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Performance-Based Measurement of Optimum Moisture for Soil Compaction

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16. Abstract (Limit: 250 words)
Part of the challenge achieving maximum field density in subgrade materials is transferring the optimal compaction and moisture content data from laboratory testing to the field. This research investigated the proficiency of four different instruments at accurately predicting moisture contents of three subgrade soils (loam, silt, silty/clay) commonly used in Minnesota roadway construction projects. The four instruments were; DOT600 (moisture content), WP4C dewpoint potentiometer (matric suction), the Button Heat Pulse Sensor (BHPS) (temperature rise vs. moisture content), and an exudation pressure test device. The DOT600 showed a strong correlation between the output period (measured in micro-seconds) and volumetric water content. The WP4C did not accurately measure matric suction for any of the loam, silt or silt/clay soils at suctions below 250 kPa. Published data shows that the matric suction of soils compacted at optimum moisture content is usually in the range of 200 – 300 kPa. The BHPS showed a strong correlation between measured temperature rise and water content but in its current configuration is not rigorous enough to withstand field conditions. The exudation pressure device was applied to soils compacted in a AASHTO T99 mold at various moisture contents. Water was exuded from the packed samples at pressures between 100 and 500 psi corresponding to AASHTO-T99 moisture contents of 10 to 25 %. Accurate moisture content readings from any of these instruments may not be as important as a more precise and simple calibration between the measurement units of the instrument and the optimum moisture content determined from the AASHTO T99 test.

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Executive Summary

Optimal compaction of subgrade materials is required during road foundation construction to maximize the longevity of the road and to minimize required pavement thickness. Unfortunately, due to variation in soils used for subgrade materials and the challenges involved in quantifying the characteristics of these soils, the quality of the subgrade compaction is sometimes less than optimal. Part of the challenge is transferring the optimal compaction and moisture content data from laboratory testing to the field. Traditionally the Proctor test AASHTO T99 has been the laboratory method of choice to obtain the optimum moisture-dry density curve. One of the issues related to AASHTO T99 is it currently is not being used as originally intended by Proctor in the 1930s and 40s (Proctor R.R. 1933, 1945 and 1948). The methodology developed by Proctor determined the required compaction at a given moisture content after delivering a compactive effort sufficient to record a penetration resistance with a cone penetrometer of 2.07 MPa (300 psi). What is now being used for the AASHTO T99 test is a single standardized compactive effort from hammer drops for all soil types. Because different soil types need different degrees of compactive effort, the standard AASHTO T99 test often does not produce the optimum density and its related moisture content. The test is also performed in a non-yielding mold that does not always correlate well to the compactive effort applied by compaction equipment in the field.

Despite the shortcomings of the AASHTO T99 test, it still is used to determine a moisture and density at which the soils should be compacted in the field. One of the main factors that determine how well field scale subgrade optimum moisture content and density match the laboratory values is how accurately the soil properties of moisture content and density can be measured in the field. One of the instruments used to measure both density and moisture content in-situ during subgrade compaction is the nuclear density gauge. A number of state transportation departments are currently trying to find alternatives to the radioactive nuclear gauge because of safety and regulation concerns.

This research focused on four potential alternatives to the nuclear density gauge for measuring moisture status (moisture content or moisture suction) of subgrade soils. The need to find a fast and accurate replacement for the nuclear gauge is important not only because of the radiation safety concerns of the nuclear density gauge but also for the following reasons:

- As the moisture content deviates from the optimum moisture content related to the AASHTO T99 compaction curves, the strength of some soils drops very quickly. A error in field subgrade moisture can result in an under-compacted foundation.
- Real-time data collection during compaction and the use of dynamic cone penetrometer (DCP) and lightweight deflectometer (LWD) compaction tests are dependent on moisture content.
- Real-time accurate measurements of moisture content will help quickly describe variations in moisture content in the subgrade profile allowing for proper blending and other remediation efforts during construction.

This research focused on four different instruments to determine if they have potential to accurately measure water content or matric suction in subgrade soils. These instruments included:

- DOT600 (moisture content and density)
- WP4C dewpoint potentiometer (matric suction)
- Button heat pulse sensor (moisture content related to temperature rise)
- Exudation pressure device (moisture content related to compressive force required to exude water from the sample)

The three soils tested were soils commonly uses in road construction in Minnesota. These were: MnRoad, A-6(4) a loam texture; Red Lake Falls, A-6(10) a silty/clay texture; and Red Wing, A-4(0), a silt texture.

The DOT600, WP4C and exudation test all require a sample to be collected from the field and prepared in some standardized manner before testing. The BHPS can measure moisture content in-situ. The sample preparation time for the BPHS, WP4C and DOT600 was minimal. The exudation test required preparation of the AASHTO T99 cores at each moisture content on the curve prior to running the test. If the test were conducted in conjunction with the AASHTO T99 test, the preparation time would also be minimal. The time to take a reading was three to five minutes for the BPHS sensor and exudation pressure test and 10 to 15 minutes for both the DOT600 andWP4C.

DOT600

The DOT600 is a portable device used to measure the moisture content of soils after a standardized compactive force is applied. Samples are compacted in a calibrated chamber by turning a compression screw to achieve a compression pressure of 0.31 MPa (45 psi). After the sample is compressed the moisture content of the sample is measured using the principle of dielectric permittivity. The sensor output period (frequency) is related to volumetric water content using a factory calibration. The results showed the DOT600's factory calibration overestimated volumetric water content from 10 to 15% in a number of tests when compared to moisture contents obtained from the oven-dried method for all soils tested.

The DOT600 was not robust enough to provide sufficient compactive effort to match dry bulk densities produced by the (AASHTO T99) test. Comparison of the dry-density water content relationship obtained by the DOT600 to the (AASHTO T99) showed the DOT600 under-estimated the dry-density and overestimated the optimal moisture content for all three test soils. The DOT600 did provide a strong correlation between the output period estimated in micro-seconds and volumetric water content. Once a curve relating the gravimetric water content to the output period has been established for a given soil the output period from the DOT600 could be used to check optimum moisture conditions in the field.

WP4C Dewpoint Potentiometer

The WP4C dewpoint potentiometer is a bench-top instrument used to estimate matric suction. A small soil sample is placed in a cup and inserted into a chamber in the WP4C. The instrument actually measures the dewpoint temperature, which is related to the relative humidity of the air in the chamber. The relative humidity in the chamber is related thermodynamically to the matric suction of the soil.

The WP4C did not accurately estimate matric suction for any of the loam, silt or silt/clay soils at suctions below 250 kPa. The suctions related to the optimum moisture content of the three test soils were between 200 and 300 kPa. The WP4C may be a viable option to measure the matric suction of soils that reach the optimum moisture content at suctions above 250kPa. However, the instrument itself is not field-resilient as it requires a quiet setting with controlled temperature conditions.

Button Heat Pulse Sensor (BHPS)

The measurement principle of the Button Heat Pulse Sensor (BHPS) developed by (Kamai, et al.; 2008) is the same as the dual probe heat pulse sensor developed by (Campbell, et al.; 1991). Instead of two parallel needles the BHPS has a heater wire enclosed inside a circular stainless steel ring surrounding a thermistor. The ring and thermistor are mounted on a Delrin plastic button. The sensor is pushed into the soil surface until the soil contacts the Delrin surface ensuring the stainless steel ring is fully embedded. A current is applied to the heater wire for exactly eight seconds causing the stainless steel ring to heat up. The heat produced conducts through the soil and the thermistor measures the temperature rise due to heating. The BHPS showed a strong correlation between the temperature rise and gravimetric water content and would have the advantage of making an in-situ reading directly on subgrade materials. The relationship between temperature rise and water content is soil specific so separate calibration curves would need to be developed for each soil. The BHPS is a prototype and in its current configuration would not stand up to the rigors of field testing.

Exudation Pressure Device

The standard use of the exudation pressure test is to apply a vertical pressure to a prepared soil sample at various moisture contents until water is exuded from the soil sample. A measure of the soil's resistance to plastic deformation, called the R-value, is determined for the soil at the moisture content for which the soil exudes water at an applied pressure of 1.65 MPa (240 psi) point. The R-value is used in standard pavement design practice to determine required pavement thickness. The purpose of this experiment was to determine if a relationship exists between the exudation pressure and the AASHTO T99 curves for the three test soils. The exudation pressure apparatus was used to apply a vertical pressure on soils compacted into AASHTO T99 molds corresponding to moisture contents on the AASHTO T99 curve. The loam test soil (MnRoad; A-6(4)) reached the 1.65 MPa exudation pressure near 16 percent moisture content, which is close to the AASHTO T99 optimum moisture content of 15.2 percent. The silt/clay soil (Red Lake Falls; A-6(10)) crossed the 1.65 MPa mark at 18 percent which again is slightly above the 17.3 percent optimum moisture content. The silt soil (Red Wing; A-4(0)) even at 15 percent moisture content, which is two percent greater than its AASHTO T99 density did not reach the 1.65 MPa line, but required a much higher pressure to achieve exudation, in the range of 3.3 MPa. The relationship between exudation pressure and optimum moisture content needs to be explored further on more soil types before it can be fairly evaluated.

1. Introduction

Optimal compaction of subgrade materials is required during road foundation construction to maximize the longevity of the road and minimize the pavement thickness. Unfortunately, due to variation in soils used for subgrade materials and the challenges involved in quantifying the characteristics of these soils, the quality of the subgrade compaction is sometimes less than optimal. Part of the challenge is transferring the optimal compaction and moisture content data from laboratory testing to the field. One metric of the successful transfer of laboratory data to the field is how quickly and accurately the density and moisture content of the field subgrade material can be measured. Historically, besides the sand cone test for measuring bulk density, the method most commonly used to measure both density and moisture content in the field has been the nuclear density gauge. The nuclear density gauge uses a source of gamma radiation and a detector to measure density and a neutron source to measure moisture content. The radiation hazard and regulations associated with the use of radioactive sources have pushed a number of agencies to seek alternative methods of measuring moisture content and density.

The four different instruments listed below, were investigated to determine if they have potential to accurately measure water content or matric suction in subgrade soils:

- DOT600 (moisture content and compaction)
- WP4C dewpoint potentiometer (matric suction)
- Button heat pulse sensor (moisture content related to temperature rise)
- Exudation pressure device (moisture content related to compressive force)

2. Description of Instruments

DOT600

The DOT600 manufactured by Campbell Scientific shown in Figure 1 is a portable device used to estimate the volumetric water content of soils. Samples are compacted in a calibrated chamber by turning a vertical screw to achieve a pressure between 15 and 45 psi. After the sample is compressed the moisture content of the sample is measured using the principle of dielectric permittivity. With an electronic circuit beneath a soil sample, the DOT600 measures the oscillation frequency of the circuit. This frequency decreases (that is, the period increases) with increase in water content. . The frequency domain of the electromagnetic field is related to the dielectric properties of the soil. Dielectric constant (Ka) in air is 1, soil is three to four and water is 80. Therefore the relative change in measured frequency due to changes in air or soil mineral will be small compared to changes in soil water. A separate scale and set of magnetic linear sensors measure the sample volume and mass, which allows calculation of bulk density and conversion of the volumetric water content to gravimetric water content. All measurements and data are computed and stored internally by the attached data logger. Factory calibrations for a number of soil types can be used to convert the output period generated by the DOT600 to volumetric water content.

Figure 1. DOT600.

WP4C Dewpoint Potentiometer

The WP4C dewpoint potentiometer manufactured by Decagon Devices shown in Figure 2 is a bench-top instrument used to measure matric suction. A small soil sample is placed in a cup and inserted into a chamber in the WP4C. The soil sample is brought to the same temperature as the air in the chamber. Water vapor diffuses out of the soil into the air inside the chamber until the relative humidity of the air comes to equilibrium. A mirror above the sample is chilled allowing water to condense, and the temperature at which the condensation occurs is the dewpoint temperature. The relative humidity of the air can therefore be determined, and since the relative humidity is related to the matric suction in the soil sample, the matric potential can be determined directly from the dewpoint temperature measurement.

