Rapid Drying Soils with Microwave Ovens

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ABSTRACT

Soils are normally dried in either a convection oven or stove. Inspections of field and laboratory moisture content testing indicated that the typical drying durations for a convection oven and stove were, 24 hours and 60 minutes, respectively. The objectives of this study were to determine the accuracy and soil drying duration of microwave ovens. This was accomplished by testing soils with and without additives. The soils were tested with a convection oven (CO), computer controlled microwave oven (CMWO), standard microwave oven (SMWO), and stove. The convection oven was considered to produce the true moisture content and was, therefore, used as a basis for comparison for the results of the other devices. Based on appraisals of the results, the standard microwave oven is the most feasible device to use in drying soils.

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IMPLEMENTATION STATEMENT

Microwave ovens are a viable means of rapidly drying soils. The procedures developed and used for drying soils with a microwave oven are timely, efficient, accurate, and safe. The standard microwave oven is the best alternate device based on accuracy, testing duration, and the benefits to cost analysis.

The Project Review Committee recommended that a specification be written to dry soils with a microwave oven. The proposed specification, "DOTD TR 403-01, Method C, Rapid Drying with Microwave Oven," was written and submitted to the specifications committee. Because of the sample size requirements in the current DOTD specifications, the microwave oven was restricted to use on soils with less that five percent aggregate.

The District 03 and 62 laboratory engineers have conducted field trials with the microwave oven. The results of these tests are shown in Appendix 1. The results from the Districts are consistent with the findings of this report.

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INTRODUCTION

The long term performance of roads is dependant on factors such as the pavement type (asphalt or concrete), base course type (stone, asphalt, cement stabilized), subbase, traffic loading, and climatic conditions. Each material used in roadway construction has its own unique properties, and testing procedures have been developed to measure them. For soil-aggregate mixtures, whether naturally occurring or chemically stabilized, compaction is a significant factor in enhancing its mechanical properties. The degree of compaction or densification is influenced by the type of soil, moisture content, and compactive effort. R. R. Proctor developed testing procedures to identify the maximum dry density and the corresponding moisture content, commonly known as optimum moisture content (OMC) of a soil at a specific compactive effort. These procedures evolved to become the AASHTO T-99 or ASTM D 698 test methods.

Earth work, base, and subbase courses are governed by Parts II and III of the Louisiana Department of Transportation and Development (DOTD) Standard specifications for Roads and Bridges, 1992 Edition. The testing procedures for determination of optimum moisture content, maximum dry density, and cement content are governed by DOTD, TR 432M/432-99, TR 418-98, and TR 415-99.

The current DOTD procedure for determining Field Moisture – Density Relationships is TR 415-99. It requires a minimum of three proctor tests per zone, which is typically one thousand feet long. Each proctor test is accompanied by a moisture content test so that a moisture-density relationship can be established. The stove method is conducted by placing soil in a pan over an open flame. The soil is stirred and heated until all the moisture is evaporated. Errors in moisture content determination can occur in several ways. First, the amount of heat used to dry the material is determined by the skill and experience of the operator. If the material is overheated, vaporization of the organics in the soil and the asphalt coating on recycled pavement blended with the base course can occur. Second, some material may spill out of the pan during the process of stirring the specimen while conducting the test. It should be noted that a survey of field technicians indicated that it takes approximately 45 to 60 minutes to perform a moisture content test using the stove method, DOTD TR 403. Quite often, the contractor is usually in the next construction zone by the time the results are tabulated.

In an effort to enhance productivity and accuracy, a new method for quickly (under 20 minutes) and accurately determining moisture content was needed. Mendoza and Orozco conducted a study called “Fast and Accurate Techniques for determination of Water Content in Soils” [1]. In that study, four alternative methods, 1) microwave ovens (MWO), 2) direct heating (DH), 3) toluene distillation, and 4) heat from alcohol combustion along with the standard laboratory method (ASTM D 2216), which uses a convection oven (CO), were used. Of the alternative methods, the microwave oven yielded the best results. Gilbert reported in “Rapid Water Content by Computer Controlled Microwave Drying” [2], that the difference between the moisture content results of a standard convection oven (ASTM D 2216) and the computer controlled microwave oven was within 0.55 percentage points for about 95 percent of the samples tested. Additionally, ASTM has established a test method entitled “(D 4643) - Standard Test Method for Determination of Water (Moisture) Content of soil by the Microwave Oven Method.” These facts were presented to the Project Review Committee (PRC). The committee decided that it was necessary to verify the accuracy and testing speed of the standard microwave oven (SMWO) and the computer controlled microwave oven (CMWO) on soils typically used in Louisiana roads.

OBJECTIVE

The purpose of this research was to develop a new method for quickly and accurately determining moisture content. This was accomplished by assessing the accuracy and testing durations of drying soils with the computer controlled microwave oven, standard microwave oven, and stove. The convection oven was considered to produce the true moisture content. Therefore, the convection oven was used as a control to which the testing results of the other devices were statistically compared.

SCOPE

In order to develop a comprehensive laboratory program and complete the objectives of this study, a representative range of soils used in highway construction and the devices used to evaluate them had to be selected.

Seven soils were selected for evaluation. The soil types were two clays, one sand, one silt, one soil-aggregate, and two recycled base course materials. Each soil was examined in its natural state. Four soils were examined with Portland cement, and two soils were examined with lime.

The devices used in the evaluation program are listed as follows:

- **Convection Oven:** The convection oven used was GS Blue M STAT 1900 and conformed to ASTM D2216 standards.

- **Computer Controlled Microwave Oven:** The computer controlled microwave oven used was purchased from Geoscience Engineers.

- **Standard Microwave Oven:** The standard microwave oven used was a Panasonic Model NN-S769S.

- **Stove:** The stove used was a propane-fueled Century Primus camping stove.

METHODOLOGY

In order to properly assess the microwave ovens, a two part evaluation program was developed. For clarity purposes, the devices and soils used for examination, statistical analysis methods, and sample preparation were defined prior to outlining the repeatability/method comparison and high/low moisture evaluation programs.

