kg/m3 (10) = (9) *0.00107		2.162
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}		1.890
Zero aid void line density		1944.39
Gravimetric moisture content (%)	12.314	14.393
Volumetric moisture content (%)		0.031
Microwave value in the field	34.11	31.57
Microwave value at lab	38.85	64.06

Date	8/16/2006
Soil Type	**Loess**
Test No.	4
Specific Gravity	2.70

Water Content Evaluation

Sample No.	1	2
Tare No.	CC	DD
Mass of wet soil+tare(1)	875.62	870.20
Mass of dry soil+tare(2)	780.20	770.80
Mass of tare (3)	402.15	401.26
Mass of dry soil (4)=(2)-(3)	378.05	369.54
Mass of moisture(5)=(1)-(2)	95.42	99.4
Water Content,w%(6) = [(5)/(4)]*100	25.240	26.898

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	25.240	26.898
Mass of soil+mold, g (7)	2514.50	2511.36
Mass of mold,g (8)	697.65	699.73
Mass of soil,g (9)= (7)-(8)	1816.85	1811.63
Wet unit weight,kg/m3 (10) = (9) *0.00107	1.944	1.938
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}	1.552	1.528
Zero aid void line density	1605.73	1564.08
Gravimetric moisture content (%)	25.240	26.898
Volumetric moisture content (%)	0.049	0.052
Microwave value in the field	32.91	39.83
Microwave value at lab	77.22	81.37

Date	8/16/2006
Soil Type	**Gumbo**
Test No.	4
Specific Gravity	2.70

Water Content Evaluation

Sample No.	1	2
Tare No.	EE	FF
Mass of wet soil+tare(1)	812.58	785.08
Mass of dry soil+tare(2)	729.25	708.45
Mass of tare (3)	402.47	404.87
Mass of dry soil (4)=(2)-(3)	326.78	303.58
Mass of moisture(5)=(1)-(2)	83.33	76.63
Water Content,w%(6) = [(5)/(4)]*100	25.500	25.242

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	25.500	25.242
Mass of soil+mold, g (7)	2565.77	2563.82
Mass of mold,g (8)	698.53	693.98
Mass of soil,g (9)= (7)-(8)	1867.24	1869.84
Wet unit weight,kg/m3 (10) = (9) *1.059	1.998	2.001
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}	1.592	1.597
Zero aid void line density	1599.044	1605.674
Gravimetric moisture content (%)	25.500	25.242
Volumetric moisture content (%)	0.051	0.051
Microwave value in the field	63.04	65.43
Microwave value at lab	79.75	75.12

Test Date 8/17/2006
Soil Type **Mixed soil at creek**
Test No. IV

Water Content Evaluation

Sample No.	1	2	3	4	5	6
Tare No.	11	4	10	C	15	1
Mass of wet soil+tare(1)	105.88	114.61	131.74	125.58	189.67	112.75
Mass of dry soil+tare(2)	84.52	95.4	107.66	105.74	146.84	91.38
Mass of tare (3)	3.81	3.79	3.81	3.80	3.80	3.80
Mass of dry soil (4)=(2)-(3)	80.71	91.61	103.85	101.94	143.04	87.58
Mass of moisture(5)=(1)-(2)	21.36	19.21	24.08	19.84	42.83	21.37
Water Content,w%(6) = [(5)/(4)]*100	26.465	20.969	23.187	19.462	29.943	24.401

Gravimetric moisture content (%)	26.465	20.969	23.187	19.462	29.943	24.401
Filtered Average from Hydro Com sensor	46.74	62.64	64.19	52.11	59.55	71.58

Data of Test Plan 5(a): Compaction of Glacial Till- Effects of change in area and volume on the microwave values

Date	9/25/2006
Soil Type	**Oxidized Glacial till**
Test No.	I
Specific Gravity	2.65

Water Content Evaluation

Sample No.	1	2
Tare No.	M1	F
Mass of wet soil+tare(1)	185.88	173.2
Mass of dry soil+tare(2)	165.2	149.41
Mass of tare (3)	17.15	16.76
Mass of dry soil (4)=(2)-(3)	148.05	132.65
Mass of moisture(5)=(1)-(2)	20.68	23.79
Water Content,w%(6) = [(5)/(4)]*100	13.968	17.934

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	13.968	17.934
Mass of soil+mold, g (7)	6230.2	6243.2
Mass of mold,g (8)	4195.1	4195.1
Mass of soil,g (9)= (7)-(8)	2035.1	2048.1
Wet unit weight,kg/m3 (10) = (9) *1.059	2155.171	2168.938
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}	1891.027	1839.105
Gravimetric moisture content (%)	13.968	17.934
Volumetric moisture content (%)	30.104	38.899

Change in microwave values with contact area and volume

No. of Holes	Microwave value 1	Microwave value 2	Contact area (cm^2)	Volume (cm^3)
0	65.92	67.38	81.073	81.073
1	66.60	68.20	80.762	80.762
2	65.40	66.86	80.450	80.450
3	66.22	67.91	80.138	80.138
4	65.43	67.12	79.826	79.826
5	65.08	67.97	79.515	79.515
6	62.77	67.25	79.203	79.203
7	62.36	67.76	78.891	78.891
8	62.85	67.22	78.580	78.580
9	62.96	67.09	78.268	78.268
10	64.24	66.98	77.956	77.956
11	62.73	66.60	77.644	77.644
12	63.39	67.40	77.333	77.333
13	63.67	66.15	77.021	77.021
14	63.78	65.28	76.709	76.709
15	64.38	64.74	76.398	76.398
16	63.28	65.91	76.086	76.086
17	62.88	65.21	75.774	75.774
18	62.43	64.94	75.462	75.462
19	62.28	64.85	75.151	75.151
20	61.36	64.41	74.839	74.839
21	59.26	62.68	74.527	74.527
22	56.55	59.63	74.215	74.215
23	54.13	59.93	73.904	73.904
24	54.82	58.88	73.592	73.592
25	55.28	57.49	73.280	73.280
30		55.90	71.722	71.722
36		52.73	69.851	69.851
42		48.85	67.981	67.981

Data of Test Plan 5(b): Compaction of Glacial Till- Influence of steel plate on the microwave values

Soil Type	**Oxidized Glacial till**
Test No.	II
Specific Gravity	2.65

Water Content Evaluation

Sample No.	1	2
Tare No.	E	A
Mass of wet soil+tare(1)	296.24	157.22
Mass of dry soil+tare(2)	273.42	146.86
Mass of tare (3)	60.87	59.98
Mass of dry soil (4)=(2)-(3)	212.55	86.88
Mass of moisture(5)=(1)-(2)	22.82	10.36
Water Content,w%(6) = [(5)/(4)]*100	10.736	11.924

Density Evaluation

Water Content,w%(6) = [(5)/(4)]*100	10.736	11.924
Mass of soil+mold, g (7)	6293.1	6272.2
Mass of mold,g (8)	4195.1	4195.1
Mass of soil,g (9)= (7)-(8)	2098	2077.1
Wet unit weight,kg/m3 (10) = (9) *1.059	2221.782	2199.6489
Dry Unit weight,kg/m3 (11) = (10)/{1+ [(6)/100]}	2006.371942	1965.297166
Gravimetric moisture content (%)	10.736	11.924
Volumetric moisture content (%)	23.854	26.230

Microwave value for	Sample placed		Sample placed	
Height of the sample	on steel plate	on ground	on steel plate	on ground
41/2"	61.32		65.35	65.91
4"	59.80	60.18	66.23	66.56
31/2"	59.17	59.88	65.15	65.97
3"	58.47	59.33	64.11	65.68
21/2"	58.27	58.75	63.86	65.57
2"	59.74	59.63	64.77	65.28
11/2"	60.14	59.14	66.34	64.79
1"	63.18	59.35	67.44	63.87
3/4"	60.36	56.36		
1/2"	65.50	56.86	67.34	62.97
(0") sensor placed directly	91.26	37.76	91.26	37.76

Data of Test Plan 6 (a): Laboratory Compaction of
Edward Till, CA6G, Kickapoo Clay, Kickapoo Top soil and FA6

Soil Type : Edward Till

Moisture Content (%)	Dry Unit Weight (KN/m^3)	Zero Air Void Line Density (KN/m^3)	Microwave Value
0.139	15.7940	26.5259	19.17
0.140	16.4137	26.5254	19.99
0.170	17.0331	26.5034	21.79
2.646	16.2523	24.8384	26.45
2.508	16.9606	24.9259	27.42
2.592	15.6851	24.8726	24.38
5.444	17.1202	23.1917	32.09
5.449	17.9684	23.1892	34.79
5.524	19.5855	23.1480	38.12
8.413	16.9848	21.6679	41.24
8.120	18.1536	21.8090	44.34
8.286	20.7528	21.7289	51.64
10.255	17.2483	20.8190	51.39
10.339	18.5124	20.7816	54.24
10.632	19.9458	20.6535	64.31
12.819	17.9867	19.7422	64.7
12.530	18.9659	19.8580	60.63
12.754	19.3327	19.7683	61.31
16.965	17.3785	18.2190	72.16
17.304	17.5080	18.1048	67.85
17.264	17.6237	18.1181	73.23
20.157	16.1778	17.1973	80.97
20.559	16.3582	17.0768	79.79
19.978	16.5292	17.2516	79.58
22.955	15.4422	16.3916	82.84
22.847	15.4126	16.4211	81.98
22.679	14.7473	16.4678	69.61

Soil Type: CA6G

Moisture Content (%)	Dry Unit weight (kN/m^3)	Zero air void line density (kN/m^3)	Microwave value
0.138	16.2418	26.7211	17.86
0.163	17.1737	26.7028	20.96
0.166	19.0280	26.7007	16.64
1.215	17.6075	25.9574	20.67
1.288	17.5140	25.9073	20.35
1.348	19.0244	25.8662	27.63
3.144	18.0750	24.6943	28.52
3.424	18.7919	24.5215	26.45
3.111	19.6851	24.7153	20.77
5.908	18.3642	23.0848	36.83
6.124	19.3602	22.9681	52.29
5.815	20.8951	23.1356	59.16
7.317	19.7059	22.3424	54.37
6.863	20.3970	22.5767	42.48
7.064	20.8780	22.4721	56.43
10.509	19.4946	20.8255	61.17
10.208	19.3417	20.9596	60.23
11.563	18.9510	20.3686	64.44

Soil Type : Kickapoo Clay

Moisture Content (%)	Dry Unit weight (kN/m^3)	Zero air void line density (kN/m^3)	Microwave value
0.221	14.2054	26.3699	16.97
0.322	14.5999	26.2987	17.31
0.389	14.3760	26.2515	17.52
2.265	13.6859	24.9943	18.2
2.287	14.4843	24.9801	18.79
2.303	15.0672	24.9700	17.88
6.062	13.4334	22.7853	25.72
5.838	14.7158	22.9042	30.62
5.697	15.2300	22.9803	26.38
8.569	14.4569	21.5286	36.78
8.632	15.3798	21.4992	37.24
8.238	17.5015	21.6866	43.84
10.936	14.6456	20.4636	42.99
11.002	15.8523	20.4354	47.38
10.785	18.0330	20.5284	57.47
13.797	14.8751	19.3085	52.33
13.088	16.2404	19.5826	56.77
13.374	18.5253	19.4712	65.96
15.786	15.5193	18.5797	63.13
16.771	16.4717	18.2388	63.14
16.428	17.9911	18.3560	70.27
17.823	15.7182	17.8882	68.07
18.683	16.7349	17.6114	75.86
19.301	16.9938	17.4178	75.29
21.789	15.8604	16.6794	78.27
21.794	16.1676	16.6781	81.16
19.692	16.5591	17.2973	78.86

Soil Type : Kickapoo Top Soil

Moisture Content (%)	Dry Unit weight (kN/m^3)	Zero air void line density (kN/m^3)	Microwave value
0.459	12.0217	25.5334	12.63
0.492	13.3023	25.5115	14.67
0.506	13.0891	25.5022	14.59
2.672	13.0486	24.1401	16.99
2.951	13.8081	23.9750	17.74
2.839	15.2887	24.0410	19.47
5.833	13.5591	22.3942	26.71
5.750	14.2204	22.4373	28.36
5.696	15.1683	22.4647	30.89
8.488	13.7941	21.1122	36.35
8.420	14.4308	21.1433	37.82
8.446	15.9747	21.1312	42.63
10.361	13.5619	20.2925	39.96
10.273	14.5020	20.3297	41.79
10.167	16.3735	20.3741	49.72
13.757	13.6913	18.9579	45.68
13.674	14.6510	18.9885	53.23
13.366	16.7019	19.1024	56.82
16.846	14.8737	17.8877	57.63
16.876	16.2089	17.8778	65.72
16.589	17.0399	17.9720	67.99
19.298	14.4800	17.1207	62.66
19.646	15.9864	17.0169	76.85
19.290	16.3702	17.1229	71.76
22.750	15.1651	16.1458	82.6
22.700	15.3957	16.1592	84.94
22.279	15.6872	16.2721	79.85

Soil Type : FA6

Moisture Content (%)	Dry Unit weight (kN/m^3)	Zero air void line density (kN/m^3)	Microwave value
0.152	18.5834	26.6133	5.25
0.137	18.8991	26.6240	11.95
0.137	19.1438	26.6245	17.03
1.356	17.5428	25.7697	20.86
1.500	17.8853	25.6729	22.04
1.306	17.7642	25.8039	21.77
3.537	17.1806	24.3710	30.43
3.380	17.9336	24.4663	31.97
3.199	18.5161	24.5775	29.78
4.660	18.6156	23.7078	38.57
4.984	19.3420	23.5232	41.55
4.830	20.1728	23.6106	43.74
7.051	18.8075	22.4104	51.17
7.355	19.3884	22.2555	52.73
7.455	20.0908	22.2050	57.43
9.174	19.4148	21.3715	61.44
9.249	19.5473	21.3367	60.49
8.830	20.0784	21.5333	65.08
10.820	19.1091	20.6303	71.97
10.646	19.2601	20.7060	72.03
10.190	19.6528	20.9075	72.66
13.057	18.9685	19.7012	78.02
11.830	19.4015	20.2003	78.59
11.318	19.3526	20.4160	76.83

Data of Test Plan 6 (b): Spot Tests on Edward Till, Kickapoo Clay, Kickapoo Top soil and FA6

Description of soil: Edward Till - Air dried
Tests Conducted: Microwave sensor test, NIR, Nuclear gauge and Oven dry moisture content tests
Test Description: Microwave sensor placed manually on the soil
Test location: Caterpillar laboratory
Tested by: Ujwala Manchikanti
Test Date: 10/24/2006

File Name	Nuclear gauge measurement		Microwave Value	Moisture content by oven dry method				
	Density (lb/ft^3)	Moisture conent (%)		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
EDTill1_1			29.05	H10	3.47	121.32	119.28	1.76
EDTill2_1	103.2	4.7	27.61	H6	3.26	87.64	85.82	2.20
EDTill1_3			29.07	H5	3.23	75.87	74.35	2.14
EDTill1_4	102.1	4.1	25.67	H7	3.26	85.59	83.56	2.53
EDTill1_5			27.81	H4	3.20	85.60	83.63	2.45
EDTill1_6			28.24	H3	3.33	78.72	77.02	2.31
EDTill1_7	103.4	4.6	28.23	X3	3.28	77.46	75.79	2.30
EDTill1_8			27.80	H2	3.35	88.74	86.86	2.25

Description of soil: Edward Till - Wet and Dry sides
Tests Conducted: Microwave sensor test, NIR and Oven dry moisture content tests
Test Description: Microwave sensor placed manually on the wet and dry sides of the soil bed
Test location: Caterpillar laboratory
Tested by: Ujwala Manchikanti
Test Date: 10/24/2006

File Name	Microwave Value (wet side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
EDTill2_1(a)	57.37	D6	20.88	52.55	49.09	12.27
EDTill2_2	65.54	D3	20.92	57.72	53.68	12.33
EDTill2_3	65.93	C6	20.84	64.36	59.20	13.45
EDTill2_4	59.92	C71	20.61	72.02	66.13	12.94
EDTill2_5	58.28	B8	20.79	68.20	62.81	12.83
EDTill2_6	59.48	B2	21.00	69.50	63.42	14.33
EDTill2_7	64.76	B5	20.73	64.57	58.99	14.58
EDTill2_8	56.50	C11	20.87	60.54	55.61	14.19

File Name	Microwave Value (dry side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
EDTill3_1	28.26	C2	20.73	72.09	69.85	4.56
EDTill3_2	30.17	C7	20.78	76.02	73.82	4.15
EDTill3_3	28.96	D1	20.80	91.29	88.87	3.56
EDTill3_4	29.21	C1	20.81	91.77	89.30	3.61
EDTill3_5	27.93	B9	20.88	89.51	87.06	3.70
EDTill3_6	27.25	B7	20.82	93.35	90.83	3.60
EDTill3_7	26.82	D2	20.85	104.02	101.13	3.60
EDTill3_8	24.78	B10	20.87	84.47	81.36	5.14

Description of soil: Kickapoo Clay - Air dried
Tests Conducted: Microwave sensor test, NIR, Nuclear gauge and Oven dry moisture content tests
Test Description: Microwave sensor placed manually on the soil
Test location: Caterpillar laboratory
Tested by : Ujwala Manchikanti
Test Date: 10/24/2006