Figure 2. WP4C dewpoint potentiometer.

Button Heat Pulse Sensor

The measurement principle of the Button Heat Pulse Sensor (BHPS) developed by (Kamai et al, 2008) is the same as the dual probe heat pulse sensor developed by (Campbell et al, 1991) . The BHPS measures the maximum temperature rise to calculate a heat capacity which can be converted to water content using a soil specific equation. Instead of two parallel needles the BHPS has the heater wire enclosed into a circular stainless steel ring surrounding a thermistor. The ring and thermistor are mounted on a plastic button (See Figure 3). The sensor is pushed into the soil surface until the soil contacts the surface of the disk ensuring the stainless steel ring is fully embedded. A current is applied to the heater wire for exactly eight seconds causing the stainless steel ring to heat up. The thermistor records the temperature rise at the thermistor, and this temperature rise is dependent on the water content of the soil sample, and also a function of soil bulk density and soil mineral type.

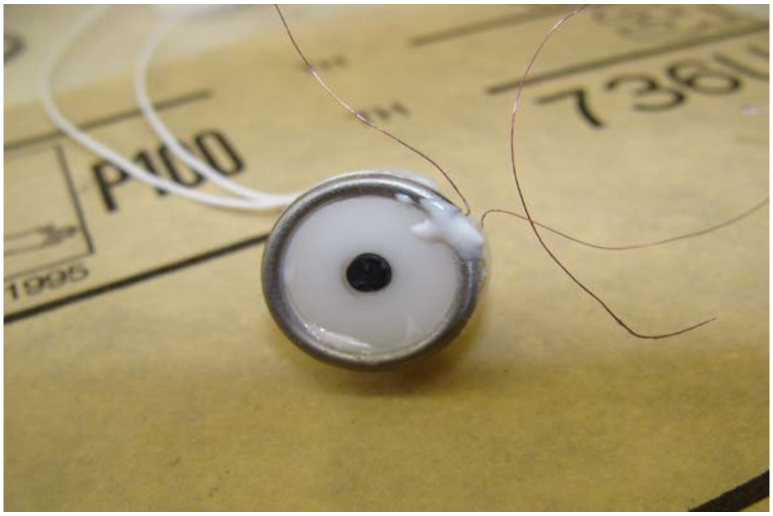


Figure 3. Button heat pulse sensor.

Exudation Pressure Test

The exudation pressure test is one part of the Hveem Stabilometer (AASHTO T246) test. The test provides information about the property of resistance to plastic flow of a compacted soil. This property is referred to as the R-value. Specifically, the R-value is equal to the pressure applied to a soil at which water will be exuded from a sample existing at a given initial moisture content. For the original California Test 301 this R-value is 2.07 MPa (300 psi). Minnesota standard pressure for this test is 1.65 MPa (240 psi). The device used to apply the force and detect the first movement of free water is called the Washington Visual Saturation Indicator shown in Figure 4. For the purpose of this research project the exudation test was used to establish an exudation pressure-water-content curve for each soil tested, compacted into molds using the AASHTO T99 test. That is, the exudation device was applied to soils compacted with the AASHTO T99 method over a range of moisture contents. The exudation pressure was determined then for each moisture content level. The question was as to how the exudation pressure for the soil initially at the optimum AASHTO T99 moisture content would relate to the Minnesota standard pressure of 1.65 MPa.

Figure 4. Exudation pressure experiment using the Washington Visual Saturation Indicator.

3. Methods and Materials

Tests of the four measurement techniques were conducted in two experiments. Soil characteristics of the three soils used in both experiments are given in Table 1.

Table 1. Soil characteristics of the three test soils from MnDOT laboratory.

	MNROAD SS120179	RED WING SS120179	RED LAKE FALLS SS120181
Sand (%)	43.2	7.8	7.5
Silt (%)	41.1	83.7	66.4
Clay (%)	15.7	8.5	26.2
MnDOT class	L	Si	SiCl
AASHTO T99 (dry density lb/ft^3)	113.1	113.1	105.3
AASHTO T99(dry density kg/m^3)	1810	1810	1680
Optimum M.C. (%)	15.5	11.3	16.7
Plastic Limit (%)	19.4	NA	20.2
R-value (240psi)	18.9	45.8	24.1
AASHTO group	A-6(4)	A-4(0)	A-6(10)

Experiment 1 compared the DOT600, WP4C and the BHPS to water content and matric suction values generated from the development of soil water characteristic curves (SWCC) for the three soils. Each of the three soils was packed into a 15-cm diameter core to a depth of five centimeters. The final bulk densities of the MnROAD, Red Wing and Red Lake Falls soils respectively were 1.25, 1.25 and 1.16(g/cm3). The cores were placed into a pressure plate apparatus (Soil Moisture Equipment Corp, 1997) and saturated for 48 hours.

The water content data was collected at pressures equivalent to matric suctions 32.6, 100, 300, 400, and 500 kPa. At each pressure setting samples were extracted from the core and analyzed by the DOT600 and WP4C. For comparison gravimetric moisture content was also determined by the oven dried method. Readings were taken by the BHPS directly on the soil core at matric suctions of 32.6, 100 and 300 kPa. For each point on the SWCC curve two replications were run through the DOT600 and three replications for each the WP4C and the BHPS.

Experiment 2 compared the data from each device to known water content data for each point on the AASHTO T99 curve for three test soils. The same three soils used in Experiment 1 were used in Experiment 2. The samples were compacted using the standard AASHTO T99 test procedures to develop the moisture-density relationship. Temperature rise using the BHPS sensor was measured directly on the compacted soil in the AASHTO T99 mold. The exudation test was also conducted directly on the soil in the AASHTO T99 mold. The soil preparation procedures for both the WP4C and the DOT600 require the soil to be broken up. Consequently, they were not taken directly from the test mold but were taken from the same container used for the AASHTO T99 test.

AASHTO T99 Test

Approximately thirty pounds of dry soil was prepared for each of the three soils for the AASHTO T99 test. Water was added using a spray bottle to bring the soil moisture to a starting point approximately four percent below the optimum moisture content. After the water was added the soil was sealed in the container and left to sit overnight to allow the moisture to evenly distribute through the soil matrix. Three replicates were conducted for all three soils for all points on the moisture–density curve. The results of the AASHTO T99 test for the three soils as an average of the three replications are given in Table 2.

Table 2. AASHTO T99 test soil data.

	Optimum M.C.(%)	**Dry density (lb/ft^3)**	**Dry density (kg/m^3)**
MNROAD	15.2	113.1	1810
Red Wing	12.9	113.6	1820
Red Lake Falls	17.3	107.25	1710

4. Measurement Devices

DOT600

The main goal of evaluating the DOT600 was to determine how accurately it could estimate volumetric moisture content and compare moisture–density curves against those developed for all three soils using the standard AASHTO T99 test. Samples from each point on the, AASHTO T99 curve were compared to gravimetric moisture content from the oven-dried method. In the original experimental plan the range of moisture contents related to the AASHTO T99 test were limited to plus or minus four percent either side of the optimum moisture content. So to expand upon this, additional samples were made up to test the DOT600 over a wider range of moisture contents. Soil was placed in glass beakers and water added to make up the range of moisture contents. The samples were sealed and left to sit for 24 hours. The moisture content range for the 10 samples for Red Wing was (4.9 to 19.6%), MNROAD (8.7 to 26.6%) and Red Lake Falls (8.5 to 26.7%). Two replications were conducted for each point. The moisture–density curve was developed from the bulk density of the DOT600 core after compaction and the oven-dried moisture content for that sample. This was compared to the moisture–density curves produced by the AASHTO T99 test.

WP4C Dewpoint Potentiometer

The main goal of evaluating the WP4C was to determine how accurately it could predict matric suction values especially in the range of moisture contents equivalent to those given by the AASHTO T99 tests. All three soils were packed into 15-centimeter cores and placed into pressure chambers. At equilibrium matric suctions of 32.6, 100, 300, 400 kPa samples taken from each core were tested in the WP4C. Three replications were conducted for each matric suction value.

Matric suctions given by the WP4C were also determined for each point on the moisture – density curve for all three soils. Soil samples were taken directly from the sample container just prior to compaction into the test molds. Three replications were run at each point.

Again because the range of moisture contents related to the AASHTO T99 test was limited the same samples made up to test the DOT600 performance were also run through the WP4C. Three replications were conducted for each point.

Button Heat Pulse Sensor

The testing of the BHPS focused on sensor construction, development of the measurement technique for reading the sensor on the soil surface, holding the sensor in contact with the soil, proper embedment of the ring into the soil surface, length of heat pulse, time to cooling of the sensor after heating and effectively measuring temperature rise related to moisture content. Three BHPS were constructed from a design developed by (Kamai et al., 2008)[3} which uses a circular configuration instead of the traditional two parallel needle design of the dual probe heat sensor. The BHPS was pushed into the soil surface until the bottom face of the Delrin button was slightly below the soil surface. This was done to ensure the ring containing the heater wire was properly embedded into the soil surface, allowing the heat pulse to conduct through the soil and not air. Once embedded, the sensor was then held in place by a 16 penny nail pushed into the soil until the nail head came in contact with the tape applying a slight downward force on the sensor.

Once the sensor was in place, a data logger was used to open a relay, sending current from a 12 volt battery through the heater wire enclosed inside the stainless ring, causing the ring to heat up. The duration of the heat pulse was eight seconds. The data logger also recorded the temperature sent by a thermistor embedded in the center of the Delrin button. To make sure the peak temperature was recorded, the data logger read the temperature eight times per second for a period of five minutes. The construction process, instrumentation and theory of operation are explained in detail in Appendix A.

Measurements were made on soil cores in the pressure plate which were similar to natural undisturbed bulk densities and on each AASHTO T99 core representing densities similar to packed subgrade materials. Three replications were made on each soil core in the pressure plate and two measurements were made on each AASHTO T99 core. There were three replications of each core so a total of six readings were made at each moisture content. Figure 5 shows the BHPS in position to read the temperature rise on top of the soil in the AASHTO T99 mold.

Figure 5. Button heat pulse sensor reading temperature rise on soil packed in AASHTO T99 mold.

Exudation Pressure Ttest

The purpose of this experiment was to see if a relationship existed between the exudation pressure and the moisture–densities curves produced by the AASHTO T99 tests. The exudation pressure apparatus was used to apply a vertical pressure on soils compacted into AASHTO T99 molds corresponding to moisture contents on the moisture-density curve. The apparatus and setup used to obtain the exudation pressure values was constructed to match the Washington Visual Saturation Indicator. (Figure 4).After the AASHTO T99 mold was packed, around disk with observation holes and filter paper was placed on the bottom of the AASHTO T99 mold. A clear acrylic plate was used between the mold and the steel support chamber. A four-inch diameter steel plate was placed on top of the soil surface mold to evenly distribute the load over the soil surface. Pressure was applied incrementally using an Instron machine. The maximum force that the steel support chamber could handle without failure was 27.2 kN (6200 pounds). This was equivalent to a pressure of 3.4 MPa (495 psi). This value is about two times greater than the 1.65 MPa value used by (MnDOT) to determine the moisture content for the design R-value. Applied pressures were limited to this upper value and, therefore no exudation values above 3.4 MPa were recorded.

5. Results and Discussion

DOT600

For Experiment 2, samples of soil taken at each moisture content on the AASHTO T99 curve for all three soils were run through the DOT600. Part way through the experiment it was obvious the gravimetric moisture contents given by the DOT600 were not matching the actual gravimetric moisture content. A range of soil samples were made up to develop a calibration curve for each soil type. Table 3 shows the average DOT600 readings for each soil compared to the actual gravimetric moisture content derived from the oven-dried method. For all three soils the DOT600 readings were 10 to 15 percent higher than the oven-dried gravimetric samples. An error was discovered in the programming software and was addressed in a new download. After the new program was installed six more samples were run through the DOT600. The average difference between the DOT600 and actual oven-dried moisture content with the new program is shown at the bottom of Table 3.