Devices used in evaluation program

In the evaluation program, a convection oven (CO), computer controlled microwave oven (CMWO), standard microwave oven (SMWO), and stove were used to determine the moisture content of the soils.

Convection Oven (CO)

The convection oven used on this project was a GS Blue M STAT 1900. It conforms to ASTM D 2216 and DOTD TR 403-92, Method B standards. The soils were dried at a constant temperature of 110^0 +/- 5^0 C for a period of 16 hours.

Computer Controlled Microwave Oven (CMWO)

The CMWO used on this project was purchased from Geoscience Engineers. It had a 700 watt output capacity and was fitted with an electronic scale that had a 3000 gram capacity accurate to +/- 0.01 grams. The cycles of heating and cooling, weight changes of the sample, and moisture content were controlled and monitored by proprietary software furnished with the CMWO [3]. The testing results were viewed on a computer monitor and were manually recorded.

Standard Microwave Oven (SMWO)

Section 6.1 of ASTM D4643-93 states the following: “A microwave oven, preferably with a vented chamber, is suitable. The required power rating of the oven is dependant on its intended use. Ovens with variable power controls and input power ratings of about 700 watts have been found to be adequate for this use. Variable power controls are important and reduce the potential for overheating of the test specimen [4].” Gilbert [3] and Mendoza and Orozco [1] both used typical house-hold microwave ovens in their studies. Neither reported any challenges or failures from using the microwave oven to dry soils. Note 3 of ASTM D4643-93 states, “The use of a microwave oven for the drying of soils may be considered abusive by the manufacturers and constitute voiding of warranties. Microwave drying of soils containing metallic materials may cause arcing in the oven. Highly organic soils and soils containing oils and coal may ignite and burn during microwave drying. Continued operation of the oven after the soil has reached constant weight may also cause damage or premature failure of the microwave oven [4].” Gilbert [3] recommended that a brick be placed in the microwave oven to prevent damage or premature failure of the microwave oven. Since there is water trapped in the brick which can not be dried out, there is no danger in creating a “no water load scenario to damage the microwave oven’s heating element.” Therefore, a standard microwave oven has been proved to be adequate for testing soils by the researchers listed above.

There are currently two types of common household microwave ovens on the market. The first type has electronic components that allow the operator to adjust the amount of time a unit is operating at full output power capacity within a selected time interval. For example, a power setting of 50 percent for a 10 minute duration on a unit with a 1000 watt output generates 1000 watts for five minutes during the 10 minute duration. The other type of microwave oven has a device called an inverter that allows the actual power output to be adjusted. A power setting of 50 percent during a 10 minute duration on a unit with a 1000 watt output generates 500 watts continuously during the 10 minute duration.

The SMWO used on this project was a Panasonic Model NN-S769S. It had an 1100 watt power output with an inverter. This SMWO allowed more flexibility in developing testing procedures since both the power and time interval could be adjusted. Moisture content testing was conducted in accordance with ASTM D 4643. Section 11.3 of the ASTM D4643-93 specifications states, “Place the soil and container in a microwave oven with the heat sink and turn the oven on for 3 minutes. If experience with a particular soil type and specimen size indicates shorter or longer initial drying times can be used without overheating, the initial and subsequent drying times may be adjusted [4].” Based on preliminary trials in the LTRC laboratory, the specimens were dried in the SMWO at 650 watts with an initial drying interval of 6 minutes and then weighed. Subsequent drying and weighing cycles were performed at one minute intervals until a constant weight was achieved.

Stove

The stove used for drying soils was a Century Primus camping stove that was fueled by propane and had dual burners. Moisture content testing was conducted in accordance with DOTD TR 403.

Sample preparation

Specimen size for moisture content

The rapid drying procedure for moisture content determination is governed by DOTD TR 403-92, Method A. The minimum specimen size allowed for moisture content testing is listed as follows:

a) Soils 500 grams
b) Aggregates 10 pounds
c) Soil-aggregate 5 pounds

Most materials tested in the field contain a soil-aggregate mixture. A specimen formed in a six-inch diameter proctor mold weighs approximately 5 pounds. It is believed that a 5-pound sample was selected for moisture content testing to minimize errors associated with stoves. There are two major problems associated with drying soils with a stove. First, the amount of heat used to dry the material is determined by the skill and experience of the operator. If the material is overheated, vaporization of the organics in the soil and the asphalt coating on recycled pavement blended with the base course can occur. Second, some material may spill out of the pan during the process of stirring the specimen while conducting the test.

Since the heat source in a microwave oven used for drying soils can be consistently regulated electronically and the sample is never stirred, a smaller specimen can be used with confidence. Gilbert found that specimens between 80 and 200 grams were suitable for testing most soils with a microwave oven [3]. Based on Gilbert's findings and the experience of the members of the Project review committee, a test specimen weight of 500 grams was used for all materials evaluated in this study.

Bulk sample preparation

Four batches of bulk (unprocessed) sample were prepared for each soil group. This was necessary since it could take up to one work day to test each batch. To ensure that enough material was available for six specimens, approximately 4000 grams (one batch) of bulk sample plus additional material to account for possible spillage during preparation was prepared and processed. The bulk sample was prepared in accordance with DOTD TR 411M/411-95 by drying it until it reached a constant weight at 60^{O} C prior to being mulled or pulverized to pass a No. 4 sieve.

Soil in its natural state

The processed bulk sample was weighed and the amount of water required to obtain the desired moisture content was added and mixed with the soil in accordance with DOTD TR 418-98. The sample was placed inside a water-proof container and allowed to slake for one hour. Heavy clays were slaked for 24 hours. Individual 500 gram specimens were portioned out of the slaked material for moisture content determination using the specified devices. All specimens were tested within 24 hours after the slaking period.

Soil with Portland cement additive

Six specimens were obtained from the processed bulk sample. Specimens were prepared separately due to slaking and testing duration limitations. DOTD TR 418-98 required two slaking periods prior to testing. First, the specimen was allowed to slake for 30 minutes in a water proof container after blending water and cement with the soil specimen. Next, the specimen was remixed and allowed to slake for an additional 30 minutes. Testing of the specimen was conducted within 30 minutes after the second slaking period. This procedure ensured sample consistency and allowed multiple tests to be performed within a work day.