File Name	Nuclear gauge measurement		Microwave Value	Moisture content by oven dry method				
	Density (lb/ft^3)	Moisture conent (%)		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
kpclay1_1			37.01	T2	3.32	63.74	57.68	11.15
kpclay1_2	75.8	15.1	31.08	X4	3.40	64.35	57.67	12.31
kpclay1_3			32.25	410	3.37	45.33	40.73	12.31
kpclay1_4			34.45	52	3.40	52.05	47.57	10.14
kpclay1_5	79.2	13	29.5	30	3.38	56.99	52.17	9.88
kpclay1_6			27.35	45	3.16	72.29	66.32	9.45
kpclay1_7			34.57	57	3.41	69.45	62.77	11.25
kpclay1_8			29.72	T3	3.34	61.53	56.04	10.42
kpclay1_9	76.5	10	29.53	H11	3.42	77.78	70.18	11.38
kpclay1_10			28.57	38	3.32	71.69	65.03	10.79

Description of soil: Kickapoo Clay - Wet and Dry sides

Tests Conducted: Microwave sensor test, NIR and Oven dry moisture content tests

Test Description: Microwave sensor placed manually on the wet and dry sides of the soil bed

Test location: Caterpillar laboratory

Tested by : Ujwala Manchikanti

Test Date: 10/24/2006

File Name	Microwave Value (wet side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
kpclay 2_1	54.51	B3	20.83	66.54	59.84	17.18
kpclay 2_2	62.36	A19	20.97	68.84	61.24	18.87
kpclay 2_3	61.55	C10	20.68	62.59	56.40	17.33
kpclay 2_4	58.81	B6	20.86	68.56	60.69	19.76
kpclay 2_5	70.69	A17	20.89	66.14	58.78	19.42
kpclay 2_6	51.91	A10	20.87	61.28	54.83	18.99
kpclay 2_7	56.87	C3	20.84	68.22	60.94	18.15
kpclay 2_8	60.83	A9	20.67	64.89	58.08	18.20
kpclay 2_9	66.14	A13	20.76	66.47	59.23	18.82
kpclay 2_10	71.77	C8	20.89	71.03	63.15	18.65

File Name	Microwave Value (dry side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
kpclay3_1	46.18	A21	20.83	54.81	51.13	12.15
kpclay3_2	50.02	B4	20.72	69.11	63.96	11.91
kpclay3_3	50.39	C5	20.80	67.29	61.97	12.92
kpclay3_4	47.18	A18	20.82	60.75	56.40	12.23
kpclay3_5	43.79	A22	20.71	69.61	64.19	12.47
kpclay3_6	48.86	C9	20.77	66.67	61.58	12.47
kpclay3_7	52.82	B1	20.78	60.93	56.74	11.65
kpclay3_8	44.22	A4	20.78	65.93	61.08	12.03
kpclay3_9	45.06	A15	20.83	55.64	51.70	12.76
kpclay3_10	43.37	A20	20.80	69.27	64.17	11.76

Description of soil: Kickapoo Top soil - Air dried

Tests Conducted: Microwave sensor test, NIR, Nuclear gauge and Oven dry moisture content tests

Test Description: Microwave sensor placed manually on the soil

Test location: Caterpillar laboratory

Tested by : Ujwala Manchikanti

Test Date: 10/24/2006

File Name	Nuclear gauge measurement		Microwave Value	Moisture content by oven dry method				
	Density (lb/ft^3)	Moisture conent (%)		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
kptop soil1_1			19.53	T2	3.10	39.94	38.43	4.27
kptop soil1_2	74.3	14.5	32.73	T1	3.21	41.80	37.84	11.44
kptop soil1_3			37.54	T6	3.52	49.05	43.58	13.65
kptop soil1_4			40.41	T17	3.24	54.81	48.77	13.27
kptop soil1_5	73.1	12.9	38.8	T7	3.40	44.26	39.53	13.09
kptop soil1_6			38.64	T16	3.15	36.48	32.78	12.49
kptop soil1_7	72.8	12.2	37.13	T12	3.44	54.51	48.58	13.14
kptop soil1_8			35.85	T4	3.36	50.98	45.65	12.60

Description of soil: Kickapoo Top soil - Wet and Dry sides

Tests Conducted: Microwave sensor test, NIR and Oven dry moisture content tests

Test Description: Microwave sensor placed manually on the wet and dry sides of the soil bed

Test location: Caterpillar laboratory

Tested by : Ujwala Manchikanti

Test Date: 10/24/2006

File Name	Microwave Value (wet side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
kptop soil 2_1	69.05	A11	20.91	73.61	63.42	23.97
kptop soil 2_2	48.54	A1	20.81	79.54	70.08	19.20
kptop soil 2_3	52.4	A6	20.79	75.03	66.00	19.97
kptop soil 2_4	48.87	A12	20.87	73.89	65.18	19.66
kptop soil 2_5	48.74	A16	20.79	78.29	69.02	19.22
kptop soil 2_6	47.58	A8	20.82	84.83	74.18	19.96
kptop soil 2_7	45.66	H19	3.39	40.81	34.96	18.53
kptop soil 2_8	47.36	H17	3.60	56.76	47.84	20.16

File Name	Microwave Value (dry side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
kptop soil 3_1	37.38	A3	20.76	70.83	64.57	14.29
kptop soil 3_2	40.57	A2	20.75	80.58	73.39	13.66
kptop soil 3_3	38.26	C4	20.86	83.58	76.34	13.05
kptop soil 3_4	40.35	A14	20.82	82.80	74.93	14.54
kptop soil 3_5	39.83	A5	20.76	79.03	72.37	12.90
kptop soil 3_6	39.36	A7	21.01	62.95	57.96	13.50
kptop soil 3_7	33.87	H18	3.10	59.60	53.40	12.33
kptop soil 3_8	37.82	H16	3.50	62.72	56.29	12.18

Description of soil: FA6 - Air dried
Tests Conducted: Microwave sensor test, NIR, Nuclear gauge and Oven dry moisture content tests
Test Description: Microwave sensor placed manually on the soil
Test location: Caterpillar laboratory
Tested by : Ujwala Manchikanti
Test Date: 10/24/2006

File Name	Nuclear gauge measurement		Microwave Value	Moisture content by oven dry method				
	Density (lb/ft^3)	Moisture conent (%)		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
FA61_1	109.7	5.7	35.16	H13	3.52	49.76	48.07	3.79
FA61_2			35.11	H12	3.51	68.95	66.88	3.27
FA61_3	106.1	6.1	35.43	H1	3.20	52.14	50.06	4.44
FA61_4			33.53	X9	3.40	78.04	75.20	3.96
FA61_5			34.8	X10	3.38	68.95	66.13	4.49
FA61_6	103.4	5.4	29.44	X8	3.39	62.96	60.88	3.62
FA61_7			30.55	X7	3.35	61.93	60.00	3.41
FA61_8			31.94	X6	3.18	52.57	50.94	3.41
FA61_9	104.6	3.2	32.92	X5	3.15	50.64	48.62	4.44

Description of soil: FA6 - Wet and Dry sides

Tests Conducted: Microwave sensor test, NIR and Oven dry moisture content tests

Test Description: Microwave sensor placed manually on the wet and dry sides of the soil bed

Test location: Caterpillar laboratory

Tested by : Ujwala Manchikanti

Test Date: 10/24/2006

File Name	Microwave Value (wet side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
FA62_1	42.75	H15	3.18	36.61	34.17	7.87
FA62_2	54.74	T14	3.37	73.63	67.99	8.73
FA62_3	47.12	T10	3.39	69.62	64.69	8.04
FA62_4	42.13	T11	3.44	76.37	71.27	7.52
FA62_5	41.85	X2	3.24	81.83	75.88	8.19
FA62_6	40.87	H9	3.44	96.37	89.29	8.25
FA62_7	46.15	H20	3.46	65.23	61.06	7.24
FA62_8	51.15	36	3.39	49.60	46.41	7.42
FA62_9	48.48	56	3.27	71.42	66.99	6.95

File Name	Microwave Value (dry side)	Moisture content by oven dry method				
		Tare no.	Weight of empty tare	Weight of tare+wet soil	Weight of tare+dry soil	Moisture content
FA63_1	34.16	T5	3.63	69.53	65.73	6.12
FA63_2	32.25	T3	3.38	75.21	72.11	4.51
FA63_3	31.2	T13	3.51	76.05	73.59	3.51
FA63_4	34.56	X1	3.44	70.69	67.72	4.62
FA63_5	32.15	H8	3.44	58.02	55.86	4.12
FA63_6	31.3	H14	3.37	81.81	78.58	4.29
FA63_7	33.92	26	3.15	74.72	72.18	3.68
FA63_8	30.28	41	3.30	72.17	69.72	3.69
FA63_9	33.03	43	3.15	69.74	67.57	3.37

Data of Test Plan 7: Accuracy and Precision tests

Date	5/3/2007
Soil Type	**Loess**
Test No.	7
Specific Gravity	2.62

Unit weight of water = 998.1646 kg/m^3

Water Content Evaluation

Sample No.	1	2	3	4	5	6	7	8	9	10
Tare No.	J	G	A	I	H	M	T8	1	102	17
Mass of wet soil+tare(1)	209.02	262.21	266.58	280.69	253.96	232.6	171.89	178.08	220.2	186.68
Mass of dry soil+tare(2)	194.07	241.79	245.94	252.83	229.43	210.84	151.05	156.38	193.07	163.88
Mass of tare (3)	50.23	49.31	49.8	49.73	50.72	49.79	17.13	17.08	16.77	16.44
Mass of dry soil (4)=(2)-(3)	143.84	192.48	196.14	203.1	178.71	161.05	133.92	139.3	176.3	147.44
Mass of moisture(5)=(1)-(2)	14.95	20.42	20.64	27.86	24.53	21.76	20.84	21.7	27.13	22.8
Water Content,w%(6) = [(5)/(4)]*100	10.393	10.609	10.523	13.717	13.726	13.511	15.562	15.578	15.389	15.464
Density Evaluation										
Water Content,w%(6) = [(5)/(4)]*100	10.393	10.609	10.523	13.717	13.726	13.511	15.562	15.578	15.389	15.464
Mass of soil+mold, g (7)	5654.4	5656.8	5659.3	5748.5	5745.7	5752.6	5824.6	5812.8	5814.6	5812.1
Mass of mold,g (8)	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9
Mass of soil,g (9)= (7)-(8)	1663.5	1665.9	1668.4	1757.6	1754.8	1761.7	1833.7	1821.9	1823.7	1821.2
Wet unit weight,kg/m3 (10) = (9) / Volume	1721.057	1723.540	1726.127	1818.413	1815.516	1822.655	1897.146	1884.938	1886.800	1884.214
Wet unit weight,kN/m3 (11) = (10) *0.009807	16.878	16.903	16.928	17.833	17.805	17.875	18.605	18.486	18.504	18.478
Dry Unit weight,kg/m3 (12) = (10)/{1+ [(6)/100]}	1559.020	1558.229	1561.779	1599.063	1596.393	1605.703	1641.676	1630.881	1635.171	1631.863
Dry Unit weight,kN/m3 (13) = (11)/{1+ [(6)/100]}	15.289	15.282	15.316	15.682	15.656	15.747	16.100	15.994	16.036	16.004
Gravimetric moisture content (%)	10.393	10.609	10.523	13.717	13.726	13.511	15.562	15.578	15.389	15.464
Volumetric moisture content (%)	17.888	18.285	18.164	24.944	24.920	24.626	29.522	29.363	29.035	29.137
Zero air void line density (kg/m3)	2055.468	2046.391	2049.997	1923.790	1923.465	1931.460	1857.760	1857.195	1863.761	1861.141
Zero air void line density (kN/m3)	20.158	20.069	20.104	18.867	18.863	18.942	18.219	18.214	18.278	18.252

Accuracy and Precision microwave test data - Loess

Moisture Content	Microwave value
10.393	45.61
10.393	45.35
10.393	45.39
10.393	45.61
10.393	45.26
10.393	44.95
10.393	45.36
10.393	45.28
10.393	45.06
10.393	44.77
10.393	45.02
10.393	45.01
10.393	44.52
10.393	44.4
10.393	44.51
10.609	45.31
10.609	45.4
10.609	45.16
10.609	45.28
10.609	45.37
10.609	45.64
10.609	45.28
10.609	45.49
10.609	45.42
10.609	45.2
10.609	45.62
10.609	45.29
10.609	45.33
10.609	45.2
10.609	44.98
10.523	45.84
10.523	45.85
10.523	45.96
10.523	45.97
10.523	45.84
10.523	45.37
10.523	45.26
10.523	45.73
10.523	45.9
10.523	45.48
10.523	45.47
10.523	45.59
10.523	45.85

Moisture Content	Microwave value
13.717	56.12
13.717	56.41
13.717	56.43
13.717	56.69
13.717	56.78
13.717	56.59
13.717	56.44
13.717	56.12
13.717	56.49
13.717	56.52
13.717	56.5
13.717	56.24
13.717	56.1
13.717	55.86
13.717	55.78
13.726	56.38
13.726	56.32
13.726	56.38
13.726	56.37
13.726	56.7
13.726	56.16
13.726	56.1
13.726	56.41
13.726	55.84
13.726	56.51
13.726	56.34
13.726	56.49
13.726	56.23
13.726	56.18
13.726	55.89
13.511	56.37
13.511	56.11
13.511	56.52
13.511	55.85
13.511	56.18
13.511	56.78
13.511	55.93
13.511	56.21
13.511	56.12
13.511	56
13.511	55.82
13.511	56.04
13.511	56.37

Moisture Content	Microwave value
15.562	66.47
15.562	66.25
15.562	66.05
15.562	66.07
15.562	66.18
15.562	66.18
15.562	66.08
15.562	66.03
15.562	65.7
15.562	65.77
15.562	66.04
15.562	66.1
15.562	66.02
15.562	65.9
15.562	65.91
15.578	64.67
15.578	64.19
15.578	64.8
15.578	64.18
15.578	64.45
15.578	64.24
15.578	64.19
15.578	64.71
15.578	64.6
15.578	64.63
15.578	64.47
15.578	64.07
15.578	64.4
15.578	64.31
15.578	64.14
15.389	64.02
15.389	64.36
15.389	64.38
15.389	64.47
15.389	64.06
15.389	64.04
15.389	64.11
15.389	64.08
15.389	64.15
15.389	63.98
15.389	64.01
15.389	63.77
15.389	63.78

Date 5/3/2007 B =Bottom
Soil Type **Edward Till** T=Top
Test No. I
Specific Gravity 2.72 Unit weight of water = 998.1646 kg/m^3

Water Content Evaluation

	B	B	B	B	B	B	B	T
Sample No.	1	2	3	4	5	6	7	8
Tare No.	N	D	W	2	A1	1101	33	ME3
Mass of wet soil+tare(1)	232.77	273.84	235.21	166.16	171.97	171.91	196.54	157.12
Mass of dry soil+tare(2)	217.36	254.96	219.51	153.53	154.63	154.56	176.47	141.72
Mass of tare (3)	49.83	50.27	50.01	17.29	16.87	16.35	16.11	17.17
Mass of dry soil (4)=(2)-(3)	167.53	204.69	169.5	136.24	137.76	138.21	160.36	124.55
Mass of moisture(5)=(1)-(2)	15.41	18.88	15.7	12.63	17.34	17.35	20.07	15.4
Water Content,w%(6) = [(5)/(4)]*100	9.198	9.224	9.263	9.270	12.587	12.553	12.516	12.365
Density Evaluation								
Water Content,w%(6) = [(5)/(4)]*100	9.198	9.224	9.263	9.270	12.587	12.553	12.516	12.365
Mass of soil+mold, g (7)	5847.7	5843.4	5840.2	5822.3	6040.9	6030.3	6025.4	6025.4
Mass of mold,g (8)	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9
Mass of soil,g (9)= (7)-(8)	1856.8	1852.5	1849.3	1831.4	2050	2039.4	2034.5	2034.5
Wet unit weight,kg/m3 (10) = (9) / Volume	1921.045	1916.597	1913.286	1894.766	2120.930	2109.963	2104.894	2104.894
Wet unit weight,kN/m3 (11) = (10) *0.009807	18.840	18.796	18.764	18.582	20.800	20.692	20.643	20.643
Dry Unit weight,kg/m3 (12) = (10)/{1+ [(6)/100]}	1759.226	1754.744	1751.090	1734.016	1883.812	1874.634	1870.757	1873.273
Dry Unit weight,kN/m3 (13) = (11)/{1+ [(6)/100]}	17.253	17.209	17.173	17.005	18.475	18.385	18.347	18.371
Gravimetric moisture content (%)	9.198	9.224	9.263	9.270	12.587	12.553	12.516	12.365
Volumetric moisture content (%)	17.670	17.678	17.722	17.565	26.696	26.487	26.344	26.026
Zero air void line density (kg/m3)	2171.667	2170.470	2168.639	2168.268	2022.549	2023.933	2025.484	2031.713
Zero air void line density (kN/m3)	21.298	21.286	21.268	21.264	19.835	19.849	19.864	19.925