Table 3. Difference between DOT 600 gravimetric water content and the oven-dried method for three test soils.

Soil	AVE. GWC DOT600	AVE. GWC Oven-dried	Difference
MnROAD	27.7	15.6	12.1
Red Wing	23.4	11.4	12
Red Lake Falls	34.0	17.0	17
New program	21.9	16.4	5.5

The DOT600 estimates the volumetric water content of the soil and uses the weight and volume of the sample to calculate the gravimetric water content. An error in either measurement could produce an inaccurate gravimetric water content reading. The DOT600 measurements of volume and weight were checked and verified to be accurate and not a cause of the difference in gravimetric water content given by the DOT600 and the actual oven-dried moisture content.

The period given by the DOT600 is a value related to the dielectric permittivity that is converted internally by the DOT600 software to volumetric water content by a series of soil specific calibration equations. The relationship between the period and the measured oven-dried gravimetric moisture content for the three test soils is shown in Figure 6.

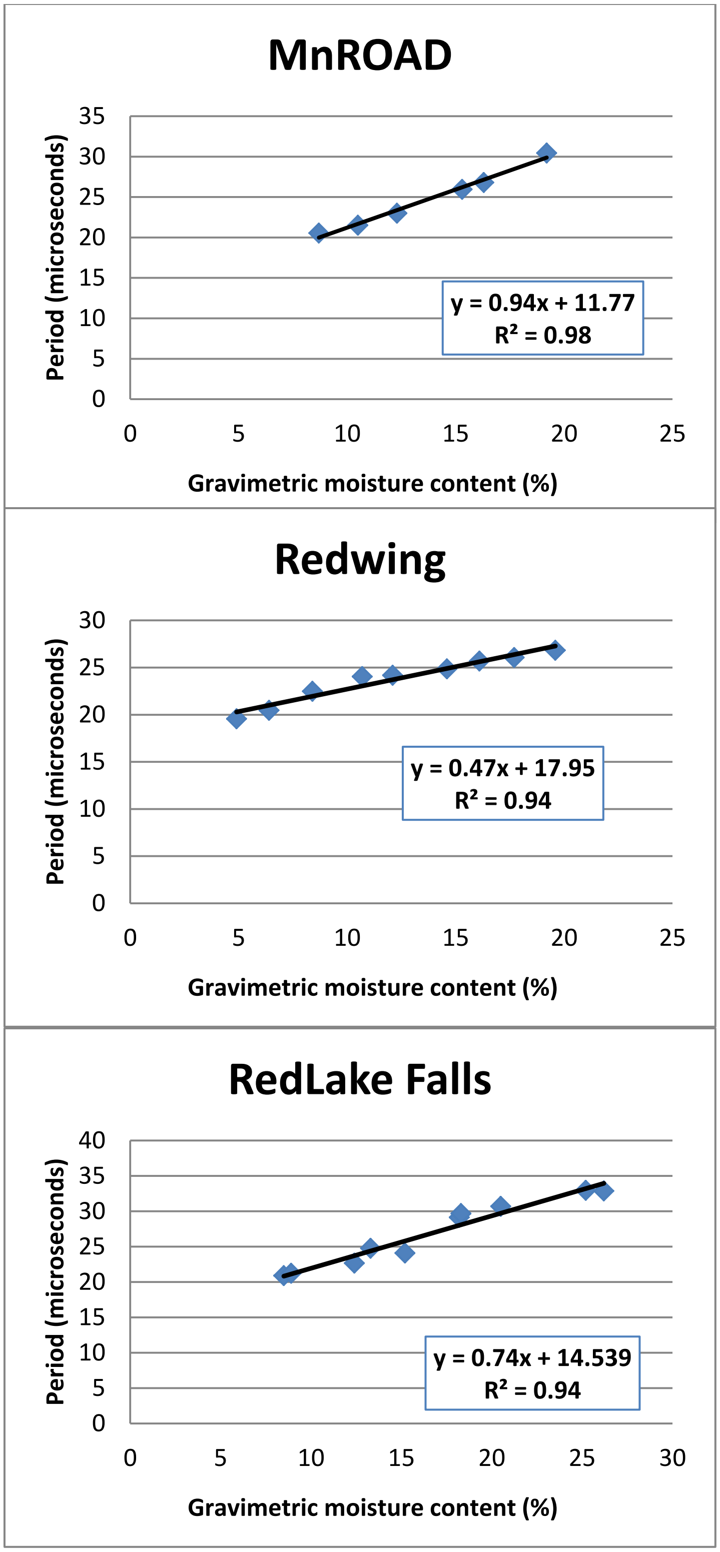


Figure 6. Plot of the period value given by the DOT600 plotted against the measured oven-dried gravimetric moisture content.

The strong relationship between the DOT600 period and gravimetric moisture content while limited for some soil moisture applications without a calibration curve is promising for measuring optimum moisture content in-situ. Because the optimum moisture content is already known from the AASHTO T99 test a simple period versus gravimetric moisture content relationship for each point on the AASHTO T99 curve for a particular soil could be used in the field to determine how closely the subgrade material matches the optimum moisture content.

The measurement of dry density produced by the DOT600 was compared to the density of the AASHTO T99) test for all three soils.The DOT600 procedure first requires sieving the soil sample to remove gravel and break up soil clusters. The sample is then compressed by turning a screw. The applied vertical stress from compression is displayed by the DOT600 and for this project the compression target was 0.275 MPa (40 psi).

Figure 7 shows how closely the dry density produced from the compression of the DOT600 at 40 psi matched the compaction and moisture content of the AASHTO T99 test.

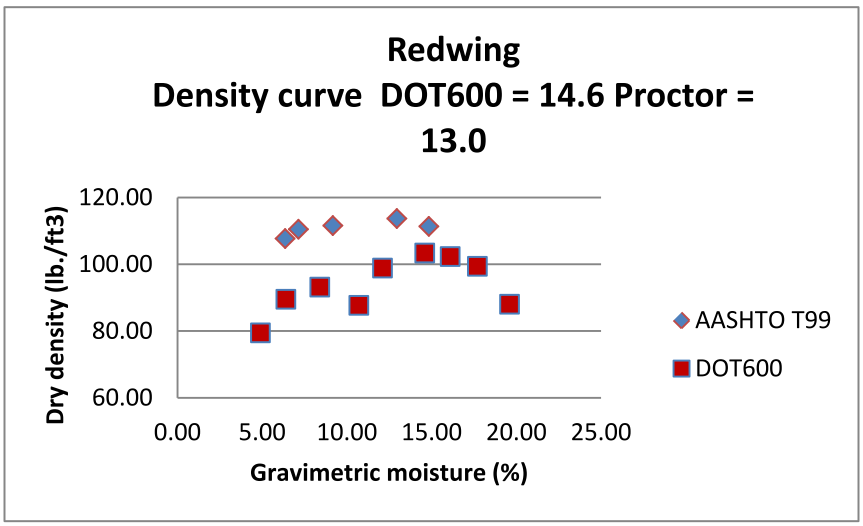
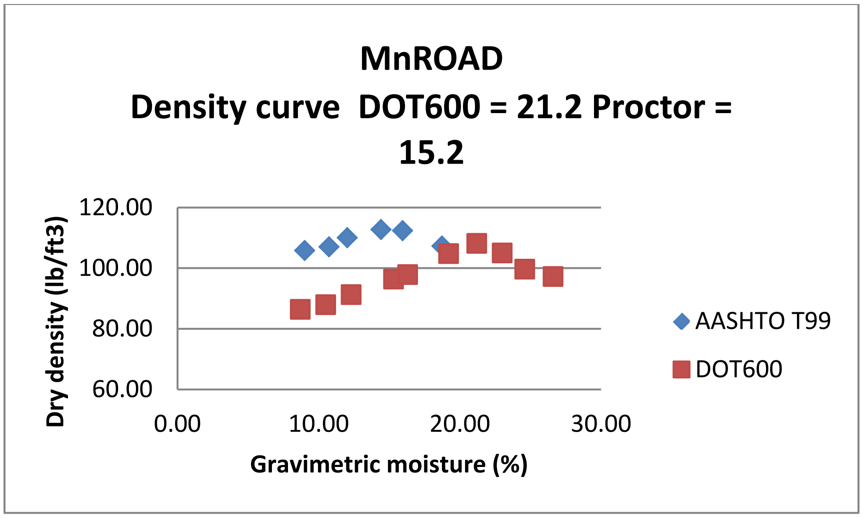


Figure 7. Comparison of the dry density produced in the DOT600 chamber at 0.275 MPa to the AASHTO T99 value.

The maximum dry density produced by the DOT600 for each soil was less than the AASHTO T99 densities by 0.76 kN/m^3 for the MnROAD soil, 1.6 kN/m^3 for the Redwing soil and 1.1 N/m^3 for the Red Lake Falls soil. The moisture content associated with the DOT600 maximum dry density was higher than the optimum moisture content from the AASHTO T99 results. The optimum moisture content values are shown on the graphs in Figure 7.



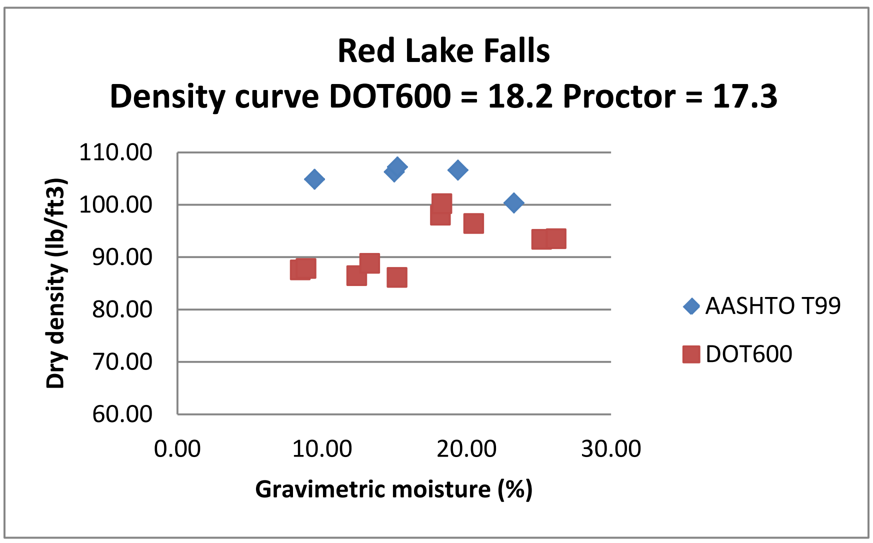


Figure 7. (continued) Comparison of the dry density produced in the DOT600 chamber at 0.275 MPa to the AASHTO T99 value.

WP4C

The accuracy at which the WP4C estimated the measured matric suctions of 33, 100, 200, 300, 400, and 500 kPa is shown in Figure 8. The WP4C did not estimate the matric suction accurately for any of the three soils in the wet range (0-200kPa). Near the matric suction of 250 kPa the accuracy of the WP4C improves and more closely matches the matric suction given by the pressure plate.