Soil with lime additive

The processed bulk sample was weighed and the appropriate amount of water and lime was mixed into the bulk sample to obtain the desired moisture and lime contents. The sample was placed in a water-proof container and allowed to slake for a minimum of 15 hours in accordance with DOTD TR 418-98. Specimens weighing approximately 500 grams were obtained from the water-proof container as moisture content testing was conducted. All specimens were tested within eight hours of the initial slaking period.

Statistical analysis methods

In order to determine the accuracy of the devices, six specimens were prepared and tested with each device per soil group. Uniformity was ensured by using 500 gram specimens for each specimen examination and by meticulously repeating sample preparation and moisture content evaluation procedures. Both the moisture content and duration required to perform examinations were recorded and appraised as deemed appropriate. The convection oven was considered to provide accurate results; therefore, its data was used as a control to evaluate the performance of the other devices. The following statistical methods were used:

- **Standard deviation:** Average of the individual values from the mean.
- **Average or mean:** Sum of the individual values divided by the total number of values.
- **Confidence Interval:** Range of values above or below the mean with a 95 percent degree of confidence. If the confidence interval is 0.5 and the mean value is 25, then 95 percent of the test results fall within the range of 25.5 to 24.5.

- **Fischer least squares difference:** Statistical method performed with the Statistical Analysis System (SAS) version 6.12. This method was used to compare the testing results obtained from the CMWO, SMWO, and stove to the convection oven.
- **TTEST:** Statistical method performed with the Statistical Analysis System (SAS) version 6.12. It was used to compare the results of two sets of data.

Soils used in evaluation program

Soils typically used or occasionally encountered in Louisiana highway construction were selected for analysis. Each soil was examined in its natural state. Four soils were examined with Portland cement and two soils were examined with lime. Additionally, two soils were examined in their natural state at moisture contents above and below optimum moisture contents for those soils. The soils used in this program are illustrated in table 1.

Table 1
Soils used in evaluation program

Soil type	Natural state {1}	Portland cement additive {1}	Lime additive {1}	High/Low moisture content (natural state only)
LA 15 Clay	Yes	No	No	No
Big River Clay	Yes	Yes	Yes	Yes
RCB 1 **{2}**	Yes	Yes	No	No
RCB 2 **{2}**	Yes	Yes	No	No
A-1	Yes	No	No	No
Alf Silt	Yes	Yes	Yes	Yes
Sand	Yes	No	No	No

{1} Used in Repeatability/Method comparison evaluation program

{2} RCB, recycled base course, is a base course that has been previously stabilized with Portland cement.

Each soil type was classified and the optimum moisture content was determined prior to developing an evaluation factorial for that soil group. These results are illustrated in Appendix 2. Unless otherwise noted, all soils were examined at or near optimum moisture content. The cement and lime additive concentrations were ten percent and nine percent by weight, respectively. Table 2 lists the soil classification test procedures used.

Table 2
Soil classification test procedures

Test	Procedure
Sample Preparation	DOTD TR 411M/411-95
Hydrometer	DOTD TR 407-89
Atterberg Limits	DOTD TR 428-67
Moisture/Density Curves	DOTD TR 418-93
Sieve Analysis	DOTD TR 113-75
Organic Content	DOTD TR 413-71
Moisture Content	DOTD TR 403-92

Evaluation Program

Six primary variables were addressed to ensure specimen testing accuracy and consistency. These were specimen size, technicians, devices, soils, sample preparation, and moisture content. All test specimens weighed 500 grams. Trial tests were performed prior to official examination by the technicians until they became proficient in using the four devices. Soils of different classifications were analyzed to ensure that the devices could be used with confidence on materials typically used or encountered in Louisiana highway construction. Results from the CO were used as control data to evaluate the performance of the other devices. Sample preparation was performed in strict accordance with the appropriate specifications. Unless otherwise indicated, testing was conducted at or near optimum moisture content for all soils. Furthermore, to ensure that the devices were accurate over a range of moisture contents, testing was conducted above and below optimum moisture content on two soils.

There were two major parts to the evaluation program: repeatability/method comparison and High/Low moisture content with the CMWO and SMWO.

Repeatability/Method comparison

The four devices were used to determine the moisture content of the soils. Table 1 lists the soils tested in their natural state and with cement and lime additives. Six specimens were examined from each soil group with each device. The moisture content and the duration required to perform each examination were recorded and evaluated.

Moisture content evaluation. The moisture content values obtained were statistically analyzed. Statistical values obtained from the standard deviation, mean values, and Fischer Least Squares Difference method (LSDM) were appraised. If the LSDM indicated that the three devices (CMWO, SMWO, and stove) were statistically the same as the CO, confidence in their accuracy is ensured. However, if the LSDM indicates that they were statistically different, then the mean values, confidence interval, and standard deviations were reviewed to determine the significance of the difference.

Evaluation of testing duration. It was important to establish a typical duration for specimens examined with each device except the CO. The CO is not considered to be a rapid moisture content determination device and is not practical to use on field projects since it can take up to 24 hours to dry a soil specimen. The average values for moisture content determination were computed and reviewed for the CMWO, SMWO, and stove.

High/Low moisture content

This evaluation was conducted to assess the accuracy of the CMWO and SMWO above and below optimum moisture content. Table 1 lists the soils that were used for moisture content testing. Twelve specimens were prepared and examined from each soil. Six specimens were examined below and six specimens were examined above optimum moisture content. The values of the moisture content and the duration required to perform each examination were recorded and evaluated.

Moisture content evaluation. The moisture content values obtained were statistically analyzed. Statistical values obtained from the standard deviation, average, and TTEST were appraised using engineering judgment. Additionally, the values were compared to the results obtained from the Repeatability/Method comparison testing.

Evaluation of testing duration. The average durations for moisture content determination were computed and reviewed for the CMWO and SMWO. These values were compared to the results obtained from the Repeatability/Method comparison testing.