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Water Content Evaluation

	B	T	B	T	B	T	B	T
Sample No.	9	10	11	12	13	14	15	16
Tare No.	SE4	M1	A/2	L/89	6	Q	N	31
Mass of wet soil+tare(1)	183.88	179.14	259.25	229.2	240.12	172.64	215.24	175.94
Mass of dry soil+tare(2)	165.49	160.99	228.23	202.09	211.43	152.7	189.89	155.92
Mass of tare (3)	17.14	15.86	17.04	17.35	17.16	16.89	16.78	17.23
Mass of dry soil (4)=(2)-(3)	148.35	145.13	211.19	184.74	194.27	135.81	173.11	138.69
Mass of moisture(5)=(1)-(2)	18.39	18.15	31.02	27.11	28.69	19.94	25.35	20.02
Water Content,w%(6) = [(5)/(4)]*100	12.396	12.506	14.688	14.675	14.768	14.682	14.644	14.435
Density Evaluation								
Water Content,w%(6) = [(5)/(4)]*100	12.396	12.506	14.688	14.675	14.768	14.682	14.644	14.435
Mass of soil+mold, g (7)	6031.3	6031.3	6034.5	6034.5	6031.8	6031.8	6031.8	6031.8
Mass of mold,g (8)	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9	3990.9
Mass of soil,g (9)= (7)-(8)	2040.4	2040.4	2043.6	2043.6	2040.9	2040.9	2040.9	2040.9
Wet unit weight,kg/m3 (10) = (9) / Volume	2110.998	2110.998	2114.309	2114.309	2111.515	2111.515	2111.515	2111.515
Wet unit weight,kN/m3 (11) = (10) *0.009807	20.703	20.703	20.735	20.735	20.708	20.708	20.708	20.708
Dry Unit weight,kg/m3 (12) = (10)/{1+ [(6)/100]}	1878.173	1876.342	1843.528	1843.745	1839.810	1841.187	1841.804	1845.164
Dry Unit weight,kN/m3 (13) = (11)/{1+ [(6)/100]}	18.419	18.401	18.079	18.082	18.043	18.057	18.063	18.096
Gravimetric moisture content (%)	12.396	12.506	14.688	14.675	14.768	14.682	14.644	14.435
Volumetric moisture content (%)	26.169	26.400	31.055	31.027	31.183	31.002	30.921	30.480
Zero air void line density (kg/m3)	2030.397	2025.877	1939.958	1940.468	1936.950	1940.181	1941.631	1949.549
Zero air void line density (kN/m3)	19.912	19.868	19.025	19.030	18.996	19.027	19.042	19.119

Accuracy and Precision microwave test data – Edward Till

Moisture Content	Microwave value
9.198	44.48
9.198	44
9.198	44.05
9.198	44.06
9.198	44.17
9.198	44.11
9.198	43.87
9.198	43.67
9.198	43.88
9.198	43.81
9.198	43.53
9.198	44.22
9.198	44.08
9.198	44.07
9.198	44.13
9.224	45.57
9.224	45.06
9.224	45.05
9.224	45.11
9.224	45.13
9.224	44.77
9.224	45.13
9.224	45.14
9.224	44.83
9.224	44.81
9.224	44.93
9.224	44.91
9.224	44.96
9.224	45.05
9.224	44.93
9.263	45.5
9.263	45.57
9.263	45.6
9.263	43.56
9.263	43.57
9.263	44.45
9.263	43.75
9.263	43.44
9.263	43.51
9.263	44.25
9.263	44.4
9.263	44.72

Moisture Content	Microwave value
12.587	62.69
12.587	63.53
12.587	63.74
12.587	63.51
12.587	63.72
12.587	63.57
12.587	63.47
12.587	63.54
12.587	62.87
12.587	62.4
12.587	62.83
12.587	63.11
12.587	63.24
12.587	63.22
12.587	63.22
12.553	64.34
12.553	63.86
12.553	63.93
12.553	64.08
12.553	63.74
12.553	63.55
12.553	63.34
12.553	63.25
12.553	63.8
12.553	63.31
12.553	63.43
12.553	63.75
12.553	63.59
12.553	63.71
12.553	63.87
12.516	61.61
12.516	61.43
12.516	60.66
12.516	60.43
12.516	60.96
12.516	61.62
12.516	61.75
12.516	61.11
12.516	60.45
12.516	61.12
12.516	61.03
12.516	60.83

Moisture Content	Microwave value
14.688	70.18
14.688	71
14.688	70.75
14.688	70.07
14.688	70.06
14.688	70.5
14.688	70.75
14.688	70.15
14.688	70.51
14.688	70.41
14.688	70.23
14.688	69.12
14.688	69.15
14.688	69.42
14.688	69.74
14.675	66.8
14.675	67.19
14.675	67.72
14.675	67.73
14.675	67.27
14.675	66.43
14.675	66.81
14.675	67.06
14.675	67.2
14.675	67.06
14.675	66.98
14.675	67.24
14.675	66.58
14.675	67.43
14.675	67.05
14.768	70.8
14.768	70.84
14.768	70.62
14.768	70.15
14.768	70.43
14.768	70.13
14.768	69.75
14.768	69.32
14.768	69.34
14.768	69.84
14.768	69.6
14.768	69.41

*Continued on next page

Moisture Content	Microwave value
9.263	44.06
9.263	44.17
9.263	44.57
9.270	43.64
9.270	43.99
9.270	43.82
9.270	43.5
9.270	43.26
9.270	43.66
9.270	43.71
9.270	43.61
9.270	43.11
9.270	44.07
9.270	43.82
9.270	43.8
9.270	43.65
9.270	43.73
9.270	43.97

Moisture Content	Microwave value
12.516	61.21
12.516	61.38
12.516	60.59
12.365	52.45
12.365	54.08
12.365	55.66
12.396	64.38
12.396	64.22
12.396	63.96
12.396	64.13
12.396	64.09
12.396	63.96
12.396	63.47
12.396	63.92
12.396	63.97
12.396	64.14
12.396	64.15
12.396	63.67
12.396	63.5
12.396	63.94
12.396	63.68
12.506	58.54
12.506	58.1
12.506	58.74
12.506	57.69
12.506	58.47
12.506	58.85
12.506	58.93
12.506	58.71
12.506	58.71
12.506	58.97
12.506	58.48
12.506	58.7
12.506	58.58
12.506	58.26
12.506	58.34

Moisture Content	Microwave value
14.768	69.07
14.768	69.75
14.768	69.76
14.682	64.49
14.682	64.85
14.682	64.89
14.682	64.63
14.682	63.98
14.682	63.6
14.682	64.37
14.682	64.1
14.682	64.23
14.682	64.3
14.682	64.1
14.682	63.63
14.682	63.69
14.682	63.22
14.682	63.64
14.644	70.51
14.644	70.34
14.644	70.48
14.644	70.3
14.644	70.53
14.644	70.97
14.644	70.68
14.644	70.45
14.644	70.84
14.644	70.52
14.644	70.33
14.644	70.35
14.644	70.14
14.644	69.96
14.644	70.69
14.435	65.54
14.435	65.64
14.435	66.59
14.435	65.29
14.435	65.91
14.435	66.35
14.435	66.29
14.435	66.92
14.435	66.89
14.435	65.34
14.435	66.52

APPENDIX B: ATTERBERG LIMITS AND GRAIN SIZE DISTRIBUTION TESTS

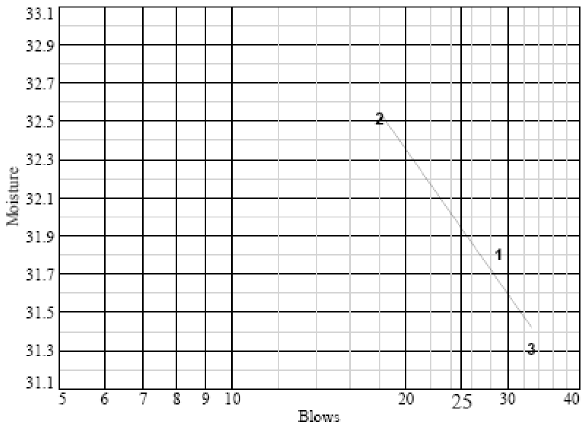
LIQUID AND PLASTIC LIMIT TEST DATA

10/26/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Rm.142 Town Engineering,ISU
Material Description: Loess(silt)
USCS: ML **AASHTO:** A-4(7)
Tested by: Alexandria H B **Checked by:** Ujwala M

Liquid Limit Data

Run No.	1	2	3	4	5	6
Wet+Tare	38.51	34.29	36.97			
Dry+Tare	33.38	29.91	32.23			
Tare	17.25	16.44	17.09			
# Blows	29	18	33			
Moisture	31.8	32.5	31.3			



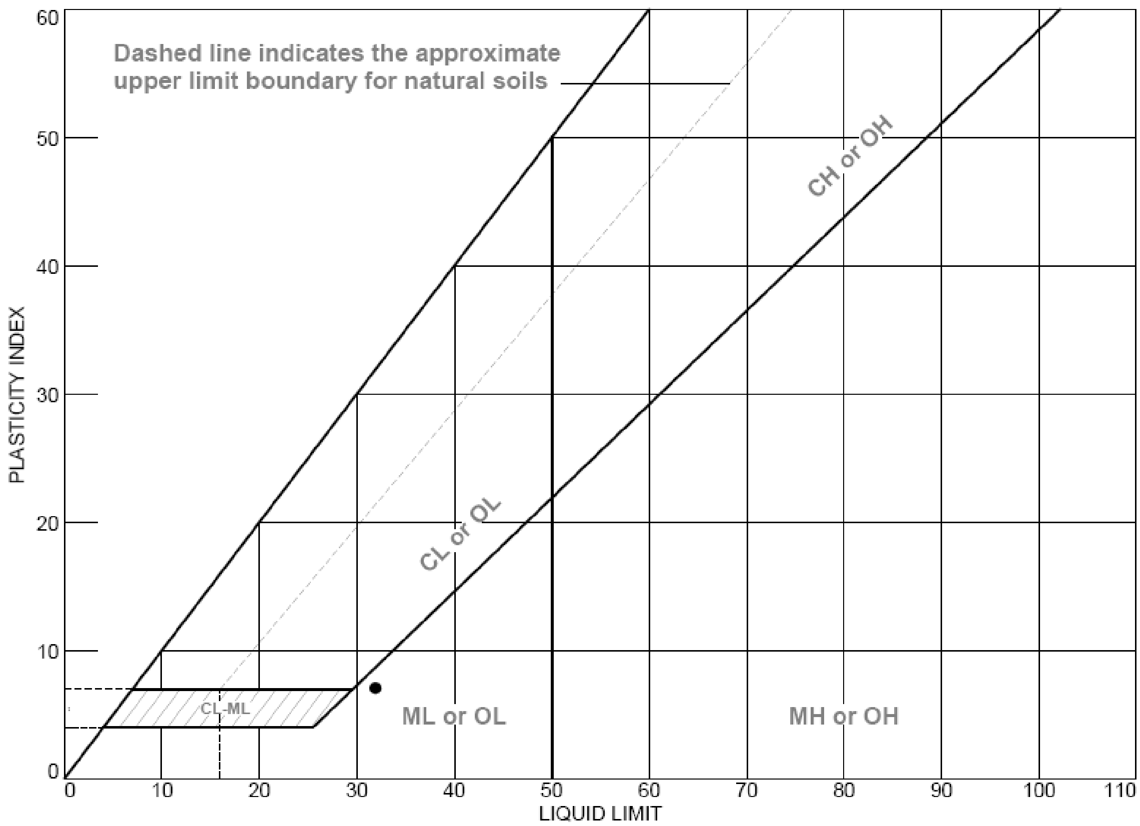
Liquid Limit= 32
Plastic Limit= 25
Plasticity Index= 7

Plastic Limit Data

Run No.	1	2	3	4
Wet+Tare	45.53			
Dry+Tare	39.65			
Tare	16.5			
Moisture	25.4			

__DEMO__

LIQUID AND PLASTIC LIMITS TEST REPORT



SOIL DATA								
SYMBOL	SOURCE	SAMPLE NO.	DEPTH	NATURAL WATER CONTENT (%)	PLASTIC LIMIT (%)	LIQUID LIMIT (%)	PLASTICITY INDEX (%)	USCS
●					25	32	7	ML

Iowa State University **Civil, Construction and Environmental Engineering Department**	**Client:** **Project:** Evaluation of Microwave Sensor for soil moisture content determination **Project No.:** **Figure**

Tested By: Alexandria H B **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA **10/26/2007**

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Rm.142 Town Engineering,ISU
Material Description: Loess(silt)
Sample Date: 6/18/07 **Liquid Limit:** 32 **Plastic Limit:** 25
USCS Classification: ML **AASHTO Classification:** A-4(7)
Tested by: Alexandra H B **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
2001.00	0.00	0.00	3	0.00	100
			2	0.00	100
			1.5	0.00	100
			1	0.00	100
			3/4	0.00	100
			3/8	5.94	100
			#4	9.50	100
			#10	13.98	99
75.00	0.00	0.00	#40	0.36	99
			#100	0.87	98
			#200	1.65	97

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 99
Weight of hydrometer sample =75
Hygroscopic moisture correction:
Moist weight and tare = 137.90
Dry weight and tare = 135.31
Tare weight = 41.61
Hygroscopic moisture = 2.8%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.62
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	22.5	47.0	41.2	0.0134	47.0	8.6	0.0277	56.4
5.00	22.5	33.3	27.5	0.0134	33.3	10.8	0.0197	37.7
15.00	23.0	23.8	18.2	0.0133	23.8	12.4	0.0121	25.0
35.00	23.0	20.5	14.9	0.0133	20.5	12.9	0.0081	20.4
60.00	23.5	18.1	12.7	0.0132	18.1	13.3	0.0062	17.5
250.00	24.0	16.0	10.9	0.0131	16.0	13.7	0.0031	14.9
1513.00	24.5	13.5	8.6	0.0130	13.5	14.1	0.0013	11.8

__DEMO__

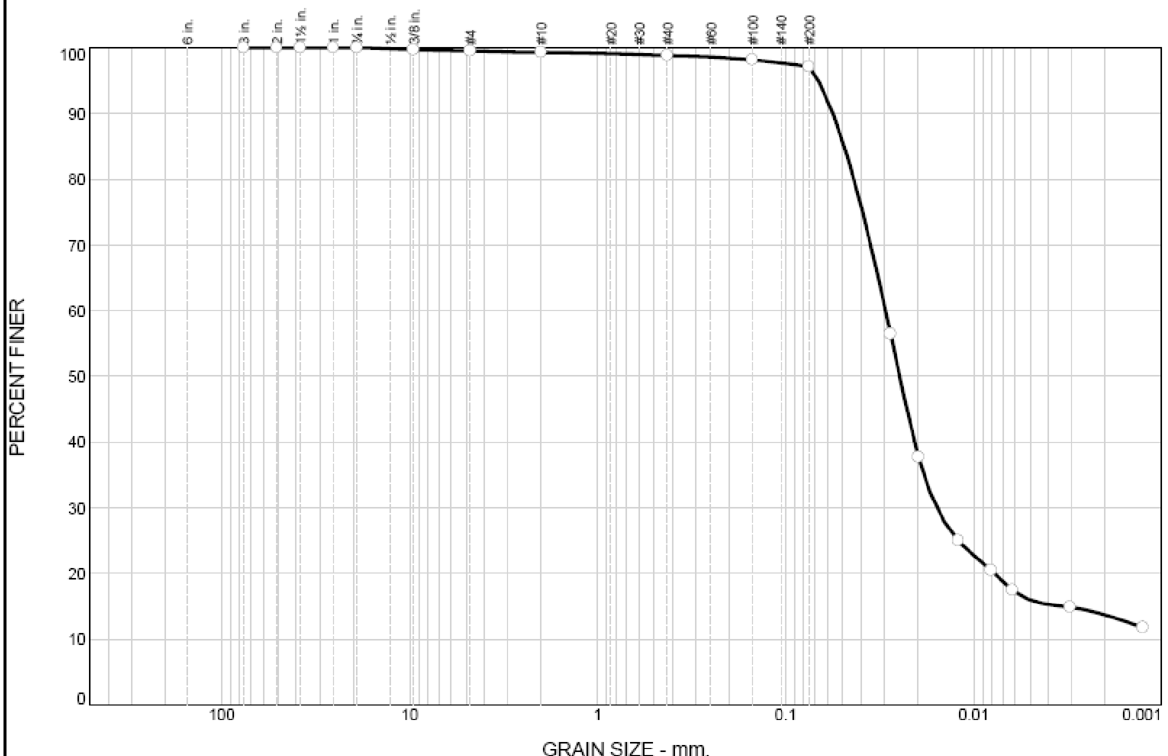
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	0	0	0	1	0	2	3	83	14	97

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
	0.0033	0.0078	0.0157	0.0248	0.0294	0.0434	0.0488	0.0560	0.0671

Fineness Modulus
0.06

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0	0	0	1	0	2	83	14

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○	32	25	0.0488	0.0294	0.0248	0.0157	0.0033			

Material Description	USCS	AASHTO
○ Loess(silt)	ML	A-4(7)

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

○ **Location:** Rm.142 Town Engineering,ISU

Date: ○ 6/18/07

Iowa State University

Civil, Construction and Environmental Engineering Department

Remarks:

Figure

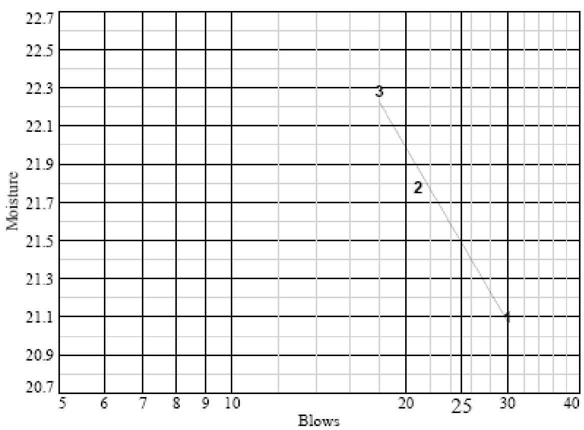
Tested By: Alexandra H B **Checked By:** Ujwala M

LIQUID AND PLASTIC LIMIT TEST DATA **10/26/2007**

Project: Evaluation of Microwave sensor for soil moisture content determination
Location: Rm.142, Town Engineering,ISU
Material Description: Oxidized Glacial Till-silty clay
%<#40: 93 **%<#200:** 92 **USCS:** CL-ML **AASHTO:** A-4(2)
Tested by: Allison M **Checked by:** Ujwala M

Liquid Limit Data

Run No.	1	2	3	4	5	6
Wet+Tare	62.60	34.86	39.85			
Dry+Tare	58.96	31.54	35.70			
Tare	41.71	16.30	17.08			
# Blows	30	21	18			
Moisture	21.1	21.8	22.3			



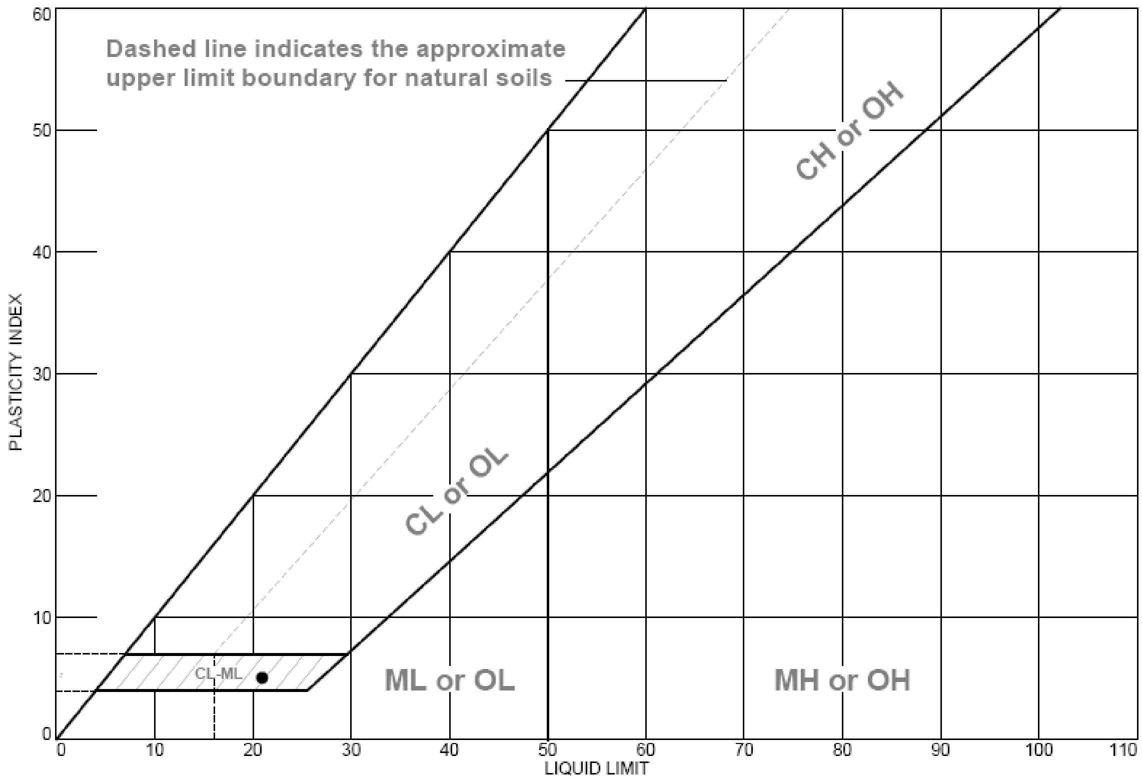
Liquid Limit= 21
Plastic Limit= 16
Plasticity Index= 5

Plastic Limit Data

Run No.	1	2	3	4	
Wet+Tare	67.68				
Dry+Tare	63.91				
Tare	40.66				
Moisture	16.2				

__DEMO__

LIQUID AND PLASTIC LIMITS TEST REPORT



	MATERIAL DESCRIPTION	LL	PL	PI	%<#40	%<#200	USCS
●	Oxidized Glacial Till-silty clay	21	16	5	93	92	CL-ML

Project No. **Client:**

Project: Evaluation of Microwave sensor for soil moisture content determination

● **Source of Sample:** Rm.142, Town Engineering,ISU

Remarks:

Iowa State University

Civil, Construction and Environmental Engineering Department

Figure

Tested By: Allison M **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA 10/26/2007

Project: Evaluation of Microwave sensor for soil moisture content determination
Location: Rm.142, Town Engineering,ISU
Material Description: Oxidized Glacial Till-silty clay
Sample Date: 5/18/07 **Liquid Limit:** 21 **Plastic Limit:** 16
USCS Classification: CL-ML **AASHTO Classification:** A-4(2)
Tested by: Allison M **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Sieve Opening Size	Weight Retained (grams)	Sieve Weight (grams)	Percent Finer
2238.60	0.00	3	0.00	0.00	100
		2	0.00	0.00	100
		1.5	0.00	0.00	100
		1	0.00	0.00	100
		.75	0.00	0.00	100
		.375	43.80	0.00	98
		#4	34.30	0.00	97
		#10	53.70	0.00	94
60.02	0.00	#40	0.40	0.00	93
		#100	0.60	0.00	93
		#200	0.60	0.00	92

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 94
Weight of hydrometer sample =60.02
Hygroscopic moisture correction:
Moist weight and tare = 133.57
Dry weight and tare = 132.28
Tare weight = 40.62
Hygroscopic moisture = 1.4%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.65
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	23.0	44.5	38.9	0.0132	44.5	9.0	0.0279	61.9
5.00	23.0	34.0	28.4	0.0132	34.0	10.7	0.0193	45.2
15.00	23.0	28.0	22.4	0.0132	28.0	11.7	0.0116	35.6
30.00	23.0	26.0	20.4	0.0132	26.0	12.0	0.0083	32.5
60.00	23.0	24.5	18.9	0.0132	24.5	12.3	0.0059	30.1
250.00	23.5	23.0	17.6	0.0131	23.0	12.5	0.0029	28.0
1440.00	23.5	21.0	15.6	0.0131	21.0	12.9	0.0012	24.9

__DEMO__

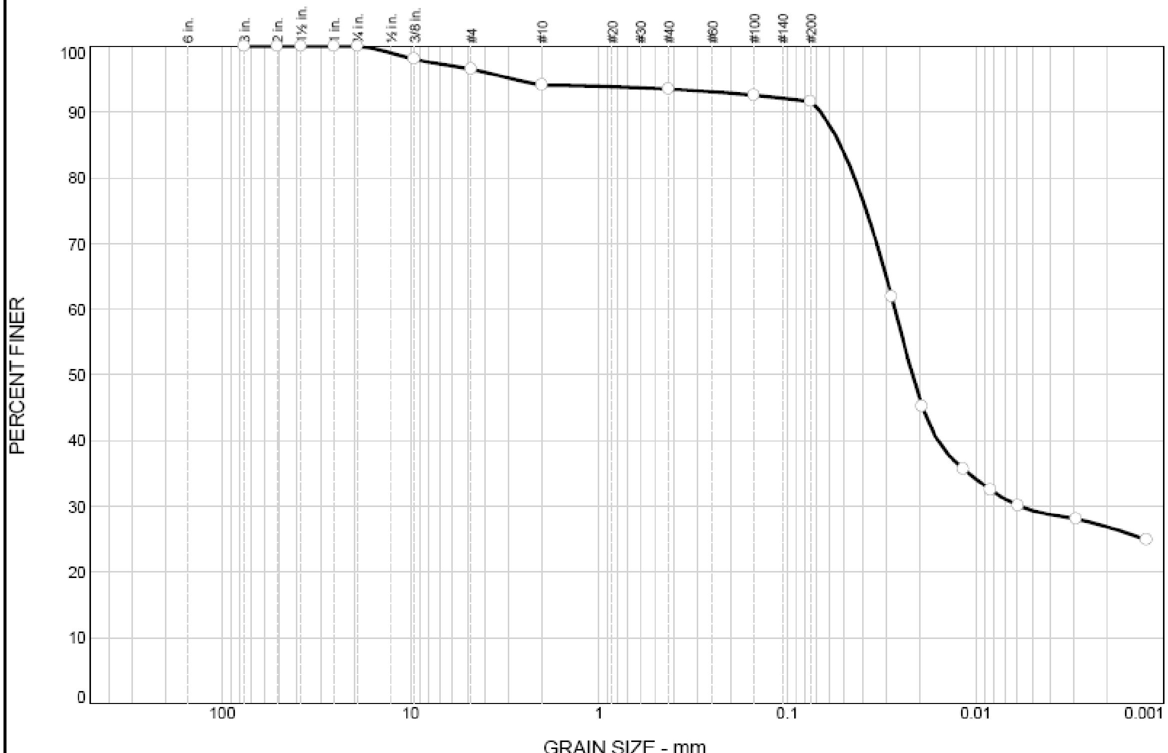
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	0	3	3	3	1	1	5	65	27	92

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
			0.0059	0.0217	0.0268	0.0439	0.0522	0.0664	2.8373

Fineness Modulus
0.37

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0	0	3	3	1	1	65	27

╳	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○	21	16	0.0522	0.0268	0.0217	0.0059				

Material Description	USCS	AASHTO
○ Oxidized Glacial Till-silty clay	CL-ML	A-4(2)

Project No. **Client:**

Project: Evaluation of Microwave sensor for soil moisture content determination

○ **Source of Sample:** Rm.142, Town Engineering,ISU

Date: ○ 5/18/07

Iowa State University

Civil, Construction and Environmental Engineering Department

Remarks:

Figure

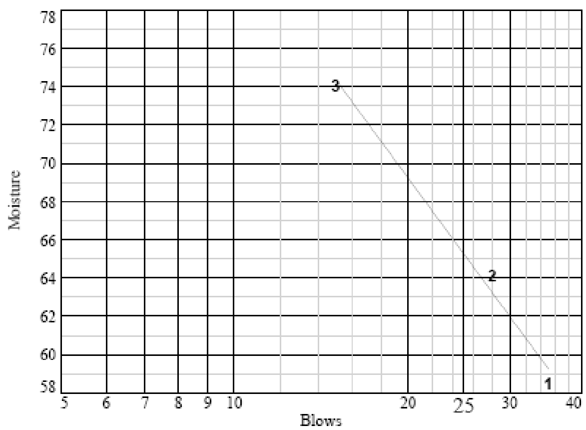
Tested By: Allison M **Checked By:** Ujwala M

LIQUID AND PLASTIC LIMIT TEST DATA 10/26/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Fairfield
Material Description: Gumbo(elastic silt)
%<#40: 99 **%<#200:** 97 **USCS:** MH **AASHTO:** A-7-5(37)
Tested by: Alexandra H B **Checked by:** Ujwala M

Liquid Limit Data

Run No.	1	2	3	4	5	6
Wet+Tare	54.08	54.50	61.39			
Dry+Tare	49.25	49.45	52.72			
Tare	41.00	41.58	41.02			
# Blows	35	28	15			
Moisture	58.5	64.2	74.1			



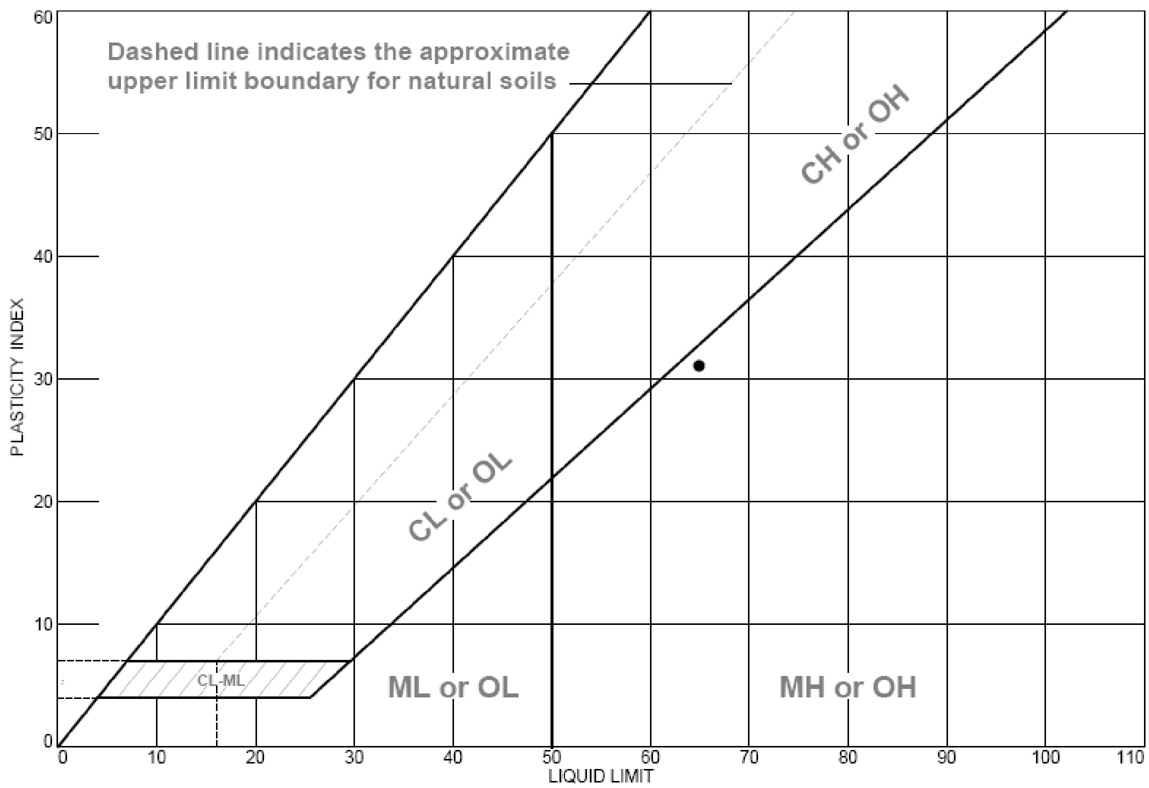
Liquid Limit= 65
Plastic Limit= 34
Plasticity Index= 31

Plastic Limit Data

Run No.	1	2	3	4
Wet+Tare	54.46			
Dry+Tare	50.97			
Tare	40.83			
Moisture	34.4			

__DEMO__

LIQUID AND PLASTIC LIMITS TEST REPORT



	MATERIAL DESCRIPTION	LL	PL	PI	%<#40	%<#200	USCS
●	Gumbo(elastic silt)	65	34	31	99	97	MH

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

● **Location:** Fairfield

Remarks:

Iowa State University
Civil, Construction and Environmental Engineering Department

Figure

Tested By: Alexandra H B **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA

10/26/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Fairfield
Material Description: Gumbo(elastic silt)
Liquid Limit: 65 **Plastic Limit:** 34
USCS Classification: MH **AASHTO Classification:** A-7-5(37)
Tested by: Alexandra H B **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Cumulative Pan Tare Weight (grams)	Sieve Opening Size	Cumulative Weight Retained (grams)	Percent Finer
2003.00	0.00	0.00	3	0.00	100
			2	0.00	100
			1.5	0.00	100
			1	0.00	100
			3/4	0.00	100
			3/8	0.00	100
			#4	0.00	100
			#10	0.23	100
71.00	0.00	0.00	#40	1.00	99
			#100	2.05	97
			#200	2.45	97

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 100
Weight of hydrometer sample =71
Hygroscopic moisture correction:
Moist weight and tare = 134.20
Dry weight and tare = 131.17
Tare weight = 41.90
Hygroscopic moisture = 3.4%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.70
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	23.5	47.0	41.6	0.0129	47.0	8.6	0.0267	60.0
5.00	23.5	34.0	28.6	0.0129	34.0	10.7	0.0189	41.2
15.00	24.0	25.0	19.9	0.0128	25.0	12.2	0.0115	28.6
30.00	24.0	22.0	16.9	0.0128	22.0	12.7	0.0083	24.3
60.00	24.0	20.5	15.4	0.0128	20.5	12.9	0.0059	22.1
250.00	24.0	18.0	12.9	0.0128	18.0	13.3	0.0030	18.5
1440.00	24.5	15.8	10.9	0.0127	15.8	13.7	0.0012	15.7