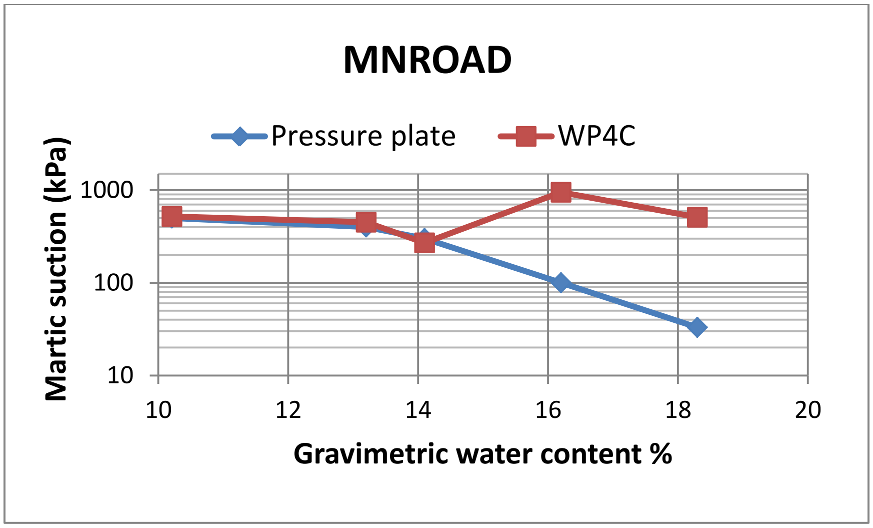
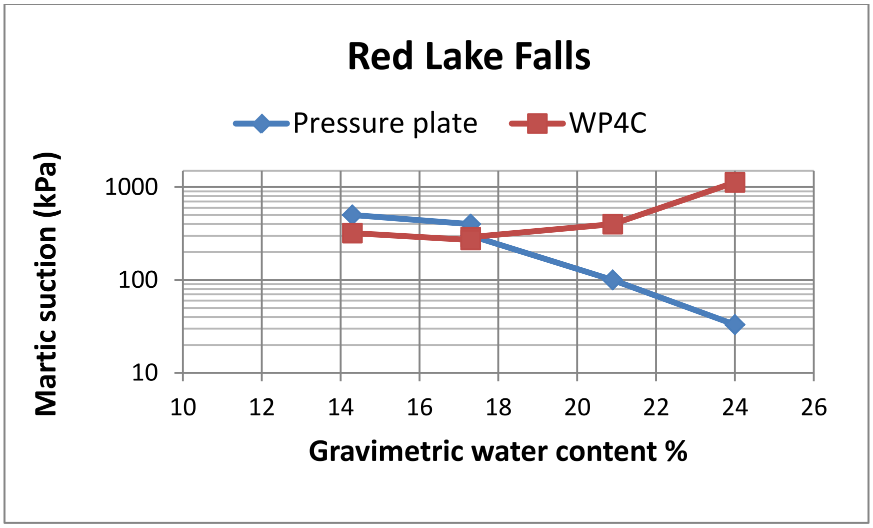


Figure 8. Graphs for each test soil showing the relationship between the water content and the pressure plate matric suction and the matric suction given by the WP4C.

At each of the moisture contents plotted on these AASHTO T99 curves the matric suction was determined using the WP4C. Three replicates were conducted for at each point. To provide a more robust data set, an additional ten samples for each soil were run through the WP4C. Figure 9 is a plot of the matric suction given by the WP4C for each soil. It also includes vertical lines which represent the optimum moisture content as determined by the AASHTO T99 test. The optimum moisture contents as a percent for the three soils are MnRoad (15.1%), Red Wing (12.9%), and Red Lake Falls (17.3%).

This data plotted in Figure 9 shows that the WP4C is not able to measure matric suction accurately at the wetter end of the water retention curve. For the Red Lake Falls soil, once the moisture content had increased above 18 percent which is equivalent to 200 kPa, the WP4C basically gave the same matric suction even as the moisture content continued to increase to above 25 percent. The same pattern existed for the MnROAD soil at approximately the same moisture content of 18 percent, but at a corresponding matric suction of about 100 kPa. This same pattern was not present for the Red Wing soil, which holds the least amount of water of the three test soils as the matric suction continued to decrease with increasing moisture content. However, the matric suction of the Red Wing soil was not measured above 20 percent moisture content. The optimum moisture content was below the level at which the WP4C was not able to accurately estimate moisture content for all three soils.



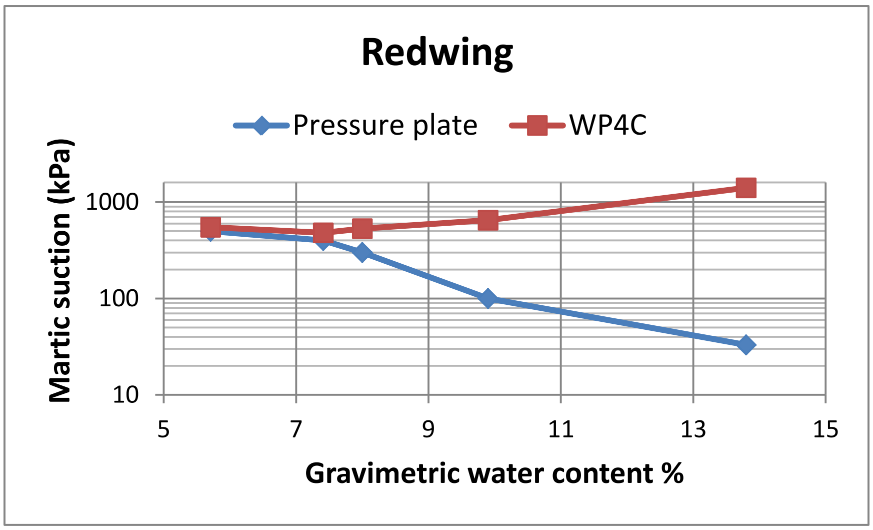


Figure 8. (continued) Graphs for each test soil showing the relationship between the water content and the pressure plate matric and the matric suction given by the WP4C.

The WP4C manual states that the soil sample should be placed loosely into the sample cup which means the bulk density of the sample would not be equivalent to the AASHTO T99 density. A third experiment was done to test the possible effect of density on the WP4C readings. Samples were made up to closely match the moisture contents from the AASHTO T99 curves. The samples were sealed and left for 48 hours to allow the water to equilibrate throughout the soil sample. A sample from each container was packed into a small core to match the AASHTO T99 density for that moisture content.

A small undisturbed plug from these cores was removed and placed into the WP4C sample cup. A second sample taken from the container which had not been packed was also tested in the WP4C.

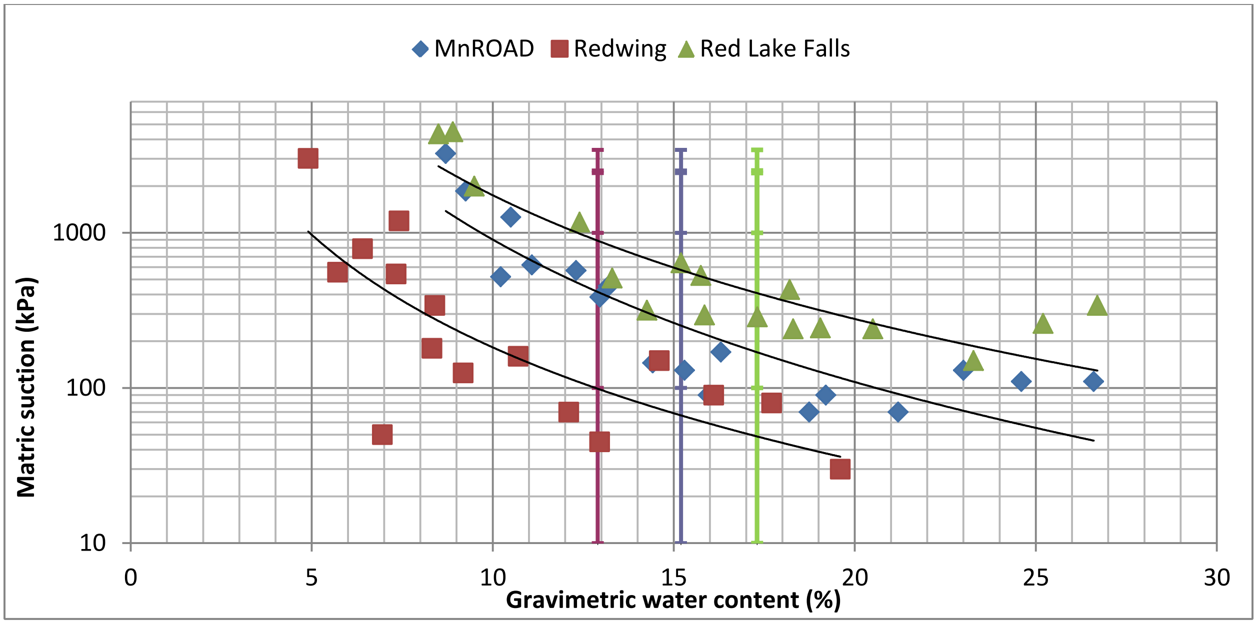


Figure 9. Matric suction estimated by the WP4C plotted against known gravimetric moisture content in relation to optimum moisture content for all three soils. The optimum moisture content is indicated by the vertical line for each soil.

For all three soils the matric suction trended higher for the packed samples as compared to the loose samples. A paired two samples for means t-test was conducted for each soil. The results are shown in Table 4. There was no significant difference at the 0.05 percent level between the loose reading and the sample packed to AASHTO T99 density for the MnROAD soil. There was however a significant difference between the two readings for both the Red Wing and Red Lake Falls soils.

The WP4C also has a precision mode and a fast mode. The precision mode reads the sample repeatedly until it has good agreement between sequential readings. The fast mode reads the sample but does not wait for good agreement before it outputs a reading. Again referring to Table 4, there was no significant difference between the fast mode and precision mode for the MnROAD soil but there was a significant difference at the 0.05 percent level for both the Red Wing and Red Lake Falls soils.

The length of time it takes for the WP4C to take a reading in the precision mode is ten to fifteen minutes for the loose sample. It took fifteen to twenty minutes for the WP4C to take a reading of the AASHTO T99 packed samples in the precision mode. The fast mode reading time was close to five minutes.

Table 4 The results of the paired two samples for means t-test for both the precision mode vs. fast mode and unconsolidated vs. AASHTO T99 density samples. The values given in the table are p-values for determining significance. Values greater than 0.05 mean the differences are insignificant.

Soil	**Loose vs AASHTO T99 density**	**Precision vs Fast mode**
MnROAD	0.122	0.128
Red Wing	0.003	0.00001
Red Lake Falls	0.004	0.005

Button Heat Pulse Sensor

Figure 10 is a plot of a typical heating and cooling cycle for the BHPS. The length of time it took to reach a maximum temperature depended on the soil type and moisture content of the soil.

For the three test soils and the moisture contents used during testing, the maximum temperature was found to occur within 60 seconds from the start of the test. The time it took for the sensor to cool down so it could be read again was typically three to four minutes. A total time of five minutes for each reading was used to ensure the maximum temperature was reached and the sensor had enough time to cool before the next reading.

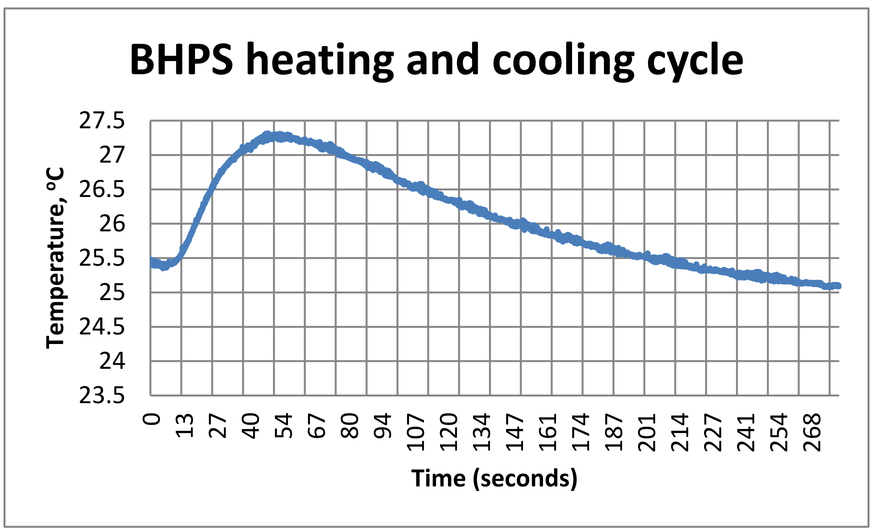


Figure 10. Heating and cooling cycle for BHPS with maximum temperature occurring before 60 seconds and sensor cooling back down to the initial temperature in less than five minutes.