DISCUSSION OF RESULTS

Soil Classifications

The seven soils used in this testing program are listed in table 1. The results of their classifications are listed in Appendix 2.

Repeatability/Method Comparison

Testing and statistical evaluation of moisture content data

The tests were conducted and the values of the moisture content along with the duration required to complete testing were recorded. The values were placed in a Microsoft Excel spreadsheet to illustrate the results as well as to calculate the statistical values for standard deviation, mean value, and confidence interval. The data and statistical results are illustrated in Appendix 3. Additionally, the Fischer least squares difference method (LSDM) was performed with SAS, and the results are illustrated in Table 3. The mean values and confidence intervals for each soil type are presented in Table 4.

Table 3
Fischer LSDM statistical analysis results

Soil Type	CO	CMWO	SMWO	Stove
Group ++	A	A	A	A
Big River Clay (Raw) ++	A	A	A	A
Big River Clay (Cement)	C	B/C	A	B
Big River Clay (Lime)	A	C	B	A
RCB 2 (Raw)	A	B	A	C
RCB 2 (Cement)	A/B	C	B/C	A
RCB 1 (Raw) ++	A	A	A	A
RCB 1 (Cement)	B/C	C	A/B	A
A-1 (Raw)	A	B	A	A
Silt (Raw)	B	B	B	A
Silt (Cement)	A/B	B/C	A	C
Silt (Lime)	A	C	B	D
Sand (Raw)	B	A	A	A
La 15 Clay ++	A	A	A	A

++ Statistically the same.

Table 4
Summary of Means and Confidence Intervals (CI)

Soil Type	CO	CMWO	SMWO	STOVE
LA 15 clay				
Mean	33.3	32.5	32.7	33.3
CI	0.63	0.67	0.66	1.26
Big River clay				
Mean	34.9	35.7	35.4	35.3
CI	0.69	0.47	0.46	0.74
Big River clay (cement)				
Mean	29.9	31.0	32.7	31.2
CI	0.24	0.48	0.46	1.51
Big River clay (lime)				
Mean	29.7	27.0	28.5	29.3
CI	0.19	0.38	0.11	0.50
RCB 2				
Mean	15.4	14.8	15.5	13.6
CI	0.04	0.21	0.05	0.44
RCB 2 (cement)				
Mean	15.1	14.6	14.8	15.4
CI	0.07	0.16	0.13	0.66
RCB 1				
Mean	12.1	12.0	11.9	12.0
CI	0.10	0.28	0.33	0.42
RCB 1 (cement)				
Mean	12.1	11.8	12.5	12.6
CI	0.07	0.24	0.21	0.37
A-1				
Mean	3.7	3.4	3.9	3.7
CI	0.14	0.18	0.18	0.14
ALF silt				
Mean	10.1	10.1	10.1	10.8
CI	0.33	0.07	0.18	0.41
ALF silt (cement)				
Mean	15.0	14.7	15.2	14.6
CI	0.04	0.07	0.26	0.34
ALF silt (lime)				
Mean	15.9	14.9	15.2	14.2
CI	0.09	0.16	0.04	0.27
Sand				
Mean	5.0	5.8	6.1	6.0
CI	0.25	0.23	0.60	0.35
Group summary				
Mean	17.9	17.5	18.0	17.8
CI	2.3	2.2	2.3	2.3

Appraisal of results: The results of the LSDM statistical analysis indicated that there was no statistical difference between devices on the soil groups as a whole. However, there were some statistical differences within the samples. Further review of the data from the statistical methods of standard deviation, mean values, and confidence intervals indicated that each of the devices should provide good results for the types of soils tested.

Statistical Analysis (Duration)

Mean: The mean values were used to evaluate the statistical performance of the CMWO, and SMWO for each soil type. The duration used for drying soil with the CO was 16 hours. Since the CO is not considered a rapid moisture content device, its duration was not included in this evaluation. Figure 1 illustrates the overall mean for each device while table 10 lists the mean values obtained with each device per soil group. The results indicated the overall mean durations for the CMWO and SMWO were 34 and 23 minutes, respectively.

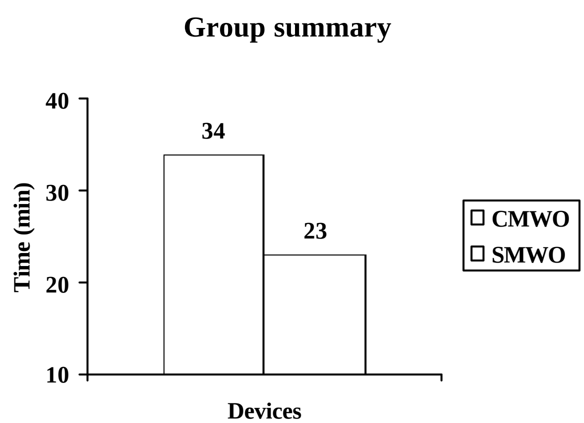

Figure 1

Summary of drying durations

Table 5
Summary of mean duration values

Soil Type	Mean duration (minutes)	
	CMWO	SMWO
Group	34.6	23.2
Big River Clay (Raw)	52.7	22.8
Big River Clay (Cement)	47.3	29.8
Big River Clay (Lime)	50.7	30.2
RCB 2 (Raw)	30.5	21.5
RCB 2 (Cement)	33.3	24.0
RCB 1 (Raw)	27.0	25.0
RCB 1 (Cement)	29.0	20.5
A-1 (Raw)	{1} N/A	24.5
Silt (Raw)	19.5	15.0
Silt (Cement)	32.0	19.8
Silt (Lime)	30.0	11.2
Sand (Raw)	34.2	24.0
La 15 Clay	29.5	31.7

{1} The time duration for this soil was erroneous.