__DEMO__

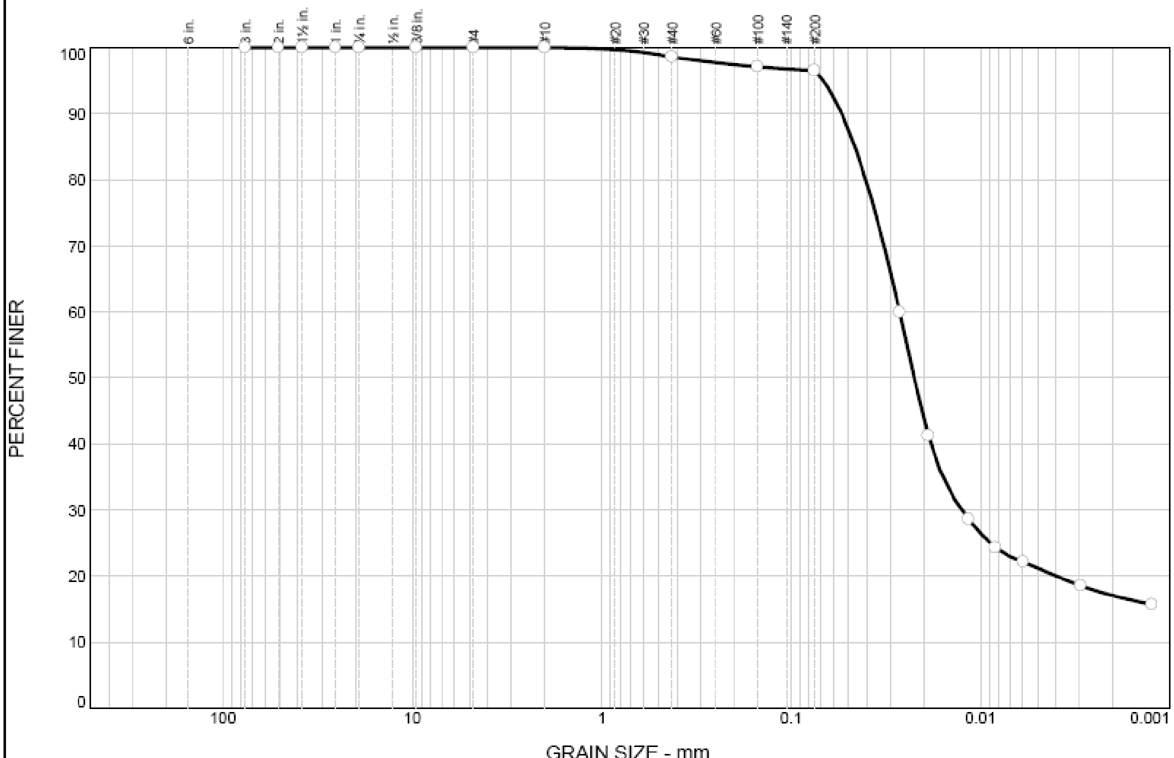
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	0	0	0	0	1	2	3	80	17	97

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0040	0.0126	0.0224	0.0267	0.0403	0.0460	0.0539	0.0673

Fineness Modulus
0.06

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0	0	0	0	1	2	80	17

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○	65	34	0.0460	0.0267	0.0224	0.0126				

Material Description	USCS	AASHTO
○ Gumbo(elastic silt)	MH	A-7-5(37)

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

○ **Location:** Fairfield

Date: ○

Iowa State University

Civil, Construction and Environmental Engineering Department

Remarks:

Figure

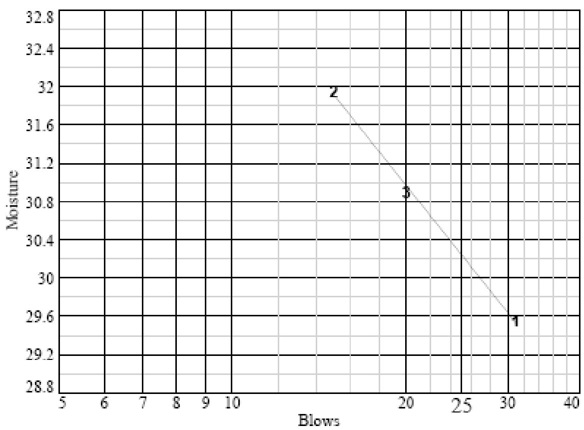
Tested By: Alexandra H B **Checked By:** Ujwala M

LIQUID AND PLASTIC LIMIT TEST DATA **10/26/2007**

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: Edward Till(sandy lean clay)
%<#40: 89 **%<#200:** 67 **USCS:** CL **AASHTO:** A-6(6)
Tested by: Allison M **Checked by:** Ujwala M

Liquid Limit Data

Run No.	1	2	3	4	5	6
Wet+Tare	21.41	19.17	20.47			
Dry+Tare	17.29	15.32	16.44			
Tare	3.35	3.27	3.40			
# Blows	31	15	20			
Moisture	29.6	32.0	30.9			



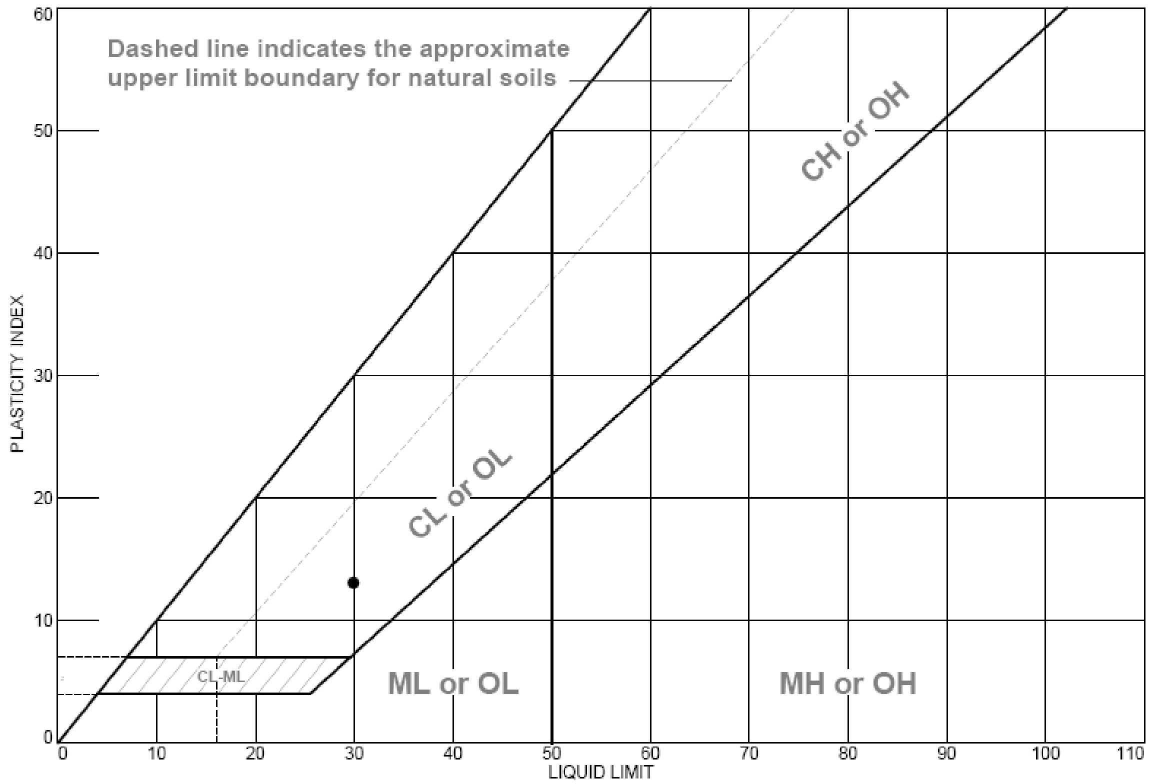
Liquid Limit= 30
Plastic Limit= 17
Plasticity Index= 13

Plastic Limit Data

Run No.	1	2	3	4
Wet+Tare	17.05			
Dry+Tare	15.11			
Tare	3.41			
Moisture	16.6			

__DEMO__

LIQUID AND PLASTIC LIMITS TEST REPORT



	MATERIAL DESCRIPTION	LL	PL	PI	%<#40	%<#200	USCS
●	Edward Till(sandy lean clay)	30	17	13	89	67	CL

Project No. **Client:**

Remarks:

Project: Evaluation of Microwave Sensor for soil moisture content determination

● **Source of Sample:** Caterpillar Laboratory, Peoria

Iowa State University

Civil, Construction and Environmental Engineering Department

Figure

Tested By: Allison M **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA 10/26/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: Edward Till(sandy lean clay)
Sample Date: 1/3/2007 **Liquid Limit:** 30 **Plastic Limit:** 17
USCS Classification: CL **AASHTO Classification:** A-6(6)
Tested by: Allison Moyer **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Sieve Opening Size	Weight Retained (grams)	Sieve Weight (grams)	Percent Finer
2048.40	0.00	3	0.00	0.00	100
		2	0.00	0.00	100
		1.5	0.00	0.00	100
		1	0.00	0.00	100
		.75	34.70	0.00	98
		.375	11.70	0.00	98
		#4	18.70	0.00	97
		#10	42.70	0.00	95
60.12	0.00	#40	3.80	0.00	89
		#100	9.30	0.00	74
		#200	4.20	0.00	67

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 95
Weight of hydrometer sample =60.12
Hygroscopic moisture correction:
Moist weight and tare = 119.64
Dry weight and tare = 116.72
Tare weight = 17.14
Hygroscopic moisture = 2.9%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.72
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	23.0	37.0	31.4	0.0129	37.0	10.2	0.0291	50.2
5.00	23.0	32.0	26.4	0.0129	32.0	11.0	0.0191	42.2
15.00	23.0	26.5	20.9	0.0129	26.5	11.9	0.0115	33.4
30.00	23.0	23.5	17.9	0.0129	23.5	12.4	0.0083	28.6
60.00	23.0	22.0	16.4	0.0129	22.0	12.7	0.0059	26.2
250.00	23.0	18.5	12.9	0.0129	18.5	13.3	0.0030	20.6
1440.00	23.0	15.0	9.4	0.0129	15.0	13.8	0.0013	15.0

__DEMO__

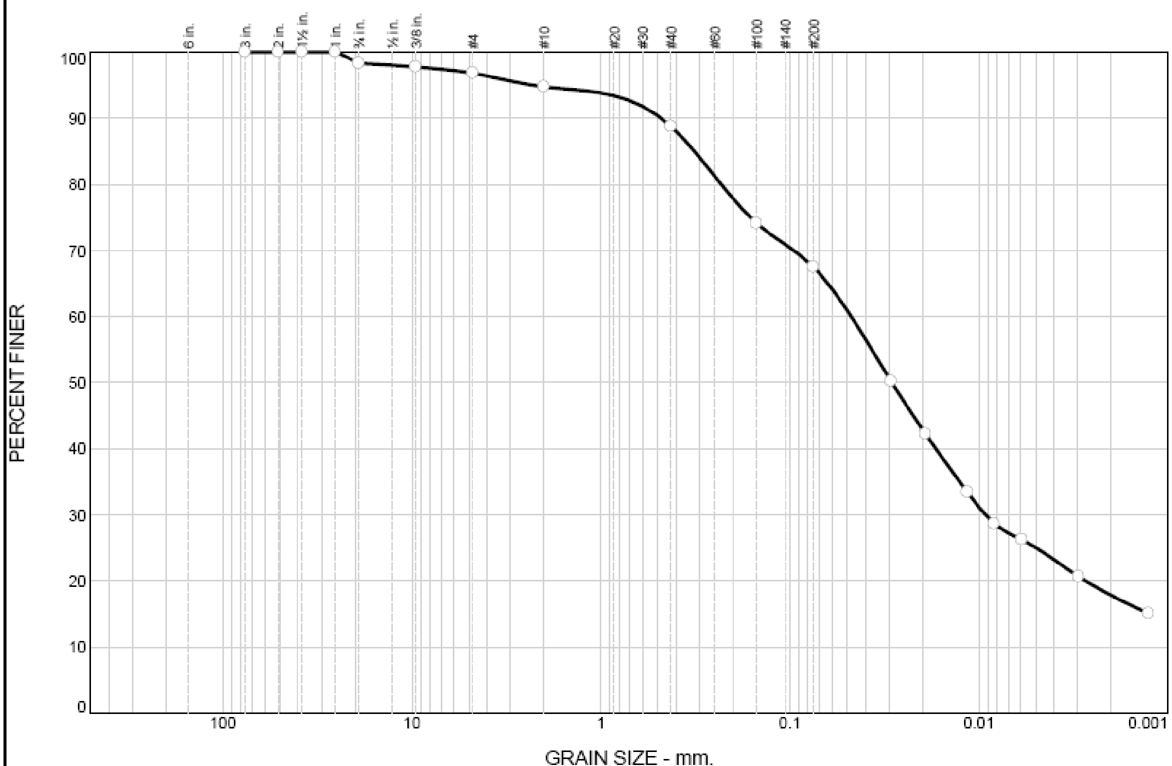
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	2	1	3	2	6	22	30	49	18	67

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0027	0.0093	0.0289	0.0474	0.2309	0.3201	0.4794	2.3087

Fineness Modulus
0.68

Particle Size Distribution Report



% +3"	% Gravel Coarse	% Gravel Fine	% Sand Coarse	% Sand Medium	% Sand Fine	% Fines Silt	% Fines Clay
0	2	1	2	6	22	49	18

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
30	17	0.3201	0.0474	0.0289	0.0093				

Material Description	USCS	AASHTO
Edward Till(sandy lean clay)	CL	A-6(6)

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

Source of Sample: Caterpillar Laboratory, Peoria

Date: 1/3/2007

Remarks:

Iowa State University

Civil, Construction and Environmental Engineering Department

Figure

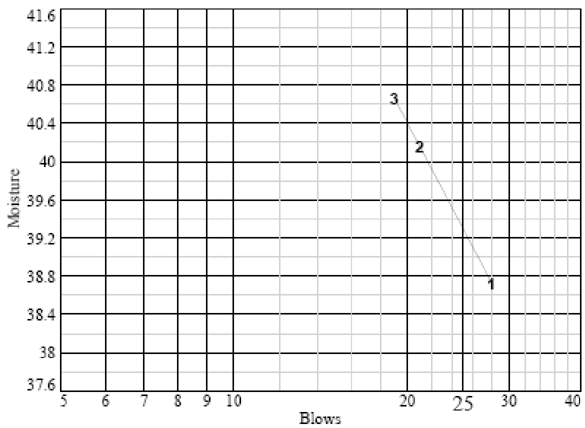
Tested By: Allison Moyer **Checked By:** Ujwala M

LIQUID AND PLASTIC LIMIT TEST DATA **10/26/2007**

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: Kickapoo Clay(lean clay)
%<#40: 98 **%<#200:** 95 **USCS:** CL **AASHTO:** A-6(16)
Tested by: Allison M **Checked by:** Ujwala M

Liquid Limit Data

Run No.	1	2	3	4	5	6
Wet+Tare	20.20	20.81	21.67			
Dry+Tare	15.44	15.83	16.38			
Tare	3.15	3.43	3.37			
# Blows	28	21	19			
Moisture	38.7	40.2	40.7			



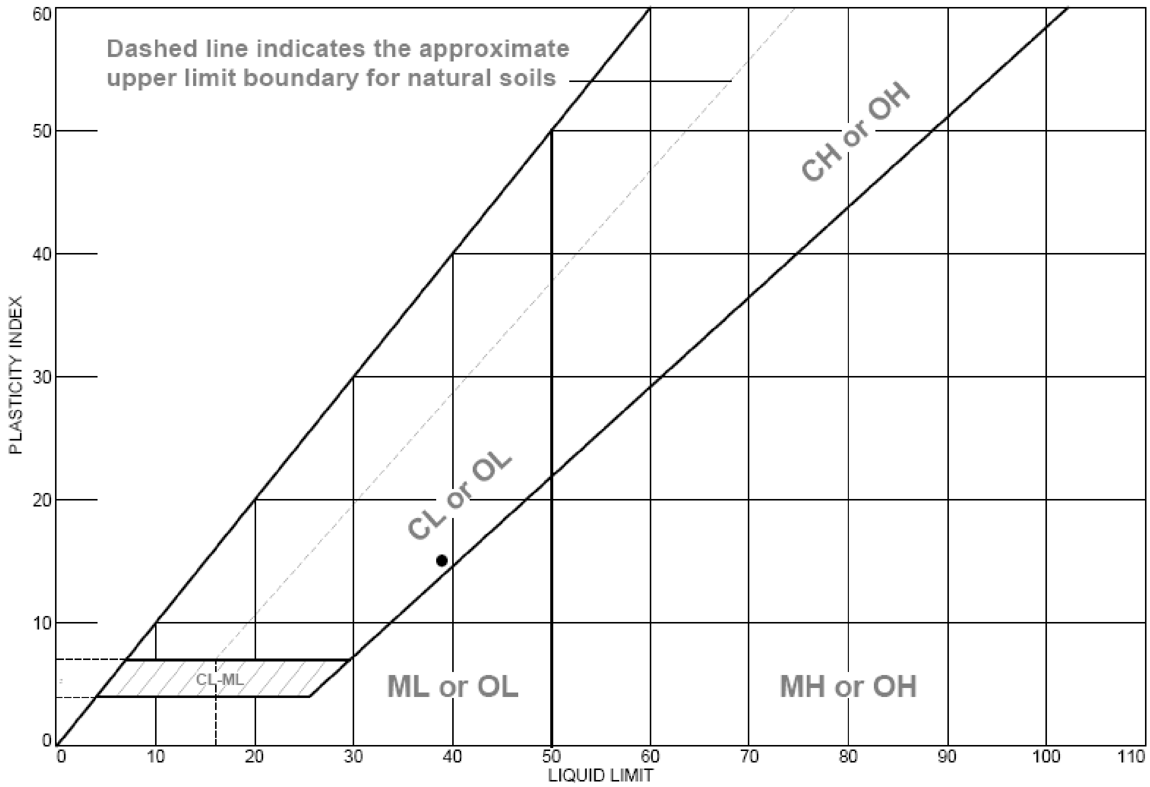
Liquid Limit= 39
Plastic Limit= 24
Plasticity Index= 15