After the soils were packed into the AASHTO T99 molds and all measurements made for the AASHTO T99 test, the temperature rise using the BHPS was determined for each mold. There were three AASHTO T99 molds made up at each moisture content. The BHPS was used to measure the temperature rise at two depths on each mold. One centimeter of soil was removed from the top of the core to remove any soil that may have paritially dried between the time the AASHTO T99 mold was last packed and when the BHPS was ready to be read. The second depth reading was made one centimeter below the first reading. A sample of soil was taken from the core at each depth and oven dried to get the actual moisture content.

This gave a total of six replicates at each moisture content on each point on the AASHTO T99 curve. Figure 11 shows all the BHPS data plotted for each soil. The six replications for each point on the curve are clustered around the corresponding moisture contents. The MnROAD soil had a steeper slope than either the Red Wing or Red Lake Falls soil which have nearly identical slopes.

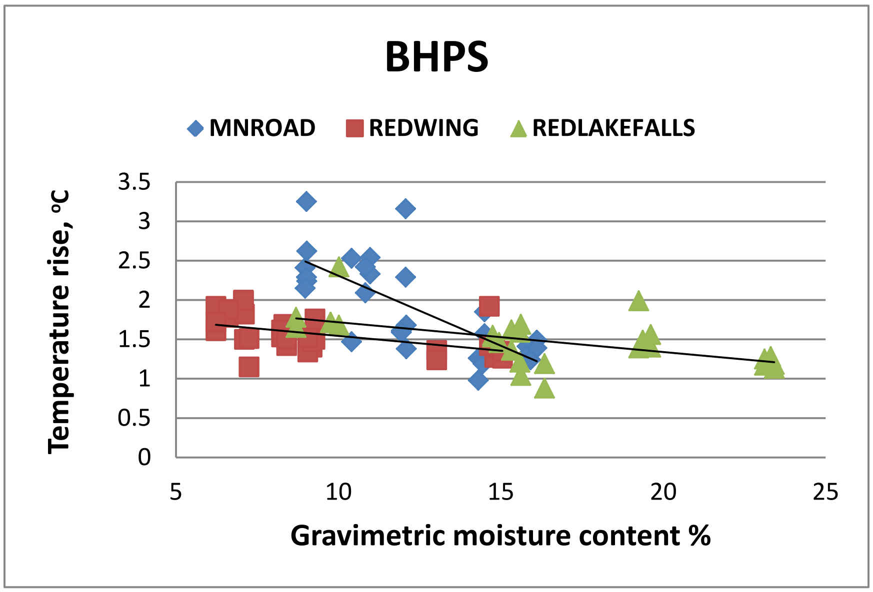


Figure 11. A plot of the BHPS temperature rise for each soil corresponding to the moisture contents on the AASHTO T99 curve.

There is some scatter in the data plotted in Figure 11. Table 5 gives the water content standard deviation between the three AASHTO T99 tests for each moisture content and the six replications made by the BHPS at each moisture content. The average standard deviation in moisture content was 0.35 percent or less between the three replications conducted for the AASHTO T99 tests. The average standard deviation for the temperature rise was the greatest for the (MNROAD) soil at 0.53 degrees followed by Red Wing at 0.31 and Red Lake Falls at 0.195.When the six replicates are averaged and plotted against water content, the strength of the relationship improves (See Figure 12). Some of the variability in readings seen in Figure 11 may be due to the difficulties experienced when reading the BHPS on a tightly packed soil core. Reading the BHPS on the cores packed in the pressure chambers in Experiment 1 was not difficult because it was easy to push the stainless steel ring down into the soil surface, providing good contact for the heat transfer. The soil in the AASHTO T99 molds was too dense to easily push the ring into the soil. To provide good contact between the soil ring and the soil surface, a small amount of soil was shaved from the soil surface. The BHPS was then embedded into the shaved soil. It was also determined that the BHPS would occasionally tip slightly and lose contact with the soil surface. A small weight was used to hold the BHPS in place during testing.

Table 5. Compares the standard deviation between the temperature rise and the water content for three replicates at each moisture content.

MnROAD			Red Wing			Red Lake Falls		
Water content	STDEV water content %	STDEV BHPS (temp, °C	Water content	STDEV water content %	STDEV BHPS (temp, °C)	Water content	STDEV water content %	STDEV BHPS (temp, °C)
9.01	0.026	0.404	6.35	0.22	0.334	9.49	0.699	0.29
10.74	0.29	0.666	7.14	0.09	0.736	15.01	0.295	0.09
12.03	0.08	0.407	8.32	0.08	0.093	15.85	0.431	0.314
14.42	0.098	0.309	9.17	0.11	0.144	19.41	0.189	0.226
15.94	0.152	0.9	14.83	0.201	0.246	23.28	0.152	0.055
Average	**0.1292**	**0.5372**	**Average**	**0.1402**	**0.3106**	**Average**	**0.3532**	**0.195**

Exudation Pressure Test

The exudation pressure was measured directly on the soil packed into each AASHTO T99 mold. The maximum force that the steel support chamber could handle without failure was 27.18 kN. This corresponds to a pressure of 3.04 MPa for the area of force application. This value is about two times greater than the 240 psi value used by (MnDOT) to determine the moisture content for the design R-value. Applied pressures were limited to this upper value and therefore no exudation values above 3.4 MPa (495 psi) were recorded. The exudation pressure and AASHTO T99 density plotted against water content for the three soils are given in Figure 14. The first part of the curve in each graph does not represent the actual pressure needed to extrude water at each moisture content but the maximum pressure the exudation stand device could withstand. The MnROAD soil reached 1.65 MPa exudation pressure near 16 percent moisture content, which is close to the AASHTO T99 optimum moisture content of 15.2 percent. The sample would have been just beyond its maximum density of 17.78 kN/m^3 (113.1 lb/ft^3). The Red Lake Falls soil crossed the 1.65 MPa mark at 18 percent which again is slightly above the 17.3 percent optimum moisture content at 16.86 kN/m^3 (107.25 lb/ft^3). The Red Wing soil at 15 percent moisture content is two percent greater than its AASHTO T99 optimum moisture, but did not reach the 1.65 MPa mark.

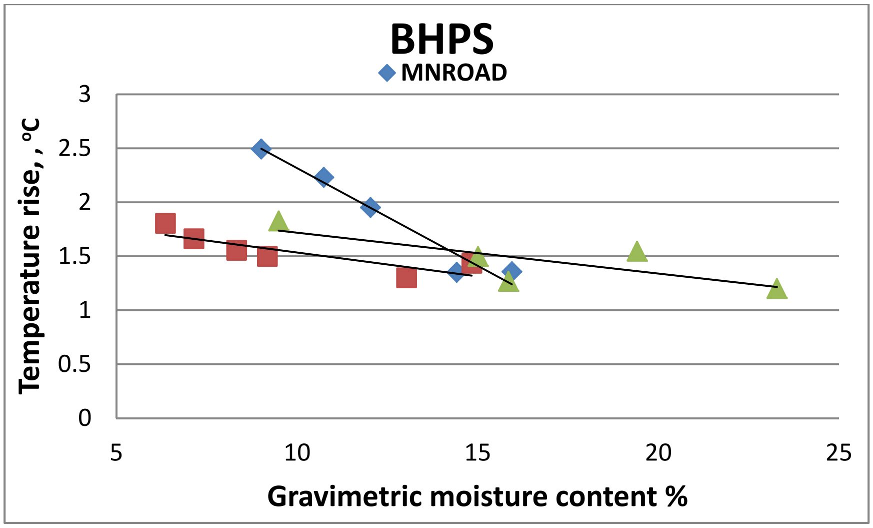


Figure 12. Plot of the average of six replications of the temperature rise measure on the three test soils versus the gravimetric moisture content.

The difference in temperature rise between soils appears to decrease as the matric suction increases (See Figure 13). The potential relationship between temperature rise in a soil due to heating and the matric suction was not explored further in this research.

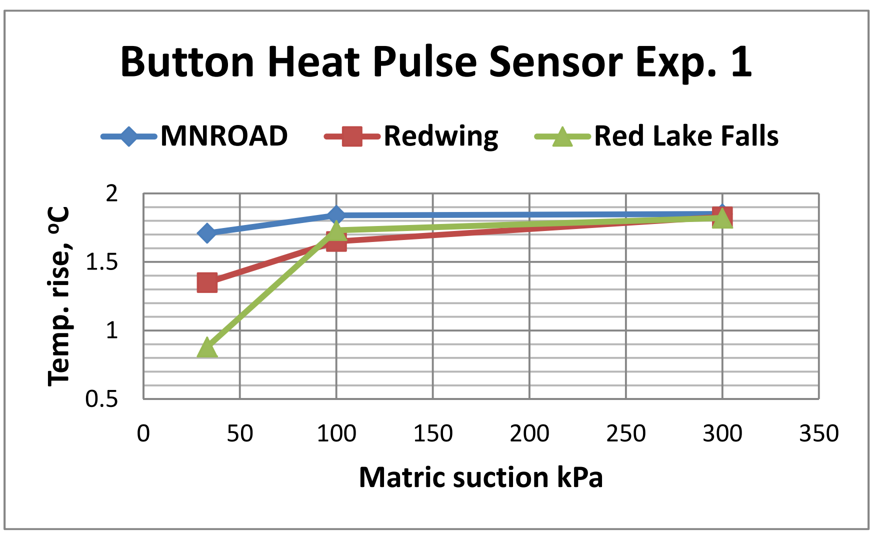


Figure 13. Relationship between temperature rise and matric suction for the three test soils.

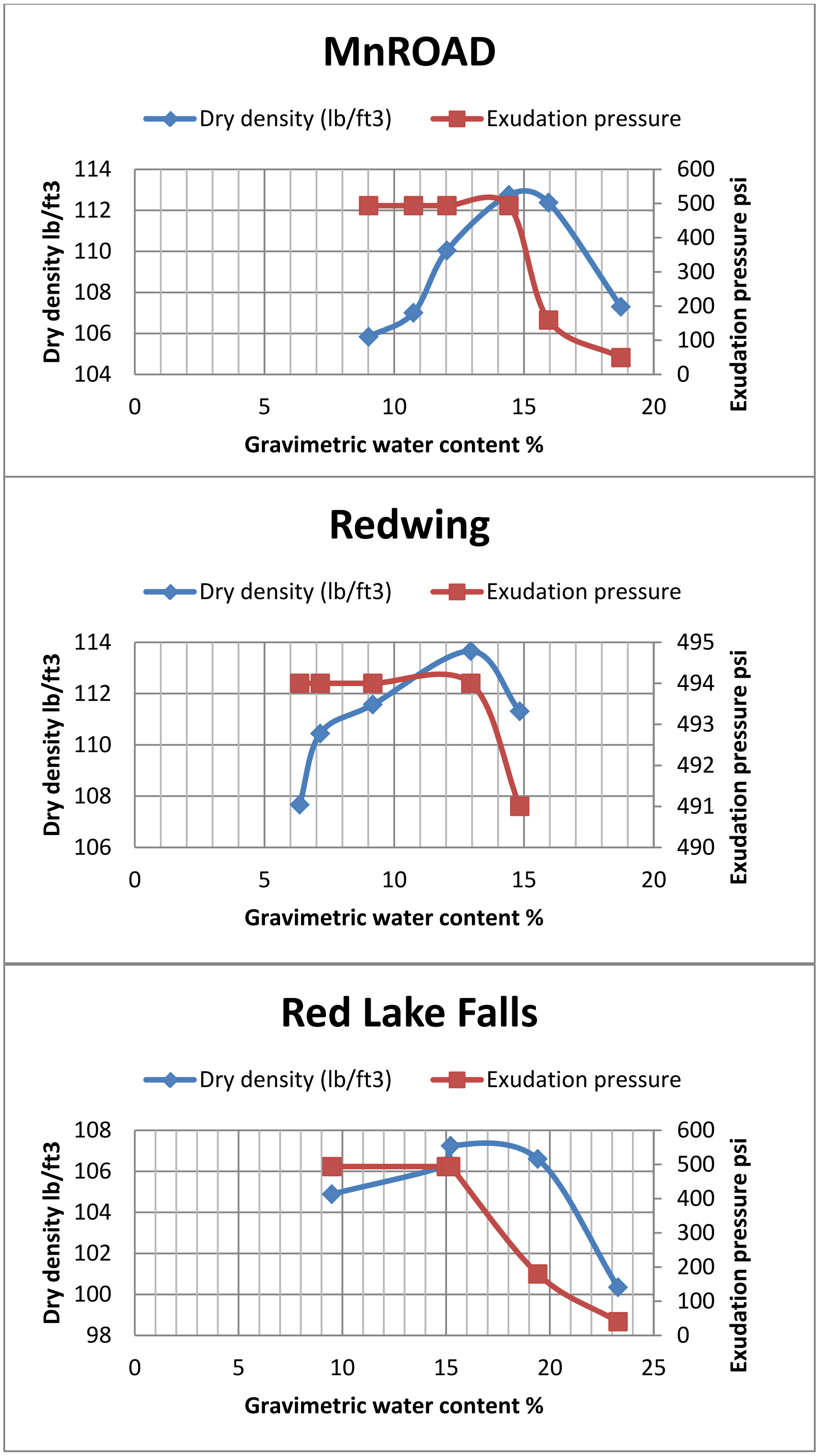


Figure 14. Plot of AASHTO T99 dry density and exudation pressure as it relates to water content.