High/Low Moisture Content

Conduction of tests and statistical analysis of moisture contents

Moisture content tests were conducted with the CMWO and SMWO on the soils listed in table 1. The values of the moisture contents along with the durations required to complete testing were recorded and placed in a Microsoft Excel spreadsheet to illustrate the results as well as to calculate the statistical values for standard deviation, average, and confidence interval. The data and statistical results are illustrated in Appendix 2. Figures 2 through 5 illustrate the moisture content results. The circles represent the mean values and the vertical lines represent the ranges of moisture contents above and below the means. Additionally, the TTEST was performed with SAS and used to evaluate the statistical performance of the CMWO and SMWO compared to each other. The results are listed in Table 6.

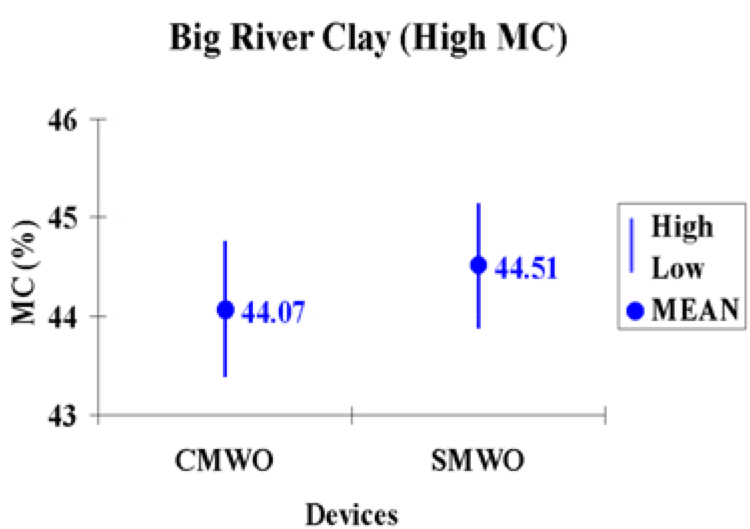

Figure 2

Big River Clay at high moisture content

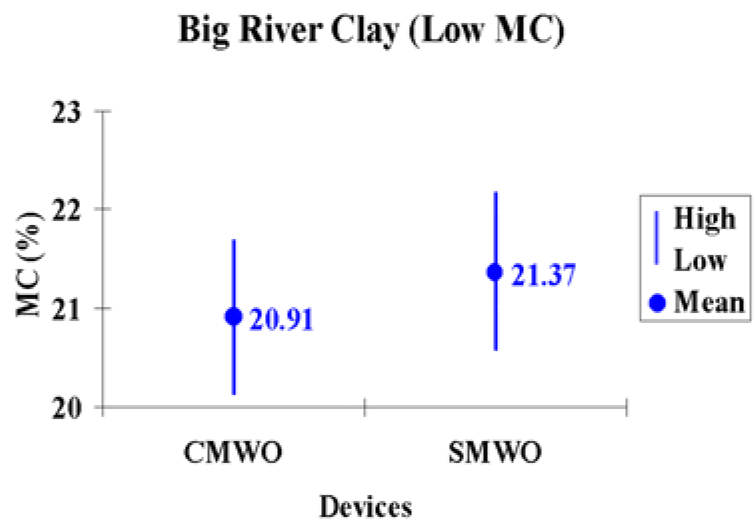

Figure 3

LA 15 Clay at low moisture content

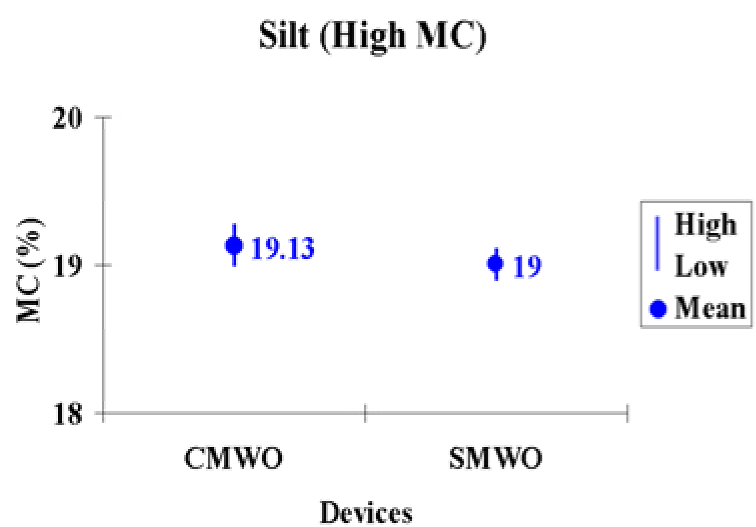

Figure 4

Silt at high moisture content

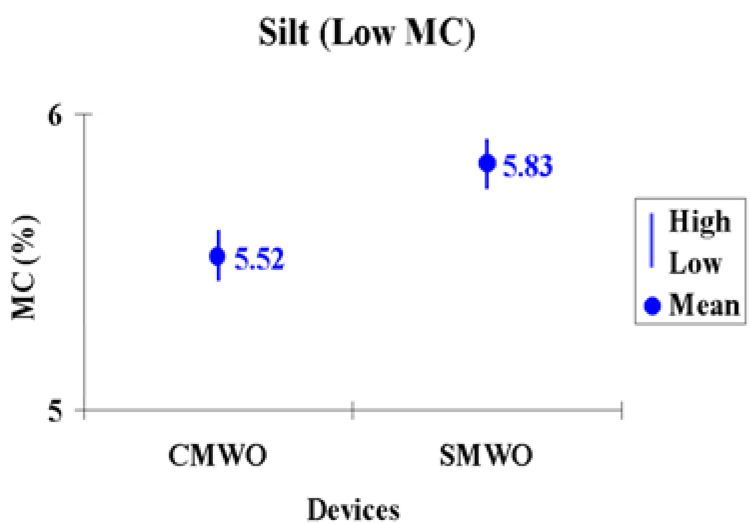

Figure 5

Silt at low moisture content

Table 6
TTEST statistical analysis results

Soil Type	CMWO	SMWO
Group	A	A
Big River Clay (High moisture content)	A	A
Big River Clay (Low moisture content)	A	A
Silt (High moisture content)	A	A
Silt (Low moisture content)	B	A

Discussion: The results of the TTEST indicated that the means of the devices were statistically the same on the high and low moisture content tests for the Big River clay and the high moisture content test on the silt. The mean values for the silt low moisture content tests were 5.5 and 5.8 percent, respectively. The difference in moisture contents, 0.3 percent, was considered insignificant in a practical sense. Therefore, based on appraisals of the data from figures 2 through 5, table 6, and appendix 2, the performance of the CMWO and SMWO are equal.