Plastic Limit Data

Run No.	1	2	3	4	
Wet+Tare	19.80				
Dry+Tare	16.60				
Tare	3.18				
Moisture	23.8				

__DEMO__

LIQUID AND PLASTIC LIMITS TEST REPORT



	MATERIAL DESCRIPTION	LL	PL	PI	%<#40	%<#200	USCS
●	Kickapoo Clay(lean clay)	39	24	15	98	95	CL

Project No. **Client:**

Remarks:

Project: Evaluation of Microwave Sensor for soil moisture content determination

● **Source of Sample:** Caterpillar Laboratory, Peoria

Iowa State University
Civil, Construction and Environmental Engineering Department

Figure

Tested By: Allison M **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA **10/26/2007**

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: Kickapoo Clay(lean clay)
Sample Date: 1/3/2007 **Liquid Limit:** 39 **Plastic Limit:** 24
USCS Classification: CL **AASHTO Classification:** A-6(16)
Tested by: Allison M **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Sieve Opening Size	Weight Retained (grams)	Sieve Weight (grams)	Percent Finer
1984.00	0.00	3	0.00	0.00	100
		2	0.00	0.00	100
		1.5	0.00	0.00	100
		1	0.00	0.00	100
		.75	0.00	0.00	100
		.375	0.00	0.00	100
		#4	2.60	0.00	100
		#10	8.70	0.00	99
60.08	0.00	#40	1.10	0.00	98
		#100	1.70	0.00	95
		#200	0.10	0.00	95

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 99
Weight of hydrometer sample =60.08
Hygroscopic moisture correction:
Moist weight and tare = 108.98
Dry weight and tare = 102.13
Tare weight = 3.83
Hygroscopic moisture = 7.0%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.71
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	23.0	47.0	41.4	0.0129	47.0	8.6	0.0268	72.4
5.00	23.0	39.0	33.4	0.0129	39.0	9.9	0.0182	58.4
15.00	23.0	31.0	25.4	0.0129	31.0	11.2	0.0112	44.4
30.00	23.0	26.5	20.9	0.0129	26.5	11.9	0.0082	36.5
60.00	23.0	23.5	17.9	0.0129	23.5	12.4	0.0059	31.3
250.00	23.0	19.5	13.9	0.0129	19.5	13.1	0.0030	24.3
1440.00	23.0	16.5	10.9	0.0129	16.5	13.6	0.0013	19.1

__DEMO__

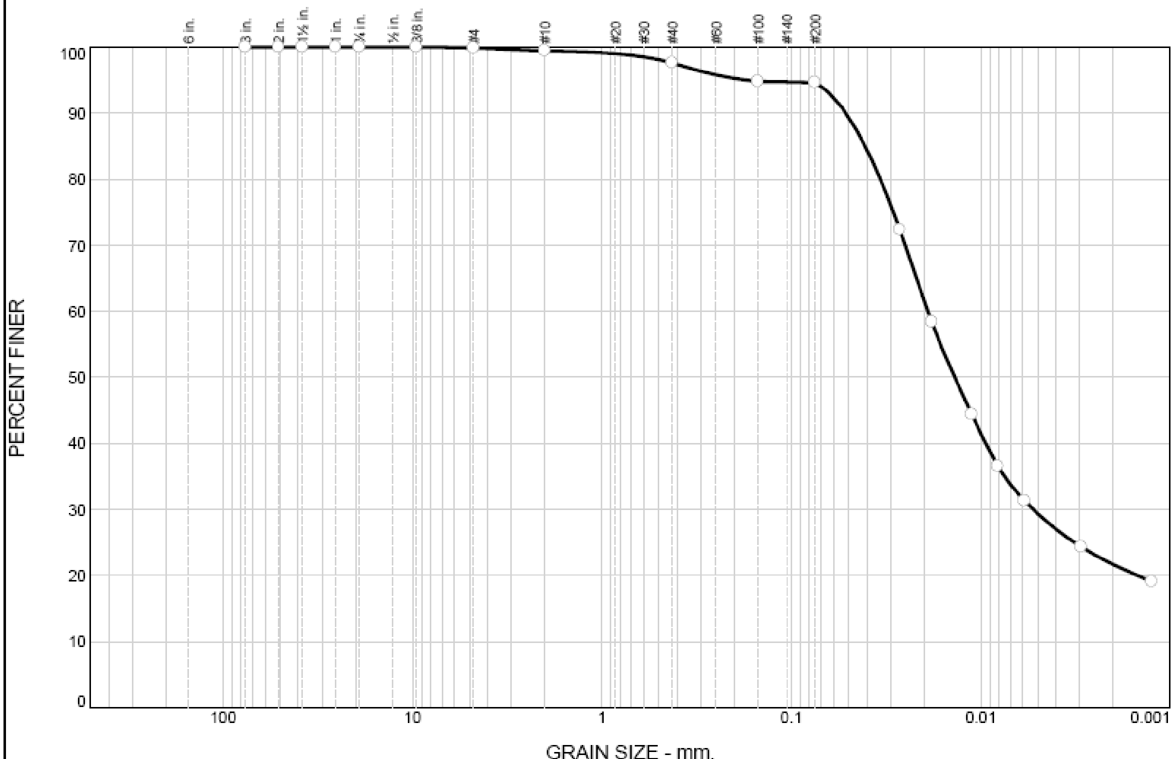
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	0	0	0	1	1	3	5	73	22	95

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0015	0.0053	0.0138	0.0191	0.0339	0.0408	0.0515	0.1730

Fineness Modulus
0.12

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0	0	0	1	1	3	73	22

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○	39	24	0.0408	0.0191	0.0138	0.0053				

Material Description	USCS	AASHTO
○ Kickapoo Clay(lean clay)	CL	A-6(16)

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

○ **Source of Sample:** Caterpillar Laboratory, Peoria

Date: ○ 1/3/2007

Remarks:

Iowa State University

Civil, Construction and Environmental Engineering Department

Figure

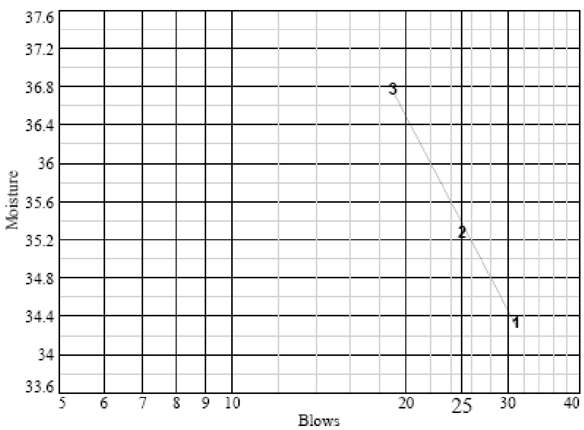
Tested By: Allison M **Checked By:** Ujwala M

LIQUID AND PLASTIC LIMIT TEST DATA 10/26/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: Kickapoo Top Soil(silt)
%<#40: 98 **%<#200:** 97 **USCS:** ML **AASHTO:** A-4(11)
Tested by: Allison M **Checked by:** Ujwala M

Liquid Limit Data

Run No.	1	2	3	4	5	6
Wet+Tare	18.37	18.34	17.84			
Dry+Tare	14.65	14.55	14.07			
Tare	3.82	3.81	3.82			
# Blows	31	25	19			
Moisture	34.3	35.3	36.8			



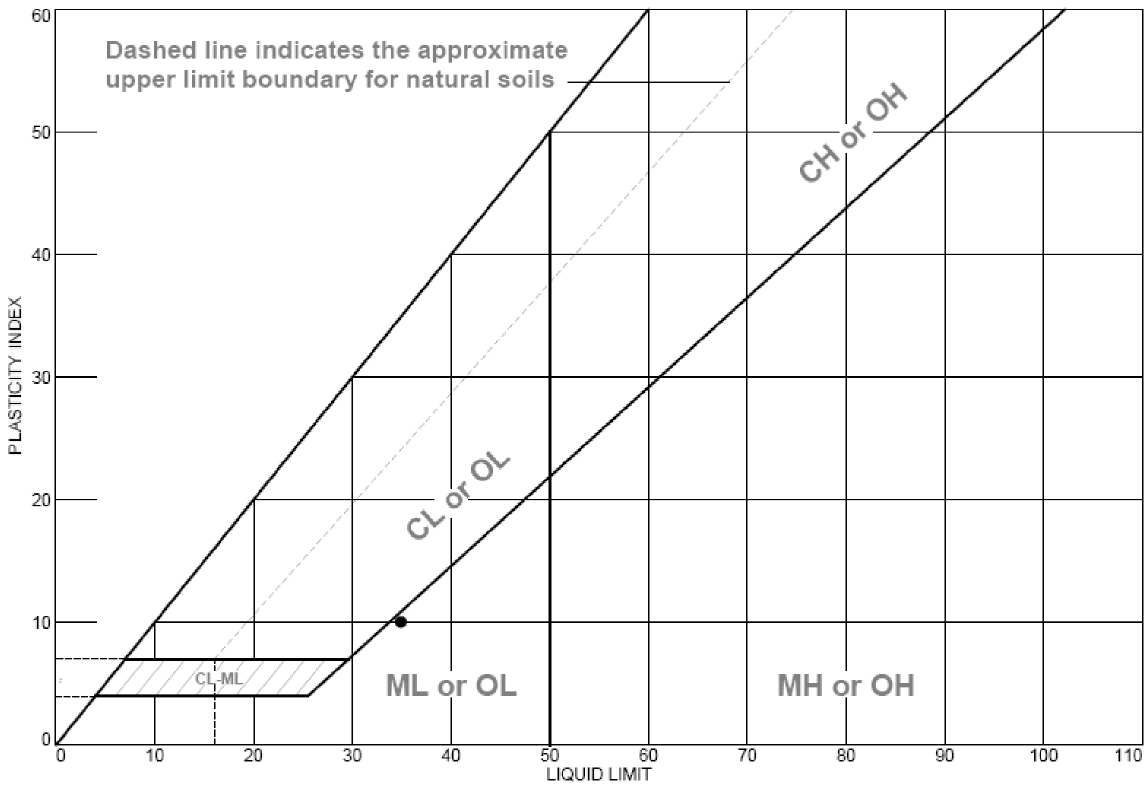
Liquid Limit= 35
Plastic Limit= 25
Plasticity Index= 10

Plastic Limit Data

Run No.	1	2	3	4
Wet+Tare	12.98			
Dry+Tare	11.06			
Tare	3.30			
Moisture	24.7			

__DEMO__

LIQUID AND PLASTIC LIMITS TEST REPORT



	MATERIAL DESCRIPTION	LL	PL	PI	%<#40	%<#200	USCS
●	Kickapoo Top Soil(silt)	35	25	10	98	97	ML

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

● **Source of Sample:** Caterpillar Laboratory, Peoria

Remarks:

Iowa State University

Civil, Construction and Environmental Engineering Department

Figure

Tested By: Allison M **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA 10/26/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: Kickapoo Top Soil(silt)
Sample Date: 1/3/2007 **Liquid Limit:** 35 **Plastic Limit:** 25
USCS Classification: ML **AASHTO Classification:** A-4(11)
Tested by: Allison M **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Sieve Opening Size	Weight Retained (grams)	Sieve Weight (grams)	Percent Finer
1998.00	0.00	3	0.00	0.00	100
		2	0.00	0.00	100
		1.5	0.00	0.00	100
		1	0.00	0.00	100
		.75	0.00	0.00	100
		.375	0.00	0.00	100
		#4	0.50	0.00	100
		#10	1.40	0.00	100
60.03	0.00	#40	0.90	0.00	98
		#100	0.70	0.00	97
		#200	0.10	0.00	97

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 100
Weight of hydrometer sample =60.03
Hygroscopic moisture correction:
Moist weight and tare = 101.60
Dry weight and tare = 98.38
Tare weight = 17.17
Hygroscopic moisture = 4.0%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.64
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	23.0	50.0	44.4	0.0132	50.0	8.1	0.0265	77.0
5.00	23.0	41.0	35.4	0.0132	41.0	9.6	0.0183	61.4
15.00	23.0	35.0	29.4	0.0132	35.0	10.6	0.0111	51.0
30.00	23.0	28.0	22.4	0.0132	28.0	11.7	0.0082	38.9
60.00	23.0	24.0	18.4	0.0132	24.0	12.4	0.0060	31.9
260.00	23.0	19.0	13.4	0.0132	19.0	13.2	0.0030	23.3
1440.00	23.0	14.5	8.9	0.0132	14.5	13.9	0.0013	15.5

__DEMO__

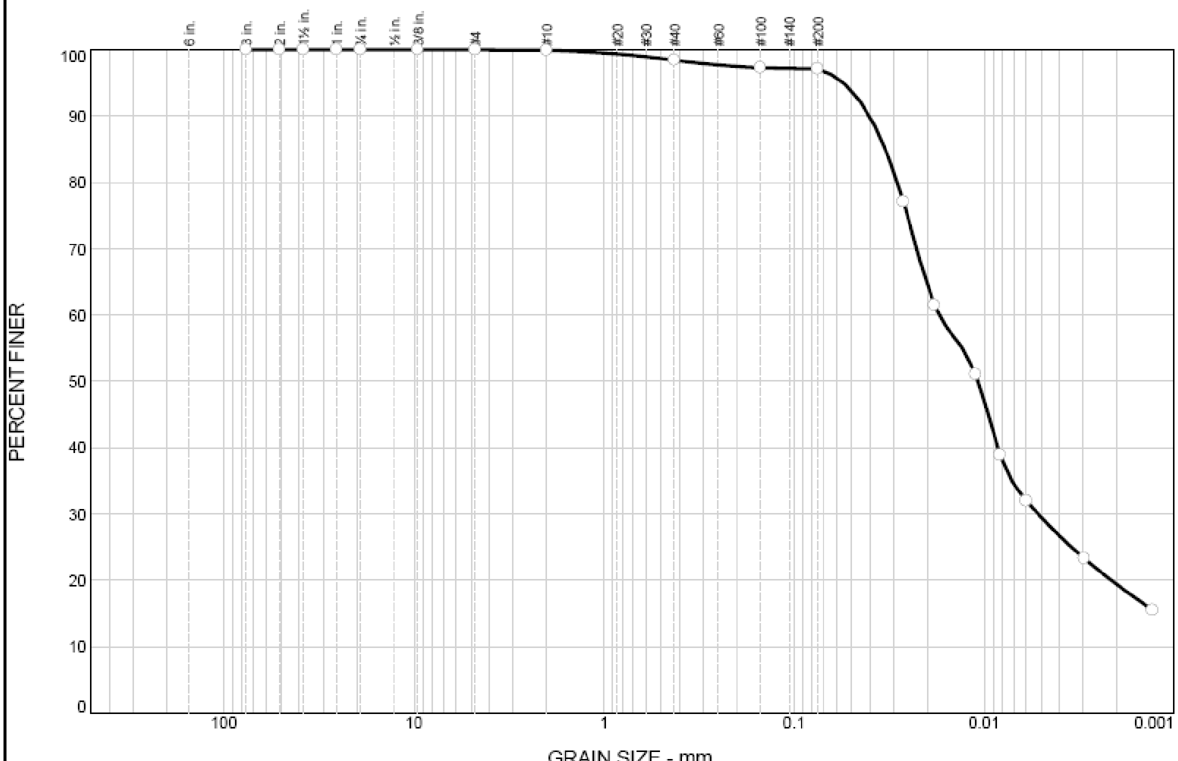
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	0	0	0	0	2	1	3	78	19	97

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
		0.0021	0.0052	0.0108	0.0173	0.0286	0.0331	0.0401	0.0551

Fineness Modulus
0.06

Particle Size Distribution Report



	% +3"	% Gravel		% Sand			% Fines	
		Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
○	0	0	0	0	2	1	78	19

	LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
○	35	25	0.0331	0.0173	0.0108	0.0052				

Material Description	USCS	AASHTO
○ Kickapoo Top Soil(silt)	ML	A-4(11)

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

○ **Source of Sample:** Caterpillar Laboratory, Peoria

Date: ○ 1/3/2007

Iowa State University

Civil, Construction and Environmental Engineering Department

Remarks:

Figure

Tested By: Allison M **Checked By:** Ujwala M

GRAIN SIZE DISTRIBUTION TEST DATA

10/30/2007

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: FA6(silty sand with gravel)
Sample Date: 5/23/2007
USCS Classification: SM **AASHTO Classification:** A-1-b
Tested by: Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Sieve Opening Size	Weight Retained (grams)	Sieve Weight (grams)	Percent Finer
2920.70	0.00	3	0.00	0.00	100
		1.5	0.00	0.00	100
		1	0.00	0.00	100
		3/4	34.30	0.00	99
		3/8	49.90	0.00	97
		#4	192.90	0.00	91
		#10	504.80	0.00	73
100.00	0.00	#20	19.60	0.00	59
		#40	22.40	0.00	42
		#100	21.60	0.00	27
		#200	14.90	0.00	16