6. Conclusions

DOT600

- The DOT600 provides a strong correlation between the output period estimated in micro-seconds and gravimetric water content. Once a curve relating the water content to the output period has been established for a given soil, the output period from the DOT600 could be used to check optimum moisture conditions in the field.
- The DOT600 factory calibration overestimated volumetric water content from five to 15 percent in a number of tests when compared to moisture contents obtained from the oven-dried method for all soils tested.
- Comparison of the dry-density- water content relationship obtained by the DOT600 to the AASHTO T99 showed the DOT600 at a compactive force of 0.275 MPa (40 psi), underestimating the dry-density and overestimating the optimal moisture content for all three test soils.

WP4C

- The WP4C did not accurately predict matric suction for any of the loam, silt or silt/clay soils at matric suctions below 250 kPa. There was better correlation between matric suctions above 250kPa. The matric suctionss related to the optimum moisture content of the three tests soils were between 200 and 300 kPa.
- If the soil water matric potential is to be determined for a specific density the sample should be collected to minimize disturbance of the pore spacing and volume. The effect of compaction on finer textured soil can affect the water potential reading as compaction tends to decrease the size of the voids. Two of the soils tested, which were compacted before testing, had significantly different water potentials compared to the same non-compacted samples, at equivalent gravimetric water contents.
- The WP4C is susceptible to environmental conditions. To achieve accurate and consistent readings the manufacture recommends the unit be placed in an area free of drafts or temperature changes.
- The fast mode setting of the instrument reads the sample but does not wait for good agreement of sequential readings before it outputs a reading. It takes about five minutes to read a sample in fast mode. There was no significant difference in accuracy between the fast mode and precision mode for the MnROAD soil but there was a significant difference at the 0.05 percent level for both the Red Wing and Red Lake Falls soils.

BHPS

- The BHPS showed a strong correlation between the temperature rise and gravimetric water content.
- The relationship between temperature rise and water content is soil specific so separate calibration curves would need to be developed for each soil.
- The BHPS is a prototype and in its current configuration would not stand up to the rigors of field testing.
- The time to take a reading is five minutes or less depending on how much surface preparation needs to be done to get the sensor properly embedded.

- The sensor ring was easily embedded into moist soil packed at densities found in natural profiles. It was difficult to embed the ring far enough into the soil surface of a heavily compacted soil. If the ring is not fully embedded it will lead to inaccurate readings. Because of the small diameter of the ring and the small volume of soil sampled by the sensor the presence of gravel could also lead to erroneous readings.

Exudation pressure device

- Water was first exuded from the cores for all three soils at or near the optimum moisture content. The exudation pressure device was unable to exude water from soils packed into a AASHTO T99 mold at moisture contents below the optimum up to a pressure of 3.4 MPa (495psi). The relationship between exudation pressure and optimum moisture content needs to be explored on more soil types before it can be more completely analyzed.

Sample preparation and time to take a reading

- The DOT600, WP4C and exudation test all require a sample to be collected and recompacted in some manor before testing. This disturbance of the soil structure and void size resulting from a different compaction method will likely provide readings different than sample collected in an undisturbed manner or tested in-situ.
- The sample preparation time for the BPHS, WP4C and DOT600 was minimal. The exudation test required preparation of the AASHTO T99 cores at each moisture content on the curve prior to running the test. If the test were conducted in conjunction with the AASHTO T99 test the preparation time would also be minimal. The time to take a reading was three to five minutes for the BPHS sensor and exudation pressure test and 10 to 15 minutes for both the DOT600 andWP4C.

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Appendix

Construction, Analysis and Testing of the Button Heat Pulse Sensor

Performance Based Measurement of Optimum Moisture for Soil Compaction

Report Task I

Construction and testing of button heat pulse sensor

Task 1 Report

by

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May 6, 2012

The objective of this project is to investigate several methods of measuring the moisture status of compacted unsaturated materials. The methods include a newly developed button heat pulse sensor for measuring volumetric water content, a Decogon 4P4C dewpoint potentiometer to measure soil potential, a DOT 600 portable unit to measure gravimetric and volumetric soil water content and bulk density and an Exudation Pressure Device to measure exudation pressure of the soil. This progress report will report on the construction procedure and initial testing for the button heat pulse sensor and the proposed experimental design to test all of the moisture sensors.

Background on the theory of heat pulse sensors

Dual probe heat capacity sensors have proven to be a reliable technique to measure soil moisture. Dual probe sensors consist of two parallel needles mounted into a plastic base for support. Resistance wire is mounted into one of the two needles and the second needle contains a small thermistor. A current is applied to the resistance needle and the temperature rise in the media being measured is recorded by the thermistor needle.

The heat capacity of the soil (C) is inversely related to the rise in temperature through the media. The heat capacity equation is given by (Campbell et al., 1991),

$$C = q/(\pi e r^2 \Delta T_m) \qquad \text{(A.1)}$$

where q is the heat output per unit length of the heater, e is the base of the natural log, and r is the distance between the heating element and the thermistor element, and ΔT_m is the maximum change in temperature measured at the thermistor. The volumetric heat capacity is related to θ by

$$C = \rho_w c_w \Phi + \rho_b c_s \qquad \text{(A.2)}$$

where ρ_w is the density of water, c_w is the specific heat of water ρ_b is the soil bulk density and c_s is the specific heat of the soil solids. These equations can then be rearranged to give an expression for computing the volumetric moisture content based solely on the soil properties and the thermal measurement. This resulting equation is

$$\theta = \frac{1}{\pi e r^2 \rho_w c_w} \frac{q}{\Delta T_m} - \frac{\rho_b c_s}{\rho_w c_w} \qquad \text{(A.3)}$$

Construction of button heat pulse sensor

For this project we have proposed to use a different configuration of the heat pulse sensor. This button heat pulse sensor developed by (Kamai et al., 2008) uses a circular configuration instead of the two parallel needles. The heater wire is embedded in an epoxy filled circular stainless steel tube mounted on a button of Delrin. The thermistor is mounted in the center of the button (Figure A.1). The three potential advantages of this button heat pulse sensor are

1. The sensor is more robust and can be pressed into the soil surface eliminating the need to insert soil probes into compacted soil

2. Larger temperature response for the same heat input provides greater sensitivity to water content
3. Requires less power

The components of the sensor we constructed are 1/16th inch stainless steel tubing bent into a circle with a 12 mm diameter. The heater wire is 40 N80 Poly Red from Pelican Wire Company. The wire was threaded through the stainless tube and the tube filled with thermally conductive epoxy (Omega 101). The same epoxy used to fill the stainless tube was used to mount the ring to the Delrin button. The mounting surface of the Delrin button was machined to create a raised 12mm diameter circle to help hold the ring in place and provide better contact of the thermistor (Omega 44006) with the soil (Figure A.2).

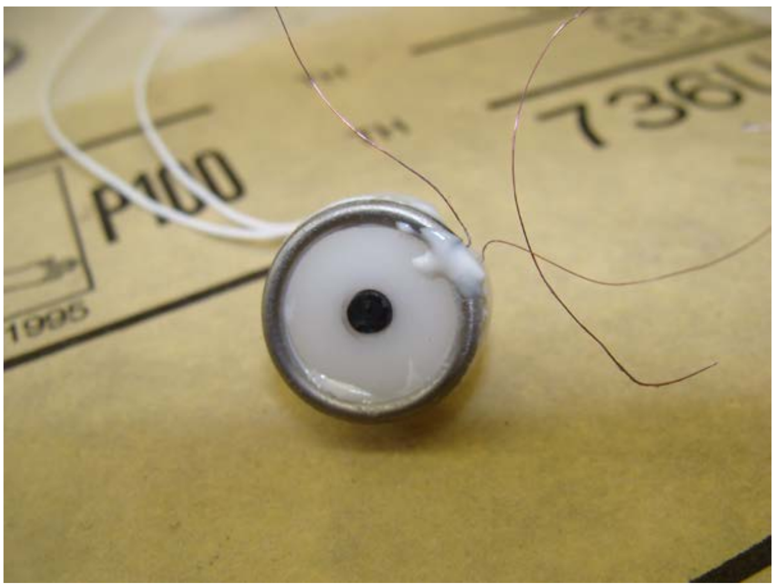

Figure A.1. Constructed button heat pulse sensor.

Figure A.2. Stainless steel ring and machined Delrin button.

Four strands of heater wire were run through the stainless steel ring for a total length of approximately 0.142 meters. The heater wire was rated at 229 ohms/meter.

Initial testing of the button heat pulse sensor

Initial sensor testing by (Kamai et al., 2008) and (Valente et al., 2010) was done by immersing the sensor in a 4 % agar solution and measuring the temperature rise after firing the heater for eight seconds. The temperature rise reported by the two researchers was 2.5 and 0.5 degrees centigrade respectively. Initial testing of the button heat pulse sensor was done following the same procedure as described above.

A typical temperature rise curve for the testing of our sensor is shown in Figure A.3. Table 1 summarizes of the initial testing for three of the constructed sensors.

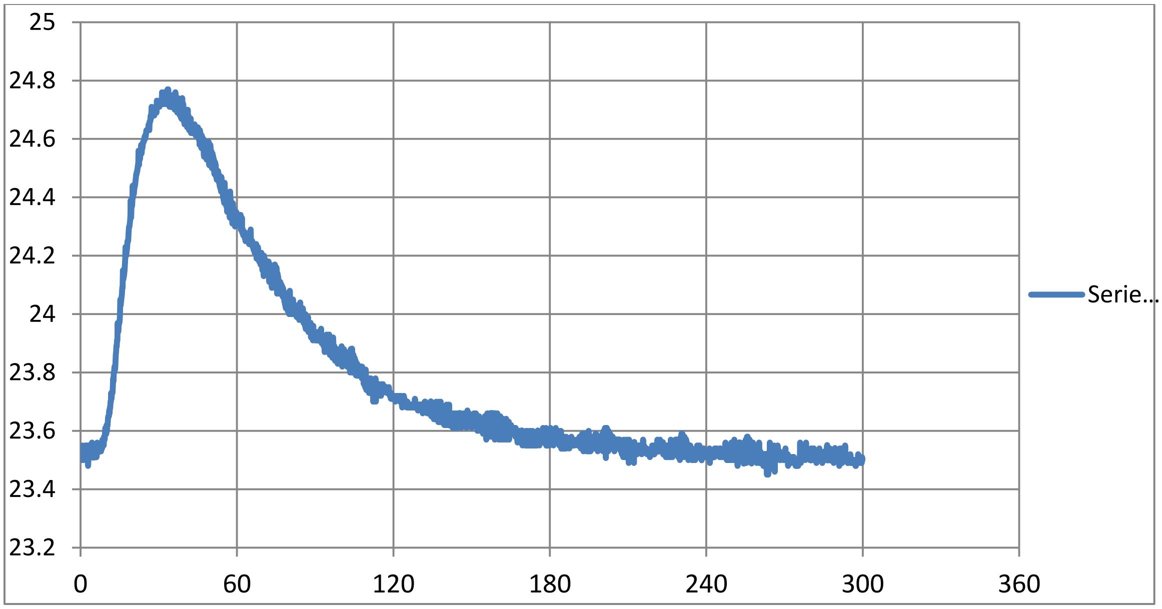

Figure A.3. Temperature response of button heat pulse sensor.