Benefits/Costs Analysis

Currently, DOTD uses the stove method to determine moisture contents of soils in the field. The sample size is approximately 2,200 grams, and it usually takes about one hour to complete testing. Since no data was available to determine its accuracy, the stove method conducted in the field was assumed to have the same accuracy as the stove method used in this study.

The laboratory study showed that both microwave ovens produced accurate results. Because the heat source can be electronically regulated and the specimen is never stirred, a smaller specimen can be used with confidence. The microwave oven testing procedures developed in this study produced accurate results in less time than the current method used by DOTD.

A summary of the initial cost of the devices and the impact on salary costs is listed as follows:

1) **Initial Cost:** The cost of the device and accessories are included. The accessories such as scoops, containers, and water beakers cost approximately the same for all methods. The CMWO has a built-in electronic scale and requires a

computer to perform testing. The stove method and SMWO both require an electronic scale to accurately measure samples.

a. DOTD TR 403-92 (stove)

Stove	$100.00
Accessories	$100.00
Scale	$800.00
Total:	**$1,000.00**

b. CMWO

Computer Controlled	
Microwave Oven	$4,500.00
Lap-Top Computer	$2,000.00
Accessories	$100.00
Total	**$6,600.00**

c. SMWO

Microwave Oven	$150.00
Accessories	$100.00
Scale	$800.00
Total	**$1,050.00**

Discussion: As shown above, the cost of purchasing the CMWO greatly exceeds the costs of purchasing the SMWO and stove. Based on initial costs, it is more feasible to use either the SMWO or stove to perform moisture content testing.

2) **Salary**: The cost to complete testing per mile was determined for each method. A salary of $15.00 per hour and 18 tests per mile were used for each testing method. Since it is more feasible to use the stove or SMWO, the salary costs for using the CMWO are not included in this portion.

a. Field method

Cost per mile: 18 tests/mile x 1.0 hr/test x $15/hr = $270.00 / mile

b. SMWO

Cost per mile: 18 tests/mile x 0.42 hr/test x $15/hr = $112.50 / mile

Discussion: As illustrated in figure 6, there is a savings of $158,500.00 for every 1000 miles of roadway constructed. Based on the initial costs of the device and salary cost savings, the SMWO method is the most feasible.

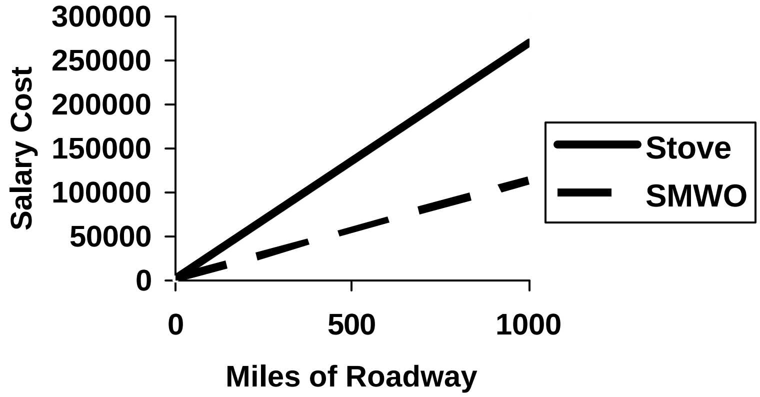

Figure 6

Salary cost comparison

CONCLUSIONS

The procedures developed and used for drying soils with microwave ovens are timely, efficient, accurate, and safe. There were no aggregate explosions, fires, or vaporization of organics at the power settings and testing intervals used in this study. The statistical analysis methods used indicated that both microwave ovens were accurate and could be used to dry soils at a rate approximately 50 percent faster than the current method used by DOTD. The benefits to costs analysis indicated that the standard microwave oven is the most feasible device to use and that, if drying soils with the SMWO were implemented, DOTD would save $158,500.00 for every 1000 miles of roadway that were constructed.

RECOMMENDATIONS

Microwave ovens are a viable means of rapidly drying soils. This study has shown that they are safe, accurate, and efficient. The standard microwave oven is the best alternate device based on accuracy, testing duration, and benefits to cost analysis. The PRC recommended that a specification be written to dry soils with the standard microwave oven. The proposed specification "DOTD TR 403-01, Method C, Rapid Drying with Microwave Oven" was written and submitted to the specifications committee for review and consideration.

The PRC also recommended that the microwave oven be evaluated with smaller specimen sizes (50 to 100 grams). If the microwave oven proves to be accurate with these smaller specimens, then it could be used to obtain moisture contents for soil classifications and Atterberg limits in the laboratory. This would enhance the efficiency of the laboratory since moisture contents could be obtained within 20 minutes instead of 24 hours. LTRC has begun a laboratory program to determine the accuracy of the microwave oven using smaller specimen sizes.

The District 03 and 62 laboratory engineers have conducted field trials with the microwave oven. The results of these tests are shown in Appendix 1. The results from the Districts are consistent with the findings of this report.

ACRONYMS, ABBREVIATIONS, & SYMBOLS

CMWO	Computer Controlled Microwave Oven
CI	Confidence Interval
CO	Convection Oven
SMWO	Standard Microwave Oven

REFERENCES

1. Mendoza, M.J. and Orozco, M., "Fast and Accurate Techniques for Determination of Water Content in Soils," Geotechnical Testing Journal, GTJODJ, Vol 22, No. 4, December 1999, pp 301-307.