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 73
Weight of hydrometer sample =100
Hygroscopic moisture correction:
Moist weight and tare = 273.00
Dry weight and tare = 271.00
Tare weight = 41.70
Hygroscopic moisture = 0.9%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.73
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	20.0	15.0	8.1	0.0133	15.0	13.8	0.0350	5.9
5.00	20.0	12.0	5.1	0.0133	12.0	14.3	0.0226	3.7
15.00	20.3	10.5	3.7	0.0133	10.5	14.6	0.0131	2.7
30.00	21.0	10.0	3.5	0.0132	10.0	14.7	0.0092	2.6
60.00	21.0	9.0	2.5	0.0132	9.0	14.8	0.0065	1.8
250.00	22.0	8.0	2.0	0.0130	8.0	15.0	0.0032	1.4
1440.00	23.0	7.0	1.4	0.0128	7.0	15.1	0.0013	1.0

__DEMO__

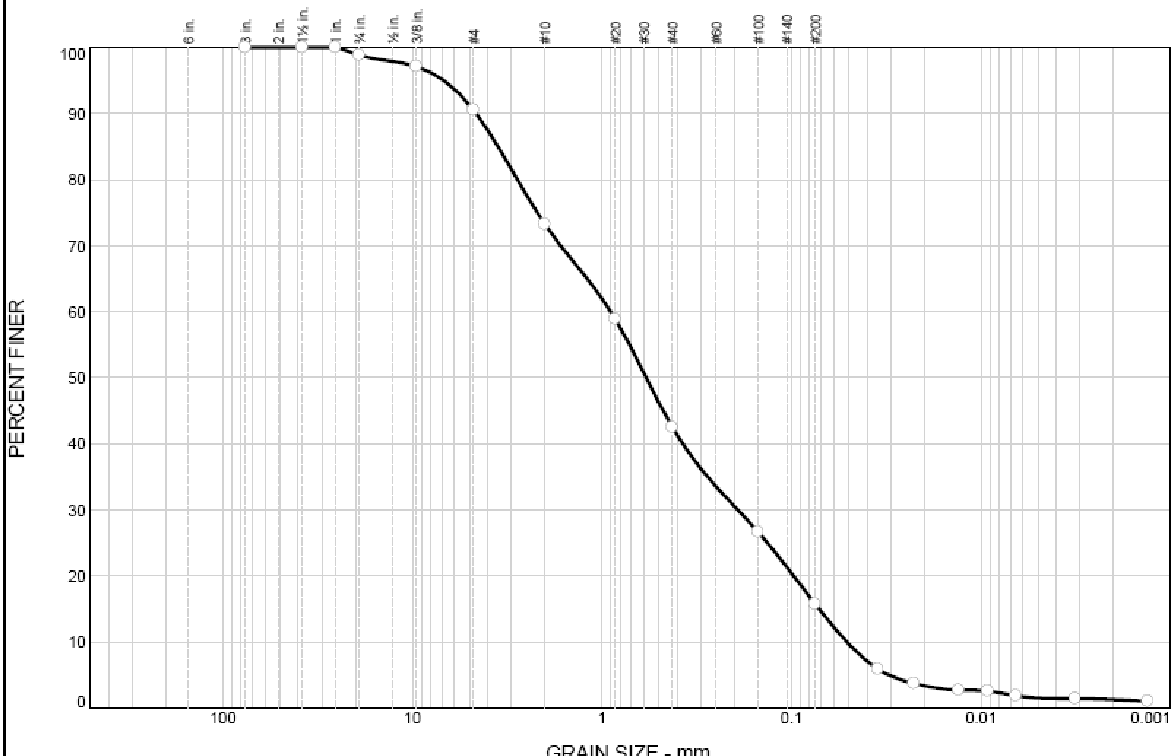
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	1	8	9	18	31	26	75	15	1	16

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0511	0.0716	0.0975	0.1921	0.5842	0.8984	2.7929	3.5352	4.6039	6.8252

Fineness Modulus	C_u	C_c
2.59	17.58	0.80

Particle Size Distribution Report



% +3"	% Gravel Coarse	% Gravel Fine	% Sand Coarse	% Sand Medium	% Sand Fine	% Fines Silt	% Fines Clay
0	1	8	18	31	26	15	1

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
		3.5352	0.8984	0.5842	0.1921	0.0716	0.0511	0.80	17.58

Material Description	USCS	AASHTO
FA6(silty sand with gravel)	SM	A-1-b

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

Location: Caterpillar Laboratory, Peoria

Date: 5/23/2007

Remarks:

Iowa State University

Civil, Construction and Environmental Engineering Department

Figure

Tested By: Ujwala M **Checked By:**

GRAIN SIZE DISTRIBUTION TEST DATA **10/30/2007**

Project: Evaluation of Microwave Sensor for soil moisture content determination
Location: Caterpillar Laboratory, Peoria
Material Description: CA6G(well-graded sand with silt and gravel)
Sample Date: 1/10/2007
USCS Classification: SW-SM **AASHTO Classification:** A-1-a
Tested by: Allison M **Checked by:** Ujwala M

Sieve Test Data

Dry Sample and Tare (grams)	Tare (grams)	Sieve Opening Size	Weight Retained (grams)	Sieve Weight (grams)	Percent Finer
2195.90	0.00	3	0.00	0.00	100
		2	0.00	0.00	100
		1.5	0.00	0.00	100
		1	101.64	0.00	95
		3/4	182.07	0.00	87
		3/8	373.24	0.00	70
		#4	322.68	0.00	55
		#10	327.72	0.00	40
80.01	0.00	#40	39.80	0.00	20
		#100	17.90	0.00	11
		#200	3.20	0.00	9.7

Hydrometer Test Data

Hydrometer test uses material passing #10
Percent passing #10 based upon complete sample = 40
Weight of hydrometer sample =80.01
Hygroscopic moisture correction:
Moist weight and tare = 108.32
Dry weight and tare = 106.67
Tare weight = 3.81
Hygroscopic moisture = 1.6%
Table of composite correction values:

Temp., deg. C:	20.0	25.0	27.0
Comp. corr.:	-6.9	-4.7	-3.8

Meniscus correction only = 0.0
Specific gravity of solids = 2.74
Hydrometer type = 152H
Hydrometer effective depth equation: L = 16.294964 - 0.164 x Rm

Elapsed Time (min.)	Temp. (deg. C.)	Actual Reading	Corrected Reading	K	Rm	Eff. Depth	Diameter (mm.)	Percent Finer
2.00	23.0	19.5	13.9	0.0128	19.5	13.1	0.0328	7.0
5.00	23.0	17.0	11.4	0.0128	17.0	13.5	0.0211	5.8
15.00	23.0	15.5	9.9	0.0128	15.5	13.8	0.0123	5.0
30.00	23.0	12.5	6.9	0.0128	12.5	14.2	0.0088	3.5
60.00	23.0	11.5	5.9	0.0128	11.5	14.4	0.0063	3.0
250.00	23.0	10.0	4.4	0.0128	10.0	14.7	0.0031	2.2
1440.00	23.0	8.5	2.9	0.0128	8.5	14.9	0.0013	1.5

__DEMO__

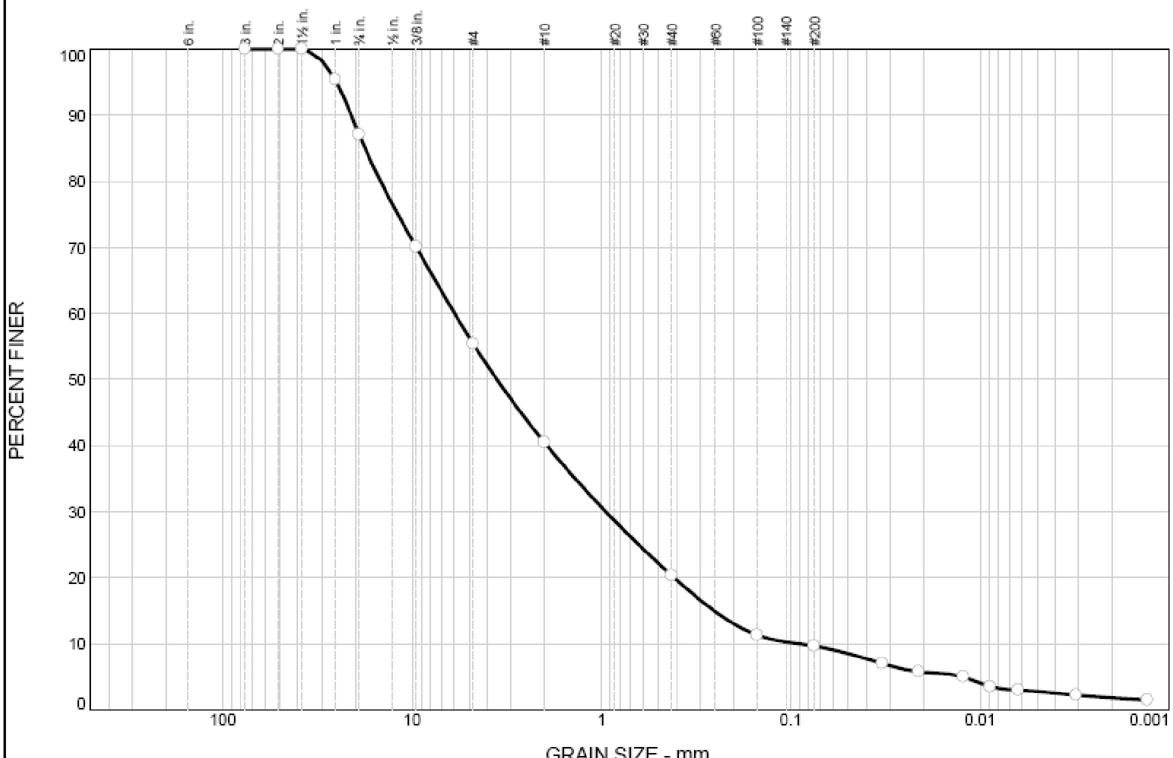
Fractional Components

Cobbles	Gravel			Sand				Fines		
	Coarse	Fine	Total	Coarse	Medium	Fine	Total	Silt	Clay	Total
0	13	32	45	15	20	10	45	8	2	10

D_{10}	D_{15}	D_{20}	D_{30}	D_{50}	D_{60}	D_{80}	D_{85}	D_{90}	D_{95}
0.0907	0.2545	0.4125	0.9498	3.5640	5.9619	14.6967	17.7386	20.9569	25.0042

Fineness Modulus	C_u	C_c
4.59	65.77	1.67

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0	13	32	15	20	10	8	2

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
		17.7386	5.9619	3.5640	0.9498	0.2545	0.0907	1.67	65.77

Material Description	USCS	AASHTO
CA6G(well-graded sand with silt and gravel)	SW-SM	A-1-a

Project No. **Client:**

Project: Evaluation of Microwave Sensor for soil moisture content determination

Location: Caterpillar Laboratory, Peoria

Date: 1/10/2007

Remarks:

Iowa State University

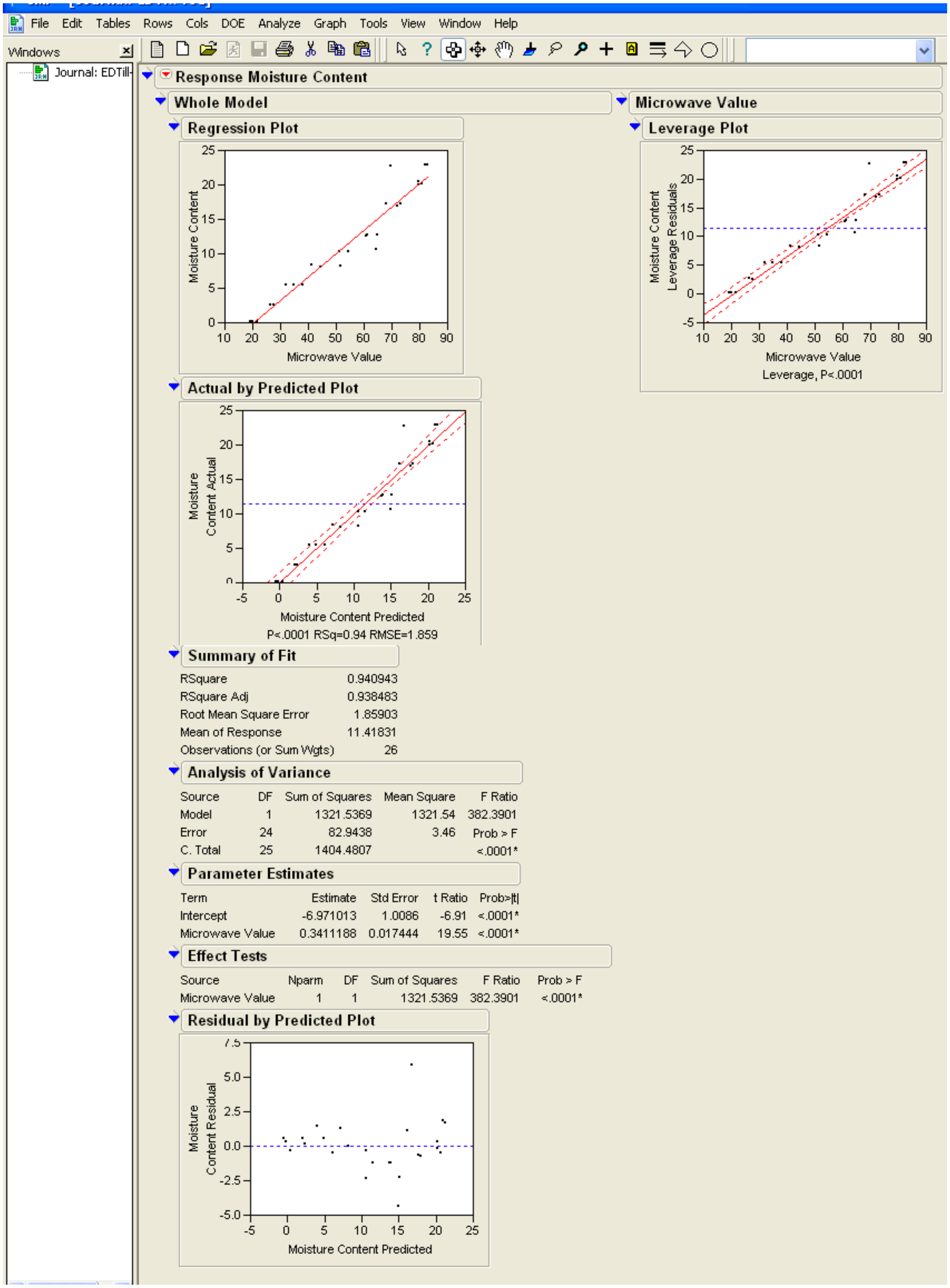
Civil, Construction and Environmental Engineering Department

Figure

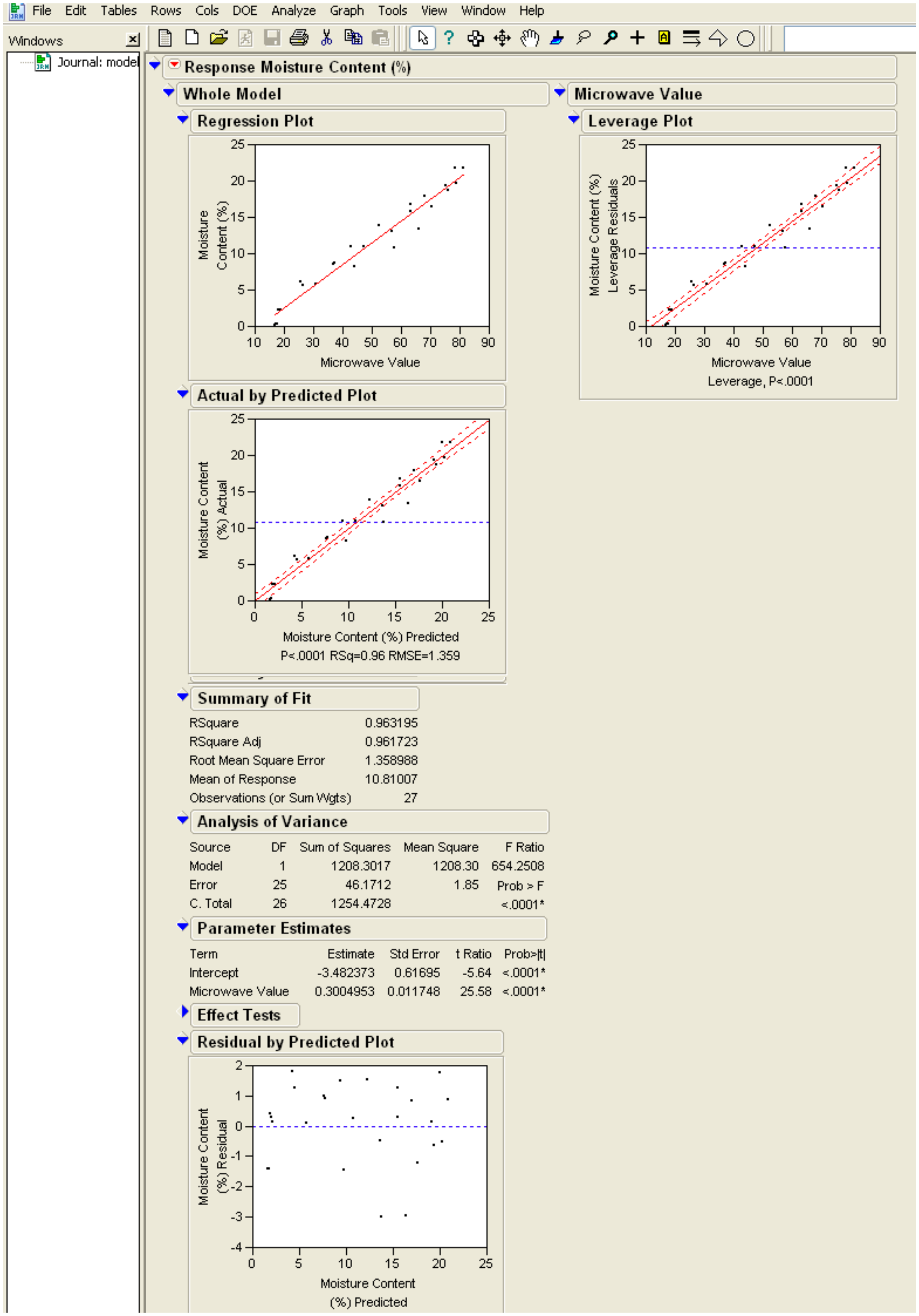
Tested By: Allison M **Checked By:** Ujwala M