Table 1. Data from initial testing of three button heat pulse sensors.

Sensor	Initial T (°C)	Maximum T (°C)	Time-to-peak T (sec)	ΔT_m (°C)
1	25.58	27.03	31.50	1.45
1	25.71	27.13	31.00	1.42
1	25.53	26.97	30.375	1.44
1	25.45	26.93	29.38	1.48
2	23.81	24.98	31.75	1.17
2	23.70	24.82	31.25	1.12
2	23.64	24.83	33.38	1.19
2	23.62	24.80	37.25	1.18
3	24.11	25.25	36.00	1.14
3	24.09	25.19	35.50	1.1
3	24.03	25.14	35.63	1.11

The average ΔT_m for sensors one, two and three respectively were 1.44, 1.165, 1.12 ^{o}C. This falls inside the range reported by (Kamai et al., 2008) and (Valente et al., 2010). This temperature rise in agar is essentially at 100% moisture content. It will be greater in soils which typically are at moisture contents less than 50%. At ΔT_m of between 1.1 and 1.5 ^{o}C we should have enough heat to measure high moisture content soils but not too much heat to dry the soil quickly and not get a good temperature response. The data from the initial testing indicates the design and construction of the sensors is sound. Testing the sensors in soil will be done in conjunction with the other soil moisture and tension measuring apparatus explained in the section below that describes the experimental procedures.

Modeling of Heat Pulse Button Sensor

Kamai et al. (2008) conducted numerical simulations of the thermal signal response generated by the heat pulse button sensor. As described in the previous section, the HPBS is composed of a heater ring and a thermistor located at the center of the ring. Both the heater ring and the thermistor (button) come into contact with a soil surface. A uniform heat pulse is injected into the heater ring for a period of 8 seconds, and then the heat is conducted into the soil volume and the thermistor senses the transported heat. The pulse produces a rise in the soil temperature, and the magnitude of that temperature rise is a function of the water content of the soil, and the thermal properties of the soil.

Assuming conditions for isotropic thermal conductivity, uniform thermal conductivity and uniform heat capacitance, and axisymmetry) the governing equation for the transient heat conduction into the soil is given by (in axisymmetric coordinates)

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{1}{r} \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} \right] \qquad \text{(A.4)}$$

where:

$\alpha \left(= \frac{k}{\rho_b c_p} \right)$ is the thermal diffusivity (m^2/sec),

k is the thermal conducitivity of the bulk soil (W/m-^{o}C),

ρ_b is the bulk density of the bulk soil (kg/m^3),

c_p is the specific heat of the bulk soil (W/kg-^{o}C),

T is temperature (^{o}C).

The bulk density of the soil is a function of the density of the dry soil and water content.

The region of interest for this problem is shown in Figure A.4a and A.4b. The initial conditions and boundary conditions for this problem are given by:

initial condition: $T\left(r,z,t=0\right)=T_0$

boundary conditions:

$$-k\frac{\partial T}{\partial r}=0;\ r=0,R$$
$$-k\frac{\partial T}{\partial z}=0;\ \mathrm{z}=0,D$$

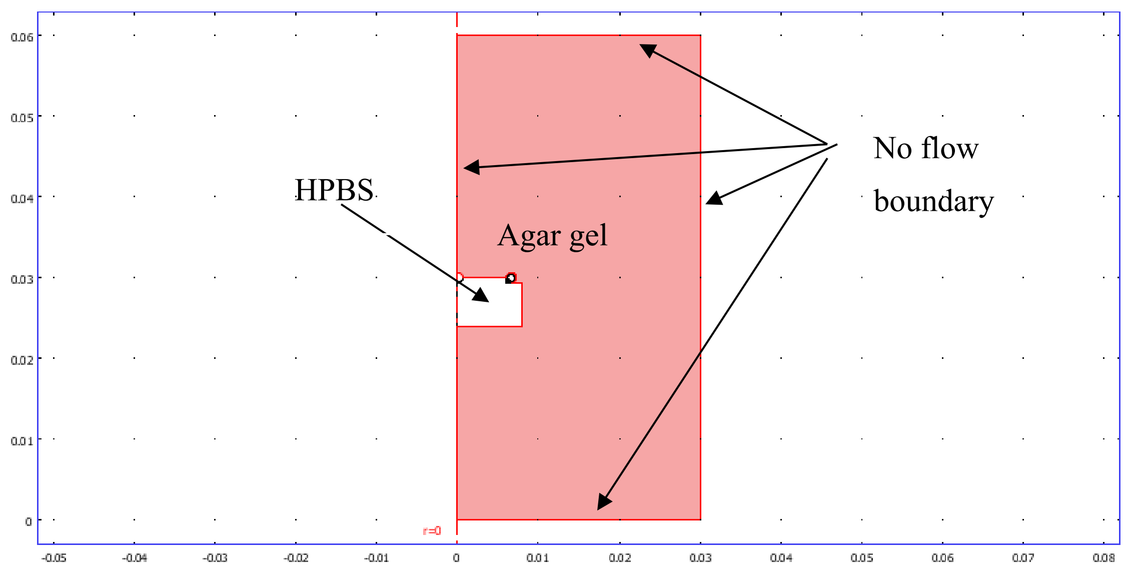

Figure A.4a. The domain for the HPBS imbedded inside of the agar solution. Boundary conditions for the solution to equation A.1 are indicated in the image.

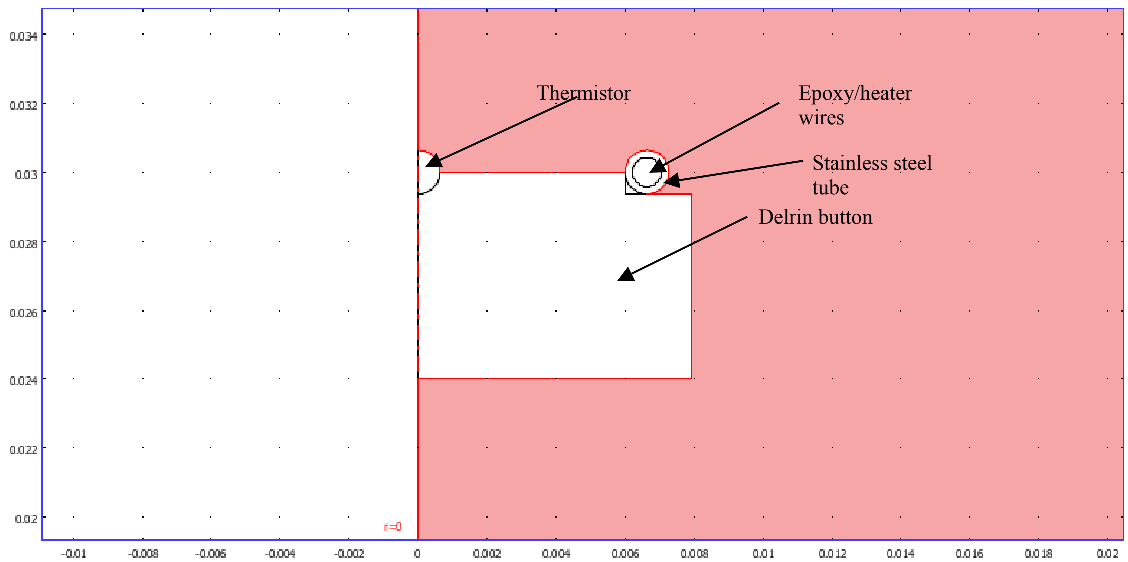

Figure A.4b. Magnified view of the HPBS embedded inside of the agar solution.

The solution of equation A.4 subject to these initial conditions and boundary conditions is derived using the finite element method implemented with COMSOL (2011) software. A test finite element grid for the problem is shown in Figure A.5. The finite elements are constructed to be small near the heater element and the button sensor to provide for more accurate results, while they are allowed to be larger as distance from the heat source increases.

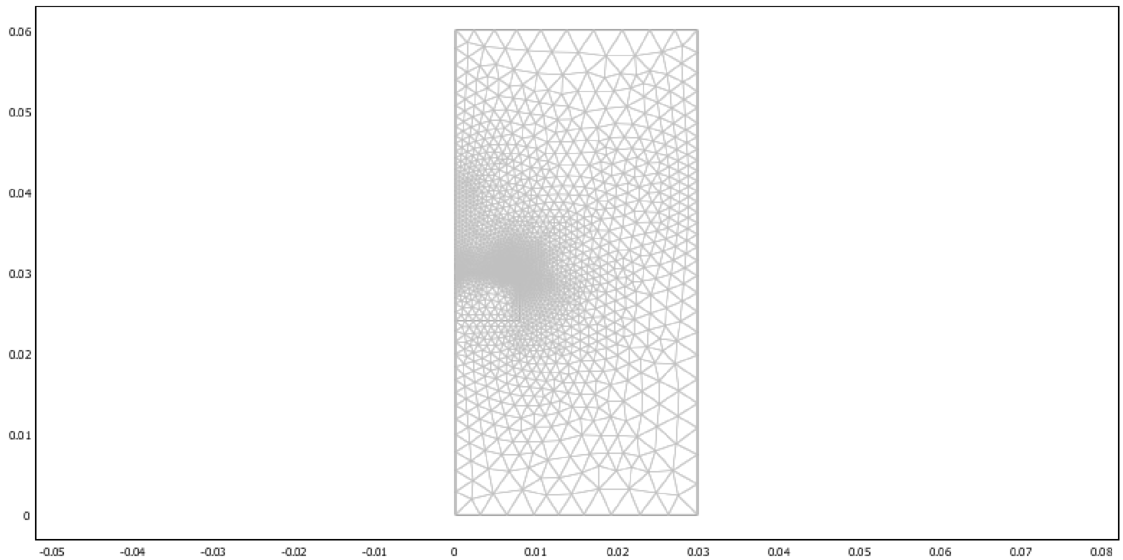

Figure A.5a. Test finite element grid for the sensor domain. The grid is very dense in the vicinity of the heater and the thermistor.

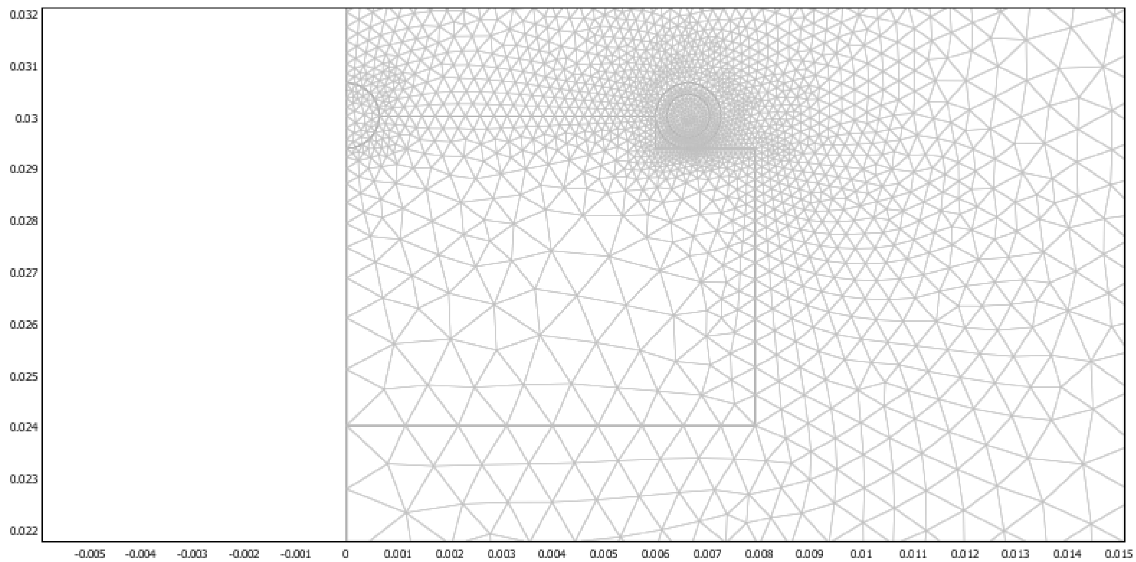

Figure A.5b. Test finite element grid for the sensor domain magnified in the vicinity of the sensor.