2. Gilbert, P.A., "Rapid Water Content by Computer-Controlled Microwave Drying," Journal of Geotechnical Engineering, Vol. 117, No. 1, pp. 118-138

3. Gilbert, P.A., "Computer Controlled Microwave Oven system for Rapid Water Content Determination", Dept. Of Army, Waterways Experiment Station, Corps of Engineers, Technical Report Number GL-88-21, November 1988

4. ASTM (1995), "Standard test method for determination of water (moisture) content of soil by the microwave oven method.", Standard D4643-93, Volume 04.08, American Society for Testing and Materials, Philadelphia, Pa.

APPENDIX 1

Moisture content testing results from Implementation program

Researcher	Moisture Contents (%)		
	CO	SMWO	Stove
District 03	18.9	20.1	20.9
District 62	----	6.9	6.5

APPENDIX 2

Soils Classifications

Soil Type	+ 10	+ 40	+ 200	% Silt	% Clay	Optimum Moisture Content	Plastic Index
Silty Sand A-4(0)	0	0.16	56.72	33.12	10	15.5	np
LA 15 Clay A-7-6(52)	0.85	4.45	4.7	25	65	32.4	50.2
Sand A-1-b	10.62	53.47	35.56	0.34	N/A	6.5	np
RCB-1 A-4(2)	1.51	7.05	19.98	53.24	16.2	14.1	6
RCB-2 A-2-4(0)	23.04	3.06	50.82	10.77	12.31	12.3	1
Sand + Aggregate A-1-a	75	20	5	N/A	N/A	4.0	np
Big River Clay A-7-6(71)	0	0	1	20	79	35	62

APPENDIX 3

Moisture content testing data

Rapid Moisture Content Testing								
Soil type	**Clay w/ cement @ Big River**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	30.00	960	31.98	52	33.00	32	29.60	20
2	30.00	960	30.75	45	32.70	29	29.90	24
3	29.60	960	30.28	46	31.90	30	33.40	25
4	30.30	960	30.70	47	32.40	30	29.90	23
5	29.50	960	30.80	47	32.50	28	33.80	25
6	30.00	960	31.39	47	33.60	30	30.60	23
Standard deviation	0.2966		0.6036		0.5776		1.8921	
Average	29.90	960.00	30.98	47.33	32.68	29.83	31.20	23.33
Confidence interval	0.24		0.48		0.46		1.51	

Rapid Moisture Content Testing								
Soil type	**Clay w/ lime @ Big River**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	29.90	960	27.60	53	28.30	29	29.00	17
2	30.00	960	26.80	47	28.60	30	28.20	18
3	29.60	960	26.20	49	28.30	30	29.20	20
4	29.50	960	27.30	53	28.60	31	29.70	20
5	29.60	960	27.00	51	28.50	30	29.90	23
6	29.40	960	27.10	51	28.50	31	29.70	21
Standard deviation	0.2338		0.4775		0.1366		0.6306	
Average	29.67	960.00	27.00	50.67	28.47	30.17	29.28	19.83
Confidence interval	0.19		0.38		0.11		0.50	

Rapid Moisture Content Testing								
Soil type	**Clay @ Big River (High Moisture)**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	46.5 {1}		44.25	24	45.15	26		
2			45.25	36	45.17	30		
3			44.71	36	45.01	28		
4			43.80	38	43.34	30		
5			43.45	37	44.58	28		
6			42.95	37	43.80	34		
Standard deviation			0.8422		0.7711			
Average			44.1	34.7	44.5	29.3		
Confidence interval			0.67		0.62			

{1} Only one moisture content test was conducted to use as a reference

Rapid Moisture Content Testing

Soil type	**Clay @ Big River (Low moisture)**							
Sample number	C O		C M W O		S M W O			
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)		
1	21.5 {1}	960	21.15	31	20.00	20		
2			19.04	28	21.18	24		
3			21.39	23	22.00	22		
4			21.24	23	22.33	22		
5			20.84	26	22.24	26		
6			21.77	25	20.46	22		
Standard deviation			0.9631			2.0656		
Average			20.9	26.0	21.4	22.7		
Confidence interval			0.77			1.65		

{1} Only one moisture content test was conducted to use as a reference

Rapid Moisture Content Testing								
Soil type	**RCB 2**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	15.40	960	15.10	28	15.50	22	12.80	11
2	15.40	960	14.98	31	15.40	20	13.30	12
3	15.40	960	14.85	31	15.50	20	14.30	11
4	15.40	960	14.74	31	15.60	23	13.40	13
5	15.30	960	14.66	31	15.50	22	14.10	12
6	15.30	960	14.37	31	15.50	22	13.50	11
Standard deviation	0.0516		0.2574		0.0632		0.5502	
Average	15.37	960.00	14.78	30.50	15.50	21.50	13.57	11.67
Confidence interval	0.04		0.21		0.05		0.44	

Rapid Moisture Content Testing								
Soil type	**RCB 2 w/ cement**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	15.20	960	14.34	33	14.50	24	14.10	14
2	15.00	960	14.62	36	14.70	25	15.10	15
3	15.10	960	14.81	32	14.90	25	15.30	13
4	15.10	960	14.73	35	14.90	25	15.40	15
5	15.20	960	14.30	31	14.80	22	16.20	15
6	15.00	960	14.57	33	14.90	23	16.40	16
Standard deviation	0.0894		0.2055		0.1602		0.8280	
Average	15.10	960.00	14.56	33.33	14.78	24.00	15.42	14.67
Confidence interval	0.07		0.16		0.13		0.66	

Rapid Moisture Content Testing								
Soil type	**RCB 1**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	11.97	960	12.24	26	12.01	22	12.11	20
2	11.98	960	12.20	29	12.15	30	12.27	20
3	11.95	960	11.94	25	12.23	24	11.56	25
4	12.26	960	12.13	26	11.86	27	12.79	20
5	12.12	960	11.35	25	11.14	24	11.31	20
6	12.16	960	12.28	31	12.21	23	11.93	20
Standard deviation	0.1258		0.3509		0.4128		0.5260	
Average	12.07	960.00	12.02	27.00	11.93	25.00	12.00	20.83
Confidence interval	0.10		0.28		0.33		0.42	