APPENDIX C: STATISTICAL MODELS

Edward Till significant statistical model – Microwave value only



Kickapoo clay significant statistical model – Microwave value only



Kickapoo Topsoil significant statistical model – Microwave value only

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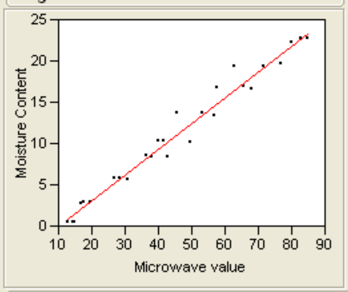
Windows

Journal: model

Response Moisture Content

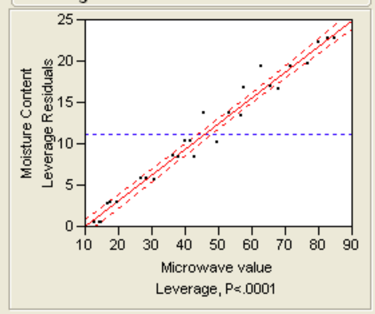
Whole Model

Regression Plot

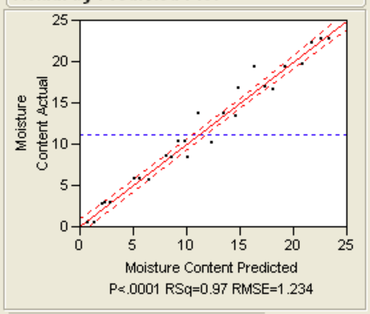


Microwave value

Leverage Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.972218
RSquare Adj	0.971107
Root Mean Square Error	1.233993
Mean of Response	11.12681
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1332.2008	1332.20	874.8711
Error	25	38.0685	1.52	Prob > F
C. Total	26	1370.2693		<.0001*

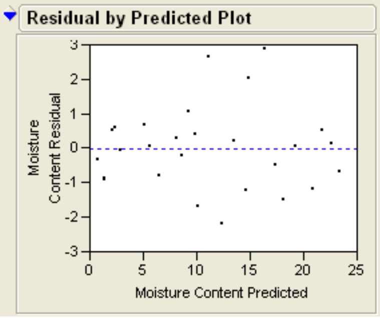
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.176467	0.538741	-5.90	<.0001*
Microwave value	0.3124377	0.010563	29.58	<.0001*

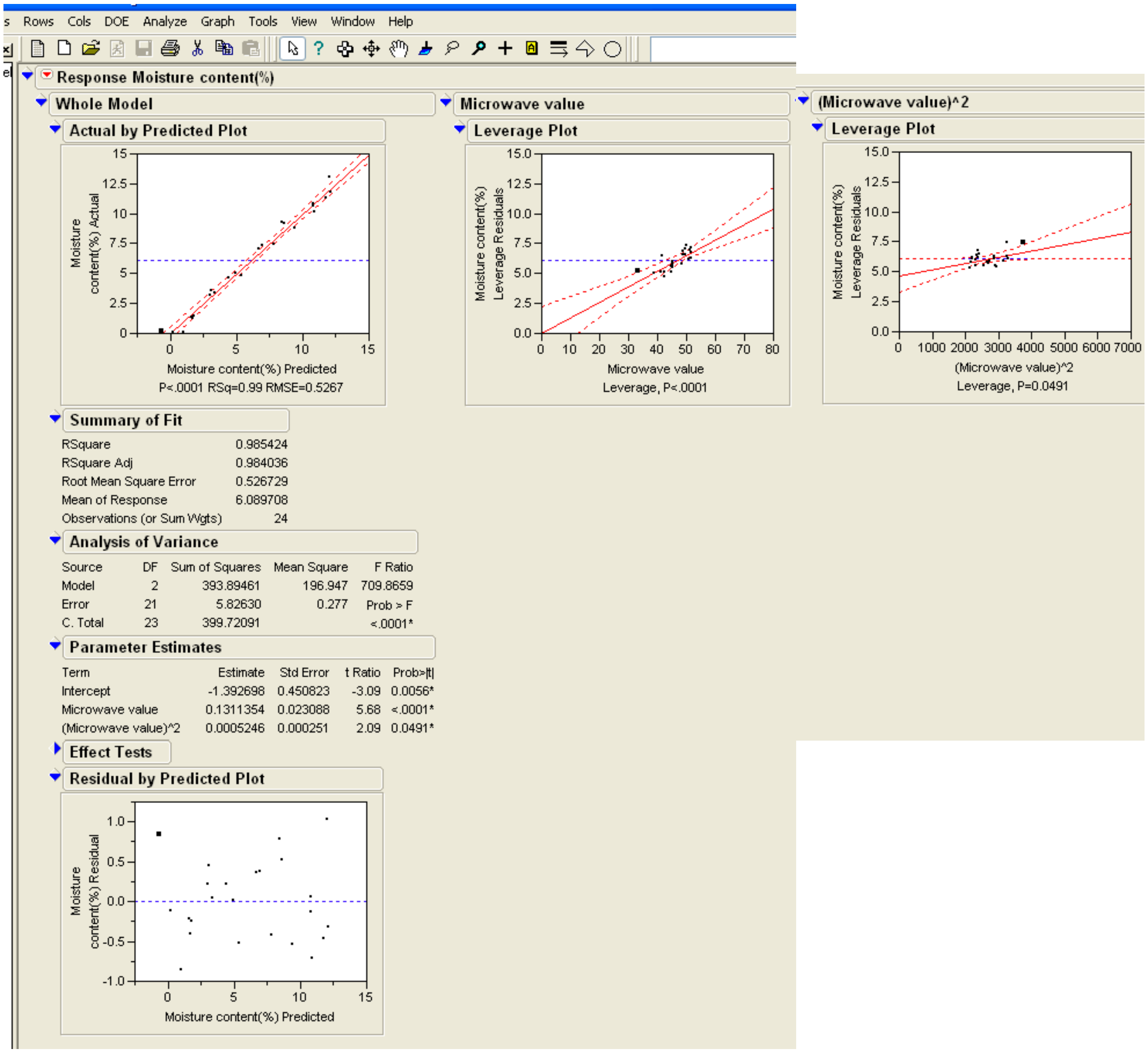
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Microwave value	1	1	1332.2008	874.8711	<.0001*

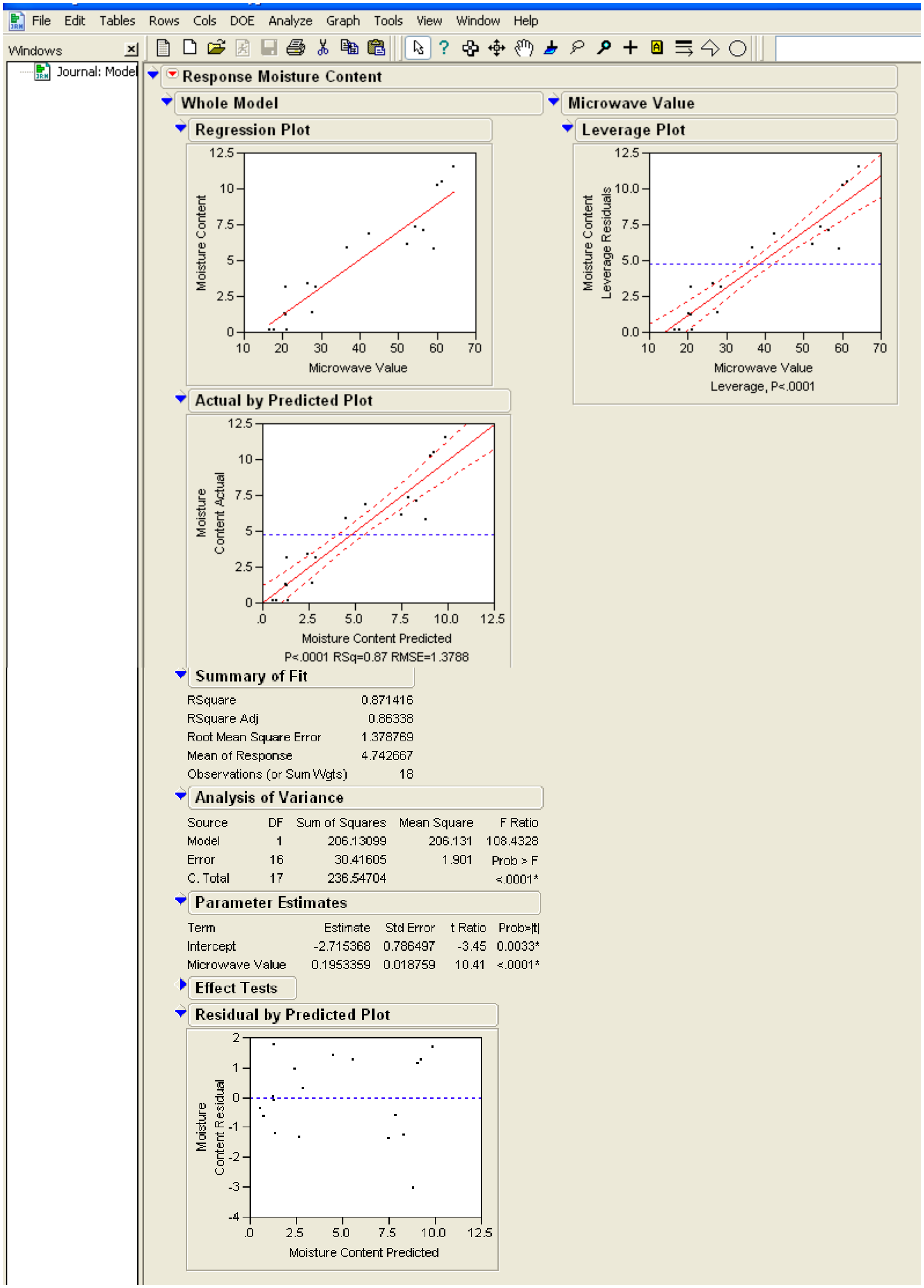
Residual by Predicted Plot



FA6 significant statistical model – Microwave value + (Microwave value) [2]



CA6G significant statistical model – Microwave value only



Summary of Fit

RSquare	0.871416
RSquare Adj	0.86338
Root Mean Square Error	1.378769
Mean of Response	4.742667
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	206.13099	206.131	108.4328
Error	16	30.41605	1.901	Prob > F
C. Total	17	236.54704		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2.715368	0.786497	-3.45	0.0033*
Microwave Value	0.1953359	0.018759	10.41	<.0001*

Reduced models slope comparisons – significance tests

Confidence Interval = $(b1 - b2) \pm 1.96\sqrt{s\varepsilon(b1)^2 + s\varepsilon(b2)^2}$

Soil 1) EDTill
Soil 2) CA6G

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.341119	0.195336	0.017444	0.018759	0.195991	0.095575

Confidence Interval = (0.095575,0.195991)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **EDTill and CA6G is significant.**

Soil 1) EDTill
Soil 3) Kickapoo Clay

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.341119	0.300495	0.017444	0.011748	0.081845	-0.00060

Confidence Interval = (-0.0006,0.081845)

Zero (0) lies in this interval, hence the **difference in** slopes of **EDTill and Kpclay is not significant.**

Soil 1) EDTill
Soil 4) Kickapoo Topsoil

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.341119	0.312438	0.017444	0.010563	0.068651	-0.01129

Confidence Interval = (-0.01129,0.068651)

Zero (0) lies in this interval, hence the **difference in** slopes of **EDTill and KpTop Soil is not significant.**

Soil 1) EDTill
Soil 5) FA6

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.341119	0.178337	0.017444	0.00509	0.198398	0.127165

Confidence Interval = (0.127165,0.198398)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **EDTill and FA6 is significant.**

Soil 2) CA6G
Soil 3) Kickapoo Clay

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.195336	0.300495	0.018759	0.011748	-0.06178	-0.14854

Confidence Interval = (-0.14854,-0.06178)

Soil 2) CA6G
Soil 4) Kickapoo Top Soil

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.195336	0.312438	0.018759	0.010563	-0.07491	-0.1593

Confidence Interval = (-0.1593,-0.07491)

Soil 2) CA6G
Soil 5) FA6

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.195336	0.178337	0.018759	0.00509	0.055096	-0.0211

Confidence Interval = (-0.0211,0.055096)

Zero (0) lies in this interval, hence the **difference in** slopes of **CA6G and FA6 is not significant.**

Soil 3) Kickapoo Clay
Soil 4) Kickapoo Top Soil

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.300495	0.312438	0.011748	0.010563	0.019023	-0.04291

Confidence Interval = (-0.04291,0.019023)

Zero (0) lies in this interval, hence the **difference in** slopes of **Kpclay and Kp top soil is not significant.**

Soil 3) Kickapoo Clay
Soil 5) FA6

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.300495	0.178337	0.011748	0.00509	0.147252	0.097064

Confidence Interval = (0.097064,0.147252)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **Kpclay and FA6 is significant.**

Soil 4) Kickapoo Top Soil
Soil 5) FA6

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.312438	0.178337	0.010563	0.00509	0.157082	0.111119

Confidence Interval = (0.111119,0.157082)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **Kp Top soil and FA6 is significant.**

Whole models slope comparisons – Significance tests

Confidence Interval = $$(b1 - b2) \pm 1.96 \sqrt{s\varepsilon(b1)^2 + s\varepsilon(b2)^2}$$

Soil 1) EDTill
Soil 2) CA6G

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.334665	0.202697	0.011479	0.025695	0.187128	0.076809

Confidence Interval = (0.076809,0.187128)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **EDTill and CA6G is significant.**

Soil 1) EDTill
Soil 3) Kickapoo Clay

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.334665	0.347097	0.011479	0.011068	0.018822	-0.04369

Confidence Interval = (-0.04369,0.018822)

Zero (0) lies in this interval, hence the **difference in** slopes of **EDTill and Kpclay is not significant.**

Soil 1) EDTill
Soil 4) Kickapoo Topsoil

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.334665	0.345613	0.011479	0.012168	0.021839	-0.04374

Confidence Interval = (-0.04374,0.021839)

Zero (0) lies in this interval, hence the **difference in** slopes of **EDTill and KpTop Soil is not significant.**

Soil 1) EDTill
Soil 5) FA6

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.334665	0.183346	0.011479	0.006241	0.176928	0.12571

Confidence Interval = (0.12571,0.176928)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **EDTill and FA6 is significant.**

Soil 2) CA6G
Soil 3) Kickapoo Clay

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.202697	0.347097	0.025695	0.011068	-0.08956	-0.19924

Confidence Interval = (-0.19924,-0.08956)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **CA6G and Kickapoo clay is significant.**

Soil 2) CA6G
Soil 4) Kickapoo Top Soil

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.202697	0.345613	0.025695	0.012168	-0.08719	-0.19864

Confidence Interval = (-0.19864,-0.08719)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **CA6G and Kickapoo Top soil is significant.**

Soil 2) **CA6G**
Soil 5) **FA6**

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.202697	0.183346	0.025695	0.006241	0.071177	-0.03248

Confidence Interval = (-0.03248,0.071177)

Zero (0) lies in this interval, hence the **difference in** slopes of **CA6G and FA6 is not significant.**

Soil 3) **Kickapoo Clay**
Soil 4) **Kickapoo Top Soil**

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.347097	0.345613	0.011068	0.012168	0.033723	-0.03076

Confidence Interval = (-0.03076,0.033723)

Zero (0) lies in this interval, hence the **difference in** slopes of **Kpclay and Kp top soil is not significant.**

Soil 3) **Kickapoo Clay**
Soil 5) **FA6**

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.347097	0.183346	0.011068	0.006241	0.188655	0.138847

Confidence Interval = (0.138847,0.188655)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **Kpclay and FA6 is significant.**

Soil 4) **Kickapoo Top Soil**
Soil 5) **FA6**

b1	b2	sε(b1)	sε(b2)	Confidence Interval	
0.345613	0.183346	0.012168	0.006241	0.189071	0.135464

Confidence Interval = (0.135464,0.189071)

Zero (0) does not lie in this interval, hence the **difference in** slopes of **Kp Top soil and FA6 is significant.**