For the model simulations we used the thermal properties summarized in Table 2. These are the same values used by Kamai et al. (2008).

Table 2. Physical and thermal properties of materials used in the construction of the HPBS.

Material element	Thermal conductivity ($W/m-^oC$)	Bulk density (kg/m^3)	Heat capacitance ($W/kg- ^oC$)
Agar	0.59	998	4,181
Stainless steel	16	8,000	500
Epoxy	1.04	1,710	961
Delrin button	0.37	1,410	1,286

For the HPBS the heat source is generated by copper wires strung through the epoxy-filled stainless steel ring. The heat source intensity was set at 1.25 x 10^8 W/ m^3. As mentioned above, this heat intensity was maintained for 8 seconds. For the volume of the heater this generates a total of 580 W-sec for the heating period. The initial temperature was set at 23.8 ^oC.

The heat response at the center of the thermistor location is shown in Figure A.6. The ΔT_m at the thermistor is (25.6-23.8) ^{o}C, or a change of 1.8 ^{o}C. The spatial distribution of temperature in the domain at the time of peak temperature is given in Figure A.7. The ΔT_m values given by the experiment ranged from 1.1 ^{o}C to 1.48 ^{o}C. The time to peak temperature in the simulation is 47 seconds, while the time to peak temperature in the experiment ranged from 29.4 sec to 37.3 sec.

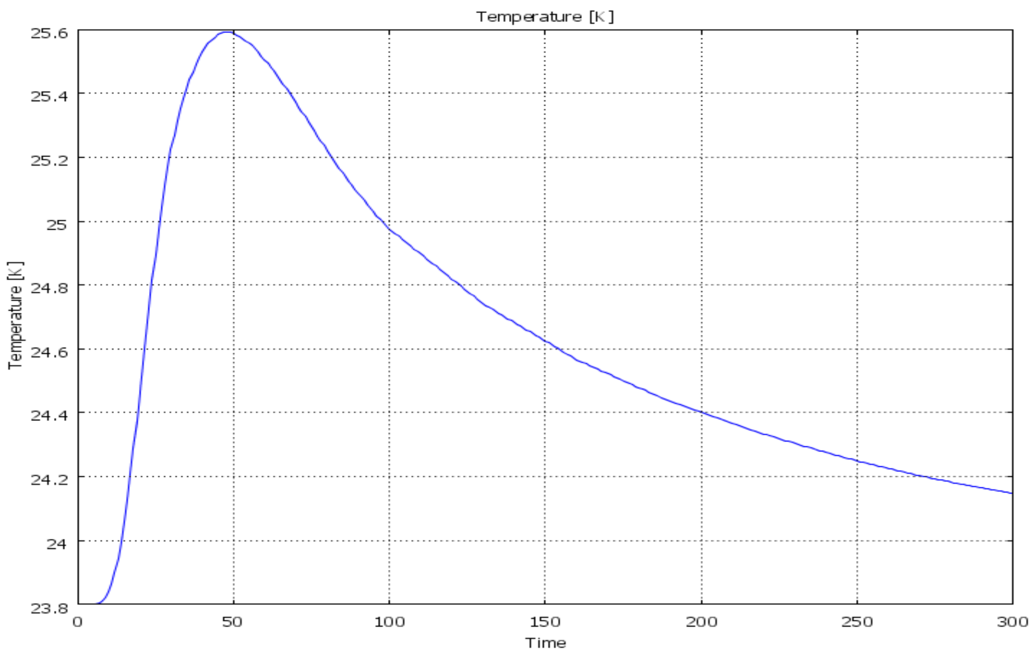

Figure A.6. Temporal response of the thermistor.

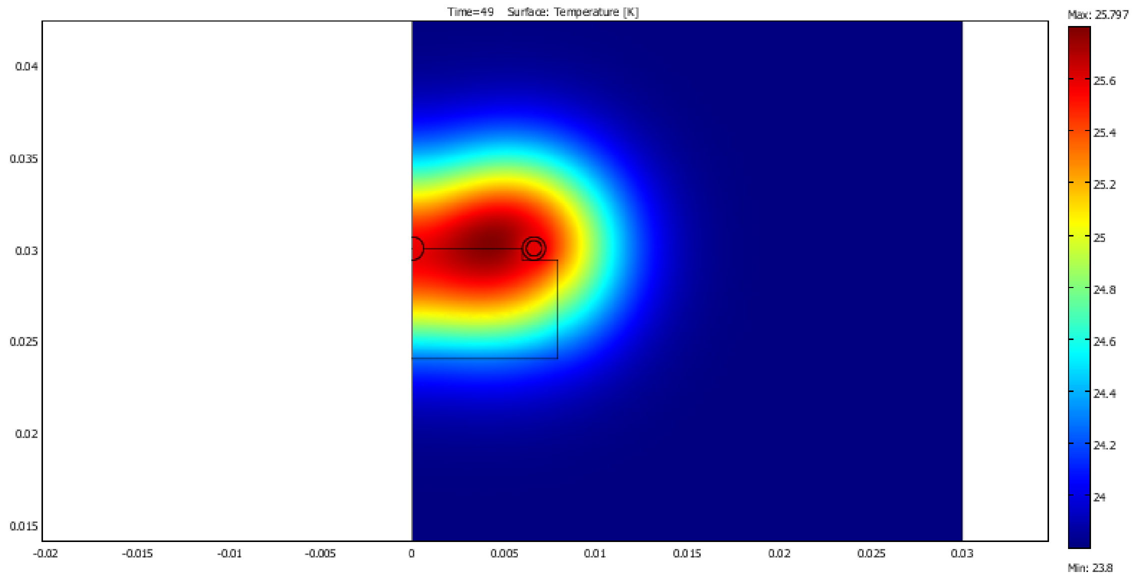

Figure A.7. Spatial distribution of temperature in the sensor domain at t=47 seconds, the time of peak temperature at the thermistor location.

The magnitude of the ΔT_m , and the time to peak temperature change both are dependent on the thermal properties of the materials and the magnitude of the heat pulse. These parameters were varied slightly to assess the sensitivity of the ΔT_m and the time to peak. It is clear from this analysis (not shown in detail here) that it is possible to match the measured response better with the simulation than that shown when comparing Figures A.3 and A.6. Additional work will be conducted with the simulation model to better define the effective system parameters, including the system geometry.

Proposed testing procedures

We propose the testing procedures be conducted in two experiments. Experiment one would evaluate the response time for the measurements with each of the instruments, the accuracy of the measurement, and the time required to make the measurements. The second part of the experiment would evaluate how the measured matric potential and volumetric water content from the various sensors relate to an optimum moisture content based on strength performance.

Experiment 1: testing response time, accuracy and time requirement of the different sensors

The control for moisture content and soil tension will be soil cores placed in a pressure plate extractor chamber (Figure A.8). The cores of the three MnDOT soils will be dried, sieved and packed to a dry density from the Proctor test. The soils will be packed in 8 inches in diameter PVC cores to a depth of 2 inches. The cores will be placed on 3 bar plates in the pressure plate extractor and saturated before the first pressure is applied.

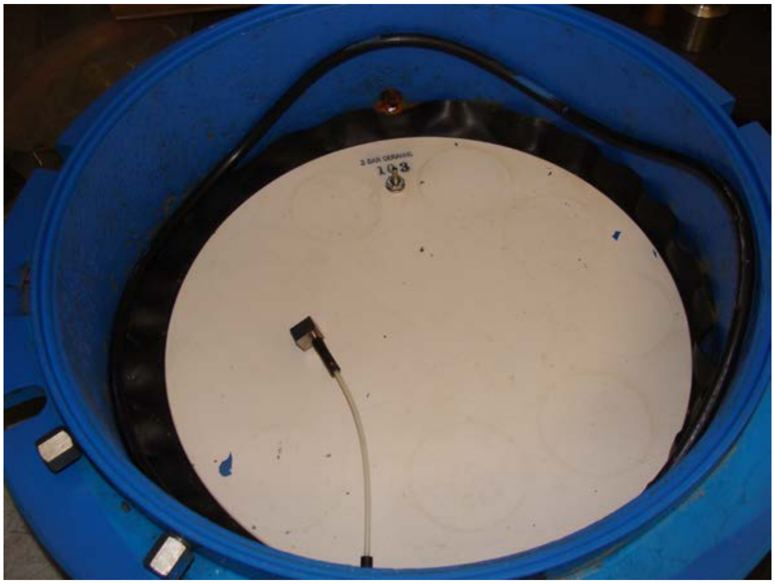

Figure A.8. Pressure plate extractor chamber for measuring soil moisture and potential.

Pressure will be applied to the cores to achieve equilibrium at the following soil potentials: 0.5,1, 3, 5 and 7 bars.

At equilibrium the soil potential will be given from the pressure applied in bars and the gravimetric moisture content measured from a subsample of the core using the oven dried method. Moisture content determined by the three button heat pulse sensors will be measured by seating the sensors firmly into the soil surface on the equilibrated soil core. Subsamples of the core will also be taken for the DOT 600 and WP4C measurements. The measurements from the various moisture sensors will be compared to the actual moisture contents and potentials from the pressure plate extractor. Observations on response time and time required for each device will also be recorded.

Experiment 2: measurement of matric potential and volumetric water content from the various sensors related to an optimum moisture content based on strength performance.

The second aspect of the project will involve the measurement of volumetric water content and soil tension of soils compacted with a standard Proctor procedure at different initial moisture contents. The volumetric water content will be measured with the button heat pulse sensor and the DOT 600. Soil tension will be measured with the activity meter and the exudation pressure will be measured using the exudation pressure device.

We propose all the measurements be conducted on four different moisture contents listed below:

4% below optimum moisture content

2% below optimum moisture content

At optimum moisture content

2% above optimum moisture content

The testing will be done on the following three soils:

UMA Red Wing SS120179

UMB Red Lake Falls SS120180

UMC MnROAD SS120181

The background data on these soils is extensive. Two different sets of index testing have been preformed and the curves depicting the relationship between moisture content and soil tension developed. Another data set will also be developed during the testing of the various sensors on moisture content vs. soil tension and Proctor densities. Data from all of the testing will be documented and variability between each level of testing and possible effects on the sensor readings will be described in the final report.

The proposed procedure for this aspect of the testing will involve packing the three different soils at the proposed moisture contents into the Proctor mold using standard Proctor testing procedures. The testing will start with the 4% below optimum moisture content and after completion proceed to the next higher moisture content. After compaction the button heat pulse sensor will be placed on the soil in the packed core to determine volumetric moisture content. Subsamples from the core will be removed for testing by the DOT 600 and water activity meter. After the sub samples have been removed the button heat pulse sensor will again be placed on the soil core to give moisture content at two depths in the soil core. The soil remaining in the core will be subjected to the exudation pressure using the Proctor mold as the container. After all testing is completed for a given moisture content the soil remaining in the core will be remixed with the original soil sample and wetted up to achieve the next higher moisture content. The procedure will be repeated until measurements at all for moisture contents have been completed. This process will be repeated three times for each soil.

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