Rapid Moisture Content Testing								
Soil type	**RCB 1 w/ cement**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	12.20	960	12.00	30	12.70	21	11.80	11
2	12.20	960	11.27	28	12.50	21	12.60	10
3	12.10	960	11.63	29	12.00	20	12.60	10
4	12.10	960	11.95	30	12.60	22	12.50	11
5	12.00	960	11.96	29	12.40	20	12.80	11
6	12.20	960	12.05	28	12.70	19	13.20	10
Standard deviation	0.0816		0.3032		0.2639		0.4579	
Average	12.13	960.00	11.81	29.00	12.48	20.50	12.58	10.50
Confidence interval	0.07		0.24		0.21		0.37	

Rapid Moisture Content Testing								
Soil type	**A-1**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	3.86	960	3.23	8	3.99	25	3.52	24
2	3.91	960	3.50	9	3.72	22	3.97	24
3	3.85	960	3.83	9	4.15	19	3.58	24
4	3.78	960	3.24	9	3.78	31	3.87	24
5	4.03	960	3.38	9	3.95	26	3.62	19
6	3.73	960	3.44	9	3.50	24	3.75	19
Standard deviation	0.1763		0.2206		0.2297		0.1763	
Average	3.72	960.00	3.44	8.83	3.85	24.50	3.72	22.33
Confidence interval	0.14		0.18		0.18		0.14	

Rapid Moisture Content Testing								
Soil type	**Silt**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	9.33	960	10.09	15	9.70	12	11.05	22
2	10.29	960	10.20	25	10.01	11	10.70	22
3	10.36	960	10.02	17	10.10	17	11.30	22
4	10.39	960	9.97	20	10.38	20	10.42	22
5	10.29	960	9.94	20	10.06	15	9.94	25
6	9.89	960	10.05	20	10.23	15	11.14	25
Standard deviation	0.4148		0.0931		0.2292		0.5122	
Average	10.09	960.00	10.05	19.50	10.08	15.00	10.76	23.00
Confidence interval	0.33		0.07		0.18		0.41	

Rapid Moisture Content Testing								
Soil type	**Silt w/ cement**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	15.00	960	14.74	32	15.50	18	14.90	7
2	15.10	960	14.77	33	15.00	19	15.00	9
3	15.00	960	14.68	33	15.60	22	14.90	8
4	15.00	960	14.72	32	15.10	21	14.40	7
5	15.00	960	14.65	32	15.20	20	14.20	9
6	15.10	960	14.89	30	14.70	19	14.00	9
Standard deviation	0.0516		0.0842		0.3312		0.4227	
Average	15.03	960.00	14.74	32.00	15.18	19.83	14.57	8.17
Confidence interval	0.04		0.07		0.26		0.34	

Rapid Moisture Content Testing								
Soil type	**Silt w/ Lime**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	15.90	960	15.04	29	15.10	12	14.00	6
2	16.00	960	15.00	32	15.20	10	14.20	6
3	15.90	960	14.94	29	15.20	11	14.20	6
4	15.70	960	14.95	30	15.20	12	14.20	6
5	15.80	960	14.74	30	15.20	11	13.80	6
6	16.00	960	14.51	30	15.10	11	14.80	6
Standard deviation	0.1169		0.2017		0.0516		0.3347	
Average	15.88	960.00	14.86	30.00	15.17	11.17	14.20	6.00
Confidence interval	0.09		0.16		0.04		0.27	

Rapid Moisture Content Testing								
Soil type	**Silt (Low moisture)**							
Sample number	C O		C M W O		S M W O			
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)		
1	19.1 {1}	960	5.43	16	6.02	17		
2			5.54	17	5.84	16		
3			5.53	17	5.71	16		
4			5.69	18	5.80	16		
5			5.42	17	5.81	16		
6			5.53	18	5.82	16		
Standard deviation			0.0975	0.7528	0.1019			
Average			5.5	17.2	5.8	16.2		
Confidence interval			0.08	0.60	0.08			

{1} Only one moisture content test was conducted to use as a reference

Rapid Moisture Content Testing								
Soil type	**Silt (High moisture)**							
Sample number	C O		C M W O		S M W O			
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)		
1	6.1 {1}	960	19.20	25	19.10	16		
2			19.30	24	18.90	18		
3			19.10	25	19.00	16		
4			18.90	22	18.90	18		
5			19.30	24	19.20	17		
6			19.00	24	18.90	17		
Standard deviation			0.1633		0.1265			
Average			19.1	24.0	19.0	17.0		
Confidence interval			0.13		0.10			

{1} Only one moisture content test was conducted to use as a reference

Rapid Moisture Content Testing								
Soil type	**Clay LA 15 (Raw)**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	34.32	960	33.65	29.8	33.24	35	34.17	60
2	32.54	960	31.22	29	31.68	35	33.18	60
3	33.48	960	32.20	29.5	32.45	30	30.31	60
4	33.86	960	33.11	41.3	32.12	25	34.90	60
5	33.10	960	32.35	30	32.72	30	33.54	60
6	32.24	960	32.21	29.3	34.00	35	33.69	60
Standard deviation	0.7895		0.8388		0.8272		1.5799	
Average	33.26	960.00	32.46	31.48	32.70	31.67	33.30	60.00
Confidence interval	0.63		0.67		0.66		1.26	

Rapid Moisture Content Testing								
Soil type	**Sand**							
Sample number	C O		C M W O		S M W O		Stove	
	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)	M C %	Time (min)
1	5.08	960	5.65	37	5.08	24	6.02	17
2	4.98	960	5.65	33	5.88	24	5.44	25
3	5.37	960	6.19	34	6.20	23	6.02	25
4	5.22	960	5.56	34	5.94	34	5.62	17
5	4.91	960	5.48	35	7.38	23	6.30	25
6	4.47	960	6.03	32	5.80	26	6.64	25
Standard deviation	0.3101		0.2830		0.7531		0.4378	
Average	5.01	960.00	5.76	34.17	6.05	25.67	6.01	22.33
Confidence interval	0.25		0.23		0.60		0.35	